DE-EE0008103

Earth Source Heat: A Cascaded Systems Approach to DDU of Geothermal Energy on the Cornell Campus

Final Project Report

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Executive Summary

This report documents the completion of the DOE study **DE-EE0008103: Earth Source Heat: A Cascaded Systems Approach to DDU of Geothermal Energy on the Cornell Campus** (hereinafter, "Cornell Study"). The main section includes a summary report that is arranged in order of Statement of Project Objectives (SOPO) subtasks. Appendices used to provide further detailed information are referenced from the main section and listed in the Table of Contents following this Executive Summary.

This study involved a comprehensive evaluation of the potential for Earth Source Heat (ESH), Cornell's specific application of Deep Direct Use (DDU) geothermal energy, to create a viable renewable source of thermal energy for its Ithaca, NY campus district heating system. The study included stochastic modeling that married each of two potential subsurface resources (two specific geological reservoirs) to documented campus heating operations based on hourly campus heating profiles and proposed integrated equipment controls (variable speed pumps and heat pumps). The outputs of the subsurface modeling were used as inputs for a Cornell-developed surface heat use Excel-based modeling program (the program was named "Modeled ENergy Use", or "MEnU"). This allowed Cornell to compute realistic annual totals of extractable and useable heat for the campus, including details like heat losses, minimum summer demand, and controllable building temperature settings. The Cornell team then evaluated the costs and benefits of each modeled scenario.

The primary evaluation was a standard "single bottom line" economic calculation for the Levelized Cost of Heat (LCOH). This represents the annualized cost (per unit heat) for Cornell. Additional valuations were also computed based on the benefit to the environment and to the regional economy (i.e., economic benefits external to campus).

The results of this study demonstrate that if suitable reservoir flow can be attained, Earth Source Heat would be a viable technology to supply Cornell's district heating system. This viability is based on the following criteria:

- The modeled system produced a total useable heat output that exceeded the minimum annual campus heat load determined at the onset of the project (i.e., offsetting **at least 20% of the annual campus thermal load**). The output range is substantial depending on both the subsurface resource and the surface applications; at the high end, our modeled solutions produced up to ~70% of existing campus heat load with a single well pair producing 70 kg/s with integrated high-temperature heat pumps.
- Modeling demonstrated that multiple geothermal reservoirs could provide **economically viable results when heat pumps were strategically integrated**, a design that has been proven in at least one European installation already. In this context, "economically viable" means that the LCOH for the project is less than the regional commercial price of heat that would be generated using natural gas (the most common and cheapest fossil

alternative in our area). LCOH values are detailed in the Results and Conclusions section of this report and summarized in Table EXEC-1.

Table Exec-1: Levelized Cost of Heat (LCOH - Single Bottom Line Economics), 2019 US$/MMBtu

Reservoir	Achieved subsurface flowrate		
	30 kg/s	50 kg/s	70 kg/s
Trenton Black River Sedimentary Layer at ~2.3 km depth	$5.62-$6.24 (mean: **$5.96**)	$4.97-$5.39 (mean: **$5.16**)	$4.84-$5.20 (mean **$5.00**)
Crystalline Basement at ~3.5 km depth	$6.34-$6.59 (mean **$6.46**)	$5.13-$5.33 (mean **$5.23**)	$4.60-$4.85 (mean **$4.77**)

The ranges in each entry of the table shows the variation between the model simulations, with the lowest LCOH cost corresponding to the upper 25 percentile temperature in the recovered fluid, the high cost corresponding to the lowest 25 percentile temperatures, and the number in **bold** represents the **mean** temperature value from all model runs. One surprising result is that the LCOH differences are relatively small between the two modeled reservoirs; the higher costs for drilling deeper reduce some of the benefit of the higher temperatures (and thus greater geothermal energy quantity) recovered. All of the results shown in Table Exec-1 assume the same surface infrastructure and controls setpoints (flow and temperature design points) and operations, and all include integrated heat pumps for extraction of additional thermal energy prior to re-injection.

In addition to LCOH, Cornell's scope also included evaluation of the Environmental value and Regional Economic value of each scenario. A description of this evaluation is included in Section 3.2 and detailed in Appendices H and I of this report. Tables Exec-2 and Exec-3, respectively, provide a summary of the results of these analyses, which are also provided in more detail in the Results and Conclusions section of this report.

TABLE Exec-2: Environmental Value ($LCOH_{ENV}$), 2019 US$ per MMBtu

Reservoir	Achieved Subsurface Flow (kg/s)		
	30 kg/s	50 kg/s	70 kg/s
Trenton Black River	$1.23-$1.34 (**$1.31**)	$1.21-$1.36 (**$1.29**)	$1.20-$1.33 (**$1.26**)
Crystalline Basement	$1.50-$1.59 (**$1.55**)	$1.52-$1.61 (**$1.56**)	$1.44-$1.55 (**$1.55**)

TABLE Exec-3: Regional Economic Development Values ($LCOH_{REG}$) 2019 US$ per MMBtu

Reservoir	Achieved Subsurface Flow (kg/s)		
	30 kg/s	50 kg/s	70 kg/s
Trenton Black River	$4.73-$5.38 (**$5.10**)	$3.39-$3.75(**$3.56**)	$2.94-$3.19 (**$3.07**)
Crystalline Basement	$6.47-$6.72 (**$6.59**)	$4.50-$4.64 (**$4.57**)	$3.80-$3.86 (**$3.80**)

Based on a single-bottom-line (LCOH) valuation, our results show that economic success is likely for any reservoir deeper than about 2.25 km where a sufficient permeability exists (or can be created with stimulation or similar engineering enhancement) and reasonable production temperatures sustained over time. The LCOH values of $4.77 to $6.46 per MMBtu are all lower than the comparable cost of providing heat energy with a natural gas boiler for a facility in the Northeast U.S. that obtains natural gas at commercial rates (Commercial heat costs would include at least $9.41 in fuel costs, representing total boiler/transfer efficiency of 85% using gas at $8.00 per MMBtu; LCOH would be higher if capital equipment and other operating costs were included).

When considering the environmental and regional economic value of such a project, the overall "triple bottom line" cost (i.e., the LCOH less the $LCOH_{ENV}$ and $LCOH_{REG}$ values) is even lower and in some cases negative; i.e., in some cases a project achieving the listed performance would have higher value to the environment and to the regional economy than the total project costs over the 30-year project timeframe.

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Compliance with Programmatic Goals

This Section summarizes the project's accomplishments in relation to the criteria outlined in the DDU Feasibility Funding Opportunity. Those criteria included the following:

1. Geothermal Resource Assessment
2. Regulatory Compliance Plan
3. End-Use Load Market Transformation Plan
4. Technical Description of Technology
5. Cost and benefits methodology

1. Geothermal Resource Assessment: The Cornell Study included a Geothermal Resource Assessment for our planned subsurface reservoir targets. This assessment included geological data analysis, temperature-depth estimation, and geothermal reservoir modeling that utilized as inputs essentially all available subsurface information from local well-drilling, surface imaging, and similar data included in past studies in our area. Appendix A outlines the geothermal resource assessment work completed and summarizes the resulting modeled flow rate and temperature of the produced geofluid for the proposed life of the project. Section 1.5 and Appendix F document the surface integration model (MEnU) that was used to estimate the extractable thermal energy based on this flow and temperature data.

2. Regulatory Compliance Plan*:* The Cornell project includes an assessment of the Federal, state, and local environmental regulations governing the characterization and utilization of the geothermal resources on the site. Section 1.7 and Appendix C document this assessment. Additional assessment tasks originally proposed for this work were deleted prior to the final SOPO to align with available funding.

3. End-Use Load and Market Transformation Plan:
    a. The Cornell project uses detailed energy use data to provide hourly and cumulative annual predictions of the useable energy that can be obtained from the system over the life of the project. The project includes clear geographical and structural boundaries for the project and documents the campus building characteristics (residential, instructional, laboratory, research, etc.). The study includes analysis of space heating and cascading heat uses for agriculture. Absorption cooling was not part of the project scope because the campus already has a renewable cooling system (Lake Source Cooling); however, absorption cooling could be integrated into modeling by another institution looking to replicate the Cornell model.

    b. Modeling assumptions, systems, and results are described in Appendices A (thermal-hydraulic models and parameters), B (heat pump performance), D

(Cornell heat demand), E (economic factors), F (surface model variables) and G (LCOH economic factors) of this report. The inputs include individual and cumulative energy loads for all proposed end uses.

4. Technical Description of Proposed Direct-Use Technology(s):
   a. A technical description of the proposed direct-use technology is included in Section 1.5 and Appendix F of the final report. This includes a description of the type and location of the wells and the direct-use heat extraction system to be used for the site. Innovative approaches include the use of centralized heat pumps to extract additional energy prior to the geothermal fluid return (Section 1.5) and thermal storage opportunities within the system (Section 1.5). The interrelationship between system efficiency and building design is also discussed in Section 1.5 and Appendix F as it applies to this project.

   b. The Cornell Project subsurface model predicted how the temperature of the geothermal resource changes over time, dependent on the pumping rates. This variation is reflected in the LCOH calculation sheet through the input of specific year-by-year heat flows. Generally, the use of centralized heat pumps tends to diminish this impact by reducing the operational criticality of specific temperatures, although electrical use increases as temperatures are reduced.

5. Costs and benefits methodology: A primary goal of the Cornell Study was to derive costs and benefits for this project, in the form of a Levelized Cost of Heat (LCOH) analysis. Chapter 2 provides a description of the analysis completed including the input metrics (assumptions and variables) and the output metrics. In addition to the primary LCOH, we also assessed the environmental and regional socio-economic benefits to a development for the Cornell campus. The assumptions, analysis, and results of these assessments are described in Section 1.6 and Appendices E and G.

Task-by-Task Reporting

Task 1: Establish and Document Processes, Data, Analyses, and Success Criteria to be used in the Feasibility Study

The completion of the Task 1 work report is organized in the following subsections by sub-task as per the SOPO.

1.1 (SOPO Subtask 1.1): Document Data Sources and Analytical Tools

The Cornell Study used the data sources and analytical tools listed in this section. Several modeling programs were used concurrently in this study. Modeling tools and associated data sources used in the Cornell Study included the following:

- **TOUGH2**. The TOUGH ("**T**ransport **O**f **U**nsaturated **G**roundwater and **H**eat") suite of software codes are multi-dimensional numerical models for simulating the coupled transport of water, vapor, non-condensable gas, and heat in porous and fractured media (Pruess et al., 2012). Developed at the Lawrence Berkeley National Laboratory (LBNL) in the early 1980s primarily for geothermal reservoir engineering, the tools have evolved over time to support broad research in subsurface resources. The Cornell Study utilized TOUGH2 to model reservoir geothermal fluid temperature, pressure, and flow over time for the Trenton-Black River sedimentary reservoir target.

  A large number of subsurface parameters and analytical choices are required for modeling with TOUGH2. **Appendix A** provides a detailed description of the data (parameters) utilized in the modeling. A list of data provided to the designated DOE data repository is included at the end of the main body of this report.

- **GEOPHIRES**. GEOPHIRES (Geothermal Energy for the Production of Heat and Electricity Economically Simulated) is a software tool originally developed at the Cornell Energy Institute, building on a former MIT-EGS model used in the Future of Geothermal Energy study. GEOPHIRES was further developed by former Cornell doctoral student Dr. Koenraad Beckers while employed by the National Renewable Energy Laboratory (NREL) as described in Beckers and McCabe (2019).

  The Cornell Study utilized GEOPHIRES primarily as an economic tool to estimate project costs, which were used to derive the single-bottom line (owner-specific) Levelized Cost of Heat (LCOH). GEOPHIRES also provides analytical reservoir models to help estimate resource characteristics (temperatures, reservoir drawdown, production wellbore heat transfer, etc.). The Cornell Study team utilized past work (especially results of the regional Play Fairway analysis, as documented in Appendix A) and other independent calculations (e.g., output from TOUGH2) to assign values for some GEOPHIRES input parameters, rather than relying on the GEOPHIRES model to derive those values independently. GEOPHIRES reservoir models were also used, and some results compared to TOUGH2.

Similarly, Cornell used a combination of model defaults and independent cost estimating methods based on Cornell-specific data to estimate capital and O&M costs for insertion into the GEOPHIRES model. GEOPHIRES (V1.2) included 96 parameters, although not all are used for any specific modeling run. A newer version of GEOPHIRES (v2.0), released at the end of January 2018, was used in the final modeling runs.

Table 1 provides a summary of the data (parameters) utilized in GEOPHIRES modeling.

- **JEDI**. The JEDI (Jobs and Economic Development Impact) Model was produced by NREL (https://www.nrel.gov/analysis/jedi/) and recently expanded to incorporate geothermal energy (although the model assumes electrical generation, limiting its use for DDU). While JEDI is **not** customized for DDU and was not suitable as a primary modeling tool, Cornell reviewed elements of the model to help estimate certain construction costs and to estimate the economic impact of job creation (not included in GEOPHIRES). Specifically, elements of this modeling program were extracted to model direct jobs creation, and that output was used as input into an analysis of external (non-Cornell) costs and benefits related to a DDU project in the Ithaca, NY region. The primary inputs needed for JEDI to provide these estimates (well numbers, dimensions, costs, flow, etc.) were derived from outputs of the other listed modeling programs. JEDI estimates were also used for reasonable input values for well stimulation costs (as noted in Appendix G).

- **Custom Modeling for Cornell Heat Utilization**. The Cornell Study team created a custom Excel modeling spreadsheet for documenting the viability of use of DDU heat for the Cornell campus. The modeling tool uses custom Macros (written in Visual Basic for Applications, or VBA) to allow the model to efficiently process large data sets and sum results. Data sources for this spreadsheet include the following:

  - Building Energy Demand Data. To quantify building energy demands for the Cornell site, Cornell utilized **campus energy management system data** (iHistorian/Proficy databases). This management system has been in continuous use for over ten years, and is continuously being improved. Section 1.3 of this report provides documentation of that data.

  - Equipment and system performance. Mechanical equipment and system performance were modeled to compare various surface use scenarios involving different quality (temperature) of geothermal resource extraction. In this modeling, a number of equipment and system performance parameters were required. **Table 2** provides a summary of key parameters used in this modeling and the sources used for those parameters. A detailed discussion of this data is included in **Section 1.5** of this report.

- **Custom Modeling for Economic Externalities**. The modeling tools listed above do not incorporate economic externalities. Cornell's project included both an assessment of the "single bottom line" value of geothermal heat (i.e., the direct economic value to the entity making the investment, in this case Cornell University) and additional valuations that incorporate the "triple bottom line", i.e., that recognize the social and environmental value of decisions. These analyses also used customized tools (Excel spreadsheets). Specifically, after developing viable technical approaches, Cornell also (separately and independently) calculated and assessed the value of two additional facets of geothermal development using the following information sources and techniques:

    - **Environmental Value**. The environmental value of development options was determined using **The Social Cost of Carbon**. The Social Cost of Carbon is a value developed through multi-agency collaboration to recognize the anticipated negative impacts of excessive carbon emissions on society. This "cost" is not one that Cornell would directly bear but, rather, a cost borne by broader society. Cornell utilized this multi-agency documented Social Cost of Carbon to produce this additional "environmental impact" aspect of the triple-bottom line $LCOH_{ENV}$ value of geothermal development. Cornell also estimated other environmental benefits (priority pollutant reductions, etc. using **standards emissions values calculated by the US EPA**) that are not part of the $LCOH_{ENV}$ value, but only report them separately as further supporting information (which may be useful, for example, in an eventual environmental risk and benefit assessment). Appendix E documents the metrics used for determining this value.

    - **Regional Societal (jobs and wealth creation) Value**. New energy development in our region will bring economic development value to the region. This is another externality; Cornell will not directly profit from this regional prosperity, so it would not typically be part of a "single bottom line" economic decision. Cornell utilized third-party published values and internally derived estimates of economic impact that apply to regional capital development, the purchase of goods and services, and the generation and accumulation of regional wealth in our study. As with the environmental valuation, the regional societal value is expressed separately from the "single bottom line" valuation to avoid any confusion. **Appendix E** documents metrics applied to the calculation of externalities.

- **Mechanical equipment performance.** Modeling the system-wide utilization of thermal energy also required assumptions involving mechanical equipment, including fluid pumps, plate and frame heat exchangers, heat pumps, and hot water storage tanks.

Assumptions used in the Cornell Study, which are determined from referenced model outputs, Cornell's analysis of standard industry data, and Cornell's own site experience, are documented in **Section 1.5** of this report.

The "Source and Notes Summary" column in Table 1 provides further information on the parameters used as inputs to GEOPHIRES for Cornell's study. Additional detailed sources and notes for use of each parameter used are documented in applicable section of this Report.

Table 1: GEOPHIRES Input Parameters with Data Sources

Type	Parameter	Source and Notes Summary
Resource Characterization	Maximum allowed reservoir temperature (maximum temperature allowed by the reservoir, degrees °C).	See Appendix A.
	Number of Segments (number of different temperature gradient segments used to define the geothermal temperature profile).	A simplified layering of strata was used based on geological models constructed in part from past natural gas wells drilled in this region.
	Gradient (change in the rock temperature per depth, °C/km). Up to 4 rock gradients allowed.	Variable depending on number of gradient segments selected. Based on provided temperature at depth information in Appendix A.
	Thickness (thickness in km of the gradient segment).	Selected based on general geological models of our area (constructed in part from natural gas wells drilled in this region), as needed (Appendix A).
	Thermal Conductivity of Rock (reservoir rock thermal conductivity in W/mK)	Selected for the reservoir segment using values in Appendix A, which are described in more detail for TOUGH2.
	Heat Capacity Rock is the rock specific heat capacity in the reservoir in J/(kgK).	Selected for the reservoir segment using values in Appendix A, which are described in more detail for TOUGH2.
	Density Rock is the rock density in the reservoir in kg/m^3.	Selected for the reservoir segment using values in Appendix A, which are described in more detail for TOUGH2.

Type	Parameter	Source and Notes Summary
Engineering Parameters	End-Use Product. This entry allows a choice of how the model assumes use of the geothermal energy.	For the Cornell study we utilized the "Direct Use Option" (All the geothermal fluid is directly used as heat). The levelized cost of energy is expressed as LCOH in $/MMBTU
	Power Plant Type Temp for CHP Bottoming Fraction of Flow Rate for Direct-Use Heat	These three parameters are not utilized for direct use studies.
	Water Loss Rate is a ratio (between 0 and 1) of water loss per reservoir to production well flow used in one pass through the reservoir.	One loss rate was assumed for all simulations as reported in Appendix A.
	System Configuration: configures the injection well and production well ratio and relative locations. The options are doublet, triplet, and star.	Cornell assumed use of a single well pair (doublet).
	Pump Efficiency: the overall efficiency (between 0 and 1) of the circulation pump that takes into account both thermodynamic and mechanic inefficiencies.	Cornell utilized values based on review of commercially-available standard pump offerings and Hydraulics Institute standard values for the assumed pump types. See Section 1.5.
	Injection Temperature: the temperature (in degrees C) of fluid at the top of the injection well.	Optimized according to various topside scenarios that resulted in different reinjection (surface leaving) temperatures. Reported results used a 20°C reinjection temperature unless otherwise noted.
	Wellbore Heat Transmission Calculation refers to the model used to calculate the wellbore heat losses/gains.	Cornell used the Ramey model. Losses ranged from 1 – 3°C and were primarily a function of flow rate.

Type	Parameter	Source and Notes Summary
	• Ramey's wellbore heat transmission model • Constant temperature drop model requires the user to input a constant temperature drop in the production well.	
	Production Well Temperature Drop: temperature loss (ºC) in the production wells as the water travels to the surface (used when constant temperature drop model is chosen)	Ramey's model is used
	Production Well Flow Rate: mass flow rate (kg/s) of the geofluid through a production well. This variable can be optimized.	Cornell modeled multiple flow rates that bracket the expected range of values based on what has been seen (after stimulation if necessary) at comparable EGS sites.
	The Injection Well Casing ID is the inner diameter (in inches) of the casing of the injection well.	After estimating flow rate, Cornell utilized a well design that restricts maximum flow rate to about 3 m/sec.
	The Production Well Casing ID is the inner diameter (in inches) of the casing of the production well.	After estimating flow rate, Cornell utilized a well design that restricts maximum flow rate to about 3 m/sec.
	The Well Deviation from Vertical is the well's deviation from vertical (in degrees) as the well enters the reservoir. The well deviation must be zero for a star configuration. This variable can be specified or optimized when the system is a doublet or a triplet.	Cornell evaluated vertical and horizontal well orientations at production depth. Horizontal wells were assumed for basement reservoirs; vertical wells for the TBR reservoir in TOUGH2 modeling.

Type	Parameter	Source and Notes Summary
	The Well Depth is the vertical depth (in km) of the well from the surface. This variable can be optimized.	Cornell evaluated two separate target reservoirs. One well depth terminates in sedimentary rock at 2300 m below the surface, and one in crystalline basement rock at 4000 m.
Reservoir Models	Drawdown Calculation: calculation of decrease in heat energy output over time from the reservoir. 4 models are available: 1. Multiple Parallel Fractures model 2. 1-D linear heat sweep model 3. m/A Drawdown Parameter model 4. Annual % Temperature Drawdown model simulates production temperature drop in %/year. Here, no reservoir dimensions are required. 5. TOUGH2 output	Cornell used model #1 for the crystalline basement reservoir, and to evaluate flow in the TBR reservoir. A plug flow model was added to GEOPHIRES and also used for the TBR reservoir. The plug flow model results are similar to the heat sweep mode results (model #2).
	m/A Drawdown Parameter: the thermal drawdown in kg/(m^2s) (for the 3rd reservoir model only)	N/A. We utilized a different model.
	Percentage Thermal Drawdown Parameter: annual temperature drawdown (%/year) for 4^{th} model.	Not used in our study; LCOH economic modeling used year-by-year model outputs.
	The Reservoir Impedance is the resistance of the rock to fluid flow through the reservoir (in GPa*s/m^3)	Values chosen based on the Reservoir Productivity Index of target formations for nearby wells (sedimentary reservoir) or from literature values (basement).

Type	Parameter	Source and Notes Summary
	The Fracture Model Option is the method of simulating the vertical temperature differential over the section of the reservoir in the injection well. The options are perpendicular fractures using top temperature and perpendicular fractures with temperature drop.	The rectangular fracture shape was assumed.
	Effective Heat Transfer Area per Fracture (in m^2): the input parameter needed for the circular fracture with known area option.	N/A; not used with selected rectangular fracture model.
	Well Separation: distance (in m) between an injection well and a production well.	Cornell assumed a well separation (at depth) of 500 m for horizontal wells in basement rock, 30 m for horizontal wells in TBR reservoir, and 1 km for vertical wells in the TBR reservoir.
	Fracture Width Perpendicular to the Plane Defined by the Well Bores: the dimension (in m) of an individual fracture in the direction perpendicular to the bore plane.	When needed for analytical reservoir models, this input was based on the geometry of the reservoirs. This value is constrained for the Trenton-Black River based on the scale of wrench fault separation, ~300 m (Camp and Jordan, 2017)
	Reservoir Volume Option: choose two of three variables (number of fractures per well-pair, fracture separation, and reservoir volume) to calculate the third.	The option to specify a reservoir volume, number of fractures, and width and height dimensions was deemed most appropriate based on local geologic knowledge.
	Number of Fractures per Well-Pair: # of stimulated fractures between injection and a production well.	Based on the fracture separation observed in the Adirondack Mountains for basement rocks (Appendix A). For the Trenton-Black River using the multiple

Type	Parameter	Source and Notes Summary
		parallel fractures model, a base case of 2 fractures was used (simplest case when fractures are modeled with the reservoir model selected).
	Fracture Separation the separation (m) between the fractures in the stacked fractures of a well-pair.	Based on the fracture separation observed in the Adirondack Mountains for basement rocks (Appendix A). For the Trenton-Black River a base case of 2 fractures was used (simplest case when fractures are modeled with the reservoir model selected).
	Reservoir Volume: total volume (m^3) of rock between the fractures between the well-pair.	Based on the projected reservoir thickness (Appendix A), height (well separation, described above), and width (described above)
	The Thermal Drawdown Fraction to Redrill is the fraction (between 0 and 1) in temperature drawdown that triggers redrilling. E.g. a fraction of 0.1 means that after a temperature drawdown of 10%, the wells are redrilled to start with a new reservoir.	Based on preliminary estimates of reservoir life, Cornell adjusted the surface use scenarios to ensure a reasonable production life without redrilling and used that reservoir lifetime in our LCOH calculations. Economic modeling extracted year-by-year production temperatures to reflect temperature losses over time.
Economic Parameters	Capacity Factor: the ratio of (1) the direct-use heat produced by a generating unit for the period of time to (2) the direct-use heat that could have been produced at continuous full-power operation during that period	Due to summer hot water and reheat needs (documented in our Task 1 Summary Report), Cornell could utilize the heat from a well-pair year-round. Thus, capacity factor assumed to be close to 100%.
	Accrued Financing during Construction is the financial cost accrued during	Accrued financing charges were calculated after estimating capital costs

Type	Parameter	Source and Notes Summary
	construction as a percentage of the total capital costs.	and O&M spend rate using a Discount Rate of 5% (nominal) (see Appendix E)
	Project Lifetime: years of operation that the plant is amortized.	A 40-year lifetime was assumed for these systems although some simulations were completed for longer periods to observe declines in thermal performance (separate LCOH calculations use the first 30 years of modeled production).
	The CHP Levelized Cost Calculation refers to the method used to calculate the LCOE/LCOH in CHP mode. There are three options.	Cornell only modeled LCOH in this study (no electrical generation)
	Fixed Annual Charge Rate (model 1): LCOH = (annualized capital costs + annual O & M costs)/(net power produced*capacity factor)	Cornell produced a custom spreadsheet using the model 1 economic model. Cornell's standard Nominal Discount Rate of 5% was used in these calculations (See Appendix E).
	Interest rate for Standard LCOE/LCOH Calculation (model 2) (GEOPHIRES model from paper)	Not used. Cornell used a form of economic model 1 with Cornell's standard Discount Rate of 5%
	The Levelized Cost Parameters are the parameters used in the BICYCLE Levelized Life-Cycle Cost Model (model 3), in report LA-8909 (1981).	Since Cornell is a not-for-profit (no taxes, investment tax credit, or property tax) a single discount rate was used, so these added features provided no value. Cornell used a form of model 1.
Capital Costs	Built-in correlation with an adjustment factor: allows capital cost components to be calculated with the internal cost correlations and with a multiplier factor. A factor value of 1 calculates the capital costs solely by internal correlations.	Cornell provided an independent assessment of capital cost values that combined model outputs and costs from other external and internal (Cornell) sources, as documented in Appendix E.

	Drilling and Completion Costs are the costs of drilling and completing the injection and production wells.	Cornell used GEOPHIRES well cost estimates with commercially mature technology in this evaluation. Drilling temperatures are not severe in this region and the proposed drill depths are within the range commonly drilled in neighboring states (OH and PA). In sedimentary layers, actual cost reductions may be more pronounced.
	Reservoir Stimulation Costs are the costs of creating artificial reservoirs between the injection and production wells.	Cornell reviewed the stimulation cost estimates that are part of NREL's GEOPHIRES model and those in the JEDI model; GEOPHIRES values were used and considered reasonable based on recent local drill industry experience in the PA/OH region.
	Power Plant Costs are the costs of building the surface plant.	Cornell used internal cost data for large capital construction including Means® Construction Cost Data to estimate the cost of topside energy utilization plant and equipment.
	Fluid Distribution Costs are the costs of the system to distribute the fluid from the wells to the plant.	Cornell used internal cost data and Means® to estimate piping costs from well to plant and from plant to our existing campus heating loop.
	Exploration Costs are the costs of initially characterizing the geothermal reservoir including the cost of hydrologic, geologic and geophysical surveys, as well as the cost of exploratory wells.	Cornell invested in studies to serve academic research purposes in addition to informing development. Since these studies were multi-purpose and represent "sunk" costs, they are not included as part of LCOH. (Note: our test well is designed to be used later as part of the operating system).
O&M Costs	Input total O&M costs in millions of 2012 US$ / year allows the option to input the	Cornell developed and documented O&M costs separate from GEOPHIRES and incorporated this value into an independent LCOH estimate (see

	total O&M costs instead of using internal correlations.	Appendix G); this applies to all entries in this part of GEOPHIRES.
	Apply built-in correlation with an adjustment factor of allows for O&M cost components to be calculated with the internal cost correlations and with a multiplier.	N/A; Cornell developed and documented an independent estimate (see Appendix G).
	Wellfield O&M costs is the cost of maintaining the wellfield.	N/A; Cornell developed and documented an independent estimate (Appendix G).
	Power Plant O&M Costs: the cost of O&M for the power plant.	N/A; Cornell developed and documented an independent estimate (Appendix G).
	Water Cost is the cost of make-up water added in the reservoir.	Cornell owns and operates water treatment with sufficient capacity to support this development; our marginal cost of water production is included in the GEOPHIRES model and reflected in the O&M outputs.
	Electricity Price for Pump Power for Direct-Use Heat: electricity price payed for driving the pump to circulate the geothermal fluid in Direct-Use heat mode.	Cornell generates its own power and is also interconnected to a local high-voltage service; the marginal cost of power production is listed in our LCOH documentation (on the LCOH calculation sheets).
	Heat Price for Heat sales in CHP LCOE option is the price for the heat sold in $/MMBTU.	N/A; Cornell did not use this option.
	Electricity Price for Electricity sales in CHP LCOH option is the price for the electricity sold in cents/kWh.	N/A; Cornell did not use this option.

Table 2: Mechanical Equipment and Systems Data Sources

The "Source and Notes Summary" column in this Table 2 provides further information on Cornell's initial intent in utilizing each of these parameters. More detailed sources and notes for use of each parameter used are included in ***Section 1.5*** *of this report.*

Parameter	Source and Notes Summary
Pump Performance (hydraulic and motor efficiency)	Hydraulics Institute. See Section 1.5.
Plate and frame heat exchanger performance (pressure losses and approach temperatures)	Standard capabilities of commercially available equipment. See Section 1.5.
Heat Pump Performance (Coefficients of Performance)	Temperature-specific Coefficients of Performance representing industry "averages", measures as a fraction of "ideal" (Carnot cycle) efficiency for each source/supply temperature evaluated. Estimates are documented in **Appendix B** to this report.
Hot water storage (losses during storage/use cycles)	Capabilities of commercially available systems. See Section 1.5.

1.1.1 Building energy demands

To quantify building heat demands for this project, Cornell utilized their campus energy management system database. This database contains hourly energy use for significant buildings on campus, with less frequent data (generally monthly) available for smaller facilities. The energy demands of some small buildings or facilities (including most of the greenhouses) are measured at a common (shared) meter. **Section 1.3** and **Appendix D** more fully describe this data set.

1.1.2 Subsurface thermal profiles

Subsurface thermal profile assumptions are defined in **Appendix A**: *Thermal-hydraulic Model Selection and Parameters for Geothermal Reservoir Simulations*. Appendix A provides a summary of the techniques and data sources that were used to estimate subsurface thermal profiles for the Cornell Study.

1.1.3 Subsurface rock properties

Subsurface rock property assumptions are defined in **Appendix A**: *Thermal-hydraulic Model Selection and Parameters for Geothermal Reservoir Simulations*. Appendix A provides a summary of the techniques and data sources that were used to estimate subsurface rock properties for the Cornell Study.

1.1.4 Mechanical equipment performance (including fluid pumps, plate and frame heat exchangers, heat pumps (for targeted heat boost), and hot water storage tanks**). Section 1.5** provides details for assumptions and values used for modeling in the Cornell Study.

1.1.5 System/component cost information

Cornell used two types of cost-estimating tools and data sources in this study:

- Models adopted and used by the US DOE (for example, GEOPHIRES). GEOPHIRES includes estimates for well drilling and development (with standard ranges based on depth), some surface cost elements, and associated soft costs (engineering, site work, legal, land, etc.).

- Models developed by other US Federal Agencies (for example, NREL JEDI cost model, recently expanded to include geothermal power applications). While the JEDI model does not reflect Eastern US conditions well, we did extract some information on typical labor breakdowns that was used in our economic evaluation of regional economic benefit (refer to Appendix I).

- Industry Data: For aspects of the work not completely described in the above models (i.e., heat pump costs, etc.), or for which we can document that local costs are not well reflected by the models, we also used data from established industry sources. One source was the R.S. Means® Company, which annually published construction cost data over a broad range of facilities types, with regional cost corrections. When using Means®, the City Cost Index for Binghamton, NY (located less than 40 miles from Ithaca) was used to adjust prices.

- Actual construction costs: For specialized system elements that cannot be priced from US Government or general industry sources, Cornell obtained estimates from completed projects; for example, the final installed cost of the specialty high-temperature heat pumps was estimated based on the experience of ENGIE, an international energy company which built and operated systems utilizing this equipment.

1.1.6 Social cost of carbon

Many widely-ranging values have been applied as the “social cost of carbon”. To develop an appropriate value for this project, the Cornell Study used the following U.S. government source:

Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, August 2016.

As documented in **Appendix E**, the Cornell Study used the value of **$50/metric ton** ($CO_2$-equivalent) as the social cost of carbon. The determination of CO_2-equivalence utilized standard published USEPA conversion factors associated with natural gas combustion (the "base case" heating source being replaced by geothermal in our study) and the local (Upstate New York) marginal emissions rate for electricity from the grid.

1.1.7 Direct employment estimates

The Cornell Study quantified the regional value of geothermal development in addition to the direct value to a future private system owner (like Cornell). The most significant established regional value is in the direct and indirect value of wages paid to local workers, although regional wealth creation is also a significant factor for geothermal development.

Cornell used the JEDI model as applicable to help provide employment estimates related to aspects of the work that JEDI covers. Specific data sources and assumptions are described in **Appendix E**.

1.1.8 Economic Multipliers

In addition to direct employment benefits, development monies can spur regional economic growth in an important, but less direct, manner. Specifically, a portion of local wages are recirculated within a local economy (for example, to pay for entertainment, local retail goods, local taxes, etc.), spurring additional economic activity. The regional economic value of these "recirculated" dollars depend on many factors, including how many of the direct jobs are held by individuals within the region under evaluation, how many dollars are spent or distributed locally, and whether the local area accumulates wealth from these transactions.

Appendix E provides additional narrative and metrics regarding economic multipliers.

1.2 (SOPO Subtask 1.2): Document SMART Metrics and Success Criteria

To the extent practical, the project team chose metrics that conform to the SMART (**S**pecific **M**easurable **A**chievable **R**elevant **T**ime-Bound) metrics concept. Specific metrics and success criteria used in this study, as detailed in this section, included the following:

- **Heat System Capacity**. A metric that describes the heat system capacity is defined, along with success criteria. To meet the success criteria, the proposed system was required to meet a minimum total load capacity using a single well-set as defined. The **metric** for value is "**Usable Rate of Heat**", i.e., the amount of heat (Watts, BTU/hr, or similar units of measure) that the geothermal system can create *and* the campus systems can use (i.e., available at temperature, pressure, and time needed). The **success criteria** for this metric, as established in the SOPO, is that a single well-set (doublet or triplet) produce **at least 20% of the annual campus heat demand** on an annual basis. This constrained the minimum well production (temperature and flow) necessary for success. Section 1.3 defines the numerical value of this goal.

- **Economics** (based on Levelized Cost of Heat [LCOH]). Three **metrics** for LCOH were developed, representing the Owner's direct costs (which we term **LCOH**); the community/regional LCOH value (**$LCOH_{REG}$**; a positive economic benefit is equivalent to a negative cost), and the global environmental LCOH value (**$LCOH_{ENV}$**). These values are further defined in the next section of this report and in **Appendix E**.

  Each of these LCOH terms use established metrics to determine their value. Success criteria associated with these metrics are as follows: the Cornell Study sought to identify at least one system arrangement whereby **the combined levelized cost ($LCOH - LCOH_{REG} - LCOH_{ENV}$) is less than the "business as usual" levelized cost using these metrics.** In this context, "business as usual" means the continued practice of utilizing available fossil fuels and grid electricity exclusively to heat and power the Cornell campus. However, the project exceeded this goal, since the LCOH of a project that produces adequate flow (at least 30 kg/s) alone was low enough to best the "business as usual" case, as documented in the Results section of this report.

  The incorporation of external (regional and global/environmental) values represents another stated goal of this project, namely, the establishment of a more specific protocol for understanding the regional and global value of geothermal energy as a renewable, regional energy source.

- **Environmental Benefits.** $LCOH_{ENV}$ (as defined above) is a measure of the impact due to carbon-based emissions only. The success criterion was reductions in emissions compared to the "business as usual" case. Standard published EPA emissions factors (https://www.epa.gov/air-emissions-factors-and-quantification/basic-information-air-emissions-factors-and-quantification) were used to derive the baseline; the fuel source used for the baseline (or "base case") was natural gas.

- **Implementability.** The metric and success criterion for implementability was the **development of a permitting strategy** that identified a logical path to regulatory approval for a demonstration system (well-set, heat exchange facility, distribution system) at a specific site at Cornell. The documentation of a *viable path* to the acquisition of all required permits was considered a "success".

- **Broad Applicability**. Another success criteria is that this feasibility study provide tools that can be broadly used for other applications at other DDU sites. Specifically, in demonstrating success, our final working model showed the following benefits:
  - **Stability**. Our models were **stable within the defined parameters.** The models provided reasonable results without "crashing" (or providing non-sensible data) across a broad depth range (~2,000 to ~5,000 meters) and across a reasonable range of anticipated subsurface geology of our region. The model also provided stable and reasonable results over a range of extraction and injection temperatures consistent with the temperatures we may obtain from "deep" geothermal resources in our region (~70 °C to ~110 °C) and consistent with a relatively wide range of potential surface uses (~40 °C to ~120 °C) which may vary based on the "design" of those surface systems. **Success of this criterion was met by demonstrating multiple model runs that cover the reasonable range of Cornell application options;** as a demonstration of the success of this criterion, all runs within such ranges provided *reasonable* and *logical* results.
  - **Flexibility/Adaptability**. The model also allowed for the **flexibility to add or remove a "simple" suite of surface "enhancements"**, including specifically heat pumps, heat storage, and/or common cascading uses. A success criterion for this metric was that multiple model runs using different equipment types and arrangements that cover a reasonable range of campus options provided *reasonable* and *logical* results that permitted evaluation of value. Our results demonstrated this model behavior.

1.3 (SOPO Subtask 1.3): Document Heat Requirements of Site

Figure 1 represents hourly data from real-time meters for all significant buildings from the chosen data set (FY 2017 hourly data). The total annual campus heating load in FY 2017 was about 0.81 Trillion Btu's (283,000 MW_{th}-hrs). The stated goal of this study (as per the approved SOPO) was to develop a conceptual geothermal system to provide the heating for **20% of campus load**. Therefore, the minimum goal has been to identify a system that could supply at least 0.166 Trillion Btu (~**49,000 MW-hours**) on an annual basis. As reported in the Results section of this report, the system energy delivered by all evaluated reservoirs met this standard.

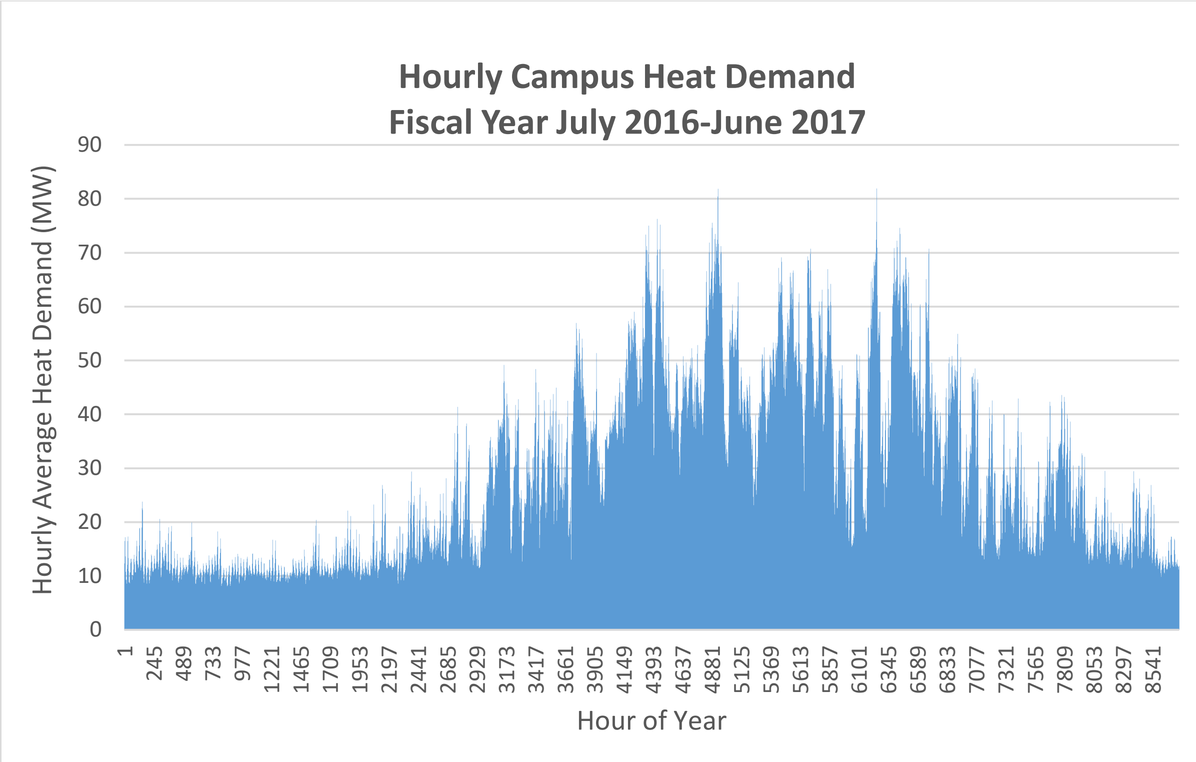

Figure 1: Hourly Campus Heat Demands, all connected buildings, Cornell (Ithaca, NY).

Appendix D provides more information and background on this data set, which was the basis for all surface modeling runs of the Cornell Study.

1.4 (SOPO Subtask 1.4) Develop Reservoir Models, Document Parameters

Reservoir model development is detailed in **Appendix A**: Thermal-hydraulic Model Selection and Parameters for Geothermal Reservoir Simulations.

1.5 (SOPO Subtask 1.5): Define Parameters of Surface Use Technology

Our feasibility study considered 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

Some assumptions regarding each of these system components follow:

Distribution and Building Piping systems:
Distribution piping for water temperatures will utilize pre-insulated piping systems conforming to European Standard EN253 (Pre-insulated bonded pipe for hot water district heating). This

piping is designed and specified for distribution temperatures of up to 248°F (120°C). EN 253 is a Cornell campus standard for hot water distribution in this temperature range and a standard adopted by many other U.S. institutions (Stanford, University of Rochester, Dartmouth, etc.) that are converting or have recently converted to hot water distribution systems.

Building hydronic distribution systems are already in place and generally represents insulated black steel piping; only minor changes to these systems (as required to connect to new hot water infrastructure) is assumed, using in-kind materials.

Cornell historically (since the early 1900s) has used distributed steam heat infrastructure to deliver heat to buildings; the transfer from steam to hot water has traditionally occurred at the building interface (generally, but not always, building-by-building). Today, an expanding portion of campus is served by hot water sub-distribution piping that contains water heated at a more central location by (generally tube and shell type) heat exchangers that receive steam. A revised campus standard has been developed (effective 2018) that requires future system expansions to be designed for low temperature (maximum of ~55°C) hot water, and Cornell is also planning and implementing the systematic change from steam to hot water distribution across campus. Our system design is based on serving this current and future hot water delivery system.

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

<u>Temperature Demands</u>
The source temperatures and flows needed to meet our project goals depend in part on the temperatures needed by various buildings within the campus. The Cornell study team examined our buildings and segregated them into three different building types, namely:

- Facilities needing high temperature hot water for heat ("High Temperature Facilities"). These are typically 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"). These include typical teaching spaces, offices, and dormitories not specifically designed for lower temperatures.
- Facilities that do not require temperatures as high as other campus facilities and may be able to utilize "return" water from other building systems to meet their needs ("Low Temperature Facilities"). These facilities may also be considered candidates for "cascading energy use".

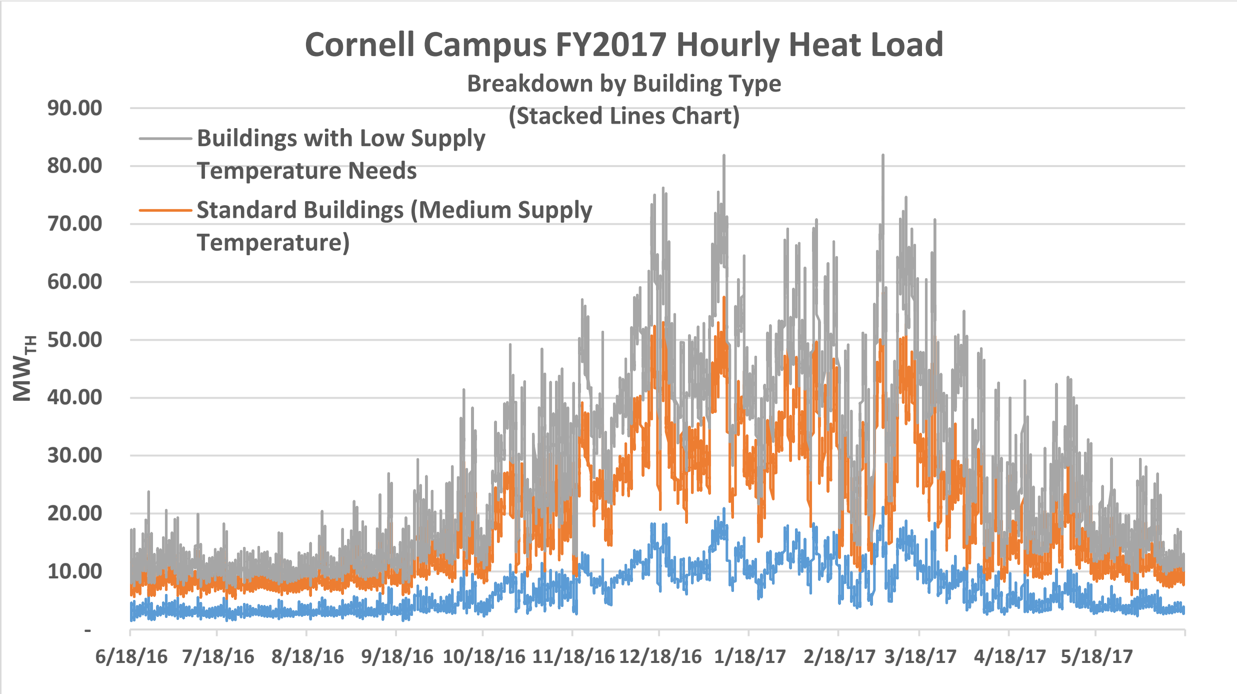

Figure 2: Graphic of campus building energy demands by facility (heat demand) type.

The modeling program allows the following:

- Operator-selectable “required temperatures” for each building type. For example, as we developed our model, we ran scenarios with the following temperature assumptions:
  - High Temperature Facilities: 80°C (176°F) minimum supply temp (highest need)
  - Standard Temperature Facilities: 70°C (158°F) minimum supply (typical office/class/dorm)
  - Low Temperature Facilities: 60°C (140°F) minimum supply (spaces designed for lower temps, greenhouses, agricultural facilities, cascading opportunities)
- Flexible reallocation of buildings into different Type categories (by modifying one number inserted in the appropriate row for the building in the hourly heat load [8760] spreadsheet).

The 8760 (hourly) data set (see **Appendix D**) has a row that allows each building to be classified (using “1”, “2”, or “3” to represent these three types). **Figure 2** shows graphically the current model allocation of load between these building types, on an hourly basis. In this example, most campus buildings are currently assigned as “Standard Temperature Facilities”, consistent with the general descriptions provided previously.

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 arrangements (central versus perimeter/building level) to electrical usage needed to maintain temperatures in various building types
- The use of "cascading" arrangement whereby return water from a higher-temperature building is used as supply for a lower-temperature facility. This ability to extract heat from water at multiple stages can have a significant positive impact on LCOH value.
- The impact of changes over time. For example, Cornell has recently changed our building design standard to require that all new buildings (and significant renovations where possible) are designed to operate with a minimum supply temperature of 55°C (130°F). 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.

In parallel with this DDU study, Cornell is independently conducting a building-by-building assessment to see 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). Thus, we fully anticipate reducing temperature needs, building-by-building, over time.

Figure 3 shows a partial schematic of how the "high temperature" buildings are arranged in the working model. Specifically, the system is arranged so that a heat pump is available to "boost" the loop temperature, as needed (based on the source scenario) to serve the building temperatures during peak winter conditions. The system also incorporates a "cascading" arrangement whereby lower-temperature facilities can be heated by the return water stream from the building, provided temperatures remain sufficient. However, in the final modeling this "cascading" function was disabled to represent current Cornell building conditions, which do not include this ability (due to temperature requirements).

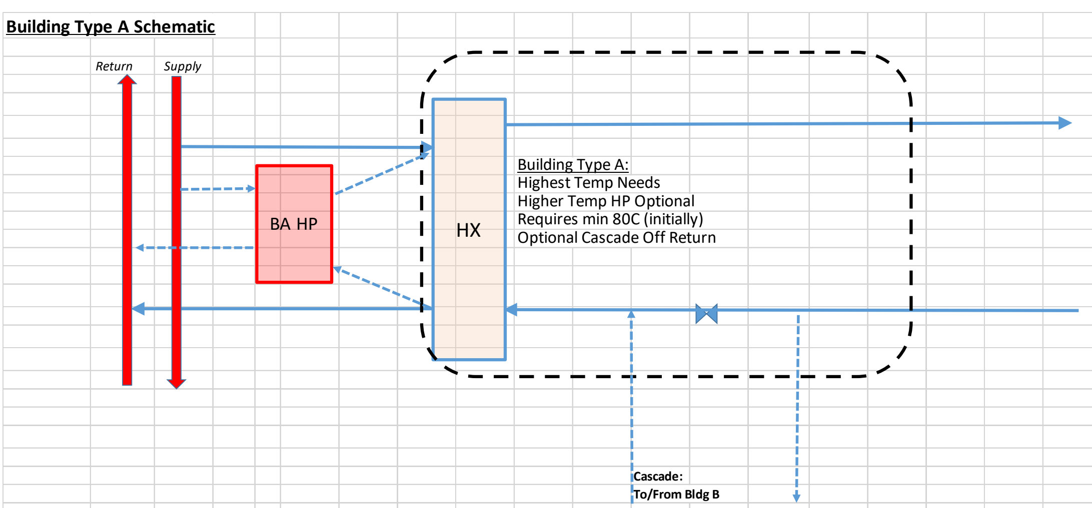

Figure 3: Screenshot of High Temperature Facility arrangement with booster heat pump and cascading flow. Cascading flow was not assumed for the final LCOH calculations as noted in the Results section. In this Figure, "BA HP" is the heat pump for the Type A building; HX represents a plate-and-frame heat exchanger.

Figure 4 shows an example "screen-shot" of the model at work. In this example, the heat pump is not engaged (not needed to meet design criteria) and return flow is hot enough to provide "cascading" heat service to low temperature buildings. At other model input selections, the heat pump will "automatically" enable in any time step when the temperature of the heating loop is insufficient to provide the building heat needs without the heat pump "boost".

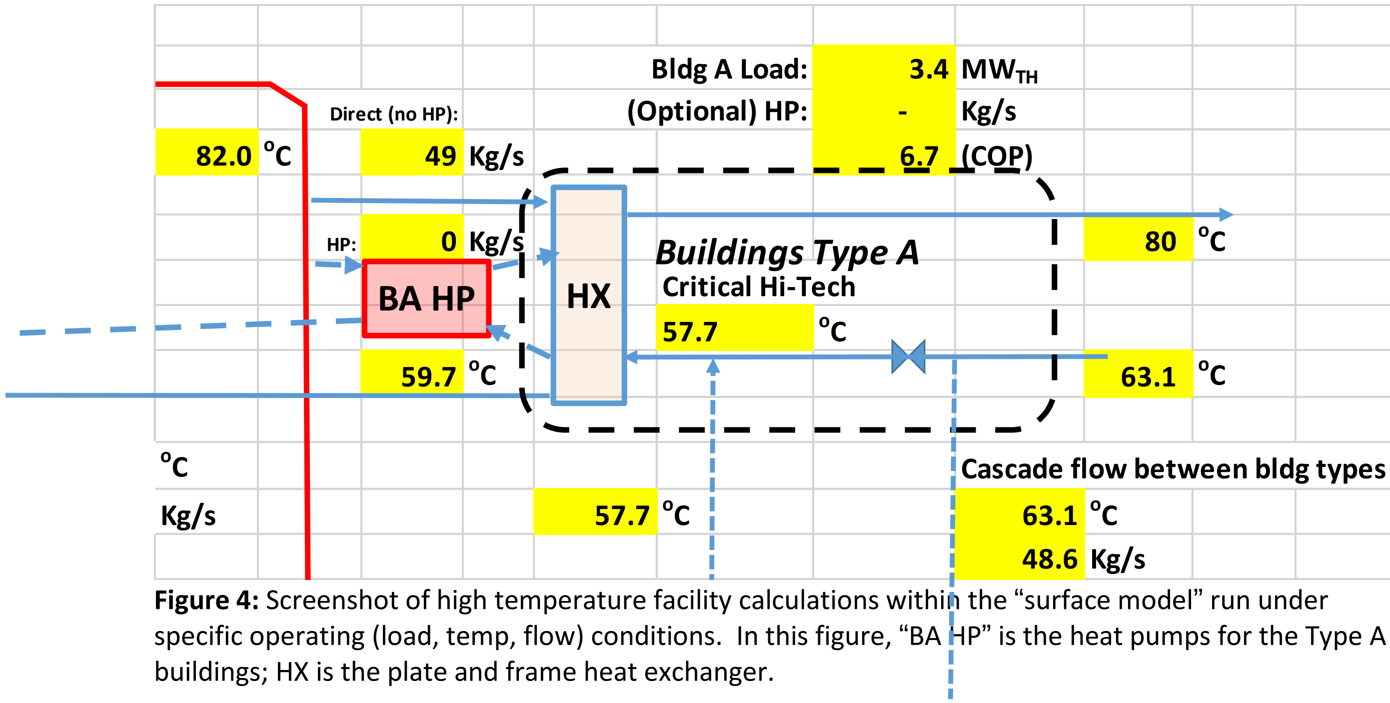

Figure 4: Screenshot of high temperature facility calculations within the "surface model" run under specific operating (load, temp, flow) conditions. In this figure, "BA HP" is the heat pumps for the Type A buildings; HX is the plate and frame heat exchanger.

Fluid pumps

Fluid pumps include three main sub-systems, specifically:

- Primary geothermal groundwater 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, as follows:

- Geothermal groundwater pumps circulate the water from the connected deep well system through the primary heat exchanger shown in Figures 1 and 2; these pumps are assumed to be submersible; suction head requirements eliminate other choices.
- Distribution system circulation pumps are in-line or base-mounted centrifugal pumps.
- Building system utilize existing pumping systems with little or no change to current operations (these are already self-contained, close-loop hot water systems).

To use in modeling across a wide range of flows and pressures, we first establish standard efficiencies (n) for incorporation into the general pump energy equation:

Pump Energy = n × A × Q × ΔP where
n = efficiency (motor/drive efficiency x pump efficiency)
A = constant (incorporates density of water and unit conversions)
Q = flowrate pumped
ΔP = pressure across the pump (pumping head)

Since this study is only a feasibility study, we have not provided specific pump selections (i.e., manufacturer and model). For efficiencies, we use the above general pump energy formula with assumed pumping efficiencies typical of these pump types, as provided in the following table (source data from the Hydraulics Institute):

Pump Type	Maximum Efficiency (%)
Double Suction/Split Code	84
Vertical Turbine (Bowl Assembly)	84
Large End Suction Pumps	84
Axial Flow Pumps	82.2
End Suction ANSI	81

(data from http://www.waterworld.com/articles/print/volume-26/issue-12/departments/pump-tips-techniques/how-to-select-a-pump-with-the-highest-efficiency.html
Referenced to: Hydraulic Institute General Obtainable Pump Efficiency by pump type

The listed efficiencies represent hydraulic efficiencies. When coupled with a high-efficiency pump and variable frequency drive, overall system efficiencies are normally somewhat lower. In addition, pumps operating over a relatively broad range of service conditions will not achieve these "optimal" efficiencies at all conditions. As the table shows, axial flow or centrifugal pump styles, which would be used for all of the applications involved in our study (general pumping, distribution system pumping, etc.) achieve similar efficiencies (over 80%). For the initial purpose of calculations used in this study, the **pumping system average efficiency (combining hydraulic and electrical) was assumed to be 75%** over the range of operations.

Plate-and-Frame Heat Exchangers

We assumed that plate-and-frame heat exchangers, similar to those used at our Lake Source Cooling Facility and elsewhere on campus, are used to exchange heat between the primary geothermal pumping system and the Distribution System, and between the Distribution System and individual buildings (or, in some cases, groups of adjacent buildings).

A primary design assumption or criteria related to the design and selection of plate-and-frame heat exchangers is the approach temperature. The larger the plate surface area, the closer that entering or leaving supply fluid can approach the temperature of the leaving or entering building fluid, respectively. For relatively small temperature changes across a plate-and-frame heat exchangers, **an approach temperature of 1ºC (1.8ºF)** using a counter-flow arrangement was used.

Larger approach temperatures allow for fewer plates and thus lower cost, but may also reflect higher velocities and thus higher pressure drops, and thus more pump power over the life of the system, as well as a loss of temperature available to the system. Thus, for the purpose of our study, we assume selection of plate-and-frame heat exchangers capable of achieving **approach temperatures of 1ºC**; our analysis reflects this selection.

Heat Pumps

This study included an evaluation of the costs and benefits of inserting heat pumps at various locations in the distribution and/or building piping systems. At this feasibility level, the analysis did not extend to specific heat pump selections. Rather, based on a broad review of commercially-available heat pumps, we assumed as a basis for energy calculations and sizing that all heat pump systems operated at **42% of ideal efficiency** (i.e., 42% of the efficiency of a Reversible Carnot Engine). Thus, we assumed:

$COP = 0.42 * (T_H/(T_H-T_L))$ where:

T_H = generated high temperature of the fluid that is being heated (in Kelvin)

T_L = leaving temperature of the fluid from which heat is extracted (in Kelvin)

More details regarding the selection of this value are included in **Appendix B**.

Hot Water Storage Tanks

The Cornell 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 was modeled at just below 100ºC (the model used 98ºC). The **model also assumes that the hot water storage tank is able to maintain storage temperature with minimal losses (~1% loss of available energy per day**). Cornell already has experience with cold water storage (we have a 2M gallon cold storage tank on campus); losses from this tank system are similarly low. These relatively low losses reflect the relatively lower temperatures used for storage and propensity of water to store heat effectively.

1.6 (SOPO Subtask 1.6): Present Assumptions and Criteria for Validation

This report provides the documentation described by SOPO Subtask 1.6. Specifically, it provides documentation of the assumptions and criteria for each of SOPO tasks 1.1 through 1.5. In addition to information explicitly described in the SOPO, additional assumptions and criteria that are important or necessary to develop our models (needed to determine LCOH, project economics, and similar results) have also been added to the body of this report and to the appendices included in this summary report.

1.7 (SOPO Subtask 1.7): Document Approvals Strategy

Cornell has documented the anticipated approvals strategy for this project in **Appendix C.**

Task 2: Conceptual Feasibility Report – Overall Site Resources and Heat Use Analysis

As defined in the Statement of Project Objectives (SOPO), Task 2 required Cornell to "utilize the assumptions and criteria documented in the Task 1 Deliverable to analyze a range of scenarios (source and use combinations) for DDU at Cornell". In documenting that work, this report is organized by sub-task per the SOPO.

2.1 (SOPO Subtask 2.1): Develop Interfaces between Analytical Tools

Cornell used two complementary models, a subsurface (geothermal reservoir) model (using GEOPHIRES) and a custom demand-side (surface use) model which Cornell named MEnU (Acroynm for "**M**odel of **En**ergy **U**se"). These two models are independent, but share specific input and output parameters, as described below.

The MEnU surface model requires two external source-related inputs, namely, the geothermal fluid supply temperature and flow rate. Outputs from MEnU include geothermal return (re-injection) temperature, a key parameter for determining the amount of geothermal heat utilized at the surface. The re-injection temperature parameter is also an input to the GEOPHIRES model.

Appendix F - *Modeling Energy Use (MEnU) Description,* describes the important relationships of source supply and re-injection temperatures to overall performance (and LCOH). Our GEOPHIRES model output provides a distribution of source temperature (T_{G1}) values, rather than a specific single value for T_{G1} as a function of the distribution and uncertainty of various model inputs. These varying source temperatures are used to more precisely evaluate source energy use opportunities and metrics and in developing the final LCOH values. In SubTask 2.5 we describe how we used confidence intervals for thermal output to select appropriate source temperatures in each region and how we used MEnU surface assumptions to establish the corresponding reinjection temperature required to meet project goals.

Professional judgment is needed to initially select inputs for these models. For example, we could select a very high flow rate to "bias" our GEOPHIRES and MEnU models to suggest a high level of energy extraction, or we could use an extremely low re-injection temperature to bias the models to suggest an advantageous energy projection. However, there are inherent "checks" on our system, as follows:

- The GEOPHIRES model calculates the energy needed to deliver the input flowrate through our geological formation; flows that are too high for the geological conditions or well size require excessive pumping energy and pressures, while lower flows produce pumping energy and pressure results that are reasonable for "standard" equipment. These results also affect the economic model, since electrical requirements (for pumping) are a factor in the annual operating cost. In this way, GEOPHIRES pumping cost results impose a practical limit on the input flowrate variable.
- The MEnU model displays the system return temperature as an output, based on the model set-up. To achieve lower re-injection temperatures, the model set-up must be varied by either altering other inputs that reflect the building operating conditions in the model or by using model options like geothermally linked heat pumps. Excessive use of the heat pump results in model outputs with high input electrical requirements which adversely affect project economics. Building operating arrangements can be compared to measured conditions found on campus and on real-life operations witnessed in other Cornell facilities and in facilities operated to improve geothermal performance in other locations (Iceland, Paris, Copenhagen, etc.) that successfully use geothermal heat. Appendix F provides more detail on the selection and impact of temperatures for return flow and reinjection and specify all input parameters and the basis for selection of each.
- The GEOPHIRES model also provides a check of the effect of re-injection temperatures on the useful lifetime of the geothermal system. Excessive withdrawal of heat, resulting in extremely low re-injection temperatures, may reduce the modeled reservoir lifetime below acceptable limits. Since our LCOH is based on actual annual outputs as predicted by GEOPHIRES (rather than a standard percentage reduction each year), excessive temperature losses adversely impact LCOH values.

These model integrations and interactions are more fully described through specific examples in Appendix F and several conference papers referenced at the end of this Report.

2.2 (SOPO Subtask 2.2): Analyze Potential DDU Resources for Project Site for Specific Target Resource Depths

Cornell first completed preliminary model runs in TOUGH2 and GEOPHIRES in order to obtain initial estimates of geothermal heat production from the two target reservoirs (i.e. crystalline basement at 3.0-3.5 km depth, and the Trenton-Black River formation at 2.7-2.8 km). These preliminary runs were performed using input parameters as discussed in the Task 1 Summary Report. Modeling was then repeated in Year 2 for the final target specifications (documented in SOPO Subtask 2.5).

Results of Monte Carlo simulations of a reservoir at the top of the crystalline basement rock (therefore conservative regarding basement rock temperatures) are shown in the plots below. Nearly all of the replicates indicate heat production rates in excess of the 5.5 MW_{th} target representing 20% of average campus demand (see next section), based on a production well flow of 30 kg/s and a 30°C reinjection temperature. The median modeled production temperature ranges from ~85°C at startup to close to ~88°C in year 50. The temperature and heat produced shown by the model increase over the first ~50 years due to the fact the 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.

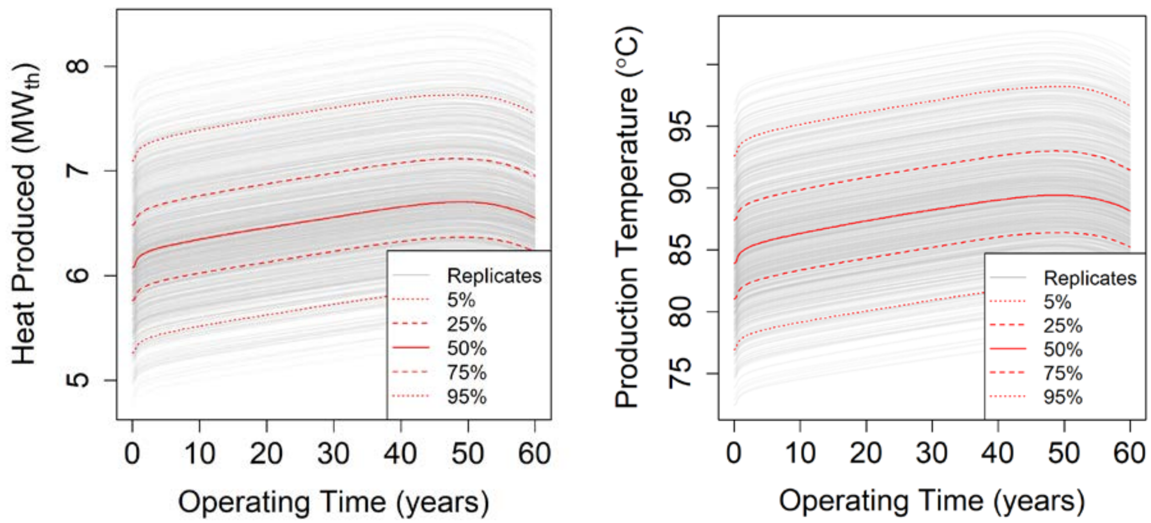

Figure 4: Heat production (left) and produced temperature (right) after 60 years of operation of a basement geothermal reservoir from 3-3.5 km depth using a parallel fractures reservoir geometry model. Gray lines show time series from one of 1,000 Monte Carlo replicates. Red lines show selected quantiles of the Monte Carlo replicates.

Preliminary modeling of the Trenton-Black River reservoir was performed using a simple plug flow model. Estimating heat extraction using a plug-flow model means that the injected water at temperature T_{INJ} perfectly extracts all the heat possible from rock temperatures T_r above T_{INJ}, creating a thermal wave where reservoir temperature $T_r=T_r(t=0)$ ahead of the wave and $T_r=T_{INJ}$ behind the wave. While this type of system is idealized, a sharp thermal front can exist in porous media where heat conduction occurs over faster time scales than convection. Although it would be reasonable to model a natural system containing a uniform porous medium with a plug-flow model, most geothermal systems are best characterized as fracture-dominated, where convection through the fracture can drain heat from the fracture surfaces much faster than conduction from the bulk media can replenish heat at the fracture face. This plug flow analysis therefore provides a first-order estimate of the available heat; subsequent phases of included refined model to account for more refined reservoir characteristics and flow geometries interpreted from local data collection efforts.

All of the replicates indicate heat production rates in excess of the 5.5 MW_{th} target representing 20% of average campus demand (see next section), based on a production well flow of 30 kg/s and a 5°C reinjection temperature. The median modeled production temperature is around ~73°C from startup until abrupt thermal breakthrough at around year 20. Once again, this is a simplistic model based on ideal porous media flow; final modeling refined these estimates using more realistic reservoir parameters as documented, with a much more gradual and extended depletion of the reservoir (as described in Appendix A and shown in the Results section). In addition, due to the much lower heat pump electrical requirements (i.e., much higher coefficients of performance) a system using heat pumps can still accomplish the target heat production when operating at higher injection temperatures (~20°C or higher). The final LCOH calculations included in this report were all based on 20°C reinjection temperatures.

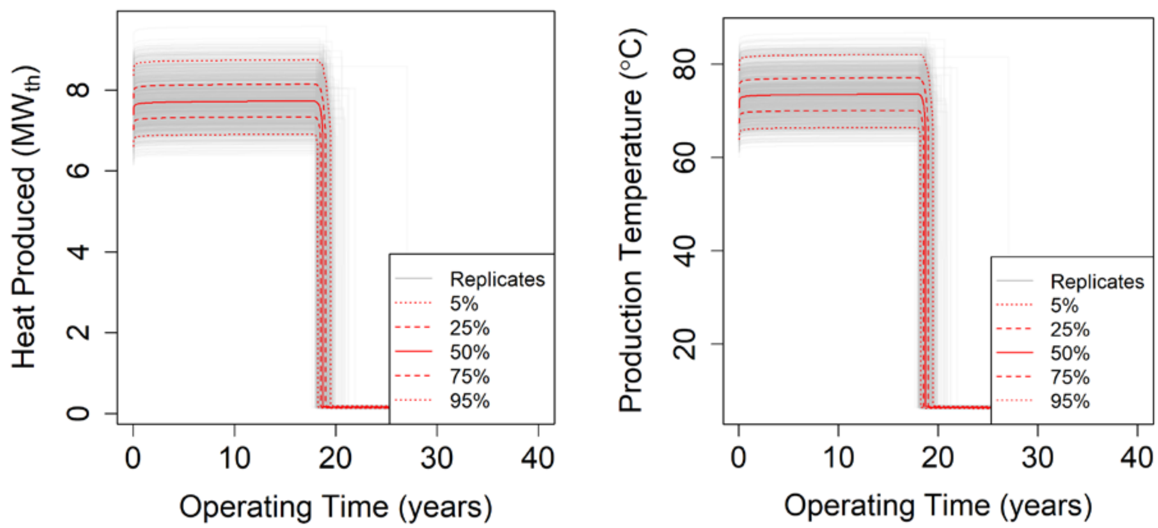

Figure 5: Heat production (left) and produced temperature (right) after 20 years of operation of a Trenton-Black River geothermal reservoir from 2.27-2.3 km depth using a simplistic plug flow reservoir geometry model with low reinjection temperatures (5°C). Gray lines show time series from one of 1,000 Monte Carlo replicates. Red lines show selected quantiles of the Monte Carlo replicates. More nuanced models show much more gradual reductions in heat production, as described in Appendix A and shown in the Results section.

2.3 (SOPO Subtask 2.3): Analyze Cornell Site Heat Needs and Value

Cornell integrated our measured site heat demand values into an hourly heat demand profile (as documented in Appendix F) for our MEnU model. Running the MEnU model with different geothermal resource conditions (source temperature and flows) created the following outputs:

- Total $MWhr_{TH}$ of energy utilized from the geothermal resource in the modeled year
- Percent of annual campus energy that was provided by the geothermal resource
- Total $MWhr_{E}$ 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).

These values all became components of our final LCOH calculations using GEOPHIRES temperature outputs that varied year-to-year.

The specific goal of this feasibility study was that the geothermal resource provide at least 20% of the campus heat load on an annual basis. This equates to a continuous thermal power rate of 5.5 MW_{TH} based on detailed campus building energy data. Our MEnU model demonstrates that Cornell's campus has a minimum heat requirement higher than this value year-round. Therefore, with proper design of the DDU system, all the produced heat could be utilized continuously throughout the entire calendar year. Thus, a geothermal system designed to deliver 5.5 MW_{TH} continuously met our feasibility study goal.

Geothermal outputs that are significantly higher (above 5.5 MW_{TH} continuous) may result in periods during which not all of the available energy is able to be utilized by existing facilities. This heat utilization rate (load availability) is accurately predicted by the MEnU model, which calculated the annual MW-hrs for each modeled scenario based on the assumptions and methods described in our previous reports and in the attached technical brief.

To quantify these discussions, we used basic conservation of energy and thermodynamic formulas. 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 (equation 1):

$P_{TH} = c_p * Q_G * (T_{G1} - T_{G2})$ w*here:*

P_{TH} = thermal power produced by the geothermal well system [W]
c_p = specific heat capacity of the fluid (water) [J/kg/K]
Q_G = Flow rate from geothermal well system [kg/s]
T_{G1} = Supply Temperature from the Geothermal Well System [°C]
T_{G2} = Return Temperature to the Geothermal Well System [°C]

Thus, the raw quantity of energy derived from the well is essentially the integration of $c_p Q \Delta T$, where c_p (specific heat capacity) is constant, Q is the well mass flow, and ΔT is the operating temperature differential (i.e., temperature of flow from the well minus the temperature of the return, or re-injected, flow).

Thus, for a given flow rate and geothermal resource temperature, we can vary the amount of energy extracted by modifying (through our surface use equipment and controls) the return (reinjection) temperature. Table 3 illustrates some examples:

Table 3: Examples of Reinjection Temperature for Various Geothermal Well Conditions to Meet Project Goal (20% of campus heat load = 5.5 MW_{TH})

Flow (GEOPHIRES input) (kg/s)	Geothermal Supply Temp (GEOPHIRES output) (^oC)	Geothermal Reinjection Temp (GEOPHIRES input) (^oC)	
		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

As Table 3 suggests, even quite modest temperatures and flowrates can successfully serve at least 20% of our campus needs, provided that the reinjection temperature can be controlled. Appendix F provides more context to that analysis.

2.4 (SOPO Subtask 2.4): Document the processes to analyze resources and needs to produce LCOH

Cornell's work includes estimating three Levelized Cost of Heat (LCOH) values, as follows:

- **Primary LCOH**. The derived LCOH represents the cost per unit energy (MW_{TH}) for the supplied heat based on calculations and assumptions regarding economics (discount rates, etc.), capital costs, and operating costs. This LCOH value is calculated by a stand-alone financial analysis spreadsheet using Excel. GEOPHIRES cost estimates and output flow and temperatures were used as inputs to this spreadsheet where applicable; additional inputs not provided by GEOPHIRES included the capital and operating cost (electricity) used by the heat pumps included in the model runs and other site-unique costs as described in Appendix G. As that appendix documents, Cornell used some additional site-specific values as inputs to the GEOPHIRES program to improve the LCOH estimate for our case. One LCOH input, namely the utilization factor, is determined for each resource analyzed by the MEnU model as described in the prior section; namely, the utilization factor is the fraction of the total geothermal resource heat value that can be utilized by the campus grid in the modeled year based on the hourly pattern of campus heat usage, which is calculated by MEnU).
- **$LCOH_{REG}$** (regional levelized economic value). This separate value used the same estimates of project costs utilized for the GEOPHIRES economic analysis together with generally-accepted economic multipliers to calculate the value of the project to the region, in this case New York State. This value represents the value that regional economic development

organizations (State or local agencies) may consider when deciding whether to invest in this technology. Appendix I provides more context to the use of this value.

- **$LCOH_{ENV}$** – (Global) Environmental (levelized) economic value. This is another value calculated for the project. The valuation was determined by multiplying the greenhouse gas emissions reductions of DDU by the "Social Cost of Carbon" value documented in Appendix H. The GHG reductions were calculated by comparison with a "Base Case", namely, the combustion of natural gas in central facility boilers to create campus heat. A combustion efficiency of 85% and the GHG emissions factors published by the USEPA were used to derive this value. The value is conservative in that it does not include other emissions or environmental impacts from use of natural gas, although we acknowledge that some other impacts of geothermal development (land and water use, etc.) may be similar to those of fossil development. Appendix H provides more context to the use of this value.

2.5 (SOPO Subtask 2.5): Recommend 3 alternative DDU applications for analysis

Two specific DDU scenarios were evaluated for LCOH and total energy extraction potential (MW_{th}), using Cornell building data to determine the current campus heat load. Each of these scenarios was evaluated for several engineering design alternatives that served as tests for optimization potential. Uncertainties in temperature and geologic conditions were also considered in modeling. The scenarios and design alternatives were:

<u>Scenario No. 1</u>: Deep sedimentary layer (depth from surface 2.24 km – 2.27 km), specifically targeting the geological formation known as the Trenton Black River (TBR).

Modeling alternatives used in estimating thermal production:

- Cornell modeled nine cases for this scenario, specifically:
  - 25th percentile (low end) of the estimated production temperature and
    - Low flow (30 kg/s)
    - Moderate flow (50 kg/s)
    - High Flow (70 kg/s)
  - 50th percentile (statistical median) of the estimated production temperature and
    - Low flow (30 kg/s)
    - Moderate flow (50 kg/s)
    - High Flow (70 kg/s)
  - 75th percentile (high end) of the estimated production temperature and
    - Low flow (30 kg/s)
    - Moderate flow (50 kg/s)
    - High Flow (70 kg/s)

- Surface use modeling included the following variables:
  - Buildings operating across the three building temperature ranges described in this Section 1.5 of this report. These three building temperature ranges represent an

approximation of current conditions within the Cornell district heating system (and they are likely similar to other institutions with a diverse network of buildings)

- A multi-stage "central" heat pump to extract heat from the system return loop, as described in Appendix F. Operating parameters for this heat pump were documented for each run.
- Additional "on-demand" heat pumps within each building's connection to the district heating system to supplement building heat delivery (extracting heat from building return loops to boost building delivery temperatures as needed) and/or to reduce return temperatures (i.e., extract additional energy from the central distribution loop). This operation is described in Appendix F.
- Modeling assumed a DDU system "target" capacity of at least 5.5 MW_{th} (about 25% of average annual Cornell heat load and a load demand that exists year-round). Higher targets were also evaluated to determine the potential limits of geothermal heat extraction and the electrical input energy required to achieve each target.
- Modeling included an example with "future" buildings designed in accordance with relatively higher European efficiency standards to improve the direct-use geothermal system performance. Appendix F provides more context for why these standards are so important.

Scenario No. 2: Crystalline Basement (depth from surface 3.0 km – 3.5 km). This second scenario targeted deeper rock with higher temperatures. Similar to scenario No. 1, Cornell used the following modeling constraints to estimate thermal production values:

- Cornell modeled nine cases for this scenario, specifically:
  - 25^{th} percentile (low end) of the estimated production temperature and
    - Low flow (30 kg/s)
    - Moderate flow (50 kg/s)
    - High Flow (70 kg/s)
  - 50^{th} percentile (statistical median) of the estimated production temperature and
    - Low flow (30 kg/s)
    - Moderate flow (50 kg/s)
    - High Flow (70 kg/s)
  - 75^{th} percentile (high end) of the estimated production temperature and
    - Low flow (30 kg/s)
    - Moderate flow (50 kg/s)
    - High Flow (70 kg/s)
- Surface use modeling for this system included the same set of variables as indicated above for the shallower resource.

The flow rates modeled above may not represent production from existing reservoir conditions at all depths without some form of geothermal stimulation. However, as previously noted, the GEOPHIRES results help to diagnose whether or not these flow rates might create unreasonable impedances, which would increase LCOH based on higher pumping energy and/or may exceed the capabilities of standard geothermal pumps.

The MEnU model developed by the Cornell team contains many additional control variables, as documented in Appendix F. Cornell has documented the variables and ranges used in each analysis (for example, the selected distribution system temperatures and flow rates and the basis for heat pump operations and efficiencies).

Task 3: Analysis of Alternatives and Final Feasibility Report

As defined in the Statement of Project Objectives (SOPO), Task 3 required Cornell to utilize the assumptions and metrics from Task 1 and the modeling protocols developed in Task 2 to derive the techno-economic feasibility of each of the two alternatives.

3.1 (SOPO Subtask 3.1): Improve Analysis of Reservoir Productivity

For the reservoir options selected in Task 2, the Cornell team refined the anticipated thermal performance range using available information and resources including additional tests using TOUGH2. This included higher reinjection temperatures (20°C was used herein for all runs leading to LCOH calculations) and subsurface modeling was improved. These reservoir thermal performance results were input, with uncertainties, to the techno-economic models to produce improved results.

3.2 (SOPO Subtask 3.2): Revise Techno-Economic Model

The thermo-economic models implemented during Task 2 were refined to integrate appropriate improvements to model data and refined estimates of reservoir thermal performance. An example of the refinement was to incorporate year-by-year thermal outputs into the model to improve the life-cycle cost accuracy by accounting for production temperature changes year-to-year, as documented in Appendix G.

3.3 (SOPO Subtask 3.3): Develop Interfaces between Analytical Tools

Using documented SMART metrics and refined model, the Cornell team analyzed the recommended Alternatives to determine the LCOH for each of the proposed scenarios (heat resource and heat use pairing). Appendix F provides more details of the final MEnU (surface heat use) model and Appendix G describes how the models outputs were used together to derive the LCOH values.

3.4 (SOPO Subtask 3.4): Present Progress report at the 2018 GRC Annual Conference

The Cornell team presented at the 2018 GRC Annual Conference and also prepared several presentations for other conferences regarding the work completed on the project. Additional technology transfer of these results will occur at upcoming conferences, including the 2020 World Geothermal Conference and the 2020 Stanford Geothermal Conference.

Results and Conclusions

Results

All of the tasks proposed for this project have been completed. This section summarizes some of the significant results of that work.

Subsurface modeling results summary

TOUGH2-modeled rock temperatures over time for the Trenton-Black River porous media scenario are shown in Figure R-1. This figure corresponds to initial conditions of the warmest 5th percentile estimated for these depths below Ithaca, and the pattern of temperature over time is similar for the other initial temperatures evaluated. Injection and production wells are located 1 km from each other, and the simulation grid x-y area is 2 km x 2 km. The simulation assumed no flow across grid boundaries.

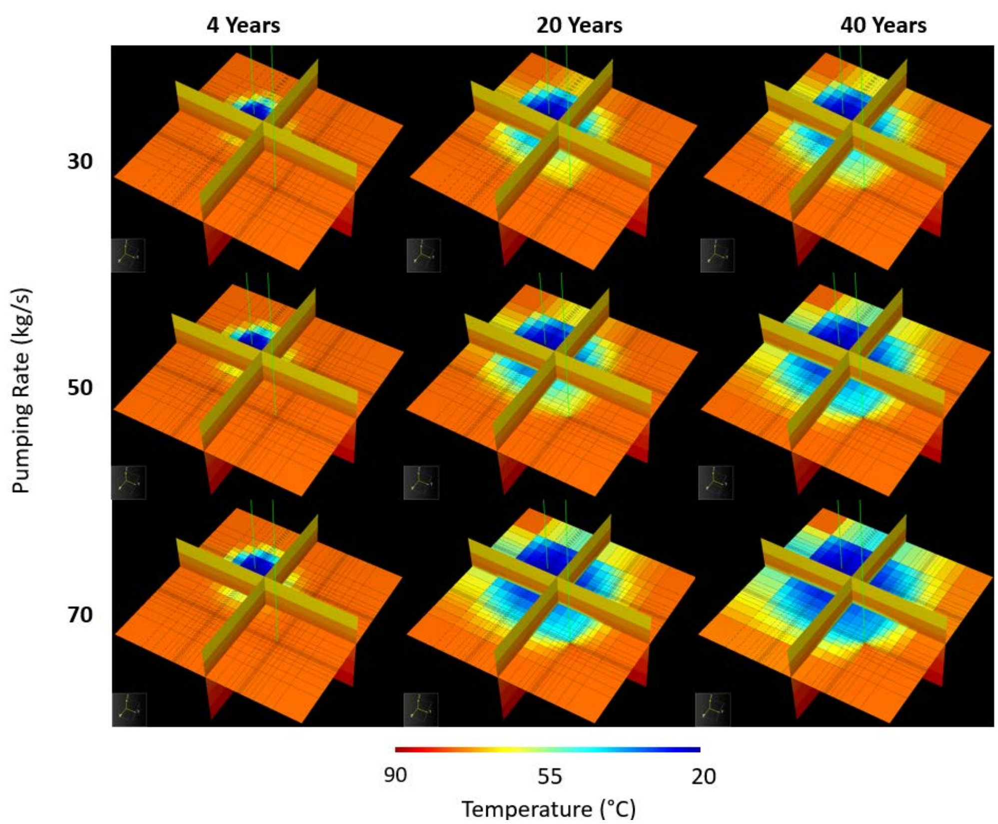

Figure R-1: Rock temperature over 40 years of production from the Trenton-Black River (TBR) reservoir for the condition of flow through matrix porosity. The initial rock temperatures corresponded to the warmest 5th percentile estimated for these depths below Ithaca. A 23.5 °C injection temperature is used with well flow rates of 30 kg/s, 50 kg/s, and 70 kg/s. The surface parallel with the x-y plane is located in the center of the TBR reservoir. The surfaces parallel with the x-z and y-z planes are located in the center of the y and x axes, respectively. The grid orientations shown in this figure are the same as in Figure R-3. Wells (vertical green lines) are injection in the top left zone and extraction in the lower right zone.

The resulting reservoir volume approximates the current knowledge of the spatial scale over which existing TBR hydrocarbon reservoirs exist in the region: 2 km is approximately the mean value of the minor axis of the elliptical shape of TBR reservoirs (data available in Cornell University, 2016).

The permeability of sedimentary reservoirs under Ithaca are generally unknown and, without specific reservoir knowledge, it is unclear what level of permeability can be attained by stimulation. However, if such a permeable reservoir exists or can be generated, the estimated production temperatures over time based on modeling would resemble those in Figure R-2. Figure R-2 provides temperatures over time after accounting for wellbore heat transfer from the reservoir depth to the ground surface using GEOPHIRES. The resulting heat production is also provided.

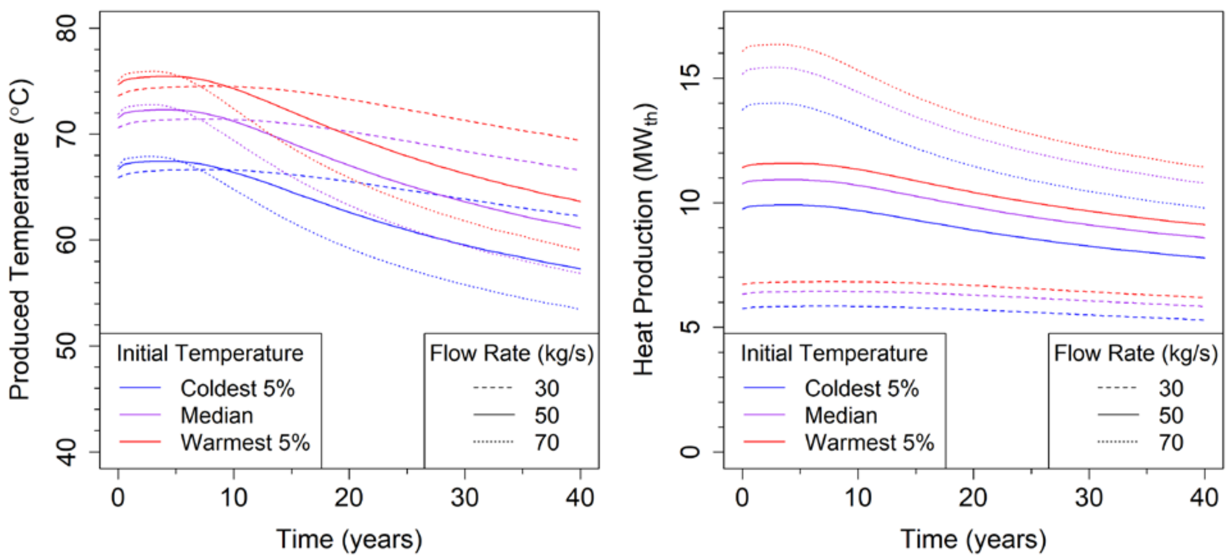

Figure R-2: Estimated heat production and temperature over time for the Trenton-Black River for injection of 23.5 °C fluid. The initial rock temperature percentiles were selected based on the estimated temperatures at depth below Ithaca.

Modeled pressures in the TBR reservoir and surrounding rocks are provided in Figure R-3 under the assumption of porous media flow. Pressures induced by re-injection of water in a two-well system are less than the total pressure estimated to be required for optimally-oriented pre-existing fractures to hydroshear (46.8 ± 5 MPa in Camp and Jordan, 2017). These model results suggest that the risk of inducing seismicity of appreciable magnitude from this operation is low.

Analysis of a deeper ("basement rock") reservoir was also completed. Figure R-4 shows the estimated temperature production over time as a function of the number of vertical parallel fractures along a 1 km lateral well segment within basement rock at 3-3.5 km depth. Such information is useful to evaluate the need for an EGS stimulation in basement rocks at these depths. The corresponding probability of producing at least 5 MW_{th} energy and 60 or 70 °C fluid temperatures is provided for an injection temperature of 20 °C and a flow rate of 50 kgs. Considering uncertainty in the number of natural fractures that could be encountered, over 40 years of producing at least 5 MW_{th} energy and a minimum 60 °C fluid is expected with a vertical fracture flow geometry in these basement rocks; attaining 70 °C over that period is less certain.

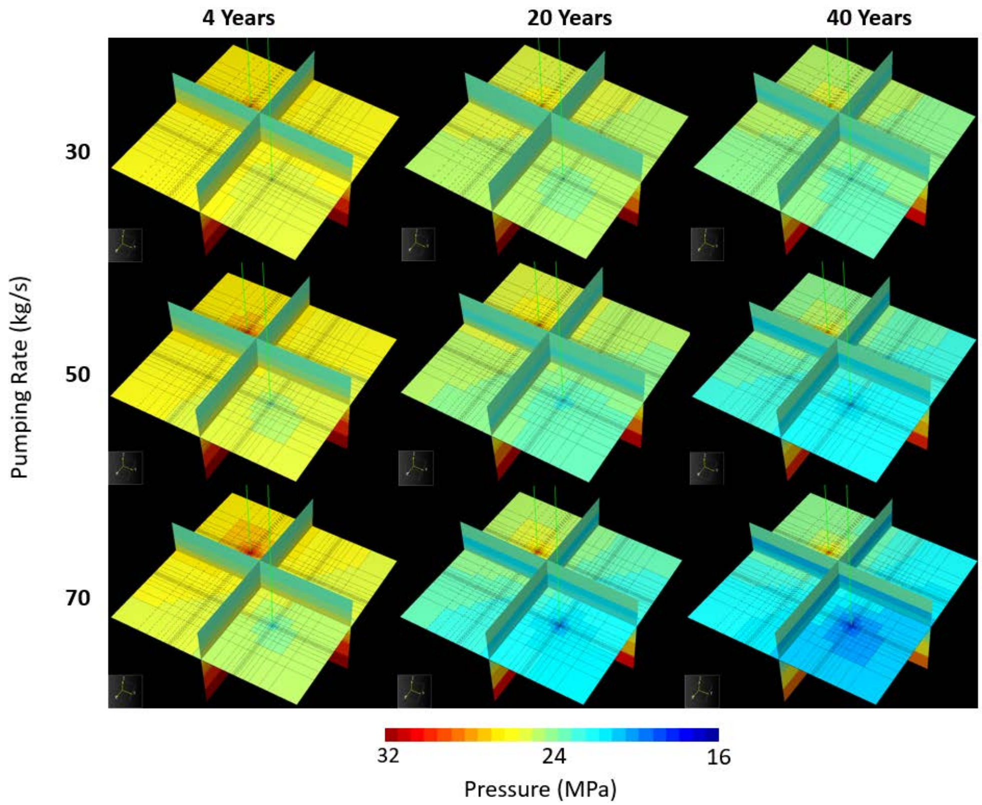

Figure R-3: Pressure over 40 years of production from the Trenton-Black River (TBR) reservoir for the condition of flow through matrix porosity. Initial rock temperatures corresponded to the warmest 5th percentile estimated for these depths below Ithaca. A 23.5 °C injection temperature is used with well flow rates of 30 kg/s, 50 kg/s, and 70 kg/s. The surface parallel with the x-y plane is located in the center of the TBR reservoir. The surfaces parallel with the x-z and y-z planes are located in the center of the y and x axes, respectively. Grid orientations are the same as in Figure R-1. Wells (vertical green lines) are injection in the top left zone and extraction in the lower right zone.

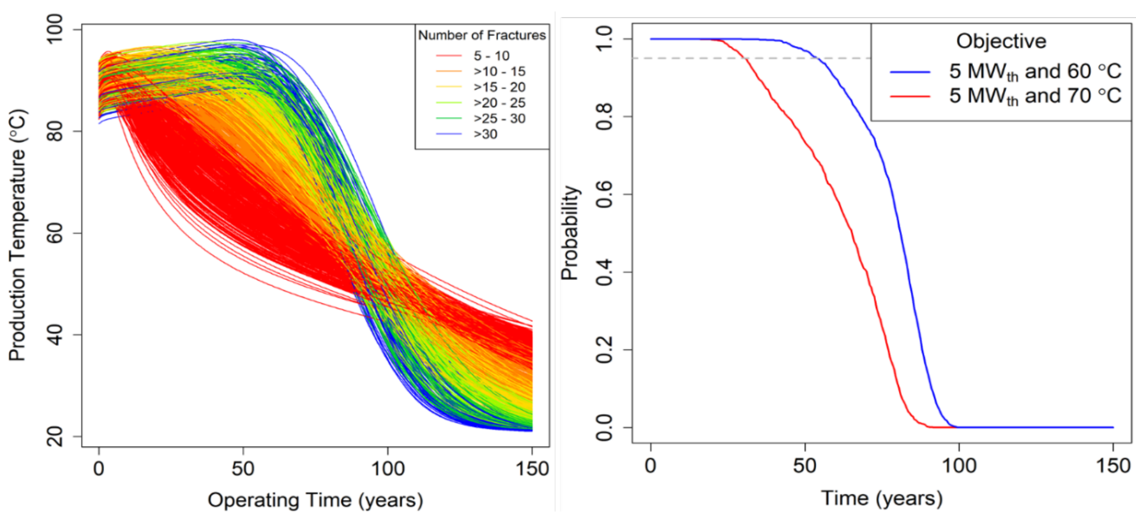

Figure R-4: Multiple parallel fractures temperature production results for basement rock at 3 – 3.5 km depth for 20 °C injection at 50 kg/s. Left: Each line provides the results of a single Monte Carlo replicate. Lines are colored by the number of fractures, which ranged from 5 to 33 over a 1 km horizontal well length. Right: The probability of producing fluid that meets the specified objectives over time.

In parallel to these subsurface modeling exercises, Cornell produced a model of subsurface energy demands and equipment which we called MEnU (for Modeling Energy Use). This model was used to determine how much of the extracted energy (as predicted by the subsurface model) could be used at the surface based on various surface operating scenarios and the existing campus heating needs (with seasonal variation based on actual data).

Primary MEnU modeling results

The MEnU program provided the following estimates of usable heat that could be extracted from subsurface reservoirs based on achieved pumping rates and production temperatures of those fluids. The following Table R-1 and accompanying figures R-5 to R-10 summarize those results for the modeled case as described in Appendix F (using the campus heating demand described in Appendix D); polynomial functions were created with each data set shown in the future to match the production that would occur based on the annual extraction temperature estimates provided by the subsurface modeling.

All of the results shown in Table R-1 assume the use of integrated central high-temperature heat pumps. When heat pumps are used to extract heat from the re-injection loop and transfer that heat to the district loop, lower production temperature resources can be used much more economically and effectively. Even for higher temperatures improvements in overall production and LCOH are noted. Thus, the integration of heat pumps for re-injection heat extraction greatly reduces the risk that an installed system will provide inadequate results over time if geothermal development results in one of the less optimistic temperature curves in R-4. Without heat pumps, based on the current campus need for higher temperature district heat, the development risk would be higher and the system would be more reliant on subsurface conditions, the success of stimulation or other enhancements, or significant improvements in surface heating systems (modification of building systems for lower temperature use).

Table R-1: Thermal production rates and electrical energy consumed as a function of geothermal temperature and flow (from MEnU)

ESH Temp	ESH Flow (kg/s)	ESH System MWh	MWh Elect	ESH Flow (kg/s)	ESH System MWh	MWh Elect	ESH Flow (kg/s)	ESH System MWh	MWh Elect
61							70	131574	35280
62							70	133572	35509
63							70	135503	35713
64	30	65486	17165	50	106612	27916	70	137390	35896
65	30	66770	17351	50	108319	28115	70	139231	36059
66	30	68047	17529	50	109981	28294	70	141032	36203
67	30	69315	17708	50	111606	28456	70	142807	36333
68	30	70576	17862	50	113188	28600	70	144561	36449
69	30	71829	18017	50	114743	28731	70	146266	36545
70	30	73075	18165	50	116258	28844	70	147934	36625
71	30	74313	18305	50	117761	28947	70	149577	36690
72	30	75544	18437	50	119237	29037	70	151197	36743
73	30	76768	18563	50	120694	29116	70	152801	36785
74	30	77984	18681	50	122140	29186	70	154390	36816
75	30	79193	18792	50	123563	29244	70	155969	36837
76	30	80395	18895	50	124962	29289	70	157539	36849
86	30	91870	19516	50	137779	29154	70	171978	36317
87	30	92945	19534	50	138934	29082	70	173331	36209
88	30	94001	19543	50	140066	29000	70	174667	36092
89	30	95025	19540	50	141188	28911	70	175985	35965
90	30	96033	19529	50	142298	28815	70	177292	35829
91	30	97011	19508	50	143394	28711	70	178576	35683
92	30	97957	19475	50	144484	28601	70	179836	35527
93	30	98890	19436	50	145551	28481	70	181068	35360
94	30	99814	19390	50	146595	28353	70	182250	35177
95	30	100727	19338	50	147627	28217	70	183408	34985
96	30	101622	19279	50	148643	28074	70	184541	34783
97	30	102510	19214	50	149658	27924	70	185640	34569
98	30	103381	19142	50	150650	27768	70	186732	34349
99	30	104245	19065	50	151642	27607	70	187811	34122

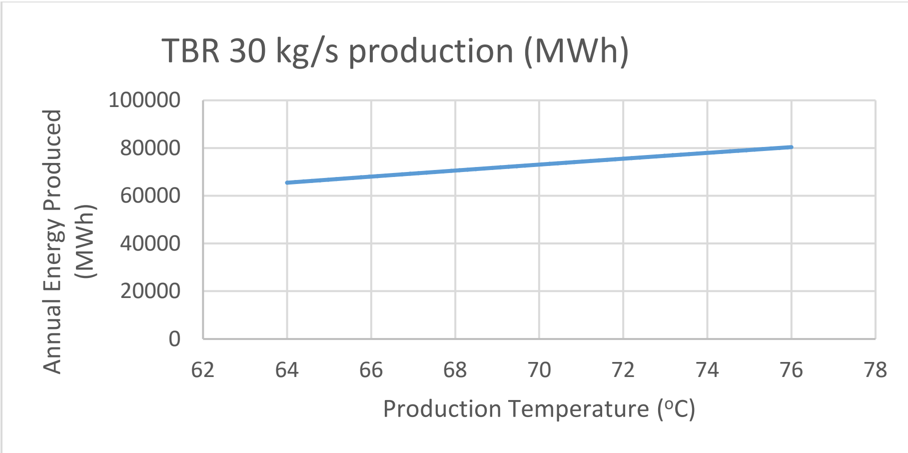

Figure R-5: Usable heat produced from TBR at 30 kg/s as a function of temperature

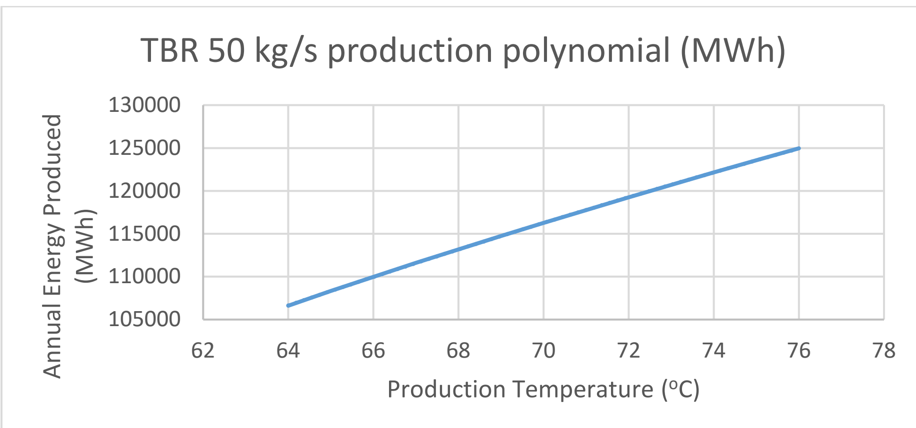

Figure R-6: Usable heat produced from TBR at 50 kg/s as a function of temperature

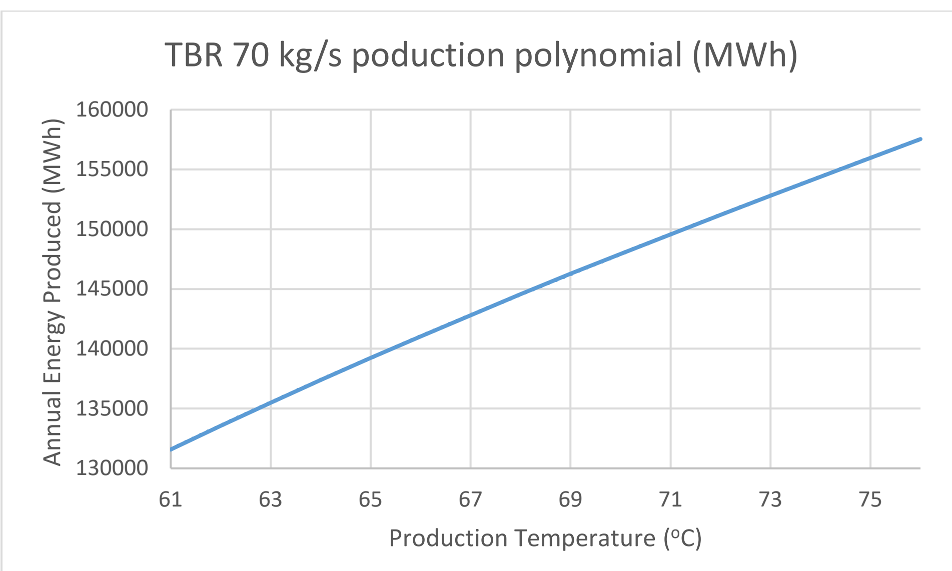

Figure R-7: Usable heat produced from TBR at 70 kg/s as a function of temperature

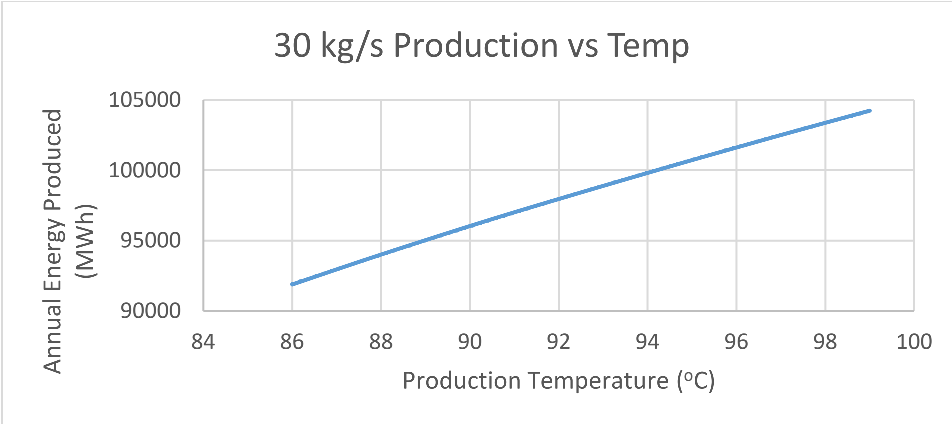

Figure R-8: Usable heat produced from basement at 30 kg/s as a function of temperature

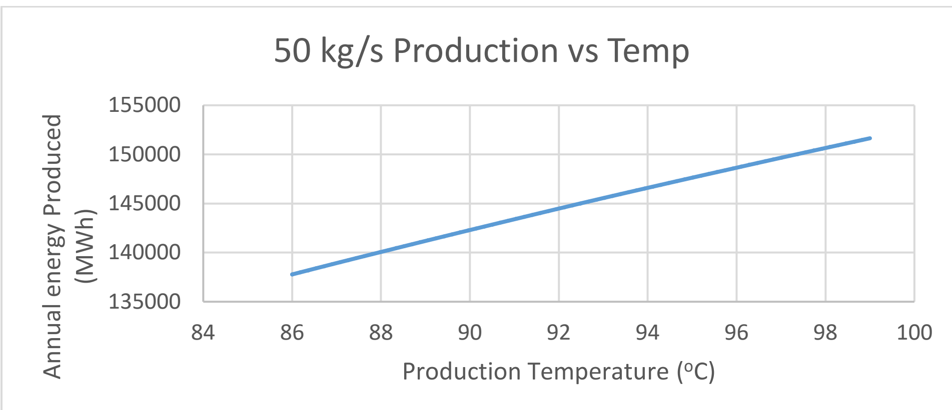

Figure R-9: Usable heat produced from basement at 50 kg/s as a function of temperature

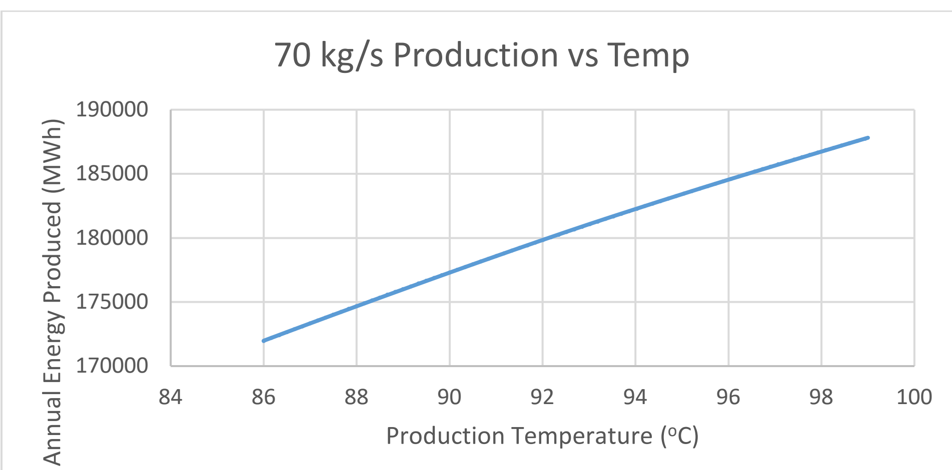

Figure R-10: Usable heat produced from basement at 70 kg/s as a function of temperature

Combining these subsurface and surface modeling results together with the financial assumptions listed in Appendices G, H, and I allowed calculation of the LCOH, $LCOH_{ENV}$, and $LCOH_{REG}$ (respectively) for the modeled cases. The following Tables R-2 through R-4 summarize these results.

Table R-2: Levelized Cost of Heat (LCOH - Single Bottom Line Economics), 2019 US$/MMBtu

Reservoir	Achieved subsurface flowrate		
	30 kg/s	50 kg/s	70 kg/s
Trenton Black River Sedimentary Layer at ~2.3 km depth	$5.62-$6.24 (mean: **$5.96**)	$4.97-$5.39 (mean: **$5.16**)	$4.84-$5.20 (mean: **$5.00**)
Crystalline Basement at ~3.5 km depth	$6.34-$6.59 (mean: **$6.46**)	$5.13-$5.33 (mean: **$5.23**)	$4.60-$4.85 (mean: **$4.77**)

The ranges in each entry of the table shows the variation between the model simulations, with the low cost representing the upper 25 percentile temperature in the recovered fluid, the high cost representing the bottom 25 percentile (lower temperatures predicted), and the bold figure represents the mean of all model runs.

We also modeled cases with “cascading” heat flow, whereby heat used in buildings would then cascade to facilities that did not require the same quality of heat – i.e., that could accept hot water at lower temperatures and use it effectively for heating. LCOH values derived from that assumption were substantially lower, because no heat pumps were needed to maximize utilization of the heat (and thus no electricity to operate those heat pumps). As seen in Appendix G, electrical costs (primarily for the heat pumps) represent most of the annual operating cost for the system. However, we do not report those findings here because we could not reasonably predict that campus would have suitable sources for this lower-quality heat, especially at a level that was well-matched to building needs, and thus may predict lower-than-realistic LCOH values. Nonetheless, it is noted that our figures above will be improved as we continue to integrate lower-temperature building design on campus.

One surprising result is that the LCOH differences are relatively small between the two modeled reservoirs and even across broad flow ranges. In regards to reservoir differences, the higher costs for drilling deeper reduce some of the benefit of the higher temperatures (and thus greater geothermal energy quantity), resulting in similar net benefits on a unit-normalized (LCOH) basis. In regards to flow ranges, the lower flow rate cases also require less pumping and heat pump application, so the capital and operating costs are lower for the lower flow cases, offsetting some of the benefit of higher flow rates (although higher flow rates support lower LCOH, as long as all the flow can be utilized on the surface). Finally, the integration of special high-temperature heat pumps to extract additional geothermal energy prior to re-injection also provides a primary benefit for all cases, since this action allows the same resource (and its large capital investment) to provide significantly higher heat quantities to campus over a long period of time, even if the resource temperature trails off in later years.

The reported LCOH values consider uncertainties in geologic rock properties and temperatures, but are conditional on the assumed reservoir flow geometries and engineering designs selected for energy utilization. We used flow geometry scenarios that aim to bound the thermal energy production in lieu of a more computationally expensive stochastic analysis of flow geometry; we do not currently have sufficient site-specific data to justify choices for the flow geometry distributions that would be needed in a rigorous stochastic analysis.

In addition to LCOH, Cornell's scope also included evaluation of the Environmental value and Regional Economic value of each scenario. A description of this evaluation is included in Section 3.2 and detailed in Appendices H and I of this report. Table Exec-2 and Exec 3, respectively, provide a summary of the results of these analyses.

Table R-3: Environmental Value ($LCOH_{ENV}$), 2019 US$ per MMBtu

Reservoir	Achieved Subsurface Flow (kg/s)		
	30 kg/s	50 kg/s	70 kg/s
Trenton Black River	$1.23-$1.34 (mean: **$1.31**)	$1.21-$1.36 (mean: **$1.29**)	$1.20-$1.33 (mean: **$1.26**)
Crystalline Basement	$1.50-$1.59 (mean: **$1.55**)	$1.52-$1.61 (mean: **$1.56**)	$1.44-$1.55 (mean: **$1.55**)

Table R-4: Regional Economic Development Values ($LCOH_{REG}$) 2019 US$ per MMBtu

Reservoir	Achieved Subsurface Flow (kg/s)		
	30 kg/s	50 kg/s	70 kg/s
Trenton Black River	$4.73-$5.38 (mean: **$5.10**)	$3.39-$3.75 (mean: **$3.56**)	$2.94-$3.19 (mean: **$3.07**)
Crystalline Basement	$6.47-$6.72 (mean: **$6.59**)	$4.50-$4.64 (mean **$4.57**)	$3.80-$3.86 (mean **$3.80**)

Conclusions

The results of this study demonstrate that Earth Source Heat is a viable technology for campus heat if sufficient subsurface flow with reasonably sustained fluid temperatures can be achieved in any subsurface reservoir modeled. This viability is based on the following criteria:

- The modeled system produced a total useable heat output that exceeded the minimum annual campus heat load determined at the onset of the project (i.e., offsetting at least 20% of the annual campus thermal load). The output range is substantial depending on both the subsurface resource and the surface applications; at the high end, our modeled solutions produced up to ~70% of existing campus heat load if a single well pair produces 70 kg/s, using integrated high-temperature heat pumps.

- Modeling demonstrated that multiple geothermal reservoirs could provide economically viable results when heat pumps were strategically integrated, a design that has been proven in at least one European installation already. In this context, "economically viable" means that the LCOH for the project is less than the regional commercial price of heat that would be generated using natural gas (the most common and cheapest fossil alternative in our area). LCOH values are detailed in the Results and Conclusions section of this report and summarized in Table R-1.

In addition to LCOH, Cornell's scope also included evaluation of the Environmental value and Regional Economic value of each scenario.

When considering the environmental and regional economic value of such a project, the overall "triple bottom line" cost (i.e., the LCOH less the $LCOH_{ENV}$ and $LCOH_{REG}$ values) is even lower and in some cases negative. In other words, for some cases studied, a project with the listed performance would have higher value to the environment and to the regional economy than the total project costs over the 30-year project timeframe. Despite these results, the challenge of funding remains; obtaining agreement on the party that should pay for environmental or regional "economic externalities" is a common challenge.

Recommendations for Further Work

To advance consideration of deep geothermal energy as a source of heat for district heating systems in the eastern United States, **a demonstration project is recommended**. Based on the analysis for the Cornell site, the character of subsurface geothermal resources (i.e., geology, temperatures, and depths) supports further development and demonstration. To further reduce development risk and confirm assumptions necessary for verification of the modeling (or adjustment of modeling parameters, as appropriate) for this region, **a full-depth geothermal test well is necessary**.

Future studies could evaluate the impact of uncertainty in heterogeneous flow geometries on the LCOH with an aim at optimizing engineering designs to be robust to the range of thermal energy production that could result from all known uncertainties. However, geologic reservoir flow geometry uncertainties could only be evaluated in a limited way for this project as a result of the available data. For the Trenton-Black River sedimentary rock target reservoir, the flow geometry is constrained only by regional studies, and the existence or extent of suitable permeability is unknown for the reservoir below Ithaca. In basement rock, the distributions and orientations of fractures are also unknown below Ithaca. A full depth test well and associated geologic data collection would help to constrain the uncertainty in target reservoir flow geometries, and the flow properties of surrounding caprocks and base rocks. In addition to constraining flow geometries, the uncertainty in temperatures at depth would be substantially reduced. As a result of reducing these geologic model uncertainties, engineering designs could be refined to better match site-specific expectations, and the uncertainty in the economic cost of the project could be reduced.

Publications and conference presentations resulting from or aided by this work

Cornell University. (2016b). Natural sedimentary reservoirs data geothermal play fairway analysis 2016 revision [data set]. Retrieved from https://gdr.openei.org/submissions/881

Gustafson, J.O., J.D. Smith, S.M. Beyers, J.A. Al Aswad, T.E. Jordan, J.W. Tester, and T.M. Khan. (2019). Risk reduction in geothermal deep direct-use development for district heating: A Cornell University case study. *Proceedings of the 44th Workshop on Geothermal Reservoir Engineering*, Stanford, CA, February 11-13.

Gustafson, J.O., J.D. Smith, S.M. Beyers, J.A. Al Aswad, T.E. Jordan, and J.W. Tester. (2018). Earth source heat: Feasibility of deep direct use of geothermal energy on the Cornell campus. *GRC Transactions*, *42*. 20 p.

Smith, J.D. and K.F. Beckers. (2020). Uncertainty and sensitivity analysis for geothermal reservoir performance and techno-economic assessments: A software package for GEOPHIRES. *Proceedings World Geothermal Congress 2020*. Reykjavik, Iceland, April 2020.

Tester, J., S. Beyers, J.O. Gustafson, T.E. Jordan, J.D. Smith, J. Al Aswad, K.F. Beckers, R. Allmendinger, L. Brown, F. Horowitz, D. May, T.M. Khan, and M. Pritchard. (2020). District geothermal heating using EGS technology to meet carbon neutrality goals: A case study of Earth Source Heat for the Cornell University campus. *Proceedings World Geothermal Congress 2020*. Reykjavik, Iceland, April 2020.

Conference Presentations:

Jordan, T.E., J.D. Smith, J.A. Al Aswad, J.O. Gustafson, J.W. Tester, and S.M. Beyers. (2018). The Geothermal Heating Resource for Cornell University, Tompkins County, New York: Exploiting and Analyzing Available Geological and Geophysical Data Sets for Pre-Drill Site Characterization. Geoscience and Sustainable Energy Solutions Poster Session. *2018 American Geophysical Union Fall Meeting*, Washington, D.C., Dec. 13.

Smith, J.D., J.A. Al Aswad, T.E. Jordan, J.W. Tester, and J.R. Stedinger. (2018). Uncertainty Analysis of Analytical and Numerical Geothermal Reservoir Simulations for Direct-Use Heating Applied to Cornell University, Ithaca, NY. Conventional and Enhanced Geothermal Systems: Characterization, Integration, Stimulation, Simulation, and Induced Seismicity I Oral Session. *2018 American Geophysical Union Fall Meeting*, Washington, D.C., Dec. 12.

Reference data uploaded to the GDR data depository

Subsurface data and simulations to estimate temperature and reservoir productivity (https://gdr.openei.org/edit?id=1181)

Appalachian Basin Temperature-Depth Maps and Structured Data (https://gdr.openei.org/edit?id=1182)

Geothermal Reservoir Simulation Results --Cornell Direct Use of Deep Geothermal Energy for District Heating (https://gdr.openei.org/edit?id=1183)

APPENDICES

Appendix A: Thermal-hydraulic Models and Parameters

Summary

This memo describes the selection of thermal-hydraulic models, describes their parameters, and provides values and assumed probability distributions for those parameters that were used in geothermal reservoir simulations for the Cornell University Ithaca, NY geothermal project site. There are two primary reservoir targets for which geologic and thermodynamic property values were gathered for reservoir simulations: 1) the Trenton-Black River (TBR) carbonate group contact at approximately 2270 m depth, and 2) basement rocks starting at 3000 m depth. Geothermal reservoir simulations in the TBR were evaluated with and without geologic reservoir stimulation (e.g. Enhanced Geothermal Systems), comprising a total of three primary subsurface cases that were modeled. The thermal-hydraulic model discussion focuses on the numerical simulation model, TOUGH2. Other analytical reservoir models whose results were compared to TOUGH2 include a 1D plug flow model and a multiple parallel fractures model. The multiple parallel fractures model is particularly useful for geothermal reservoir simulations in fractured basement rocks, and for the reservoir stimulation in TBR rocks. For each of these thermal-hydraulic models there are 3 primary requirements: simulation of a rock matrix within which heat and fluids will transfer, selection of initial conditions, and the selection of thermal-hydraulic model-specific simulation parameters. The geologic and thermodynamic properties and initial conditions are discussed for a generalized geologic column specific to the Ithaca campus. Supplementary material provides further details and justification for selected values and distributions of the thermal-hydraulic model parameters.

The following supplementary material is available upon request.

S1. Non-Equilibrium Temperature Logs from Wells Near Cornell

S2. ESOGIS Formation Top and Well Log File (LAS File) Processing Notes

S3. Porosity, Density, and Other Formation Property Estimates based on Local Deep Wells and Literature Data

S4. GEOPHIRES parameters for selected reservoir model types

S5: Two Memos on Fracture Orientations in the Adirondack Mountains in New York State

S6: Estimation of Depth-to-Reservoirs beneath the Cornell Campus

S7: Geothermal Reservoir Stimulation Methods and Applications to the Cornell DDU Project

S8: Monte Carlo Analysis of GEOPHIRES Inputs using Parallel Computations

Introduction

Three potential geothermal reservoir target formations are under investigation for the Cornell University Ithaca, NY campus. The shallowest target is in sedimentary rocks within the Trenton-Black River (TBR) carbonate group, which regionally contains relatively high permeability in a hydrothermally altered dolomite (Camp and Jordan, 2017). The intermediate depth targets are sedimentary rocks within Cambrian sandstone formations. The deepest targets are in

Precambrian basement rocks, for which little information about hydrogeologic and thermal properties are known in the Ithaca region. This memo addresses the selection of geologic properties and their probability distributions for the TBR and basement rock geothermal reservoir targets, which are the two targets for the Cornell Deep Direct Use geothermal project.

There are three main considerations for modeling a geothermal reservoir: 1) generation 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 is the type of model to use for thermal-hydraulic simulations. Selection of thermal-hydraulic models, and selection of values and probability distributions for variables and parameters are discussed in the following sections.

Thermal-hydraulic Models

Numerical and analytical mathematical solvers are routinely used within thermal-hydraulic models that have been developed and implemented for geothermal reservoir simulations. There are a suite of available simulation software and methodologies that use each type of solver. One of the main concerns in selecting between thermal-hydraulic models is the computation-accuracy tradeoff. Analytical models generally provide a simpler version of reality than a numerical model could provide, and, as a result, complete computations faster than numerical models. Faster computation time means that uncertainty analyses with large sample sizes may be evaluated more efficiently with analytical models compared to numerical models. The cost for efficient analytical computation is usually a reduction in accuracy of the results compared to what numerical models could provide if the physical system were well understood, as informed by available data.

Numerical models are commonly used in geothermal simulations. We used the numerical thermal-hydraulic model, TOUGH2 (Transport of Unsaturated Groundwater and Heat, version 2), to simulate a porous-media scenario for the Trenton-Black River (TBR) geothermal reservoir in this project. This simulation considered that permeability would vary among the modeled geologic formations, which could not be completed by analytical models. The analytical models that were compared to TOUGH2, and those models that were used to evaluate stimulation of the TBR by Enhanced Geothermal System (EGS) technology are discussed in detail in S4. The first analytical model is a 1D linear heat sweep model (Hunsbedt et al., 1984), which represents a best-case scenario in which all available thermal energy is extracted from the reservoir and surrounding rocks. In this study, we consider a plug flow model as a simplification of the heat sweep model. This method provides an upper bound of heat that could be extracted from a porous media reservoir with a defined rock volume. The second analytical model is a multiple parallel fractures model (Gringarten et al., 1975). This model was used to evaluate a worst-case scenario for the TBR of a fracture directly connecting the injection well to production well, which would likely short-circuit the reservoir heat extraction. The real TBR reservoir that we observe below the Cornell site will likely lie in between these two end member simulations. The parallel fractures model was also used to simulate EGS scenarios in both the TBR and in basement rocks.

TOUGH2 Numerical Model

The TOUGH suite of software provides 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). We utilized TOUGH2 to model geothermal fluid temperature, pressure, and flow rate over time within geothermal reservoir simulations. In particular, the EOS1 (water, heat) module was used. In future phases of this project, we may compare results for the EWASG (water, salt, heat, noncondensible gas) module (Battistelli et al., 1997) because we expect our reservoirs will have brine rather than freshwater (see Pressure Initial Conditions section below).

The subsurface parameters and modeling choices required for TOUGH2 are summarized in Table A1, along with data sources for these parameters used in our analysis. More detail on each parameter is provided in the sections that follow Table A1.

Table A1: Parameters required for TOUGH2 simulation, and their data sources.

Type	Parameter	Source and Notes Summary
	Generalized Stratigraphic Column Includes depths, thicknesses, and rock type for geologic units expected below the Cornell site.	Deep wells with log data that includes target sedimentary reservoir formations. Wells of greatest interest are located within 30 km of Ithaca (Figure A1 for well locations, Table A2 for wells used in our analysis). Basement lithologies for central New York deep boreholes from B. Valentino (2016).
	Rock Density	Density logs for wells in Table A2. Simmons (1964) Table A1 for Adirondack rock types.
	Rock Porosity	Porosity and density logs for wells in Table A2, corrected for shale and gas in our study. Queenston Formation: Tamulonis et al. (2011) Figure 7 Utica Shale: Gas porosity from few Ohio wells in Carter and Soeder (2015). Trenton and Black River: Camp (2017), Camp and Jordan (2017) Cambrian Units: Smith et al. (2005), and Kolkas and Friedman (2007) Rose Run Sandstone:

Type	Parameter	Source and Notes Summary
		Riley et al. (1993), Fry et al. (2006) Basement rocks: Very scant laboratory data in Lynch and Castor (1983)
	Rock Permeability Absolute, along 3 principle axes.	In addition to sources for sedimentary rock porosity: Waller et al. (1978) for hydraulic conductivities.
	Rock Thermal Conductivity Saturated and unsaturated	Values assumed from Carter et al. (1998), as processed in Cornell University (2016) Devonian units ~100 km SSE of Ithaca: Rauch et al. (2018) Basement: Divided bar measurements on 2 samples from Southern Methodist University
	Rock Specific Heat	We use data and estimation methods provided in Robertson (1988) and Robertson and Hemingway (1995). We assume generic values by lithology, rather than formation specific.
	Pore Compressibility Pore Expansivity Tortuosity Factor For rock matrix	Sources are not readily available for rocks in New York. We assume generic values by lithology, rather than formation specific.
Initial Conditions for Simulation Grid	Pressure	Hydrostatic pressure will be assumed. Water density and water chemistry data from local well logs support that dense brines are likely. See discussion below for more details.
	Temperature	Based on data from local and regional wells. Specific values at depth from Smith (2016) 1D thermal model (Horowitz, Smith, & Whealton, 2015), and Smith (2019).
Boundary Conditions for Simulation Grid	Heat Flow Upward into deepest grid cells.	Basal (mantle) heat flow estimates are available from several regional studies: Roy, Blackwell, and Birch (1968), Jaupart and Mareschal (1999), Sclater, Jaupart, and Galson (1980), Artemieva and Mooney (2001) Specific values at the bottom of the simulation grids will be obtained from

Type	Parameter	Source and Notes Summary
		Smith (2016) 1D thermal model (Horowitz, Smith, & Whealton, 2015).
Rock Geometry Parameters for Simulation Grid Under natural and hydro-sheared conditions for proposed basement and sedimentary reservoirs	Fracture Orientations Fracture Density / Spacing Fracture Aperture	Basement Rocks: Data collected in September 2017 by several Cornell project team members in the Adirondack Mountains provides this data. Most fractures are mineral-sealed and therefore likely to not have formed during exhumation of the mountains in the recent geological past. Memo provided in this project describes evaluation of distributions and orientations. Trenton-Black-River: Camp and Jordan (2017) Camp (2017)
Well Parameters	Injection Well Temperature Injection Flow Rate	The injection well temperature and flow rate must match the results of the surface modeling. We evaluate reservoir performance for several combinations of flow rates and temperatures, as discussed below.
	Well Separation Well Depth	Well separation on the surface is limited by the site size. We assume 1 km separation at depth for this study. Well depth in sedimentary reservoirs must match their depth. Basement reservoirs could be at any reasonable drilling depth. Specific values are presented below.
Simulation Parameters	Maximum number of Newton-Raphson iterations per time step Maximum number of time steps Length of time step Relative and absolute error convergence (tolerance levels)	The total simulation length will be 40 years, which matches the proposed useful life of the system for evaluation. We used default values for the other parameters, which includes adaptive timesteps over the course of the simulation.

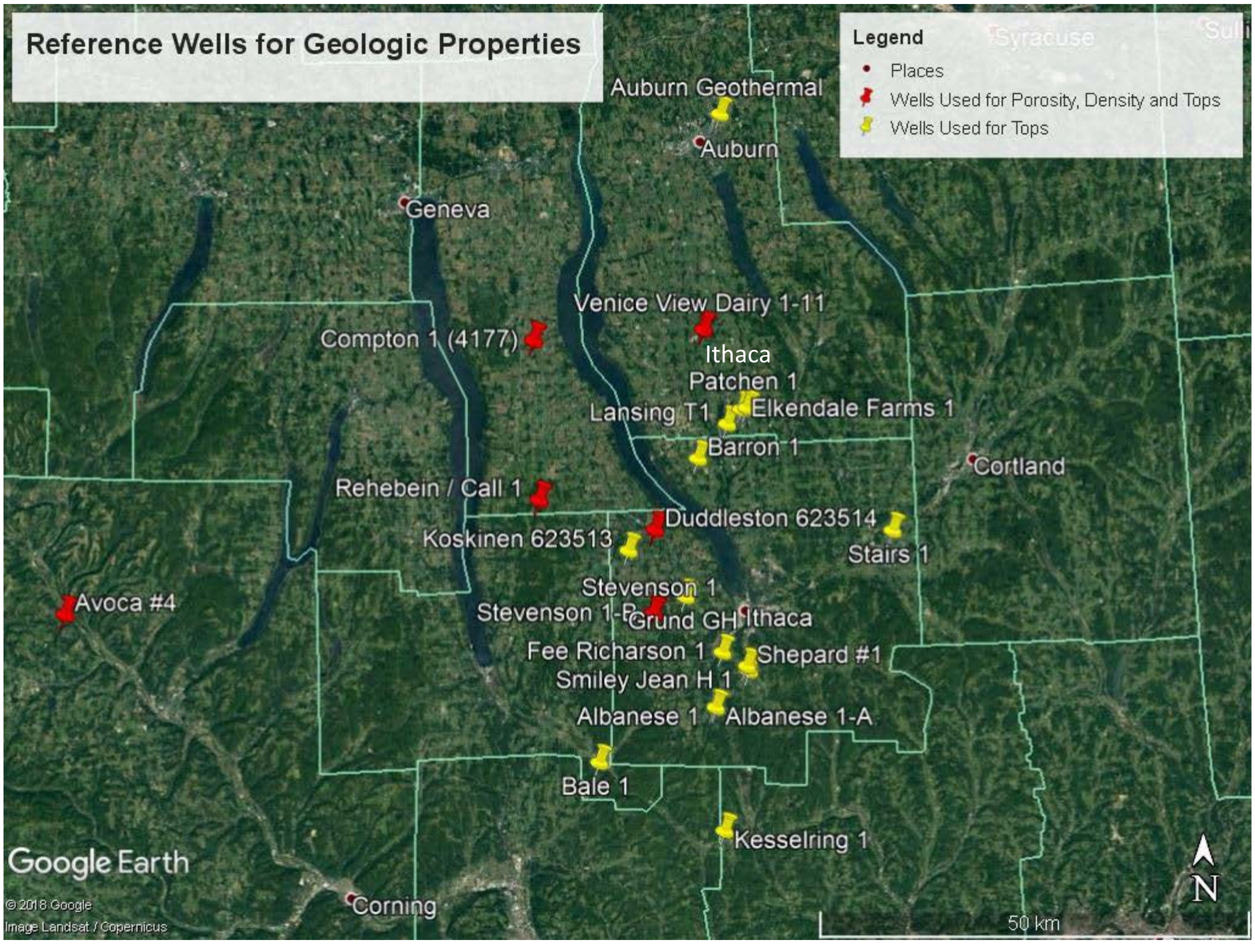

Figure A1: Locations of reference wells for lithologic properties and well logs near the Cornell project site. Wells with yellow pinpoints were used to inform formation tops below Cornell. Wells with red pinpoints were used for formation tops, density, and porosity information. Ithaca, the location of Cornell, is shown on the map.

Table A2: Deep wells with density (+) and porosity (*) logs near the Cornell project site. Some of these wells were used to estimate formation tops at the Cornell project site (T). Wells with density and porosity logs that were processed and used in this study have the Well Name in bold and italics. The symbols indicating data types provided by wells are printed next to well names.

API Number	Well Name	County	Distance from Ithaca (km)	Deepest Formation
31109044670000	Fee-Richarson 1 + T	Tompkins	7	Rose Run
31109039730000	Shepard 1 * T	Tompkins	8	Precambrian
31109041300000	Grund GH	Tompkins	8	Galway
31109040070000	Smiley Jean H 1 *	Tompkins	9	Little Falls
31109229980000	***Stevenson 1*** *+ T	Tompkins	12	Tribes Hill
31109229980100	***Stevenson 1-A*** *+ T	Tompkins	12	Tribes Hill
31109229980200	***Stevenson 1-B*** *+ T	Tompkins	12	Black River
31109229980400	***Stevenson 1-D*** *+ T	Tompkins	12	Black River
31109227670000	***Duddleston*** 623514 *+ T	Tompkins	14	Little Falls
31109229970000	Albanese 1 *+	Tompkins	14	Trenton
31109229970100	Albanese 1-A *+	Tompkins	14	Trenton
31109229970200	Albanese 1-B *+	Tompkins	14	Trenton
31109227530000	Koskinen 623513 *+ T	Tompkins	15	Black River
31109260390000	Barron 1 *+ T	Tompkins	17	Black River
31109217160000	Stairs 1 *+	Tompkins	18	Little Falls
31109260560000	Lansing T1 *+ T	Tompkins	20	Black River
31011238400000	Patchen 1 *+	Cayuga	22	Black River
31011239820000	Elkendale Farms 1 *+	Cayuga	22	Trenton
31097214950000	Bale 1 *+	Schuyler	26	Precambrian
31015004430000	Kesselring 1 T	Chemung	27	Galway
31109227890000	***Rehebein / Call 1*** *+ T	Tompkins	27	Galway
31011161200000	***Venice View Dairy*** *+T	Cayuga	31	Precambrian
31109204460000	***Compton 1*** *+	Seneca	39	Precambrian
31011214690000	Auburn Geothermal *+	Cayuga	56	Precambrian
31101216240000	***Avoca 4*** *+	Steuben	80	Precambrian

TOUGH2 Model Parameters

The model parameters for TOUGH2 are discussed in the sections below in the same order as they are listed in Table A1. For any model of physical systems, it is important to consider which parameters may be altered with engineering design choices or modifications once real data are observed at Cornell. These engineered parameters were evaluated not as probability distributions, but rather as specific fixed values that correspond to surface use scenarios. Other parameters related to the geologic and thermal system properties were assigned probability distributions for reservoir modeling, as described in the following sections.

Geologic Parameters

Formation Tops for Generalized Ithaca Sedimentary Column

The geologic formations of interest for geothermal reservoir simulation include 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 in numerical simulations, such as those completed using TOUGH2.

For the Trenton-Black River sedimentary reservoir, a low permeability shale, the Utica, overlies the Trenton and will likely act as a barrier to fluid flow. Therefore, units shallower than the Utica are likely unimportant for advective heat transport, but may provide conduction recharge to the Trenton-Black River reservoir. For sedimentary formations deeper than the Utica, there is no known geologic unit that would restrict fluid flow, until the basement rocks.

Using these expectations, we simplified the geologic column for reservoir analysis by starting at the depth to the top of the Utica Shale and ending in basement rocks. The modeled formations deeper than the Utica shale were selected and grouped into blocks according to observed changes in density and porosity in local well logs. 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 (supplementary material S1 provides plots of the local temperature logs).

The resulting generalized stratigraphic column for Ithaca is provided in Table A3, along with the assumed formation properties. Details on the formation property selection are discussed further below. Figure A2 illustrates the implementation of this geologic column in TOUGH2. Within Table A3, the Lorraine and Utica formations are grouped because these formations have similar signals in well logs across the Ithaca region. Another group, the Upper Beekmantown Group (referred to as the Tompkins Group in a previous version of this report), was named because the formations it contains are of interest as a third geothermal reservoir target that is not specifically evaluated for this project. These formations are affected by erosion related to the Knox Unconformity (Smith et al, 2010), which may have caused an increase in porosity relative to other formations.

Table A3: Generalized geologic column below Cornell with estimated formation depths, geologic properties, and grid cell sizes used in numerical geothermal reservoir simulations.

Formation Name	**Modeled Formation Top Depth** (m)	**Porosity** (-)	**Permeability H: horizontal V: vertical** (mD)	**Density** (kg/m^3)	**Thermal Conductivity** (W/m-K)	**Specific Heat Capacity** (J/kg-K)	**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)
Upper 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; 2010), 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.

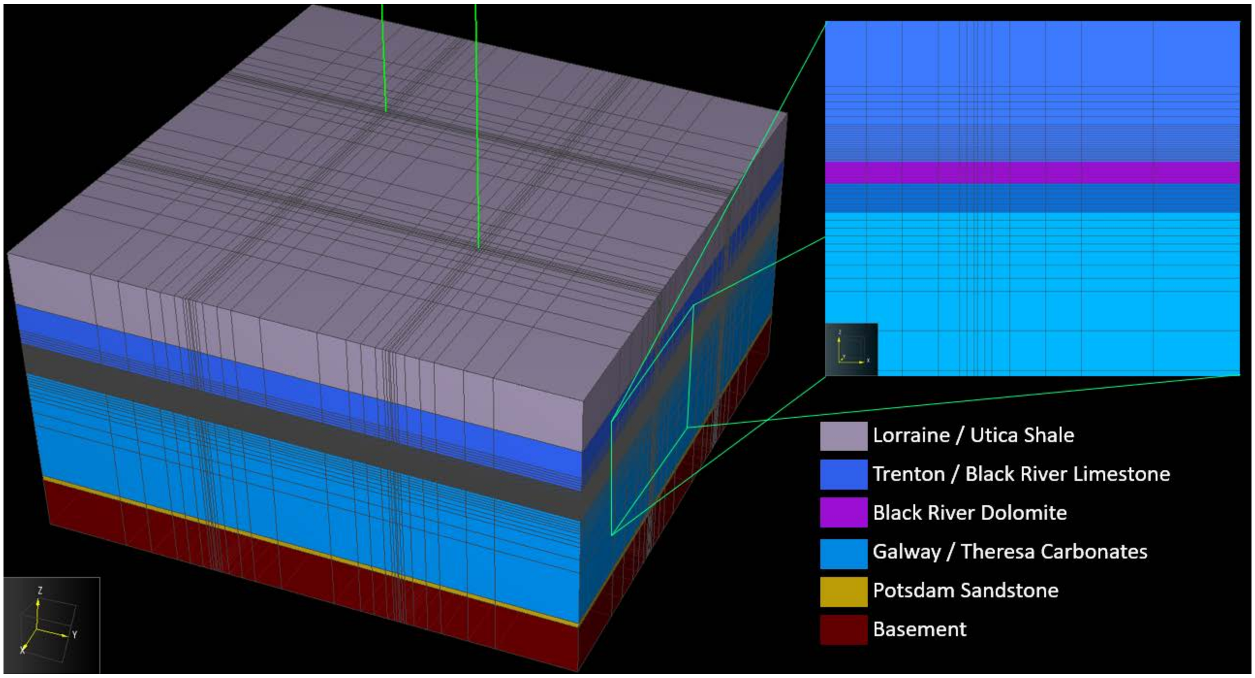

Figure A2: Modeled geologic strata and simulation grid in the TOUGH2 numerical model. Grid cells are colored by the rock lithology: blue: carbonate, gray: shale, yellow: sandstone, red: basement. Wells are shown as vertical green lines extending from the top of the grid. The injection well is in the top left finely grid area.

Depth to Reservoirs

Local well logs were used to estimate the depth to the top of the Trenton-Black River group (T. Jordan and J. Aswad, supplementary material S6). The Trenton-Black River reservoir is expected to be located at about 2270-2300 m vertical depth below the Cornell site. Depth to the basement was estimated using three methods (T. Jordan and J. Aswad, supplementary material S6). The estimated depth to basement rocks for the Cornell site range from 2760 m to 2865 m ± 200 m. For the purposes of this project, we assume that basement rocks begin at a depth of 2800 m.

The depths reported in Table A3 and for our reservoirs are uncertain, owing to estimation from regional well log data. However, for the purpose of geothermal reservoir simulation, variability in the depth to formations or the thickness of non-reservoir units will likely not have a significant impact on the resulting reservoir performance. Based on a memo for this report provided by T. Jordan (supplementary material S6), the estimated uncertainty in the depth to the basement is +/- 200 m. A 200 m difference in the depth to basement would result in only a few °C change in the temperatures at the top of the reservoir. Additionally, Whealton (2016) showed that the thicknesses of formations were not among the most sensitive parameters for a 1D heat conduction model. Therefore, it is likely not worth simulation time at this stage of the feasibility analysis to vary these depths to formation tops. Further stages of the project could evaluate these uncertainties; however, once a well is drilled on the Cornell site, the tops will be constrained.

TBR Reservoir Thickness

The expected thickness of permeable zones is discussed for the Trenton-Black River. The presence of higher permeability hydrothermally altered dolomite is not guaranteed below the Cornell campus, as some wells in the local area encountered unaltered Black River limestone (Patchen, 2006). Of the wells surrounding Ithaca, more have dolomite than limestone at the top of the Black River, so based on proximity rather than geological trends, it may be more likely that Ithaca has dolomite than limestone.

The dolomite thickness is expected to be a maximum of 30 m thick based on regional hydrocarbon reservoirs; however, the thickness could be as small as 0 m if a wrench fault system that allows for hydrothermal dolomitization, as described in Camp and Jordan (2017), does not exist where the well is drilled. Therefore, there is a chance that we do not encounter a permeable TBR reservoir of use to the project, and will have to rely on EGS stimulation techniques to use the TBR reservoir. A summary of stimulation methods for geothermal projects are provided in supplementary material S7.

We evaluated reservoir simulation results for Black River dolomite with a 30 m thickness with and without EGS stimulation. EGS stimulation considers that fracture flow dominates matrix flow, and therefore can be modeled with a parallel fractures model, which ignores any porous media contribution to the flow geometry of the heat extraction.

Basement Rock Lithologies

A Cornell internal report by B. Valentino (2016) evaluated the lithologic composition of well cuttings and cores of basement rock in the Finger Lakes region, and in the southern Adirondack Mountains in New York State. A summary of the lithologic composition findings is provided in the map below from Valentino (2016). This study confirms that we expect to see crystalline basement rocks in Ithaca similar to those rocks that are exposed in the Adirondack Mountains. It is apparent from a cluster of well cores in the Adirondacks that the composition of these rocks can change on small 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 this analysis. Granitic gneiss is the most common lithology, and properties in Table A3 reflect that lithology for basement rocks.

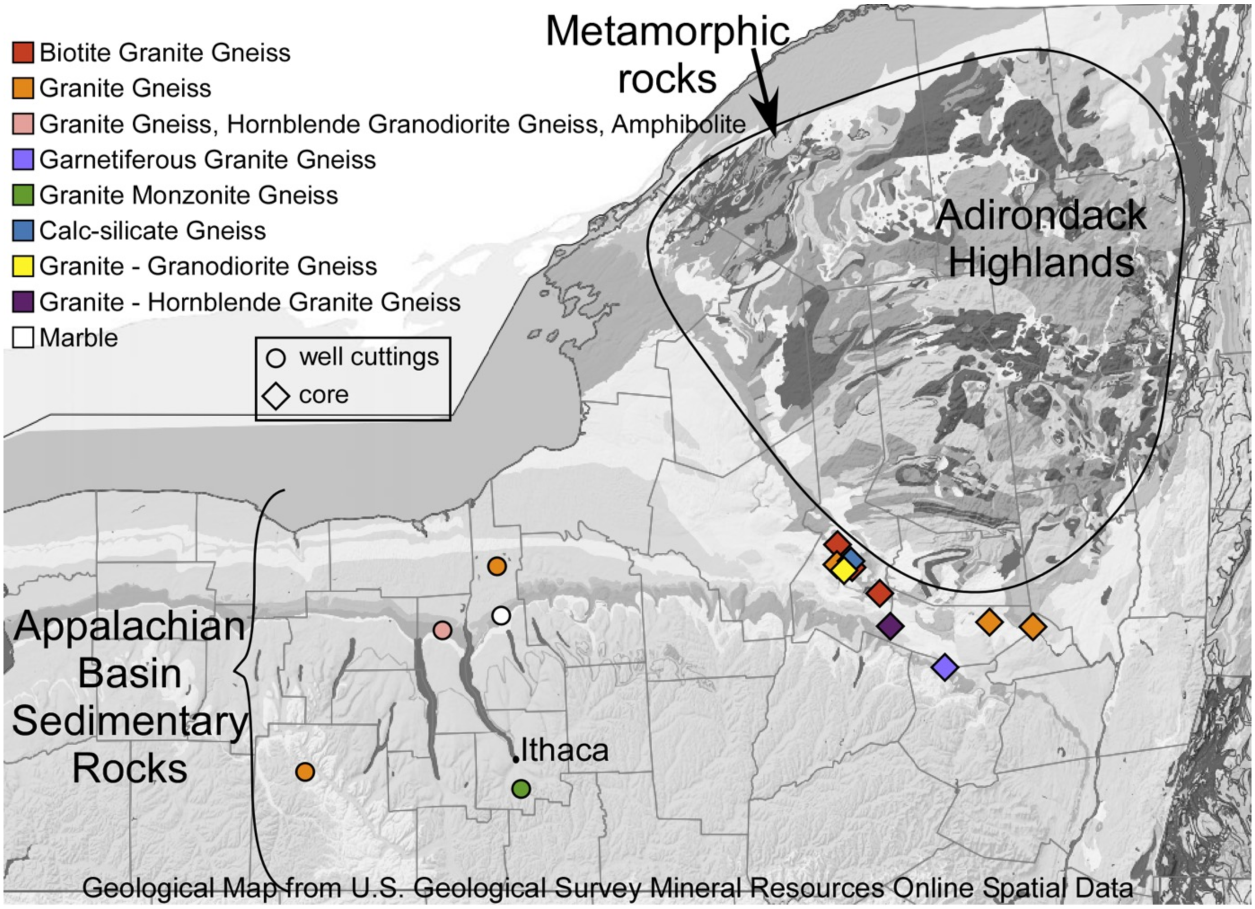

Figure A3: From B. Valentino (2016), map showing the compositions of well cuttings and cores of crystalline basement rocks in New York State.

Rock Density

Rock density was estimated from local deep well logs. Estimates of rock density for the Ithaca rock column are provided in Table A3. Additional data that informed the selection of rock density from the deep well logs and other sources, when necessary, are provided in supplementary material S3.

Porosity and Permeability

The formations of greatest importance for porosity and permeability are those nearest the reservoir depth. The Trenton-Black river group is likely hydrologically confined above by the low permeability Lorraine/Utica Shale. The Utica Shale is a formation of roughly 40 m – 50 m thickness, so even leaky portions of the Utica Shale would likely have a barrier to upward flow over that vertical distance. We focus here on units from the Utica Shale to the basement rocks.

A set of interpreted well logs from 6 wells in NY state (Figure A1, Table A2) was used to gather likely values for formation effective porosity and density. These wells were selected because they contain gamma ray, neutron and density logs that continuously run throughout the entire observed interval. These logs are needed to correct for the effects of shale and gas on the porosity calculations. An analysis of the density and porosity for the formations deeper than the Utica Shale are provided in supplementary material S3.

Permeability values are not as readily available from published studies for all of our formations, and values that were obtained are not *in situ* values, and are rather from cores. Permeability is likely to be a sensitive parameter in the geothermal reservoir simulations, but we do not have local data with which to constrain the permeability of formations of interest. The values obtained are the best available, generally from core studies from Ohio, Pennsylvania, and western New York. Permeabilities for other formations not discussed below were obtained from generic values for lithologies, as described in supplementary material S3.

For the Utica Shale, Carter and Soeder (2015) provide mercury injection permeability data for 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. Porosity is also commonly below 1% across wells, but as high as 8%. Density porosity logs near Ithaca are similar in value.

Specific to the Trenton-Black River, Camp and Jordan (2017) show porosity and permeability measurements for a small (N = 23) dataset from a Black-River site about 50 km southwest of Ithaca. Smith (2019, Ch.4) uses this porosity-permeability dataset to develop censored regression relationships that predict permeability for a given porosity (example in Figure A4). We assume that these relationships and findings from Camp and Jordan (2017) will hold for the TBR located below Ithaca. Permeability values ranged from 0.01 mD to an upper detection limit of 10,240 mD, and averaged around 4,680 mD. Vertical permeability was orders of magnitude less variable, ranging from essentially 0 mD to 58.2 mD, and averaging around 2.6 mD.

Note that for the Black River, the hydrothermal dolomite was modeled separately from the limestone, as shown in Table A3.

Porosity and permeability data on other, deeper formations is limited in the Cornell region. The Rose Run sandstone in Ohio has porosity that ranges from 3% to 20% with an average of 9%, and permeability ranges from 0.01 mD to 198 mD with an average of 5 mD (Fry et al., 2006). The Galway / Theresa formation permeability ranges from 0.75 to 3.7 mD (Smith et al., 2005). The Potsdam formation porosity is low, generally less than 5%, and permeability ranges from below detection limit (0.001 mD) to 0.02 mD (Kolkas and Friedman, 2007). Based on the air permeability data reported in Kolkas and Friedman (2007), the average permeability is likely close to 0.002 mD. Based on Waller et al. (1978), the permeability in the vertical direction is likely about an order of magnitude smaller than the lateral direction. For a detailed discussion of selected values for porosity and permeability, see the supplementary material S3.

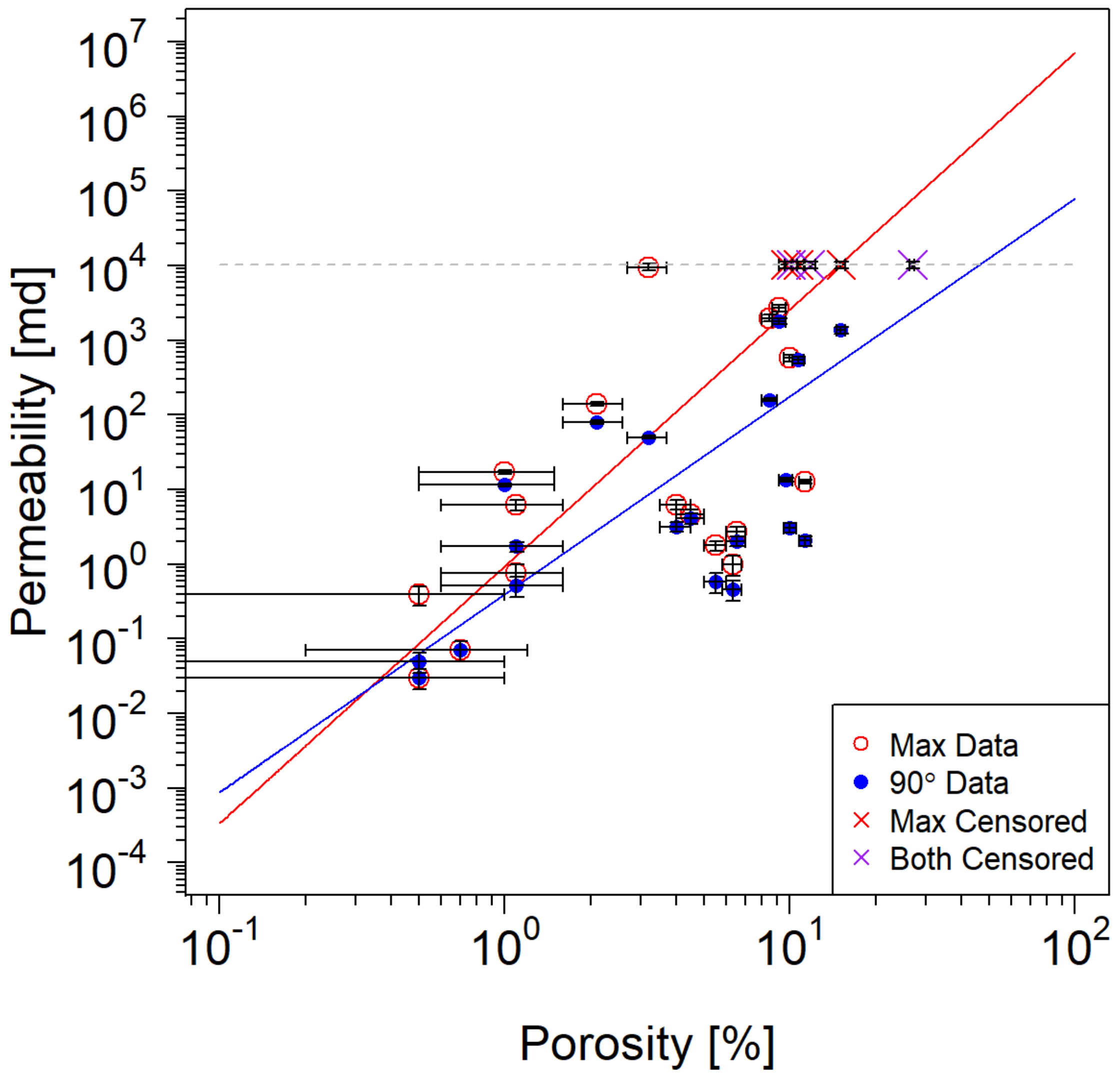

Figure A4: Tobit censored regression for maximum (red) and 90°-to-maximum (blue) horizontal permeability from the Whiteman #1 core (New York State Museum, 2014) of a Trenton-Black River reservoir. The measurement device upper limit of 10,240 millidarcy (mD) is shown as a dashed line. Censored measurements are plotted with x symbols, and uncensored measurements use circles. Error bars are provided for uncensored data

Thermal Conductivity – from Smith (2016) MS thesis.

Carter et al. (1998) was the primary source used for thermal conductivity values when basin-specific information was not available. Their samples were taken from the Anadarko Basin, which has a similarly deep burial history as the Appalachian Basin. Relative to present depths, multiple studies suggest that the eastern margin of the Appalachian Basin was buried an additional 3 km to 4 km (e.g. Rowan, 2006; Reed et al., 2005; Johnsson, 1986), and the western margin in the New York-Pennsylvania-West Virginia region of interest was buried up to an additional 2 km (e.g. Rowan, 2006; Johnsson, 1986); whereas the Anadarko basin was buried up to 1.5 km deeper (Carter et al., 1998). Carter et al. (1998) measured water-saturated thermal conductivity values on cores from the Anadarko Basin, and presented average values for the major lithologies. The resulting thermal conductivity values for the formations in our study are listed in Table A3. The thermal conductivities have not been adjusted for formation depth or temperature (e.g. Birch and Clark, 1940; Clauser and Huenges, 1995); however these affects may be captured by the use of conductivities from a similarly deeply buried basin.

Initial Conditions

Formation Pressure Profile

The simplest assumption for formation pressures is that of hydrostatic conditions. For an ideal calculation of the hydrostatic pressure column, the pore fluids (i.e. brine or hydrocarbons) and their densities with depth would be known. To evaluate the pressures at depth in Ithaca, there are primarily two uncertain quantities: the depth to the water table, and the density of the pore fluids with depth. Brine density is a function of the temperature, pressure, and concentration of salts in the brine. Of those properties, temperature and salt concentration are more influential on the density of the brine than pressure (e.g. Thomas et al., 1984). We did not model density as a function of temperature and salt concentration in this analysis. Rather, we used density samples from regional wells to predict the formation pressure with depth, and assume that the density is constant with depth.

The depth to the water table in counties South and Southeast of Ithaca in New York State has been evaluated by Williams (2005). Williams (2005) found that the depth to freshwater zones for about 110 wells in these counties ranged greatly, from less than 12 ft to as much as 800 ft with an average of about 120 ft. About 75% of the freshwater zones were found shallower than 150 ft., and the depth distribution approached a lognormal distribution (Williams, 2005). For the Cornell Study, we assumed an average depth to water of 120 ft., with the density as described below. We show expected maximum and minimum pressure profiles as well, with water starting at 0 ft. and 800 ft., respectively.

Brine density at the depth of the well is reported in some well logs available on the Empire State Organized Geologic Information System (ESOGIS), but it is uncertain if these samples are representative of the formation fluids, or if they are a combination of drilling fluids and formation fluids. Instead of using well log fluid density values, we use several datasets with 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). These datasets are from counties in the Northern Tier of Pennsylvania, and other areas within the north-central part of the state, as well as the Southern Tier of New York. There are 56 wells with density measurements. Based on these wells, we assume that the pore fluids have densities ranging from 1000 kg/m^3 to 1250 kg/m^3. For this analysis a triangular distribution for density is used, with mode equal to 1180 kg/m^3.

The pressure profile is calculated using Equation A-1

$$P(z) = \begin{cases} \rho_a g z + P_{atm} \quad , & z \leq z_a \\ \rho_b g(z - z_a) + \rho_a g z_a + P_{atm}, & z > z_a \end{cases}$$

[A-1]

where P(z) is the formation pressure as a function of z, z is the depth below the ground surface, g is the local acceleration of gravity, z_a is the depth of air filled pores, ρ_a is the density of air, ρ_b is the density of brine, and P_{atm} is the atmospheric pressure. Uncertainty in g, ρ_a, and P_{atm} induce orders of magnitude smaller changes in the pressure at depth as compared to the uncertainty in ρ_b. Therefore, we assume that the local gravity is 9.81 m/s^2, the air density is 1.225 kg/m^3, and the atmospheric pressure is 1 atm. The triangular probability density function (pdf) for ρ_b is defined in Equation A-2

$$f_{\mathrm{P_b}}(\rho_b) = \begin{cases} \dfrac{2(\rho_b - 1000)}{(1250 - 1000)(1180 - 1000)}, & 1000 \leq \rho_b \leq 1180 \\ \dfrac{2(1250 - \rho_b)}{(1250 - 1000)(1250 - 1180)}, & 1180 < \rho_b \leq 1250 \end{cases}$$

[A-2]

where $\mathrm{P_b}$ is the random variable for brine density, and ρ_b is a realization of the random variable. To compute the pressure profile with depth, we assume that the brine density is the same in the entire column, and is not variable with depth. Using these assumptions, the conditional distribution of pressure profiles given a value of z is computed analytically using a transformation of variables provided in Equation A-3 for the case of water filled pores beginning at the surface

$$f_{P|z}(p|z) = \begin{cases} \dfrac{2(x - 1000)}{(1250 - 1000)(1180 - 1000)gz}, & 1000 \leq x \leq 1180 \\ \dfrac{2(1250 - x)}{(1250 - 1000)(1250 - 1180)gz}, & 1180 < x \leq 1250 \end{cases}, \quad x = \frac{p - P_{atm}}{gz}$$

[A-3]

where "|" indicates that z must be known for the pressure, p, to be determined, and other variables are as previously defined. If water filled pores begin at deeper depths, then the constant corresponding to $\rho_a g z_a + P_{atm}$ must be added, and the depth z is instead the depth within the water column, $(z – z_a)$. A plot of Equation A-3 for the case of water filled pores starting at the surface, 120' and 800' depth is provided in Figure A5. Figure A5 illustrates that the uncertainty in the pressure at depth increases with depth.

For the Trenton-Black River target depth of about 2200 m, the maximum pressure is about 27 MPa, and the minimum is 20 MPa. The most likely value of pressure based on the scenarios below is between 23 MPa and 26 MPa. The difference in pressure between the model with water at the surface to 800' is about 2 MPa.

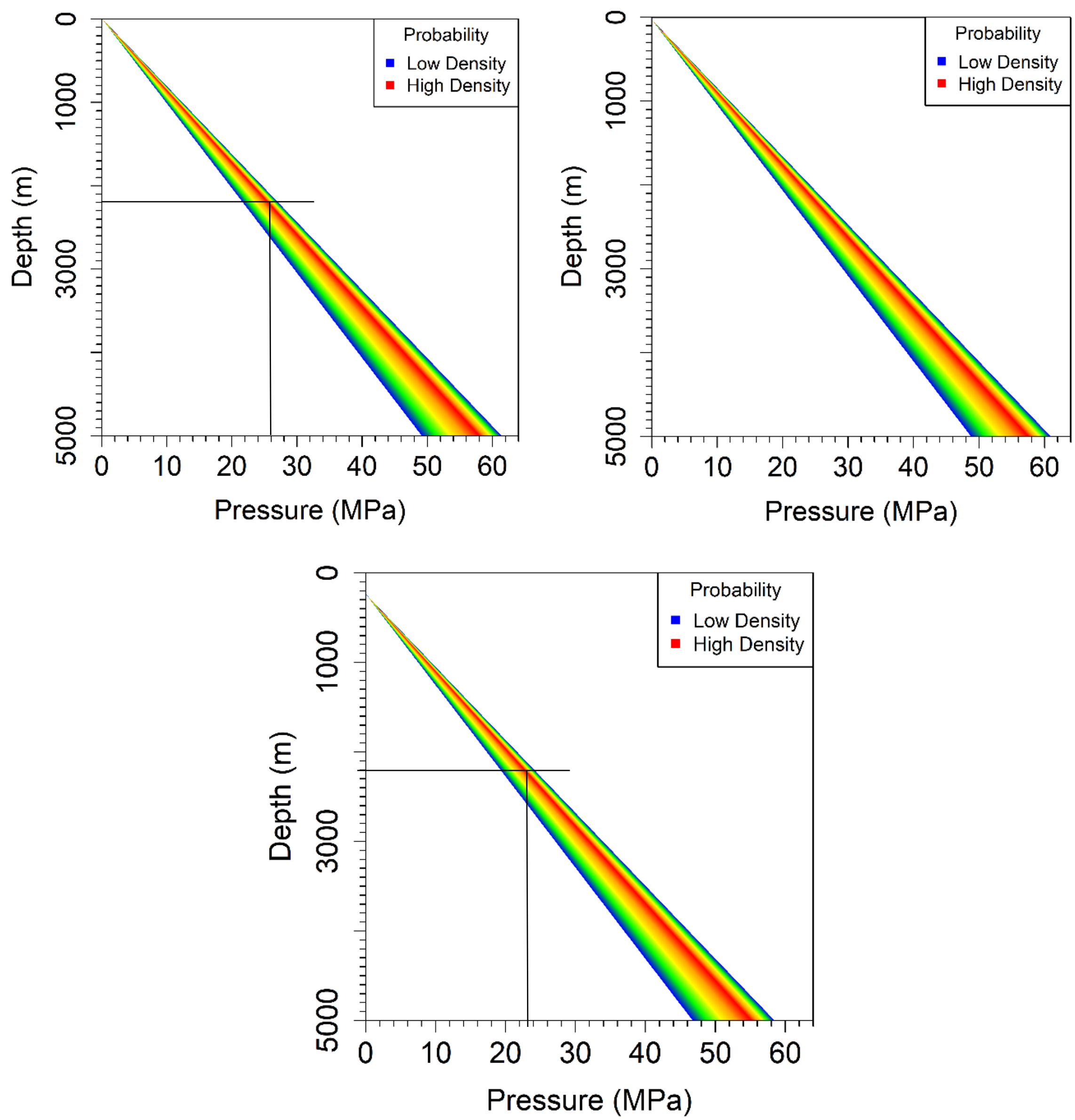

Figure A5: Initial pressure profiles for a range of brine densities from 1000 kg/m^3 to 1250 kg/m^3. Colors indicate the probability density for pressure. Lines of the same color correspond to the same density value. The top left plot assumes water starts at the surface, the top right assumes water starts at 120 ft., and the bottom plot assumes water starts at 800 ft. depth.

Temperature Profile

The average annual ground surface temperature for Ithaca was derived from Gass (1982) shallow (15 m to 46 m) groundwater temperature measurements (SMU Geothermal Lab, 2016). These measurement depths are considered resistant to annual surface temperature fluctuations, as shown by Lovering and Goode (1963). For the Ithaca area, the average annual ground surface temperature from the SMU Geothermal Lab (2016) map is about 11 °C.

Temperatures at depth have been estimated by Smith (2019, Ch. 3) using a 1D heat conduction model and a generalized stratigraphic column. This generalized column was slightly different that the Ithaca-specific column above. 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 interpolation uncertainty). Parameter values assumed for this simulation are the same as those provided in (Whealton, 2016) for sensitivity analysis. Example maps for quantiles of the temperature at 3 km depth, a target for basement reservoirs in Ithaca, is provided in Figure A6. Table A4 provides the 5^{th}, 50^{th}, and 95^{th} percentiles of temperature at depth below Ithaca in 500 m increments. Figure A7 shows the full distribution of temperatures at depth in 500 m increments as violin plots. These 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. The exact value for the gradient in basement rocks is uncertain, but that uncertainty is not captured with this analysis.

For this analysis, we assume that the quantiles at 1 km depth correspond to the same quantiles at 5 km depth, such that only one simulation is needed to determine the initial conditions.

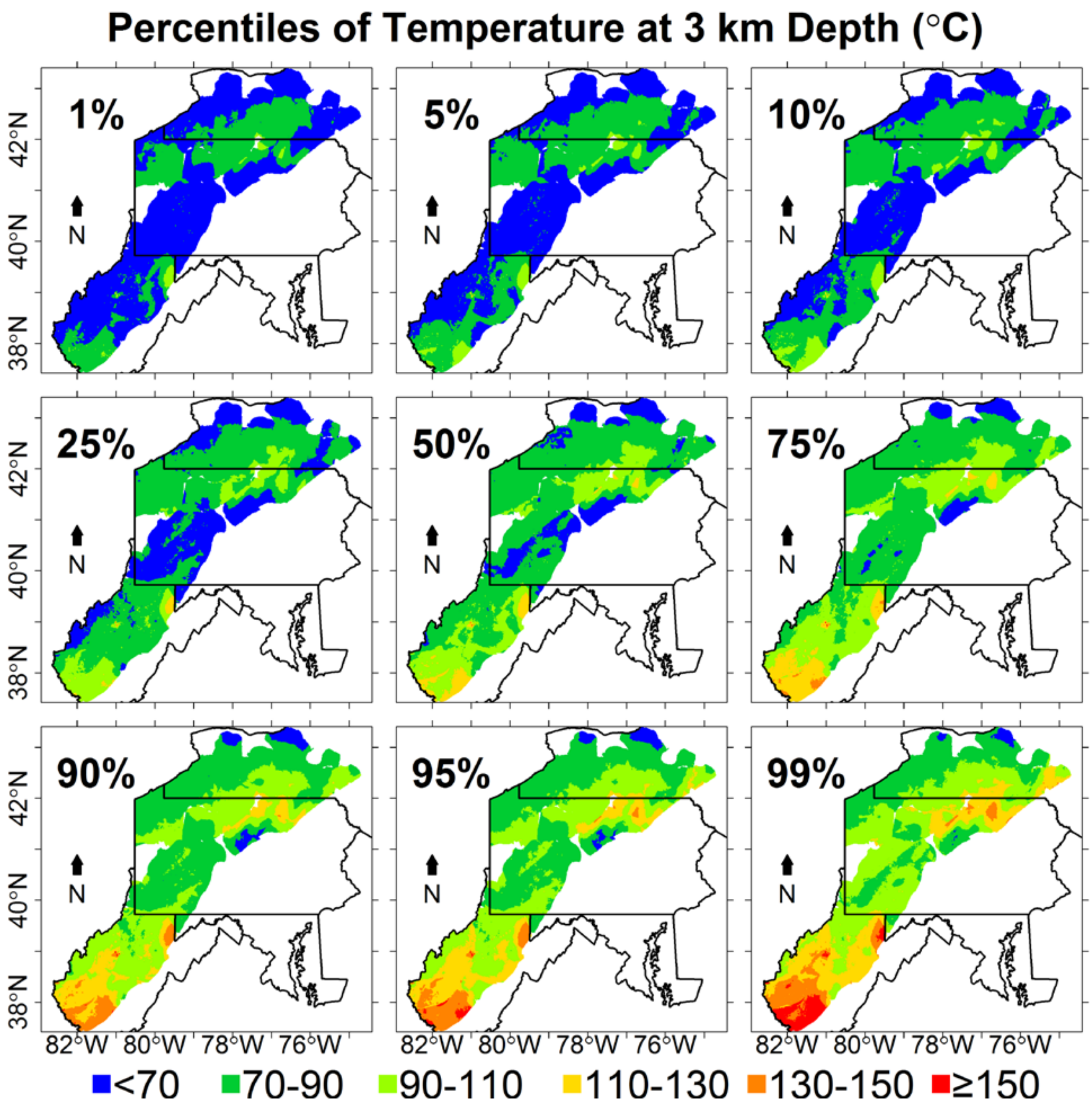

Figure A6: Percentile estimates of the simulated temperature at 3 km depth from a Monte Carlo analysis with 10,000 replicates of uncertain geologic properties and spatial data correlations.

Table A4: Temperatures at depth estimations of the 5th 50th and 95th percentiles for Ithaca, NY obtained from a Monte Carlo simulation of 10,000 replicates that considered thermal, geologic, and spatial correlation uncertainties.

Depth (km)	Temperature (°C) 5th Percentile	Temperature (°C) 50th Percentile	Temperature (°C) 95th Percentile
1	35	39	46
1.5	49	54	61
2	60	66	73
2.5	73	79	86
3	81	87	95
3.5	89	96	104
4	97	104	113
4.5	105	112	121
5	112	120	130

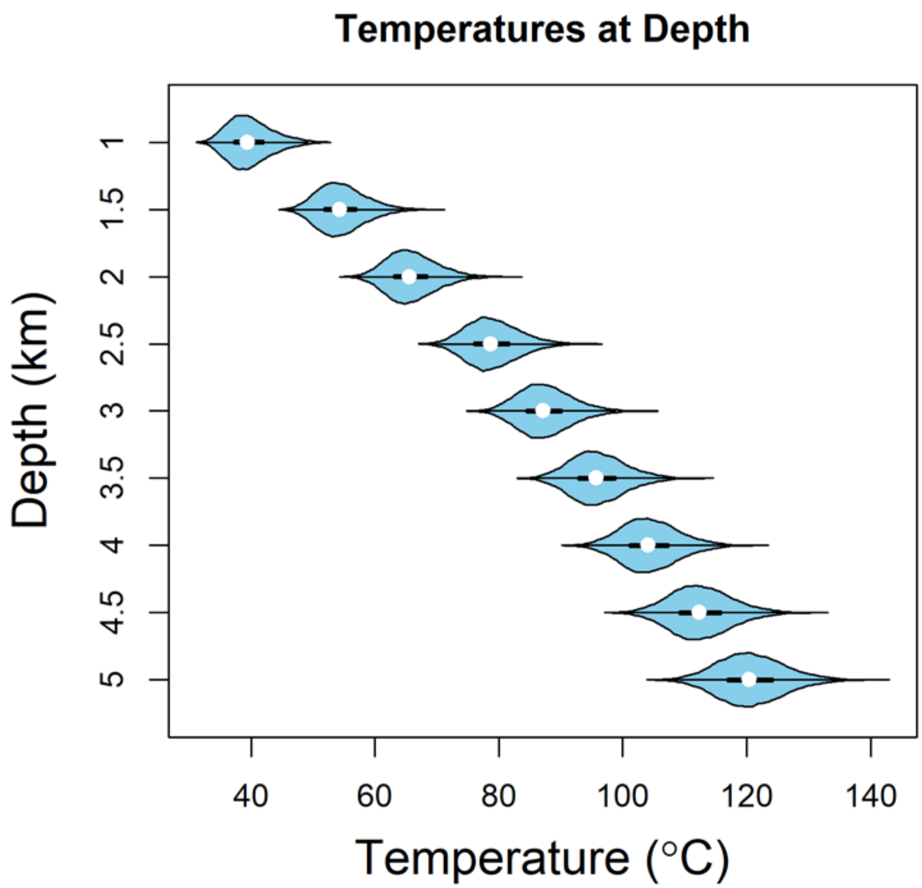

Figure A7: Violin plots (smoothed histogram plot) of the predicted temperatures at depth in Ithaca, NY. White dots are the median value of the predicted temperatures at depth. The black box in the center extends from the 25th to the 75th percentile estimates.

Boundary Conditions

Heat Flow

Specific values of the heat flow at the bottom of the simulation grid were obtained by projecting the Smith (2016) map of the surface heat flow (also in Cornell University, 2016), 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/m^2 (Sclater et al., 1980). For the purposes of this study we assume a heat flow at the bottom of the simulation grid, 3 km depth, of 46 mW/m^2. Based on Whealton (2016) sensitivity analysis, uncertainty in this value is unlikely to significantly affect geothermal reservoir simulation results.

Rock Geometry

Fracture aperture and spacing

Fracture aperture and orientation in basement rocks were estimated based on a September, 2017 field trip to the Adirondack Mountains, which contain rocks of similar age as rocks that likely underlie Ithaca. Additionally, an analysis of existing airborne LiDAR data is being performed to supplement the field observations. Fractures in basement rocks are presented in terms of larger scale (visible to the eye standing on the road tens of meters away from the outcrop) and microscale (only visible up close to the outcrop or with a hand lens). The larger scale fractures can be simulated in geothermal reservoir models, whereas the microscale fractures are likely too small to capture. Micro-fracture data were analyzed for seven rock samples collected from the September, 2017 field trip. These samples represented a range of lithologies that were observed on the field trip.

Larger scale fracture apertures in basement rocks ranged from 0.1 mm to as much as 2 cm. The average was likely close to 1 mm. Large scale fractures in basement rocks in the Adirondacks tended to be vertical with high angles. Their spacing ranged from as dense as 5 cm to as much as 7 m, with 1 – 2 m being the most common separation. We assume 30 m fracture separations for basement rock reservoir simulations, which allows for some fractures being unable to transmit fluid. Multiple orientations may be present at any given site, as discussed in a memo by Smith et al. (supplementary material S5) as part of this Cornell Study.

Many of the micro-fractures were mineral filled, rather than open, which indicates that stimulation of basement rocks could be beneficial for opening these preexisting fractures. The apertures of these filled fractures were 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.

For the Trenton-Black River, Camp and Jordan (2017) report East-Northeast trending normal faults, with 500 m to 1000 m spacing. It is therefore possible that we do not encounter a fault in the TBR reservoir below the Ithaca campus. We therefore evaluated two scenarios for the

Trenton-Black River reservoir simulations. One scenario assumed that no fracture is present, and served as a base case modeled with a plug flow reservoir model. Another scenario assumed that two fractures were present within the reservoir (this is the minimum number of fractures that can be modeled in GEOPHIRES). The aperture of fractures is not constrained by available data, so we will assume the aperture distribution presented in Camp (2017, Table 3.5) for an outcrop in New York. Apertures ranged from <0.1 mm to >10 mm with an average around 2 mm.

Fracture Orientation

For basement rocks, the fracture orientations memo by Smith et al. (supplementary material S5) shows two reasonable scenarios for large scale, near vertical fracture orientations within the basement rocks. The first scenario reflects a naïve assumption that fractures are equally likely to be in any direction at a given site. Such distributions were observed at sites visited in the Adirondack Mountains. 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). Ithaca local principle compressive stress from the smoothed World Stress Map is aligned in a similar orientation. Figure A7 shows these two possible distributions, as described further in the fracture orientations memo.

For the purpose of this study, we assume that fractures exist in one direction using a multiple parallel fractures model, for illustrative purposes. Future phases of project research may include orientations as shown in Figure A7.

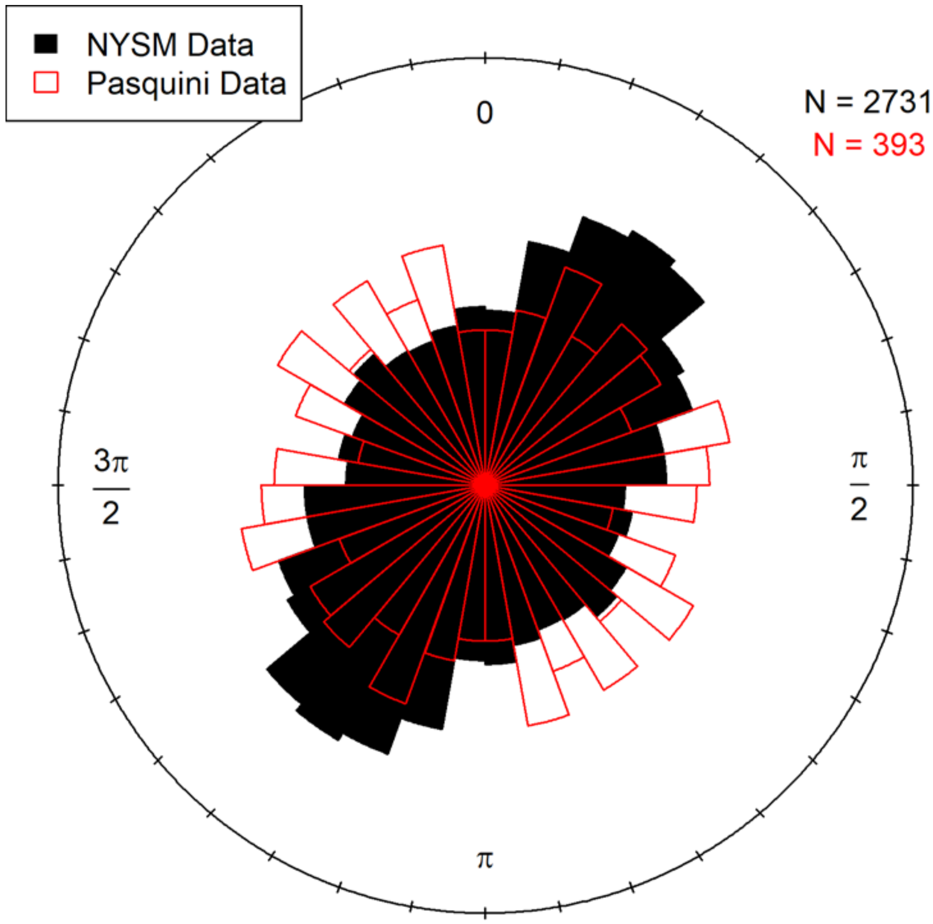

Figure A7: Orientations of structural features within the Adirondack Park (supplementary material S5, Figure 1). Orientations from the NYSM (n.d.) dataset are shown in black, and fracture orientations recorded by Pasquini (2017) on the Cornell field trip are shown in red. 0 is North, and petals are binned into 10° increments. The petals of the rose diagram are scaled by area.

Reservoir Stimulation

Stimulation of the Trenton-Black River carbonate reservoir could be achieved by hydraulic stimulation of fractures, by acid stimulation, or a combination of both (see supplementary material S7 for a discussion of these practices). For either of these cases, it is unclear how specifically the reservoir would behave. We assume a simple parallel fractures model to simulate a stimulated reservoir.

Well Parameters

Injection Well Flow Rate

We evaluated several values of the injection well flow rate as scenarios. These ranged between 30 kg/s and 70 kg/s, which are common values for productive geothermal systems.

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 used a base case of 1 km well separation at depth for vertical wells with lateral flow, 30 m separation for horizontal wells with vertical flow in the TBR reservoir, and 500 m separation for horizontal wells with vertical flow in basement rock. Vertical flow may work well for basement reservoirs if Ithaca has vertical or subvertical fractures, as were observed in the Adirondack Mountain basement rocks.

Injection Well Temperature

The evaluated injection well temperatures ranged from 5 °C – 50 °C for simulations; results are provided for 20, 30, and 50 °C.

GEOPHIRES Input Parameters

The parameters selected for reservoir modeling using GEOPHIRES are provided in Table A5. In addition to the TOUGH2 parameters, GEOPHIRES also required a system capacity factor. The capacity factor considers the fraction of the year that energy is extracted by the geothermal system. As described above, we assume near 100% capacity throughout the year. We assume capacity factors of 0.970 to 0.994, corresponding to a system being down for maintenance two to ten days on average per year.

Probability distributions assigned to geologic properties were derived from observed ranges and most common values in the literature for the formation lithology. 1000 Monte Carlo replicates of these uncertain parameters were used to evaluate the uncertainty in reservoir performance for the listed models of the TBR reservoir and basement reservoirs. Further information on the selection of these parameter values, and the additional parameter values for GEOPHIRES economic calculations, are provided in supplementary material S4. A description of how the uncertainty analysis for GEOPHIRES was implemented is provided in supplementary material S8, and also in Smith and Beckers (2020).

Table A5: Summary of parameters used in GEOPHIRES analytical reservoir models. Probability distributions are listed for those variables that were selected randomly within Monte Carlo simulations. Triangular distributions list the lower bound, mode, and upper bound. Normal distributions list the mean and standard deviation. Lognormal distributions list the real space mean and standard deviation. Beta distributions list the lower tail shape parameter, the upper tail shape parameter, lower bound, and upper bound.

Variable	Trenton-Black River Plug Flow	Trenton-Black River Parallel Fractures	Basement Parallel Fractures	Notes and Sources
Reservoir Depth (km)	2.27 - 2.30	2.27 - 2.30	3 - 3.5, or 3.5 - 4	
Well Orientation in Reservoir	Vertical	Horizontal	Horizontal	
Reservoir or Fracture Height (m)	30	30	500	
Reservoir or Fracture Width (m)	1000	1000	500	
Reservoir or Well Lateral Length (m)	1000	1000	1000	
Fracture Separation (m)	NA	20	fixed at 30 m, or Triangular: 30, 30, 200	Adirondack Mountains
Fracture Width (mm)	NA	0.5	0.5	Camp and Jordan (2017), Adirondack Mountains
Reservoir Impedance (GPa-s/m^3)	Triangular: 0.05, 0.15, 0.5	Triangular: 0.05, 0.15, 0.5	Triangular: 0.05, 0.15, 0.5	Camp et al. (2018) regional reservoir productivity.
Reservoir Rock Density (kg/m^3)	Normal: 2800, 40	Normal: 2800, 40	Triangular: 2550, 2730, 3200	Local well logs, Simmons (1964)
Reservoir Rock Porosity (-)	Lognormal: 0.08, 0.046	NA	NA	Local well logs
Reservoir Rock Heat Capacity (J/kg-K)	Triangular: 900, 930, 940	Triangular: 900, 930, 940	Triangular: 800, 825, 850	Roberson and Hemingway (1995)
Reservoir Rock Thermal Conductivity (W/m-K)	Triangular: 1.92, 2.91, 3.9	Triangular: 1.92, 2.91, 3.9	Normal: 2.83, 0.36	Cornell University (2016), matches assumptions in Smith (2019, Ch. 3)
Surface Temperature (°C)	Triangular: 8, 10, 12	Triangular: 8, 10, 12	Triangular: 8, 10, 12	Gass (1982), SMU Geothermal Lab (2016), 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	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	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	Smith (2019, Ch. 3)
Utilization System Capacity Factor (-)	Beta(4,2), 0.97 - 0.994	Beta(4,2), 0.97 - 0.994	Beta(4,2), 0.97 - 0.994	Allows for two to ten days on average per year for maintenance.
Number of Monte Carlo Replicates	1000	1000	1000	

Output Collected from Geothermal Reservoir Simulations

The primary output variables from all thermal-hydraulic models are the temperature drawdown over time at the injection and production wells, the estimated lifetime of the reservoir, and the pressure throughout the reservoir. These variables were collected at points of interest within the reservoir.

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END OF APPENDIX A

Appendix B: Heat Pump Coefficient of Performance for Modeling

To efficiently evaluate the economics of heat pump use in various applications, the Cornell Study team has established a Coefficient of Performance (COP) for heat pumps. The COP for a heat pump in heating mode is the ratio of delivered heat to the input (electrical) in equivalent units (COP is dimensionless).

Heat pump COP is primarily dependent on temperature, and limited by thermodynamics. Specifically, an “idea” (Carnot Cycle) heat pump has a COP determined solely by the temperature of the source (T_s) and delivery (T_d) temperatures using absolute temperatures (Kelvin or Rankine). Specifically, the ideal COP for a heat pump delivering heat is as follows:

$$COP_{hp,\ heating,\ ideal} = T_d/(T_d - T_s)$$

Real heat pumps, while still governed by this “maximum COP”, temperature-dependent formula, are significantly less efficient. In fact, using manufacturer’s test values and field studies, we have observed that real-life COPs are approximately 40-45% of the value of “ideal” COPs. The following table provides some example values from a sampling of manufacturer’s literature to collaborate these values:

The Cornell Study team reviewed several reports (including one by NREL) that provided information on heat pump COP, as well as compared COPs directly from manufacturer’s data. Based on the preponderance of data, we propose in our study to assume for the purpose of the study that our **actual heat pump COP_a is 42% (0.42 times) COP_{ideal}.** While optimal selection of a heat pump for a future project and the use of specialty large heat pumps would likely improve this COP, this value seems realistic given available information across a wide range of heat pumps and appears relatively constant over a typical range of heat pump operating temperatures.

Data used to select efficiency for model

The Cornell Study team reviewed a wide range of published data to obtain guidance on appropriate COP values as they relate to source and supply temperatures. Only sources that provided clear document of both temperatures (source and supply) and COP were used in this analysis. The following data sources and results are provided from various sources as indicated. Some general comments on each data set are also included. The intent of this information-gathering exercise was to obtain data to determine a representative “efficiency from ideal” value for use in this feasibility level modeling.

Source 1: NREL Study (https://www.nrel.gov/docs/fy11osti/52175.pdf)
Description: Study of field efficiencies of small residential air-source split units (Mitsubishi)

Data (calculations mine from reported data):

Model/Mfgr	Air (source) Temp F	Delivery Temp F	Source deg R	Delivery deg R	Ideal COP	Measured COP	Fraction COP/COPideal
H-SS-62-H-MX	59.4	130.0	519	590	8	2.78	0.33
H-SS-62-H-MN	59.4	100.2	519	560	14	5.31	0.39
H-SS-62-M-MX	59.4	124.8	519	585	9	3.38	0.38
H-SS-62-M-INT	59.5	103.5	520	564	13	5.11	0.40
H-SS-62-L-MX	59.6	131.4	520	591	8	2.97	0.36
H-SS-62-L-MN	59.6	119.7	520	580	10	4.04	0.42
H-SS-47-H-MX	43.4	123.7	503	584	7	2.53	0.35
H-SS-47-M-MN	43.6	123.7	504	584	7	2.6	0.36
H-SS-47-L-INT	43.8	126.6	504	587	7	2.99	0.42
H-SS-47-L-MN	44.0	132.6	504	593	7	2.45	0.37
H-SS-35-H-MX	32.6	121.9	493	582	7	2.5	0.38
H-SS-35-M-MX	30.8	131.4	491	591	6	2.35	0.40
H-SS-35-M-INT	31.0	121.3	491	581	6	2.33	0.36
H-SS-35-L-MX	30.6	130.4	491	590	6	2.11	0.36
H-SS-35-L-MN	30.2	129.9	490	590	6	2.09	0.35
H-SS-27-H-MX	22.3	116.1	482	576	6	2.48	0.40
H-SS-27-L-MX	22.9	130.0	483	590	6	1.75	0.32
H-SS-27-L-MN	23.0	132.6	483	593	5	2.01	0.37
H-SS-17-M-INT	14.9	119.3	475	579	6	2.11	0.38
H-SS-7-H-MX	2.8	95.3	463	555	6	1.84	0.31
H-SS-7-L-MX	2.8	119.7	463	580	5	1.33	0.27
H-SS-n3-H-MX*	-9.7	88.1	450	548	6	1.75	0.31
						Average	**0.36**

<u>Cornell Comments on Source 1</u>: Source 1 was for air-source residential heat pumps and represents field data from a significant national study, rather than manufacturers' test data. In some cases the electrical input is for both the heat pump itself and some associated fans, which may create lower COP values (note: hydronic heat pumps do not use fans for heat transfer). Based on discussions with manufacturers, the Cornell team expects that larger commercial hydronic heat pumps systems can at least marginally outperform this general class of equipment.

Source 2: Multistack (published manufacturer's data for Model M3010XN modular heat recovery chillers)

LEAVING HOT WATER															
MS010XN	110°F			120°F			125°F			130°F			135°F		
Leaving Source Water °F	Power (kW)	Heat (MBH)	Heat COP	Power (kW)	Heat (MBH)	Heat COP	Power (kW)	Heat (MBH)	Heat COP	Power (kW)	Heat (MBH)	Heat COP	Power (kW)	Heat (MBH)	Heat COP
30°F	11.5	116.7	3.0	12.8	112.3	2.6	13.5	110.0	2.4	14.3	107.7	2.2	15.2	105.4	2.0
35°F	11.3	126.9	3.3	12.7	122.0	2.8	13.4	119.6	2.6	14.2	117.1	2.4	15.1	114.5	2.2
40°F	11.2	137.7	3.6	12.6	132.4	3.1	13.3	129.7	2.9	14.1	126.9	2.6	15.0	124.2	2.4
45°F	11.1	149.4	3.9	12.4	143.5	3.4	13.2	140.5	3.1	14.0	137.5	2.9	14.8	134.4	2.7
50°F	11.0	161.9	4.3	12.3	155.4	3.7	13.0	152.0	3.4	13.8	148.7	3.2	14.7	145.3	2.9
55°F	10.9	175.6	4.7	12.2	168.3	4.1	12.9	164.5	3.7	13.7	160.8	3.4	14.5	157.0	3.2

Data (calculations mine from reported data):

Model/Mfgr	Water Source Temp F	Delivery Temp F	Source deg R	Delivery deg R	Ideal COP	Mfgr Data COP	Fraction COP/COPideal
MS010XN	30.0	110.0	490	570	7.1	3.00	0.42
MS010XN	35.0	110.0	495	570	7.6	3.30	0.43
MS010XN	40.0	110.0	500	570	8.1	3.60	0.44
MS010XN	45.0	110.0	505	570	8.8	3.90	0.44
MS010XN	50.0	110.0	510	570	9.5	4.30	0.45
MS010XN	55.0	110.0	515	570	10.4	4.70	0.45
MS010XN	30.0	125.0	490	585	6.2	2.40	0.39
MS010XN	35.0	125.0	495	585	6.5	2.6	0.40
MS010XN	40.0	125.0	500	585	6.9	2.90	0.42
MS010XN	45.0	125.0	505	585	7.3	3.10	0.42
MS010XN	50.0	125.0	510	585	7.8	3.4	0.44
MS010XN	55.0	125.0	515	585	8.4	3.70	0.44
MS010XN	30.0	135.0	490	595	5.7	2.00	0.35
MS010XN	35.0	135.0	495	595	6.0	2.20	0.37
MS010XN	40.0	135.0	500	595	6.3	2.40	0.38
MS010XN	45.0	135.0	505	595	6.6	2.70	0.41
MS010XN	50.0	135.0	510	595	7.0	2.90	0.41
MS010XN	55.0	135.0	515	595	7.4	3.20	0.43
						Average	**0.42**

Cornell Comments on Source 2: Multistack supplied water-source hydronic heat pump equipment to the Cornell "Bloomberg Center" project in NYC; the COP table is from their design submittal for that project and reflects their standard published data for the units provided.

Source 3: Data from Canadian paper: Caneta Research Inc, 2010

http://www.energy.gov.yk.ca/pdf/yukon_airsource_heatpump_mar_2010.pdf

Data: (calculations mine from reported data):

Model/Mfgr	Air (source) Temp F	Assumed Delivery Temp F	Source deg R	Delivery deg R	Ideal COP	Measured COP	Fraction COP/COP_{ideal}
Acadia	-5.0	110.0	455	570	5	2.05	0.41
Acadia	5.0	110.0	465	570	5	2.3	0.42
Acadia	15.0	120.0	475	580	6	2.45	0.44
Acadia	25.0	120.0	485	580	6	2.55	0.42
Acadia	35.0	120.0	495	580	7	3.0	0.44
Acadia	45.0	120.0	505	580	8	3.50	0.45
Mitsubishi	-5.0	120.0	455	580	5	1.95	0.42
Mitsubishi	5.0	120.0	465	580	5	2.05	0.41
Mitsubishi	15.0	120.0	475	580	6	2.25	0.41
Mitsubishi	25.0	120.0	485	580	6	2.50	0.41
Mitsubishi	35.0	120.0	495	580	7	2.70	0.40
Mitsubishi	45.0	120.0	505	580	8	2.80	0.36
						Average	**0.42**

Cornell Comments on Source 3: This report covered small residential air-source split units (Three different models); however, the data was not consistently reported. Data from York was not used because the reporting information on COP was not clear in the report (discontinuous).

Source 4: Published literature - Report on a high-temperature heat pump (research subject, not commercial). http://www.sciencedirect.com/science/article/pii/S0378778814003302

Data: (calculations mine from reported data):

Water Source Temp C	Delivery Temp C	Source deg K	Delivery deg K	Ideal COP	Mfgr Data COP	Fraction COP/COPideal
60.0	90.0	333	363	12.1	3.50	0.29

Source 4 Cornell Commentary: COP values are not as well documented as some commercial sources and are lower than commercially-available heat pumps for these temperatures, despite the author's commentary that this represents an "efficient" heat pump system.

Source 5: Report (by manufacturer) on high temperature heat pumps being marketed in Europe

http://www.vikingheatengines.com/news/new-industrial-heat-pump-produces-heat-in-the-very-high-temperature-range

Data: (calculations mine from reported data):

Water Source Temp C	Delivery Temp C	Source deg K	Delivery deg K	Ideal COP	Mfgr Data COP	Fraction COP/COPideal
90.0	130.0	363	403	10.1	4.50	0.45
90.0	150.0	363	423	7.1	3.00	0.43
					AVER:	**0.44**

Source 5 Cornell Comments: The data provided by this established industrial source suggests that higher temperature delivery can provide similar COP efficiencies (based on temperatures) as more moderate HP choices, provided equipment and refrigerants are properly selected.

Source 6: ORNL heat pumps study

http://web.ornl.gov/sci/usnt/06InHPsAchmaEDFPeureux.pdf

Data: (calculations mine from reported data)

Water Source Temp C	Delivery Temp C	Source deg K	Delivery deg K	Ideal COP	Data COP	Fraction COP/COPideal	
30.0	65.0	303	338	9.7	4.10	0.42	From slide data
60.0	125.0	333	398	6.1	2.50	0.41	From figure (example)
50.0	110.0	323	383	6.4	3.50	0.55	From figure (example)
40.0	110.0	313	383	5.5	2.50	0.46	From figure (example)
55.0	130.0	328	403	5.4	2.10	0.39	From figure (example)
					AVER:	**0.45**	

Source 6 Cornell Comments: The COP values are extracted from figures (rather than listed data) and as such are only approximate.

Source 7: Manufacturer's Data (Gorenje)

http://www.gorenje.com/heating-systems/en/filelib/cataloques/heat-pump-catalogue2013.pdf

Data: (calculations mine from reported data)

Source Temp C	Delivery Temp C	Source deg K	Delivery deg K	Ideal COP	Data COP	Fraction COP/COPideal
10.0	35.0	283	308	12.3	5.60	0.45

10.0	45.0	283	318	9.1	4.30	0.47
10.0	55.0	283	328	7.3	3.30	0.45

AVE: **0.45**

Source 7 Cornell Comments: The COP values are extracted from various tables in the report.

Source 8: http://www.ehpa.org/technology/best-practices/large-heat-pumps/drammen-district-heating-norway/

Data: (calculations mine from reported data)

Water Source Temp C	Delivery Temp C	Source deg K	Delivery deg K	Ideal COP	Data COP	Fraction COP/COPideal	
4.0	90.0	277	363	4.2	3.05	0.72	From slide data

Source 8 Cornell Comments: The COP value is extracted from a slide provided by the author and far exceeds the other data reviewed. The Cornell Team suspects that the source and delivery temperatures may not have been clearly accurate or that the COP may have represented a different operating condition (temperatures).

END OF APPENDIX B

Appendix C: Permit and Approvals Strategy (SOPO Subtask 1.7)

This Appendix documents the Permit and Approvals Strategy Cornell utilized in the DOE study **DE-EE0008103: Earth Source Heat: A Cascaded Systems Approach to DDU of Geothermal Energy on the Cornell Campus** (hereinafter, "Cornell Study"). The Cornell Study team has completed a regulatory and local approval review and developed a strategy for the approvals process. This summary describes the plan and pathway for local, State, and Federal approvals anticipated for implementation of a test well and demonstration.

Permits for Current Work Scope

No permits were required for this DDU feasibility study. The planning scope contained in this study does not require environmental review under the New York State Environmental Quality Review Act (SEQRA) nor any local or regional permits; the only approvals are the internal approvals and requirements of the funding agency (U.S. Department of Energy).

However, should this work continue and involve physical work on site (i.e., a test well, a demonstration project, or a full deployment of the technologies contemplated by this study), both discretionary and ministerial approvals would apply. The remainder of this Appendix addresses the approval path for such additional work.

Physical and Regulatory Setting

The central campus of Cornell University under study for deployment of Earth Source Heat is predominantly located in the City and Town of Ithaca, NY. Cornell also owns and maintains property and facilities across over 700 contiguous acres and "satellite" campuses across New York State and beyond, but these areas are outside the primary campus "district heat" footprint that is the subject of this study. Thus, Cornell is subject to laws and regulations from these local municipalities (City and Town of Ithaca, NY), State regulatory agencies (New York), and Federal regulatory bodies (United States).

Should this work advance to a test well and/or production well set, our proposed (for the purpose of this study) drilling site is part of extensive continuous campus land holdings exclusively owned and controlled by Cornell University, which greatly reduces permitting and approval needs. This proposed site (Figure C-1) is within a Town of Ithaca development parcel specifically zoned for academic and research development ("Planned Development Zone"). The site is also significantly disturbed by past use; the entire development area is an existing fill site used exclusively for contractor parking and staging for Cornell capital projects.

This anticipated future site is large enough (up to 8 acres available) to fit the primary infrastructure (piping, heat exchange buildings, pump stations, and treatment facilities as needed) that may accompany such a development. The site is served by Cornell power (high-tension three-phase), water (primary Cornell private water main), public sewer (a significant sewage lift station is locate within Cornell's property within several hundred feet of the proposed site), and transportation systems (private Cornell roads accessible off State Highway NY366). The site is also within about 1000 meters of the Cornell central steam (future hot water) distribution system. All of these factors affect future approvals and permitting needs. Cornell also already has its own heat and power facilities and generates essentially all of its campus electric (and water).

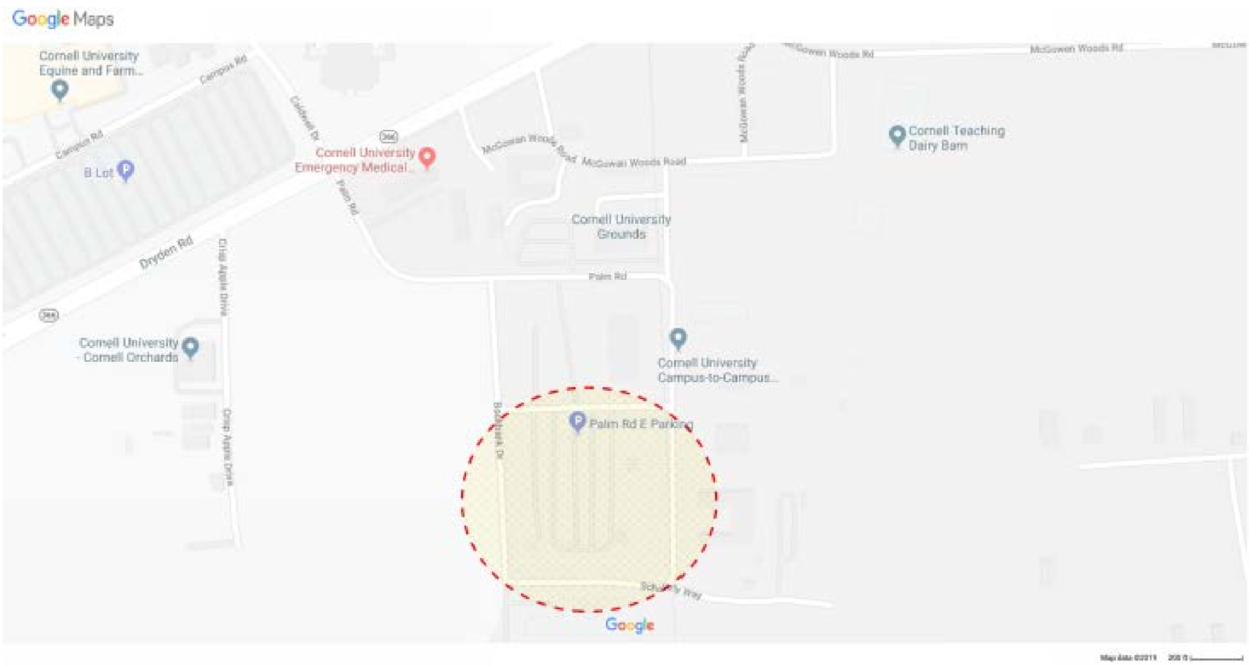


Figure C-1: The proposed drill site, a fill area currently used for contractor staging.

There are no private wells within ~1 mile of the site, and none down-gradient (Cayuga Lake and its drainage areas are down-gradient); all adjoining municipalities have surface water sources. Cornell intends to specify and utilize only tank-based temporary water storage (i.e., no lined lagoons or other systems that may create a higher potential for concern in regards to local run-off and water quality). Use of tanks in lieu of lagoons is consistent with the regional (northern PA) oil-and-gas industry practice (for example, this is a Shell standard practice in the area) and has simplified permitting for many drill sites in the region.

Future aboveground technologies (e.g. thermal storage, heat pumps, heat distribution infrastructure, building system upgrades) are not expected to create any special permitting requirements beyond normal building permits. The local municipality (Town of Ithaca) is the Authority Having Jurisdiction for State building code enforcement and buildings permits and the site is preapproved (and has been through a GEIS process) for substantial development via a Planned Development Zone designation.

Future Permits and Approvals

<u>Discretionary Approvals and Environmental Review:</u>
Assuming Cornell receives internal approvals and funding necessary to advance Earth Source Heat to at least a test well, key discretionary permits and approvals will be as follows:

- A drilling permit from the NY State Department of Environmental Conservation (NYSDEC)
- Water injection permit from the US Environmental Protection Agency (Underground Injection Control or UIC program)
- Site plan approval (for permanent surface infrastructure) from the local municipality (Town of Ithaca, assuming planned location is authorized)

While the UIC program is largely ministerial (i.e., approvals are essentially automatic if they meet standard conditions), the EPA has documented that they retain "discretionary authority" within this program. For example, the USEPA has considered the case of geothermal well development specifically and offer this policy guidance:

"The Class II UIC program does not have regulations specific to seismicity rather includes discretionary authority that allows additional conditions to be added to the UIC permit on a case-by-case basis. Examples of this discretionary authority include additional requirements for construction, corrective action, operation, monitoring or reporting; as necessary to protect USDWs. In the included case studies, the UIC Directors used discretionary authority to manage and minimize seismic events" (source: https://www.epa.gov/sites/production/files/2015-08/documents/induced-seismicity-201502.pdf).

The Cornell Project team cannot yet predict the eventual type or nature of underground injection that may be designed for our system, but we anticipate that this activity will be generally less of a risk than typical high-volume fracking for which permits are commonly issued.

Discretionary approvals, as listed above, require a pre-approval assessment for environmental impact. These assessments include the following:

- Federal environmental regulations require an environmental assessment in compliance with the National Environmental Policy Act (NEPA) prior to federal funding of any future demonstration project. This may only apply if we receive any federal funding for the project.
- In NY State, the State Environmental Quality Review Act (SEQRA) requires an environmental assessment prior to state or municipal funding or discretionary approvals for any project requiring local Site Plan approval or a discretionary action (such as deep (>500 foot depths) drilling, water withdrawal, or subsurface injection).

<u>Non-discretionary (ministerial) permits and approvals</u>
Some non-discretionary permits (building permits, storm water permits, etc.) would also be required. These are routinely granted based on compliance with well-developed rules and standards and can be obtained by any competent contractor based on a compliant design.

Environmental Review Form and Breadth

The form of and breadth of environmental assessment may vary depending on the approval agency and scope of the project, from a simple checklist (common for many NEPA programs) to a full draft Environmental Impact Statement (DEIS).

For permits (State and local) requiring SEQRA, the law allows for either independent environmental review or “coordinate” review. In the past, Cornell has always suggested a coordinated review, and local officials have always agreed (for example, our Combined Heat and Power Plant involved a single coordinated review between three municipalities and one State agency). This process involves agreement among the agency as to which party will be the “Lead Agency”. In the past, we have found most agencies are not opposed to ceding this responsibility, since the coordinated review (and approval process itself) still allows significant input, discretion, and leverage.

SEQRA

The SEQRA process in NY is initiated through completion of a state-generated Short or Full Environmental Assessment Form (SEAF or FEAF). While SEQRA law does not dictate the more detailed FEAF based on the assumed project scope, Cornell has by tradition provided a more extensive assessment (FEAF with DEIS-like appendices) to educate stakeholders about the project and ally local concerns about any aspects of the project that may be considered unusual or containing unfamiliar risks. Cornell would expect to follow the same approach for ESH, although this more elaborate process would likely only occur after a test well is constructed to refine the overall project scope and impact assessment.

As an example of Cornell’s experience in this area, Cornell built our Combined Heat and Power plant in 2007-2008 (including a private high-pressure gas main) and used a FEAF with additional appendices to describe the project environmental risks and benefits, and specific mitigations that would be used to reduce risks or negative impacts. Cornell also held voluntary public meetings and performed other community outreach including frequent meetings with local elected and appointed officials. This process resulted in that projects success; we received positive community and agency support and avoided the longer DEIS process. This general approach is also proposed for the Earth Source Heat project and we have already held local informative meetings about the potential future project.

Once submitted, the approval authority determines if more detailed analysis (via a DEIS) is required for any aspect of the work scope.

Since deep-hole drilling is not yet common in the area and oil/gas drilling with high-volume fracking has been opposed in New York, a full DEIS <u>may</u> be necessary and appropriate to satisfy state and local concerns. The scope of this formal environmental assessment will depend on the target reservoir (this project considers two, subject to investigation by test well) and on prepermit discussions with the local regulatory community (NYSDEC and local town officials). These discussions with the local permitting authority and community (including one or more public hearings) will result in a "Scoping Document" to focus the DEIS on areas of relevant community/regulator interest or concern.

It would be our expectation that any Scoping Document, if needed, would require in-depth focus on only a few areas of concern. There has already been substantial review and study of drilling impacts in New York State due to an extensive assessment of high-volume hydraulic fracturing. That State-wide assessment, which was documented as a DEIS by the NY State Department of Environmental Conservation, resulted in the restriction of high-volume hydraulic fracturing for oil and gas development based on a handful of specific concerns related to specific industry practices. The DEIS also documented a comprehensive evaluation of other potential drilling development impacts and concluded that most related activities would not have a substantial negative impact. As a result, high-volume hydraulic fracturing for oil and gas development was (and is) prohibited in NY State, but drilling and other types of reservoir stimulation is not. Importantly, there are no specific restrictions placed on geothermal development.

Having carefully reviewed the State's DEIS, we do not believe our ESH project would have any of the potential impacts cited in the DEIS that is associated with high-volume hydraulic fracturing for oil and gas development, pending confirmation of the resource characteristics. Thus, despite opposition to high-volume hydraulic fracturing for gas development, a future ESH project appeared well positioned for approval based in part of this same analysis.

In short, Cornell anticipates that this project may be approved with a less formal Environmental Assessment process and not require a formal DEIS, but is nonetheless well prepared to move to a DEIS process if appropriate.

Cornell already has one firm with extensive geothermal knowledge (AltaRock) on board and would assemble other experts as needed to conduct the DEIS. In the past Cornell has sometimes self-authored DEIS studies but would still ensure that the assessment involved experienced professionals with knowledge of risks, benefits, and appropriate mitigation measures.

Site Plan Approval

Once the NEPA and SEQRA requirements are satisfied, the project will be eligible to be considered for applicable federal and state permits and site plan approvals. At that point, the review of individual permits is by the relevant agency (not a "joint review"). Cornell has successfully engaged with our State and local regulators on numerous scientific and energy projects over the past decades (Lake Source Cooling, the Cornell Combined Heat and Power Projects, hydropower upgrades, renewable energy development, etc.) and anticipates success should Earth Source Heat advance to that stage.

Local Site Plan approval is a well-established process in our area. Our local municipal agencies have professional planning staffs that help guide both applicant and Planning Board members through this process and frequently deal with large construction projects (Cornell typically spends >$100M annually on construction). Members of the Cornell Study team have personal experience successfully representing high-profile projects to the local Planning Board and anticipate success for Earth Source Heat based on past discussions with Planning staff and local officials.

Summary

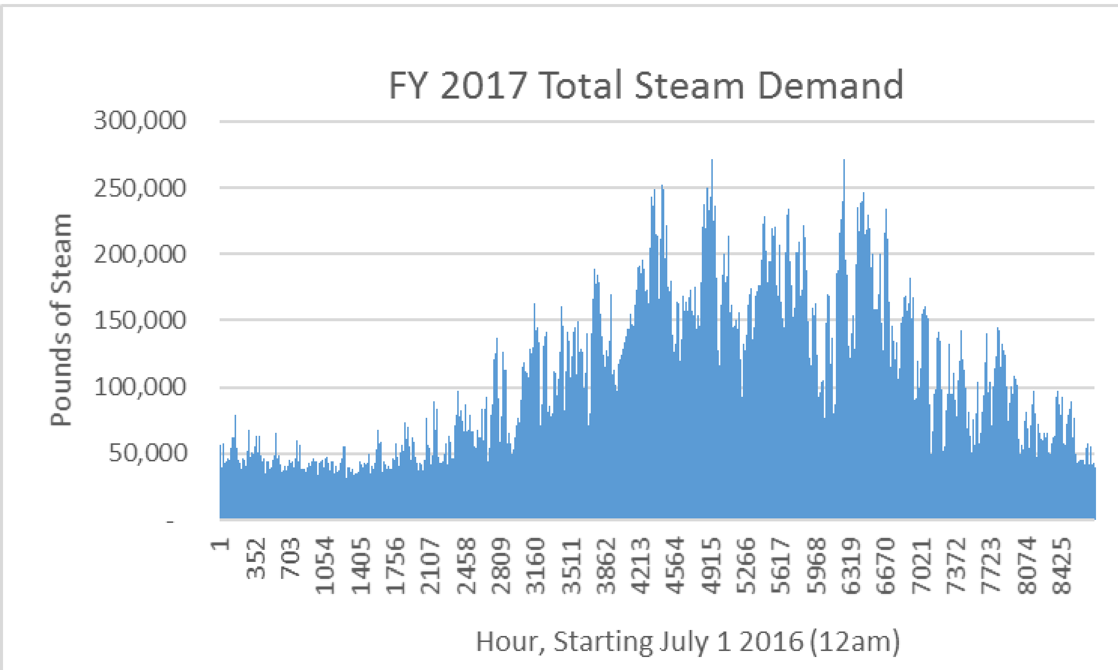
This Appendix C summarizes our knowledge and approach to obtaining the necessary approvals for future potential Earth Source Heat work scope. No permits are required for the current DDU feasibility study. However, should this work continue and involve physical work on site (i.e., a test well, a demonstration project, or a full deployment of the technologies contemplated by this study), both discretionary and ministerial approvals would apply. However, using a similar strategy of community and regulatory engagement and appropriate environmental assessment and mitigation, Cornell has successfully completed similar permitting and approvals process for other projects of similar scale and impact (Lake Source Cooling; Cornell Combined Heat and Power Project; Residential Initiatives) in these same communities, and has never failed to obtain environmental approvals for a campus project. Based on this strategy and that history, Cornell also anticipates success in permitting Earth Source Heat.

END OF APPENDIX C

Appendix D: Cornell Study Heat Demand

Cornell University employs extensive energy metering throughout our campus to measure and track energy usage, and provides annual energy and emissions reporting for both regulatory bodies and voluntary reporting systems. Our campus energy systems provide the Cornell Study team with comprehensive energy information (not just models or estimates) that allow us to do sophisticated modeling and analysis of the impacts of various energy projects.

Figure 1 represents hourly data from real-time meters for all significant buildings from the chosen data set (FY 2017 hourly data). The total annual campus heating load in FY 2017 was about 0.81 Trillion Btu's (283,000 MW_{th}-hrsl). The stated goal of this study (as per the approved SOPO) is to develop a conceptual geothermal system to provide the heating for **20% of campus load**. Therefore, the minimum goal is to identify a system that can supply at least 0.166 Trillion Btu (~**49,000 MW-hours**) on an annual basis.



For smaller buildings without *real-time* metering, available (monthly) metering data is still used, but for modeling purposes an approximate hour-by-hour usage pattern is calculated based on comparison to real-time usage patterns; this modeled data, which we routinely use to conduct system-wide analysis and load projections that include hourly peaks, was similarly used in this study. Where there are data gaps (momentary lapses of data within the system of over 1,000,000 records), those gaps were "filled" using estimates based on usage in the hours immediately before or after the gaps to create a complete data set for the full period. This "gap-filling" also ensures we do not underreport totals based on infrequent data gaps.

Currently, campus heat is distributed as steam. Real time steam metering data is obtained via Cornell University Energy Management and Control System (EMCS) and available in 15-minute intervals. The data units are lbs/hour; historical information on steam quality is used to convert to other units (the factor used is 1# steam = 1030 BTU). There are more than 80 real-time meters (of 150 total meters). Real-time meters capture over 70% of total campus steam usage; the remainder of the usage is captured on meters that are currently read at periodic intervals (monthly) rather than continuously.

Utility grade condensate meters are used for steam billing for the metered facilities. Real time steam metering data is accessed via Cornell University Energy Management and Control System (EMCS). The data is available in 15-minute intervals. The data units are lbs/hour and converted to other units (MMBTU/hr or Watts-thermal) based on historical steam quality.

To verify accuracy and reasonableness, usage data is routinely plotted, trended, and reviewed by staff. Steam production data is also correlated with the building usage data; the two data sets are checked to verify that system losses are reasonable based on campus historical records. Central Energy Plant steam production data is obtained via the iHistorian/Proficy system. Steam production is available for each of the units, including the Heat Recovery Steam Generators and the boilers. The desired time interval is set by the user (the typical interval is “hourly”).

For the purpose of this study, Cornell is using data from our Fiscal Year 2017 (the period July 1, 2016 through June 30, 2017). This represents our most current, complete, and accurate data set. FY 2017 provides the data set with the most real-time data, since Cornell has been continuing to upgrade metering and each progressive years’ data includes more real-time metering rather than modeled/approximate data from periodic metering. FY 2016 and 2017 data set reflects slightly lower heat demands than in prior years, due to a combination of high-efficiency building construction, continued aggressive and targeted campus energy conservation, and statistically milder winters.

For context, Table D-1 compares the total metered heat energy use (by fiscal year, our standard means of reporting) for the periods FY10 through FY 2017. Weather impacts heat usage year-to-year, but energy conservation gains are still evident. Note from Table D-1 that FY 2012 was the mildest winter in this record (lowest Degree Days), but heat requirements are lower in FY 2016 and 2017, despite with some additional campus growth. This reduction is primarily due to the impact of additional energy conservation work since FY 2012.

Table D-1: Cornell Heat Usage, FY 2010-2017

Fiscal Year *(July 1 of prior year to June 30 of year shown)*	**Degree Days** *(note 1)*	**Campus Size** *(million gross SF)*	**Cumulative Campus Heat Usage** *(Trillion BTUs)*	**Cumulative Campus Heat Usage** *(Thousand MW-hrs)*
2017	6525	15.87	0.81	237
2016	6461	15.83	0.83	243
2015	7822	15.83	1.00	293
2014	7771	15.80	1.01	296
2013	6756	15.20	1.04	305
2012	5767	15.20	0.97	284
2011	7221	15.20	1.16	340
2010	6856	14.81	1.09	319

Note 1: *Degree days based on degrees Fahrenheit; per ASHRAE the historical "normal" for Ithaca is ~7,220 degree days per year. Higher degree days are associated with more heating demand.*

Based on continuing aggressive conservation and low-energy design initiatives on campus, we anticipate a continuation of this steady or slightly declining energy use into the near future, despite modest campus growth in regards to students, total building area, and in the types of programs at Cornell. These "no-growth projections" result from our annual analyses completed for the purpose of establishing campus utility rates and budgets for upcoming years.

END OF APPENDIX D

Appendix E: Assumptions for use in economic evaluations

The purpose of this Appendix is to document certain assumptions (and associated rationale) that the Cornell Study used in economic evaluations. These values included the following:

- Discount Rate: (Nominal) 5%.
- Social Cost of Carbon (2018 US$): $50 per metric ton CO_2 equivalent
- Economic Multipliers and Factors: 2.0 multiplier for portion of costs that remain in local region (see Appendix I for more details)
- Natural Gas Price (commercial retail average): $8/MMBtu
- Electrical Price: $33.00 per MWhr ($0.033/kWh).

Discount Rate

When considering future investments, economists recognize the *time value of money* by selecting an appropriate Discount Rate. A discount rate as used in this context represents the reliable value that the money would otherwise receive in a long-term investment or, conversely, the rate of interest that one would pay for financing the investment. Since there are relatively wide ranges in discount rates used in different applications, it is essential to assume a discount rate in order to make credible long-term financial decisions.

When Cornell University does present-worth or life-cycle analysis, we use a Discount Rate of between 5 and 5.5 percent. This is the rate that our internal financial experts anticipate is the long-term return on our convertible endowment (i.e., the money we have available for investment). It is also just above the rate at which we can borrow money on the market (as a strong institution with a strong history of positive borrowing). **This Cornell Study used a (nominal) discount rate of 5%.**

Social Cost of Carbon as part of Levelized Cost of Heat

One important anticipated outcome of this study is the development of a Levelized Cost of Heat (LCOH) for the site. Three versions of this LCOH were developed:

- Owner Economics LCOH (**LCOH**): LCOH considers only the cost to the local "owner" (in our study, Cornell University). This may also be considered the "single-bottom-line" LCOH value used in traditional economic evaluations.
- Regional Economics (**$LCOH_{REG}$**). This "cost" includes the value of external benefits (negative cost) to the regional economy with a comparison to current energy practices of the University. As such, it includes quantifiable economic benefits from development of DDU technology in the local/regional community.
- Global Environmental Cost Impact (**$LCOH_{ENV}$**): As described in the body of the report, this includes environmental impacts in comparison to the "base case" of fossil energy use for heat (assuming natural gas).

The purpose of this analysis of different LCOH values is two-fold. First, it quantifies both internal and external costs so that the energy user (in this case, Cornell) can consider both the direct fiscal impact of future energy decisions as well as indirect societal impacts. Second, it suggests a rational approach to project financing by allocating costs to the user (representing the financial value to the user), local/state/regional government or foundations (representing local economic value to the region), and federal or globally-involved private foundations (representing costs/value to global environmental or social systems).

LCOH is not the only metric that Cornell uses internally to decide on an appropriate investment; other formulations of DDU "value" may be considered. While strong stewardship over Cornell's finances is important, Cornell's financial decisions are not always based on the same economics that apply to for-profit corporations, tax-funded government operations, or other types of enterprises. Specifically, as a not-for-profit educational institution, Cornell derives much of its value based on its perception as an institute of exceptional quality and leadership rather than "profitability", since these "soft qualities" significantly impact the amount of income we generate from alumni and foundation gifts, student enrollment; and grants.

Nonetheless, for the purpose of this grant program, we utilized "traditional economic" principals to calculate LCOH, since this is assumed to have the broadest application to other potential applications in the region.

Social Cost of Carbon

The United States has vast energy resources in oil, gas, sunlight, geothermal temperatures, wind, hydropower, and nuclear. Each of these resources requires different techniques for extraction/generation and each has unique and different environmental and social impacts. Impacts include land use, toxic pollutants, greenhouse gas emissions, job and wealth generation, water pollution, radiation, and others. Since these impacts largely affect external society (rather than the energy producer), economists consider these "externalities".

Carbon emission impacts are one specific externality that has been extensively studied. Most traditional fuels (gas, oil, coal, wood) derive their energy value from embedded carbon that is converted during combustion to gaseous forms, primarily CO_2. CO_2 is a known "greenhouse gas" that alters the energy balance of the earth. Humans have become so dominant on earth that our CO_2 emissions have started to have measurable impacts on the environment. Economics recognize this impact, even if the quantification of the impact is complex and difficult to assess accurately. Nonetheless, great efforts have been expended to derive a credible cost for the Social Cost of Carbon both within the US and worldwide.

Our $LCOH_{ENV}$ value was solely based on the published Social Cost of Carbon. Consistent with many national and international entities, we used a 3% discount rate for this value, as representative of the lower cost of money associated with federal government economics.

The Cornell Study used the value of $42 (2007$) per metric ton CO_2-equivalent, which represents the anticipated Social Cost of Carbon value for the approximate project midpoint of 2020. Adjusting for inflation (as measured by US Consumer Price Index) since 2007, this is about $49/metric ton in 2017 dollars (http://stats.areppim.com/calc/calc_usdlrxdeflator.php). We assumed an additional 2% inflation rate from 2017 to 2018 to arrive at a value for our use: **This study used $50/MT-$CO_2$ (2018 US$) as a Social Cost of Carbon in comparing energy options.**

The table below is from the technical support document: *Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866 by the Interagency Working Group on Social Cost of Greenhouse Gases, United States Government, August 2016.*

Table ES-1: Social Cost of CO_2, 2010 – 2050 (in 2007 dollars per metric ton of CO_2)

Year	5% Average	**3% Average**	2.5% Average	High Impact (95th Pct at 3%)
2010	10	**31**	50	86
2015	11	**36**	56	105
2020	12	**42**	62	123
2025	14	**46**	68	138
2030	16	**50**	73	152
2035	18	**55**	78	168
2040	21	**60**	84	183
2045	23	**64**	89	197
2050	26	**69**	95	212

The application of this “Social Cost of Carbon” is relatively straightforward. For each scenario, the associated carbon emissions was calculated based on standard carbon accounting protocols, which when multiplied by this factor provides an Environmental Cost factor.

Economic value of development to a community or region

In determining the economic value of development to a community or region ($LCOH_{REG}$), experts consider job creation, job retention, improvement in the cost of goods and services, and similar factors. Our analysis included consideration of these regional economic factors, using Federal sources wherever practical. In this context, the report defines the following:

- The Region is the boundary of the Southern Tier Regional Economic Development Commission (of NY State). Cornell’s Ithaca campus is located within this region.
- Calculation of Benefits. This study assumed regional economic benefits based on consideration of labor and material project expenses, including an estimate of how much of this money remains in the local region.

The U.S. National Renewable Energy Laboratory had recognized the complexity of calculating economic value, as suggested by past webinar materials:
https://energy.gov/sites/prod/files/2014/05/f15/tap_webinar_20090729_jedi.pdf

As noted by NREL, renewable energy (like geothermal energy) represents new industry that is not isolated as an industry in conventional I/O tables. Therefore, estimates of economic impact require detailed knowledge of project costs and industry specific expenditures, including but not limited to equipment, engineering, labor, permitting, O&M, etc. JEDI's intent was to provide a project basic project recipe for specific renewable energy technologies.

Appendix G provides additional information regarding the determination and use of $LCOH_{ENV}$ values.

Economic Multiplier Factor

In addition to direct employment benefits, development monies can spur regional economic growth in a less direct, manner. Specifically, a portion of local wages are recirculated within a local economy (for example, to pay for entertainment, local retail goods, local taxes, etc.), spurring additional economic activity. The regional economic value of these "recirculated" dollars depend on many factors, including how many of the direct jobs are held by individuals within the regional under evaluation, how many dollars are spent or distributed locally, and whether the local area accumulates wealth from these transactions.

The determination of appropriate economic multipliers is not straightforward, but is nonetheless critical to understanding the value of an industry or technology to a local community or region. The Cornell team reviewed the following sources in determining reasonable economic multipliers for use in this study:

- IMPLAN software – for areas of work reasonably described by IMPLAN. IMPLAN is one of the most widely used and accepted tools for calculating economic development potential. However, its value is severely limited for this study, since no solid statistics exist for geothermal development in the East. JEDI applies Industry Specific Multipliers derived from IMPLAN based on costs derived from NREL's geothermal industry analysis. Cornell also reviewed JEDI's data for applicability and use under our project conditions.

- FEDFit (Economic Development Tool developed by the Federal Reserve). Cornell has requested a copy of this (free to the public) calculation tool to evaluate its usefulness in defining the economic impact of regional actions but has been advised that the Federal Reserve is no longer offering or supporting this product. However, we learned that FEDFit was no longer supported and as such could not use this source.

Once expenditure and development estimates were quantified and detailed using modeling tools and independent estimating efforts, the Cornell Study documented specific economic multipliers (and their sources) appropriate for use in this analysis, as detailed in Appendix I.

Appendix I provides details regarding the final multiplier (2.0) and expenditure assumptions used in computing $LCOH_{REG}$.

Energy Costs

To estimate the price of natural gas, we used the U.S. Energy Information Administration (EIA) estimates. Listed below are recent prices per the EIA website (1/30/18):

Natural Gas Prices
(Dollars per Thousand Cubic Feet, except where noted)

	Aug 2017	Sept 2017	Oct 2017
Citygate Price	4.57	4.54	4.04
Residential Price	18.32	17.01	13.50
Commercial Price	8.77	8.49	7.96
Industrial Price	3.83	3.89	3.82
Electric Power Price	3.27/MWh	3.31/MWh	3.27/MWh

(https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm)

The data from EIA shows that a commercial institution pays, on average, almost twice the industrial or wholesale price for natural gas, and a residential client about three times as much. For the purpose of the Cornell Study, we will assume that a typical institutional customer will pay the average commercial price for **natural gas**, or about **$8 per MMBtu** (in late 2017). We will also use this same data source for the price of **electricity (~$33/MWhr**).

Energy prices (used primarily to compare a "business as usual" baseline) are a one-cell entry on our LCOH spreadsheet that can be adjusted for later work if new EIA estimates that are substantially different are developed over time.

END OF APPENDIX E

Appendix F: Modeling Energy Use (MEnU) Description

Executive Summary

This Appendix describes MEnU (for "**M**odel of **En**ergy **U**se"). MEnU is a custom modeling tool developed by the Cornell team for the purpose of assessing and optimizing the integration of geothermal energy into building heat infrastructure, using Cornell as an example. This appendix includes the following:

- General description of the MEnU tool
- Parameters and assumptions used in its operation
- Cornell's existing heating infrastructure and how it compares to the model
- Fundamental principles of model operation
- Insights into DDU capacity and effectiveness as revealed by modeling using MEnU

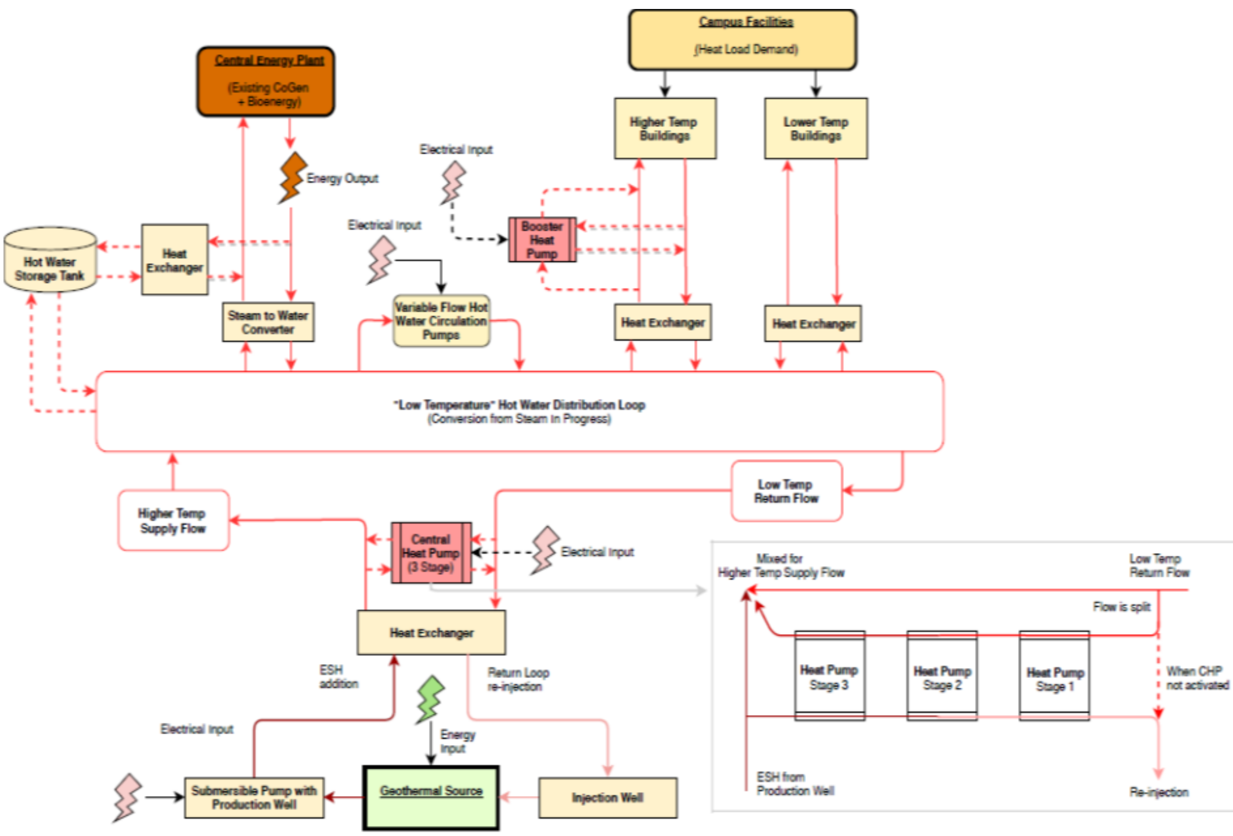


Figure F-1: Block Diagram of Menu Program

Year 1 preliminary analysis using the MEnU model demonstrated how appropriate facility design standards and integrated energy approaches can significantly improve the Levelized Cost of Heat (LCOH) for a given geothermal resource. A simple example showed how reasonable adjustments in design and operating parameters of surface systems ("demand side" conditions) can create a more than 10-fold improvement in heat output from a modest geothermal resource. While this result will vary with each arrangement of resource and surface use potential, our work suggests that determining the "break-even" point for "deep direct use" of low-temperature geothermal resources may rely more in an understanding of key demand side strategies than on moderate improvements to the geothermal resource. The work also suggests that new metrics may be necessary to describe and compare these opportunities.

Research of using the model provided important insights into future design strategies which improve the cost-effective use of DDU resource in geological and climactic settings similar to the Ithaca campus in central New York State.

Introduction to MEnU

The Cornell DDU team is using a novel demand-side model named called MEnU ("**M**odel of **EN**ergy **U**se"). Cornell's MEnU model is coupled to the GEOPHIRES subsurface resource model initially developed at Cornell University and further developed at the National Renewable Energy Laboratory (NREL). Together, these coupled models help predict the effective heat use which is used to derive the LCOH for the DDU resource at our site. This Section describes findings and insights related to both our demand-side modeling and to the coupling of models.

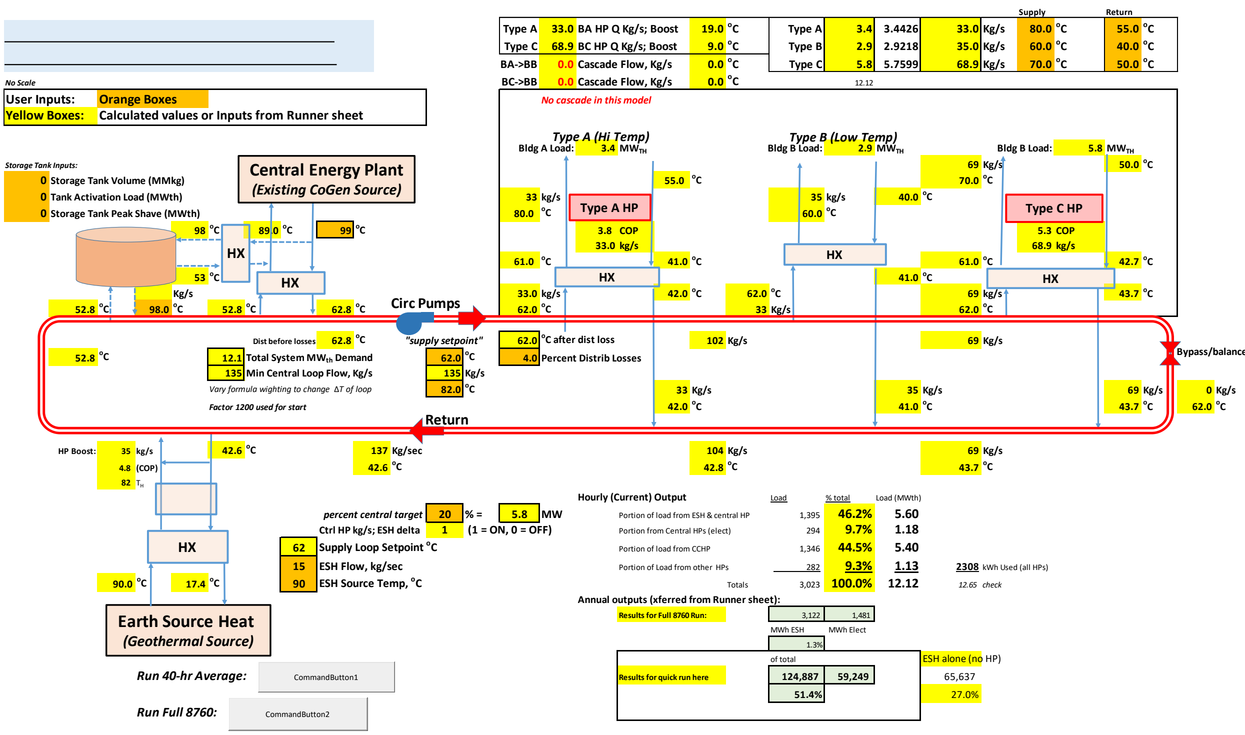


Figure F-2: Screen Shot of the MEnU Model

Figure F-2 shows a screen-shot of the primary data entry screen and primary graphical MEnU model, which was created in Excel (incorporating macros). Calculations used in the model are embedded both within this page and within other Excel tabs that are part of this same Workbook (for example, heat pump operations are part of detailed calculations on other Workbook sheets and heat load input and export values are contained on another).

While the scale of Figure is insufficient to allow a detailed review (without magnification), the following system components are part of this figure:

- The red loop in the center is a presentation of the district heating (hot water) loop.
- The salmon-colored box in the lower left represents Earth Source Heat (Cornell's name for its DDU source); the orange-colored boxes to the right and just above are the basic MEnU input parameters (fluid flow rate in kg/s and temperature in ^{o}C).
- Just above the Earth Source Heat box is a box labeled "HX" which represents the main system plate and frame heat exchanger (separating well water from the close-loop district heating loop)
- Just above the HX box is another box labeled "Cent HP". This represents the central heat pump (described herein). The orange box to the left of that unit allows modeling input for the target heat extraction for the system with heat pump "assist".
- The orange cylindrical structure near the top left represents a future hot water storage tank. The purpose of the storage tank is to moderate peak loads to reduce future capital equipment needs (i.e., by reducing peak heat demands through "load-shifting").
- To the left of the storage tank is a salmon-colored box labeled "Central Energy Plant". This represents Cornell's existing combined heat and power plant, which currently provides essentially all district heat and will continue as a back-up (marginal load and redundant supply) until such time as ESH or a similar source replace all heating needs for campus.
- To the right of the Central Energy Plant are three parallel loops within on rectangle labeled "Campus Facilities (Load)". The three loops (representing building hydronic heating systems) are labeled "Type A", "Type B", and "Type C". Each loop is separated from the district heating loop by a heat exchanger (HX box). These represent three distinct building types within the Cornell campus district energy system with different heat requirements. Two of these building types also include heat pump systems (labeled "Type A HP" and "Type C HP", these building-level heat pumps are described later in this appendix).
- The various boxes in orange above the Campus Facilities rectangle are for the entry of input parameters (described herein). The other boxes (not in orange) generally show "real time" data (temperatures, flows, etc.) and intermediate calculations that resulted from the specific modeling setup.

The use of this simple "graphical interface" has proven valuable in developing the model. Data representing Cornell's actually hourly heat load variations over the course of a full year (as further described in prior submittals) is input into the appropriate fields via a macro and output values are automatically calculated in each hour step, which can be visually observed during the processing. This "real time" data allows conditions with various portions of the model to be viewed as the "model year" progresses, revealing important insights. For example, the real-time display of heat pump coefficient of performance as the system runs through a typical heat (summer to winter and back to summer) provides insights into appropriate loop temperature targets and building design temperatures for optimizing overall heat distribution. It also provides a valuable trouble-shooting tool for model development, since unrealistic values (i.e., heat exchangers that show hotter temperatures on the building use side than the delivery side, or negative flow values) are readily identified so that appropriate algorithm corrections could be made.

The GEOPHIRES model NREL developed includes numerous input parameters. Several input parameters are directly relevant to the eventual valuation of the resource – the LCOH. There inputs are also important parameters – inputs or outputs – of Cornell's demand-side MEnU model. To better discuss some of these interactions, some basic equations used in the MEnU model are provided here.

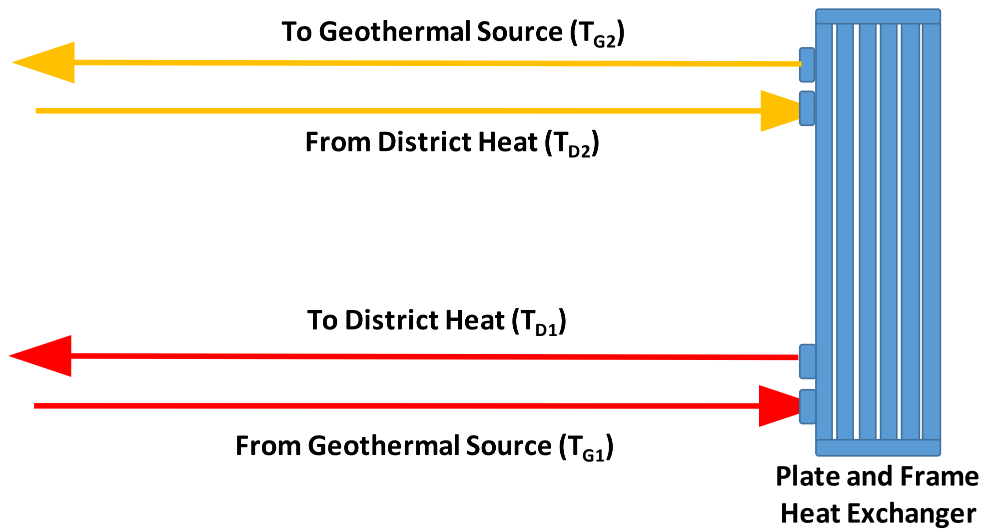


Figure F-3: Primary Heat Exchanger Schematic

Figure F-3 provides a simple diagram of the heat transfer from well to district energy that can be used to describe these simple relationships. From the figure, we define:

T_{G1} = Supply Temperature from the Geothermal Well System
T_{G2} = Return Temperature to the Geothermal Well System
T_{D1} = District Energy Supply Temperature
T_{D2} = District Energy Return Temperature

The raw quantity of energy derived from the well is essentially the integration of $c_pQ\Delta T$, where cp is the specific heat capacity of the water, Q is the well mass flow, and ΔT is the available temperature differential at the surface (i.e., temperature of flow from the well minus the temperature of the return, or re-injected, flow). If we let Q_G = the mass flowrate from the geothermal well (supply side) and Q_D = the mass flow through the heat exchanger from the district energy system (demand side), we can use conservation of energy (ignoring the very small thermal losses at the heat exchanger) to produce the following:

$P_{TH} = c_p * Q_G * (T_{G1} - T_{G2}) = c_p * Q_D * (T_{D1} - T_{D2})$ (*equation F-1*)

Where:

P_{TH} = thermal power produced by the geothermal well system
c_p = specific heat capacity of water (~4200 J/kg/K)

Since the specific heat of water is essentially a constant for the ranges of temperature we considered, Equation F-1 shows that the thermal power produced – the essential asset of the LCOH calculation – requires only three variables, namely, the flowrate and the input and output temperatures to the well.

The GEOPHIRES model essentially allows these critical input values to be "assumed". Specifically, the flowrate Q_G is directly assumed; GEOPHIRES then predicts the pumping pressure (and input energy) needed to produce that flow based on other inputs. Pumping energy provides a practical check of reasonableness and forms a component of the LCOH since pumping costs are included in this derivation. Similarly, the supply and return temperatures are also modeling inputs to GEOPHIRES. The supply temperature (T_{G1}) assumption is typically an estimate based on available measured data for a given resource extraction design. However, the *return* (or re-injection) temperature (T_{G2}) – the third and final critical value in equation F-1 – is based solely on demand-side conditions (how the heat is used at the surface) rather than any characteristic of the resource itself.

GEOPHIRES allows for a simple assumption of re-injection temperature. Cornell adopted a strategy for the temperature of re-injection using our demand-side modeling tool (MEnU) and our research into effective geothermal heating systems in Iceland, France, and Copenhagen.

Figure F-3 shows the heat exchange from the district energy loop to facilities at the building (or in some case multi-building) level. Again, conservation of energy is used to calculate temperatures that result, as indicated by equation F-2.

$P_{BTH} = c_p * Q_{DB} * (T_{D1} - T_{D2,B}) = c_p * Q_B * (T_{B1} - T_{B2})$ (*equation F-2*)

Where:

P_{BTH} = Thermal power transferred at the building heat exchanger
c_p = specific heat capacity of water (~4200 J/kg/K)
T_{B1} = Supply temperature to the building heat loop
T_{B2} = Return temperature from the building heat loop
T_{D1} = District energy supply temperature
$T_{D2,B}$ = District energy return temperature for the building
Q_{DB} = Flow from district system through the building heat exchanger
Q_B = Flow from the building heating loop through the building heat exchanger

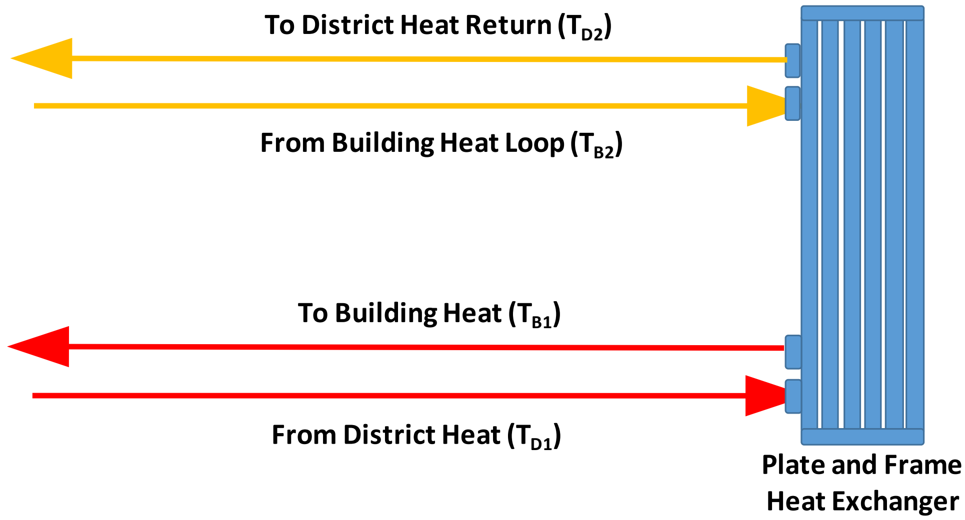


Figure F-4: Secondary Heat Exchanger Schematic

To determine district heat return temperatures, MEnU calculates the return temperature of the building system from the building hot water flow rate and known (input based on historical data) heat demand of the building. The building supply temperature and flow rate are both inputs (the latter a derived input, as discussed later in this paper) based on building type and facilities experience; the return temperature is the only unknown. However, return temperature can also be predicted based on the design and operating parameters of the building system, or even controlled to “demand” that return temperature. For example, in Iceland, a common operating design is to modulate the flow within the hydronic system to hold the return temperature steady, with a typical target of 40°C return. Similarly, the return temperature to the district system can also be determined from equation F-2, since this is the only unknown for that portion of the equation (the district supply temperature is a user-selected input for the entire system; the flow through the exchanger is a derived value calculated from a sum of the building systems).

MEnU thus allows for multiple input parameters and has embedded a number of specific assumptions related to how hot water is distributed within the district and building-level heating systems. This paper further describes the model, the impact of significant input parameters, and the impact of different operating assumptions on the usefulness (value expresses as LCOH) of a representative subsurface resource.

In addition to a tool for calculating realistic energy use for the Cornell campus, the MEnU model is also generic enough for adaptation to other district energy systems and can be used as a planning tool for the conversion of a district heating system to a system optimized for geothermal use. Cornell is in fact currently planning and implementing campus district heat changes based in part on the fundamental principles developed with this model, and plan to continue this progress.

Description of the MEnU Model

MEnU was constructed using a standard Excel spreadsheet. Unlike the GEOPHIRES Model, the calculations within the MEnU model uses relatively simple energy balances (conservation of energy), heat transfer principals, and typical equipment performance information to calculate results. 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.

To model actual performance, Cornell used a data set of hourly, building-by-building heat demands that represents the complete and total energy use of the entire district heat-connected campus (over 150 major residential, teaching, and research facilities within over 14 million square feet of building) and an annual heat demand of approximately 240,000 MW_{th}-hrs. The hour-by-hour loads, classified among three separate facility types (each type representing a set of facilities that require specific supply temperatures), are sequentially computed using an embedded calculation loop to provide hourly results which are then summed to provide a totals for annual performance.

The fundamental importance of district heat system (demand-side) design and operations is revealed by our early model runs. Table F-1 provides a brief summary of MEnU input values and the impact of each value on overall heat energy use.

Table F-1: Parameters used in MEnU

MEnU Parameter	**Basis of Value**	**Impact on Power Supplied (MW_{TH})**
Q_G = Geothermal Flowrate	Input from GEOPHIRES	Proportional to Geothermal power (P_G)
T_{G1} = Geothermal Supply Temperature	Input from GEOPHIRES	P_G is proportional to ($T_{G1} – T_{G2}$)
T_{G2} – Geothermal Return Temperature	Calculated by MEnU from equation F-1	P_G is proportional to ($T_{G1} – T_{G2}$)
Q_D = District Flow through primary heat exchanger	Can be modified in MEnU. Cornell runs assume variable flow proportional to load	Controls return temperatures (T_{D2} and T_{G2}) as described in this paper (or vice-versa)
T_{D1} = District Heat Supply Temperature Setpoint	User Input in MEnU	P_G is proportional to (T_{D1}-T_{D2}) per equation F-1; T_{D1} impacts T_{D2}; set based on district needs and set-up (details in this appendix)

T_{D2} – District Heat Return Temperature	Calculated by MEnU from equation 3; flow-weighted building returns	P_G is proportional to (T_{D1} – T_{D2}) per equation F-1
T_{B1} – Building Heat Loop Supply Temperature	Operator set point	Limited to (T_{D1} – 1°C) unless heat pump used, see discussion. Current MEnU setup allows three different building types (independent temp settings)
T_{B2} – Building Heat Loop Return Temperatures	Calculated by MEnU from equation 2	See Figure F-3 and equation F-2; impacts final geothermal return temperature as described in this appendix
District Loop and Building Loop pump rates	Assumed variable flow proportion to instantaneous building load	Flow rates at building and district level control critical temperature differentials that directly impact energy flows via equations F-1 and F-2 (see text)
Building Heat Loads and Temperature Demands	Hourly data set included in MEnU for three (3) building types, each having a separated user-designated minimum supply temperature input.	Building temperature needs impact geothermal usage; lower building temperatures are more advantageous. Division of buildings into categories can be modified, allowing impact of individual or multiple building renovations to lower temperature to be modeled.
Heat Pump Operation	Algorithm in MEnU automatically activates pumps as needed to meet modeler's input requirements (see text).	Activation of heat pumps impact total heat supplied and electrical power needed to operate the overall system. Outputs can be used to model "system coefficient of performance".

Heat Pumps in MEnU

As part of Cornell's DDU study, the application of 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., use of Air Source Heat Pumps, ASHPs, or Ground Source Heat Pumps, GSHPs). Specifically, warmer DDU resources allows more efficient (i.e., high coefficient of performance, meaning low energy usage per unit heat transferred) heating 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 (prior to reinjection) to the supply side, in a manner equivalent to "cascading use". By equation 1, 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 can "bump" temperatures when needed (often for short durations of peak demand) if the geothermal resource temperature is insufficient to meet the peak building heating temperature needs based on heating system design. Similarly, heat pumps at the building level can extract heat at a building loop if only some buildings are not designed for more effective heat transfer (i.e., they can lower return temperatures to the district loop).

The latter concern is especially important for design of many older American facilities. Most U.S. buildings are heated with fossil fuels which combust at high temperatures. With high-temperature combustion, there was no practical incentive to design for temperatures below about 80^{o}C since higher temperature design minimize the sizing of terminal heat transfer surfaces (radiators and heating coils), and many such systems also have a relatively high return temperature (i.e., a relatively low quantity of heat is extracted from the building loop to the terminal systems).

In the Cornell study, we used MEnU to help inform the appropriate placement of heat pumps in our system. Figure F-5 shows a schematic with the heat pump applied "across" the heat exchange with the geothermal loop. In this set-up, the temperature of the incoming geothermal water is boosted by the heat pump while the return flow temperature is decreased leading to the geothermal heat exchanger. Since the differential temperature between well supply and return is thus increased, the net impact, per equation F-1, is an increase in energy extracted (assuming the district system has sufficient demand to accept this heat).

Building-level heat pumps, conversely, can allow reduced temperatures for the distribution water for existing mixed-temperature systems, since building level heat pumps can "boost" temperature in some areas (reducing return temperature in the process). To minimize operating and capital costs, it is important to select and control heat pumps to minimize capacity and electrical requirements. Figure F-6 shows a building-level heat pump arrangement.

Since our model is set up to "preheat" the hydronic loop with the central plant making up whatever difference is required, the impact of heat pumps is that the central plant operates less, due both to the improvement to the extraction from the geothermal well and through conversion of the electric power added at the heat pump(s). Total energy is still conserved (minor thermal losses are included in the overall model).

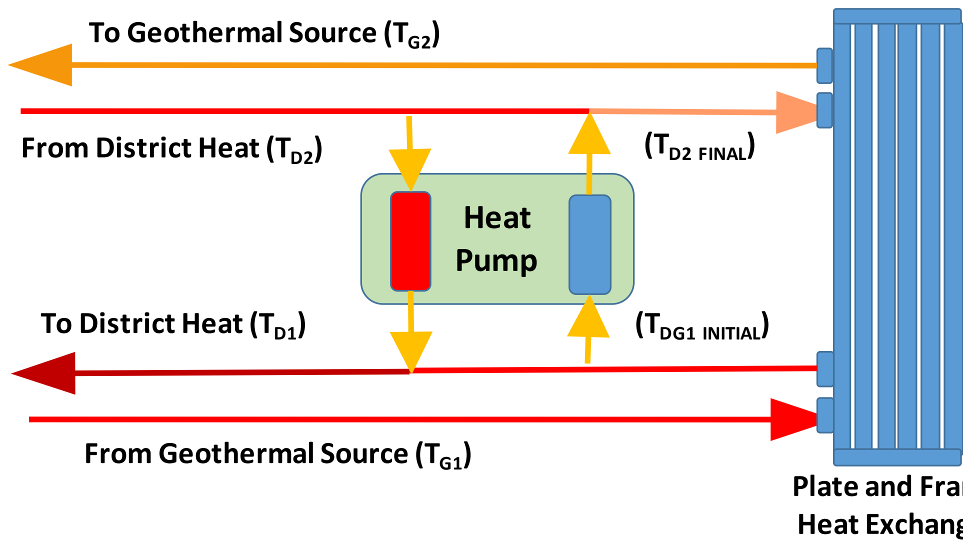


Figure F-5: Heat Pump Located Adjacent to the Geothermal Source Heat Exchanger

Heat pumps installed at the building level improve the value of the geothermal system in a similar way, by extracting heat from the return water stream (but in a more remote location) and thus improving the delta across the geothermal well system (assuming the flow is adjusted to take advantage of this improvement).

In our modeling work, water source heat pumps placed at the building level are primarily used to boost temperatures in select areas to meet "local" needs, which may often only be required for short periods. In addition to allowing more heat extraction at the building level, this might allow a lower district loop delivery temperature, which improves 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.

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 building being served (temperatures, load variations, and diversity of each). Significant goals in using heat pumps are to enhance the use of DDU resources while minimizing electrical requirements (i.e., managing temperatures to allow high coefficients of performance) and capital needs (i.e., total capacity).

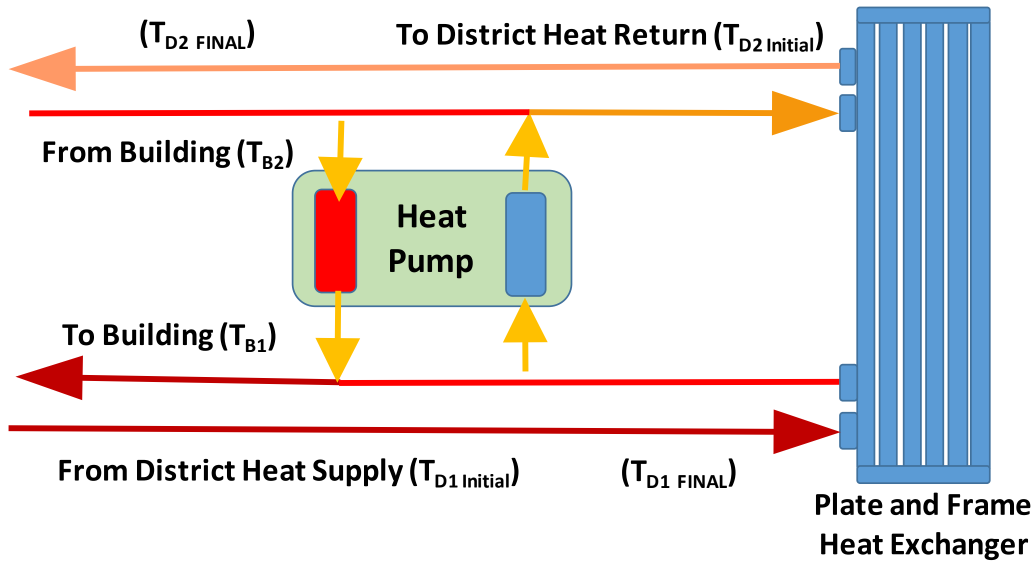


Figure F-6: Heat Pump at the Building Level

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 (a subroutine within the model) are as follows:

- The central heat pump "activates" if the flow and temperature from the geothermal source is insufficient to meet a user-selected "target" geothermal heat production rate.
- The building-level heat pump(s) are individually activated if the temperature of the district loop is insufficient to meet user-selected "building temperature" supply and/or return temperatures.

The MEnU program allows for three building types, two of which are equipped with heat pump options. Each building type can be programmed for unique temperature setpoints (supply and return). As we witnessed with several European systems, our MEnU program assumes control based on maintaining lower return temperatures (which maximizes the benefit of the well assuming a fixed supply temperature and flow capacity).

Building Heat System Operating Temperatures: Optimizing Resource Use

Appropriate building operating temperatures are critical parameters to effective use of lower-temperature resources. Thus, the quantification of temperatures is central to accurately estimating the LCOH for a given geothermal source and distributed heating network. Modeling surface energy flows can quantitatively demonstrate the value of various operational parameters for surface use. Modeling is also useful in demonstrating the impact of design and operational principals on the quantity of energy derived from a DDU resource, and thus the LCOH from a given subsurface investment.

Some key design principals of these principals for improving (lowering) LCOH are addressed in this Section. These principals are mostly derived from the Laws of Thermodynamics. The first Law, the Conservation of Energy, was used in Equations 1 and 2. The Second Law of Thermodynamics reminds us that (absent external work such as heat pumps) heat flows freely from hot to cold, but not the other way around.

<u>Design Principal 1: Reduce building heat loop return temperature to the lowest value possible</u>

Extracting maximum energy from hot water circulated through a building's heating loop is essential to effective use of a thermal resource. HVAC systems for building heating, domestic hot water, and similar services can effectively use water of moderate temperatures, but many are designed or operated in such a way that high temperatures are necessary. For example, most U.S. building commercial air heating systems raise return air temperature no higher than about 75^{o}F (24^{o}C) at the terminal units, yet use minimally-sized heating coils that are selected for use with 180^{o}F (82^{o}C) water. Other choices are possible; for example, buildings designed for hydraulic systems heated and cooled with heat pump systems are routinely designed for maximum 130^{o}F (55^{o}F) fluids, and lower temperature systems are very common in areas with district hot water. For example, district heating systems connected to the extensive Paris Basin geothermal resource in France typically utilize source temperatures below 80^{o}C and aim to extract heat down to 40^{o}C or lower to maximize investment.

<u>Design Principal 2: Use variable speed pumping of hydronic fluids and minimize pump speed</u>

It is also important to control water flow rates. Water with twice the flow is only reduced in temperature by half as much as water at a given base flow for a given heat load (assuming proper selection of terminal units to allow equivalent heat transfer). Both building and district system ΔT (equation F-2) improve with lower flows, all else being equal.

Lower flow rates result in lower district system return temperatures. For a given resource supply temperature, the geothermal loop low (reinjection) temperature dictates maximum geothermal power output via equation F-1 (without using electricity to drive heat pumps). Building return temperatures also control the overall district system return temperatures; for example, if the building return loop temperature is 170^{o}F, the district energy system return temperature transferred by plate-and-frame heat exchanger cannot be below this value (unless heat pumps are used to extract additional heat at the building level to modify this temperature). This basic understanding of flow and temperature are critical to effective DDU applications.

Figures F-6 and F-7 illustrate examples of two demand-side designs, both based on an assumption that the heat exchangers all have a 1^{o}C minimum approach temperature. While both designs seem reasonable, the results of difference demand-side design approaches is very significant. As shown in Table F-2, optimal surface design can result in significantly greater LCOH value from the exact same geothermal resource; conversely, poor design can destroy the effectiveness of DDU resources. Notably, the "improved" design parameters listed as "Fair DDU surface design" represent a very small difference in cost from the "poor" design. In fact, the improved designs may even have lower cost, since distribution piping size and pump capacities are reduced. Also notably, the "optimal" design represents only "standard" low temperature building design coupled with optimized district flow control, rather than some unproven or complex building control arrangement.

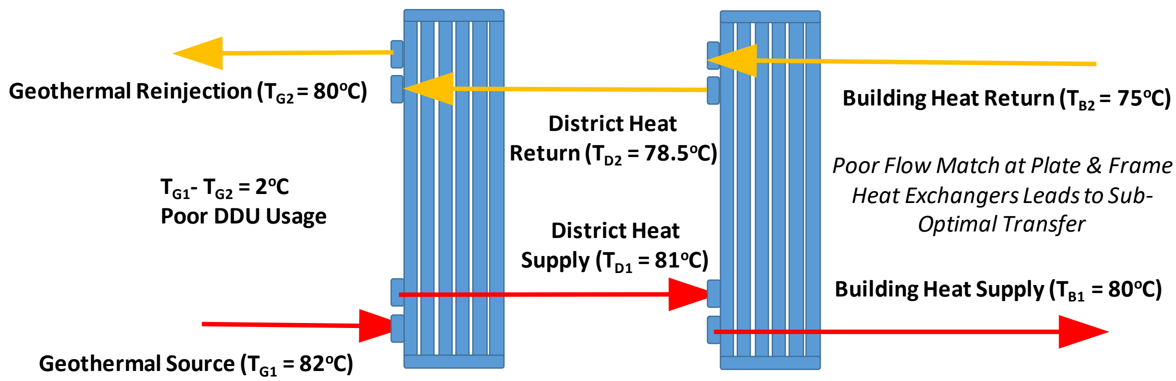


Figure F-7: Example of Poor DDU Surface Design

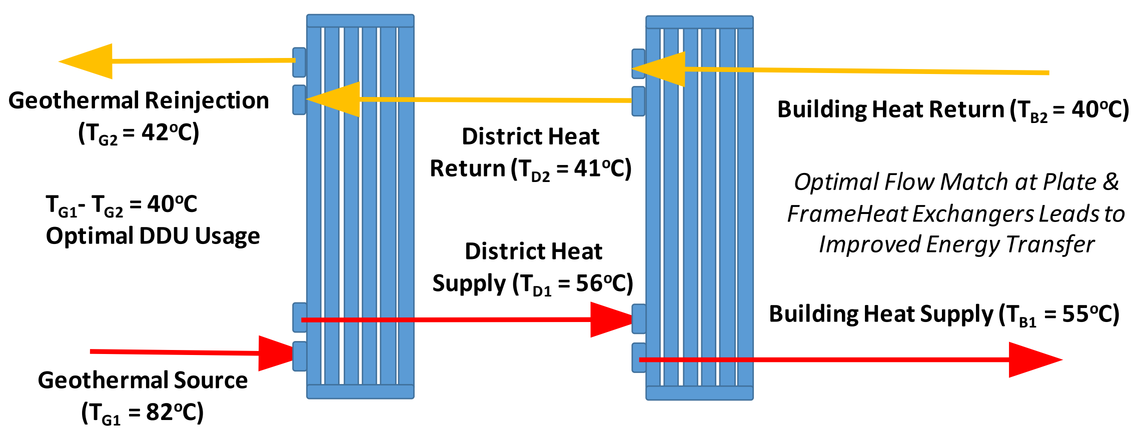


Figure F-8: Example of Optimized DDU Surface Design ("European Standard")

Table F-2: Example: Geothermal Heat Extracted from a Modest DDU Resource (Q_G = 50 kg/s, T_{GS} = 82°C) using Various Demand-Side Conditions

Example System Design	Extracted Power (Heat Rate)
Poor DDU surface design: District loop set to 81°C; Building heat loop set point 80°C and return 75°C; District loop flow double building flow (District loop return 78.5 °C); insufficient flow on district side of geothermal heat exchanger so geothermal return flow is at 80°C.	0.42 MW_{TH}
Average DDU surface design: District loop set to 81°C; building heat loop set point 80°C and return 60°C; district loop flow matches building flow (district loop return 61 °C); matched flow on district side of geothermal heat exchanger so geothermal return flow is at 62°C.	4.2 MW_{TH}
Optimal DDU surface design: District Loop set to 56°C; Building heat loop set point 55°C and return 40°C; district loop flow-matched to yield 41°C district return; district return flow modulated across geothermal heat exchanger so that geothermal return flow is 42°C.	8.4 MW_{TH}

As noted previously, heat pumps can extract more energy from the geologic formation in cases in which return temperatures are not otherwise optimized. Figure F-9 provides one example whereby heat pumps allows a system with “average building design” to match the thermal well extraction rate of the “optimal” design scenario; however, this result requires more input electrical energy. It might also be considered as an example of how a heat pump might improve DDU performance for a building with an “average” heat transfer design until the building is itself improved (as per Figure F-8) at which time the same DDU output (8.4 MW_{TH}) can be accessed without the use of supplemental heat pumps.

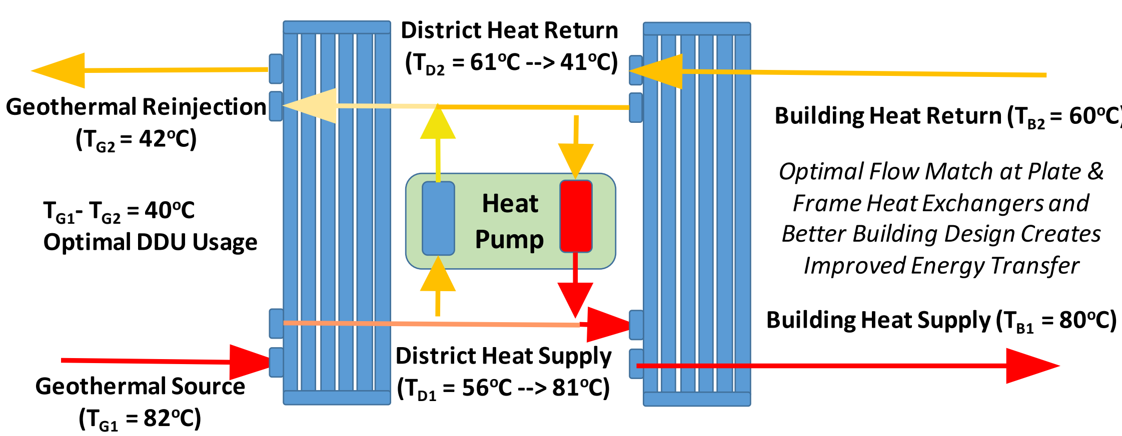


Figure F-9: Heat Pump Assisted DDU Design

Demand-side designs that focus on temperature needs are not only helpful but essential for efficient and cost-effective DDU application. Other areas with a longer history of geothermal use all recognize the critical importance of these design parameters. Table F-3 provides a summary of some of these successful geothermal project temperature standards, including the following:

- In Iceland, the vast geothermal heating systems are all designed for 80^{o}C supply and 40^{o}C return. The 40^{o}C return is typically controlled by variable flow at the building interface; if the return temperature is higher, the flowrate is slowed to provide less overall heat until the 40^{o}C goal is achieved.
- In the Paris Basin (France), there are more variations in supply and return temperatures due to the wider variety of Paris Basin resources and arrangements. However, engineers at ENGIE, one of the major energy companies, confirm that a maximum return temperature of 40^{o}C is a typical design basis, and even lower temperatures are beneficial to financial performance; at least one system uses a central heat pump system to improve overall delta T and thus increase geothermal capacity. For example, at EuroDisney, where ENGIE designed essential elements of both resource and demand management, design was for a return temperature of 30^{o}C.
- Copenhagen engineers distributing hot water below 80^{o}C are also seeking return temperatures of less than 40^{o}C (in some cases below 30^{o}C) as a means to improve system economics and performance.

Integrating DDU into District Heat System

The Cornell MEnU tool assumes that the first DDU well set was used within a district hot water system, with the DDU resource being used as a “preheat” of the system return, allowing it to provide maximum benefit since return temperatures are lower and maximize the temperature difference expressed in Equation 1. This arrangement is schematically shown later (Figures F-9 and F-10).

Cornell’s existing district heating system is a combination of steam and hot water distribution, with steam being the primary distribution to buildings, where steam is converted to hot water for internal building use (primarily heating, hot water, and cooled air reheat), as shown in Figure 8. Cornell is planning a full conversion of the steam system to hot water and has already converted heat distribution in some peripheral campus areas to hot water. Plans are to continue this conversion systematically and strategically, until the entire distribution system is based on hot water, in parallel with the Earth Source Heat (DDU) planning and build-out. Our basis of design for ESH assumes that the conversion is completed prior to implementing the modeled DDU project, at least in sufficient areas to accommodate all of the available heat of the first (assumed) doublet (Figure F-9).

Since Cornell uses substantial heat year round (summer usage is mostly for domestic hot water and cooling system reheat), modeling shows that that system can utilize a modest geothermal resource year-round at essentially steady flow once conversion is substantially complete (Figure 9). Better resources (higher flows, higher temperatures, or both) can also be accommodated; modeling suggested a capacity factor of over 90% within the general range studied in this DOE project for the mean case (higher for low flow; lower for high flow).

Cornell owns and operates other central resources, including the most efficient campus district cooling system in the country (Lake Source Cooling) and a combined heat and power (CHP) plant, which essentially provides all Cornell's power and coproduced steam for district heating. Both Lake Source Cooling and the CHP will remain at least until the ESH is fully proven, whereby the CHP will serve as a supplement and backup for the ESH system; no other new production facilities are planned or needed.

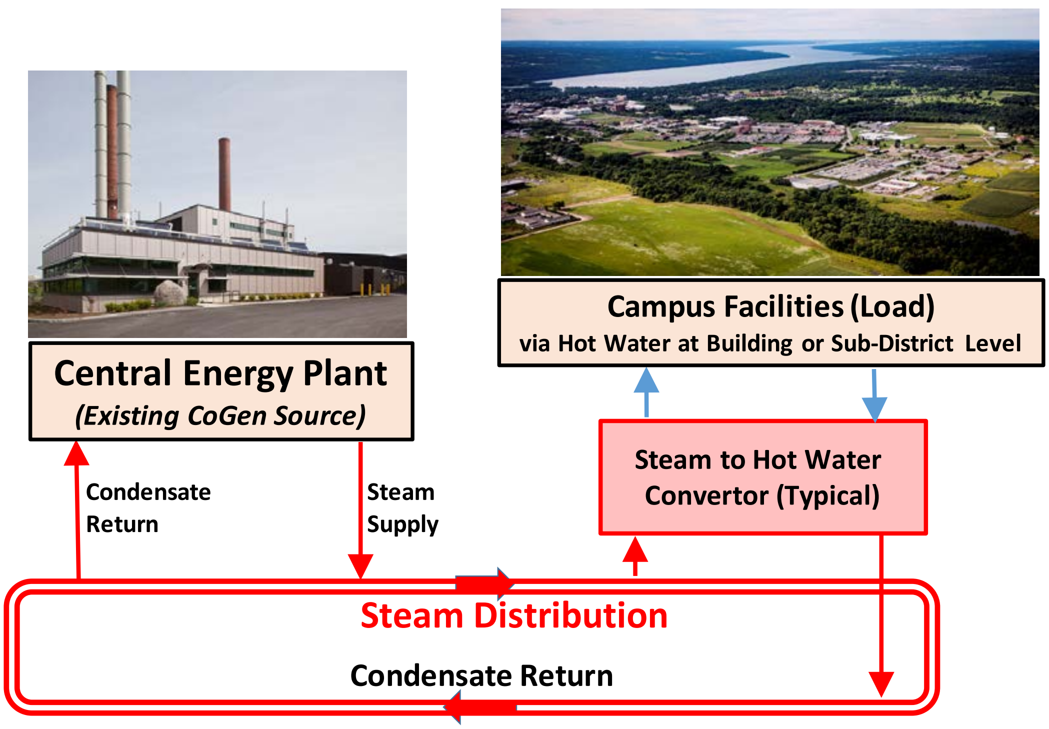


Figure F-10: Cornell (pre-2018) Campus District Heat System

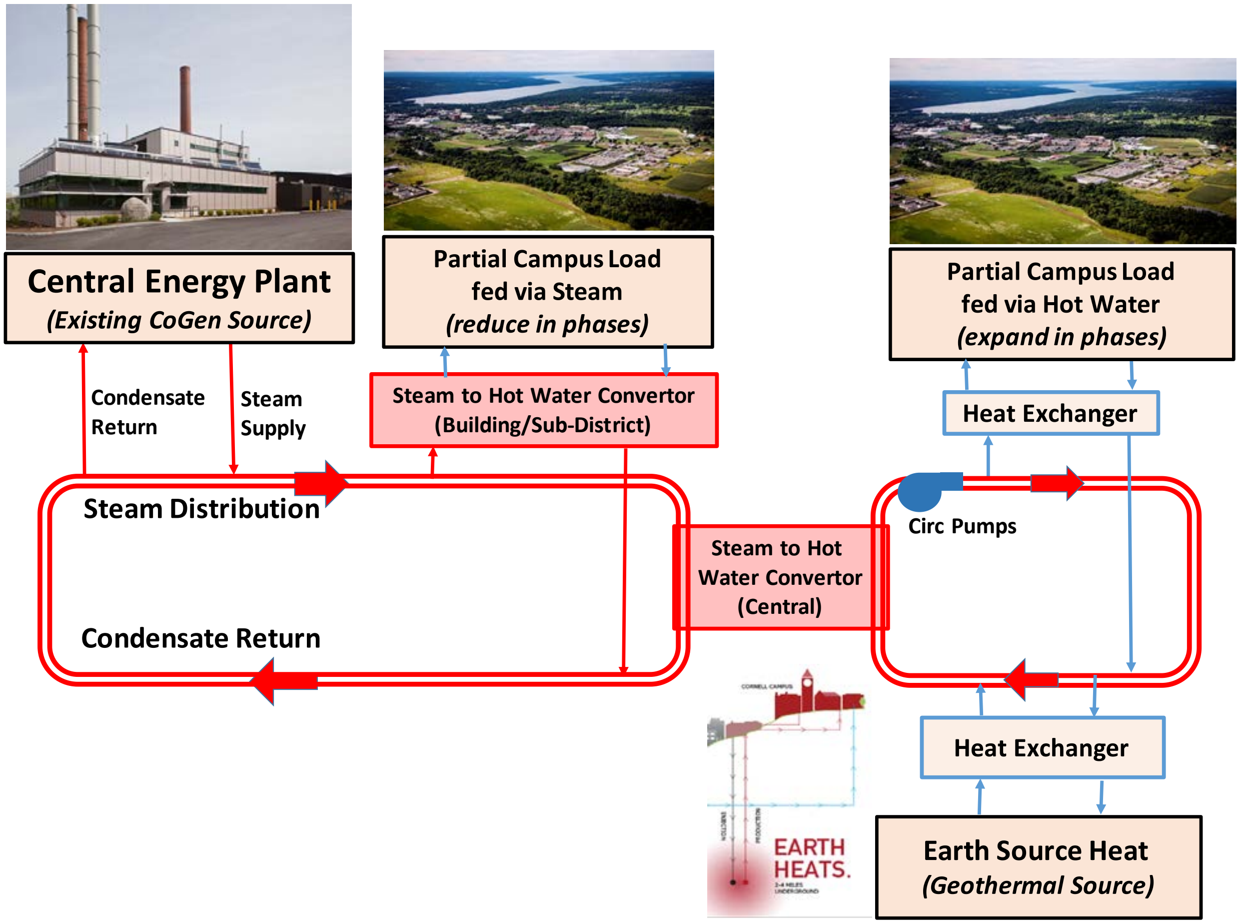


Figure F-11: Transition of Cornell Campus District Heat System to Hot Water (underway)

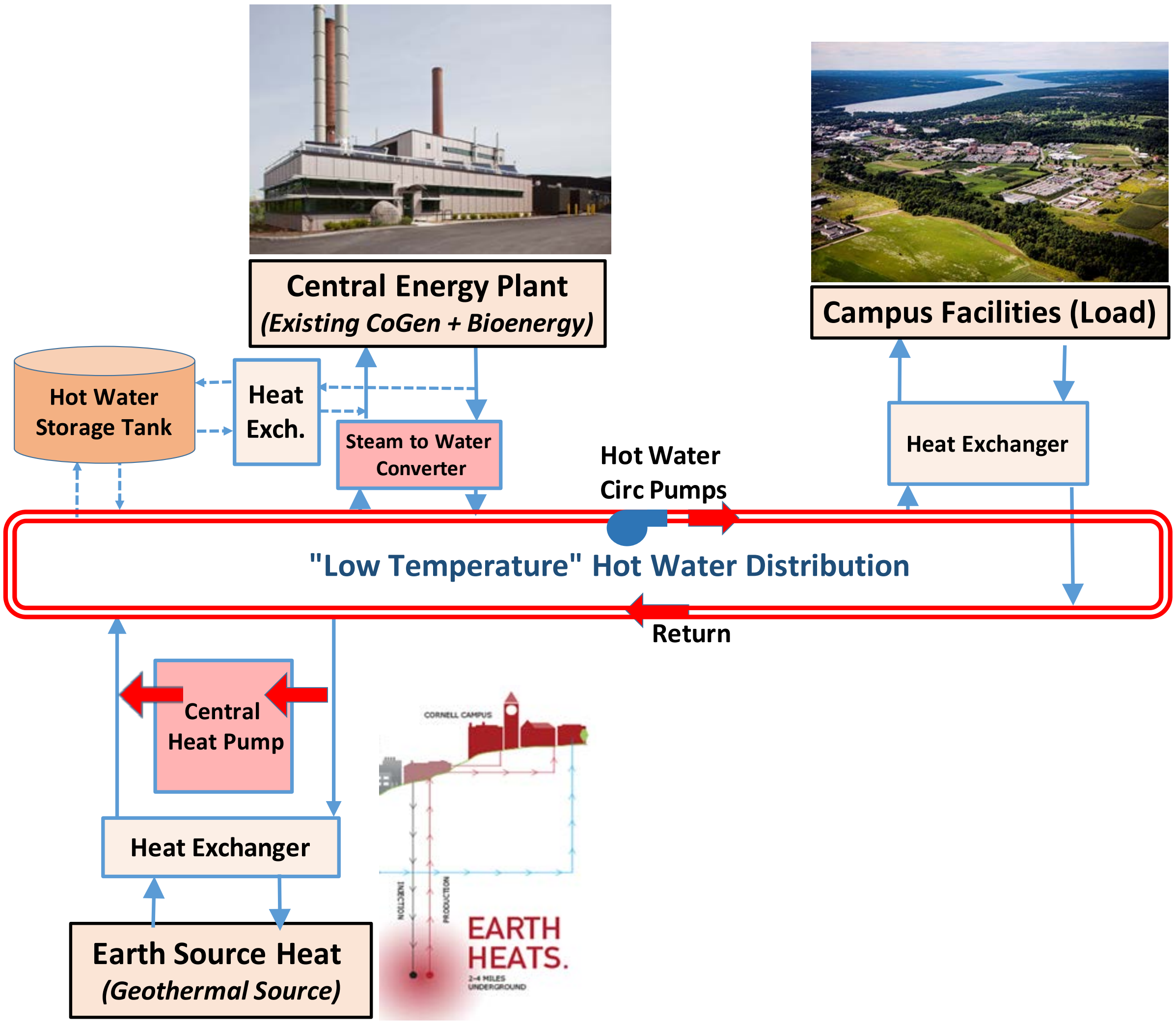


Figure F-12: Future Cornell Campus District Heat System

<u>Hot Water Storage</u>

The model was also used to explore the benefits of hot water storage. Storage is not a feature essential to initial geothermal operations (single doublet), since there is full backup capacity already available and storage is not needed to use the full anticipated capacity of a single well set throughout the year. However, projecting outward, storage provides substantial operational advantage in reducing peak loads, which will be important to minimize the number and extent of future well pairs (or other renewable resources) needed to support a future hot water district that strives to achieve zero emissions for campus heat. Initial runs of the storage subroutine provide ample demonstration of this impact. Figures F-13 through F-15 provide a quick visual summary of how hot water storage can alter the heat demand over time.

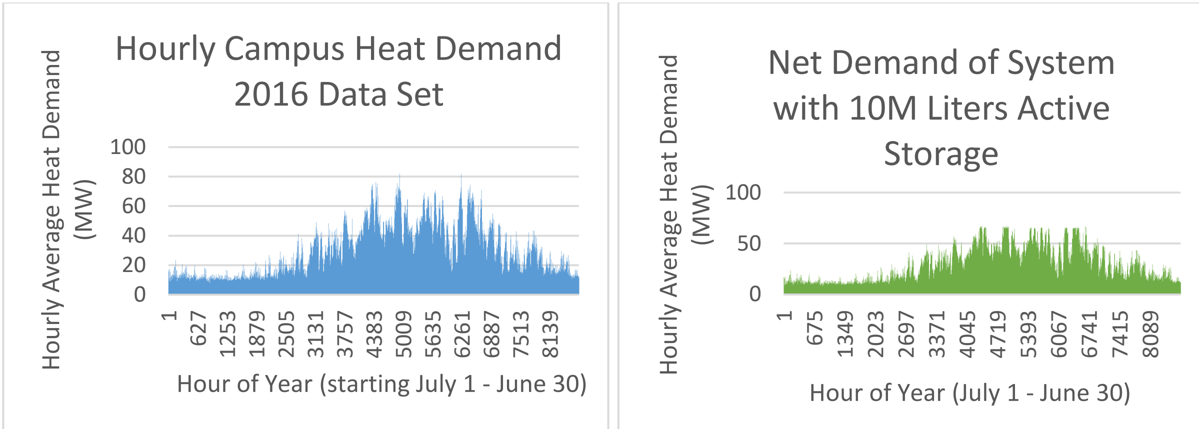


Figure F-13: These side-by-side graphs show the modeled reduction in peak heating demand using 10M liter storage tank activated during peak heating times. While not impactful for the LCOH calculations for one well-set (the scope of this project), storage could substantially reduce the capital investment needed to manage peaks with other equipment.

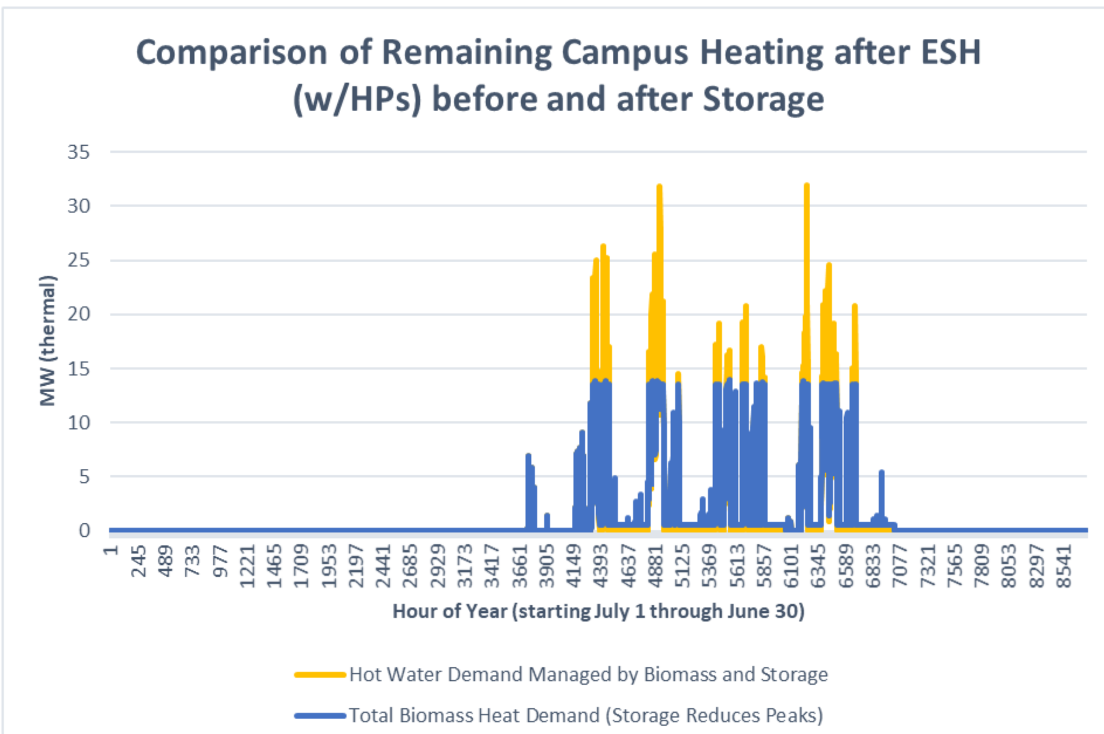


Figure F-14: This model run shows the "remaining" heat load to be accomodated by other resources if geothermal heating capacity (with or without heat pumps) is capped at 50 MW. The yellow (higher) line represents the original load remaining while the blue line represents the remaining load after storage is included. Cornell envisions using woody biomass or other biofuels sources from Cornell lands for at least some peak load once geothermal energy is integrated, hence the legend's reference to biomass.

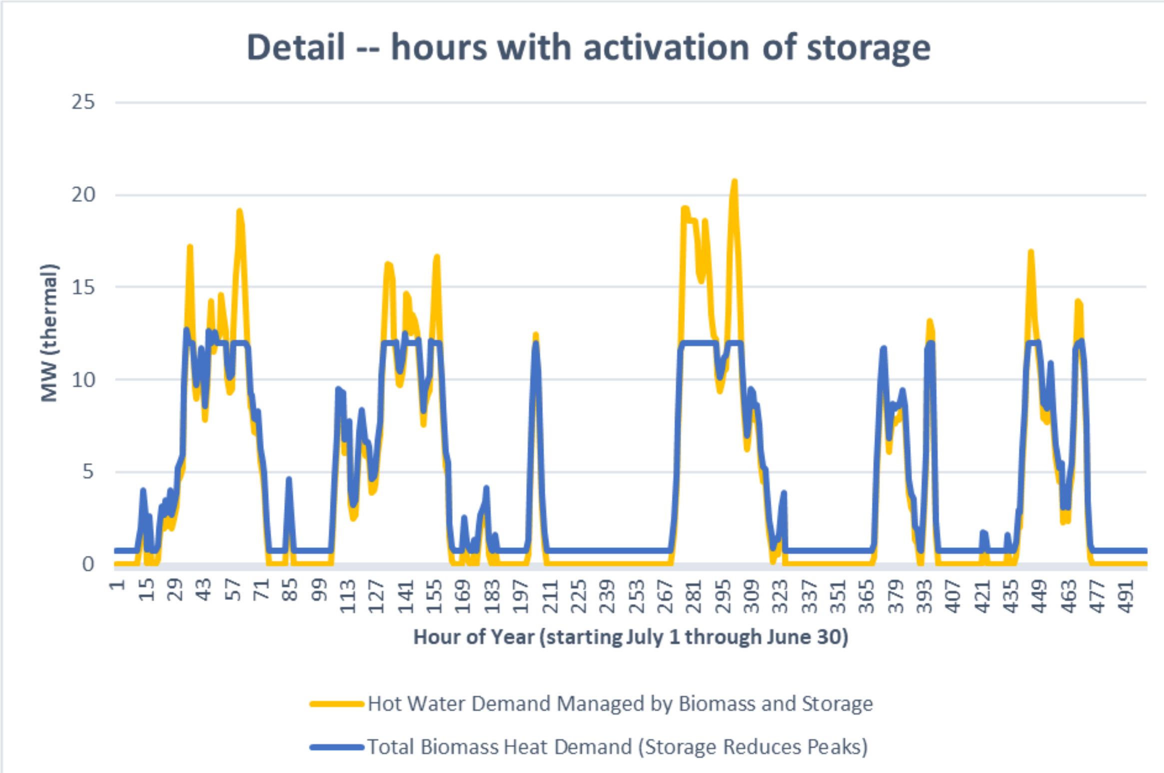


Figure F-15: This model run shows a detail of about 500 hours near the peak of winter use. The yellow line shows the "original" heat load that remains after geothermal integration while the blue line shows the impact of including storage. In this example, one sees not only the reduction in peak load that results from storage, but also the "smoothing" of load that would facilitate operators in matching load on a real-time basis. The use of building-side heat pumps can also be used in this manner to smooth and reduce peaks, but would require higher uses of electricity than storage alone.

To summarize, because of the way Cornell is integrating the DDU source (as the first load element), typical storage arrangements have no significant impact on LCOH within the scope of our "single well set" DDU analysis. Storage will likely provide substantial benefits in the future as the DDU coverage is expanded using multiple well sets and can be used to optimize use during periodic low-use periods as well as during high-use periods by "smoothing" the load. Relatively large storage volumes (~20 million liters) could effectively reduce the size and capital cost of both geothermal (well sets) and non-geothermal assets in such a system.

Thermal System Losses

Our model also includes the ability to incorporate realistic system losses, either by assuming a percentage loss and increasing loads proportionally, or assuming a drop in temperature from the well to the building system. As Cornell plans to install at least the first well set right on campus near a connection to the campus hot water loop and to use a high quality pre-insulated piping system, these losses are expected to be small. For the purpose of this study, we operated our model assuming that the hot water distribution system is well designed (i.e, high quality pre-insulated piping) with total thermal losses of **4%**. In the model, this is effected by a calculation which increases the required energy inputs by a factor sufficient to provide the full calculated load at the set point design temperature).

Integration with GEOPHIRES

Integration of topside modeling results with the GEOPHIRES subsurface modeling results is also underway. Specifically, as part of Subtask 2.5 Cornell has defined how GEOPHIRES outputs will be used to analyze surface design options and develop LCOH and capacity (DDU MW_{th} output) for several test cases.

GEOPHIRES includes reinjection temperature as an input. This input variable is dependent on a host of MEnU input parameters (i.e., flow rates, building temperature parameters, and heat pump operating strategies). For the purpose of this DOE study, the Cornell team is setting this input based on our stated project goal (i.e., one well set to provide a minimum of 20% of annual campus load); a number of combinations of campus design standards and heat pump usage can accomplish that result (return temperature) for each case studied. Additional (higher) geothermal well loading were also explored during initial modeling, based on intermediary results (i.e., whether these input values of reinjection temperature result in reasonable resource life, electrical usage, excessive flow impedance, etc.), however, a constant re-injection temperature of 20^{o}C was used in all the final LCOH values presented in the report Results section and in the Executive Summary.

END OF APPENDIX F

Appendix G: LCOH Assumptions and Clarifications

Overview

Cornell's DDU project ***Earth Source Heat*** includes calculation of the Levelized Cost of Heat (LCOH) values for two geothermal target depths included in the project scope, based on use of this heat within the Cornell campus district heating system.

As noted by the Geothermal Technology Office Geothermal Deep Direct Use DOE program, DDU project teams are proposing to use geothermal sources for a wide variety of uses, from direct heating to inlet cooling to storage and exchange systems, making comparison of derived LCOH values difficult. Additionally, the wide range of regional/geothermal settings, unique project system costs, system design/components, and model inputs chosen also create different baselines for comparison. Finally, a number of critical inputs embedded in LCOH calculations can significantly change the resultant LCOH values derived.

To accommodate the need to compare dissimilar projects to the extent practicable, this Assumptions and Clarifications document details the equations, assumptions, and other inputs that lead to our LCOH results. It also allows for consistent data uploads to the Geothermal Data Repository uploads such that these data uploads are interpretable by the scientific community.

1. LCOH Equation (Standard Levelized Cost Model)

Cornell's project uses the standard LCOH model described below (as suggested by the US DOE)[1], with the minor exceptions noted:

$$LCOE\ or\ LCOH = \frac{C_{cap} + \sum_{t=1}^{LT} \frac{C_{O\&M,t} - R_t}{(1+d)^t}}{\sum_{t=1}^{LT} \frac{E_t}{(1+d)^t}} \quad [¢\ kWh^{-1}\ or\ \$\ MMBtu^{-1}]$$

The variables use in the above equation include the following:

C_{Cap}	Capital Cost ($)
$C_{O\&M}$	O&M Cost ($)
d	Discount rate (%)
E_t	Energy Production (MMBtu)
LT	Plant Lifetime (years)
R_t	Secondary Revenue Stream ($)
t	Time (years)

Cornell's project does **not** include a Secondary Revenue Stream (R_T); the value of R_T is therefore zero in for all of Cornell's calculations. Per our project scope, Cornell provides as separate

[1] **Ref:** Beckers, K and McCabe, K, *GEOPHIRES v2.0: updated geothermal techno-economic simulation tool*, Geothermal Energy, p. 17, February 2019, https://geothermal-energy-journal.springeropen.com/articles/10.1186/s40517-019-0119-6

information other values representing environmental and regional economic benefits that DDU development would provide, but these values are not part of our basic LCOH calculation, which is written without a subscript as the "single-bottom-line" value (direct economic value to the developer/owner of the project).

2. Basic System Description for the Cornell Earth Source Heat Project

A block diagram (Figure F-1 of Appendix F) illustrates the general arrangement of the proposed DDU system relative to the Cornell District Energy System that it will serve. The system (and the modeling thereof) was described in detail in our Year 1 Summary Report and this description was updated for this report. Figure 2 is the same diagram formatted to highlight only those components within this integrated system that are included in the capital costs or expenses (CAPEX) and operating costs or expenses (OPEX) calculation for LCOH; other components are either already in place or considered to be outside the scope of the DDU effort.

3. Variables Required for LCOH Reporting in GDR

Capital Costs:

The LCOH calculations include all of the capital costs necessary to build and operate a complete geothermal system for supplying the Cornell District Heat System and the tie-in from the generation system to the district energy system, inclusive of the heat pumps included centrally (heat pumps were also modeled at the building level during some runs, but the LCOH calculations were based on the use of central heat pumps only). More specifically, the total capital costs include all of the system components indicated below:

- Wells, pumps, surface plumbing, and surface heat transfer equipment:
    - Well drilling and completion costs. The values used were the estimates provided by Geophires; the estimates vary between the two depths of interest and our modeling also incorporated a range of costs; the values used in the calculations are contained in Summary Table 1. For the "statistical mean 50 kg/s" cases highlighted in the report, the well drilling and completion costs range from almost **$8 million** (shallower Trenton Black River target) **to almost $16M** (deeper crystalline basement target) for the well pair.
    - Well stimulation Costs. A lump sum cost for well stimulation is included. The actual stimulation program will be finalized only after the first well is constructed, so we have provided any estimate of **$1.25M**, slightly higher than the range of values ($400k to $1M) that can be chosen using NREL's JEDI software for their techno-economic assessment.
    - Submersible pipe and discharge line (well pumping infrastructure). The Cornell LCOH values assumed a single lump sum cost for all pumping and piping equipment and the facility that incorporates the bulk of that system (see next item).
    - A surface facility for pump power and control, heat exchangers, and chemical injection (as needed to control heat exchanger surface deposition) The Cornell LCOH values assumed the lump sum of **$1.8 to $2.6M** ($2.2M for the median case),

inclusive of the subsurface pumps and piping within the recovery well casing. The lower and higher values were used for the lower and higher flow rate cases respectively, since flow rates impact mechanical and electrical system sizes.

- Central Heat Pumps. Our final LCOH estimates are all based on the use of "central" high-temperature heat pumps. The total installed cost for these systems is calculated based on a unit price **of $300,000 per MW** unit capacity. This estimate is based on installed pricing that firms using similar systems in Europe (ENGIE) provided to the Cornell team, and on quotations provided to other US DOE DDU teams (University of Illinois; University of West Virginia), which ranged from $172,000 per MW (equipment quote for two projects) to $258,000 per MW (highest total installed cost reported). Our costs were estimated slightly higher to include more heat exchange surface to ensure highest efficiency.
- Connection of the pipeline to our existing district heating loop. Based on the anticipated location of our well pad and the location of Cornell's existing district heating system, we added a cost of **$1M**. This figure covers ~2000 feet of pipeline to and from the district system (@ $300/LF total project cost) and the cost of heat exchangers at the interface (to be located in existing space in an unused former chiller building) for heat transfer ($400K estimate).

- Exploration cost

  Cornell's LCOH did not include separate Exploration Costs. The project's intent was to demonstrate the apples-to-apples cost comparison with other energy systems, and as such did not include exploration costs primarily related to research and development and not broad implementation. In our specific case, we plan to use our "exploration" well ("Test Well") as our future supply or reinjection well; other scientific work will be funded by appropriate research and donor funds, and are not considered part of "development" costs.
- Engineering design costs

  All capital costs assume reasonable soft costs (engineering, planning, contractor O&M, project management, etc.) Cornell substantially self-manages even large campus projects and plans to so the same with this project. We have self-managed other energy projects (Lake Source Cooling, Combined Heat and Power, etc.) of similar or greater cost and complexity.
- Control and instrumentation costs

  Instrumentation and controls are not explicitly itemized but assumed to be part of the building costs. Cornell maintains comprehensive campus-wide control systems for all of our energy uses and would incorporate the new pumping and exchange building instrumentation into this existing campus system.[2]

[2] Cornell has a similar direct energy system, Lake Source Cooling (LSC), that serves all of campus. Like LSC, which is an unstaffed facility, Cornell expects to operate a future direct heating system from our existing Central Energy Plant control room, relying on instrumentation and routine checks and inspections to plan and implement operations and maintenance.

Operations and Maintenance (O&M) Costs:

- Maintenance/Labor

  Maintenance costs were calculated as a fraction of the equipment cost for each case. The total is between about **$138K and $265K per year** across the 18 example cases studied. The estimated costs vary depending on the system because a portion of the costs are calculated as an annual fraction of equipment replacement costs; the inclusion of heat pumps is a significant portion of the overall capital cost and thus a significant portion of the (proportional) maintenance costs.
- Electricity cost for heat pumps, pumping, and re-injection, $/kWh
  - The cost for electricity to operate the system is **$.033 per KWh** ($33/MWh). The cost that applies in each case depends on the pumping rate and modeled flow impedance. The total cost was calculated for each working case with the totals varying from about **$620,000** to **$1,214,000** per year depending largely on the extent to which heat pumps were employed to improve the geothermal heat extraction. A substantial portion of the LCOH electrical cost is attributable to the electricity needed to operate heat pumps.
  - The other significant LCOH electrical cost is for operating the submersible pump that lifts hot briny water from the production well for circulation through the primary heat exchanger. These costs range from about **$34,000 to $106,000** per year, dependent on achieved flow rates.
  - Cornell currently produces all campus power using a combination of gas turbine generators, steam turbines, hydropower turbines, and on-campus renewables (solar within our “microgrid”).
  - The electrical cost for circulating flow *within* the campus hot water loop is not included; this is an existing fixed cost that is independent of heating source (Central Plant, Earth Source, or other sources) and not part of the LCOH valuation.
  - The campus also has access to low cost grid power via a central utility substation that ties into a 115kV NYSEG utility line and distributes it to campus at 13.2 kV. The siting of the Earth Source Heat pump facility will allow connection to our own 13.2 kV distribution grid (“micro-grid”).
- Annual water usage and cost
  - Most systems of this sort do not actually use make-up water, since losses (if measurable) result instead in a very slowly dropping water level in the production well that can be accommodated setting the submersible pump at an appropriate depth. Cornell has its own water filtration plant with spare capacity of over 1M gallons <u>per day</u>. The marginal cost for production is less than **$1 per hundred cubic feet**; the cost to Cornell Utilities (who would run both systems).
- Brine flow rate

  Cornell’s project modeled three different brine flow rates: 30, 50, and 70 kg/s. LCOH values are reported for each case. **50 kg/s** is used in reporting the “median” case for each target geology.
- System production and rejection temperature
  - The system production temperatures are defined by the output of the GEOPHIRES modeling for each case. In all cases, those temperatures are not steady by change

over time, and these changes impact the recovered heat value year-to-year. Our calculations include the effect of this annual variance in each case by calculating the recoverable energy value in each year and using the LCOH discount rate formula (via a spreadsheet) to appropriately value each year's output. For different cases, **production temperatures vary from just under 70ºC to almost 100ºC**.

- The **system re-injection temperature** was generally set in the GEOPHIRES model at **20ºC** unless otherwise noted.[3,4]

Financial and Misc. Variable Reporting:

- Discount rate

  The Discount Rate used was **5% Nominal**; this is the rate documented for use on Cornell capital projects[5] . To account for inflation, a **Real Discount Rate of 2.5%** was used in LCOH calculations.
- IRR

  IRR is not an LCOH variable and was not used in our analysis. Cornell is a not-for-profit educational institution so we do not have a profit goal. However, our discount rate (and LCOH variable) generally implies an internal rate of return.
- Inflation

  For the purpose of our project, we assumed a uniform inflation rate of **2.5% for all capital and operating costs and expenses**; thus our 5% Nominal Discount Rate is equal to a 2.5% Real Discount Rate for use in the calculations.
- System Lifetime

  A **30-year** timeframe was used. Components are designed for at least this period and portions of the capital investment (building, piping, etc.) will hold value beyond this period; however, that residual value is not incorporated into the analysis. Thus the LCOH values we use are slightly higher than would be calculated if we considered residual value of investments.
- Income tax rate

  Income tax rate is not an LCOH variable and **was not used** in our analysis; Cornell is a not-for-profit educational institution so would not be subject to income taxes (or incentivized to reduce taxes)
- Bond interest rate

  Bond interest rate is not an LCOH variable and **was not used** in our analysis. However, bond rate is related to the Discount Rate used at Cornell. Cornell holds a high bond rating and can bond thought a State agency (DASNY) at rates

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[3] This represents the temperature of reinjection using the heat pump controlled reinjection temperature in our LCOH analysis, but in the future could also represent the "ideal" cascading system. Our MeNU model calculates the actual hour-by-hour reinjection temperature for various model cases to provide the overall energy recovery calculation. Thus, the Geophires model overestimates the temperature degradation of the reservoir (since the return temperature may be higher when, for example, insufficient surface load exists to accept the full heat pump duty). This effect is likely not substantial.

[4] Cornell ran test cases with differing re-injection temperatures; the effect of differing re-injection temperature on overall well performance is discussed in Appendix F; all final LCOH results were based on reinjection at 20ºC.

[5] Reference: https://www.dfa.cornell.edu/treasurer/debt/internal-debt/borrowingrate

approximating the Discount Rate we use (or slightly below). Cornell currently holds a Standard and Poor's AA Debt Rating (the same rating the U.S. holds as a nation).

- Equity interest rate

  Equity interest rate is not an LCOH variable and **was not used** in our analysis.
- Number of production and injection wells

  Cornell's study assumed **a single duplex well set** (one production well and one injection well) for each case studied.
- Well diameter, meters

  Cornell's study uses the standard Geophires model default assumptions regarding well diameter. For the cases studied, **the Geophires program assumed an 8.5" internal well diameter (0.216m) at the bottom of well** for both injection and production wells.
- Well depth, meters

  Cornell's study included several well depths, ranging from about 2.25 km (Trenton Black River Formation) to 3.0-3.5 km (Basement formation).
- Annual heat production

  Cornell's study used a model incorporating real-time hourly data to calculate hourly heating needs and geothermal system supply hour-by-hour; the total of this supplied energy is the annual heat production. As a result, annual **productive heat transfer differs for each and every test case and each case is modeled to include year-to-year differences for the 30 year LCOH present value period**. These results are provided in tabulator format in the Results section of the report.
- System water source:
  - The source of make-up water would be Cornell's Water Filtration Plant (WFP). The WFP has excess capacity during all seasons and the marginal cost for additional water is very low.
  - Cornell's study assumes that reservoir formation water is extracted using a custom submersible pump system, run through a heat exchanger, and discharged into the reinjection bore hole, similar to direct-use systems in much of Europe[6].

4. Technical Report Content Required for all GDR LCOH Uploads: Geothermal System Description, Assumptions, and Discussion of LCOH Results

- Block flow diagram clearly defining system/cost boundaries: Figures 1 and 2 (previously referenced) are attached to this Assumptions and Clarifications report.
- Discussion of system, components, assumptions and unknowns: This report provides significant additional information about the overall system, including additional cost and benefit details.

[6] Due our relatively low elevation above sea level, any void spaces in the subsurface will likely be water-filled, as observed in other deep wells in our region. Our use of submersible pumps and gravity reinjection should avoid over-pressurization and related water loss to surrounding formations; the expectation therefore is that make-up would be very low or non-existent.

- Discussion of LCOH results and assumptions: This report, including the appendices, provides all assumptions uses to derive LCOH results. Tables 1 and 2 attached to this document provide some basic information.
- Model/model version used to calculate LCOH: The appendices of this report document the modeling and assumptions used in the calculation of LCOH. Due to the limitations of existing models (which did not incorporate all custom equipment, such as heat pumps), we used a custom Excel spreadsheet to calculation LCOH as described herein.
- Model assumptions: All assumptions regarding our models are included in this Report (including this Assumptions and Clarifications Document).
- Model defaults used or description of defaults changed: All model modifications and extensions used are described in this report.
- LCOH Sensitivity Analysis: Cornell's analysis included extensive probability analysis to capture the range of costs and performance that might be expected from systems operating in a real-world bidding and operational environment. Extensive discussion of these variables and probable ranges are contained in this report.

5. Misc. Data for GDR Uploads

As part of this Final Technical Report, we provided uploads of appropriate files including Geophires input data files; however, the detailed narrative contained in this Report will likely be necessary for a third party to fully understand and correctly interpret some of the file information provided.

Table G-1-1: "Screen Shot" Summary of basic CAPEX and OPEX Values used for LCOH Calculations, TBR (sedimentary, mean temperature cases)

		4	**5**	6
Depth, statistical temp, flow (Kg/s)		TBR mid 30	TBR mid 50	TBR mid 70
Capital Costs	Drilling (note 1)	$ 7,410,000	$ 7,800,000	$ 8,200,000
	Stimulation (note 1)	$ 1,250,000	$ 1,250,000	$ 1,250,000
Surface HX and Pump Facility (note 2)		$ 1,800,000	$ 2,200,000	$ 2,600,000
	HP Equip (note 3)	$ 2,556,815	$ 4,094,144	$ 5,201,267
Interconnection to CU District System (note 4)		$ 1,000,000	$ 1,000,000	$ 1,000,000
	Total Capital	**$ 14,016,815**	**$ 16,344,144**	**$ 18,251,267**
Estimated Breakdown	Labor	*$ 7,308,408*	*$ 8,472,072*	*$ 9,425,634*
	Materials	*$ 4,976,408*	*$ 6,062,072*	*$ 6,935,634*
	Specialty	*$ 1,732,000*	*$ 1,810,000*	*$ 1,890,000*
Operating Cost	Labor	$ 50,000	$ 50,000	$ 50,000
	Pump Elect	$ 33,996	$ 66,103	$ 105,765
	HP Electricity	$ 594,000	$ 950,400	$ 1,207,800
	Maint	$ 140,168	$ 163,441	$ 182,513
Total Capital Cost		$ 14,016,815	$ 16,344,144	$ 18,251,267
Total O&M Cost		$ 818,164	$ 1,229,944	$ 1,546,077
Present Value of Capital Plus Operating		**$ 24,212,946**	**$ 31,671,970**	**$ 37,518,809**
estimated annual production MWh		74,659	119,549	151,877

Table G-1-2: "Screen Shot" Summary of basic CAPEX and OPEX Values used for LCOH Calculations (basement mean temperature cases)

		13	**14**	15
Depth, statistical temp, flow (Kg/s)		Base mid 30	Base mid 50	Base mid 70
Capital Costs	Drilling (note 1)	$ 15,660,000	$ 15,660,000	$ 15,660,000
	Stimulation (note 1)	$ 1,250,000	$ 1,250,000	$ 1,250,000
Surface HX and Pump Facility (note 2)		$ 1,800,000	$ 2,200,000	$ 2,600,000
	HP Equip (note 3)	$ 3,148,356	$ 4,776,952	$ 5,985,651
Interconnection to CU District System (note 4)		$ 1,000,000	$ 1,000,000	$ 1,000,000
	Total Capital	**$ 22,858,356**	**$ 24,886,952**	**$ 26,495,651**
Estimated Breakdown	Labor	*$ 11,729,178*	*$ 12,743,476*	*$ 13,547,825*
	Materials	*$ 7,747,178*	*$ 8,761,476*	*$ 9,565,825*
	Specialty	*$ 3,382,000*	*$ 3,382,000*	*$ 3,382,000*
Operating Cost	Labor	$ 50,000	$ 50,000	$ 50,000
	Pump Elect	$ 33,996	$ 66,103	$ 105,765
	HP Electricity	$ 638,550	$ 943,800	$ 1,171,500
	Maint	$ 228,584	$ 248,870	$ 264,957
Total Capital Cost		$ 22,858,356	$ 24,886,952	$ 26,495,651
Total O&M Cost		$ 951,129	$ 1,308,772	$ 1,592,221
Present Value of Capital Plus Operating		**$ 34,711,530**	**$ 41,197,150**	**$ 46,338,247**
estimated annual production MWh		91,932	139,487	174,781

Table G-2: Primary LCOH Calculations for Two ("Mean") Cases

LCOH from Net Present Value with annually varying output

Discount Rate:	5.0%	NOMINAL	Discount Rate:	2.5%	REAL
Inflation Rate:	2.5%	(applies to all O&M)	Number of Years:	30	

This sheet assumes CAPEX in FY 2019 and includes two cases: (1) TRB with annual outputs as predicted by Geophires w/TOUGH2; (2) Basement with decline per Geophires

Capex and Opex as NPV

50 kg/sec flow	TBR Mid Range	Basement Mid Range
Capex ($US 2019)	**$15,190,959**	**$24,053,973**
30 yr NPV starting 2019 ($US 2019)	**$40,510,845**	**$50,874,603**
Levelized Annual Cost	**$1,935,513**	**$2,430,668**
Spend year (FY)		
2020	$16,418,385	$25,363,429
2021	$1,227,427	$1,309,457
2022	$1,227,427	$1,309,457
2023	$1,227,427	$1,309,457
2024	$1,227,427	$1,309,457
2025	$1,227,427	$1,309,457
2026	$1,227,427	$1,309,457
2027	$1,227,427	$1,309,457
2028	$1,227,427	$1,309,457
2029	$1,227,427	$1,309,457
2030	$1,227,427	$1,309,457
2031	$1,227,427	$1,309,457
2032	$1,227,427	$1,309,457
2033	$1,227,427	$1,309,457
2034	$1,227,427	$1,309,457
2035	$1,227,427	$1,309,457
2036	$1,227,427	$1,309,457
2037	$1,227,427	$1,309,457
2038	$1,227,427	$1,309,457
2039	$1,227,427	$1,309,457
2040	$1,227,427	$1,309,457
2041	$1,227,427	$1,309,457
2042	$1,227,427	$1,309,457
2043	$1,227,427	$1,309,457
2044	$1,227,427	$1,309,457
2045	$1,227,427	$1,309,457
2046	$1,227,427	$1,309,457
2047	$1,227,427	$1,309,457
2048	$1,227,427	$1,309,457
2049	$1,227,427	$1,309,457

Resultant LCOH Based on Varying Annual Outputs

50 kg/sec flow	TBR Mid Range	Basement Mid Range
30 yr NPV in MBH	**2,366,091**	**2,894,566**
LCOH ($/MWh)	**$17**	**$18**
LCOH ($/MMBtu)	**$5.02**	**$5.15**
2020		
2021	119,549	139,487
2022	119,634	139,954
2023	119,652	140,239
2024	119,607	140,430
2025	119,501	140,589
2026	119,339	140,732
2027	119,123	140,866
2028	118,856	140,993
2029	118,540	141,117
2030	118,180	141,237
2031	117,777	141,354
2032	117,335	141,469
2033	116,856	141,583
2034	116,344	141,696
2035	115,801	141,807
2036	115,230	141,917
2037	114,634	142,026
2038	114,018	142,134
2039	113,383	142,242
2040	112,733	142,349
2041	112,071	142,455
2042	111,402	142,561
2043	110,728	142,667
2044	110,054	142,772
2045	109,384	142,876
2046	108,720	142,980
2047	108,068	143,084
2048	107,430	143,187
2049	106,813	143,290

Table G-2 provides two examples of the final LCOH values calculated for this study. These examples used central high-temperature heat pumps to extract heat from the return water prior to re-injection. We also modeled cases with "cascading" heat flow, whereby heat used in buildings would then cascade to facilities that did not require the same quality of heat – i.e., that could accept hot water at lower temperatures and use it effectively for heating. LCOH values derived from that assumption were substantially lower, because no heat pumps were needed to maximize utilization of the heat (and thus no electricity to operate those heat pumps). As seen in Table G-1-1 and G-1-2, electrical costs (primarily for the heat pumps) represent well over half of the annual operating cost for the system. However, we do not report those "fully cascading" findings here because we could not reasonably predict that campus would have substantial sources for this lower-quality heat in the near term, especially at times that were well-matched to the demand of higher-temperature buildings, and assuming such would likely predict lower-than-realistic LCOH values. Nonetheless, it is noted that our figures above will be improved as we continue to design for lower-temperature heating on campus.

END OF APPENDIX G

Appendix H: Environmental Value Details and Results ($LCOH_{ENV}$)

Global/Environmental Levelized Cost of Heat ($LCOH_{ENV}$)

The incorporation of external (regional and global/environmental) values represents another stated goal of this project, namely, the establishment of a more specific protocol for understanding the regional and global value of geothermal energy as a renewable, regional energy source. Since the use of DDU reduces the rate of release of CO_2, the primary greenhouse gas emission associated with fossil energy use, $LCOH_{ENV}$ represents a "negative" cost, or value-added component of the fiscal valuation of DDU.

Appendix E provides more information and context for the use of the Social Cost of Carbon for the $LCOH_{ENV}$ calculations.

For the specific case of a renewable energy resource that replaces a natural gas boiler for heat, the value of $LCOH_{ENV}$ can be determined based on the assumptions stipulated in the first year of this work if we ignore the electrical energy used to pump fluid and/or operate heat pumps in our model system. Specifically, as shown in the calculations included in the next section, the social cost of carbon is **~$3.12 per MMBtu of delivered heat**. Stated otherwise, each MMBtu of DDU energy provides a global economic benefit equal to ~$3.12, not including any emissions associated with the electricity used to power the system or operate heat pumps.

When electricity is considered, however, the value is reduced and the calculation is more complicated. Specifically, a more comprehensive evaluation would consider the GHG emissions associated with the generation of electricity used to deliver the final DDU heat quantities. This consideration changes the valuation for each system configuration, since the estimated electrical use varies in each case, and also changes based on the assumed supply of electricity, which various from location to location.

Cornell's CAP goals are for all electricity used on campus to be generated from renewable electricity. At this time, Cornell has not identified sufficient on-campus resources for that generation and expects to rely on a combination of internal and external generating resources (i.e., hydropower, wind power, and photovoltaic electricity generation both within the University "microgrid" and within the regional electrical grid that is interconnected to Cornell's systems).

For the purpose of this analysis, Cornell has assumed that the **marginal emissions factor** for every MWh of electricity needed to operate the DDU system is 1022 lbs/MWh, the figure published by eGrid (as the "non-baseload emissions rate") for the "New York Upstate (NYUp)" grid location. This marginal emissions factor is much higher than the average emissions factor in our region, since the regional grid is mostly contained within New York State, and NY has significant hydropower and nuclear facilities and some wind and solar to supplement the primarily gas-based generation. Generation of power from either coal or oil is relatively small and rapidly diminishing, and based on regional energy economics and announced plant construction plans, the recovery of these industries is not expected within the project lifetime. Similarly, nuclear plants in the state are nearing the end of their design lives and at least one large plant (Indian Point) is scheduled for closure in the near term, so that at least in near future (within ~20 years) the predominant marginal fuel for electrical production is expected to remain natural gas. Therefore, marginal emission rates are not likely to change dramatically in the near future.

Cornell's modeling work provides an estimate of the electricity required annually to pump fluids (briny water) associated with the DDU well system as well as the electricity used in the specialty heat pumps to boost output (by extracting additional heat energy prior to return of flow to the subsurface). Using the above marginal emissions factor (MEF), the net $LCOH_{ENV}$ is calculated.

Results of Calculations

$LCOH_{ENV}$

The global environmental value of the DDU system based only on the displacement of natural gas (the fuel Cornell would use for heat in the absence of DDU) is calculated as follows:

Using the Social Cost of Carbon (Appendix E) of $50/metric ton CO_{2e}, the published natural gas emissions factor of 53.06 kg CO_{2e} per MMBtu (US EPA, see Appendix E), and an assumed net conversion factor (natural gas to heat) of 85%, the computation of the social cost of carbon per MMBtu of delivered heat is as follows: $50* (53.06/1000)*(1/0/85) = **$3.12 per MMBtu of delivered heat**.

Incorporating the embodied carbon of the electrical usage into these calculations reduces the magnitude of this environmental benefit as illustrated by the calculations in Table H-1:

Table H-1: Range of $LCOH_{ENV}$ calculated for the Cornell project

	TBR runs	Basement runs
HP Electric (MWh	17,800 – 36,800	19,350 – 34,800
Pump Electr (MWh)	1,030 – 3,205	1,030 – 3,205
CO_{2E} of Elect (MT)	9,138 – 40,005	9,962 – 20,264
Delivered heat (MWh)	70,653 – 158,568	90,150 – 176,918
MT CO_{2E} from avoided NG	15,053 – 33,783	19,206 – 37,692
Net CO_{2E} Benefit (MT) (after including electric at marginal rates)	5,915 – 14,370	9,244 -17,428
$LCOH_{ENV}$ per MMBtu	$1.23 – 1.40	$1.50 – 1.61

There is a significant range of performance included in the various model runs, most importantly due to the variation in assumed achievable flowrates (ranging from 30 to 70 kg/s). However, the effect on $LCOH_{ENV}$ is less substantial over these runs, since these values are normalized by production. The $LCOH_{ENV}$ for deeper resources are generally higher simply because the coefficient of performance (COP) for the heat pump is improved with warmer resources, so that there is less electricity required for each unit of heat produced (and thus less embedded carbon based on the marginal emissions rate).

END OF APPENDIX H

Appendix I: Regional Economic Value Details and Results ($LCOH_{REG}$)

Community/Regional Economic Impact ($LCOH_C$)

The scope of work for the Cornell DDU project requires calculation of an additional Levelized Cost factor representing the local economic impact ("$LCOH_{REG}$"). As noted in the Scope of Work statements, one purpose of including $LCOH_{REG}$ (and $LCOH_{ENV}$) is to acknowledge that certain societal benefits of new technology development are not reflected by more traditional LCOH evaluations that consider only the costs and benefits to the end user.

The development of a "new" energy technology like DDU within the Ithaca campus can create an economic benefit for the region. This benefit is the result of both direct spending and indirect spending. For example, local workers providing construction or operating services spend a portion of their wages for goods and services in the community, benefitting additional workers and businesses. In turn, those secondary workers also spend a portion of their wages locally. These benefits extend beyond the simple economics of LCOH for the customer/user (Cornell University).

Regional development councils, state economic or energy organizations, or similar entities seeking economic development may contribute some portion of project or operating costs to encourage this type of regional development, representing an economic investment in people, materials, and equipment within the region. The value of this economic impact varies according to the nature of the expenses and the size of the region for which the impact is calculated.

The $LCOH_{REG}$ developed in this work reflects only the economic impact of the specific work scope included. The regional economic development that might result from a successful demonstration that leads to replication of the technology could be at least on order of magnitude higher. Such additional benefits are addressed in a qualitative manner only, since the level, timing, and scope of future development is difficult to quantify at this time and these "broader" value applies only to early-adoption (future projects may not provide this same multi-site development value with benefits extending outside their specific development scope). In other words, by including only benefits resulting directly from investment to this project, the values derived can be more readily applied to future projects.

This subsection describes the assumptions for and intent of presenting this factor, and suggests a way that $LCOH_{REG}$ might be useful in creating an appropriate funding model for DDU development. However, the $LCOH_{REG}$ values presented do not represent rigorous and precise economic evaluations. Rather, the intent of this valuation is simply to provide an acknowledgement of an "order of magnitude" projection of economic impact of DDU development in our region for consideration by those with regional economic interests.

As detailed, this analysis utilizes the following assumptions:

- The Economic Impact Area applicable to this calculation is "New York State"
- A Value Added Multiplier of 2.0 was applied for the project. This value represents a reasonable order-of-magnitude value and is not meant to be precise to within one decimal.
- The $LCOH_{REG}$ calculations assume 80% of labor costs paid for the construction and operation of the DDU project will be paid to workers living in New York State
- Project costs used in the $LCOH_{REG}$ calculations are identical to those estimated for the project LCOH using GEOPHIRES.

- The partitioning of costs (labor costs versus materials costs, etc.) are derived from example projects using the JEDI model developed by NREL. However, because JEDI does not reasonably model DDU projects, the economic results of JEDI directly could not be directly adopted.
- 30% of the total net costs for materials is assumed to be paid to vendors in New York State (New York State has regional manufacturing for some but not all primary materials)
- Only 10% of the specialty drilling rig and similar costs are assumed to be paid to firms in New York State.

Regional Boundaries, Economic Multipliers, and Leakage

As documented in a policy brief by Dr. David Kay of Cornell University (reference source), additional spending/investment within a local or regional economy is amplified over time by an appropriate “economic multiplier”, which reflects the total economic impact of that spending/investment. The size of that multiplier depends on assumptions about the amount of the project costs that enter the area of interest (locality or region) and the amount of those costs that remains in (or leaves) that area with each “spending cycle”. The latter concept is expressed using the term “leakage” which is defined as the proportion of the net direct money that leaves the “local” (area under consideration) with each spending cycle. For instance, if a specific area has a 50% leakage rate, then for each $1 earned in that region, $0.50 will remain after one cycle, $0.25 after two, and so on; **the net “multiplier” for that region is 2.0** based on that assumption. Some simple leakage rates and their impact on the multipliers are listed below:

Table 1: Leakage Rates and Multipliers

Leakage Rate (%)	90	80	70	60	50	40	30	20
Economic Multiplier	1.111	1.250	1.429	1.667	2.000	2.500	3.326	4.887

Economic Multipliers for small regions (a single town or a small county) are smaller than multipliers for larger regions (states or multi-state regions). Dr. Kay’s analysis of rates used by IMPLAN in New York State, for example, concludes that average multipliers for expenditures at our campus (Ithaca, NY within Tompkins County, NY) are approximately as follows:

Table 2: Multipliers for specific regions (Total Value Added Multipliers, average of all industries)

Regional Limits	Tompkins County	New York	United States
Economic Multiplier	1.78	2.31	4.74

Comparing Tables 1 and 2, one can deduce that for this example IMPLAN estimates that, for every $1 earned in Tompkins County, approximately 40-50% of that money remains in the County with each subsequent spending cycle (50-60% leakage rate); 50-60% remains in NY State (40-50% leakage); and 70-80% remains within the U.S. (leakage between 20% and 30%).

Sophisticated estimates of leakage and multiplier rates are sometimes warranted for specific development proposals based on detailed analysis of industry data (for example, a recent hospital economic impact analysis using RIMS II provided county multipliers to four decimals!). However, such analysis is beyond the scope of this DDU project for several reasons, including the following:

- Every project is unique such that precise economic evaluations are not possible in advance. Specifically, each project decision on sourcing of labor, equipment, or materials can shift "leakage" from one region to another[7] ; these decisions are often the result of competitive bidding based in part on time-of-year availability of crew and equipment and are not well predicted by these economic tools.
- DDU is a new technology for which proven cost data is not yet readily available. While the technology uses similar tools to the oil and gas industry, the application and locations of use are different enough (specifically for our site, New York State has banned high-volume hydraulic fracturing, so there is little volume gas and oil development in NYS currently) that detailed cost breakdown data is likely not reliable.
- Cornell's standard and expectations is to have local staff engineers and geologists closely involved in every aspect of the work; this close management process differs significantly from "typical development industry standards" and likely will result in spending splits that are not reflective of the broader market.
- Cornell anticipates using a competitive bidding process for all of the major work; this process routinely results in pricing differences on the order of 10-15% or more over a broad range of work. The price spread for specialty work is typically higher. This means that the absence or presence of a single bidder can change the cost of work (and the location of the prime contractor) significantly – often much more significantly than the assumptions used for rigorous economic estimates.
- A precise and rigorous estimate of cost breakdown that is specific to Cornell is of little use to the US DOE, sponsors of this effort, since it may not represent the value (higher or lower) of DDU in other northern U.S. regions. For example, RIMII lists different multipliers for at least 12 different regions within New York State alone, implying that the local economic impact of each region is unique.

While precise economic multipliers are beyond the scope of this work, incorporating a factor to acknowledge the economic importance of new technology development remains an important goal of this project.

Converting Economic Impacts to $LCOH_{REG}$

The US DOE seeks to normalize costs and benefits for DDU development by converting all valuations to "Levelized Costs of Heat". To express an Economic Impact (in total dollars) in LCOH units requires two basic steps, specifically:

- Step 1: Convert one-time (construction-related) and annual Economic Benefits to a single Present Worth value. This calculation uses the same economic assumptions (discount rate, period, mode of financing, etc.) as used for the GEOPHIRES LCOH evaluation.

[7] For example, on a recent high-visibility Cornell building project a $10M metal panel wall façade system was specified by the Architect. The specifications listed only a single-source German manufacturer. While bidding the project, Cornell project management instead accepted an alternate from a Pennsylvania firm who re-tooled to provide the product. This single project decision shifted over 10% of total project cost from Germany to Pennsylvania, thus reducing US "leakage" 10%.

- Step 2: Using the energy (MW-hr or BTU) output of the DDU system, determine the $LCOH_{REG}$ value that corresponds to the Present Value of the economic benefit. This calculation involves simple trial-and-error substation using an Excel spreadsheet, with the same assumptions and inputs used in the GEOPHIRES LCOH evaluation.

Interpreting $LCOH_{REG}$

$LCOH_{REG}$ is intended to represent the economic value of the project to the region (in this case, New York State). The establishment and documentation of $LCOH_{REG}$ communicates the fact that there are benefits to this project beyond those direct financial benefits to the energy user (in this case, Cornell University). Thus, investment in the project by an outside entity with a stake in regional economic development may be appropriate.

A regional economic development interest is not likely to provide the full investment equivalent to that $LOCH_{REG}$, since many types of community investment may lead to positive economic impact – and some investments might be expected to provide higher benefits, or may require less incentive to result in the same regional benefit. More typically, an economic development organization may weigh the benefits of the project against other opportunities and may apply their own “multiplier” to determine an appropriate level of support – say, $1 for every $5 of regional benefit (i.e., about double what a simple infusion of cash into the local economy might yield by a typical regional multiplier affect). For these types of consideration, a calculation of $LCOH_{REG}$ is a first and necessary step to making such assessment.

END OF APPENDIX I