Earth Source Heat: Feasibility of Deep Direct-Use of Geothermal Energy on the Cornell Campus

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ABSTRACT

Cornell University aspires to become the first major U.S. cold-climate university to completely heat and cool its campus with renewable energy. Having already created the sustainable, emissions-free Lake Source Cooling system, we now explore Deep Direct-Use (DDU) as part of a hybrid system: an Engineered Geothermal System (EGS) for base-load district heating, and biomass combustion for peak demand. This comprehensive Feasibility Study will identify ways to optimize and improve the technical feasibility and economics of DDU for heating Cornell's campus, including:

- Refined probabilistic estimates of the geothermal resources beneath campus by modeling two distinct reservoirs (sedimentary at ~2300 m and crystalline at ~3000-4500 m).
- Integration of base-load geothermal heat with additional energy resources. To reduce geothermal capital costs, peak heating would be augmented by local biomass sources, thermal storage, and heat pumps.
- Design of cascading systems for produced heat to be utilized in several stages, from building heating, to hot water supplies, to agricultural uses, to snow melting or similar low-T uses. This will yield options for utilizing geothermal fluids at various flows/temperatures, identifying the highest value applications for a range of potential reservoir production conditions.

Our study will also address the complex economics of DDU. In addition to determining whether DDU is feasible on our site, our overall goal is to identify development options that provide a

positive economic return when capital costs, local economic benefits, and regional/global environmental benefits are considered.

This paper will describe the methods and data sources used and preliminary findings after Year 1 of this two-year project. The Feasibility Study sets the stage for a future exploration well and EGS demonstration project on Cornell's Ithaca campus.

1. Introduction

Under an award from the Department of Energy, Cornell University is assessing the feasibility of Deep Direct-Use (DDU) geothermal energy for meeting 20% of the thermal energy needs of our main campus in Ithaca, NY. We are exploring a range of technology options for surface energy use and investigating the compatibility of two potential subsurface reservoirs with those technology options. The resulting Feasibility Study will guide the University's preparations for a detailed engineering design and pilot demonstration. This paper presents our preliminary findings in Year 1 of this two-year study, during which our goal was to develop our modeling approach, refine input parameters and describe their uncertainties, and complete initial model runs to identify the two most promising combinations of subsurface reservoir and surface use. Those two will be carried forward for a detailed techno-economic evaluation in Year 2. Here we summarize details of the analysis methods we are employing.

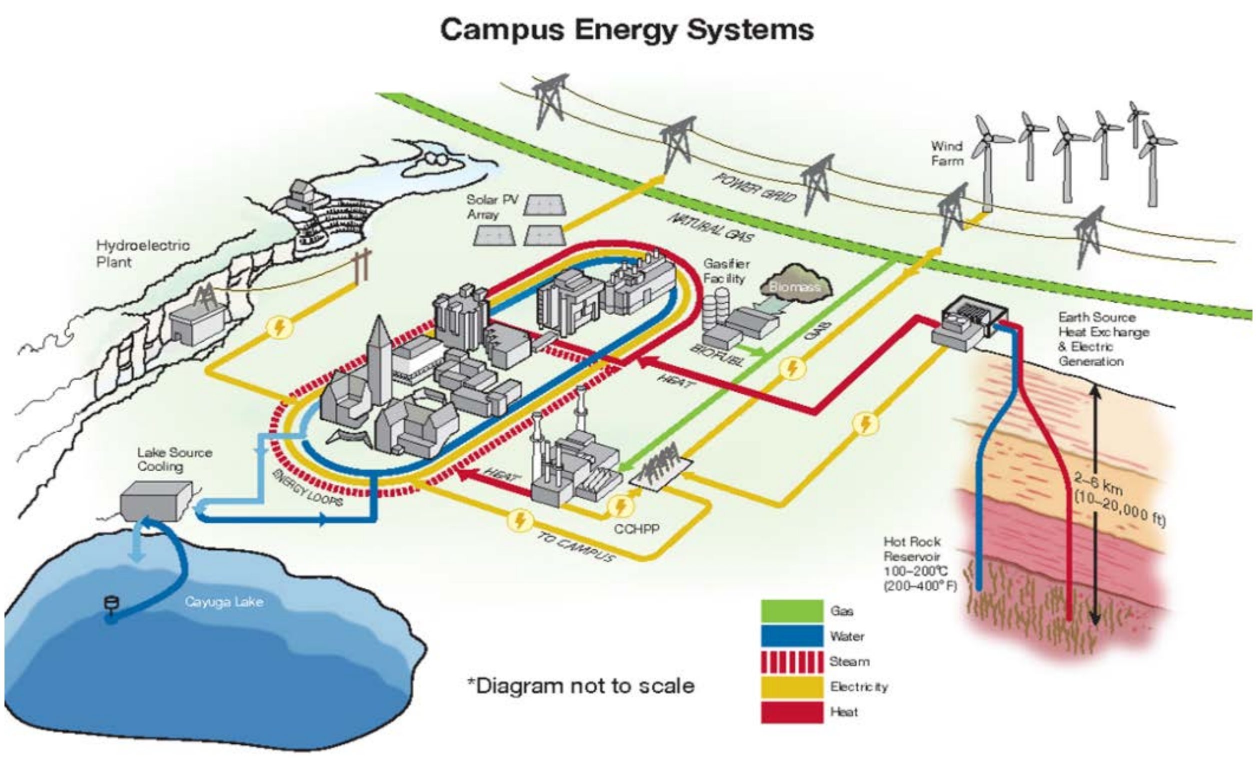


Figure 1: Schematic showing future integration of DDU geothermal energy (right side of sketch) into the comprehensive Cornell University energy system. Major portions of this system are already in place. The Lake Source Cooling component (lower left) and existing district heating set the stage for evaluating the feasibility of DDU.

2. Background

The U.S. Geological Survey has estimated that 46,000 MWth of beneficial heat is available in the U.S. from low-temperature (<90 oC) geothermal resources, enough to supply ~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 the end use requires, 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, producing economic and environmental benefits and assisting electric utilities with grid management.

In addition, low-carbon and carbon-free approaches to heating campus 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 serves as a living laboratory (Fig. 1).

To these ends, Cornell faculty and facilities engineers have partnered to develop and demonstrate innovations of energy systems at scales serving our entire campus of 30,000 people. Previously, Cornell successfully implemented renewable direct-use cooling (Lake Source Cooling) throughout campus (Cornell University, 2005); now Cornell is exploring utilization of geothermal energy for direct-use heating (Earth Source Heat).

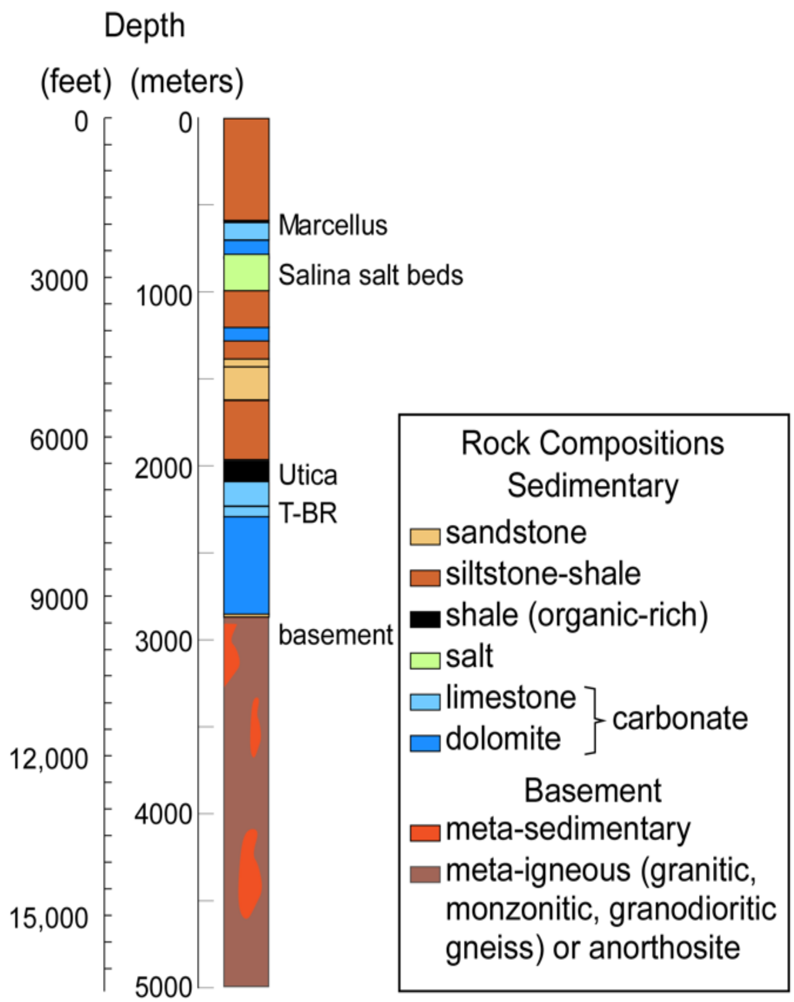
Cornell is an attractive demonstration site for multiple reasons: 1) extensive land holdings; 2) an expected geothermal resource that is representative of the region and moderately well known; 3) annual heating demands characteristic of the nation's Northern Tier states; 4) well-instrumented district energy infrastructure to its buildings and laboratories; 5) extensive, well-documented energy use data for design modeling; 6) multiple on-campus users of thermal energy at a range of temperatures; 7) a public commitment to lower its carbon footprint and recognition of external costs; 8) a commitment to outreach as NY's land grant university, including active collaboration with industrial and government partners interested in the use of low temperature geothermal energy; and 9) a "living laboratory" environment where academic research and real-world applications are pursued together.

We are studying options for using geothermal resources anticipated to be less than 120 °C to meet our seasonal heating demands. Features being evaluated include thermal storage and heat pumps, flexible cascading use of the thermal resource over a range of temperatures, and using biofuels to help meet peak demands. Beyond the core application of providing heat and hot water for campus buildings and laboratories, the evaluated cascaded uses for heat include controlled agriculture (hydroponics, aquaculture, greenhouses), specialized agricultural uses (biomass drying), and snow melting.

This two-year study will determine target performance for a pilot demonstration system that accommodates at least 20% of Cornell's annual campus heating demand, or about 166,000 MMBtu per year (175,000 GJ/yr), while providing additional cascaded heat estimated at over 100,000 MMBtu per year (106,000 GJ/yr). This demand could be met, for example, by a continuous geo-fluid production rate of 50 kg/s and a total effective temperature difference (production minus reinjection temperature) of 77 oF (43 oC). Our flexible approach described below also allows us to accommodate a wide range of geothermal resource qualities.

We are performing a detailed evaluation of surface thermal demand in conjunction with modeling the ability of different potential subsurface reservoirs to supply heat to the surface systems. Together, we used the surface and subsurface analyses to model integrated solutions.

The subsurface evaluation builds upon the knowledge of thermal and reservoir conditions revealed by the Geothermal Play Fairway Analysis that placed Ithaca on the margin of a high priority play fairway (Cornell University, 2017). Our team is assessing techno-economic outcomes for two types of geothermal reservoirs that may underlie Ithaca: sedimentary rocks at ~2300 m depth, and crystalline basement rocks at ~3000-4500 m (Fig. 2). Thermalhydraulic models are used to estimate the ranges of potential flow and thermal performance for each reservoir type.



Demand-side analyses have identified and documented thermal loads and potential uses. Our study also considers a number of optimization schemes to improve the economics of a potential DDU application, such as the integration of biomass, heat pumps, hot water storage, waste energy recovery, and specific agricultural cascading energy uses. The goals of this analysis will be to find a cost-effective and productive means of using available DDU energy for the Cornell campus, and to provide flexible tools suitable for analyzing similar sites with different thermal resources and needs in the Northeast United States.

3. Overview of Models Used

Several modeling programs are being integrated for geothermal reservoir simulations, surface direct-use heat utilization modeling, and economic evaluations for the Cornell Ithaca campus project. These models are described in the subsections below, and more detailed descriptions of the geothermal reservoir and surface use models are presented in the following sections. An overview of our economic modeling approach is presented here, but a detailed discussion is not presented since that modeling will primarily be completed during the next phase (Year 2) of this feasibility study.

For modeling of physical systems it is important to consider which parameters may be specified by engineering design choices once real data are obtained. In our study, these parameters will be modeled using specific values that correspond to chosen surface use scenarios. At Cornell, the heat demand and the performance of various top-side mechanical components that might supply or distribute that heat are well supported by building-use data and described by physical and thermodynamic relationships. Overall, the surface analysis is relatively certain compared to the subsurface analysis.

Much of the subsurface modeling effort in Year 1 has involved data analysis to establish uncertainties on the likely values of parameters for which we have regional data. Parameter uncertainties for which we do not have local or regional data are necessarily comparatively larger, and are based on available literature data on rocks and reservoirs external to the Ithaca region within the Appalachian Basin, previously compiled and analyzed by Jordan et al. (Cornell University, 2017), Camp (2017), Whealton (2016) and Smith (2016). We present subsurface data uncertainties for some key parameters within the geothermal reservoir modeling section. The interface between surface uses and subsurface reservoirs is the well field; selection of well field design parameters is required for some of our modeling.

3.1 Custom Modeling of Cornell Heat Utilization

The authors are creating and testing a custom Excel modeling spreadsheet for investigating the use of DDU heat for the Cornell campus. The model uses standard thermodynamic equations to track heat use through multiple facility types based on real hourly loads. While the mathematics are straightforward, the model allows customized inputs to reflect the various system operating options, including: three sets of building temperature inputs; variable pump speeds; booster heat pump "target heat percentage" settings; alternative distribution loop temperature settings; and hot water storage tank fill and drain settings based on peaking needs. The model also allows modification of inputs to subsurface well production sets (flow and temperature) to evaluate performance of various surface-side operational scenarios against different geothermal resource values.

The model incorporates the hourly heat demand data set to track realistic performance of the system over time. The modeling tool uses custom Macros (written in Visual Basic for Applications, or VBA) to efficiently process large data sets, calculating precise energy (MWth) recovered from the selected reservoir output stream and electrical power consumption for heat pump boosting (when used) to produce that recovered energy.

More details are described below in the "Surface Use Modeling" section.

3.2 Geothermal Reservoir Models

Both numerical (TOUGH2) and analytical (GEOPHIRES) models are being used for geothermal reservoir simulations. A variety of simulation tools and options are available for each model. The analytical models available in GEOPHIRES will provide a simpler version of reality than what numerical TOUGH2 could provide, and, as a result, complete computations faster, allowing uncertainty analyses with large sample sizes to be evaluated more efficiently. When a geothermal reservoir system is well understood, TOUGH2 or a similar numerical simulator is commonly used to estimate or calibrate model parameters from data (e.g. Finsterle et al., 1997), or as an accuracy standard to which analytical methods are compared (e.g. Fox et al., 2013). However, the greater computational time required compared to an analytical model limits the potential to evaluate uncertainty.

Both GEOPHIRES and TOUGH2 require similar subsurface information as input. Subsurface parameters defining reservoir target depths, temperatures, pressures, porosity/permeability, and confining units will be based on new analysis of well log and cuttings data from wells near Ithaca, building on earlier regional analyses performed by Camp (2017), Smith (2016), and Whealton (2016). For basement rock units, a minor amount of lithologic information is available from borehole cuttings, and fracture distribution and properties will be informed by fracture data from analog outcrops in the Adirondack Mountains. Cornell's approach to selecting key input parameters is discussed in the "Geothermal Reservoir Modeling" section below. A list of values for other input parameters not discussed herein is available upon request from the authors.

3.2.1 Numerical Reservoir Model (TOUGH2)

The TOUGH2 (Transport of Unsaturated Groundwater and Heat, version 2) suite of software codes are multi-dimensional numerical models for simulating the coupled transport of water, vapor, noncondensible gas, and heat in porous and fractured media (Pruess et al., 2012). TOUGH software has become a standard for geothermal reservoir simulations. Cornell will use TOUGH2 to model geothermal fluid temperature, pressure, and flow rate over time in the reservoir. In particular, the EOS1 (water, heat) module will be used. We also plan to compare results for the EWASG (water, salt, heat, noncondensible gas) module (Battistelli, Calore, and Pruess, 1997) because central New York deep sedimentary rocks may contain saturated brine rather than freshwater (Lynch and Castor, 1984).

3.2.2 Analytical Reservoir Model (GEOPHIRES)

GEOPHIRES (Geothermal Energy for the Production of Heat and Electricity Economically Simulated) is a software tool developed at the Cornell Energy Institute [Beckers, 2016; Beckers et al., 2013]. GEOPHIRES has proven to be sufficiently useful to merit further development at the National Renewable Energy Laboratory (NREL) as GEOPHIRES v2.0 (Beckers and McCabe, 2018). GEOPHIRES provides several analytical reservoir model options to help estimate resource characteristics (temperatures, reservoir drawdown, etc.). We will evaluate these analytical models in this project.

3.3 Economic Models

Cornell's study considers both traditional single-bottom-line economics (i.e., impact to the owner or developer) and what is commonly called triple-bottom-line economics, in which cost or value externalities (e.g. for environmental or social impacts) are considered. Economic modeling will be accomplished primarily during Year 2 of our study.

GEOPHIRES contains standard methods of evaluating economics of a project as single-bottom line Levelized Cost of Heat (LCOH). However, Cornell will largely use independent cost estimating methods based on Cornell-specific data to estimate capital and O&M costs for insertion into the GEOPHIRES model. Cornell will also review the GEOPHIRES-embedded or derived values for comparison purposes and may use GEOPHIRES-derived data where appropriate.

Regional and global economic impacts are less straightforward, but Cornell will develop estimates of these, in parallel with the project owner LCOH calculation. Specifically, Cornell will provide a calculation of the likely regional economic (jobs and wealth) impact of geothermal development in our area, using standard protocols in conjunction with standards used in economic development. Global environmental impacts will be calculated using the Social Cost of Carbon as documented by the USEPA in 2012. This latter calculation is rather straightforward and utilizes a consensus value for the impact of carbon-based Greenhouse Gas (GHG) emissions to derive a value for the impact on society at large (globally). Each of these values will be clearly presented separately to avoid any confusion when comparing the Cornell work with past calculations or other DDU projects.

4. Surface Use Modeling

4.1 Heat Requirements of Site

For the purpose of this study, Cornell is using data from 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 3 represents hourly data from real-time meters for all significant Cornell buildings for FY 2017, totaling about 0.81 Trillion BTUs (283,000 MWth-hrs). The goal of this study is to develop a conceptual geothermal system to provide the heating for 20% of this campus load. Therefore, the minimum goal is to identify a system that will supply at least 0.166 Trillion BTUs (~49,000 MWTH-hours) on an annual basis.

For smaller buildings without real-time metering, monthly metering data are used. For modeling purposes, Cornell routinely decomposes the monthly data to an approximate hour-by-hour usage pattern, based on comparison to real-time usage patterns in other buildings, and uses those model data to conduct system-wide analysis and load projections that include hourly peaks.

4.2 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 boosting the overall well performance; and perimeter/building level, for targeted heat boost)
- Hot water storage systems

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

4.2.1 Distribution and Building Piping systems:

Since the early 1900s, Cornell has used distributed steam heat infrastructure to deliver heat to buildings; 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 which are in turn served by more centrally located heat exchangers that receive steam. A revised campus standard was recently adopted that requires future system expansions to be designed for hot water. Cornell is also planning to continue conversion from steam to hot water distribution in all existing buildings and laboratories. This feasibility study is based on serving this current and future hot water delivery system.

For this study, we assume that all hot water district distribution utilizes pre-insulated piping systems conforming to European Standard EN253 (Pre-insulated bonded pipe for hot water district heating). EN253 is a Cornell campus standard for hot water distribution in this temperature range and a standard adopted by many other U.S. institutions that have recently converted to hot water distribution systems. Hot water distribution systems within each building are already in place; only minor changes to these systems (as required to connect to new hot water infrastructure) are assumed.

For any work on this project that requires specific pipe data, (i.e., pumping losses per unit length, thermal losses, etc.) Cornell is using published data for piping meeting this standard.

4.2.2 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 segregated them into three different building types, namely:

- Facilities needing high temperature hot water for heat ("High Temperature Facilities" 82oC (180oF) 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" 70oC (158oF) 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" 60oC (140oF) minimum supply temperature). These facilities may also be considered candidates for cascading energy use (e.g., greenhouses, agricultural facilities).

The surface use modeling program allows the following:

- Operator-selectable required temperatures for each building type. For example, as we develop our model, we have run scenarios with the temperature assumptions listed above for high, standard, and low temperature facilities.
- Flexible reallocation of buildings into different Type categories.

Figure 3 shows graphically how the total heat load can be allocated between these building types, on an hourly basis. In this example, most campus buildings are classified as Standard Temperature Facilities, consistent with the general descriptions provided previously.

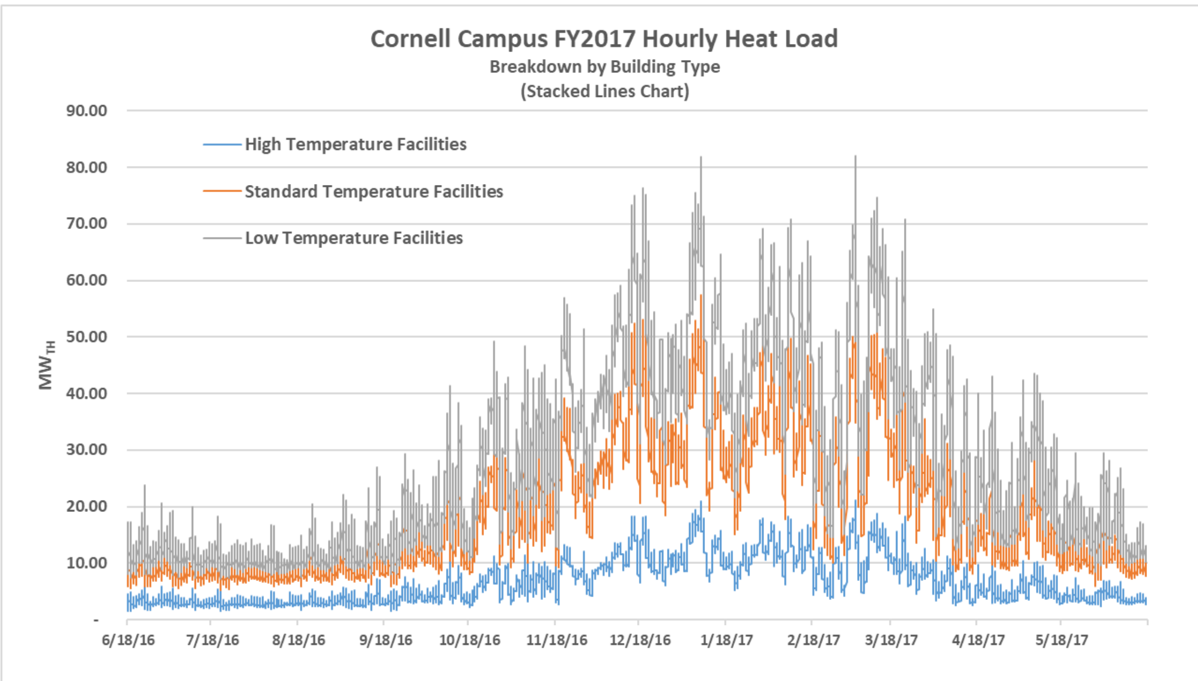


Figure 3: Hourly Cornell Campus Heat Demand for all connected buildings, shown by facility (heat demand) classification. Values are stacked, so the gray line represents the total campus demand.

This model arrangement allows testing of various scenarios, including but not limited to:

- Sensitivity of LCOH to building temperature and distributed loop temperatures. This is especially relevant for lower temperature geothermal sources.
- Impact 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. This ability to extract heat in multiple stages can have a significant positive impact on LCOH.

- The impact of infrastructure changes over time. For example, Cornell has recently changed our building design standard to require that all new and renovated buildings be designed to operate with a minimum 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.

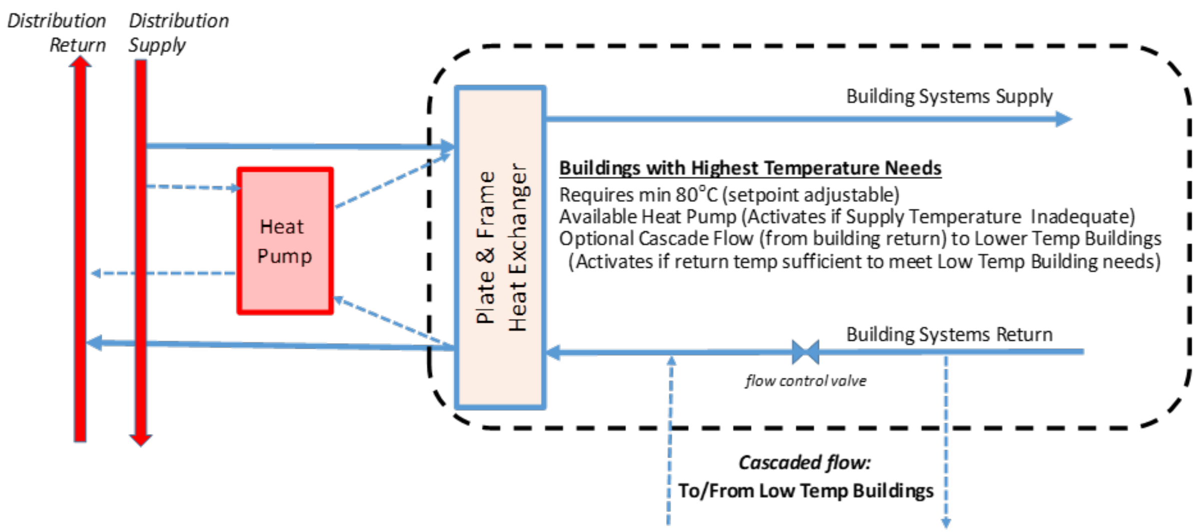


Figure 4: Modeled High Temperature Building arrangement with booster heat pump and cascading flow (some spreadsheet data not shown to improve visual clarity).

In parallel with this DDU study, Cornell is independently conducting a building-by-building assessment to examine which buildings can operate without any significant modifications at lower temperatures (i.e., those with slightly oversized hot water heating coils and radiators) and which require changes, and the extent of such changes. We anticipate reducing required supply temperatures building-by-building over time. Cornell is also exploring modifications to building systems to create in-building cascading, so that high temperature needs (older radiators) can absorb the highest temperatures and lower temperature needs (reheat, preheat, domestic hot water) can then reduce the exit temperature further.

Figure 4 shows a partial schematic of how the High Temperature Facilities are arranged in the working model. Specifically, 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.

<u>4.2.3 Fluid pumps</u>

Fluid pumps will be included in three main sub-systems, specifically:

- Primary geothermal fluid injection and/or production pumps

- Distribution system circulation pumps
- Building heat distribution pumping systems

To estimate pump performance (hydraulic efficiency), we use a conceptual description of pump operation together with data from the Hydraulics Institute.

Several types of pumps are used. The primary geothermal pumps circulate the water from the connected geothermal well system through the primary heat exchanger; these pumps are assumed to be base-mounted centrifugal pumps. Distribution system circulation pumps will use in-line or base-mounted centrifugal pumps. Finally, building systems will generally utilize existing installed self-contained, close-loop hot water systems with little or no change to current operations.

For modeling across a wide range of flows and pressures, we first established standard efficiencies typical of each pump type (n) for incorporation into the general pump energy equation:

Pump Energy = n x Q x ΔP where:

n = efficiency (motor/drive efficiency x pump efficiency)

Q = flowrate pumped

ΔP = pressure across the pump (pumping head)

The Hydraulics Institute lists hydraulic efficiencies. The axial flow or centrifugal pumps which would be used for all of the applications involved in our study, represent similar hydraulic efficiencies (over 80%). Overall system efficiencies, which include both hydraulic and electrical losses, will be lower. For the initial purpose of calculations used in this study, we assume that the pumping system average efficiency is 75%.

4.2.4 Plate-and-Frame Heat Exchangers

We expect that plate-and-frame heat exchangers, similar to those used at our Lake Source Cooling Facility and elsewhere on campus, will be used to exchange heat between the primary geothermal pumping system and the distribution system, and between the distribution system and individual buildings. A primary design assumption or criteria related to the design and selection of plate-and-frame heat exchangers is the approach temperature, which is the temperature difference between the leaving distribution water and the entering supply water. A larger plate surface area will result in a lower approach temperature. Accepting larger approach temperatures would allow for less plates and thus lower capital cost, but may also result in higher water velocities and thus higher pressure drops and more pump power over the life of the system, as well as lower temperature water being delivered by the system. Thus, for the purpose of our study, we will assume selection of plate-and-frame heat exchangers capable of achieving maximum approach temperatures of 1 oC.

4.2.5 Heat Pumps

This study will include an evaluation of the costs and benefits of inserting heat pumps at various locations in the distribution and/or building piping systems. This would allow additional heat to be extracted from the geothermal fluid as a cascading use prior to reinjection, improving system efficiency and economics. Based on a broad review of commercially-available heat pumps and some specialty (higher temperature) heat pumps in development, we are assuming as a basis for energy calculations and sizing that all heat pump systems will operate at 42% ideal efficiency (i.e., 42% of the efficiency of a Reversible Carnot Heat Pump). Thus, we assume:

COP = 0.42 * (TH/(TH-TL)) where:

TH = generated high temperature of the fluid that is being heated

TL = leaving temperature of the fluid from which heat is extracted

4.2.6 Hot Water Storage Tanks

Cornell's study includes analysis of the temporary storage of hot water to accommodate peak loads. The model assumes water is stored at atmospheric (or near-atmospheric) pressure, and as such the maximum storage temperature will be just below 100 oC. The model also assumes that the hot water storage tank is able to maintain temperature with minimal losses (~1% loss of available energy per day). Cornell already has experience with cold water storage on campus; losses from this tank system are similarly low. These relatively low losses reflect the relatively low temperatures used for storage and propensity of water to store heat effectively.

5. Geothermal Reservoir Modeling

There are three main considerations for modeling a geothermal reservoir: 1) description of the rock matrix and associated geological structures, 2) setting the initial thermodynamic conditions for the rocks and fluids, and 3) selecting the parameters of the simulation. A fourth consideration addressed above is the type of thermalhydraulic model to use for simulations. This section addresses the selection of geologic and thermal properties and their uncertainties for geothermal reservoir simulations in our target formations.

There are two potential geothermal reservoir target formations under investigation for the Cornell University, Ithaca, NY campus. The shallower target is in sedimentary rocks within the Trenton-Black River (T-BR) carbonate group, which regionally contains relatively high permeability in a hydrothermally altered dolomite (Camp and Jordan, 2017) but occurs only in widely separated thin bands. The deeper target is Precambrian basement rocks, for which little information about hydrogeologic and thermal properties is available in the Ithaca region.

5.1 Geologic Parameters

This section presents the geologic model parameters specific to Ithaca, NY. Additional details are available upon request.

5.1.1 Generalized Ithaca Sedimentary Column

The formations of interest for geothermal reservoir simulation include all of the reservoir rocks through which fluid may flow, and the surrounding reservoir caprocks and base-rocks that may supply conductive heat recharge to the reservoir. Simplifications to the full geologic column, where appropriate, are beneficial for computational efficiency for large numerical simulations like TOUGH2.

For the shallower Trenton-Black River (T-BR) sedimentary target reservoir (Fig. 2), a low permeability shale (the Utica) overlies the Trenton and will likely act as a barrier to fluid flow. Carter and Soeder (2015) provide mercury injection core permeability data for the Utica from 9 wells in Ohio. The permeability ranges from as low as 1E-7 mD to as high as 2E-3 mD, and most commonly is between 1E-7 and 5E-6 mD. The Utica Shale is a unit of roughly 40 – 50 m thickness in Ithaca, so even leaky portions of the Utica Shale would likely have a barrier to upward flow somewhere in that vertical distance. Thus, for detailed reservoir modeling of the T-BR, we focus on a 600-700 m thickness of units between the Utica Shale and the basement rocks. Finer resolution grid cells will be used in this lower portion of the stratigraphic column.

Units immediately above the Utica are likely important for conduction recharge of the T-BR reservoir, but not for advective heat transport. We simplified the geologic column above the Utica shale based on a set of deep well logs of formation density and porosity collected near Ithaca. Changes in density and porosity in the well logs were used to select geologic blocks for which statistical distributions of density and porosity could be made. Blocks were selected to contain similar density and porosity mean and variability within the block. Where available, we also used temperature logs, which provide insights into important changes in thermal conductivity where changes in geothermal gradient occur. Thermal conductivity values assumed in our study are the same as were used in the Geothermal Play Fairway Analysis of the Appalachian Basin (Cornell University, 2017).

5.1.2 Trenton-Black River (TBR) Reservoir Target

Local well logs were used to estimate the depth to the top of the Trenton-Black River (T-BR) contact. Based on these logs, the T-BR reservoir is estimated to be about 2230 m depth in Ithaca (Fig. 2). Whereas the majority of wells surrounding Ithaca have dolomite rather than limestone at the top of the Black River, the presence of higher permeability hydrothermal dolomite at the T-BR contact below Ithaca is highly uncertain (Patchen, 2006; Camp and Jordan, 2017). Where dolomite exists, the thickness is expected to be a maximum of 30 m, hence we model alternatives ranging from 0 m to 30 m thickness.

TBR Porosity and Permeability

A set well logs from the Ithaca, NY region was used to gather likely values for formation porosity. The porosity values among wells generally agreed within our formations of interest, which supports regional consistency in porosity for these formations.

Permeability values are not as readily available from published studies, and values that were obtained are from cores rather than in situ measurements or reservoir flow tests. Permeability is likely to be a sensitive parameter in geothermal reservoir simulations, but we do not have much local data with which to constrain the permeability in formations of interest. Camp and Jordan

(2017) show porosity and permeability measurements for a small (N = 23) dataset from a T-BR site about 50 km away from Ithaca. We will assume that these relationships and findings from Camp and Jordan (2017) will hold for the T-BR located below Ithaca. Permeability values ranged from 0.01 mD to an upper detection limit of 14,590 mD, and averaged at 4,680 mD. Vertical permeability was orders of magnitude less variable, ranging from essentially 0 mD to 58.2 mD, and averaging 2.6 mD.

5.1.3 Basement Rock Reservoir Target

Based on local wells that reached basement, the depth to the basement in Ithaca is estimated to be about 2865 m, with an uncertainty of +/- 200 m. For the purposes of this project, we will assume that a reservoir in basement rocks begins at a minimum depth of 3000 m. For economic reasons, we will use 4500 m as a maximum depth for reservoir simulations.

Basement Lithologies

A Cornell internal report by B. Valentino (2016) evaluated the lithologic composition of well cuttings of basement rock in the Finger Lakes region, borehole cores in the Mohawk Valley south of the Adirondack Mountains of New York State, and potential field geophysical data. This study leads us to expect to find crystalline basement rocks below Ithaca similar to those rocks that are exposed in the Adirondack Mountains. It is apparent from a cluster of well cores in the Mohawk Valley that the composition of these rocks can change over spatial scales on the order of kilometers or less. Therefore, we will assume that the lithology of Ithaca basement rocks could be any of the compositions sampled in that analysis, in which granitic gneiss is the most common, and marble and amphibolite are also observed. Anorthosite is also anticipated, based on potential field data.

Basement Fracture Geometry

Fracture aperture, spacing, and orientation in basement rocks have been estimated based on field observations of outcrops of Grenville basement rocks in the southern Adirondack Mountains. Large-scale fractures in basement rocks can be simulated in geothermal reservoir models, whereas microscale fractures provide information about the potential for stimulation of additional fracture permeability. Many microfractures are mineral-sealed and thus are likely to have existed prior to exhumation of the Adirondack Mountains in the recent geological past, and therefore are potentially analogous to what exists beneath Ithaca. This section discusses key findings from that field trip that are being used to inform the selection of basement rock fracture geometry in the Cornell study.

Fracture aperture and spacing

Larger scale fracture apertures in basement rocks can range from less than 0.1 mm to as much as 2 cm. The most common apertures observed were about 1 mm. Large-scale fractures in basement rocks in the Adirondacks tended to be near vertical. Their spacing ranges from as dense as 5 cm to as much as 7 m, with 1 – 2 m being the most common separation. Scenarios for dense vs. sparse fracture spacing in basement rock can be evaluated to gain insight about differences in expected reservoir performance.

The abundance of mineral-filled micro-fractures indicates that stimulation of basement rocks could be beneficial for opening of preexisting fractures. The observed apertures of these filled fractures were estimated to cluster around 0.1 mm. The spacing of these microfractures ranged from 0.5 cm to greater than 10 cm, with 2 cm being the most common.

Fracture Orientation

For basement rocks, our Adirondack analog study showed two reasonable scenarios for large scale, near-vertical fracture orientations within the basement rocks. The first scenario reflects a simplistic case where fractures are equally likely to have any orientation at a given site. Such distributions were observed at the surface at some Adirondack sites visited. The second scenario has fractures with a preferred NNE orientation, which generally agrees with the smoothed World Stress Map principle compressive stress orientation based on Horowitz (2015).

5.2 Initial Conditions

Establishing stable initial conditions is a necessary first step of any geothermal reservoir modeling effort. Here we discuss the selection of the starting values of initial conditions before allowing time to reach equilibrium conditions. Starting values are based on available regional data.

5.2.1 Formation Pressure Profile

The simplest assumption for formation pressures is that of hydrostatic conditions. For this analysis we use pore fluid density samples from regional wells to predict the formation pressure with depth, and we will assume that the fluid density is constant with depth.

Williams (2005) found that the depth to the water table near Ithaca ranged greatly, from less than 12 ft (3.6 m) to as much as 800 ft (244 m) with an average depth of about 120 ft (36.5 m). About 75% of the freshwater groundwater zones were found shallower than 150 ft (45.7 m). For aquifers containing brine, several datasets provide densities, such as oilfield brine composition data (Dresel, 1985), disposal well data (Waller et al., 1978), and the produced waters database from the USGS (Siegel et al., 1990; Skeen, 2010; Lynch and Castor, 1983; Matsumoto et al., 1996). Based on these data, pore fluid brine densities are estimated to range from 1000 kg/m3 to 1250 kg/m3.

Using these parameters, the most likely values of pressure at the T-BR target depth of about 2230 m are between 23 MPa and 26 MPa. The difference in pressure at this depth between a model with water starting at the surface vs. a model with water starting at 800 ft (244 m) is about 2 MPa.

5.2.2 Temperature Profile

Temperatures at depth within the Ithaca region and the Appalachian Basin have been estimated by Smith (2016) using a 1D heat conduction model (Horowitz, Smith, & Whealton, 2015) and a generalized regional stratigraphic column different than the Ithaca-specific column (Fig. 2). The estimation by Smith accounted for geological (formation depth and thickness) and thermodynamic (thermal conductivity, radioactivity) variable uncertainties, and spatial correlations of the temperature data (kriging spatial interpolation uncertainty).

Figure 5 shows the predicted distributions of temperatures at depth below Ithaca in 500 m increments. The temperature distributions are skewed right at shallow depths and become more symmetric with increasing depth. Uncertainty increases with increasing depth, as expected. The basement depth is located between 2.5 km and 3 km, after which a change in geothermal gradient appears to occur. This is a result of modeling assumptions; the exact values for the gradient and heat generation in basement rocks are uncertain, and those epistemic model uncertainties are not captured with this analysis.

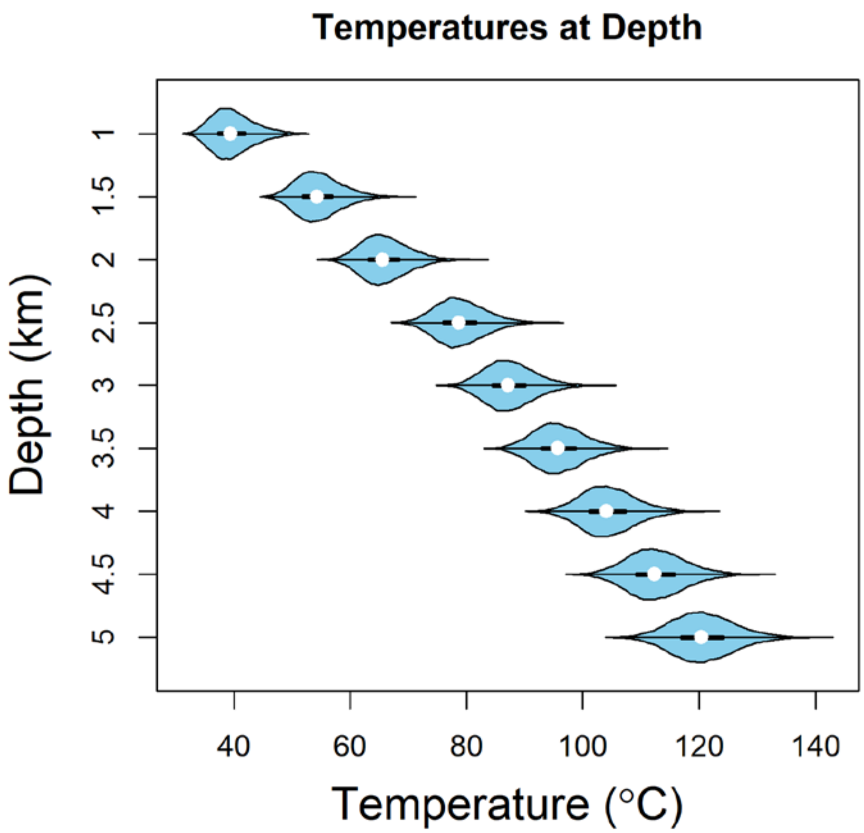


Figure 5: Violin plots (kernel density plots with a boxplot in the center) of the temperature at depth based on 10,000 Monte Carlo replicates of uncertain variables. White dots are the median estimates of the temperature at depth. The black box in the center extends from the 25th to the 75th percentile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

5.2.3 Heat Flow Boundary Condition

Specific values of the steady state heat flow at the bottom of the simulation grid will be obtained by projecting the Smith (2016) map of the surface heat flow to the depth of the bottom of the simulation grid using a 1D heat conduction thermal model (Horowitz, Smith, & Whealton, 2015). The minimum value of the basal heat flow is poorly constrained in the Ithaca area from direct measurements. Studies of stable continental regimes, which the Appalachian Basin is part of, have an average basal (mantle) heat flow value of 25 mW/m2 (Sclater, Jaupart, and Galson, 1980). Based on Whealton's (2016) sensitivity analysis, uncertainty in this value is unlikely to significantly affect geothermal reservoir simulation results.

5.2.4 Desired Output from Thermalhydraulic Modeling

The primary output variables from all thermalhydraulic models are the pressure and temperature field in the reservoir, the pressure drop within the reservoir, the output temperature as a function of time at the production well, and the estimated lifetime of the reservoir. The impedance between the injection and production wells, defined as the change in pressure between the injection and production well, divided by the production well flow rate, is also of interest. Low flow impedance is preferred to efficiently extract heat from the reservoir.

6. Discussion

6.1 Early Surface Modeling Insights

The development and testing of our surface model has allowed the Cornell team to quantify some important findings that we expect will have significant impact on our calculated economics in the next phase of this study. Some early examples of these results are as follows:

- Using heat pumps can significantly improve the energy extraction rate of a DDU source – in some cases the quantity of energy is multiplied by a factor of 2 or more. Not only does a heat pump allow for "boosting" of the resource temperature to meet basic system needs, but it also results in extraction of additional energy so that re-injection temperatures are lower, thus increasing the energy recovered per cycle. A key is to integrate heat pumps at optimal temperatures so that the coefficient of performance remains high (i.e., electrical use remains small compared to the heat provided).
- Designing facilities for effective use of low temperature heat can greatly improve the LCOH of a DDU source. Both distribution and end-use temperatures are important variables in determining the energy value of extraction from a given DDU source. This intuitive fact – that lower temperature facilities are easier to heat with lower temperature resources - can be quantified with modeling to help institutions like Cornell design and modify facilities to optimize use of DDU resources. Whereas past DOE studies have focused on the geothermal supply side of the system, operations at the surface for institutions like Cornell may be just as important in achieving reasonable LCOH.
- Variable flow pumping matched to load demand is important. Excessive flow means that the temperature drop from supply to return is too small to provide optimal economic performance. Slowing down water flow in distribution pipes and in the buildings saves energy and results in higher differential temperatures: more heat used per gallon available. This may be critical with flow-limited DDU systems.

In addition to their value in designing DDU systems, these insights are also useful in facilities planning for institutions like Cornell. The ability to model these design alternatives – lower building design temperatures, variable distribution flow, etc. – is also useful when evaluating other types of low-carbon or lower temperature heat resources (e.g. waste heat, solar thermal, biomass) and in minimizing distribution system energy use and thermal losses.

6.2 Well Field Parameters

Based on preliminary results from our analysis of how potential subsurface resources might best be utilized within existing or future campus facilities, we have identified the following broad constraints on anticipated well field parameters, which will guide our ongoing modeling effort.

6.2.1 Injection Well Flow Rate

We will evaluate injection well flow rates ranging between 20 - 50 kg/s, which are common values for geothermal systems.

6.2.2 Well Separation Distance

The distance between the injection and production wells is limited by the area available on the Cornell site to space the wells. We will start with a base case of 1 km well separation, and we may evaluate other separation distances to optimize performance of the geothermal system. We anticipate that the plan view area covered by the reservoir fluid flow will extend beyond the area bounded by the wells. We will evaluate both horizontal flow between vertical wells and vertical flow between horizontal wells. For example, vertical flow may work well for potential basement reservoirs if these units have near-vertical fractures.

6.2.3 Injection Well Temperature

Based on our preliminary surface use models, we will model injection well temperatures from 20 °C – 60 °C. We may vary the injection temperature during the simulation based on optimized surface use of the production fluid. To do this, we would need to pause the reservoir simulation, output intermediate results, optimize the surface model, update the injection temperature and flow rate, run a simulation, and repeat. Such a strategy would be most important towards the end of the modeled reservoir life when the production temperatures are expected to decline. At that point, for example, management of the surface distribution loop may be re-optimized for lower supply temperatures.

7. Future Work

Having developed the analytical tools, surface use scenarios, and geothermal reservoir modeling parameters described in the previous sections, Cornell will continue to perform model runs to identify the combinations of likely subsurface reservoir production and surface use options that provide the most overall value. This will include an analysis of model sensitivity to subsurface parameters in order to improve the model and the resulting probability estimates for production from the two reservoir depths.

For Year 2 of the study, we will add a detailed economic analysis of anticipated costs and benefits for the two most promising reservoir production/surface use scenarios, producing a Levelized Cost of Heat for each.

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