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District Geothermal Heating Using EGS Technology to Meet Carbon Neutrality Goals: A Case Study of Earth Source Heat for the Cornell University Campus

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ABSTRACT

Many states in the U.S. are adopting mandates and regulations to significantly lower their carbon footprints as well as increase their use of renewable energy. Most of these policies focus on using renewables for generating electricity and electrifying land transportation, yet they ignore the need for thermal energy. However, in almost half of the U.S. states — most of them in the Northern Tier region — over 20% of total statewide end-use energy demand is for thermal applications, predominantly space and water heating in the residential and commercial sector. This heat demand is mainly supplied by burning fossils fuels, however, lower temperature geothermal resources (<150°C) could provide an attractive, low-carbon alternative. Unlike high-grade resources, which are concentrated in the western U.S. and have been the focus of geothermal development — mainly for electricity production — lower temperature resources are widely available throughout the country. They include hydrothermal reservoirs, sedimentary aquifers and deep Enhanced Geothermal Systems (EGS) in low-permeable, crystalline rock, and can all be categorized under Earth Source Heat (ESH). Cornell University in New York State is attempting to use ESH to provide geothermal baseload heating as a key component of its strategy to reach carbon neutrality for its campus of 30,000 people. Project research and analysis is ongoing — an update of which is presented in this paper — and includes (1) characterizing the subsurface (using data obtained from regional core logs, bottom-hole temperature measurements, and stratigraphic columns, outcrops in the Adirondacks Mountains, and local active seismic, passive seismic, magnetic, and gravity surveys), (2) performing reservoir simulations, (3) reviewing optimal integration into existing campus district heating system, (4) site-selection for an initial exploratory well on campus, and (5) assessing required capital investment and overall levelized cost of heat. A successful Cornell ESH demonstration project could serve as example for rural and urban communities in New York State and the Northern Tier of the U.S., where annual heating loads are high and low-temperature geothermal resources are widespread.

1. INTRODUCTION

1.1 Motivation and scope

A closer look at how the U.S. uses primary energy today reveals a major challenge for achieving a sustainable energy supply with low carbon emissions. More than 25% of total primary energy demand in the U.S. provides low-temperature heat for residential and commercial buildings, and industrial processes (Fox et al., 2011). This heating demand is typically met using furnaces, boilers and hot water heaters that burn fossil fuels (mostly natural gas, heating oil and propane) at much higher temperatures than are needed at their end use. Combustion-based heating processes — while economically scalable over a wide range of outputs from a few kW_{th} to 1000+ MW_{th} — suffer large losses in their exergy: the heat is produced at high temperatures (> 1000°C) but used at low temperatures (100°C or less). Higher exergetic efficiencies are possible with co-generation of heat and electric power. However, these combined cycle plants are typically fired by combusting natural gas, still a depletable, non-renewable resource producing carbon dioxide emissions.

In order to achieve a low-carbon U.S. energy system to address climate change without creating unachievable renewal energy requirements, there are only three viable options for heating buildings: nuclear, biomass, and geothermal. Although scalable to meet large demands, nuclear energy is not renewable and has large public acceptance issues in the U.S., and developing nuclear-based district heating systems in America's many smaller communities in rural locations appears challenging. Biomass provides a renewable option that could be harvested, stored, transported and combusted (either directly or after gasification). Biomass combustion because of its high temperatures has similar exergetic efficiency losses to burning fossil fuels. Biomass also has a range of other uses (e.g., transportation fuels), and at the scale needed to meet the U.S. heating demand it would have large impacts on food, water, land and nutrient resources.

Geothermal energy can provide heat at temperatures much closer to the temperature of end-use of heating buildings and supplying hot water (commonly 60 to 100°C) — subsurface temperatures in the range of 50-100°C are obtained at most locations at moderate depths (< 3 km). Sustainably managed geothermal systems can be operated in a renewable manner to provide baseload energy, unlike wind or solar which are intermittent and need storage. In addition, geothermal systems have low carbon emissions and small land footprints. Although the U.S. installed a geothermal district heating system in Boise, Idaho in the1880s (Tester et al., 2016), for the last 140 years, geothermal development in the U.S. has been almost exclusively limited to generating affordable electricity using high-grade locations in the Western U.S. where hot resources (150-250°C) are close to the surface. For heating applications, indigenous geothermal resources are accessible and abundantly available in the temperature range of 60-120°C throughout the U.S., including the densely populated Northeast.

1.2 Objectives and approach

The main objectives of this paper are to describe the technical progress and plans for Cornell's Earth Source Heat (ESH) geothermal district heating demonstration project. The rationale behind why Cornell is pursuing a geothermal option is also covered, as it is a key element of the university's overarching goal to achieve carbon neutrality. Cornell's district energy system provides the framework to show how geothermal heating can be integrated as a part of its transformation to a renewable energy supply. Importantly, a successful demonstration of ESH at Cornell could catalyze the deployment of geothermal district heating as an economically scalable and carbon neutral option for other communities in New York State and the Northern Tier of the U.S. where seasonal heating demand is high.

Our approach has involved several steps to evaluate the technical and economic feasibility of geothermal heating for the campus. They include:

1. Analysis of regional and local geology, heat flow, and temperature gradients
2. Geophysical characterization of the subsurface including seismic imaging, gravity and aeromagnetic surveys
3. Target reservoir selection, well design and placement and performance modeling
4. Drilling site selection
5. Modeling of integration of geothermal heating into Cornell's energy infrastructure
6. Overall techno-economic assessment

1.3 Paper outline

This paper consists of 6 sections including this introductory section. Section 2 discusses the potential for geothermal direct-use in the U.S. Section 3 presents Cornell's Climate Action Plan (CAP) and describes how ESH would be integrated into Cornell's existing district energy system, to provide renewable, baseload heating for the campus while avoiding the carbon emissions associated with its current use of natural gas for heating. Section 4 covers Cornell's ESH project including a summary of the major findings of a regional geothermal resource assessment (Section 4.2), and a summary of geological and geophysical characterization results of the Ithaca subsurface (Section 4.3). Section 5 describes the technical and economic performance requirements for the ESH system (based on reservoir and surface equipment modeling and wellbore design), and the results of an overall techno-economic assessment. Section 6 summarizes major findings and describes the path forward for Cornell's ESH project.

2. U.S. POTENTIAL FOR GEOTHERMAL DISTRICT HEATING TO LOWER CARBON FOOTPRINT

As of 2020, 28 U.S. states have enacted greenhouse gas (GHG) reduction targets to lower their carbon footprint (see Table 1). These targets typically constitute a moderate target by 2020-2030 (e.g., 20% reduction below 1990 levels) and a more aggressive target by 2050 (e.g., 80% reduction). The policy focus and conversation to meet these targets have generally been on decarbonizing electricity production, for example through a Renewable Portfolio Standard (RPS) program. Several of the states listed in Table 1 have an RPS program in place, e.g., New York State has an RPS target of 50% by 2030 (USCA, 2018). However, electricity production in some states only has a moderate contribution to overall GHG emissions for that state. In the U.S., 35% of all CO_2 emissions are attributed to electricity production, whereas, for example, for New York, the electricity contribution is only 17% (EIA, 2018a). For states to meet their GHG reduction targets — especially the aggressive mid-century targets — decarbonizing the energy consumption across all sectors (i.e., residential, commercial, industrial, and transportation) will be required.

In several states in the northeastern U.S., demand for low temperature heat (<150°C) represents over 30% of total statewide energy end-use demand (see Figure 1 and Table 2). These heat demand numbers were calculated based on data reported by the EIA (2018b; 2018c; 2019) and an analysis by McCabe et al. (2016). The heat demand includes space and water heating, cooking, clothes drying and hot tub heating in the residential sector, space and water heating and cooking in the commercial sector, process heating (requiring temperatures less than 150°C) and HVAC energy demand (not explicitly space heating) in the manufacturing sector, and greenhouse heating in the agricultural sector. This low-temperature heat demand is predominately supplied by on-site combustion of fossil fuels (natural gas, propane, fuel oil, and kerosene). Local geothermal heat production and community-wide distribution may be an attractive approach for decarbonizing part of this low-temperature heat demand. Several examples of successful geothermal district heating networks are found around the world, e.g., the geothermal district heating systems in Boise, Idaho and Reykjavik, Iceland (Tester et al., 2016). Urban areas, where population and businesses, and correspondingly heat demand are concentrated— with Table 2 showing several northeastern U.S. states having over 80% of population living in urban areas — would be target locations for such systems. The recently published GeoVision study (DOE, 2019) highlights the tremendous opportunity for geothermal district heating in the U.S. and identified 17,500 U.S. communities, a large share of which are located the Northeastern U.S., where geothermal district heating using EGS technology is expected to become cost-competitive.

Table 1. Enacted U.S. State greenhouse gas reduction targets as of 2020 (USCA, 2019; C2ES, 2019; NCSL, 2020)

	U.S. State	State Greenhouse Gas Reduction Targets
1	California	40% below 1990 levels by 2030; economy-wide carbon neutrality by 2045
2	Colorado	50% below 2005 levels by 2030; 90% below 2005 levels by 2050
3	Connecticut	10% below 1990 levels by 2020; 45% below 2001 levels by 2030; 80% below 2001 levels by 2050
4	Delaware	30% below 2008 levels by 2030
5	District of Columbia	50% below 2006 levels by 2032; 100% below 2006 levels by 2050
6	Florida	2000 levels by 2017; 1990 levels by 2025; 80% below 1990 levels by 2050
7	Hawaii	Carbon neutrality by 2045
8	Illinois	26-28% below 2005 levels by 2025
9	Maine	45% below 1990 levels by 2030; 80% below 1990 levels by 2050
10	Maryland	40% below 2006 levels by 2030; 80%-95% below 2006 levels by 2050
11	Massachusetts	25% below 1990 levels by 2020; 80% below 1990 levels by 2050
12	Michigan	26-28% below 2005 levels by 2025
13	Minnesota	30% below 2005 levels by 2025; 80% below 2005 levels by 2050
14	Montana	Net-zero for annual electric loads by 2035
15	Nevada	28% below 2005 levels by 2025; 45% below 2005 levels by 2030; carbon neutrality by 2050
16	New Hampshire	20% below 1990 levels by 2025; 80% below 1990 levels by 2050 (goals are none-statutory)
17	New Jersey	1990 levels by 2020; 80% below 2006 levels by 2050
18	New Mexico	45% below 2005 levels by 2030
19	New York	40% below 1990 levels by 2030;100% below 1990 levels by 2050
20	North Carolina	40% below 2005 levels by 2025
21	Oregon	10% below 1990 levels by 2020; 75% below 1990 levels by 2050
22	Pennsylvania	26% below 2005 levels by 2025; 80% below 2005 levels by 2050
23	Puerto Rico	50% reduction from 2019 levels by 2024
24	Rhode Island	10% below 1990 levels by 2020; 45% below 1990 levels by 2035; 80% below 1990 levels by 2050
25	Vermont	40% below 1990 levels by 200; 80-90% below 1990 levels by 2050
26	Virginia	100% zero-carbon electricity by 2050 (state has no specific GHG reduction targets)
27	Washington	1990 levels by 2020; 25% below 1990 levels by 2035; 50% below 1990 levels by 2050
28	Wisconsin	100% zero-carbon electricity by 2050 (state has no specific GHG reduction targets)

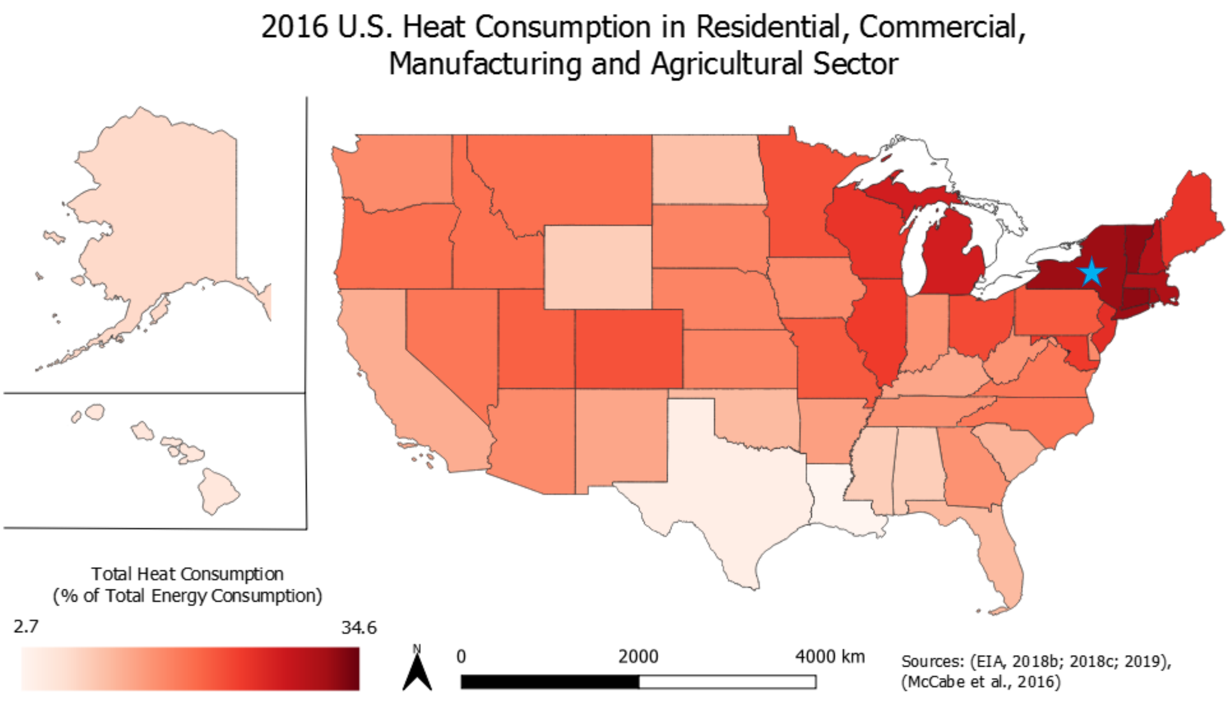


Figure 1. Demand for heat (<150°C) in residential, commercial, manufacturing and agricultural sectors as a percentage of total end-use energy demand in each U.S. state. In the Northeast, several states have a low-temperature heat demand over 30% of their total energy demand. Blue star pinpoints Ithaca, NY.

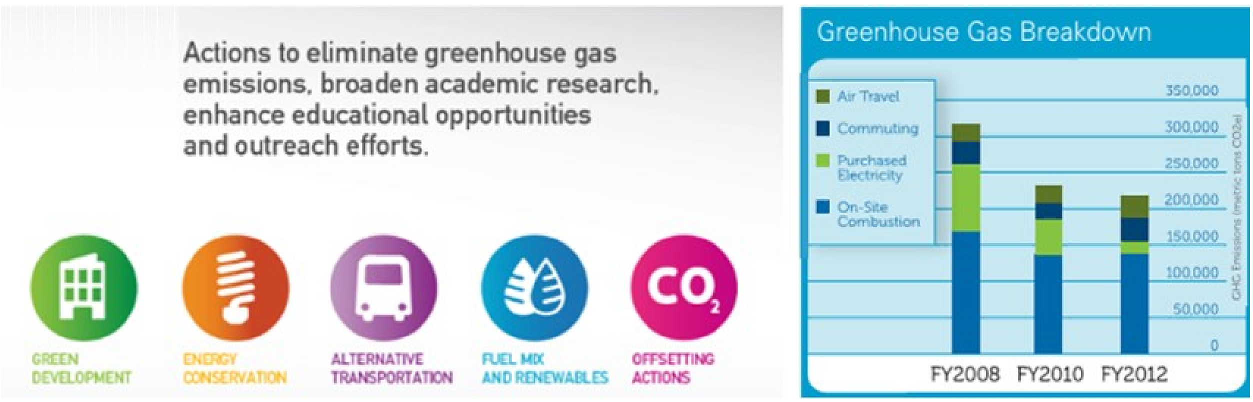
Table 2. Total energy demand, heat demand (in residential, commercial, manufacturing, and agricultural sectors) and percentage of population living in urban areas for different U.S. states. Table is sorted by heat demand as percentage of total energy demand. Data is provided by EIA (2018b; 2018c; 2019), McCabe et al. (2016), ISU (2019) and Census (2018).

	State	Total 2016 Energy Demand [PJ (trillion Btu)]	Estimated Heat Demand in Residential, Commercial, Manufacturing and Agricultural Sector			Percentage of people living in urban areas (2010 Census) [%]
			Total Heat Demand [PJ (trillion BTU)]	Heat Demand Per capita [GJ per person (million Btu per person)]	Heat Demand as Percentage of total energy demand [%]	
1	District of Columbia	95 (90)	32.8 (31.1)	46.7 (44.2)	34.6	100.0
2	Connecticut	581 (551)	187.2 (177.4)	52.4 (49.7)	32.2	88.0
3	Vermont	128 (121)	40.8 (38.7)	65.2 (61.8)	32.0	38.9
4	Rhode Island	155 (147)	48.9 (46.4)	46.3 (43.8)	31.5	90.7
5	New York	2,931 (2,779)	918.5 (870.6)	47.0 (44.5)	31.3	87.9
6	Massachusetts	1,133 (1,074)	343.0 (325.1)	49.7 (47.1)	30.3	92.0
7	New Hampshire	238 (226)	70.8 (67.1)	52.2 (49.5)	29.7	60.3
8	Michigan	2,157 (2,045)	582.7 (552.3)	58.3 (55.3)	27.0	74.6
9	New Jersey	1,844 (1,748)	456.0 (432.3)	51.2 (48.5)	24.7	94.7
10	Wisconsin	1,360 (1,289)	328.5 (311.3)	56.5 (53.6)	24.2	70.2
11	Maine	352 (333)	84.3 (79.9)	63.0 (59.7)	24.0	38.7
12	Illinois	3,009 (2,852)	711.0 (674.0)	55.8 (52.9)	23.6	88.5
13	Maryland	942 (893)	219.9 (208.5)	36.4 (34.5)	23.4	87.2
14	Ohio	2,767 (2,623)	611.5 (579.6)	52.3 (49.6)	22.1	77.9
15	Minnesota	1,461 (1,385)	315.3 (298.9)	56.2 (53.3)	21.6	73.3
16	Colorado	1,163 (1,102)	244.4 (231.6)	42.9 (40.7)	21.0	86.2
17	Pennsylvania	2,923 (2,771)	610.8 (579.0)	47.7 (45.2)	20.9	78.7
18	Missouri	1,262 (1,196)	262.8 (249.1)	42.9 (40.7)	20.8	70.4
…						
40	California	6,599 (6,255)	841.5 (797.7)	21.3 (20.2)	12.8	95.0
…						
50	Texas	11,166 (10,584)	507.7 (481.2)	17.7 (16.8)	4.5	84.7
51	Louisiana	3,887 (3,685)	105.4 (99.9)	22.6 (21.4)	2.7	73.2

3. CORNELL'S CLIMATE ACTION PLAN (CAP) AND ROLE FOR GEOTHERMAL HEATING

3.1 Cornell's approach to climate neutrality

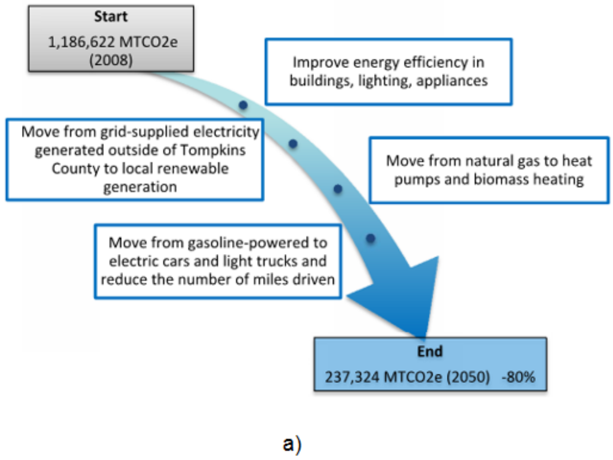
Cornell became a Charter Signatory to the American College & University Presidents' Climate Commitment (ACUPCC) in 2007. By signing, Cornell pledged to strive for net zero greenhouse gas (GHG) emissions by the year 2050. By 2010, there were nearly 700 universities and college signatories in all 50 U.S. states and the District of Columbia, representing an American student population of over 5.6 million. To meet one if its ACUPCC commitments, Cornell developed the climate action plan (CAP) for its main campus (in Ithaca, NY, USA). The CAP focusses on 5 action themes to transform to a campus with no GHG emissions (see Figure 2a). The CAP requires predominately Cornell-based resources, e.g. solar, biomass, wind and geothermal, for local, sustainable, and low-carbon heat and electricity production. The goal of climate neutrality has since been accelerated to 2035. By phasing out coal, a significant drop was achieved in GHG emissions from FY2008 to FY2012 (see Figure 2b). The direct use of geothermal heat using ESH technology is a key component of Cornell's CAP as it will completely transform how campus buildings and laboratories are heated. Transitioning to geothermal heating was one of 17 specific actions included in the final CAP recommendation, approved by Cornell's Board of Trustees in 2009.



a) b)

Figure 2. a) Cornell's CAP is a broad-based initiative to reduce GHG emissions to zero by the year 2035; b) Although a significant drop in GHG emissions was obtained by switching from coal to natural gas for on-site heat and electricity generation, on-site combustion remains the primary GHG component.

In recent years, other regional entities have announced similar goals as Cornell. New York State enacted in 2019 the following targets: 40% reduction in greenhouse gas emissions from 1990 levels by 2030, 100% carbon-free electricity by 2040, and net-zero greenhouse gas emissions by 2050. Tompkins County (home to Cornell's primary campus in Ithaca) launched their own Green Energy Roadmap to cut GHG emissions by 80% by 2050, relative to 2008 levels (see Figure 3a). Transportation and on-site natural gas combustion are the two main sources for local GHG emissions (see Figure 3b). The Green Energy Roadmap led the City and Town of Ithaca to adopt a Green Building Policy and to sign up as "2030 Districts". 2030 Districts voluntarily commit to reducing building energy use, water consumption, and transportation GHG emissions by at least 50% by the year 2030, with 2015 as baseline year for Ithaca.



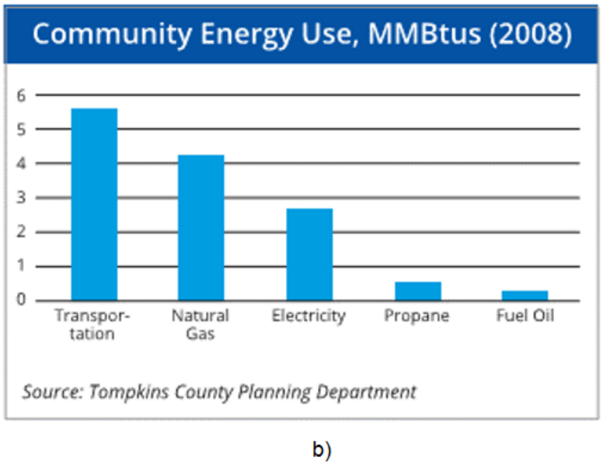
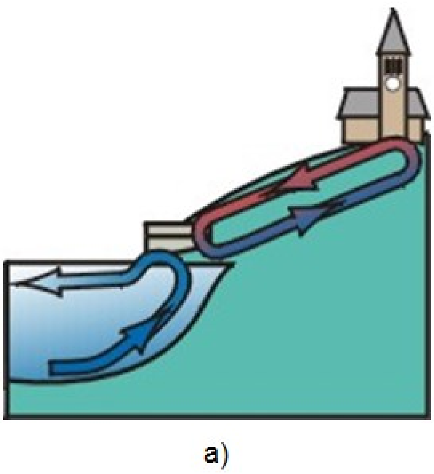


Figure 3. a) Tompkins County Green Energy Roadmap targeting an 80% reduction in GHG emission by 2050 (based on a 2008 baseline); b) Current energy use by source in Tompkins County: natural gas for heating remains a major source of local generated GHGs.

3.2 Integration of geothermal heating in Cornell's district energy system

The Cornell district energy system (DES) provides chilled water, hot water, and electricity to campus facilities.

Cooling: Over 98% of the annual campus cooling load is supplied by Lake Source Cooling (LSC), a renewable, direct cooling system that uses the deep waters of nearby Cayuga Lake (see Figure 4). The remaining 2% (summer peak loads) are supplied using mechanical chillers and chilled water storage. LSC's "direct cooling" means that only pumps (but no refrigerant cycle) are used: cold lake water cools the district cooling loop by conduction through a series of plate-and-frame heat exchangers. The result is that cooling is provided with an "effective" coefficient of performance (COP) of over 30, far surpassing even the most efficient chiller arrangement possible. [The effective COP is defined as the total cooling energy out divided by the total input electrical power.] The thermal footprint of LSC on Cayuga Lake is negligible, as the lake contains 2.5 trillion gallons of water (9.5×10^{12} L) and has an area of over 67 square miles (170 km^2). Compared to a conventional chiller-based cooling system, the LSC system reduces summer electrical loads by about 10 MW$_e$, resulting in annual electricity savings of almost 25 GWh (see Figure 5). This reduction is substantial when compared to an overall campus load of about 26 MW$_e$ for all services, including high-energy science. As a result, the University exports electricity during the peak summer season, when the regional electrical grid needs power the most. Because of its similarities, experience gained with developing and operating the lake-source district cooling system directly benefits the ESH project.



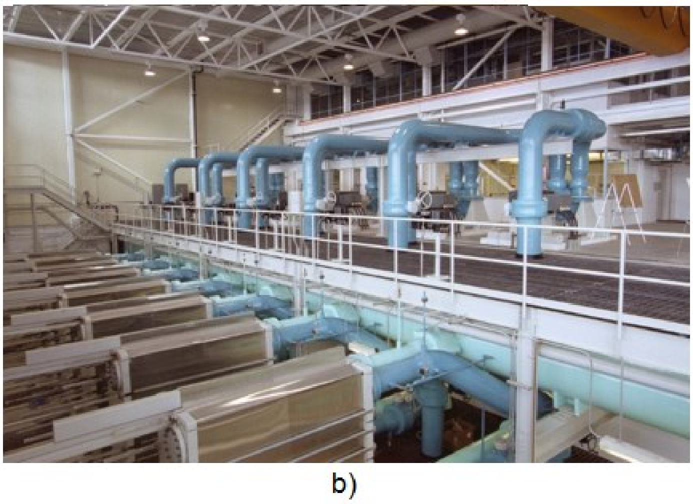


Figure 4. a) Lake-Source Cooling (LSC) schematic diagram; b) LSC equipment: pumps, heat exchangers and controls (but no mechanical refrigeration). Direct use of geothermal heat will require similar equipment.

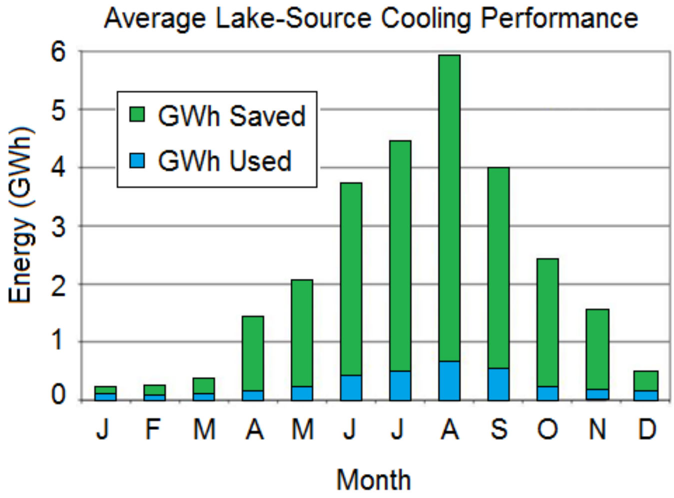


Figure 5. The energy needed for Lake Source Cooling (LSC) pumps, shown in the blue bars, is only a fraction of the energy needed for conventional refrigerant-based cooling (green bars). The result is a significant reduction in peak summer electrical load

Electricity: Cornell's electrical "microgrid" is anchored by a gas-fired combined cycle heat and power plant (see Figure 6) and accepts power from a small on-campus hydropower plant and rooftop/campus solar photovoltaic (PV) panels. Owning and controlling this microgrid allows Cornell to consider storage and demand management options that can benefit its operations, the environment, and/or the regional electrical grid. Cornell has recently upgraded the hydropower plant controls to improve plant output and is rapidly expanding on-campus solar PV. Nonetheless, complete electrification of our microgrid using only renewable power remains a significant challenge.

Within the public electrical grid outside of the microgrid, Cornell has developed several renewable energy projects including five solar PV farms on Cornell land using Power Purchase Agreements (each providing at least 2 MW_e) and another 18 MW_e community solar project. Cornell plans to expand that activity through a consortium of higher education institutions in NY State that will solicit developers for renewable wind, water, and solar projects.

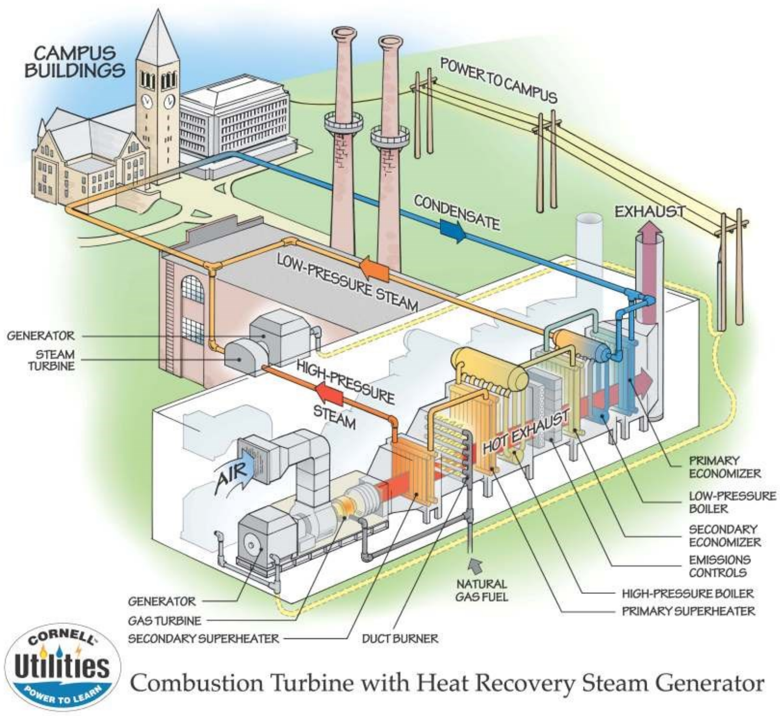


Figure 6. Combined heat and power (CHP) plant at Cornell uses a gas turbine, heat recovery steam generator, and backpressure steam turbines to provide electricity and heat for its main campus. While efficient, replacing CHP with renewable heat and power is needed to meet Cornell's ambitious carbon goals.

Heat: Using the model provided by LSC, Cornell plans to use its district heating infrastructure to integrate renewable heat. Currently, the combined heat and power plant provides about 90% of the campus heating, with the remainder provided by conventional gas-fired boilers. Cornell is in the process of converting its distribution system from steam to hot water to facilitate this renewable energy integration. To efficiently integrate renewable energy, the delivery system will supply "low temperature" (80°C or less) hot water.

All new buildings are being designed for 55°C supply water; all older ones are being converted to handle low-temperature water as well. As the conversion continues, heat can be supplied by a wide range of renewable heat sources, including geothermal heating, heating from biomass combustion, research process waste heat, and solar thermal hot water heating.

Geothermal heating was selected as the most viable option available for demand scale among several primary heating sources considered. Biomass combustion is technically feasible for supplementing heat on the coldest days, but it is not able to meet Cornell's total heating demand while utilizing Cornell's land resources in a sustainable manner. Given the low levels of solar insolation in our region and limitations of current thermal storage technologies, solar thermal heating is not practical for campus-wide winter heating in Ithaca. Geothermal heating can provide renewable baseload heating for the campus. To distinguish geothermal heating from other U.S. geothermal energy systems that generate electricity, Cornell has defined its direct use of geothermal energy as Earth Source Heat or ESH.

Cornell reviewed several existing geothermal systems worldwide to determine how best to utilize the geothermal resources located under its campus. One system of special interest is the ENGIE system in Paris (Beyers and Racle, 2020). This system is part of a district energy system that includes two other primary assets, namely, a gas-fired heating plant and a central heat pump. The gas-fired heating plant allows the district to meet peak heating needs without oversizing the geothermal system, which acts as a "baseline heat source". The central heat pump achieves high COPs and allows additional heat extraction "on-demand" from the geothermal resource. Beyers and Racle (2020) provide more details on that system and on the strategic incorporation of industrial heat pumps into geothermal district energy solutions. One key finding was that central heat pumps can improve both operations and economics, especially when tied to a lower temperature source (below ~90°C). Other benefits of this "hybrid" concept are elucidated in their paper.

4. CORNELL'S EARTH SOURCE HEAT (ESH) PROJECT

4.1 Overall approach

Ithaca's annual average temperature is about 7°C (45°F), resulting in significant thermal demand for the Cornell campus (90 MW_{th} at peak). This heating is predominantly supplied by gas-fired combined heat and power, which generates substantial local GHG emissions, despite its high efficiency. Integration of renewable heat is necessary to reach the Cornell's CAP goals. Figure 7 schematically illustrates how cooling (LSC in operation) and heating (ESH under development) are connected to the energy system.

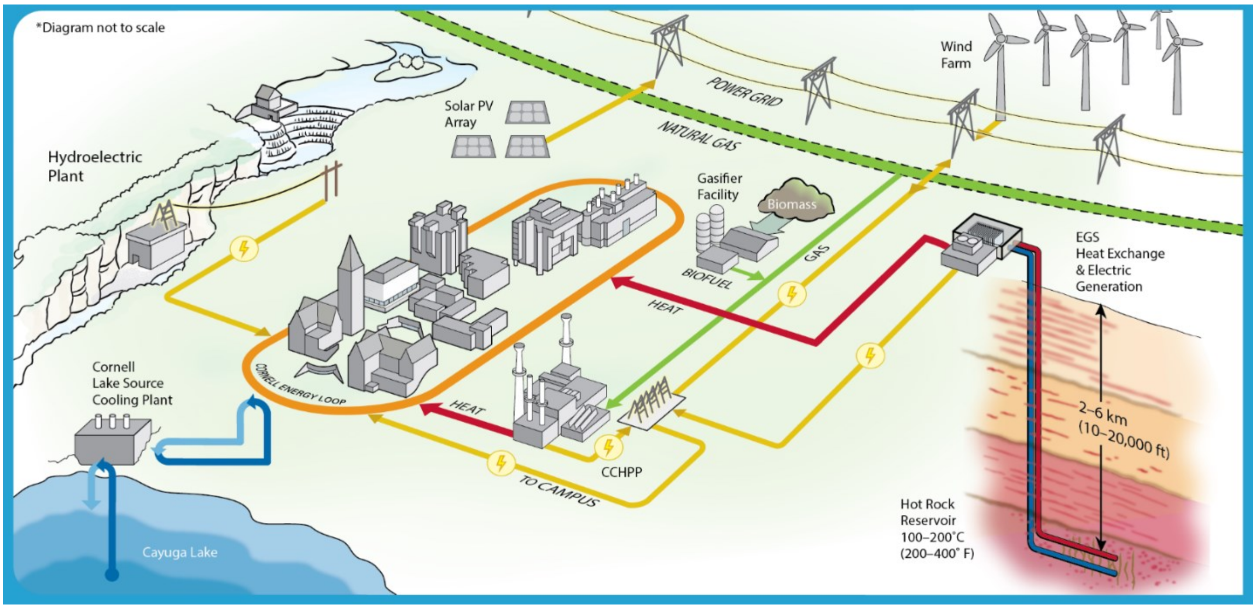


Figure 7. Planned Cornell campus energy infrastructure: District heating, cooling, and electricity supplied by highly efficient direct heating (ESH with bioenergy peaking), cooling (LSC), and renewable electricity (wind, hydro, solar), respectively. The gasifier facility, wind farm and ESH are not developed yet, and the solar PV deployment is only partially complete.

The ongoing activities of Cornell's ESH project are resource exploration, reservoir mapping, surface plant integration modeling, and site selection and preparation. Future activities include drilling, continued reservoir mapping, reservoir stimulation, water and seismic management, testing, and operation. Significant technical and financial participation by government, industrial and institutional partners is envisioned to support various phases of the project required to develop ESH and integrate it into Cornell's energy system.

4.2. Characterizing the regional geothermal resource

The potential for, and technical challenges to, the extraction of geothermal heat in New York and nearby states, specifically Pennsylvania and West Virginia, have been examined and revised through a series of recent studies (Blackwell et al., 2006; Reber et al., 2014; Stutz et al., 2015; Frone et al., 2015; Jordan et al., 2016; Camp, 2017; Camp et al., 2018). Recent geothermal play fairway analyses have examined a set of technical, environmental, and economic factors, including thermal resource, reservoir opportunities, seismic risk, and levelized cost of heat, all of which require knowledge of geological parameters.

Surface heat flow in those states varies from approximately 35 to 75 mW/m^2 (Blackwell et al., 2006) and the nature of rocks in which to develop hot water reservoirs varies from sedimentary aquifers to fractured metamorphic basement (Horton et al., 2017). Much of the subsurface of New York state, Pennsylvania and West Virginia consists of the Appalachian Basin, for which properties of the sedimentary rocks can be extracted from 150 years of data collection for oil and gas boreholes that is archived by state agencies. In particular, from these borehole data it is possible to assess the regional variations in thermal resources as well as the opportunities for sedimentary rock natural reservoirs. To obtain information that is vital to assessing Enhanced Geothermal System (EGS) potential or fractured natural reservoirs in basement rock, the nature of the underlying crystalline basement and the distribution of fractures can be best documented in the Adirondack Mountains of northern New York.

Tens of thousands of borehole temperature (BHT) data (Figure 8A) and generalized regional stratigraphic columns were used by Whealton (2015) and Smith (2019) to build basin-specific models of appropriate corrections of non-equilibrium BHT data. The models were calibrated against equilibrium temperature data sets. The temperature data and geologic uncertainties were transformed to estimated well-site heat flow using a 1-D conduction model, and these values were extrapolated to estimate heat flow across the basin (see also Horowitz, Smith, & Whealton, 2015). The information has been used to estimate temperatures at depths of interest, such as the top of the crystalline basement (Figure 8B) and within sedimentary reservoirs documented to be able to store and flow oil or gas (Figure 9).

The potential that geothermal reservoirs can be developed within the natural pore systems of the sedimentary rocks has been examined using the oil and gas development data for New York, Pennsylvania, and West Virginia. Camp et al. (2018) used a probabilistic approach and subsurface data to locate reservoirs with high potential for productivity and low uncertainty; only reservoirs located deeper than 1250 m were examined in Pennsylvania and West Virginia. They conclude that only 27 known oil and/or gas reservoirs have adequate natural fluid storage and flow properties to be exploited for hot water circulation; nearly another 100 natural systems could become economically viable if stimulated to function as EGS systems. Most of the area of the Appalachian Basin lacks reservoir data, and thus the sedimentary reservoir opportunities are likely broader than documented by Camp et al. (2018). Nevertheless, the sedimentary reservoir opportunities are fundamentally limited by the widespread tendency for low porosity and low permeability in the deeply buried sedimentary rocks of the Appalachian basin.

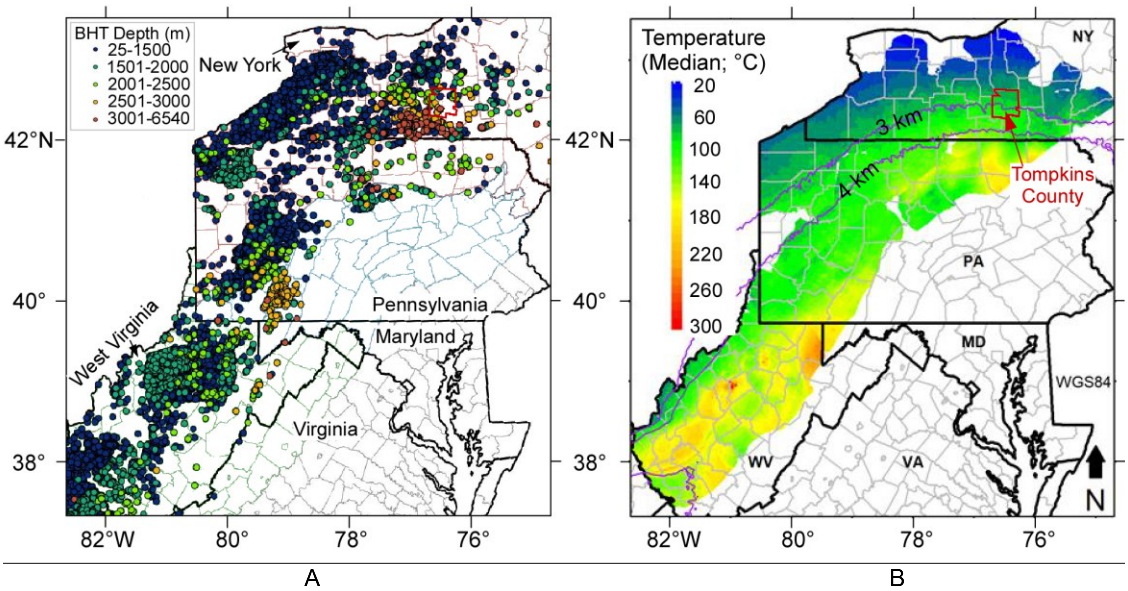


Figure 8. (A) Over 20,000 oil and gas boreholes provide Bottom Hole Temperature data for central and southwestern New York, western Pennsylvania, and throughout most of West Virginia. Over 13,000 of these correspond to reliable data and positions >1000 m below the local surface, well removed from near-surface thermal disturbances. Thermal properties are estimated from these data. (B) Estimated temperature at the depth of the top of crystalline basement for each of 138,400 1 km^2 grid cells. This map shows the median among estimated values, based on an analysis that propagated all the uncertainties derived from input data, assumptions, and interpolations (Smith, 2019). The two irregular purple lines are contours of 3 km and 4 km depths to the top of basement, which is progressively deeper from north (and west) to south (and east). State (black lines) and county (gray lines) boundaries shown. State abbreviations: KY: Kentucky, MD: Maryland, NY: New York, OH: Ohio, PA: Pennsylvania, VA: Virginia, WV: West Virginia. From Smith (2019).

Smith (2019) estimated the temperatures in the 16,700 areas of potential sedimentary geothermal reservoirs (reservoirs from Camp et al., 2018), including uncertainty on variables that are both geological (formation depth and thickness) and thermodynamic (thermal conductivity, radioactivity) as well as considering spatial correlations of the available temperature data (kriging spatial interpolation uncertainty). A Monte Carlo analysis consisting of 10,000 replicates of these uncertain variables was used to estimate temperatures at depth. The map in Figure 9 shows the estimated mean temperatures (black dots of part B), based on an analysis that propagated all of the uncertainties derived from input data, assumptions, and interpolations.

The estimated temperatures in the reservoir (Figure 9) illuminate the range of uses applicable to geothermal exploitation of Appalachian basin sedimentary reservoirs. At the mean depth of the reservoirs, mean predicted temperatures that range from 60–120°C occur below south-central New York, northwestern Pennsylvania, and in many parts of West Virginia (Smith, 2019). The predicted temperatures are quite uncertain for specific reservoirs (Figure 9B), yet for depths greater than about 2,700 m it is highly likely that the reservoir rock temperature is above 80°C.

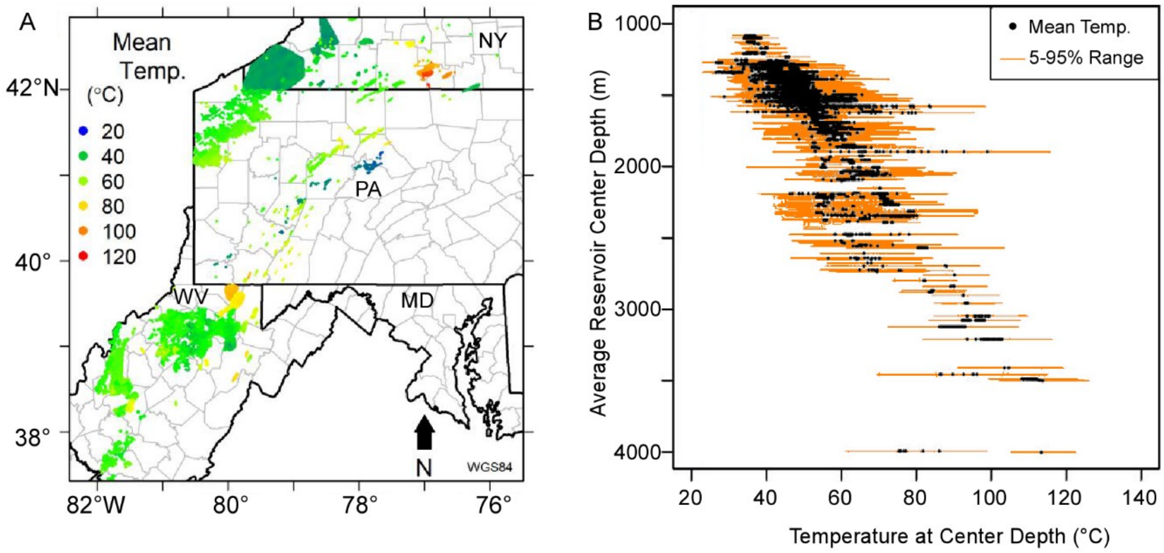


Figure 9. (A) The estimated temperature calculated at the center depth of each 1 km² area corresponding to a documented sedimentary reservoir in the Appalachian Basin. (B) The estimated mean temperature (black dot) and 5-95% temperature range (orange lines) for each 1 km² area of the reservoirs evaluated in A. Points are plotted at the average depth to the center of the reservoir. From Smith (2019).

4.3 Geological and geophysical characterization of Ithaca subsurface

Regional Geologic Context: The Geothermal Play Fairway Analysis of the Appalachian Basin noted above placed Ithaca on the margin of a high priority play fairway (Jordan et al., 2016; Camp et al., 2018; Whealton et al., in review; Smith, 2019). The Appalachian Basin was the foreland of the Alleghanian orogeny fold-thrust belt, and at the end of the Paleozoic the strata near Ithaca were buried 3-4 km greater than the current exhumed depths (Roden, 1991; Miller and Duddy, 1989; Roden and Miller, 1989; Heizler and Harrison, 1998). As a result, porosity and permeability are considerably lower than one might expect for a sedimentary basin. Characterizing the geologic column below Cornell and selecting target geothermal reservoirs with suitable permeability in local geologic records was a first step of the analysis.

Within a 150 km² area surrounding Cornell, 12 oil and gas exploration wells with logs were bored to depths >1865 m (>6119 ft); 1 penetrated into crystalline basement, and 11 reached or exceeded the Ordovician Trenton Formation, one of the target formations for developing a geothermal reservoir. Ten kilometers south of Cornell, a borehole to 3181 m depth penetrated 48 m thickness of crystalline basement in 1959; only gamma and resistivity log data were collected. Wells to basement depths were routinely air drilled until the last few decades, and commonly cased only through a thick interval rich in halite and other evaporite rocks. That successful drilling practice is testimony to the high cohesive strength of the Paleozoic section.

The geologic formations of interest for geothermal reservoir simulation include the reservoir rocks through which fluid must flow, and the surrounding caprocks and base rocks that primarily supply conductive heat recharge to the reservoir. Simplifications to the full geologic column, where appropriate, are beneficial for computational efficiency in numerical simulations, such as those completed using TOUGH2 (Pruess et al, 2012).

The sedimentary aquifer targets occur at depths where temperatures are estimated to exceed 60°C and encompass the dominantly carbonate and sandstone section from the Ordovician Trenton Formation down to the Cambrian Potsdam Formation. The interval with most prospective reservoir properties spans approximately 2300–3000 m below the surface. Above the Trenton limestones exists a thick shale sequence, the Lorraine/Utica (see Figure 11 in *Temperature estimation* section below), which will likely act as a barrier to fluid flow (e.g. nanodarcy permeability in Carter and Soeder, 2015). Based on local well logs, this shale sequence is expected to be about 200 m thick below Cornell. Given the Lorraine/Utica properties, we expect these to be caprocks.

Formations between the Utica and basement rocks were analyzed in greater detail (see Figure 11 in *Temperature estimation* section below). A subset of 6 local boreholes (within 50 km of Cornell) provide well logs suitable to estimate porosity data for the sedimentary rock interval of interest, from a combination of logging tools that are sensitive to either H^+ content in the pore fluids, or to the bulk electron density. With few exceptions, the sedimentary rocks in the zone of interest have porosity <10%, and lack permeability data.

Outcrop analyses: In the absence of borehole data that would document rock properties or fractures in the crystalline basement, we have used the Adirondack Mountains as an analogous study area (Figure 10A), because there the medium to high grade metamorphic basement reaches the surface. We hypothesize that similar rock properties make it appropriate to use the spectrum of fracture spacings and apertures found in the Adirondacks, over scales ranging from centimeter to tens of kilometers, as a suitable basis for EGS modeling. In the future, when Cornell-specific data are available, this hypothesis needs to be tested.

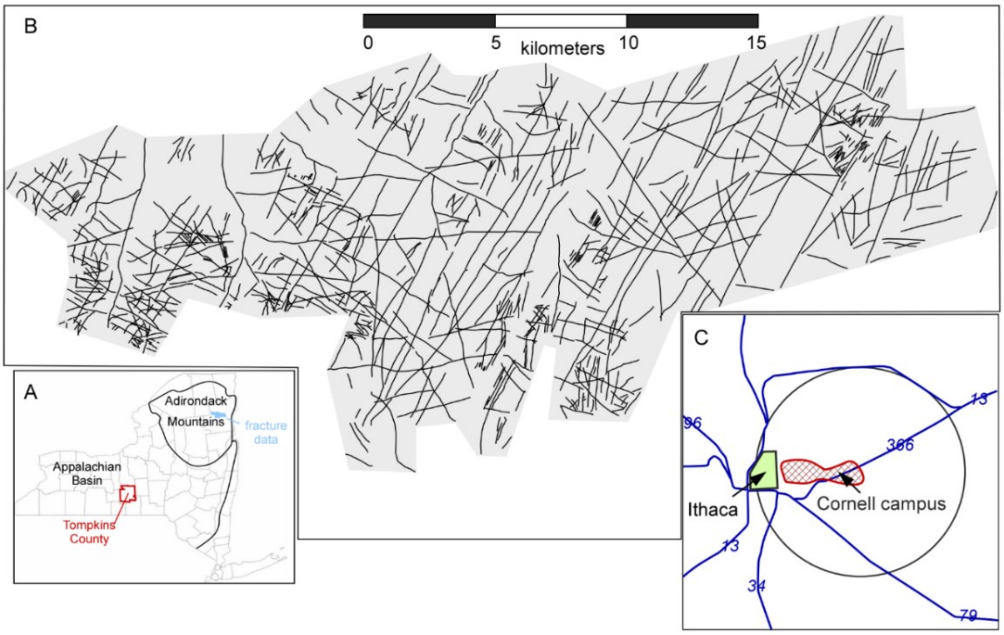


Figure 10: (A) Location of the Adirondack Mountains and Appalachian Basin in New York State. Cornell University is located in Tompkins County, highlighted in red, within the Appalachian Basin. The blue polygon indicates the area shown in B. (B) The distribution of fractures in and near the Mount Marcy highland of the Adirondack Mountains, identified based on LiDAR-DEM analysis. The gray background delimits the region analyzed. (C) At the same scale as the Adirondack fracture map, the region of interest for investigation of a Cornell direct-use geothermal energy project. Shown are roads (blue lines, with route numbers), the footprints of Cornell's Ithaca campus, and the high population density section of the City of Ithaca (green polygon). Circle radius is 4 km.

Table 3. Generalized geologic column for Cornell (see also Figure 11A) with estimated formation depths, geologic properties, and grid cell sizes used in TOUGH2 numerical geothermal reservoir simulations. For information on the sources of these values, see Gustafson et al. (2019). Generic sources are provided in Table 4.

Formation Name	Modeled Formation Top Depth (m)	Porosity (-)	Permeability H: Horizontal V: Vertical (md)	Density (kg/m³)	Thermal Conductivity (W/m-K)	Specific Heat Capacity (J/kg-K)	TOUGH2 No. of Vertical Grid Cells: Cell Size (m)
Lorraine/ Utica shale	1860	0.04	H: 5E-6 V: 5E-6	2700	0.9	830	Boundary Condition 1: 0.1m 1: 199.9 m
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
Black River Dolomite	2270	0.07	H: 250 V: 2.6	2800	2.91	930	15: 2 m
Black River Limestone	2300	0.01	H: 0.5 V: 0.0005	2700	2.11	880	20: 2 m
Beekmantown Group: Tribes Hill/ Little Falls Carbonates	2340	0.02	H: 2.6 V: 2.6	2780	3.79	880	5: 11m 3: 18.3 m 2: 55 m
Galway/ Theresa Carbonates / Rose Run Sandstone	2560	0.01	H: 2.6 V: 2.6	2610	3.34	880	1: 220 m
Potsdam Sandstone	2780	0.01	H: 0.002 V: 0.0002	2640	4.27	860	1: 20m
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

Note: m^2 is the SI unit for permeability; darcy is the traditional engineering unit. 1 darcy = 10^{-12} m^2 and 1 md = 10^{-15} m^2.

Multistage remote sensing methods have long been used to map brittle structures in the Adirondack Mountains (e.g., Isachsen and McKendree, 1977). Extending that approach to much higher spatial resolution modern data, digital elevation models (DEMs) for Adirondack analog sites were constructed using LiDAR images at 1 m spatial resolution in the software Global Mapper (Blue Marble Geographics, 2018). For each area, a single LiDAR DEM was illuminated from three directions, corresponding to solar azimuths at 135°, 225°, and 315°, and approximately linear breaks in topographic slope were mapped. Optical satellite images were examined to eliminate linear features such as rivers and roads. A comparison of this data set to published maps (e.g., Isachsen and McKendree, 1977) is consistent with interpreting the linear features as fracture zones (Figure 10), along which weathering is enhanced with a resultant expression in the topography.

In outcrop, fractures in Adirondack rocks are present across a range of length scales from less than 1 m in densely fractured rock, to tens of meters in sparsely fractured rock. Mapped using LiDAR DEMs (Fig. 10B), the scale of fractures which affect topography includes fracture lengths that vary from hundreds of meters to >12 km, and distances between adjacent fractures that vary from approximately 100 m to over 2 km. Although we document that there are multiple orientations of fractures, we expect the orientations of fractures beneath sub-regions of the Appalachian basin sedimentary rocks to differ from the orientations in the Adirondacks.

It is instructive to compare the frequency and lengths of Adirondack fractures to the scale of an area of interest for geothermal direct use projects. As an example, Figure 10 compares the near-Cornell area to one region within the Adirondack Mountains. If the basement beneath this 144 km^2 near-Cornell area (Figure 10C) has a fracture density like in the Adirondack Mountains (Figure 10B), then it is highly likely that there will be fractures within the basement near any geothermal energy target zone that one might choose. Nonetheless, their aperture distribution, degree of sealing, and connectivity needs to be determined by field testing.

Estimation of bulk rock properties: Field *in situ* measured values of permeability are not available from published studies for our target reservoirs. Lugert et al. (2006) report that the *best* laboratory-derived core permeability for rock in productive gas reservoirs near Ithaca, in the Trenton-Black River play, ranges from 0.1-4 millidarcy (10^{-16} – 10^{-15} m^2). Hence, we expect permeability of most of the deep strata to be lower, on the order of microdarcy (10^{-18} m^2), and for reservoir modeling we rely on values obtained from core studies from Ohio, Pennsylvania, and western New York (see Table 3).

Additional petrophysical data that are needed for reservoir modeling (e.g., thermal conductivity and heat capacity) are based on published datasets for the formations of interest, or of similar lithologies (Table 4). Thermal conductivity values for the Southern Tier of NY State, including the Cornell region, were estimated as part of the Appalachian Basin Geothermal Play Fairway Analysis project (Cornell University, 2017). Carter et al. (1998) was the primary source used for thermal conductivity values when basin-specific information was not available. The Carter et al. (1998) samples were taken from the Anadarko Basin, which has a burial history similar to the Appalachian Basin. Numerical reservoir modeling is based on the properties in Table 3, and on the estimated depths to each of the formation tops. For the estimated uncertainty in the depth to the basement of ± 200 m, about ± 3.5 °C change in the temperatures at the top of the basement are expected.

Lithology from well cuttings and cores: We expect the basement to be a mixture of middle to high grade meta-sedimentary and meta-igneous rocks, repeatedly folded while ductile (McLelland et al., 2010; Chiarenzelli et. al., 2011), as in the Adirondack Mountains, located about 170 km from Cornell (Figure 10A). If represented by the Adirondack Mountains, the heterogeneity of lithology may span marbles to anorthosite, with compositionally variable gneisses and schists. We expect the characteristic length scales of variations to span centimeters to tens of kilometers, and that there is strong anisotropy of metamorphic fabrics at scales of millimeters to kilometers. Superimposed brittle fractures in the Adirondacks are of many orientations and spacing, and most are filled with mineral veins.

Table 4. Generic sources of geologic properties for formations listed in Table 3 (Gustafson et al., 2019).

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

Valentino (2016) examined well cuttings from five boreholes in central New York that penetrated basement, and cores from mineral exploration boreholes located near the northeastern margin of the Appalachian Basin in New York; these samples are archived by the New York State Museum. Whereas most of the cuttings material consists of disaggregated individual crystals, rock fragments include marble, hydrothermally altered granite to monzonite gneiss, calcite vein fragments, hornblende granodiorite gneiss, and amphibolite (Valentino, 2016). The 55 km distant Auburn geothermal borehole, drilled in 1982, penetrated 60 m of basement, all of it marble. This pair of studies confirms that we expect to see crystalline basement rocks at Cornell similar to those rocks that are exposed in the Adirondack Mountains, which leads to the expectation that a borehole at Cornell will traverse several lithologies, whether the borehole within the basement rock is vertical or inclined. Owing to this heterogeneity, for reservoir modelling we assume geologic properties that are representative of Adirondack Mountain rocks in aggregate from Simmons (1964). These aggregate properties are similar to granitic gneiss.

Temperature estimation: To estimate temperatures at depth below Cornell, we combine the approach to estimating temperatures at depth used in the Appalachian Basin regional analysis (Section 4.2), with explicit treatment of the uncertainty of properties in rocks below Cornell. Figure 11B shows the predicted distributions of temperatures at depth below Cornell in 500 m increments (Smith, 2019), based on a Monte Carlo analysis consisting of 10,000 replicates of the uncertain variables (see Section 4.2). Uncertainty increases with increasing depth. A category of epistemic uncertainty that is not included in this analysis is the assumption that geothermal gradient changes at the lithological change corresponding to the top of basement, which occurs between 2.5 km and 3 km. This important assumption about heat conduction is not based on local data, which are not available, but rather on the assumed parameters of a heat generation model for basement rocks (e.g., Lauchenbruch, 1970). The sedimentary rock interval from Trenton Formation (T) through Potsdam Formation (P) (Figure 11A) has a high likelihood to possess temperatures between 70 °C and 85 °C (Figure 11B), and potential ESH targets in basement to be at temperatures in excess of 85 °C.

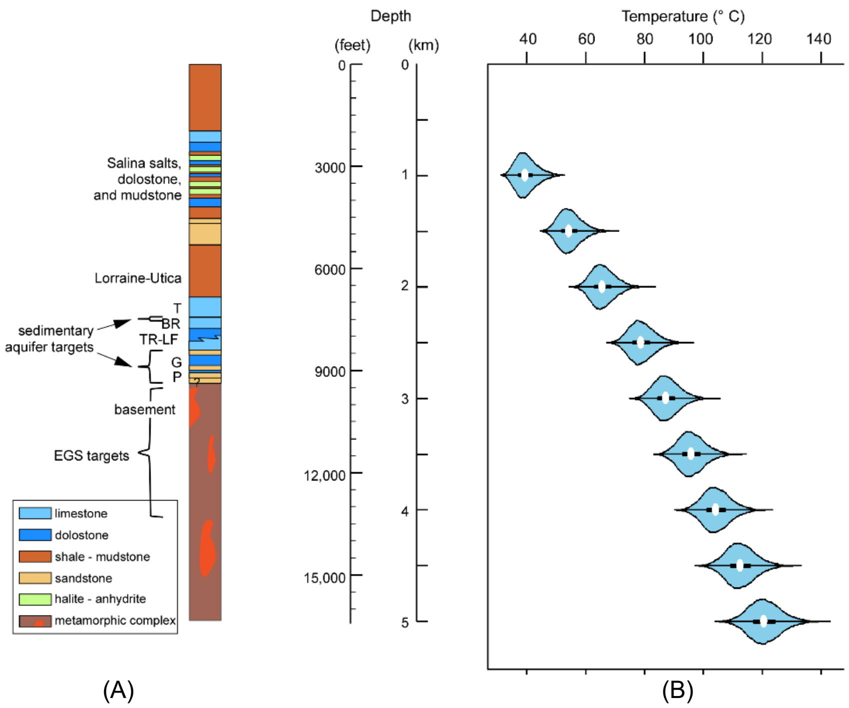


Figure 11. (A): Approximate geological column beneath Cornell University, taken in part from Al Aswad (2019). Sedimentary rocks are estimated to extend to nearly 2800 m depth, underlain by metamorphic basement. Potential reservoirs in the Trenton-Black River (TBR), the Galway Group (G) and Potsdam (P) Formations, and upper part of the basement are under evaluation. (B): Violin plots (kernel density plots with a boxplot in the center) of the temperature at depth in 0.5 km increments based on 10,000 Monte Carlo replicates of uncertain variables. White dots are the median estimates of the temperature at depth. The black box in the center extends from the 25th to the 75th percentile estimate. From Smith (2019) and Gustafson et al. (2019).

Active seismic: To investigate the structure of the bedrock near its Ithaca campus, Cornell purchased a license for approximately 167 km of 2D hydrocarbon-industry seismic reflection profiles collected mostly in Tompkins County in 2007. These data were then commercially processed and are being examined by Cornell geoscientists. The vertical distribution of sedimentary rocks known from deep hydrocarbon boreholes is being used as the basis for the approximate sedimentary unit identification of packages of seismic reflections to a depth of about 3 km. Sedimentary units with possible interest as geothermal reservoirs at Cornell are expected within the lowest 300–600 m of sedimentary rocks, above the basement. A primary goal of this analysis is to identify disruptions to the positions or continuities of the reflective sedimentary rock units and classify them as either folds, which are smooth undulations of the rocks, or faults, which are breaks in the units. Additionally, the analysis will classify possible faults as either subvertical or subhorizontal (i.e., thrust faults) in order to facilitate evaluation of any associated technical or environmental risks. This analysis is ongoing, and the results when available will inform the geologic and reservoir models, risk analyses, and drilling/development strategy for Cornell's ESH project.

To supplement the leased industry seismic survey data, Cornell carried out its own active seismic survey in 2018. Whereas the industry surveys provide insight into the subsurface geology for a region of about 600 km^2, the Cornell survey focused on investigation of potential structures in a 3 km^2 area close to proposed ESH drill sites. A Vibroseis truck and a network of 382 receivers was deployed for the survey, as shown in Figure 12. The receiver nodes and shot locations were generally spaced 25 m apart. Once the surveying was completed, the nodes remained in the ground for a period of two weeks during which they continuously recorded, serving as a passive survey used to monitor background vibrations. Data reduction and analysis for the Vibroseis survey are ongoing; the resulting subsurface profiles will be compared to the industry data profiles in order to identify bedrock structures and to improve estimates of the depth to basement in the area.

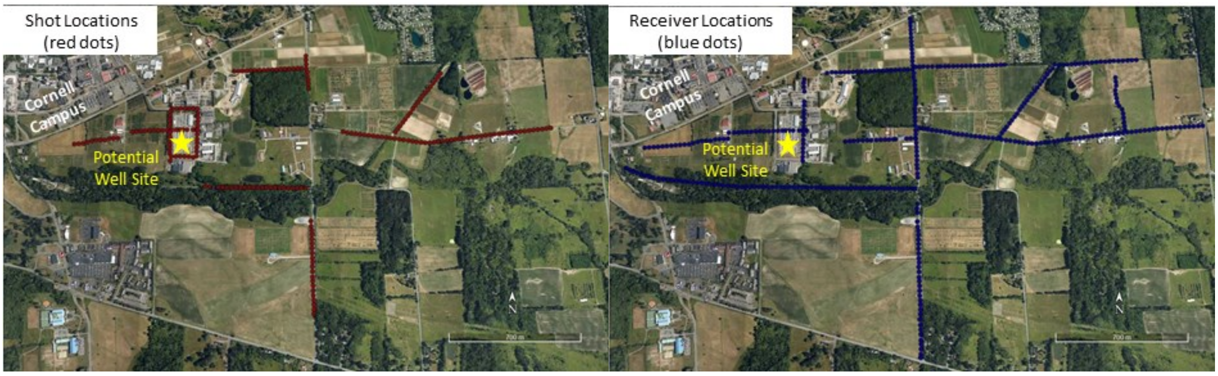


Figure 12. Shot and receiver locations for the 2018 active seismic survey.

***Passive seismic*:** For approximately 12 months in 2015-16, Cornell operated a network of 12 seismographs on and near the Ithaca campus to monitor background seismic activity. This monitoring project had two main purposes: to determine the baseline level of seismic activity in our area prior to development of our geothermal reservoir, and to identify any faults or other geologic structures near campus that might be producing previously undetected microseismic activity.

The Ithaca area is notable for its lack of recorded and historic seismic activity. The lack of observed earthquake activity in a given area could be construed as due to the lack of sufficient subsurface stress and/or appropriately oriented weaknesses in the crust. A prime candidate for such weaknesses are faults formed by ancient geological processes but which fail to exhibit modern activity in the form of earthquakes. An alternate hypothesis is that such weaknesses may be active but represented by seismic events that are very rare and/or too small to be detected by the long-term seismic networks that have operated on regional scales. Such small magnitude seismicity, if present, might identify a structure that could possibly host a future earthquake of larger magnitude if underground stresses were to change sufficiently.

Anthropogenic activities such as underground storage of waste fluids, hydraulic fracturing for unconventional gas recovery, and operation of EGS have been linked with induced seismicity in some areas. Measuring the background level of seismic activity is essential for understanding the potential for induced seismicity and for implementing a plan to mitigate unwanted induced seismicity. In addition, detection of faults or other structures through passive seismic imaging is useful for developing a conceptual geologic model of the subsurface; such a model provides important constraints on drilling and reservoir development.

Preliminary examination of the data from our network identified 72 events that are likely to be earthquakes in our region. Considering only events for which the array geometry and signal quality allowed reasonably precise hypocenter location, 19 earthquakes were detected in Central NY. Comparison of these locations with those logged by the USGS at the National Earthquake Information Center indicates that most, if not all, of these events were not detected by the permanent U.S. national seismic network. We interpret this to indicate that the Cornell network was able to detect events well below the M3.0 threshold for catalog completeness associated with the US permanent network, and that the apparent aseismicity of the Ithaca area is an artifact of the detection limits of conventional networks rather than complete lack of natural seismic events. Formal estimation of the magnitudes of these events is underway; preliminary estimates suggest that they are $M<2$ with most $M<1$. There have been no reports that any have been felt at the surface. No events above the detection limits of our array were found near the proposed drilling site for the ESH project.

To build on this preliminary data set of microseismic events, Cornell is installing in 2019 a second passive network consisting of 15 seismometers deployed across a ~10 x 20 km area surrounding the campus. The aperture of this array was chosen to facilitate hypocenter location for potential microseismic events occurring along previously mapped faults and anticlines in the area. To improve sensitivity, seven of the instruments are installed in 10-meter deep boreholes; the remaining eight instruments are placed in shallow surface pits. This improved sensitivity will allow detection of more subtle movements along any currently unknown faults or other structures near the proposed drill site, should any exist. In addition, the ability to detect lower energy events will provide a better characterization of baseline microseismic activity, either natural or anthropogenic.

Gravity and Magnetics: Cornell researchers obtained and analyzed gravity and aeromagnetic survey data near campus to look for geological structures that might be encountered at the proposed drilling site (Horowitz, 2019). Gravity measurements were collected at 395 stations across a 12.5 km x 12.5 km area centered near the Cornell campus. We purchased rights to a 1999 aeromagnetic survey data collected over Tompkins County (nominal flight-line spacing of 1/3 mile and along-line sample spacing of approximately 25 meters). Both of these data sets were analyzed using a Poisson wavelet multi-scale edge analysis of potential fields, informally known as the 'worm' technique (Hornby et al., 1999; independently derived by Moreau et al., 1997). This technique uses gravity and magnetic fields to detect lateral contrasts ("edges") in mass density or magnetization strength, respectively, and is widely deployed in the mining community in Australia and elsewhere (e.g., GoldCorp, 2001).

Map views of the inferred 3D structures are shown in Figures 13 (based on gravity survey) and 14 (based on aeromagnetic survey). The gravity survey found one strong and apparently deep structure of interest to the south of the Cornell campus. The structure strikes roughly E-W and dips about 60° to the north. The analysis of the aeromagnetic data shows another strong and deep feature in roughly the same area, with a similar strike but the opposite sense of dip. Shallower and weaker features were also inferred near the proposed drilling site; we interpret them as being relatively minor lateral discontinuities in shallower sections of the sedimentary basin above our potential geothermal reservoir. The limited precision inherent in these measurements, along with multiple possible explanations for the inferred lateral contrasts in bedrock properties, do not allow us to reach specific conclusions regarding the nature of the geologic structures present. However, these data complement the seismic reflection data to further illuminate the deep bedrock structure near the Cornell campus, and will provide context for planned cutting and core sample analysis during installation of the initial test well.

***Remote sensing using InSAR**:* Cornell is analyzing satellite interferometric synthetic aperture radar (InSAR) data to determine if sub-cm/yr rates of ground movement can be measured and to assess the extent of any background surface deformation before drilling begins. There are reports of cm/yr rates of ground motion above an old salt mine about 10 km north of Cornell's campus, from ground surveys; this is a good target to assess the accuracy of our measurements. There are limited useful InSAR data available for the region, but there is a good time series from the openly available Sentinel-1a/1b satellites from the European Space Agency starting in late 2016, and we have paid for the TerraSAR-X satellite of the German Space Agency to collect data over Ithaca starting in 2018. Examples from geothermal energy plants in Germany show that rates of movement can be detected to sub-cm accuracy in areas with similar vegetation and seasonal snow cover to Ithaca (e.g., Heimlich et al., 2015). Continued InSAR measurements during ESH operations will seek to detect ground deformation caused by subsurface fluid injection, removal, or well casing leaks. Use of satellite technologies allows greater density of observations over a larger area at lower cost than ground surveys, but ground surveys will also be undertaken to validate the satellite results.

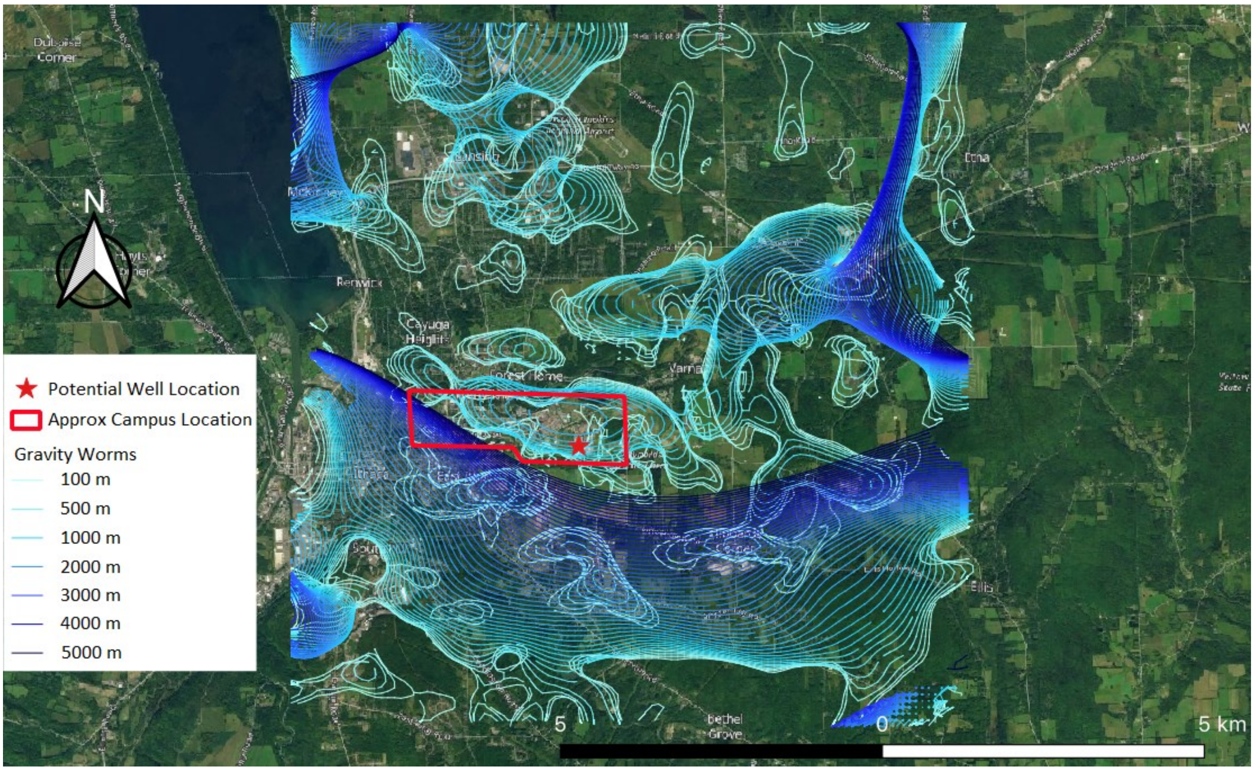


Figure 13. Contours of subsurface density boundaries inferred from gravity data.

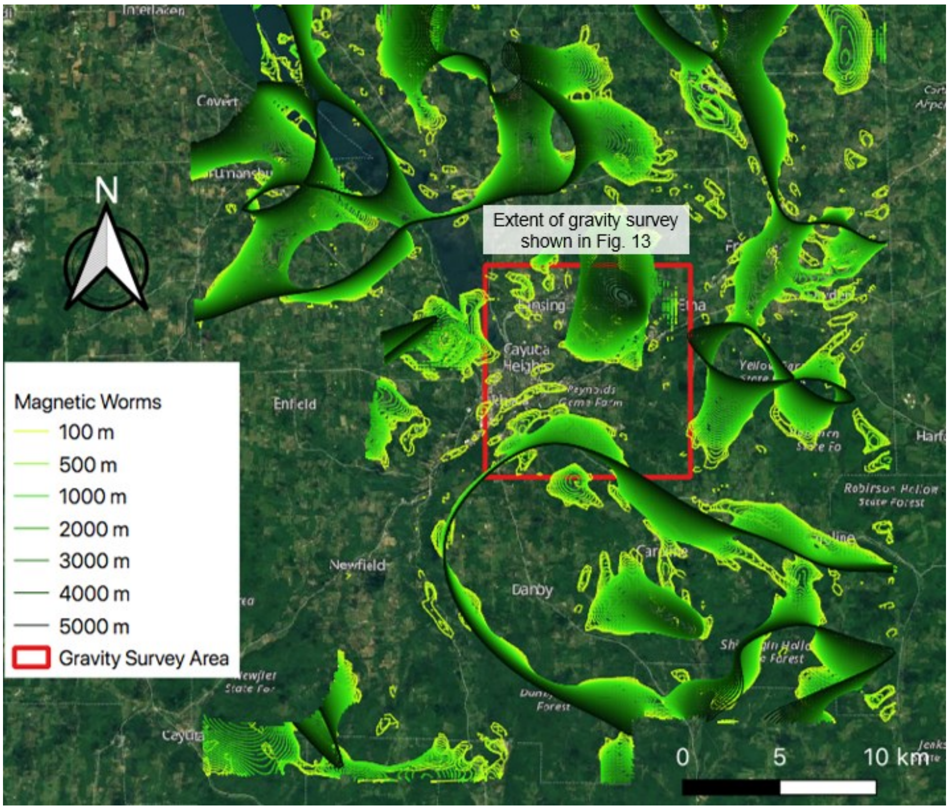


Figure 14. Contours of subsurface rock property boundaries inferred from magnetic data. The areal extent of the gravity survey (Figure 13) is shown by the red box.

5. TECHNICAL AND ECONOMIC PERFORMANCE REQUIREMENTS OF ESH RESERVOIRS

5.1 Reservoir and system performance goals

Reservoir performance: To supply geothermal heat reliably to a district energy system, the reservoir must have sufficient capacity to meet demands. Specifically, for Cornell's energy system, this requires potential reservoirs to have rock temperatures higher than 60°C and effective permeabilities that will enable fluid production rates of 30 to 50 kg/s to insure thermal extraction rates of 5 to 15 MW_{th} for each well pair. In addition, based on the financial assumptions we are using, reservoir lifetimes of 30 years are desired to be competitive with today's energy market prices.

We anticipate designing the active reservoir based on the rock volume contained between an injection and production well doublet. To ensure acceptable reservoir lifetimes, inter-well spacings ranging from 500 m to 1000 m will be needed. Furthermore, pressure drops between the injection and production wells must be sufficiently low to minimize parasitic pumping losses and to ensure that water losses and induced seismicity are within acceptable levels. This will require that effective *in situ* reservoir pressures are kept below a maximum value determined by the confining stress field. Using downhole pumps in the production well will help keep reservoir pressures at acceptable levels while still maintaining sufficient production flow. If insufficient production rates occur within these pressure constraints, hydraulic stimulation may be used to enhance inter-well connectivity.

District heating demonstration goals: Modeling shows that high value is obtained by integrating one well pair into Cornell's DES. Specifically, a viable system (one with 50 kg/s flow within any of the available subsurface heat reservoirs) could provide the following benefits:

1. Provide over 20% of annual heat load
2. With strategic integration of heat pumps, provide up to 40% of annual heat load
3. Achieve a nearly 100% annual utilization, i.e., the derived heat could be used year-round (In the summer months, most heating is used for domestic hot water and cooling system reheat.)
4. Provide heat at costs comparable to that obtained from commercial natural gas

The single most significant unknown remains the flow rate achievable within the geology under the Cornell campus, followed by the companion unknown of how well distributed that flow might be, which is a necessity to capture heat effectively. An initial single well drilled at the site will reduce uncertainties by allowing us to measure rock temperatures, in situ rock matrix permeability, and confining stresses over a range of depths from 2 to 5 km. The first well pair will be used to establish reservoir flow production levels and to estimate reservoir lifetimes.

Beyond the first well set, the financial challenges to completely transforming Cornell's DES to a geothermal energy supply are substantial. Specifically, whereas the second well set would require a similar investment (if not quite the same level of perceived risk), the return on investment would be reduced because the increased capacity of geothermal energy heating system use would bring value to campus only seasonally, unless new warm-season uses for the heat are developed. For this same reason, the third well set becomes even more challenging.

5.2 Wellbore and ESH reservoir modeling and simulation

General modeling approach: Cornell's modeling program provides a useful tool for determining the optimal build-out, as well as the optimal integration of other technologies (e.g., "peripheral" heat pumps for specific loads; biomass generation, storage, and winter combustion; hot water storage; solar thermal, etc.) By simply modifying the anticipated flow to represent multiple well-sets, the program can provide realistic expectations of heat use for essentially any number of well sets placed in a defined reservoir with specified geometric, geologic and hydraulic properties.

Potential reservoirs: Two potential geothermal reservoir target formations were evaluated for their feasibility to meet the heating demands of the Cornell campus. The shallower target is in sedimentary rocks at approximately 2,270 m depth within the Trenton-Black River (TBR) carbonate group (Figure 11A). While known to be excellent gas reservoirs at some nearby locations, these reservoirs are spatially dispersed, with locations controlled by subtle faults that have no surface expression (Camp and Jordan, 2017), and suitable rocks may not underlie Cornell. The deeper target modeled to date is in Precambrian basement rock starting at 3,000 m depth, for which only very limited information about hydrogeologic and thermal properties is available in the Cornell region.

The reservoir models utilize temperature profile uncertainties corresponding to the coolest 5^{th} percentile, median, and warmest 5^{th} percentile (Figure 11B). The shallowest grid cells use a constant temperature boundary condition consistent with these temperature profiles. Uncertainties in the expected temperature at depth and geologic properties are propagated through thermal-hydraulic models of each reservoir using stochastic simulations to estimate the range of likely thermal production for incorporation into several utilization scenarios.

***Reservoir performance simulations*:** Without actual information about rock properties in the depth regions of interest for ESH at the Ithaca site, we adopted, first, a simplified first-order modeling approach, and second, to quantify the impacts of the uncertainties on reservoir heat extraction performance. The TBR sedimentary reservoir was modeled as a uniform porous media layer confined above and below by impermeable rock, using the numerical thermal-hydraulic model TOUGH2 (Pruess et al., 2012). The basement reservoir was modeled using the Gringarten et al. (1975) heat transfer model incorporated in the GEOPHIRES code (see Section 5.4) which assumes unidirectional, uniform flow through a set of parallel, vertical fractures. There are three main considerations for each of these geothermal reservoir models: 1) selection of the properties for the rock matrix and associated geological structures, 2) setting the initial and boundary thermodynamic conditions, and 3) selecting the parameters of the model simulation.

Smith (2019) documented the geological parameters, grid cell sizes, and simulation parameters for the numerical TOUGH2 simulations. For the reservoir in basement rocks, fracture spacings and apertures were estimated based on mapping of outcrops and airborne LiDAR in the Adirondack Mountains (Section 4.2). In analytical models, we considered flow in fractures with spacings ranging from 30 m to 200 m over a 1 km horizontal lateral well length. For simulations near the top of basement, results revealed that fracture spacing greater than about 50 m may not provide adequate long-term production. We present basement reservoir results for simulations with 30 m fracture spacings, which produces favorable long-term production. If such spacings do not occur naturally for basement rocks below Cornell, it may be possible to use EGS techniques to engineer such a fracture system.

The impacts of uncertainties on reservoir heat extraction performance were evaluated and are reported in a separate 2020 WGC paper (Smith and Beckers, 2020). Representative predictions of reservoir thermal performance are presented in this paper. Predicted temperature production results for the TBR play at 2.27 – 2.3 km depth and for crystalline basement at 3.0 – 3.5 km depth are shown in Figure 15.

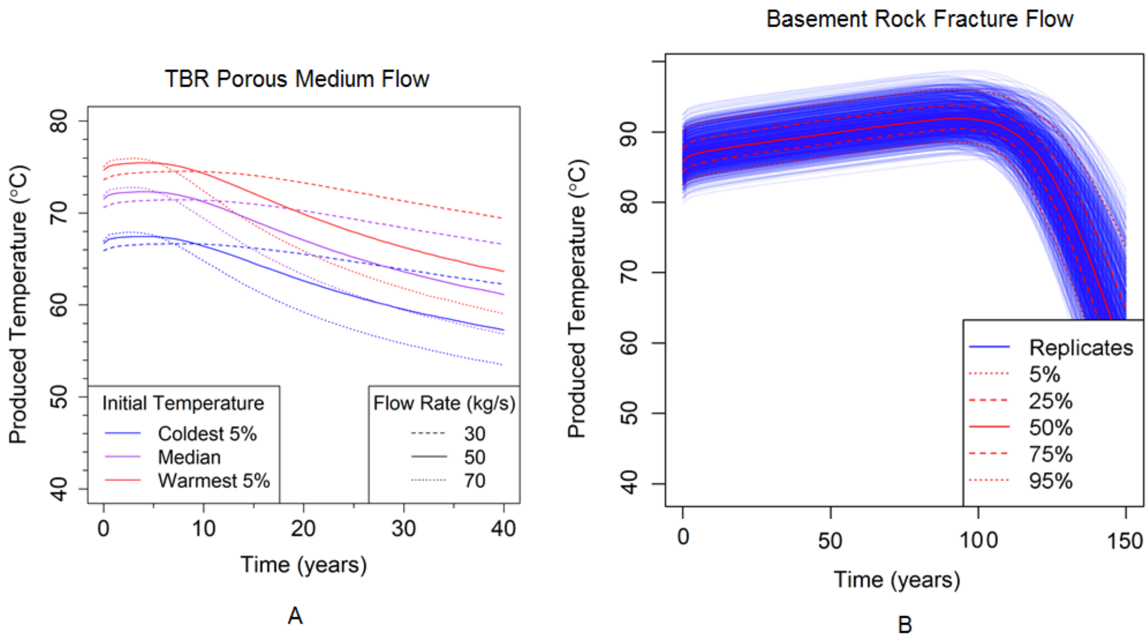


Figure 15: Estimated production temperature over time for the Trenton-Black River (A) and the basement rock (B). Injection temperature is 20°C. The initial rock temperature percentiles were selected based on the estimated temperatures at depth (Figure 11). In (B), the flow rate is 30 kg/s, each blue line provides the results of a single Monte Carlo replicate, and selected quantiles are provided in red.

For all the TBR scenarios shown, thermal heat production meets or exceeds the target heat production of 5.5 MW_{th}. The produced temperatures exceed the "low temperature facilities" (see Surface Use Modeling section) supply temperature of 60°C for a minimum of about 20 years for the coolest 5th percentile temperature estimates. Even for the most optimistic case it is unlikely that the TBR reservoir would provide produced fluid temperatures at 80°C or above, as needed for use in Cornell's "high temperature facilities". As expected, pumping rates have a clear impact on the time to thermal breakthrough. Pumping rates of 50 and 70 kg/s result in temperature declines within 10 years of operation. Pumping at 30 kg/s results in temperature decline beginning around 15 years, and a relatively longer time to complete thermal breakthrough.

All of the Monte Carlo replicates for the basement heat extraction indicate heat production rates in excess of the 5.5 MW_{th} target. The median modeled production temperature ranges from ~85°C at startup to close to ~88 °C in year 50. Such temperatures would be sufficient for "high-temperature facilities," and could be used for additional cascaded heat demands. The temperature and heat produced shown by the model increase over the first ~100 years because we have modeled the injection well at the bottom of the reservoir and the production well at the top; the resulting fluid flow carries heat from deeper in the reservoir up toward the production well until thermal breakthrough begins to occur.

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

5.3 Modeling the use of heat within the Cornell district energy system

To conduct a complete techno-economic assessment of ESH, the reservoir models were coupled to models that simulate the surface DES. This modeling effort (Figure 16) utilized detailed data on building energy use (hourly heat sales for over 100 metered buildings; Figure 17) with district heating system variable flows and other system assets to predict how much heat could be obtained for each hour of usage throughout the year. The hour-by-hour thermal needs on campus are broken down by building types that use heat similarly (i.e., require specific temperatures for operation and reject heat at like temperatures).

The model — which Cornell named MEnU (for "Modeling Energy Use") — also allows verification of the best arrangement for other system assets, from placement of each system that adds heat (geothermal, heat pumps, CHP, boilers, storage tank) to optimization of pumping rates to investments in building efficiency improvements. An example simulation run is shown in Figure 18, illustrating how the Cornell heating load could be managed in the future using different assets (geothermal heat, storage, central plant or biomass).

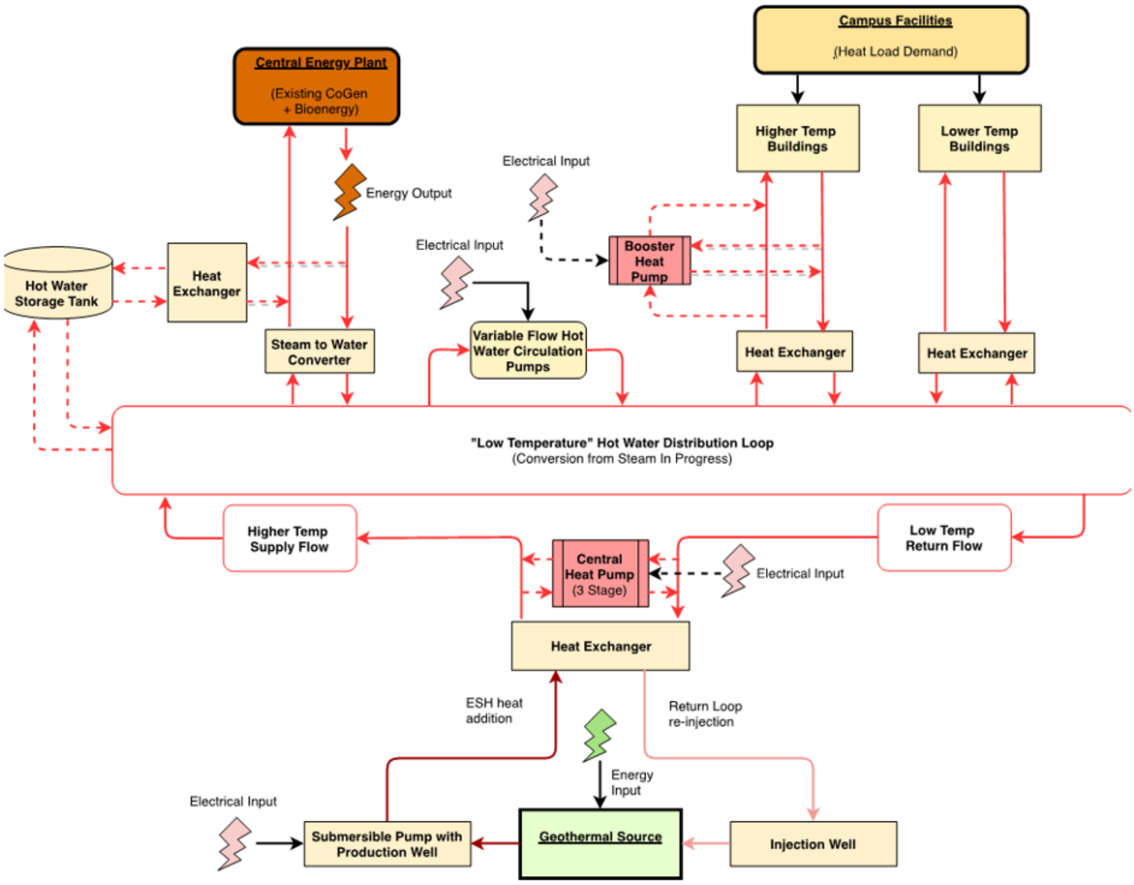


Figure 16. Schematic of Cornell's geothermal energy integration model (MEnU). A geothermal resource provides the first energy input to the district heating loop, offsetting downstream fossil energy inputs at the Central Heating Plant and thereby reducing GHGs.

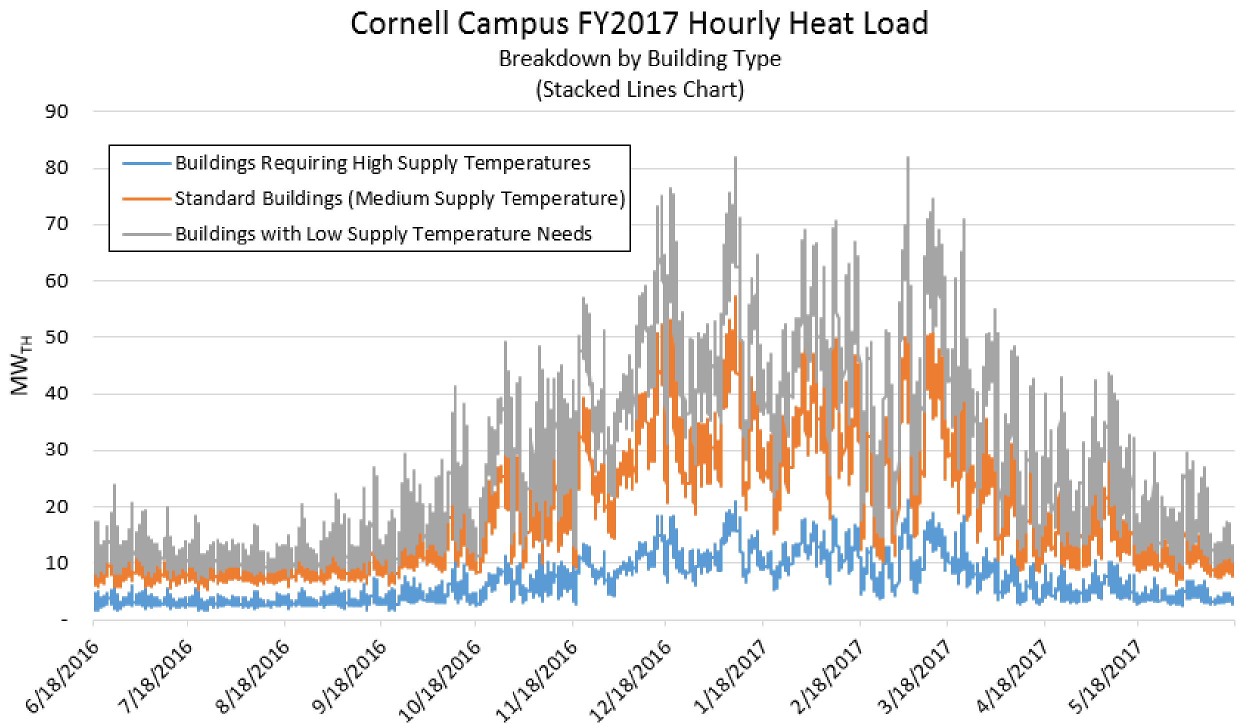


Figure 17. Hourly heat demands of campus based on hourly metered totals, July 1 through June 30 (campus fiscal year). The chart is a stacked line chart: the blue line represents the demand by buildings with higher temperature needs (>80°C); the orange line represents the demand by buildings requiring at least 70°C, and the grey line represents the entire heat load, and thus including buildings with lower temperature needs (modeled as 60°C demand). Categorizing buildings allow modeling of cascading flow arrangements and/or peripheral heat pumps to boost a lower distribution loop temperature only where needed. Cornell's model shows the impact of building design on geothermal extraction value.

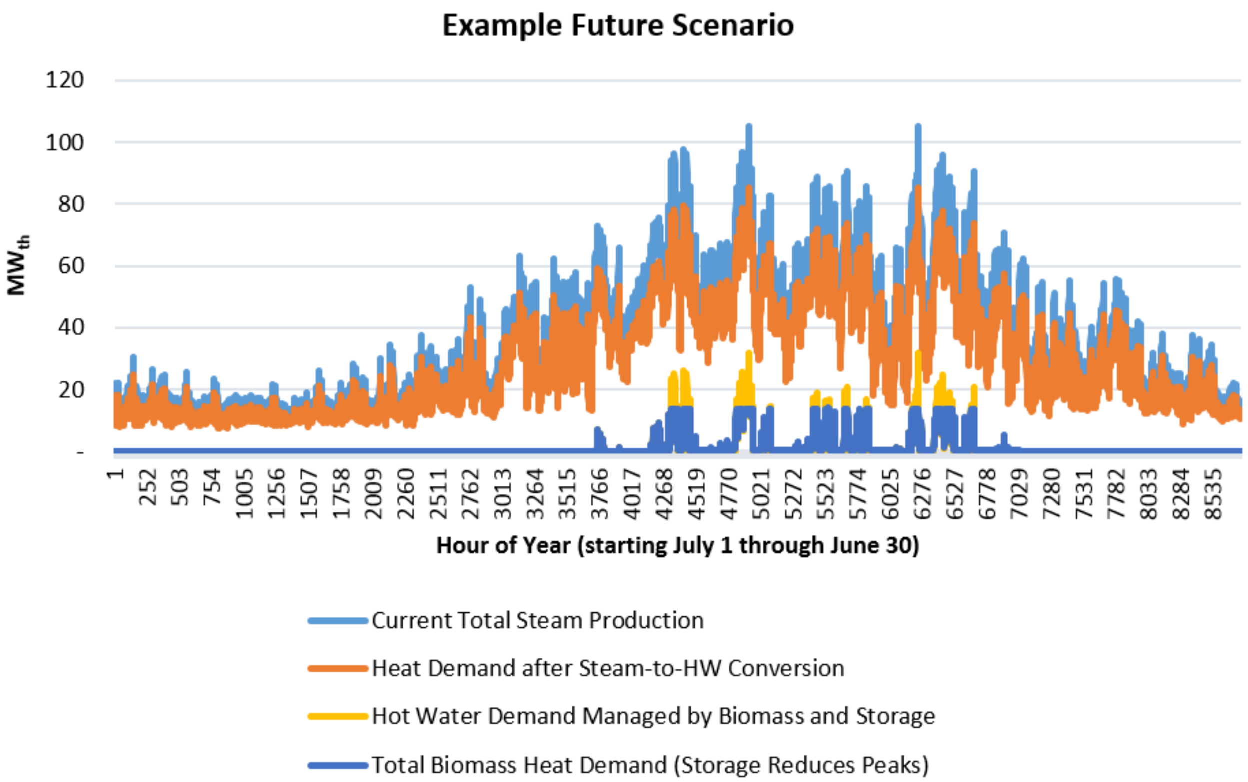


Figure 18. MEnU example simulation run for a future scenario. In this run, the campus load (up to 80+ MW_{th}) is accommodated using four geothermal well sets to supply approximately 52 MW_{th} to the campus distribution system including augmentation of fluid temperature by heat pumps when needed, 16M liter of hot water storage, and 14 MW_{th} of peaking bioenergy for coldest days. Peaking boiler size can be further reduced with more thermal storage, additional heat pump augmentation, or if buildings are modified to extract more heat (return cooler water).

These modeling efforts enabled the development of strategies for efficiently utilizing the heat supplied by the first geothermal well set:

- Base design on the lowest distribution temperature that can serve campus needs. For the Cornell campus, a temperature of 80°C was chosen.
- Use the geothermal source as a "pre-heater". Like the system serving Rosny-sous-Bois just outside Paris, France (Beyers and Racle, 2020), the geothermal source is most useful as baseload to add energy to the lowest temperature water in the distribution loop. Allowing the geothermal source as the first input results in more energy extraction and higher GHG reductions.
- Use variable flow pumps for the distribution loop. Over-pumping not only wastes energy but limits the degree of heat exchange (temperature drop) at the building heat exchangers; minimizing flow to what is needed results in maximum heat extraction on a per-liter basis.
- Use a central heat pump. A heat pump located at or near the geothermal well can significantly increase the temperature extraction by transferring from fluid that has already circulated the campus loop much of the remaining heat that would otherwise return to the subsurface. This return flow is typically still hot enough to result in a high heat pump COP (>6) — much higher than for a conventional ground-source heat pump (~4). This latter strategy is addressed in more detail in another WGC paper (Beyers and Racle, 2020).

5.4 Techno-economic analysis of ESH using GEOPHIRES

Techno-economic analysis (TEA) has been conducted to estimate the required upfront capital investment, annual operation and maintenance (O&M) costs, and overall cost-competitiveness of an ESH system at the Cornell Ithaca campus. The analysis was performed using the updated GEOPHIRES v2.0 software (Beckers and McCabe, 2018) combined with the spreadsheet-based MEnU tool (see Figure 16) for simulating the geothermal reservoir and campus surface energy system and calculating the overall levelized cost of heat (LCOH).

The model assumptions and input parameters are listed in Table 5, and build on the two reservoir models discussed in Section 5.2. For each reservoir, a doublet was assumed with one injection well and one production well. Flow rates from 30 to 70 kg/s were considered, however, the results presented in this section are for the median flow rate (50 kg/s). As discussed in Section 5.3, an industrial heat pump unit is included to extract additional heat from the geothermal fluid (at very high COP) and boost production temperature on demand. The MEnU simulator estimates the annual delivered heat to campus from the coupled deep geothermal doublet and heat pump system. Limited system downtime is assumed with a capacity factor on the order of 98%. The capacity factor is defined here as the percentage of time the system is in operation. Thermal drawdown was considered separately, when calculating the annual amount of heat produced. Given that Cornell is a not-for-profit academic institution, the discount rate is low (2.5% real discount rate or 5% nominal discount rate) and tax rates are set to zero. A typical value of 30 years is assumed for the plant lifetime.

Table 5. Techno-economic base case parameter values for Cornell ESH system. The base case assumes median formation temperatures and production well flow rate. HP refers to heat pump.

Parameter	Value
Geothermal Reservoir Technical Parameters	
Well Depth	TBR: ~2.2 km; Basement: ~3.5 km
Formation Temperature	TBR: ~72°C; Basement: ~96°C
Well Configuration	Doublet
Reservoir Drawdown	See Section 3.3
Production Well Flow Rate	50 kg/s
Water Loss Rate	1%
Surface Plant Technical Parameters	
End-use Application	Direct use for campus heating with HP boosters
Capacity Factor	~98%
Reinjection Temperature	~20°C (with use of HP)
Financial Parameters	
System Lifetime	30 years
Nominal Discount Rate	5% (campus published standard rate)
Inflation Rate	2.5%
Real Discount Rate	2.5%
Tax rate	0% (Cornell is not-for-profit institution)
Incentives/Subsidies	No subsidies or incentives applied
Levelized Cost Model	Standard levelized cost model with discounting
Cost Parameters	
Well Drilling and Completion Cost	GEOPHIRES built-in correlations
Well and Reservoir Stimulation Costs	$800k based on JEDI tool
Electricity Rate (for pumping and HPs)	$33/MWh (campus marginal rate)
Make-up Water Rate	$35 per 100 m^3 (campus marginal rate)
Exploration Costs	Not considered
Maintenance and Labor Cost	Based on campus LSC system

Table 6. Estimated Cornell ESH system installed capacity, annual heat production, capital costs, operating and maintenance costs, and levelized cost of heat (LCOH) for the Sedimentary Trenton Black River (TBR) rock and Basement rock reservoirs. Results are reported for the base case with a 50 kg/s production well flow rate.

	TBR	Basement
Installed Capacity	10.5 MW_{th}	13 MW_{th}
Average Annual Heat Production	92 GWh/year	115 GWh/year
Total capital costs	$21.9M	$30.0M
Well Drilling and Completion (for 2 wells)	$7.4M	$12.9M
Reservoir Stimulation	$0.8M	$0.8M
Surface Heat Exchanger and Pump Facility	$2.2M	$2.2M
Heat Pump Equipment	$10.5M	$13.1M
Connection to Campus District Heating System	$1.0M	$1.0M
Total Operating & Maintenance Cost	$918K/year	$865K/year
Operating Labor	$50K/year	$50K/year
Pump Electricity	$98K/year	$75K/year
Heat Pump Electricity	$541K/year	$429K/year
Water	$11K/year	$11K/year
Maintenance	$219K/year	$300K/year
Levelized Cost of Heat (LCOH)	$6.16/MMBtu ($21/MWh)	$5.94/MMBtu ($20/MWh)

Capital cost estimates were based on GEOPHIRES built-in correlations for well drilling and completion costs, the NREL JEDI tool for reservoir stimulation cost, and experience gained with the existing campus cooling facility and reported piping and heat pump cost figures for surface equipment costs (heat exchanger and pump facility, heat pump unit and interconnecting pipe to existing heating network). Exploration and science costs, and costs for converting the existing steam-based to a liquid water-based district heating system were not considered as part of the LCOH calculation. O&M costs are based on current labor and maintenance costs for the campus district heating and LSC system. Electricity and make-up water rates are based on respective campus marginal rates.

Techno-economic simulation results are presented in Table 6. The installed capacity of the deep geothermal doublet – heat pump system is on the order for 10.5 MW_{th} and 13 MW_{th} for the TBR and basement reservoir, respectively. As discussed in Section 5.1, this plant size allows for continuous heat production during the summer months, resulting in high capacity factors and delivering on the order of 100 GWh of heat per year. The capital and O&M costs for the TBR case are around $22M and $920k/year, and for the basement case around \$30M and \$870k/year. Lower heat pump electricity consumption is the main reason for lower O&M costs in the basement case. The overall levelized cost of heat (LCOH) for both the TBR and basement case is around \$20/MWh or \$6/million BTU. This relatively low LCOH is a result of a combination of factors including a low discount rate, low electricity rate (for heat pump electricity consumption) and high capacity factor. Uncertainty in results are discussed in other works including Smith (2019), and Smith and Beckers (2020).

6. CONCLUSIONS AND PLAN

6.1 Conclusions

An important facet of Cornell's efforts to achieve a carbon-neutral campus is demonstrating that Earth Source Heat (ESH) could be used in an operating district heating system at sufficient scale for widespread deployment. For example, NY state, the six New England states, and many other states in America's Northern Tier have significant space and water heating demands. As a percentage of their total statewide energy consumption, the heating demand in this region is comparable to the electrical demand. To meet state targets for mitigating climate change will require substantial reductions in GHG emissions associated with heating. To get there, an integrated system approach will be needed to decarbonize the entire energy system, not just the part for electricity production. Geothermal district heating provides an attractive renewable energy option for providing low-temperature baseload space and water heating to entire communities in these northern states.

The Cornell's ESH project team is investigating utilizing deep geothermal heat extraction combined with central heat pumps to provide a significant fraction of Ithaca campus heating demand. The status of the project was reported in this paper. Various methods have been applied to characterize structure and properties of the subsurface in our region to identify the best sites for drilling the first set of geothermal wells. The methods applied included: review and correlating extensive bottom hole temperature (BHT) data and subsurface geology in our region, active and passive seismic imaging, gravity and aeromagnetic mapping, and well log analysis.

In this paper, two potential reservoirs were considered: a sedimentary rock system in the Trenton Black River (TBR) formation at ~72°C and ~2.2 km depth, and one in basement rock at ~96°C and ~3.5 km depth. The thermal performance of these two potential reservoirs was estimated using a TOUGH2 model for the TBR system and a discrete fracture model for the basement rock system. A techno-economic assessment (TEA) was conducted that incorporated estimated reservoir thermal production with a model of Cornell's district heating system, and incorporating parameter uncertainty — to optimize geothermal system integration and to predict ESH system technical and economic performance. One well pair is considered (1 injector and 1 producer) with well spacing of 1000 m and production flow rate of 50 kg/s. The overall system capacity factor is 98%. The levelized cost of heat (LCOH) was estimated to be on the order of \$6/MMBtu which would be very competitive in commercial energy markets in NY State today. To sum up, the TEA modeling indicates that, with proper planning and system integration, at least the first ESH geothermal well pair can be incorporated economically. The first well pair has the advantage of almost 100% utilization, as Cornell's summer loads are sufficient to occupy the output of one well pair.

We believe that a successful demonstration of geothermal district heating at Cornell with these levels of technical and economic performance would catalyze development of ESH for direct use in other communities in New York and in the northern regions of the U.S. with comparable annual heating demands.

6.2 Outlook for the future

Cornell's ambitious plan for climate neutrality is on track, but the integration of renewable heat remains a significant challenge. This challenge requires two parallel campus actions: continuing the conversion of the steam system to hot water so that it is ready to accept renewable heat from a variety of potential sources, and creating a geothermal well set to demonstrate and test the performance of direct geothermal heat for the Ithaca campus.

Planned phased development: Future development of geothermal well sets becomes more financially challenging because Cornell does not have as extensive a demand for heat in the summer months as in winter, spring, or fall seasons, resulting in a lower return on essentially the same capital investment. The Cornell MEnU model helps with future development: different mixes of hot water storage, heat pump arrangements and operation scenarios, biomass (or other renewable) heat inputs, and new cascading uses can be readily modeled to determine best system-wide financial matches.

Keys to demonstrating value:

- Upgrade Cornell's heating network: Modify the heating distribution and building heating systems (and design new systems) to maximize use of low-temperature fluids, and continue to incrementally improve the campus moving forward
- Incorporate key operating assets: hot water storage, variable speed distribution pumps, heat pumps, and other "tools" to modulate operations over time and over seasons. These assets help create an integrated system that can be optimized for different loads and asset availability, while reliably meeting building needs.
- Utilize other renewable sources for peak loads: Although biomass or solar thermal hot water are not feasible at the scale needed for primary heating, nevertheless modeling demonstrates that they may be ideal for optimizing total system performance at lowest cost during peak heating periods.

Keys to managing risk: There are two primary risks involved in developing geothermal heat for campus: technical and financial risks. Cornell will manage technical risks in the following ways:

- Cornell will retain our natural-gas fired CHP plant. For the initial demonstration project, ESH will essentially be just another asset for campus heat.
- Cornell will integrate the ESH flow so that it adds heat at the lowest temperature point in the distribution system, which is the return flow to the CHP plant. Adding heat at the lowest temperature point maximizes the geothermal heat extraction.

- Multiple geothermal assets (different fluid temperatures and flow rates) can be modeled with MEnU, so we can optimize any resource flow and temperature we are able to achieve.
- Using assets like central heat pumps and storage permits a further optimization of configurations.
- Setting a goal for the first well pair of optimizing fossil reductions — rather than supplying 100% of the system — provides an ability to look at multiple configurations and asset sets to maximize potential.
- Drilling of an exploratory borehole is scheduled for the second half of 2021. This borehole will allow to obtain in-situ subsurface data, thereby significantly decreasing our uncertainty on rock and reservoir properties (e.g., temperature, porosity, permeability).

Although there remains the risk of aggressive fluid chemistry or insufficient flow, based on work done around the world on geothermal reservoir management, we expect to be able to engineer workable solutions.

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