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Risk Reduction in Geothermal Deep Direct-Use Development for District Heating: A Cornell University Case Study

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ABSTRACT

Cornell University in Ithaca, NY is potentially well-suited for a deep direct-use (DDU) geothermal heating system to serve our campus of ~30,000 people in >14 million sq. ft. of buildings. The heating demand for the existing natural-gas-fed district heating system is ~240,000 MW_{th}-hrs/yr; successful integration of DDU at Cornell would serve as a model for similar institutions and communities in cold-climate locations. Our current feasibility study focuses on risk reduction through joint analysis of two key aspects of developing a DDU system: 1) uncertainty quantification for reservoir modeling, and 2) surface-use options. We identify a range of coupled subsurface reservoir and surface-use scenarios for successful DDU implementation based on modeled estimates of heat production from the subsurface reservoir and a menu of flexible surface use options.

Quantifying uncertainty and constraining values of geologic properties is a necessary component of reservoir modeling. Lacking direct drilling data for the deep (>1 km) bedrock beneath Ithaca, we rely on petrophysical and stratigraphic analysis of well logs and reported cuttings from drilling performed regionally into the sedimentary basin rocks to estimate potential sedimentary reservoir properties. For potential crystalline basement rock targets (2.8-4.5+ km), which are essentially undrilled in our region, we have undertaken studies of Adirondack surface exposures of crystalline rocks considered to be analogs to the basement rocks beneath Ithaca.

Multiple options for the surface-use system to accommodate a range of subsurface temperatures and flow rates have been identified using a custom surface-use model we developed for the Cornell campus. The model is grounded in extensive energy use records for campus facilities, and includes options for cascaded thermal loads at a variety of temperatures, thermal storage, and the use of water-source heat pumps to extract additional heat at high COPs as a final cascaded use before reinjection to the reservoir.

Our models demonstrate that reasonable adjustments in design and operating conditions of surface systems could create a more than 10-fold improvement in heat output from a modest geothermal resource. While this result varies with each arrangement of subsurface resource and surface use design, our work suggests that determining the break-even point for DDU of low-temperature geothermal resources may rely more on an understanding of how heat can be beneficially used at the surface than on moderate differences in reservoir production. This type of integrated analysis can reduce DDU development risk by identifying positive value scenarios for a range of potential reservoir heat production rates at locations where subsurface data are limited.

1. INTRODUCTION

The United States Geological Survey has estimated that 46 GW_{th} of beneficial heat is available from low-temperature (< 90 ^{o}C) geothermal resources in the United States. This amount of heat is nearly 23% of the nation's residential heating demand. Space heating and other low-temperature end uses are currently supplied predominantly by combustion of fossil fuels at much higher temperatures than these end uses require, either directly in heaters or boilers, or indirectly through consumption of fossil-fuel-generated electricity. Direct use of low-temperature geothermal energy could displace consumption of these high-value resources, resulting in economic and environmental benefits. Additional benefits may be derived if power grid management is considered.

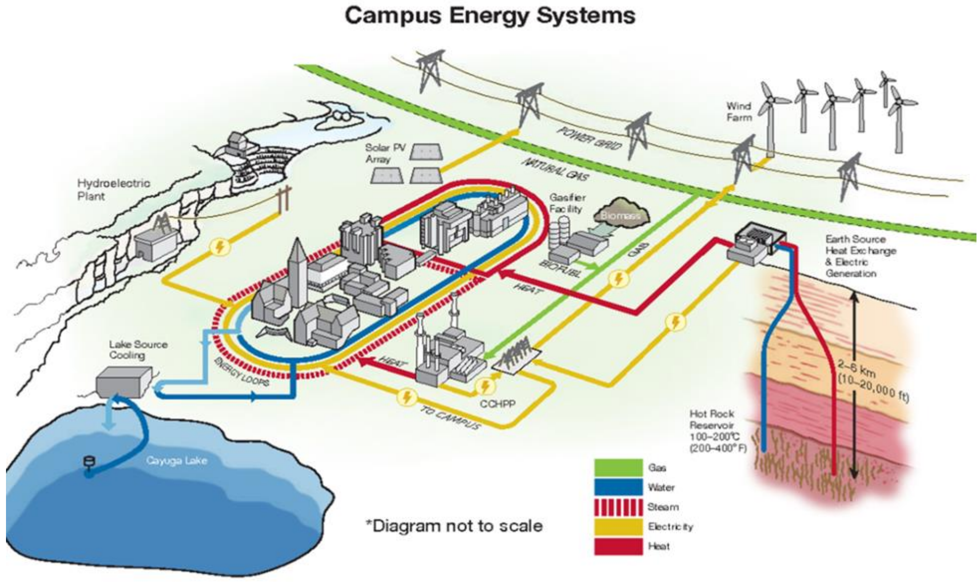


Figure 1: Schematic showing future integration of geothermal heat (right side of sketch) into the comprehensive Cornell University energy system. Major portions of this system are already in place, including the Lake Source Cooling component (lower left) and the central district heating loop.

Cornell University's campus of ~30,000 people in >14 million sq. ft. of buildings is located in the northeastern United States, in a region where the monthly average air temperature during the four months of winter varies between 22.3 °F (January) and 32.6 °F (March)[1]. Development of low-carbon and carbon-free approaches to heating are foundational pieces of Cornell University's Climate Action Plan (Cornell University, 2016). The University envisions that research leadership in energy innovation will play a key role and that the campus itself will serve as a living laboratory (Fig. 1). Under contract from the U.S. Department of Energy, Cornell University is assessing the feasibility of Deep Direct-Use (DDU) geothermal energy for meeting a minimum of 20% of the heating needs of our main campus in Ithaca, NY. This amounts to about 166,000 MMBtu (175,000 GJ) per year, a level expected to remain relatively constant over the next 20 years or more. Additionally, > 100,000 MMBtu (106,000 GJ) per year of cascaded heat would be provided. We are exploring a range of technology options for surface management of thermal resources and investigating the compatibility of two potential subsurface reservoirs with those technology options.

In the context of the U.S. geothermal resources, the Appalachian Basin is a low-temperature region (Fig. 2A); however, the Southern Tier of New York State near Cornell is estimated to be a relatively hot spot, with temperatures suitable for district heating at reasonable drilling depths (Fig. 2B). The Cornell study is focused on utilizing geothermal resources estimated to be less than 120 °C. Conventional reservoir modeling is used to estimate the thermal energy produced over time for two potential target formations.

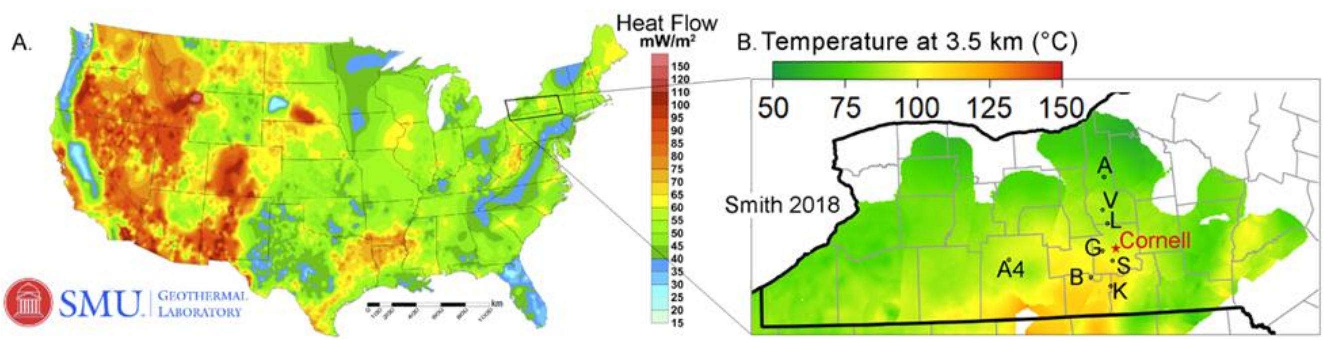


Figure 2: Location of Cornell University feasibility study relative to A) heat flow across the United States (Blackwell et al., 2011) and B) median modeled temperature at 3.5 km depth across the Appalachian Basin sector of New York state (J. Smith, 2018, unpublished). Fig. 2B shows Cornell's location as a star, and the locations of a small subset of the available deep boreholes. This subset contains some of the most critical data sets for our analysis (A, Auburn Geothermal; V, Venice View Dairy; L, Lansing; G, Grund; S, Shepard; B, Bale; K, Kesselring; A4, Avoca-4).

[1] http://www.nrcc.cornell.edu/wxstation/ithaca/normal.html

To properly connect reservoir sizing with end use requirements, we have performed a detailed evaluation of surface thermal demands on the Cornell campus. Demand-side analyses have identified and documented thermal loads and potential uses. Our study considers a variety of optimization schemes to improve the economics of a potential DDU application. These include thermal storage and heat pumps, flexible cascading use of the thermal resource over a range of temperatures, and minimization of necessary geothermal fluid supply through coupling to other heat sources at times of peak heating needs (e.g., using biofuels when demand peaks). Beyond the core application of providing heat and hot water for campus buildings and laboratories, potential cascaded uses for heat include controlled agriculture (hydroponics, aquaculture, greenhouses), specialized agricultural uses (biomass drying), and snow melting. The first goal of this analysis is to find a cost-effective and productive means of using available DDU energy for the Cornell campus. A second goal is to provide flexible tools suitable for analyzing other sites with different thermal resources and needs.

A key outcome of the Feasibility Study will be an assessment of the economic (financial) risk associated with the University's pursuing DDU heating on a large scale. The Cornell team is developing Levelized Cost of Heat (LCOH) estimates that consider the technical uncertainty in heat production from the potential subsurface reservoirs as well as uncertainty in economic values, such as the cost of drilling. Heat production uncertainty is quantified by stochastic simulations of thermal-hydraulic geothermal reservoir models that are based on local and regional subsurface datasets. Cornell has not performed deep drilling on campus and very few deep reservoir tests have been conducted nearby. For a potential sedimentary aquifer at a depth suitable to produce a temperature of approximately 70 °C, regional drilling for oil and gas exploration has provided ranges for some of the geologic parameters needed for geothermal reservoir modeling. For a potential deeper and hotter crystalline basement reservoir, almost no directly sampled temperature or geologic data exist in the region, so the uncertainty in modeled heat production is higher.

The first section of this paper describes Cornell's approach for subsurface modeling of two potential target reservoirs, including how geologic parameters are estimated and constrained in the absence of direct measurements near the Cornell campus. The second section describes Cornell's current thermal energy use profile, the potential for additional cascading uses, and strategies for thermal management or enhancement (e.g. hot water storage, heat pumps) to maximize the productive utilization of heat from the subsurface. The last section presents estimates of reservoir production and how various combinations of flow and temperature can be efficiently and economically utilized for campus heat.

2. UNCERTAINTY IN GEOTHERMAL RESERVOIR PRODUCTION

The subsurface geothermal resource evaluation builds upon the knowledge of thermal and reservoir conditions estimated by the Appalachian Basin Geothermal Play Fairway Analysis, which placed Cornell on the margin of a high priority geothermal play (Cornell University, 2017). Two potential geothermal reservoir target formations are being evaluated for their feasibility to meet the heating demands of the Cornell campus. The shallower target is in sedimentary rocks at approximately 2270 m depth within the Trenton-Black River (TBR) carbonate group. Regionally, TBR reservoirs contain hydrothermally altered dolomite with Darcy-scale permeability, yet these suitable reservoirs are spatially dispersed, with locations controlled by subtle faults that have no surface expression (Camp and Jordan, 2017). The deeper target is in Precambrian basement rock starting at 3000 m depth, for which limited information about hydrogeologic and thermal properties is available in the Cornell region. Uncertainties in the expected temperature at depth and geologic properties are propagated through thermal-hydraulic models of each reservoir using stochastic simulations to estimate the range of likely thermal production for incorporation into several utilization scenarios. In this section, we present the selection of geologic properties and their probability distributions for the TBR and basement rock geothermal reservoir simulations.

The TBR sedimentary reservoir was modeled as porous media using the numerical thermal-hydraulic model TOUGH2 (Pruess et al., 2012). An analytical model with multiple parallel fractures (Gringarten et al., 1975) was used to model fractured basement rocks. There are three main considerations for each of these geothermal reservoir models: 1) selection of the properties for the rock matrix and associated geological structures, 2) setting the initial and boundary thermodynamic conditions, and 3) selecting the parameters of the model simulation. The values and data sources used in our study are discussed in the following sections. Summaries are provided in Table 1A/1B, Table 2, and Table 3. Following those discussions, reservoir modeling results are presented.

2.1 Stratigraphy

The geologic formations of interest for geothermal reservoir simulation include the reservoir rocks through which fluid must flow, and the surrounding caprocks and base rocks that primarily supply conductive heat recharge to the reservoir. Simplifications to the full geologic column, where appropriate, are beneficial for computational efficiency in numerical simulations, such as those completed using TOUGH2.

Sedimentary rocks beneath Cornell accumulated in the marine Appalachian Basin during the Paleozoic. Above the Trenton-Black River (TBR) sedimentary reservoir target exists a thick shale sequence, the Lorraine/Utica (Fig. 3). The Utica will likely act as a barrier to fluid flow (e.g. nanodarcy permeability in Carter and Soeder, 2015). Based on local well logs, this shale sequence is expected to be about 200 m thick below Cornell. Given the properties of these formations, we expect these to be caprocks to the TBR reservoir, so we did not model shallower geologic formations.

Formations between the Utica and basement rocks were analyzed in greater detail because there is no known geologic unit that will restrict fluid flow (Fig. 3). Changes in density and porosity in local well logs were used to select geologic formations to treat as groups containing similar density and porosity mean and variability. The resulting generalized stratigraphic column for Cornell is provided in Table 1A. The estimated depths to each of the formation tops are provided along with formation properties that were used in numerical reservoir modeling. For the estimated uncertainty in the depth to the basement of ± 200 m, about ± 3.5 °C change in the temperatures at the top of the basement are expected. We do not explicitly model the stratigraphy uncertainty in reservoir models in this paper, although these uncertainties were considered in the estimation of temperatures at depth (Figure 5).

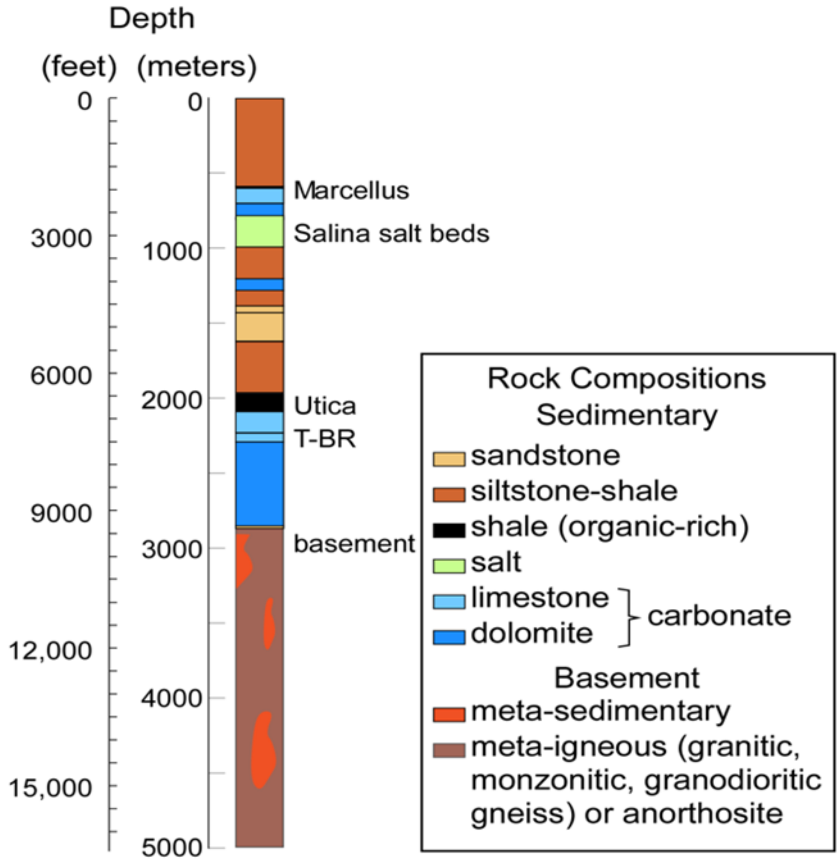


Figure 3: Approximate geological column beneath Cornell University. Sedimentary rocks are estimated to extend to nearly 2800 m depth, underlain by metamorphic basement. Potential reservoirs in the Trenton-Black River (TBR) and uppermost part of the basement are under evaluation in this study.

Basement Rock Lithologies

We expect that the basement metamorphic rocks are of a wide range of petrological groups (metanorthosite and anothosite gneiss; metasedimentary; granitic, charnockitic, mangeritic, and syenitic gneiss; biotite and/or hornblende granite gneiss; mangerite, pyroxene(hornblende) syenite gneiss; etc.), as in the Adirondack Mountains, located about 170 km from Cornell. B. Valentino (Cornell internal report, 2016) examined well cuttings from five boreholes in central New York that penetrated basement, and cores from mineral exploration boreholes located near the northeastern margin of the Appalachian Basin in New York; these samples are archived by the New York State Museum. Whereas most of the cuttings material consists of disaggregated individual crystals, rock fragments include marble, hydrothermally altered granite to monzonite gneiss, calcite vein fragments, hornblende granodiorite gneiss, and amphibolite (B. Valentino, 2016). This study confirms that we expect to see crystalline basement rocks at Cornell similar to those rocks that are exposed in the Adirondack Mountains. The cores examined (B. Valentino, 2016) and maps of the Adirondack Mountains indicate that the basement composition changes over horizontal distances of meters to kilometers, and imply that a borehole at Cornell will traverse several lithologies, especially if directional drilling is used in basement rocks. Owing to this heterogeneity, we assume geologic properties that are representative of Adirondack Mountain rocks in aggregate from Simmons (1964). These aggregate properties are similar to granitic gneiss, the most common lithology.

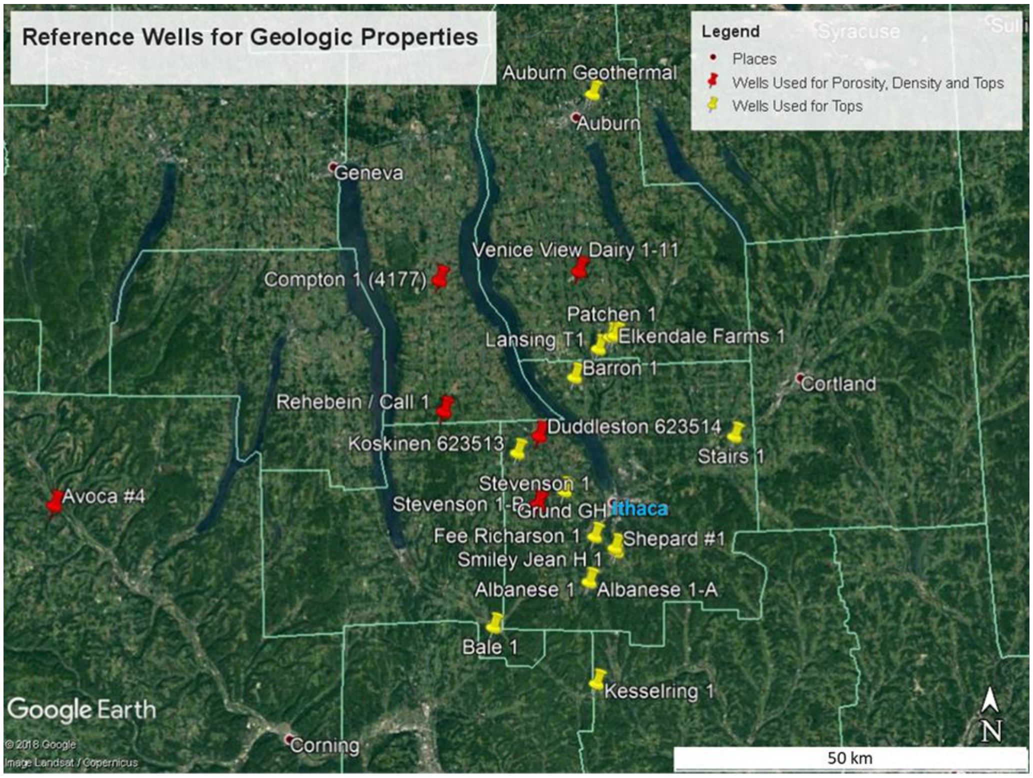


Figure 4: Locations of reference wells for lithologic properties and well logs near the Cornell project site. Wells with yellow pinpoints were used to inform formation tops at Cornell. Wells with red pinpoints were also used for density and porosity information. Ithaca, the location of Cornell, is shown on the map.

2.2 Petrophysical properties

Key petrophysical data needed for reservoir modeling include porosity, permeability, thermal conductivity, heat capacity, and rock density (Table 1A/1B). Since we do not have site-specific measurements of these parameters at our target depths, we used regional well logs (Figure 4) and published datasets for the formations of interest, or of similar lithologies.

A set of well logs from six boreholes within 50 km of Cornell (Fig. 4), provided values for formation porosity and density. Permeability values are not as readily available from published studies for our formations, and values that were obtained are laboratory-derived core values, not *in situ* values. The values obtained are the best available, generally from core studies from Ohio, Pennsylvania, and western New York (Table 1A).

Thermal conductivity values for the Southern Tier of NY State, including the Cornell region, were estimated as part of the Appalachian Basin Geothermal Play Fairway Analysis project (Cornell University, 2017). Carter et al. (1998) was the primary source used for thermal conductivity values when basin-specific information was not available. The Carter et al. (1998) samples were taken from the Anadarko Basin, which has a burial history similar to the Appalachian Basin.

Formation Name	Modeled Formation Top Depth (m)	Porosity (-)	Permeability H: horizontal V: vertical (mD)	Density (kg/m³)	Thermal Conductivity (W/m-K)	Specific Heat Capacity (J/kg-K)	TOUGH2 No. of Vertical Grid Cells: Cell Size (m)	Sources and Notes
Lorraine / Utica Shale	1860	0.04	H: 5E-6 V: 5E-6	2700	0.9	830	Boundary Condition 1: 0.1 m 1: 199.9 m	Permeability: Carter and Soeder (2015) Heat Capacity: Waples and Waples (2004)
Trenton Limestone	2060	0.02	H: 5 V: 0.005	2690	2.11	870	1: 105 m 5: 10.5 m 10: 3.15 m 10: 2.1 m	Permeability anisotropy based on Camp and Jordan (2017)
Black River Dolomite	2270	0.07	H: 250 V: 2.6	2800	2.91	930	15: 2 m	Vertical permeability from Camp and Jordan (2017)
Black River Limestone	2300	0.01	H: 0.5 V: 0.0005	2700	2.11	880	20: 2 m	Permeability anisotropy based on Camp and Jordan (2017)
Beekmantown Group: Tribes Hill / Little Falls Carbonates	2340	0.02	H: 2.6 V: 2.6	2780	3.79	880	5: 11 m 3: 18.3 m 2: 55 m	Permeability: Camp (2017)
Galway / Theresa Carbonates / Rose Run Sandstone	2560	0.01	H: 2.6 V: 2.6	2610	3.34	880	1: 220 m	Porosity and Permeability: Smith et al. (2005), Camp (2017)
Potsdam Sandstone	2780	0.01	H: 0.002 V: 0.0002	2640	4.27	860	1: 20 m	Porosity and Permeability: Kolkas and Friedman (2007), Waller et al. (1978) Heat Capacity: Abdulagatov et al. (2014)
Precambrian Basement: Granitic Gneiss	2800	0.01	H: 0.001 V: 0.001	2730	2.83	825	1: 199.9 m Boundary Condition 1: 0.1 m	Porosity and Permeability: Selvadurai et al. (2005) Density: Simmons (1964, Table 1) Thermal Conductivity: Southern Methodist University divided bar measurements on 2 samples of Adirondack granite gneiss.

Table 1A: Generalized geologic column for Cornell with estimated formation depths, geologic properties, and grid cell sizes used in TOUGH2 numerical geothermal reservoir simulations. Sources specific to each formation are provided in this table, and generic sources are provided in Table 1B

Parameter	Source and Notes Summary
Depths, thicknesses, and rock types.	A generalized stratigraphic column for geologic units expected below the Cornell site was estimated using deep wells with log data that include target sedimentary reservoir formations. Figure 4 provides well locations used in our analysis. Basement lithologies were gathered from central New York deep boreholes, as analyzed by B. Valentino (2016).
Rock Density	Density logs for six nearby wells (Figure 4).
Rock Porosity	Porosity and density logs for six nearby wells (Figure 4), corrected for shale and gas in our study.
Rock Thermal Conductivity	We use the mean value for each formation, as processed in Cornell University (2016). Most values in that dataset are assumed from Carter et al. (1998) by lithology.
Rock Specific Heat Capacity	We use data and estimation methods provided in Robertson and Hemmingway (1995). We use their generic temperature-heat capacity equations by lithology. We used the estimated mean formation temperature at depth in the equations.
Pore Compressibility Pore Expansivity Tortuosity Factor	We set these parameters to 0 for our study, which are the default values in TOUGH2 (Pruess et al., 2012). Setting the tortuosity to 0 results in using the Millington and Quirk (1961) relationship to compute tortuosity within TOUGH2 (Pruess et al., 2012). The Millington and Quirk (1961) relationship is related to rock porosity.

Table 1B: Generic sources of geologic properties for formations listed in Table 1A.

2.3 Fracture systems for basement reservoir modeling

As a first-order simplified approach, the basement reservoir was modeled assuming unidirectional, uniform flow through a set of parallel vertical fractures (Gringarten et al., 1975). Fracture spacings and apertures in basement rocks were estimated based on field mapping of outcrops in the Adirondack Mountains, and on mapping of larger scale fracture sets using airborne LiDAR data. Fractures in Adirondack rocks are present across a range of length scales from less than 1 m in densely fractured rock to tens of meters in sparsely fractured rock. In analytical models, we considered flow in fractures with spacings ranging from 30 m to 200 m over a 1 km horizontal lateral well length. For simulations near the top of basement, results revealed that fracture spacing greater than about 50 m may not provide adequate long-term production. We present basement reservoir results for simulations with 30 m fracture spacings, considered a reasonable assumption, which produces favorable long-term production. If such spacings do not occur naturally for basement rocks below Cornell, it may be possible to use EGS techniques to engineer such a fracture system.

2.4 Initial conditions and boundary conditions

Establishing stable initial conditions is necessary for any geothermal reservoir model. Initial conditions are based on available regional data, and numerical simulations are allowed 5000 years to reach a steady state before geothermal production begins. Initial conditions and boundary conditions are discussed in the following sections for pressure, temperature, and heat flow.

Formation Pressure Profile

Hydrostatic pressure conditions have been observed in central New York boreholes (e.g., Auburn geothermal borehole, Lynch and ENG, 1983). Based on brine density data from 56 wells across northern PA and southern NY, we assumed a hydrostatic pressure profile with pore fluid density of 1180 kg/m^3. For numerical modeling, the shallowest grid cells have a constant pressure boundary condition consistent with this hydrostatic pressure profile.

Temperature Profile

Temperatures at depth within the Appalachian Basin were estimated by Smith (Ph.D. thesis Ch. 3, in preparation) using a 1D heat conduction model (Horowitz, Smith, & Whealton, 2015) and a generalized regional stratigraphic column. The estimation by Smith considered uncertainty in geological (formation depth and thickness) and thermodynamic (thermal conductivity, radioactivity) variables, and spatial correlations of the available temperature data (kriging spatial interpolation uncertainty). A Monte Carlo analysis consisting of 10,000 replicates of these uncertain variables was used to estimate temperatures at depth.

Figure 5 shows the predicted distributions of temperatures at depth below Cornell in 500 m increments. Uncertainty increases with increasing depth. The basement depth is located between 2.5 km and 3 km, after which a change in geothermal gradient occurs. This is a result of modeling assumptions; local data were not available with which to estimate the parameters of a heat generation model for basement rocks (e.g. Lauchenbruch, 1970), and that epistemic model uncertainty is not considered in this uncertainty analysis.

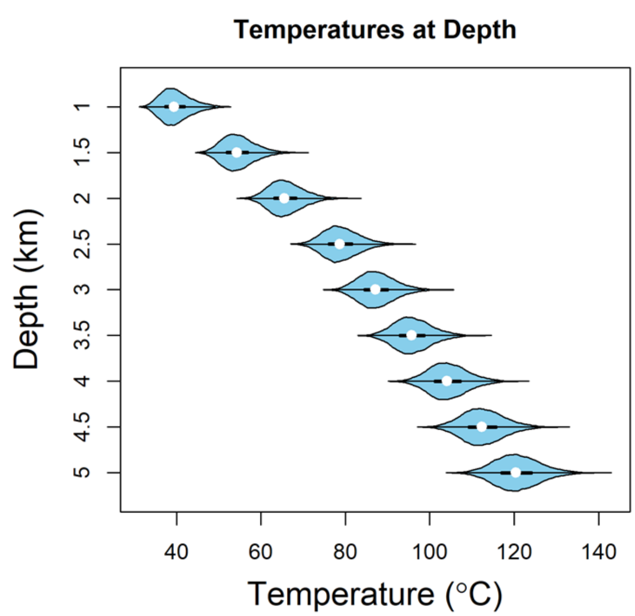


Figure 5: Violin plots (kernel density plots with a boxplot in the center) of the temperature at depth based on 10,000 Monte Carlo replicates of uncertain variables. White dots are the median estimates of the temperature at depth. The black box in the center extends from the 25th to the 75th percentile estimate.

For numerical reservoir modeling, we evaluated temperature profiles corresponding to the coolest 5th percentile, median, and warmest 5th percentile in Figure 5. The shallowest grid cells used a constant temperature boundary condition consistent with these temperature profiles.

Heat Flow Boundary Condition

The heat flow upwards into the bottom of the numerical simulation grids was obtained by projecting the predicted surface heat flow to the depth of interest using the Smith (2016) 1D thermal model heat balance (Horowitz, Smith, & Whealton, 2015). For Cornell, we obtained a heat flow of 45 mW/m^2 at 3 km depth in the basement.

2.5 TOUGH2 simulation parameters

Numerical geothermal reservoir simulations completed using TOUGH2 used the geological parameters and gird cell sizes in Table 1A to define the simulation grid. Simulation parameters for the TOUGH2 numerical solver are described in Table 2.

Maximum number of Newton-Raphson iterations per time step Maximum number of time steps Length of time step Relative error tolerance	An adaptive timestep with a minimum of 100 seconds was used in numerical simulations. A maximum of 8 iterations per timestep was selected to achieve a relative error tolerance of 1E-5. The total simulation length was 40 years, which matches the proposed useful life of the Cornell system.

Table 2: TOUGH2 Numerical Geothermal Reservoir Simulation Parameters

2.6 Reservoir modeling uncertainty analysis

Given the lack of Cornell site-specific geologic and temperature measurements, an important aspect of this study is characterization of the uncertainty in the modeled reservoir performance given uncertainty in the input data. We base the uncertainty analysis on the ranges, distributions, and assumptions documented in the previous sections.

For numerical modeling of the Trenton-Black River (TBR) reservoir using TOUGH2, sensitive input parameters (flow, temperature gradient, reinjection temperature) were fixed for various cases. For flow rate, 30, 50, and 70 kg/s cases were evaluated. For temperature gradient, 5th, 50th, and 95th percentile cases were evaluated (Figure 5). For reinjection temperature, we assumed 20 °C because our surface heat utilization systems will allow us to control the reinjection temperature through variable extraction of heat from the geothermal fluid (see discussion of surface use technology below). Values of geologic parameters are used as specified in Table 1A, and were not considered uncertain for TOUGH2 analyses.

For analytical models, we used a Monte Carlo stochastic geothermal reservoir modeling approach to propagate the uncertainties in model input variables to the modeled reservoir performance. The analytical multiple parallel fractures model is implemented in the GEOPHIRES software (Beckers et al., 2018). We made modifications to GEOPHIRES for Monte Carlo analysis of uncertain geologic properties and temperatures. A summary of the input values and probability distributions used in GEOPHIRES is provided in Table 3.

For both numerical and analytical models, wellbore heat transfer losses in the production well over time (Ramey, 1961) were modeled using GEOPHIRES.

Variable	Basement Parallel Fractures Model	Notes and Sources
Reservoir Depth (km)	3 - 3.5	
Well Orientation in Reservoir	Horizontal	
Fracture Height (m)	500	
Fracture Width (m)	500	
Well Lateral Length (m)	1000	
Fracture Separation (m)	30 m	Adirondack Mountains
Fracture Width (mm)	0.5	Camp and Jordan (2017), Adirondack Mountains
Reservoir Impedance (GPa-s/m^3)	Triangular: 0.05, 0.15, 0.5	Camp et al. (2018) regional reservoir productivity.
Reservoir Rock Density (kg/m^3)	Triangular: 2550, 2730, 3200	Local well logs, Simmons (1964)
Reservoir Rock Porosity (-)	NA	Local well logs
Reservoir Rock Heat Capacity (J/kg-K)	Triangular: 800, 825, 850	Roberson and Hemmingway (1995)
Reservoir Rock Thermal Conductivity (W/m-K)	Normal: 2.83, 0.36	Cornell University (2016), matches assumptions in Smith (2019, Ch. 3)
Surface Temperature (°C)	Triangular: 8, 10, 12	Gass (1983), matches assumptions in Smith (2019, Ch. 3)
Geothermal Gradient (°C/km)	0 – 1.5 km: Triangular: 26.5, 29.5, 33.7 1.5 – 2.8 km: Triangular: 23.7, 24.4, 25 2.8 – 4 km: Triangular: 16.5, 17, 17.5	Obtained using Figure 5 data from J. Smith, 2019 (dissertation in progress), Ch. 3
Utilization System Capacity Factor (-)	Beta(4,2), 0.97 - 0.994	Allows for 2 - 10 days on average per year for maintenance
Number of Monte Carlo Replicates	1000	

Table 3: Summary of parameters used in the parallel fractures analytical reservoir model for basement rocks. Probability distributions are listed for those variables that were selected randomly within each Monte Carlo simulation. Triangular distributions list: lower bound, mode, and upper bound. Normal distributions list: mean and standard deviation. Lognormal distributions list: real space mean and standard deviation. Beta distributions list: left shape parameter, right shape parameter, lower bound, and upper bound.

2.7 Reservoir modeling results

We present predicted heat and temperature production results for the Trenton-Black River (TBR) play at 2.27 - 2.3 km depth, and for crystalline basement at 3.0 - 3.5 km depth.

The TBR reservoir porous-medium play was evaluated using TOUGH2. Heat production and production temperature results for several flow rates and initial rock temperatures are provided in Figure 6. For all of these scenarios, the heat production meets or exceeds the target heat production of 5.5 MW_{th}. The produced temperatures exceed the "low temperature facilities" (see Surface Use Modeling section) supply temperature of 60 °C for a minimum of about 20 years for the coolest 5th percentile temperature estimates. Given the uncertainty in the initial rock temperature, it is unlikely that the TBR reservoir would provide temperatures sufficient for "high temperature facilities" with 80 °C supply temperature.

Pumping rates have a clear impact on the time to thermal breakthrough. Pumping rates of 50 and 70 kg/s result in temperature declines within 10 years of operation. Pumping at 30 kg/s results in temperature decline beginning around 15 years, and a relatively longer time to complete thermal breakthrough.

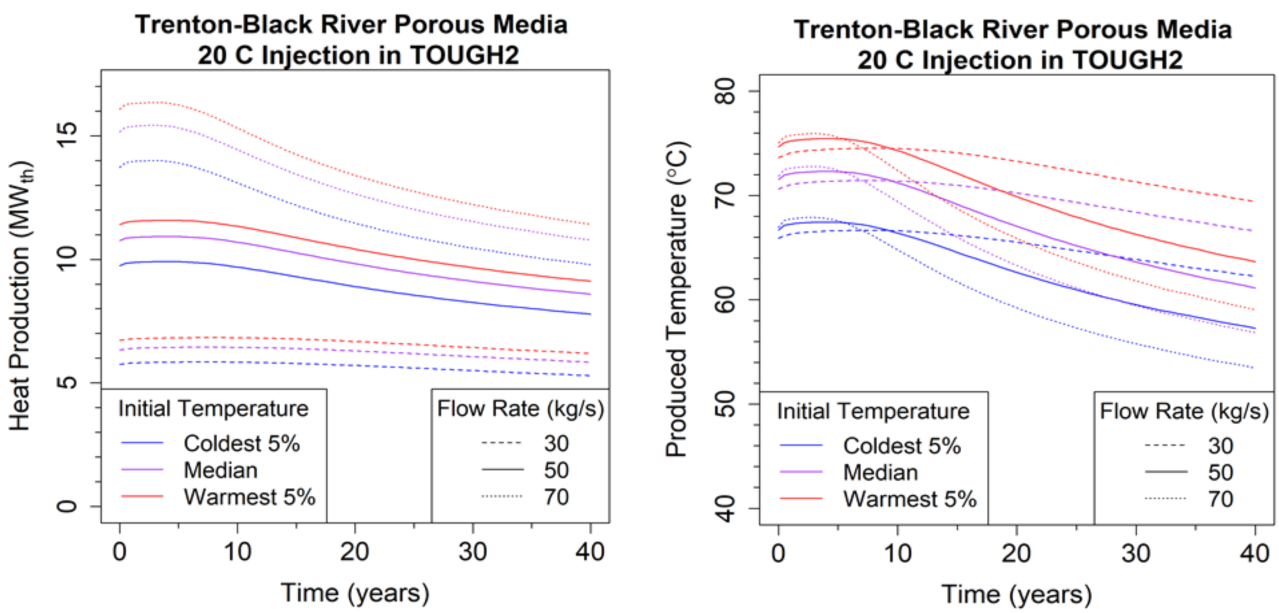


Figure 6: Estimated heat production and temperature over time for the Trenton-Black River for injection of 20 °C. The initial rock temperature percentiles were selected based on the estimated temperatures at depth (Fig. 5).

Results of Monte Carlo simulations of a hypothetical fracture-dominated reservoir at 3.0 – 3.5 km depth in basement rocks are shown in Figure 7 for a production well flow of 30 kg/s and a 20 °C reinjection temperature. All of the Monte Carlo replicates indicate heat production rates in excess of the 5.5 MW_{th} target. The median modeled production temperature ranges from ~85 °C at startup to close to ~88 °C in year 50. Such temperatures would be sufficient for "high-temperature facilities," and could be used for additional cascaded heat demands (see Surface Use Modeling section). The temperature and heat produced shown by the model increase over the first ~100 years because we have modeled the injection well at the bottom of the reservoir and the production well at the top; the resulting fluid flow carries heat from deeper in the reservoir up toward the production well until thermal breakthrough begins to occur.

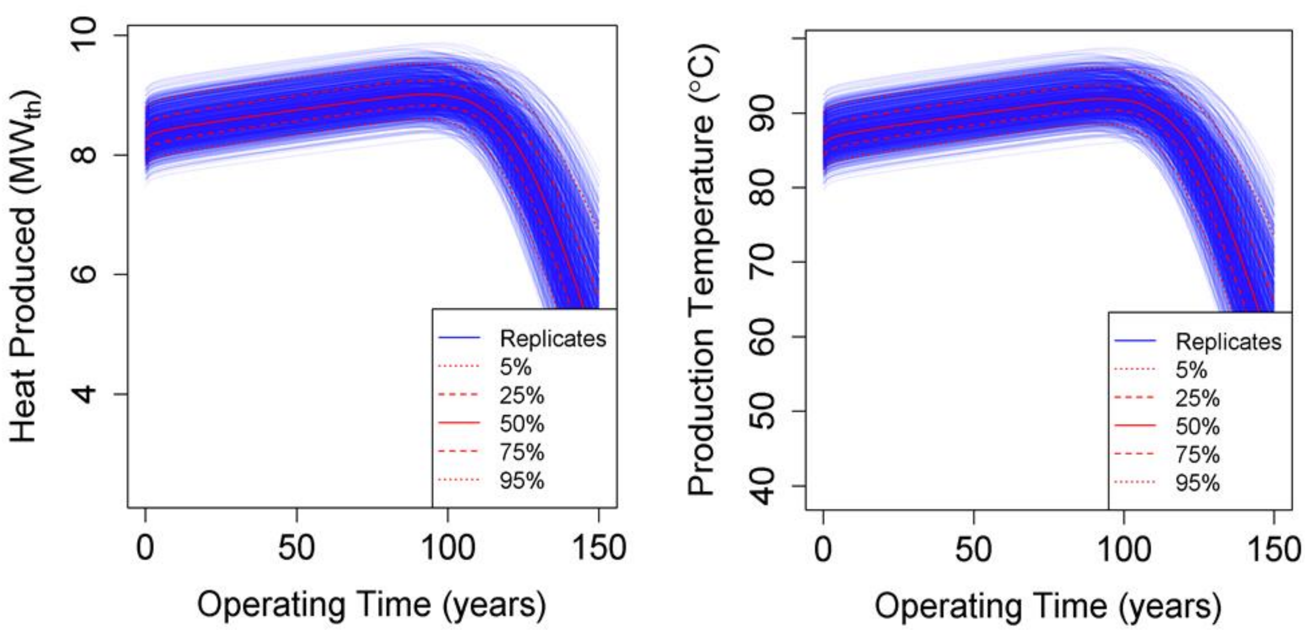


Figure 7: Heat production and temperature over time for a flow rate of 30 kg/s and injection of 20 °C for basement rocks at 3 - 3.5 km. Each blue line provides the results of a single Monte Carlo replicate. Selected quantiles are provided in red.

Our models required that we make assumptions about several key parameters, including wellbore spacing, fracture spacing, and production flow rate. We chose values, or ranges of values, that we considered reasonable considering the local geology and what has been learned during development and operation at commercial geothermal reservoirs elsewhere. Given the limitations and uncertainties of reservoir modeling in the absence of operational data, the next step in project development would be to drill and test a two-hole system to confirm and improve the modeling predictions.

3. SURFACE USE MODELING

A key component of this feasibility study was to create a detailed model of thermal energy use at the Cornell campus that is able to incorporate a variety of potential future scenarios for energy management and cascading uses of heat. Our starting point was to document the current heat requirements of campus (see Appendix A for more details). Figure 8 represents hourly data for all district-connected Cornell buildings for FY 2017, totaling about 0.81 Trillion BTUs (~247,400 MWh_{th}). Since the goal of our feasibility study is to develop a conceptual geothermal system to provide heating for 20% of this campus load, our system should supply at least 0.162 Trillion BTUs (~47,500 MWh_{th}) on an annual basis, or an average of about 5.5 MW_{th} continuously. This amount of energy is close to the year-round baseload heating demand for the campus.

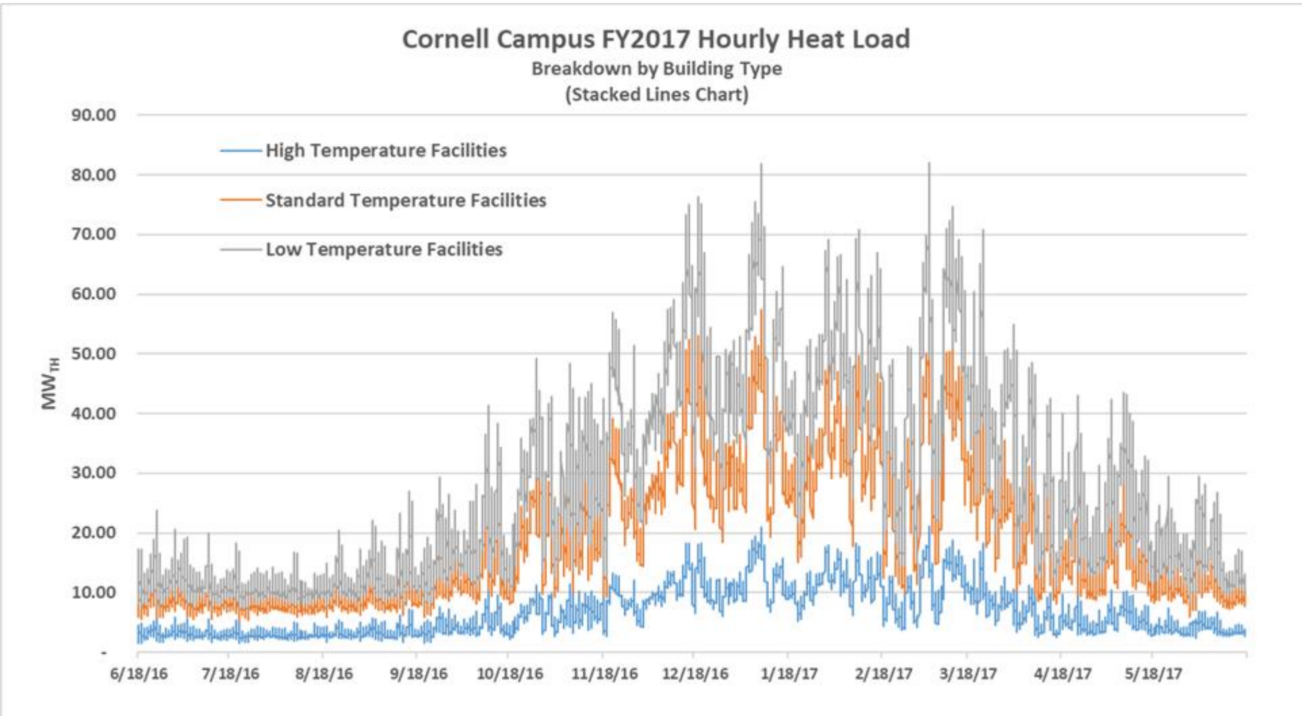


Figure 8: Hourly Cornell Campus Heat Demand for all connected buildings, shown by facility (heat demand) classification. Values are stacked, so the gray line represents the total campus demand.

3.1 Surface use technology

Our feasibility study considers the following primary surface use technologies:

- Distribution piping systems
- Variable speed/flow distribution pumps
- Plate and frame heat exchangers
- Heat pumps (centralized, for extracting additional heat from return water to boost overall well performance; and perimeter/building level, for targeted heat boost)
- Hot water storage systems

An important task during the first phase of the feasibility study was to determine the appropriate data sources and performance specifications to build the surface use model, including equipment and system performance characteristics that form the basis of the calculations inherent in the model.

3.2 Facility temperature demands

The geothermal source temperatures and flows needed to meet project goals depend in part on the temperature requirements of various campus buildings. The Cornell Study team has examined our buildings and grouped them into three different facility types, namely:

- Facilities needing high temperature hot water for heat ("High Temperature Facilities" 80 ^oC [176 ^oF] minimum supply temperature). These are buildings with research, teaching laboratories, research plant or animal holdings, or similar facilities that require large make-up air flows.
- Facilities needing "standard" temperature water for heat ("Standard Temperature Facilities" 70 ^oC [158 ^oF] minimum supply temperature). These include typical teaching spaces, offices, and dormitories not specifically designed for lower temperatures.
- Facilities that may be able to utilize return water from other building systems to meet their needs ("Low Temperature Facilities" 60 ^oC [140 ^oF] minimum supply temperature). These facilities, which include greenhouses and other agricultural facilities, may be candidates for cascading energy use.

Figure 8 shows graphically how the Cornell FY17 total heat load would be allocated between these facility types, on an hourly basis. In this example, most campus buildings are classified as Standard Temperature Facilities.

3.3 MEnU model for surface heat utilization

Cornell has created an Excel-based model of surface thermal energy use called MEnU (Model of Energy Use), which allows user-defined supply temperatures and thermal loads to be set for each facility category described above (see Appendix A for a more detailed discussion of the MEnU model). The MEnU model allows testing of various scenarios, including:

- Sensitivity of LCOH to building temperature and distributed loop temperatures. This is especially relevant for lower temperature geothermal sources.
- Effect of various heat pump configurations (e.g. operating on the central hot water distribution loop versus operating on a distribution subsystem or individual building) on the electrical usage needed to maintain temperatures in various building types.
- The use of cascading arrangements, whereby return water from a higher temperature building is used to supply a lower temperature facility.
- The impact of infrastructure changes over time. For example, Cornell recently changed the campus building design standard to require that all new and renovated buildings be designed to operate with a supply temperature of 55^oC (130^oF). This temperature corresponds to the typical temperature available from standard heat pumps on the market today and as such represents a readily achievable standard for all anticipated campus building types.

Running the MEnU model with different geothermal resource conditions (source temperature and flows) creates the following outputs:

- Total MWh_{th} of energy utilized from the geothermal resource in the modeled year
- Percent of annual campus energy provided by the geothermal system
- Total MWh_E used by heat pumps (if any) to provide the heat energy needed in the modeled year

Thus, the MEnU model shows the value (in energy units) of the geothermal resource and can effectively provide a utilization factor for the resource for the specific demand (campus load).

For a given flow rate and geothermal resource temperature, we can vary the amount of energy extracted per pass of circulating fluid by modifying (through our surface use equipment and controls) the return temperature. Table 4 shows some examples, which illustrate that even quite modest resource temperatures and flowrates can successfully serve at least 20% of our campus needs.

Table 4: Examples of Reinjection Temperature for Various Geothermal Well Conditions to Meet Project Goal (20% of campus heat load = 5.5 MW_{TH})

Flow (reservoir model input) (kg/s)	Geothermal Supply Temp (reservoir model output) (°C)	Geothermal Reinjection Temp (reservoir model input) (°C)	
		20% of campus needs (5.5 MW_{TH})	30% of campus needs (8.25 MW_{TH})
30	85	40.8	18.3
30	120	75.8	53.3
50	85	58.5	45
50	120	93.5	80
70	85	66.1	56.4
70	120	101.1	91.4

3.4 Heat pumps to boost supply temperature and extract more heat

As part of Cornell's DDU study, the application of electrically powered heat pumps to the system is also modeled in MEnU. While the geothermal resources being explored are ideally applied without the aid of heat pumps, the inclusion of heat pumps could provide the following benefits:

- Heat pumps used with DDU sources for heating can be substantially more efficient than conventional air or shallow water exchange (i.e., Air Source Heat Pumps, ASHPs, or Ground Source Heat Pumps, GSHPs). Specifically, warmer DDU resources allow a higher heat pump coefficient of performance, meaning lower energy usage per unit heat transferred, as predicted by thermodynamic principles and revealed by manufacturer's data.
- Heat pumps can extend the capacity of the geothermal resource by moving heat from the return fluid (prior to reinjection) to the supply side, in a manner equivalent to a cascading use. The thermal power produced by a closed-loop well pair is proportional to the temperature differential from source to return; reducing the return temperature increases the thermal power production of a given geothermal flow.
- Heat pumps at the building level can extract additional heat and boost supply temperatures for a building distribution sub-loop for any buildings not designed for more effective heat transfer, while simultaneously lowering return water temperatures.

Two of the three facility categories within MEnU are modeled with heat pump options. Each facility type can be programmed for unique temperature setpoints (supply and return). Consistent with the design standards in successful European systems, our MEnU program assumes control based on maintaining a preset temperature for the fluid returned from the building to the district heating loop. Setting this temperature as low as practical maximizes the amount of heat obtained from the district heating loop. See Appendix a for a more detailed discussion of strategies for integration of heat pumps.

4. INTEGRATION OF RESERVOIR PRODUCTION AND SURFACE USE

Integrating the results from the reservoir models and the demand side model (MEnU) provides useful insights into the effective and efficient use of geothermal energy. Insights include both general results applicable to all such systems, as well as more refined results that demonstrate the effect of various operating scenarios on Cornell's distributed heat system.

4.1 General results and insights

A key general insight gained from exploring district heating options is the importance of exploiting the fact that the amount of heat extracted from a geothermal reservoir at any given pumping rate is directly proportional to the temperature difference between the withdrawn water and the returned water. Since the developer has limited control over the temperature of the source, a focus for the development should be on extracting as much heat as possible from the water prior to re-injection. This principle is shown below in Figure 9 and Table 5:

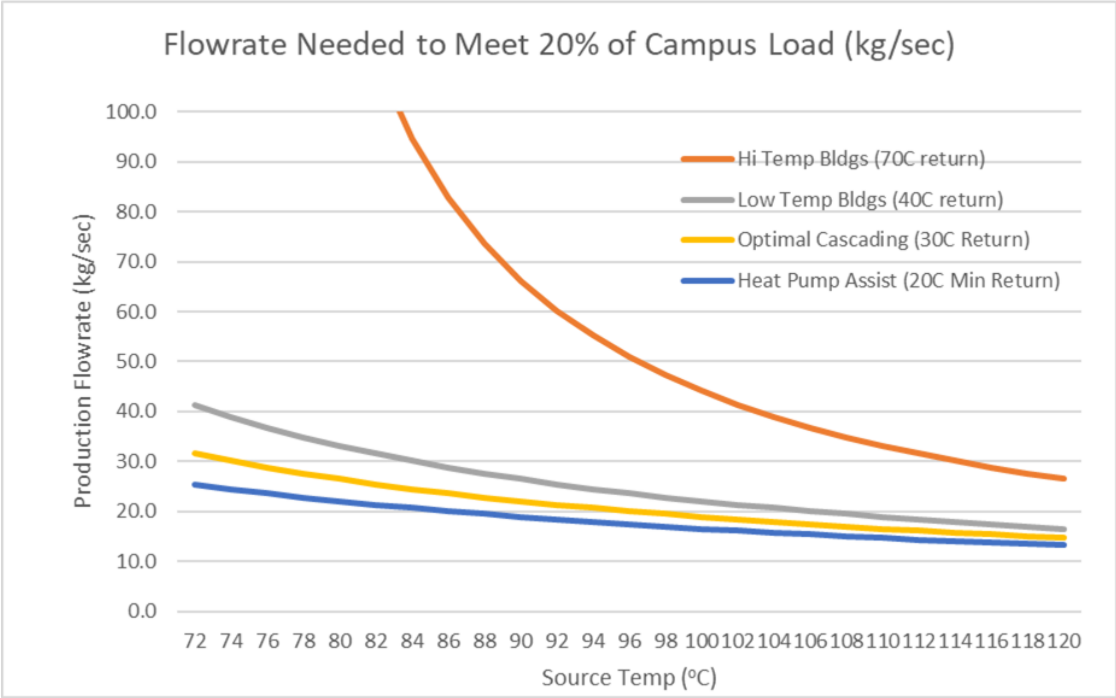


Figure 9: Well production flow rate and temperature needed to meet 20% of Cornell campus heating load for different reinjection temperatures, corresponding to the return temperature from different surface use scenarios

Production Flow Rate Required to Meet 20% of Campus Load (kg/sec)

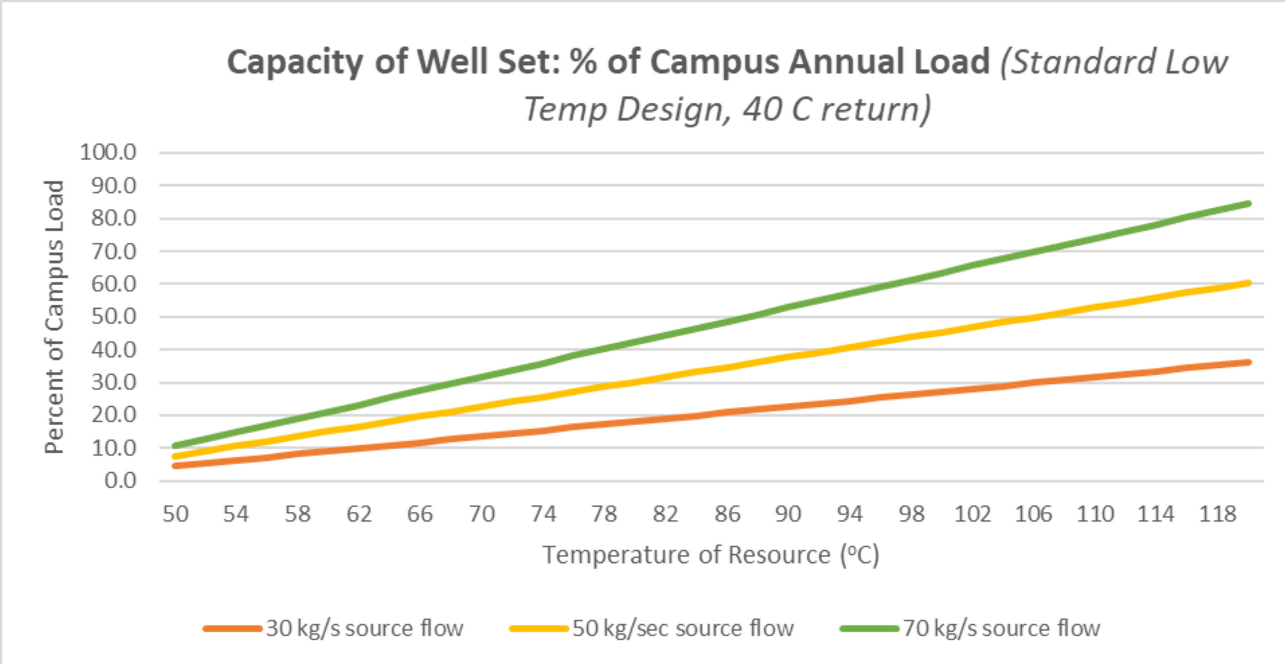
	Reinjection Temperature			
Source Temp (°C)	70 °C (Inefficient building design)	40 °C (Optimal* building design)	30 °C (Optimal* cascading)	20 °C (With use of heat pumps)
50	N/A	132.5	66.3	44.2
60	N/A	66.3	44.2	33.1
70	N/A	44.2	33.1	26.5
80	132.5	33.1	26.5	22.1
90	66.3	26.5	22.1	18.9
100	44.2	22.1	18.9	16.6
110	33.1	18.9	16.6	14.7
120	26.5	16.6	14.7	13.3

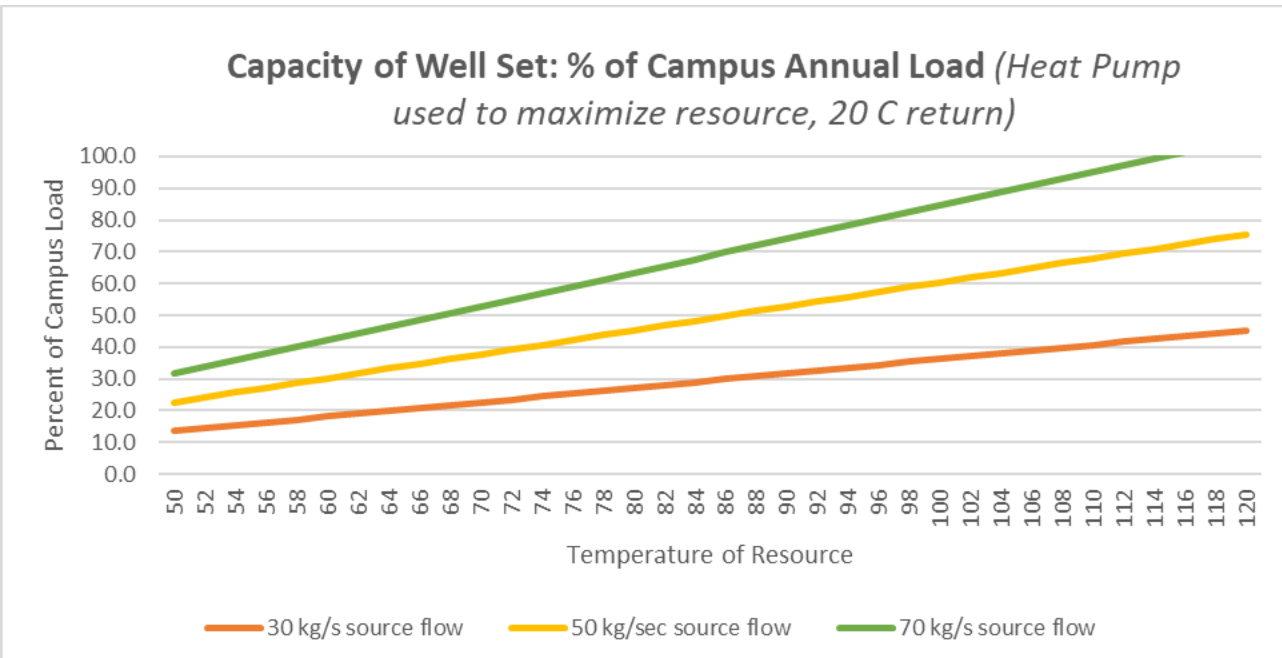
* "Optimal" refers to designs that minimize return temperatures within the bounds of available commercial heating equipment technology

Table 5: Well production flow rate needed to meet 20% of Cornell campus heating load for different geothermal supply (source) and reinjection temperatures.

As can be seen in these figures, lowering the reinjection temperature through improved design and operation of building heating systems, incorporation of cascading uses, and the strategic use of heat pumps to recover additional heat will allow Cornell to meet its target to supply 20% of campus heat using even modest production temperatures and flow rates. See Appendix A for additional discussion regarding lowering return temperatures.

Figures 10 and 11 provide some examples of how these strategies impact the available heat recovery for a system modeled on Cornell's plant. As can be seen on the figures, all three variables (resource temperature, flow rate, and reinjection temperature) have a significant impact on the amount of heat extracted. Of these three, reinjection temperature is the easiest to control (through the use of heat pumps), since it is an engineered solution whose benefits can be precisely estimated. Figures 10 and 11 demonstrate that reducing the reinjection temperature from 40 °C to 20 °C opens up a much wider range of resource temperature and flow combinations that will meet our minimum project goals.





Figures 10 and 11: Percentage of Cornell campus heating load that could be supplied at various production temperatures and flows assuming a 40 °C reinjection temperature (top; corresponding to standard low temperature building heating system design) and a 20 °C reinjection temperature (bottom; case where heat pumps are used to lower the reinjection temperature).

4.2 Heat storage

Heat storage is an important practical consideration for the design of an institutional heating system. For such a system, the instantaneous peak heating demands can be substantially higher than the average seasonal demand. To ensure that sufficient heat is available for these infrequent peaks, either the entire system must be oversized or storage must be used. Storage can also be useful for lower-load periods; storing excess heat on days with low loads (warmer days) for use during other periods (cooler nights or times of higher domestic hot water needs) such that the utilization of the resource is more consistent. See Appendix A more additional details regarding our modeling of heat storage.

5. CONCLUSIONS

Our study supports the following broad conclusions regarding approaches to reduce the development risks associated with DDU projects at greenfield geothermal locations that have limited (or no) in-situ reservoir data or field testing results:

1. Defining a range of potential subsurface reservoir production, even with sparse and/or uncertain geological data, can help quantify the likelihood of success for any potential geothermal development when combined with a specific plan for the use of a range of flow and temperature resources;
2. For any given reservoir fluid production temperature and flow, reservoir heat utilization can be improved by lowering the re-injection temperature (i.e., removing more thermal energy from the circulating geothermal fluid for productive surface end uses before reinjection);
3. Detailed historical real-time heat use and system modeling provides a means to more precisely estimate the amount of heat from a geothermal system that can be utilized by a given district energy system, and thus estimate the future value of the DDU system;
4. Incorporating hot water storage to help meet short-duration peaks in heat demand can significantly reduce the required maximum heat production rate, resulting in reduced capital expenses for heat-producing systems;
5. Appropriate design standards to increase energy efficiency for building heating systems and distribution systems, cascading uses, and the use of heat extraction pumps can significantly improve the feasibility of geothermal heat integration. These features also improve system flexibility and lower risks by greatly expanding the range of reservoir production values (flow, temperature) that can be effectively utilized.

For the Cornell campus, we estimated temperatures and geologic properties for formations of interest for potential geothermal reservoirs. Propagating uncertainties in the data through reservoir simulations allowed for probabilistic interpretations of the reservoir's ability to meet heating demands, which will inform decision making regarding surface utilization and allow for economic evaluations. By incorporating the best available information prior to drilling a well, such evaluations will help quantify the potential economic benefits and risks before committing the substantial resources needed for drilling.

Our results show that basement reservoir targets can potentially meet 20% of the thermal energy demands of the Cornell campus for over 50 years. Shallower sedimentary targets could sustain desirable heat production and temperatures for over 40 years, but temperatures may begin to decline within 10 years. However, this decline in production temperature could be accommodated through flexible surface utilization strategies, including the use of heat pumps.

SOFTWARE CREDITS

Numerical modeling was completed using the TOUGH2 software as implemented in PetraSim (Thunderhead Engineering, 2018). Analytical reservoir modeling, wellbore heat transfer, and some economic calculations were completed using GEOPHIRES (Beckers and McCabe, 2018; Beckers, 2016) in Python version 2.7.15. Modifications were made to the GEOPHIRES software to complete Monte Carlo analysis, and add additional reservoir modeling functionalities. The modified software is available upon written request to Jared Smith (jds485@cornell.edu).

Statistical analyses were completed using R version 3.5.0 (R Core Team, 2018) and the packages vioplot (Adler, 2005), doParallel (Microsoft Corporation and S. Weston, 2017), abind (Plate and Heiberger, 2016), dataframes2xls (van Steen, 2016), readxl (Wickham and Bryan, 2018), and Hmisc (Harrell Jr. et al., 2018).

The map in Figure 2B was created using QGIS version 2.18.15 (QGIS Development Team, 2016).

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APPENDIX A – SURFACE USE MODELING DETAILS

Heat Requirements of the Cornell Campus

For the purpose of this study, Cornell is using baseline thermal demand data for the Ithaca campus collected for Fiscal Year 2017 (July 1, 2016 through June 30, 2017), which represents the most current, complete, and accurate annual record of campus heat demand. Figure 8 represents hourly data for all district-connected Cornell buildings for FY 2017, totaling about 0.81 Trillion BTUs (~247,400 MWh_{th}). For most of the campus, real-time hourly meters provide direct data. For smaller buildings with only monthly metering, Cornell converts the monthly data to an approximate hour-by-hour usage pattern, based on real-time usage patterns in other buildings. This results in a complete hourly data set that is used to conduct system-wide analysis and load projections that include hourly peaks.

Since the goal of our feasibility study is to develop a conceptual geothermal system to provide heating for 20% of this campus load, our system should supply at least 0.162 Trillion BTUs (~47,500 MWh_{th}) on an annual basis, or an average of about 5.5 MW_{th} continuously. This amount of energy is less than the minimum baseload heating demand for the campus (which in the summer is mostly from domestic hot water and building air reheat), so Cornell can use this amount of heat year-round.

Distribution and Building Piping systems:

Since the early 1900s, Cornell has used district steam heat infrastructure to distribute heat across campus; steam is typically converted to hot water at the building interface. Today, an expanding portion of campus is served by hot water sub-distribution systems. Cornell is continuing this conversion from steam to hot water distribution, and this feasibility study is based on integrating future geothermal heat production into the future hot water delivery system.

MEnU Model Details

Cornell has created an Excel-based model of surface thermal energy use called MEnU (Model of Energy Use), which allows user-defined supply temperatures and thermal loads to be set for each facility category described above. The MEnU model allows testing of various scenarios, including:

- Sensitivity of LCOH to building temperature and distributed loop temperatures. This is especially relevant for lower temperature geothermal sources.
- Effect of various heat pump configurations (e.g. operating on the central hot water distribution loop versus operating on a distribution subsystem or individual building) on the electrical usage needed to maintain temperatures in various building types.
- The use of cascading arrangements, whereby return water from a higher temperature building is used to supply a lower temperature facility.
- The impact of infrastructure changes over time. For example, Cornell recently changed the campus building design standard to require that all new and renovated buildings be designed to operate with a supply temperature of 55ºC (130ºF). This temperature corresponds to the typical temperature available from standard heat pumps on the market today and as such represents a readily achievable standard for all anticipated campus building types.

Figure A1 shows a partial schematic of how the High Temperature Facilities are arranged in the MEnU model for the Cornell campus. The system is arranged so that a heat pump is available to boost the distribution loop temperature as needed (based on the available geothermal resource) to supply building heat during peak winter conditions. The system also incorporates a cascading arrangement to the extent that distribution loop temperatures remain sufficient. The arrangement for the “standard temperature” buildings is similar, while the “lower temperature” buildings do not include heat pumps or further cascading uses of the (already lower temperature) return heat.

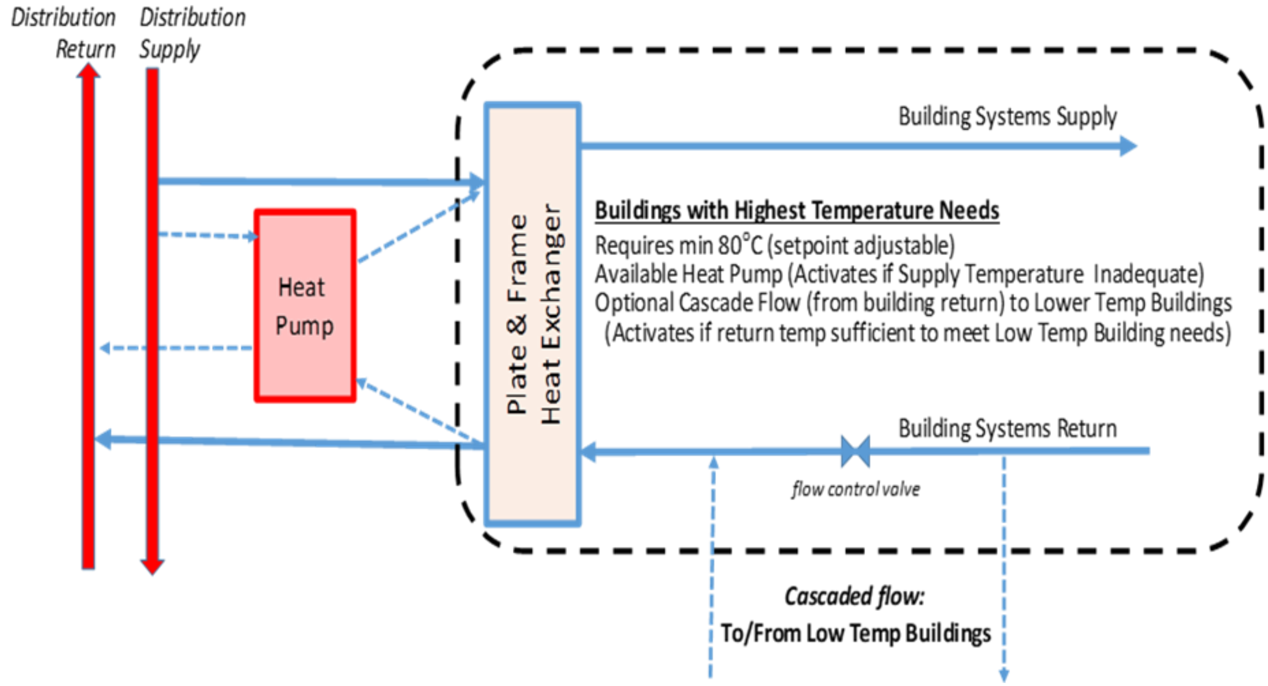


Figure A1: Modeled High Temperature Building arrangement with booster heat pump and cascading flow.

MEnU was constructed using a standard Excel spreadsheet. The calculations within the MEnU model include relatively simple energy balances (conservation of energy) and heat transfer principles. Calculations rely on typical equipment performance information. The essential result of the model is a value for the total annual energy extracted from a given geothermal system, a critical component for calculating LCOH of the resource.

Running the MEnU model with different geothermal resource conditions (source temperature and flows) creates the following outputs:

- Total MWhth of energy utilized from the geothermal resource in the modeled year
- Percent of annual campus energy provided by the geothermal system
- Total MWhE used by heat pumps (if any) to provide the heat energy needed in the modeled year

Thus, the MEnU model shows the value (in energy units) of the geothermal resource and can effectively provide a utilization factor for the resource for the specific demand (campus load).

Our feasibility study target of meeting 20% of the (seasonally variable) annual campus heat load is equivalent to providing continuous thermal power of ~5.5 MW_{th}. Due to the existence of summertime heat loads such as domestic hot water and building air reheat, Cornell's campus has a minimum heat requirement higher than this value year-round. Our MEnU model indicates that with proper system design, all the produced heat from a geothermal system designed to deliver ~5.5 MW_{TH} continuously can be utilized, thereby meeting our feasibility study goal.

Geothermal outputs that are significantly higher than 5.5 MW_{th} may result in periods during which not all of the available energy can be utilized by existing facilities. This heat utilization rate (load availability) is predicted by the MEnU model, which calculates the hour-by-hour MWh output for each modeled scenario and automatically sums these to an annual total.

To quantify these discussions, basic conservation of energy and thermodynamics are used. Because water at moderate temperatures has an essentially constant heat capacity, the essential relationship of flow and temperature to geothermal output is described by the following simple formula:

$$P_{TH} = H*Q_G*(T_{G1}-T_{G2}), \text{ where} \qquad \textit{(equation 1)}$$

P_{TH} = thermal power produced by the geothermal well system
H = specific enthalpy of the fluid (water)
Q_G = Flow rate from geothermal well system
T_{G1} = Supply Temperature from the Geothermal Well System
T_{G2} = Return Temperature to the Geothermal Well System

Thus, the total energy derived from the well is essentially the integration of $HQ\Delta T$, where H (enthalpy) is constant, Q is the well flow, and ΔT is the operating temperature differential (i.e., T_{G1}-T_{G2}).

For a given flow rate and geothermal resource temperature, we can vary the amount of energy extracted per pass of circulating fluid by modifying (through our surface use equipment and controls) the return temperature. In this manner, even quite modest geothermal resource temperatures and flowrates can successfully serve at least 20% of our campus needs.

Details of Heat Pump Integration

As part of Cornell's DDU study, the application of electrically powered heat pumps to the system is also modeled in MEnU. While the geothermal resources being explored are ideally applied without the aid of heat pumps, the inclusion of heat pumps could provide the following benefits:

- Heat pumps used with DDU sources for heating can be substantially more efficient than conventional air or shallow water exchange (i.e., Air Source Heat Pumps, ASHPs, or Ground Source Heat Pumps, GSHPs). Specifically, warmer DDU resources allow a higher heat pump coefficient of performance, meaning lower energy usage per unit heat transferred, as predicted by thermodynamic principles and revealed by manufacturer's data.
- Heat pumps can extend the capacity of the geothermal resource by moving heat from the return fluid (prior to reinjection) to the supply side, in a manner equivalent to a cascading use. The thermal power produced by a closed-loop well pair is proportional to the temperature differential from source to return; reducing the return temperature increases the thermal power production of a given geothermal flow.
- Heat pumps at the building level can extract additional heat and boost supply temperatures for a building distribution sub-loop for any buildings not designed for more effective heat transfer, while simultaneously lowering return water temperatures.

The third item may be especially important in older American facilities. Most U.S. buildings are heated with high-temperature fossil fuel combustion, which provides no practical incentive to design for building supply temperatures below ~80ºC since higher temperature design minimizes the size and cost of terminal heat transfer surfaces (e.g. radiators and heating coils). Many such systems also have a relatively high return temperature (i.e., a relatively low quantity of heat is transferred from the building loop to the terminal systems). Heat pumps thus may provide support for integration of DDU resources with existing building heat systems until they can be redesigned for lower temperature hot water.

In the Cornell study, we used MEnU to help inform the appropriate placement of heat pumps in our system. Figure A2 shows a schematic with the heat pump installed to extract heat from the district heating loop prior to fluid entry into the heat exchanger where it is reheated by the geothermal fluid. The temperature of the district heating loop supply fluid is boosted by the heat pump, while the return fluid temperature is decreased. This increases the differential temperature between the geothermal well fluid supply and return, increasing the energy extracted (assuming the district system has sufficient demand to accept this heat).

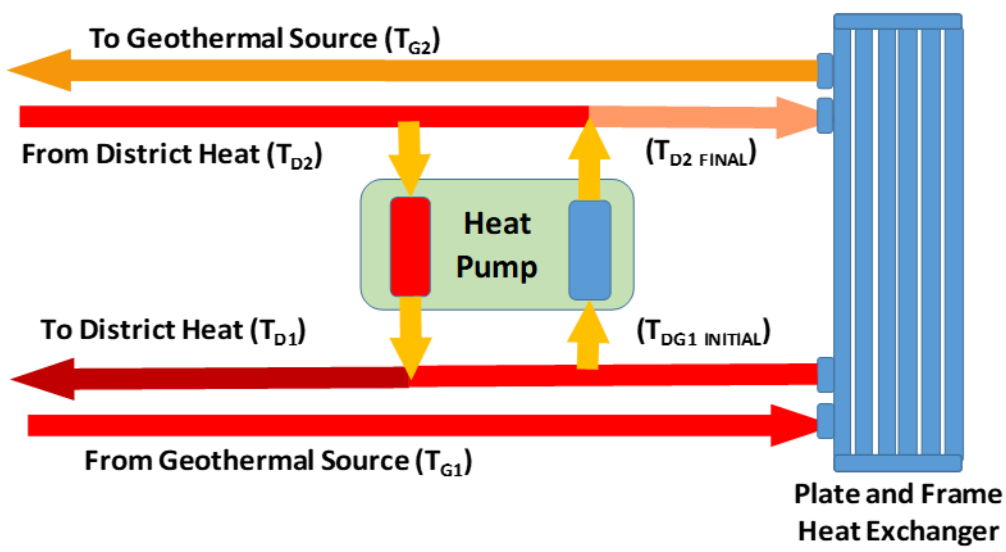


Figure A2: Heat Pump Located Adjacent to the Geothermal Source Heat Exchanger

Water source heat pumps can also be placed at the building level to boost temperatures as needed for facilities that either require a higher temperature supply, or have occasional peak heating needs that exceed the district loop capacity. In addition to allowing more heat extraction at the building level, this might allow a lower district loop delivery temperature, which would improve overall system performance if properly designed, especially in cases where a higher temperature is only needed for a small portion of the facilities or for short time periods. Similarly, building-level heat pumps provide operators with additional options to meet load in the event of unpredicted or changing load profiles. Figure A3 shows a building-level heat pump arrangement.

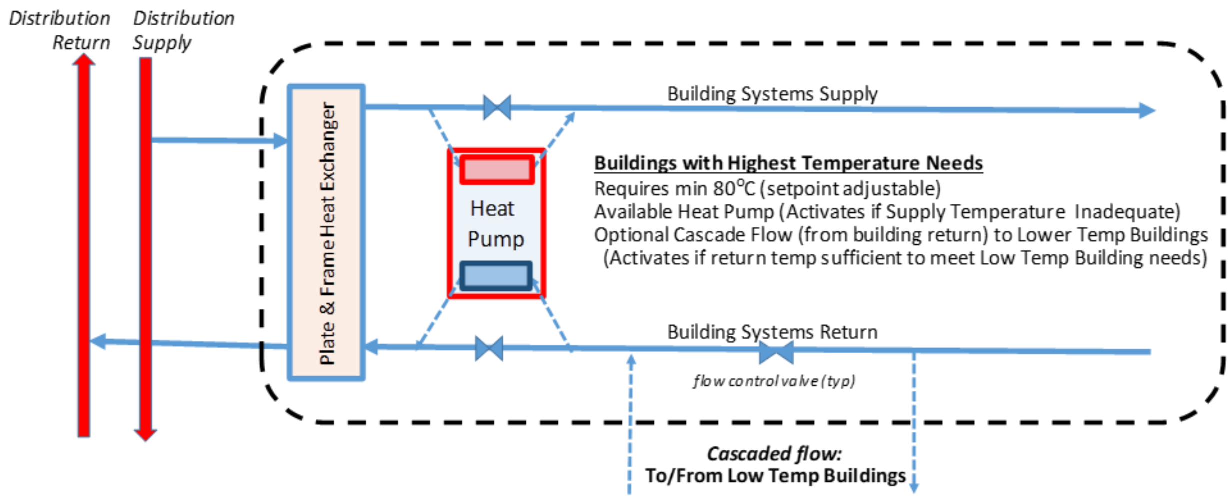


Figure A3: Heat Pump integration at the Building Level

Overall, the selection of where heat pumps should be placed and how they are operated depends on many factors related specifically to both geothermal resources (temperature and flow of the geothermal source) and the buildings being served (temperatures, load variations, and diversity of each). Significant goals in using heat pumps are to enhance the energy obtained from the DDU resource while minimizing electrical requirements (i.e., managing temperatures to allow high coefficients of performance) and capital costs (i.e., number of wells and total heat pump capacity).

To quantify the impacts of heat pump use, Cornell's MEnU program includes both a central heat pump in the district loop across the geothermal heat exchanger, and building level heat pumps within the district loop. The general rules for activation of the heat pump in the model are as follows:

- The central heat pump activates based on a user-selected return water temperature. If the distribution loop returns a higher temperature, the central heat pump extracts heat from the return flow and adds heat to the supply (provided the campus load is sufficient in that hourly time step to accept the additional transferred heat). For a given geothermal supply temperature and flow rate, a user-selected return temperature is essentially equivalent to a user-selected geothermal heat extraction rate.
- The building-level heat pump(s) are individually activated (automatically) if the temperature of the district loop is insufficient to meet user-selected building temperature supply and/or return temperatures.

Two of the three facility categories within MEnU are modeled with heat pump options. Each facility type can be programmed for unique temperature setpoints (supply and return). Consistent with the design standards in successful European systems, our MEnU program assumes control based on maintaining a preset temperature for the fluid returned from the building to the district heating loop. Setting this temperature as low as practical maximizes the amount of heat obtained from the district heating loop.

Controlling Return Temperatures

There are at least three basic strategies for controlling return temperatures, namely:

1. After utilizing the higher temperature district heating fluid, direct the lower-temperature return water to appropriate uses where low temperatures provide benefits. This cascading heat use might include lower-temperature (e.g. < 50 °C) applications for greenhouses, fish farming, biomass/crop drying, or ice melting under roads and sidewalks.
2. Design (or retrofit) buildings to use lower temperatures. For example, Cornell has instituted a new design standard that requires all buildings to be designed for maximum ~55 °C supply temperature and ~38 °C return water. Generally, these standards require careful selection of heating coils and radiators and support more radiant floor and surface heating.
3. Use heat pumps to extract additional heat from return water prior to re-injection, and transfer the recovered heat to the supply stream. Heat pumps may be considered as a permanent feature or as an interim design feature to accommodate buildings not yet modified for lower temperatures.

The first of these strategies is optimal whenever the valuable uses of lower temperature resources are available. However, for an existing campus infrastructure like Cornell's, proposed cascading uses sometimes represent new loads; when this is the case, the additional heat extracted does not help meet *existing* campus loads. Nevertheless, such use is productive provides additional economic value.

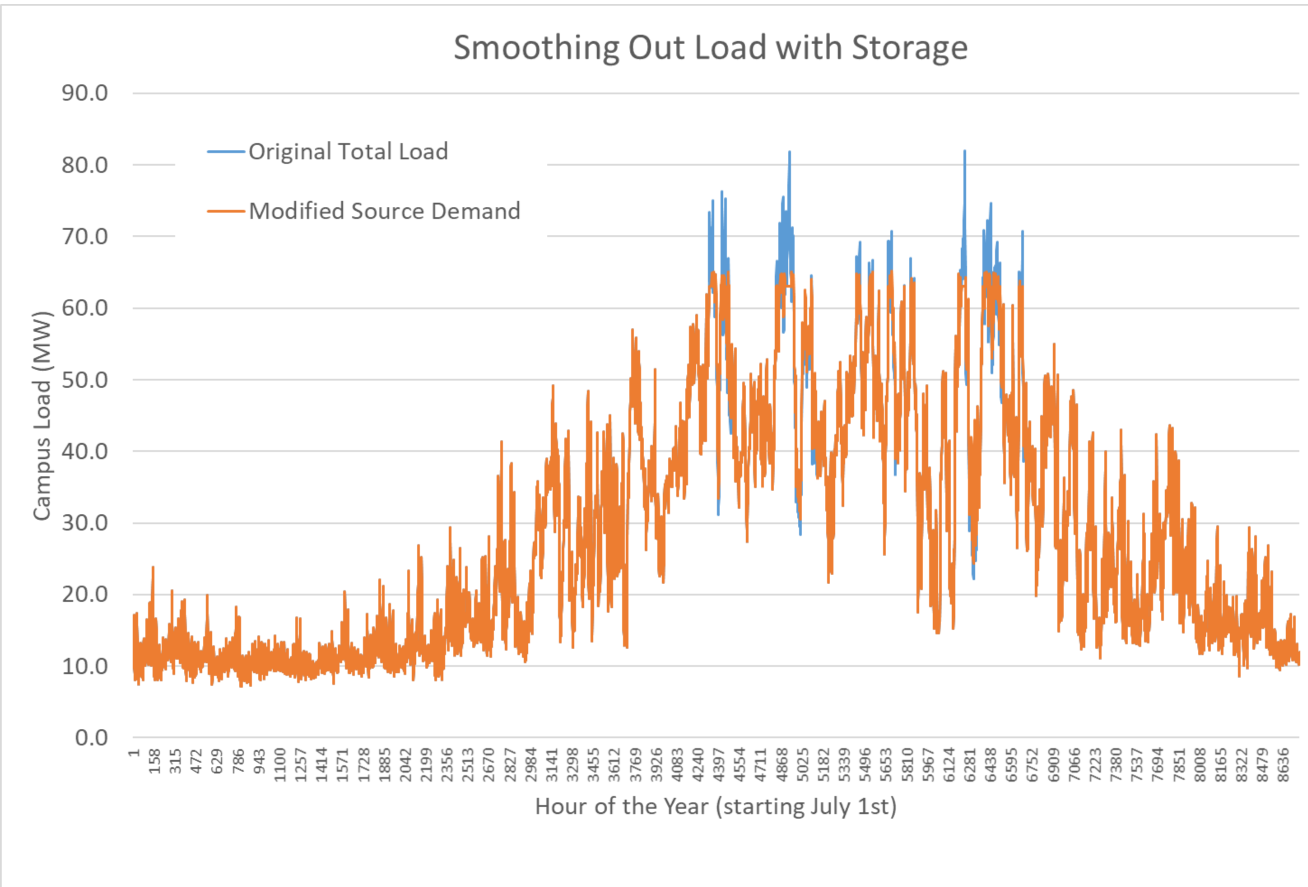
The second strategy provides clearer value, as improved building design will allow more of the existing or planned building load to be supplied with a given resource.

The third strategy (utilize heat pumps or heat recovery chillers) provides the greatest system controllability and function. The heat pumps can be selectively operated only when needed, and essentially any return temperature (above 0 °C) can be used as a controlling point, provided that the right equipment and refrigerants are specified. However, heat pumps require both substantial capital investment and operating power (electricity), both of which affect the cost of the generated heat when life cycle costing is considered. Generally, the lower the return design temperature for the heat pump, the lower the Coefficient of Performance (COP), resulting in higher electric usage. Modeling the economic impact of various heat pump utilization scenarios can help define these costs and benefits.

Implications of Heat Storage

Heat storage is an important practical consideration for the design of an institutional heating system. For such a system, the instantaneous peak heating demands can be substantially higher than the average seasonal demand (Figure 15). For example, the average hourly heating demand for the Cornell campus is about 28 MWh (about 55 MWh in the winter) but hourly peaks over 80 MWh are typical for a few hours per year. To ensure that sufficient heat is available for these infrequent peaks, either the entire system must be oversized or storage must be used. Storage can also be useful for lower-load periods; storing excess heat on days with low loads (warmer days) for use during other periods (cooler nights or times of higher domestic hot water needs) such that the utilization of the resource is more consistent.

Figure A4 shows an example of thermal storage modeling for one specific storage case. This example models the storage of hot water (in a 10 million liter tank) whenever the campus load is below 60 MW and the tank is not full, and the release of hot water whenever the campus load exceeds 68 MW. The result is that the effective heating load (load for all heat-producing equipment, not including the tank itself) is reduced to 68 MW. Similar modeling exercises can be performed with differing tank sizes, operational rules, etc. However, it is clear that hot water storage can effectively reduce capital expenses. For a geothermal well system, properly designed storage can offset the need for an additional well bore or well pair, while increasing the utilization rate (hours of operation per year) for developed well sets.



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