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Geothermal direct use for decarbonization — progress towards demonstrating Earth Source Heat at Cornell

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ABSTRACT

Space and water heating in residential and commercial buildings and low-temperature industrial process heat in New York State are provided primarily by the combustion of fossil fuels (natural gas, fuel oil and propane) in furnaces and boilers. As a result, heating currently accounts for about 40% of the State's carbon footprint. To reach New York's aspirational goal of achieving carbon-neutrality by 2050, a transformation of its heating systems is necessary. In addition, other heating–dominated states in the Northern Tier of the U.S. face similar challenges. Geothermally-heated fluids at temperatures below 100°C could provide an affordable low-carbon alternative for meeting a majority of these heating demands. In fact, direct use geothermal energy is a key component of Cornell University's overall strategy to reach carbon neutrality by 2035.

Since 2010, Cornell has been evaluating using Earth Source Heat (ESH) for heating its campus. The basic idea of Cornell's ESH project is to circulate water through fractured regions of deep hot rock containing naturally-stored heat at temperatures high enough to be used directly to supply thermal energy to the campus district energy network. With its high baseload winter heating demand of about 50 MW_{th}, a successful demonstration of geothermal heating at Cornell would also serve as a representative and scalable model for carbon neutral heating in many other rural and urban communities. This past summer, Cornell's Earth Source Heat (ESH) project took an important step forward. In June through August 2022, an exploration well was drilled to a depth of 3 km (TD = 9790.5 ft). The exploration well is formally called the Cornell University Borehole Observatory or CUBO. The main function of CUBO is to identify and characterize target rock regions having temperatures of 80°C or higher that have the potential to be used as ESH reservoirs. Additionally, CUBO will be used for monitoring reservoir performance during the stimulation and heat extraction phases of the ESH well field contained by a set of injection and production wells. CUBO data allow identification of preliminary target regions in sedimentary rock (e.g., 8600-8750 ft. [2.6-2.7 km]), in the basal sedimentary, contact zone, and shallowest weathered basement rock (9350-9500 ft. [2.85-2.9 km]), and deeper in the metamorphic basement (9600-9720 ft [2.93-2.96 km]). Data collected during drilling and testing and subsequent analyses performed will be summarized. Results presented include: 1. Well and casing designs, 2. Drilling performance results, 3. Lithology based on mud logging, drill cuttings analysis, image logs and side wall cores, 4. Temperature and pressure based logs, 5. Preliminary flow testing to determine target formation permeability, 6. Stress direction and magnitude from caliper logs, image logs, and mini-frack tests, and. Several other papers will be presented by the Cornell ESH research team at this Workshop to provide additional details regarding the analysis of CUBO results.

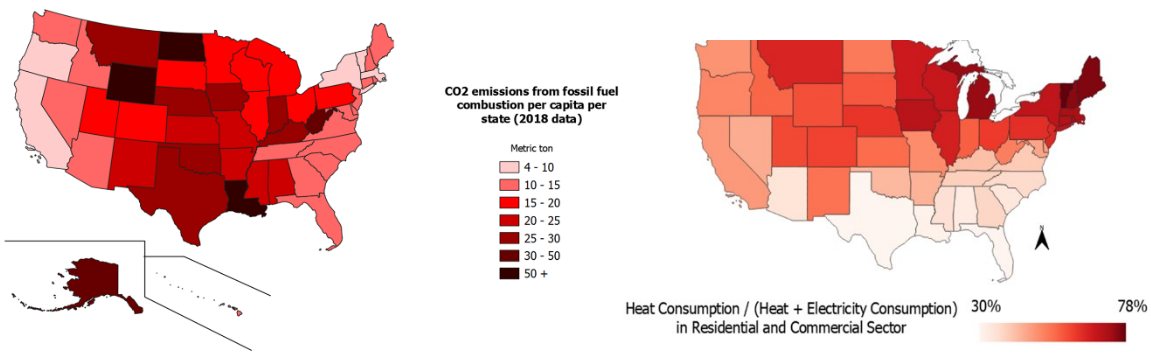
1. INTRODUCTION AND MOTIVATION

The United States, like many other developed countries, has a large carbon footprint due to its dependence on fossil fuels to meet the majority of its primary energy needs. In 2021 in the U.S. about 80% of the total primary energy consumption of 102.7 EJ was supplied by coal, natural gas, and petroleum. (EIA, 2022). In 2020, energy-related fossil fuel consumption in the U.S emitted about 4.9 Gigatons of CO_2-equivalent emissions per year, which is about 81% of the nationwide greenhouse gas footprint (EPA, 2022). Globally, primary energy demand is currently about 572 EJ per year (Ritchie et al., 2022) and greenhouse gas emissions about 50 Gigatons of CO_2-eq per year (Ritchie et al., 2020). The sustained growth of combustion-based energy from fossil fuels over the last 100 years has led to a significant increase in the atmospheric concentration of CO_2 reaching 419 ppm by the end of 2022 (NOAA, 2022). With growing climate-related concerns such as rising global temperatures and sea levels, it is becoming clear that carbon management will get more serious attention worldwide as it will require deployment on a global scale.

To achieve a significant reduction in GHG emissions in the U.S. will require decarbonizing all end use sectors — electricity generation, transportation, buildings, and industry. Currently, fossil fuel combustion is directly linked to about 81% of US's annual energy consumption with 39 EJ used for electricity generation and 28 EJ for transportation (EIA, 2022). The remaining 36 EJ are used to supply heat in residential and commercial buildings and to industrial processes with more than 20 EJ with supply temperatures below 100°C (Fox et al., 2011). U.S. heating demand is typically met using furnaces, boilers and hot water heaters that burn fossil fuels (mostly natural gas, heating oil and propane) all of which contribute directly to the nation's carbon footprint by emitting carbon dioxide. Contributions to greenhouse gas (GHG) emissions in the U.S. follow similar trends to primary energy consumption (EPA, 2022), with about 25% from electricity generation, 27% from transportation, and 31% from energy use in the residential, commercial and industrial sectors.

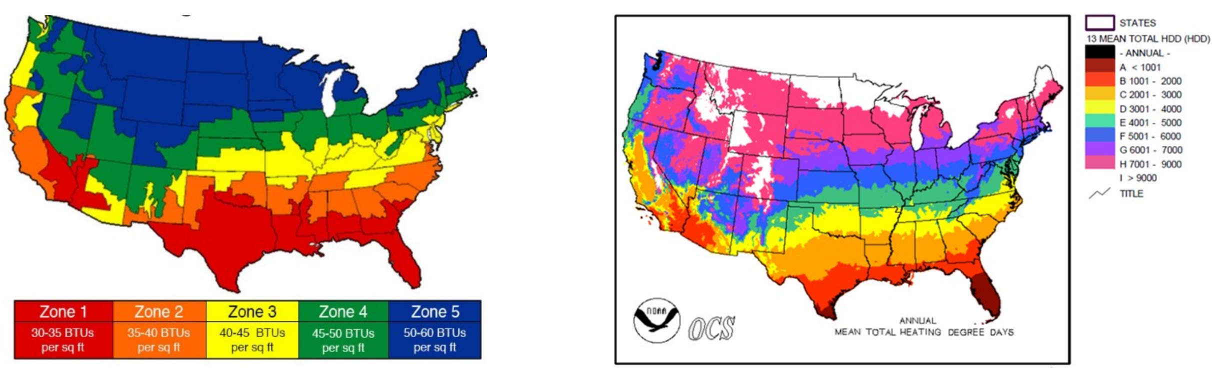
Figure 1 shows the distribution of energy consumed in the U.S. for electricity versus low-temperature heating in the residential and commercial sectors. As a result, heating demand of states in the Northern Tier constitutes a higher percentage of their total energy consumed. Southern states are located in warmer climate zones and have relatively lower heat demand but higher electricity demand usually linked to air conditioning. In any state in the U.S., low temperature heating accounts for 20 to 40% of the state's carbon footprint. With more than 16 states setting aggressive goals to decarbonize 80% of their energy use in 30 years, states need to be developing practical low-carbon alternatives to heat buildings. In northern states (e.g., New York and Illinois), which are located in colder climate zones with a higher number of heating degree days (see Figure 2), a larger fraction of the GHG emissions are due to heating. In a few states (e.g., Texas and Wyoming), relatively low contributions from residential electricity and heat demand exist with much larger from transportation, petroleum processing and other manufacturing areas. These topics are discussed in more detail in earlier papers from our group (Fox et al, 2011 and in Tester et al, 2021b). For example, in Tester et al (2021b), Table 1 provides decarbonization objectives in terms of GHG reduction targets for each state and Table 2 corresponding energy use data for each state.

While carbon emissions can technically be limited by capturing and sequestering CO_2 in geologic formations, this approach alone is not easily scalable and will not lead to a permanent solution. We need to find and develop alternatives to burning fossil fuels that are widely accessible, scalable, and affordable. In the long term, a major transformation from using depletable fossil resources to low-carbon emitting renewable energy resources is needed. A considerable amount of effort has gone into developing and deploying renewable solar and wind energy resources in the U.S. to decarbonize the generation of electricity. In addition, carbon-neutral renewable electricity can be used for electric vehicles and to power heat pumps for heating and cooling.



a) b)

Figure 1 (a): Regional climate impacts expressed in metric ton CO_2 emissions per capita from fossil fuel combustion in each state and (b): U.S. low-temperature heat demand vs electricity consumption in residential, commercial, manufacturing and agricultural sectors (2018 data). Please note that that electricity consumption data includes electrical energy used for heating.



(a) Climate Zones (b) Heating degree days

Figure 2: (a): Climate zones and (b): Annual heating degree days in U.S. (ElDoradoWeather, 2021). Colder climate states tend to have a relatively high heat demand (see Figure 1). Source – U.S. National Oceanic and Atmospheric Administration

A key question is whether electricity from solar and wind could provide a fully scalable solution for decarbonizing heating buildings and providing industrial process heat. In 2022, the power generating capacity of the U.S. is about 1,000 GW_e. To cover the increased demand for electrifying vehicles and heat pumps we would need to more than triple our current generating capacity and make it completely carbon-neutral. Furthermore, this capacity would need to be dispatchable on a daily and seasonal basis. But solar and wind are intermittent resources with both diurnal and seasonal fluctuations which would require storage for significant periods to be viable for heating. In principle, expanding, hydropower and nuclear energy could provide large amounts of carbon neutral electricity to offset the intermittency of solar and wind and limited storage capacity we have. All three of these resources should be an integral part of America's strategy for decarbonizing energy. However, there are several barriers that have limited the attention they are getting. Expanding hydropower would experience technical resource limits and both hydropower and nuclear face major public acceptance and economic issues in the U.S. Biomass provides another renewable energy option that could be harvested, stored, transported and combusted (either directly or after gasification). However, biomass feedstocks would need to be managed sustainably to keep carbon emissions low and growing biomass at a scale needed to provide significant levels of baseload electric power or heat in the U.S. would have large impacts on land use and food, water, and nutrient resources.

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 not only have low carbon emissions but they also have small land footprints. Although the U.S. installed a geothermal district heating system in Boise, Idaho in the 1880s (Tester et al., 2015), for the last 140 years, U.S. geothermal development 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 relatively close to the surface. With climate change concerns growing, renewed interest in direct use has surfaced.

Although expanding geothermal provides a potential option for decarbonizing electric power generation in high grade areas of the Western U.S., geothermal requires more resource assessment, exploration, and demonstration before a resource can be declared economically viable at new locations. This often leads to longer development times and more challenging financing arrangements than other renewable resources experience (see Tester et al. 2006 and 2019 DOE GeoVision Study). Converting high grade hydrothermal resources to electric power using produced fluid temperatures ranging from 150 to 250°C has thermodynamic limits resulting in thermal efficiencies that range from about 10 to 15%. As a result, 85 to 90 % of the thermal energy contained in the geothermal fluid will be rejected to the environment as waste heat unless it is used to provide useful low temperature heat for buildings or industry. Unfortunately, co-generation combined power and heating plants in the United States are extremely rare.

Because the direct use of geothermal does not suffer the same thermodynamic losses that accompany electric power generation, utilization efficiencies are much higher and can reach over 90% in well-designed district heating system. These higher efficiencies also improve the economics of direct use as subsurface development costs expressed in $ per unit of marketable energy delivered are inherently lower than for power generation.

As a result, using geothermal directly for carbon-neutral heating requires a closer look given that it could be viable anywhere in the U.S. For example, even in lower grade areas, rocks having temperatures ranging 50-100°C are accessible at moderate depths (< 3 km) in all 50 states, and the thermal energy extracted from them could be efficiently used for space and water heating having end-use temperatures of 40 to 80°C.

An associated benefit of transitioning to geothermal district heating could be that creation of an extensive distribution system for delivering hot water to buildings would be part of a forward looking strategy to replace the failing infrastructures that supply energy, water, communications, and manage sewage and waste of many post-industrial cities in the Northeast.

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 for context, 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 more generally in the U.S. Northern Tier region where seasonal heating demand is high and represents a large percentage of its carbon footprint.

The paper is divided into separate sections that cover:

- **Section 2: Regional geologic conditions** — Geophysical characterization of subsurface conditions in the Ithaca region
- **Section 3: Cornell's strategy for decarbonizing its energy footprint** — an energy systems approach that integrates local renewable sources for electricity, heating and cooling and energy efficiency measures to lower demand.
- **Section 4: Cornell's Earth Source Heat Project - Phased program** — including geothermal site selection, well design and placement of Cornell University's Borehole Observatory (CUBO), drilling operations, and performance modeling
- **Section 5: Preliminary results of target formation characterization and evaluation**
- **Section 6: Conclusions and plans for next phases of Cornell's ESH program.**

2. REGIONAL GEOLOGIC CONDITIONS

Cornell University, located in Ithaca, New York, is geologically located in the northern sector of the Paleozoic Appalachian sedimentary basin. These strata are a combination of marine and continental deposits encompassing a wide range of compositions (siliciclastics, carbonates and evaporites) (Figure 3). During the late stage of basin formation, the Allegheny Orogeny created a thrust belt along the southeastern margin of the basin (Figure 3, inset). Even strata that now sit at or near the surface were previously buried several kilometers deeper than present below sediment shed from the Allegheny uplifts, yet that original overburden was eroded away during the last 250 million years. For instance, rocks at Ithaca are estimated to have been buried 3 to 4 km deeper at the end of the Paleozoic (Miller and Duddy, 1989; Shorten and Fitzgerald, 2019). Underlying the thousands of meters of sedimentary rock is a lithologically abrupt contact over crystalline basement rock. Regionally, most of those metamorphic rocks are high grade metamorphic lithologies such as paragneisses and orthogneisses like those of the Adirondack Mountains (Figure 3), transformed by extremely high temperatures and pressures while buried to about 30 km depth during the Grenville Orogeny (McClelland et al, 2010). Yet locally in the Appalachian Mountains, Neoproterozoic basin-fill occurs between the high-grade basement and the Paleozoic strata; these are low-grade metamorphosed metasediments and metavolcanics (Bailey et al., 2007; McLellan and Gazel, 2014). Also locally, particularly in the southwestern Appalachian Basin, strata deposited in latest Precambrian or earliest Cambrian rift basins such as the Rome Trough (e.g., Ammerman and Keller, 1979) are interposed between high-grade basement and the Appalachian basin strata.

The subsurface geology of the Appalachian Basin is known well due to extensive hydrocarbon exploration and exploitation. Oil and gas exploration in the Appalachian basin began in 1820s with commercial gas wells in westernmost New York state, and oil booms straddled the PA-NY border from the 1860s-1880s following the nation's first oil well in Titusville, PA in 1859. It is estimated that hundreds of thousands of exploration or production wells have been drilled during the past two centuries. State agencies developed extensive archives of many of the hydrocarbon wells (Figure 4), enabling exploitation of bottomhole temperature (BHT) and reservoir data for assessment of geothermal direct-heat opportunities. Filtering for only wells deeper than 1,000 m with BHT data, and relying on sparse temperature data for equilibrated wells, about 13,000 wells were used to construct maps of regional temperature variations across the Appalachian Basin regions of NY, PA and WV (Figure 4).

Compared to the high thermal gradient regions exploited for geothermal electricity in the western states (Figure 5), the thermal resources of the central and eastern United States are lower grade. At a depth of 3.5 km, rocks under much of the northern tier of central and eastern states are expected to be in the range of 75-100°C. For the Appalachian Basin, the spatial variability of the temperature has been deduced from the extensive BHT data (Fig. 6 (a), (b)), and displays a regional texture with especially favorable heat resources in ENE trending bands that favor West Virginia and a zone straddling the New York-Pennsylvania border.

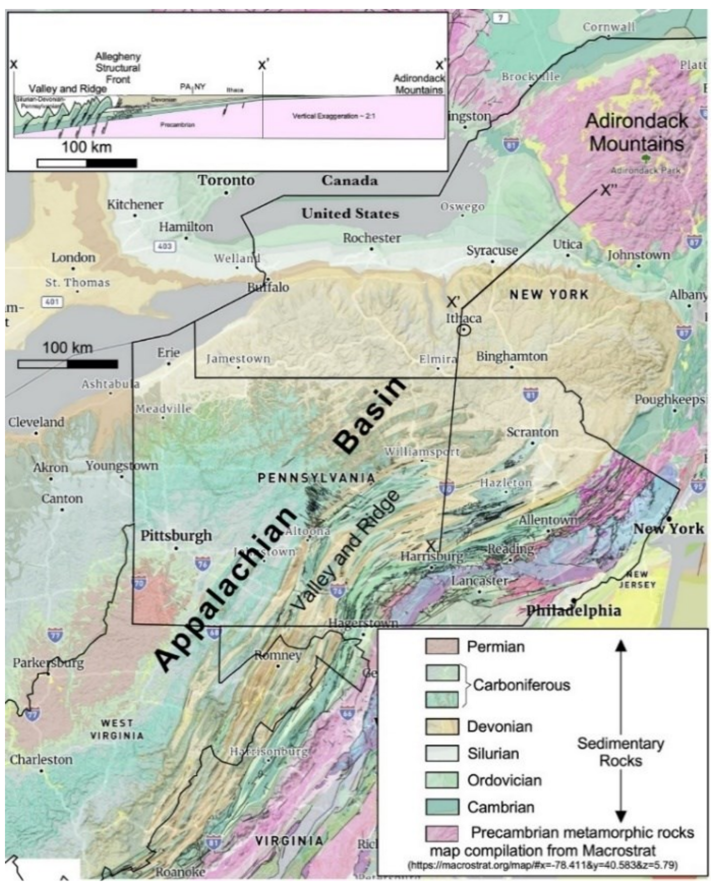


Figure 3: Geological map of the Appalachian Basin sector of West Virginia, Pennsylvania, New York, and neighboring states and provinces. The simplified legend identifies only Paleozoic strata of the Appalachian Basin, and the underlying basement. The inset shows a 2:1 exaggerated simplified geological cross section, from the highly deformed mountains of the Allegheny Orogeny in the south, to the Adirondack Mountains in the north. Map from Macrostrat.org. Cross section from X-X' simplified from Mount (2014), Mount et al. (2017) and Trippi et al (2019). Continuation to X'' drawn by authors.

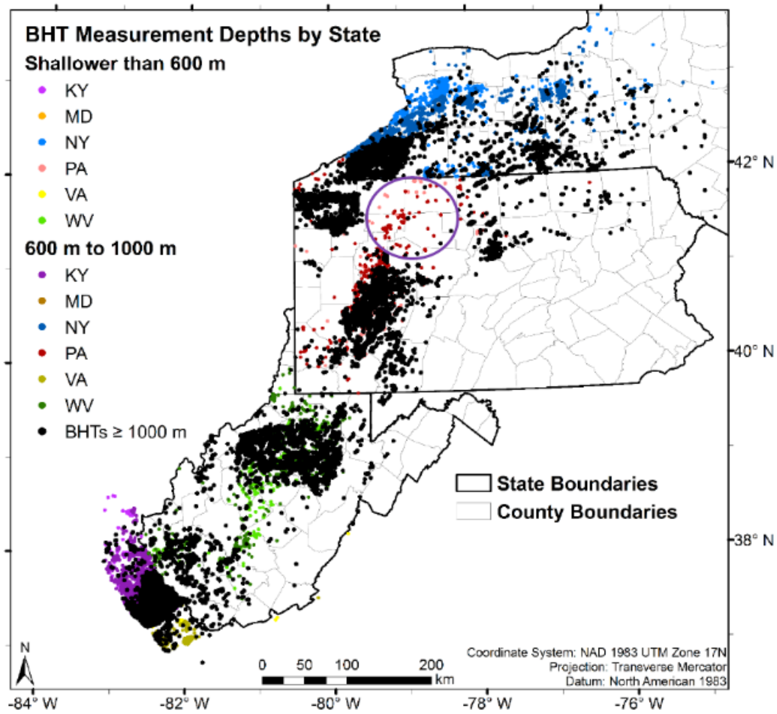


Figure 4: Among the hundreds of thousands of oil and gas wells in NY, PA and WV, state agency archives contain Bottomhole Temperature (BHT) data for tens of thousands. The roughly 13,000 boreholes located in this figure mark the ones whose data were integrated into regional analysis of thermal gradients by Whealton (2015) and Smith et al. (2016), as part of an Appalachian Basin Geothermal Play Fairway Analysis. Colored dots mark BHT depths shallower than 1000 m. Within the circle, a scarcity of data forced inclusion of the data for depths of 600-1000 m.

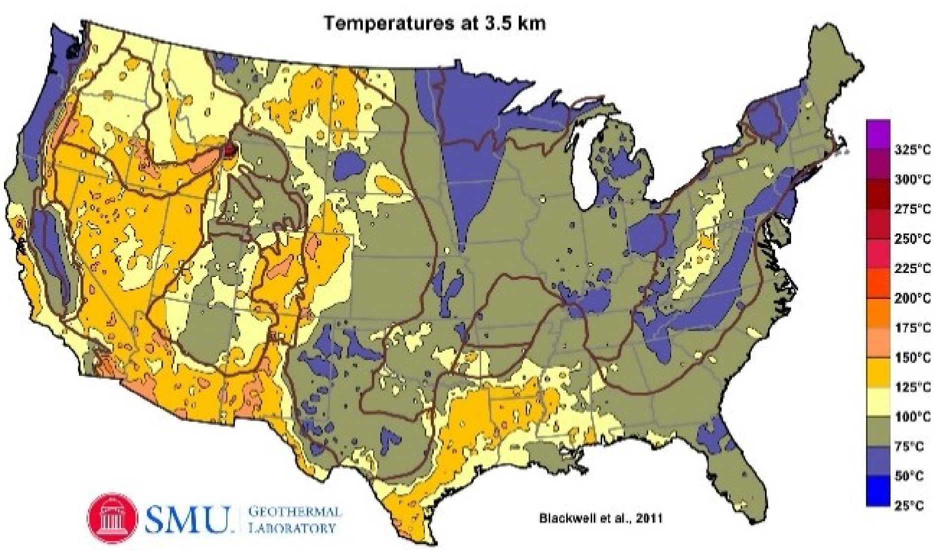
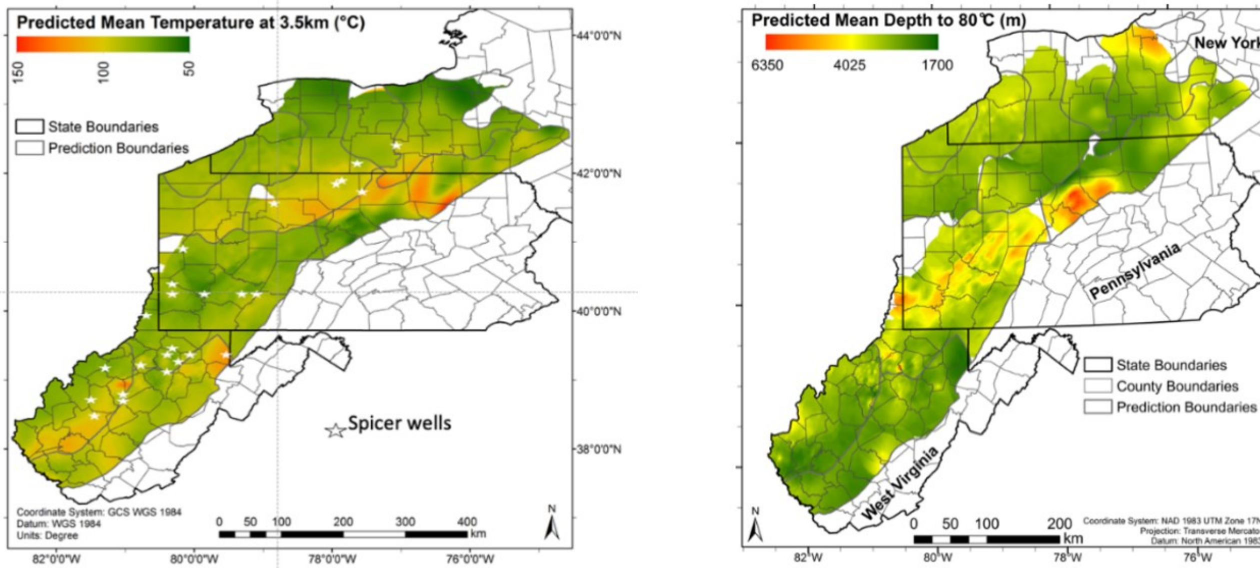


Figure 5: Predicted temperatures of rock at 3.5 km depth below the surface in the Continental U.S. Geothermal electric power generation is limited to the western United States where suitable temperatures are more likely to occur locally because of the regionally high temperature gradient. At 3.5 km (11,500 ft) depth, typical temperatures in the central and eastern U.S. are 50 °C cooler than in western states. From Blackwell and Richards (2011, personal communication) after Blackwell et al. (2011).



(a) (b)

Figure 6: (a) Temperature at a depth below surface of 3.5 km in the Appalachian Basin sectors of West Virginia, Pennsylvania and New York. Higher temperatures for the standard geothermal industry convention, with red signifying favorability. (b): Taking 80°C as a base case temperature desired for a direct-use geothermal reservoir, map shows the spatial variation in drilling depth needed for that target temperature. Shallower drilling depths are deeper green color, conforming to DOE's standard for a play fairway analysis (in which green indicated "move forward" and red indicated "stop".) From Smith (2016), Smith et al. (2016), and Jordan et al. (2016).

3. CORNELL'S STRATEGY FOR DECARBONIZING ITS ENERGY FOOTPRINT

Figure 7 shows Cornell's annual energy demand for electricity, heating and cooling for the past 20 years. Due to decades of investment in energy conservation and strict energy standards for new buildings, Cornell's energy needs continue to be relatively steady or even slightly decreasing despite continued campus growth (shown in purple). This translates to lower carbon-based emissions at the energy sources. Heating (shown in red) is responsible for over 40% of campus energy use, which places decarbonization of heat sources as a central challenge.

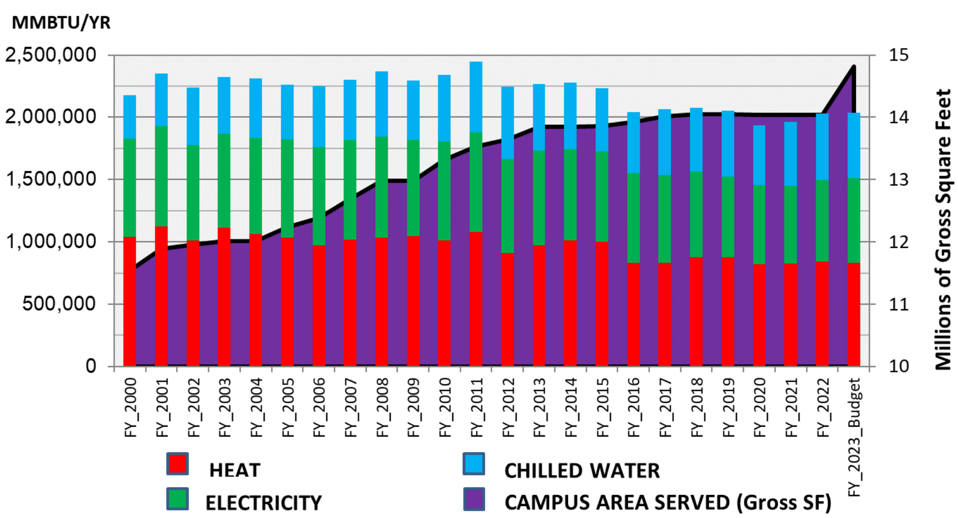


Figure 7: Cornell campus annual energy demand for electricity, heating, and cooling from FY 2000 to FY 2023. Because of adopting aggressive energy efficiency standards for new and retrofitted buildings, Cornell's total demand for energy has remained relatively constant despite the addition of over 3 million square ft of new building space from 2000 to 2023

3.1 Cornell's Energy System Approach

Figure 8 schematically illustrates Cornell's broad systems approach to transforming its energy supply to carbon-neutral sources. Currently, the campus utilizes all available renewable resources and an efficient natural gas co-generation plant. The main features include an on-campus hydropower plant, Lake Source Cooling, rooftop solar, combined heat and power, thermal storage, and similar resources connect to campus buildings through a district energy system (a "microgrid" for electricity, heat, and cooling), providing reliable and efficient energy services to the Ithaca campus. Proposed new renewable energy systems, include geothermal energy (Earth Source Heat) and bioenergy for district heat, additional grid scale solar PV and wind power, are indicated on the figure but not yet developed. Significant PV solar has also been built on Cornell lands. With net metering arrangements, PV on an annual basis now provides about 20% of the campus's electricity.

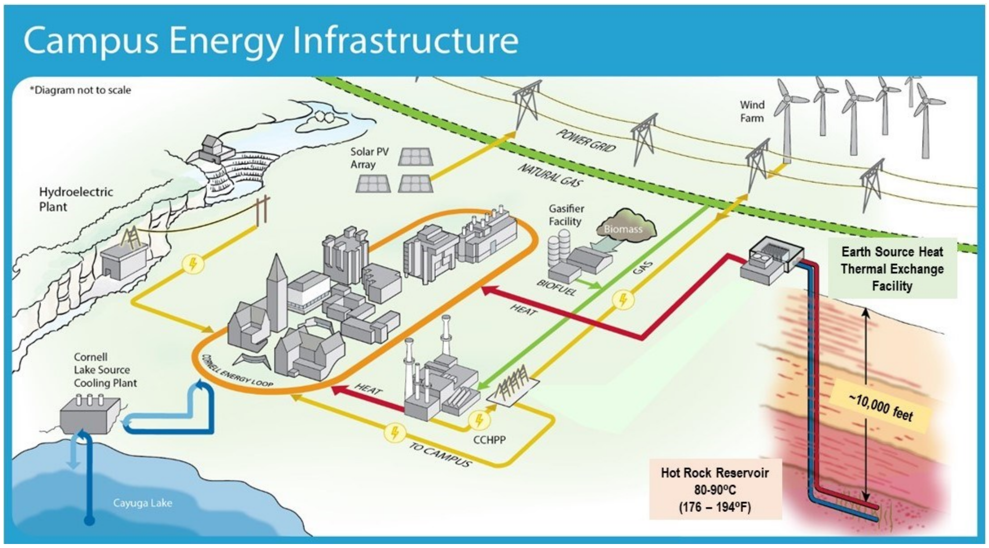


Figure 8: Schematic of the Cornell approach to decarbonize its campus energy infrastructure by utilizing renewable energy from hydro, solar, wind, geothermal, and waste biomass resources. Both existing and proposed systems are shown.

Lake source cooling: Cornell's approach to efficient and reliable campus cooling is shown schematically in the lower left-hand corner of Figure 8. Using the cold (39-40ºF/4-5ºC) deep waters of Cayuga Lake, Cornell employs a thermal heat transfer system (using large plate and frame heat exchangers) to extract heat from the campus cooling loop and deliver cooling to campus buildings. This is accomplished with very low electrical requirements, a small fraction (~15-20%) of the electricity that would be needed if typical refrigerant-based systems using compressive chillers or heat pumps were used. This keeps Cornell's summer electrical loads much lower than similar college campuses and supports New York State's efforts to create a renewable grid (see Beyers, Becker, and Tester, 2022 for more details)

Renewable electricity from solar, wind and hydro: Even though the combined impacts from Cornell's Lake Source Cooling, efficient Combined Heat and Power, and robust energy conservation efforts are an annual energy consumption significantly lower than business-as-normal would project (Figure 7), additional changes will be required to decarbonize its electricity supply and achieve climate neutrality. Cornell needs to replace all fossil fuel energy with integrated renewable (non-carbon emitting) energy to produce the electricity and heat needed for campus. While the current use of available resources like Fall Creek's flow for hydropower and electricity generation through roof-top solar photovoltaics and solar fields (the latter feeding the regional grid) provides Cornell a good baseline, more innovative solutions are still needed to meet its zero-carbon goal for electric power generation. For example, future cooperative agreements with NY State wind farms or other grid assets including storage would be necessary to eliminate emissions related to electrical purchases (see Beyers et al,, 2022 for details)

Carbon-neutral heating from geothermal energy and bioenergy: Cornell's current distribution system for heating supplies a mixture of steam and hot water to its buildings with the majority of them directly heated with hot water. To meet its Climate Action Plan goals, all existing steam piping will be converted to hot water as a hot water distribution system transfers heat more efficiently and economically from renewable energy resources. The conversion from steam to a distribution system with hot water, which is more efficient, safer, and easier to operate, is occurring incrementally to limit disruption, maintain redundancy, and control capital expenses. In addition, thermal energy storage for up to a few days, renewable natural gas from biomass sources and renewable hydrogen generation, and other technologies are also being explored to reduce loads and lower costs (see Figure 9).

To complete the transition to carbon neutrality, carbon neutral heat resources are needed. Currently the primary candidates are deep geothermal (ESH) and bioenergy generated from campus agriculture and food wastes. They are being evaluated to meet both base load and peak heating requirements.

A significant source of renewable energy for Cornell could be biomass. As New York's Land Grant Institution, Cornell has significant expertise in sustainable agricultural and agroforestry which could be deployed to help provide peak energy needs in mid-winter. Figure 9 shows a modeling result assuming biomass is harvested over the year to provide about 3% of annual heating needs. Although Cornell researchers have estimated that about 7% of the heating load could be generated by solid biomass fuels managed sustainably on existing Cornell lands near campus, there are other options as well. For example, a series of studies have shown that renewable natural gas (RNG) produced by processing manure from Cornell's 700 dairy cows and a small amount of campus food waste could also meet the peak demand shown in Figure 9. (Kassem et al.2020a,b,c). A unique hybrid process that combines anaerobic digestion, hydrothermal liquefaction and biomethanation would produce RNG and other marketable sustainable co-products. Using current incentives available, competitive levelized costs for peak heating would result. Thermal energy storage used in combination can further enhance this potential by reducing short-term peaks so that biomass heating systems can also be more appropriately sized and evenly operated.

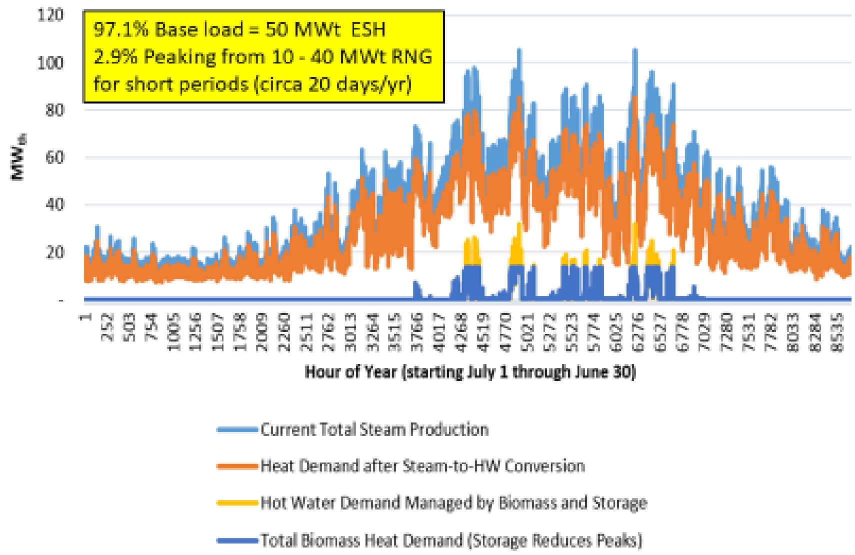


Figure 9: A representative future scenario simulation of carbon-neutral heating at Cornell. In this simulation, the campus heating load (up to 80+ MW_{th}) is accommodated using four geothermal well pairs to supply approximately 50 MW_{th} of base load heat to the campus distribution system. The modeled system includes a provision for using centralized heat pumps to increase geothermal reservoir output if needed as well as 16 M liters of hot water storage and 14 MW_{th} of peaking heating for coldest days using bioenergy generated by campus agricultural and food wastes. Peaking heat demand can be further reduced by adding seasonal thermal storage or if buildings are modified to extract more heat (return cooler water to the reservoirs). (see Beyers and Racle 2020, Tester et al. 2021 and Kassem, et al 2020 a,b,c)

4. CORNELL'S EARTH SOURCE HEAT PROJECT - PHASED DEVELOPMENT PROGRAM

4.1 Phase 0 - Site Evaluation

The initial phase of development of ESH at Cornell was the Preparation Phase (Phase 0). The main objective of this phase was to evaluate available background geological data and perform additional data collection to support an assessment of the feasibility and risks associated with moving to the Exploration Well Phase. Background data obtained and analyzed included historical local and regional seismicity, regional crustal stresses, stratigraphic data from offset wells, geologic maps of faults and other structures, 2D hydrocarbon-industry seismic reflection profiles, and commercial aeromagnetic data (Gustafson et al., 2020). These data sources were supplemented by additional data collection campaigns conducted by Cornell: installation of a local 15-node seismometer network, completion of a multichannel seismic reflection survey, high-resolution gravity measurements, and installation/sampling of five groundwater monitoring wells near the proposed drill site.

These background studies supported an initial characterization of potential geothermal reservoir targets (Tester et al., 2020) and the potential risk of induced seismicity, as well as establishing baseline levels of microseismicity (Gustafson et al., 2020) and groundwater quality to use as a reference during future drilling or geothermal development. To select the preferred site for drilling the initial exploration well, Cornell considered both those geologic factors as well as factors such as proximity to sensitive ecosystems, residential areas, or research facilities, site topography and degree of existing site development, drill rig access, and proximity to utility infrastructure. The chosen drill site is adjacent to Cornell's main Ithaca, NY campus, within a gravel parking lot surrounded by campus support facilities such as the Grounds Department, warehouses, trades shops, and maintenance facilities. During the site selection process, Cornell initiated multiple outreach programs to stakeholders within the university and the local community, including establishing a Community Advisory Team consisting of key individuals from Cornell and community organizations to promote robust lines of communication regarding potential geothermal development activities.

4.2 Phase 1 – Cornell University Borehole Observatory (CUBO)

CUBO was designed as an ESH exploration well to evaluate target formations and provide subsequent monitoring. The main steps in Phase 1 included well design, permitting, seismic and water monitoring, borehole drilling, casing and cementing, mud logging, geophysical well logging and coring operations.

In 2021, Cornell began work on CUBO, with initial funding from the U.S. DOE Geothermal Technologies Office. Major technical objectives for this phase were to confirm the general bedrock stratigraphy, specific rock types, pore pressure and fracture gradients, and in-situ stress conditions; to refine the drilling and casing program needed to ensure well control and wellbore stability; and to evaluate the properties of potential deep-direct use target formations, including the poorly characterized crystalline basement. Cornell engaged Capuano Engineering Company to prepare the initial Drilling and Casing Plan and the associated preliminary cost estimate. In order to streamline the contracting process, Cornell chose to utilize a single Integrated Well Services firm to provide drilling support services. The project team consisted of the following major members:

- Cornell University – Owner and Operator (including faculty, facilities and contracting staff)
- Capuano Engineering Company – Drilling Engineer and Drill Site Supervisor
- Precision Drilling – Drilling services
- Schlumberger (SLB) – Integrated Well Services, (including fluids, cement, mud logging, bits, directional drilling, and wireline services)
- J.P. Reilly Construction – Site preparation, pad construction, conductor installation, drill site support
- IADC and Casella Waste Services – waste management

The required drilling permit was secured from the NY Department of Environmental Conservation, Division of Mineral Resources. The vertical CUBO well was considered a wildcat stratigraphic well for regulatory purposes. Conductor installation was completed in April 2022, and the 1500 HP triple drill rig (PD 539) was mobilized in June 2022. Drilling commenced on June 21, 2022, and TD was achieved at a depth of 9,790 feet on August 13, 2022 (see site photo in Figure 10). As shown in Figure 11, the well was completed in five sections: a 36-inch conductor section with 30-inch casing to 110 feet; a 26-inch surface section with 20-inch casing to 789 feet; a 17.5-inch first intermediate section with 13.375-inch casing to 4,256 feet; a 12.5-inch second intermediate section with 9.625-inch hung liner to 7,809 feet; and an 8.5-inch open hole section to 9,790 feet. Each section of casing and liner was fully cemented. The number of well sections and casing set points were chosen to ensure well control and wellbore stability while drilling through potential hazards such as the Syracuse Salt (water soluble), Vernon shale (a hydrophilic swelling shale), and several known gas-producing shale and carbonate units. Water-based mud was utilized, in part due to issues of community acceptance with oil-based muds. Drill cuttings, excess cement, and waste drilling fluids were containerized on site and trucked off-site for disposal at licensed facilities.

Continuous mud logging, generally at 10-foot intervals, was performed for all sections below the conductor casing. A team of Cornell students was trained as sample catchers to assist the professional mud logging crew. Continuous gas monitoring by gas chromatography (GC) was performed for C1-C6 hydrocarbons entrained in the drilling fluid. In the 8.5-inch open hole section, a DQ-1000 mass spectrometer was also utilized to identify additional gas species such as noble gases, CO_2, aromatics, and sulfur compounds.

In the cased intervals of the well, wireline logging consisted primarily of natural gamma ray logs to assist with stratigraphic mapping and correlation, caliper logs to monitor well bore stability and assist with cement volume calculations, and ultrasonic cement bond logs. Within the open hole section that spanned the potential geothermal reservoir zones of interest, a more extensive suite of wireline geophysical logs was collected, including gamma, resistivity, neutron porosity, density, spectral gamma, sonic velocity, ultrasonic imaging, and micro-resistivity imaging (FMI). Additional open-hole wireline testing included several mini-frac (MDT) test stations, collection of 25 XL sidewall cores, and collection of pressure-temperature logs during flow testing. Flow testing was the last testing phase performed while the drill rig was on site. Air-lift equipment was used to lower the water level in the well to measure inflow; this was followed by reinjection (bull-heading) to measure the ability of the open hole section to accept water. A complete history of rig assembly, drilling, casing and logging operations is shown in Figure 12. The logging and testing activities are described in more detail in Section 5 of this paper.

Prior to drilling, environmental monitoring was performed to establish background levels of micro-seismicity in the Ithaca area as well as groundwater and surface water quality in the vicinity of the drill site. Monitoring continued during and after drilling to assess whether drilling activities had any significant impact on micro-seismicity or water quality; no impacts were observed. Environmental monitoring of groundwater, surface water and seismic activity continued during and after drilling to assess whether drilling activities had any significant impact on micro-seismicity or water quality. No impacts were observed.

The CUBO drilling project was successfully completed into the target formations with no safety or environmental incidents. The sampling and testing programs were fully implemented, providing the data needed to support reservoir modeling, stimulation testing, and the design of a demonstration system as described in the following section.

Figure 10: CUBO Drill site photo (circa June 2022).

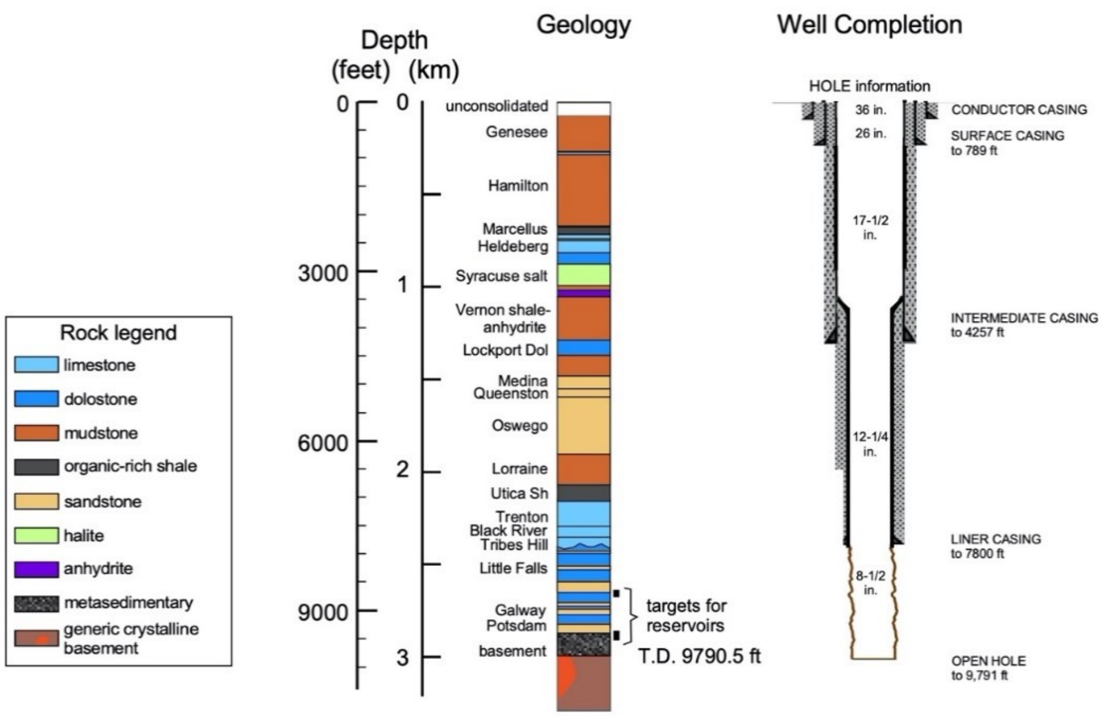


Figure 11: CUBO Lithology and well design. The depth region for potential heat reservoirs was completed as an open hole from 2,380 m (7,809 ft) to 2,984 m (9,790 ft). Within that depth range, target zones were identified that have a higher density of fractures and favorable signals of hydrologic transmission.

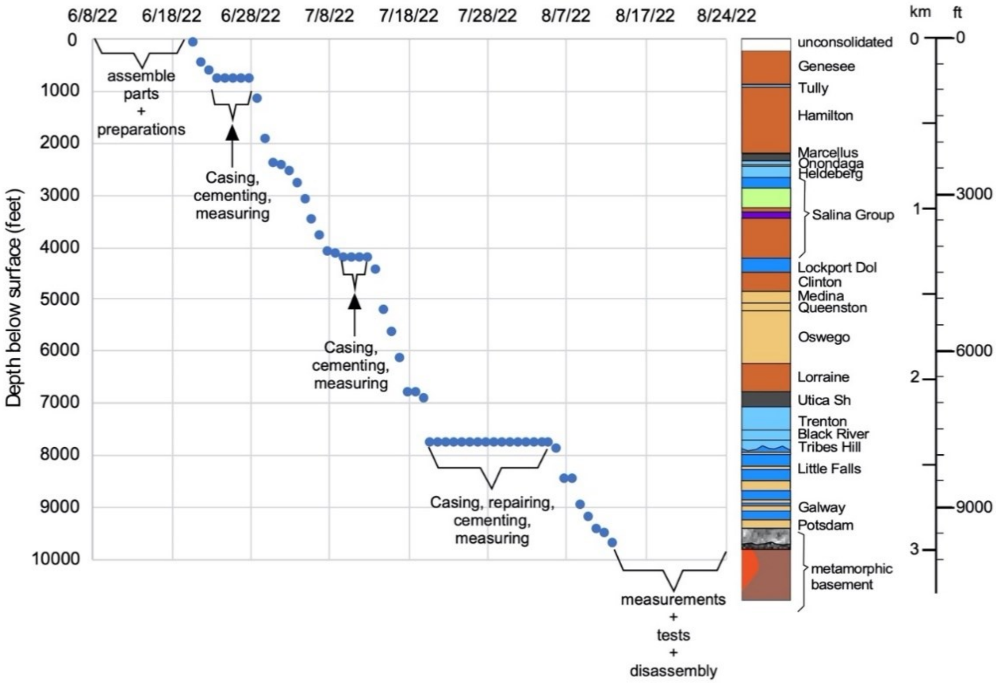


Figure 12 CUBO drilling performance history and final lithologic column.

4.3 Phase 2 - Two-well ESH Reservoir Demonstration

The main objective of Phase 2 will be to demonstrate the performance of a two-well, doublet system to provide sustainable thermal energy to meet about 20% of the Cornell campus's base load heating demand. The drilling experience and subsurface knowledge obtained from evaluating data from CUBO will inform the design of the injector and production wells and of the stimulation program that will be used. In this phase we expect to specify the total drilled depth and inclination of the first well, and then drill it. The next step will be to design the depth and inclination of the second well to create a viable reservoir target with sufficient rock temperatures and active heat transfer surface area. Preliminary reservoir modeling of thermal performance as described conceptually in the next section will be used as guide to specify the geometry of the second well. Then the second well would be designed, drilled, tested and stimulated if needed to establish connectivity with the first well. An extensive period of reservoir heat extraction testing and modeling would be carried out to validate the doublet's energy extraction performance and establish its sustainable production capacity to meet the 20% production objective.

The final step would occur in Phase 3, in which additional well pairs would be drilled to create a full-scale ESH system to provide 50 MWth of base load heating.

4.4 Preliminary Modeling of Thermal Performance of Phase 2 ESH Reservoir

Using a simplified first order approach, one can easily illustrate the effects of reservoir size as well as rock and fluid thermal physical properties. If we assume uniform flow in discrete fractures, the rate of heat removal from the reservoir is limited by thermal conduction through the rock mass surrounding the fracture due to the rock's low thermal diffusivity of order 10^{-6} m^2/s relative to forced convection of fluid flowing within the fracture. Initial thermal power production rates can easily be determined showing the effects of reservoir design, mass flow rate, and an assumed thermal drawdown rate.

Using the Gringarten (1978) solution for EGS heat extraction (i.e., error function solution for single fracture), the required fracture area for an EGS reservoir is calculated to obtain 20% thermal drawdown after 20 years as a function of initial thermal power and number of parallel fractures (Figure 13). We assumed an initial reservoir temperature of 90 °C and injection of 40 °C to obtain an initial ΔT of 50 °C. We considered water as the heat transfer fluid with specific heat capacity of 4,200 J/kg-K. The initial thermal power scales linearly with flow rate.

With our assumption of uniform fracture flow, the well separation distance is a direct measure of effective heat transfer area. With discrete fractures spaced sufficiently far apart, thermal conduction interference between fractures is negligible and total reservoir heat transfer area equals the number of fracture zones times the area of each zone. The initial thermal power per well pair is (4,200 J/kgK × total mass flow rate in kg/s × ΔT [= 90-40 ºC or K]). The log-log plot of (well pair separation distance in m) versus (initial thermal power produced in MWth) shows the parametric dependence of well separation distance for a specified number of fractures ranging from 1 to 50, and assuming 20% drawdown after 20 years.

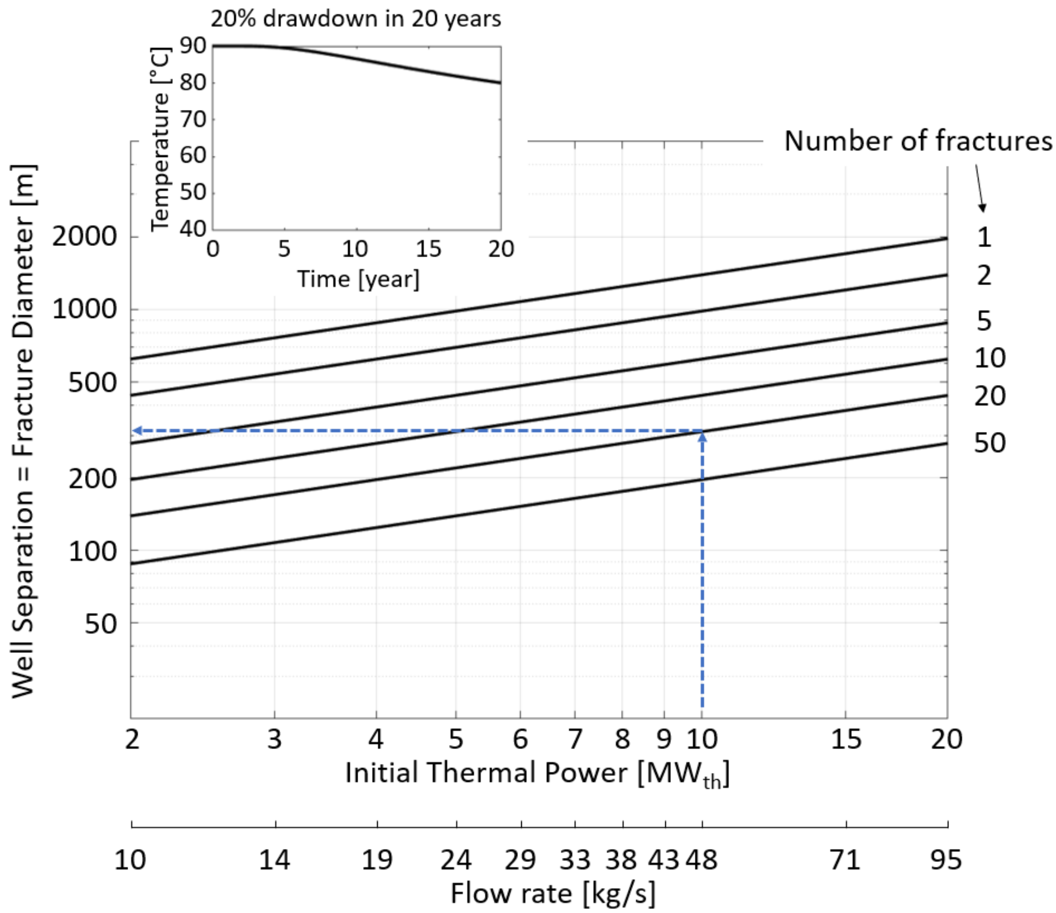


Figure 13. Required well separation (in m) as a function of initial thermal output (in MW$_{th}$) and number of fractures. All cases assume circular fractures with well separation corresponding to the fracture diameter, an injection temperature of 40°C, initial rock temperature of 90°C, and 20% thermal drawdown after 20 years (see inset). The area of each zone is approximated by well separation distance squared times π/4 . The initial thermal power scales directly with flow rate, e.g., the vertical blue dashed line at 10 MW$_{th}$ corresponds to about 48 kg/s total flow rate. The required fracture diameter for 10 MW$_{th}$ in case of 20 fractures is about 300 m (horizontal blue dashed line). In this particular case, the corresponding area of an individual fracture is about 70,000 m^2, and a total fracture area is 20×70000 m^2 or 1.4 km^2. Flow rate values are rounded to closest integer. No thermal interference between fractures is considered and uniform flow through fractures is assumed.

5. PRELIMINARY RESULTS OF TARGET FORMATION CHARACTERIZATION AND EVALUATION

Subsurface logging, testing, and sampling were conducted within CUBO during and soon after drilling with the primary objectives of characterizing the lithostratigraphy, temperature, hydrogeology, and stress conditions within the subsurface. These fundamental characterizations are necessary to identify potential reservoir targets and guide the design of subsequent wells, stimulation strategies, and operational requirements.

5.1 Formation Temperature

To supply heat to campus building, heat in the form of hot fluid must be supplied at a sufficient rate for a reasonably long period of time. The first technical uncertainty is the subsurface temperature. Because borehole circulation during drilling temporarily cooled the near wellbore region, borehole temperature measurements taken immediately afterwards underestimate true formation temperatures as seen in Figure 14. However, analysis of several bottom hole temperature measurements (see Purwamaska and Fulton (2023)) reveal a re-equilibration trend suggesting an equilibrium formation temperature at 9710 feet depth of ~81 ºC. This estimate is well within the range anticipated prior to drilling.

Higher resolution temperature logs before, during, and after subsequent disturbances during hydrologic testing show temperatures of at least 77°C at 9,500 ft immediately after drilling (Figure 14).

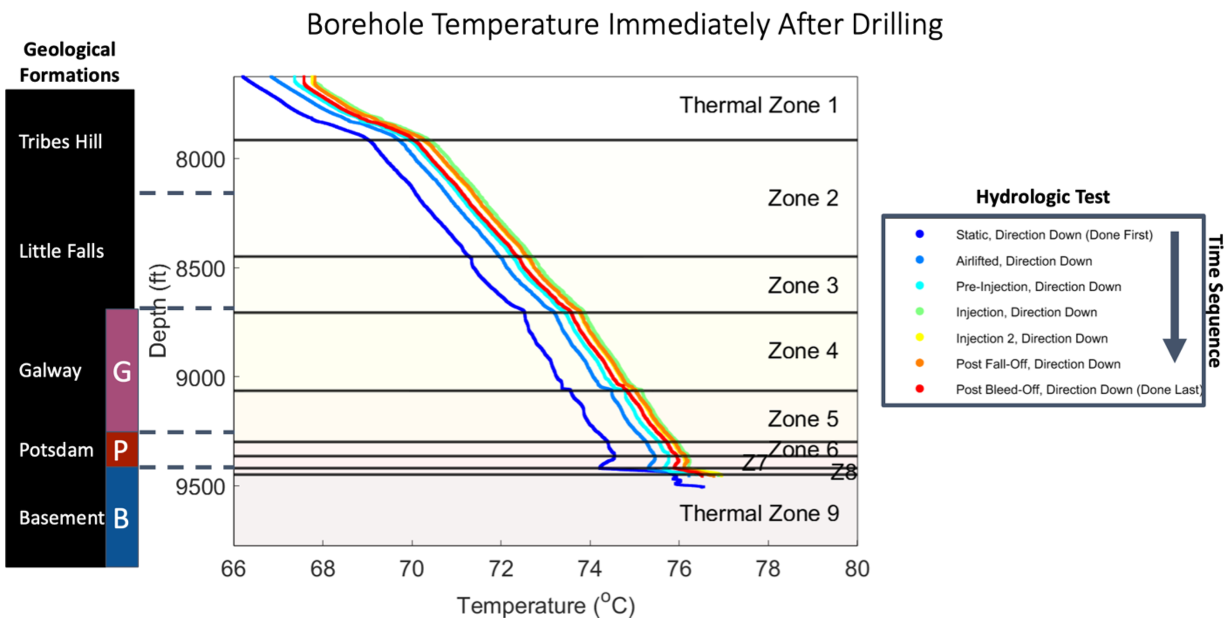


Figure 14: Temperature logging measurements in the lower, open–hole section of CUBO obtained immediately after drilling and casing operations and before, during, and after a hydrologic airlift drawdown test and subsequent re-injection of displaced borehole fluid.

In addition to providing constraints on formation and potential fluid production temperatures, analysis of the high-resolution temperature surveys associated with hydrologic testing provide insights into the hydrogeology — a key technical uncertainty prior to CUBO drilling. In addition to temperature, fluid flow at considerable rates and across sufficient surface area within the rock between injection and production well are needed to effectively supply heat. The surface area and ability to flow fluid through the rocks are controlled by the subsurface permeability and hydrogeologic structure. Analysis of the depth and time-varying thermal response to borehole circulation and hydrologic perturbations can highlight permeable intervals in which considerable drilling fluid infiltration occurred and also permeable producing intervals from which formation fluid infiltrates into the borehole or annulus (e.g., Fulton et al., 2013; Fulton & Brodsky, 2016). The CUBO temperature data reveal several permeable zones which seem to both take and produce fluid. Most notably, there is a zone of particular interest with a large negative temperature anomaly associated with fluid infiltration during drilling within the upper basement and along its interface with Paleozoic strata – a known geologic unconformity (see Figure 14 and companion paper by Purwamaska and Fulton, 2023).

5.2 Formation Permeability and Hydrogeology

In addition to the temperature data, other data including downhole geophysical logs, peaks in inorganic gases and both large-scale and isolated-downhole fluid infiltration and production tests provide additional insights into the permeability and hydrogeologic structure (see Figure 15 and the companion paper by Clairmont et al., 2023).

In general, the deep subsurface beneath Cornell has relatively low intrinsic permeability and the few zones of relatively higher permeability appear to be fracture controlled. Understanding the distribution and orientation of fractures in space as well as relative to the subsurface stress field are therefore important for understanding where existing permeable pathways may exist and for guiding stimulation strategies that can utilize and enhance existing fracture networks to enhance permeability and surface area for heat exchange.

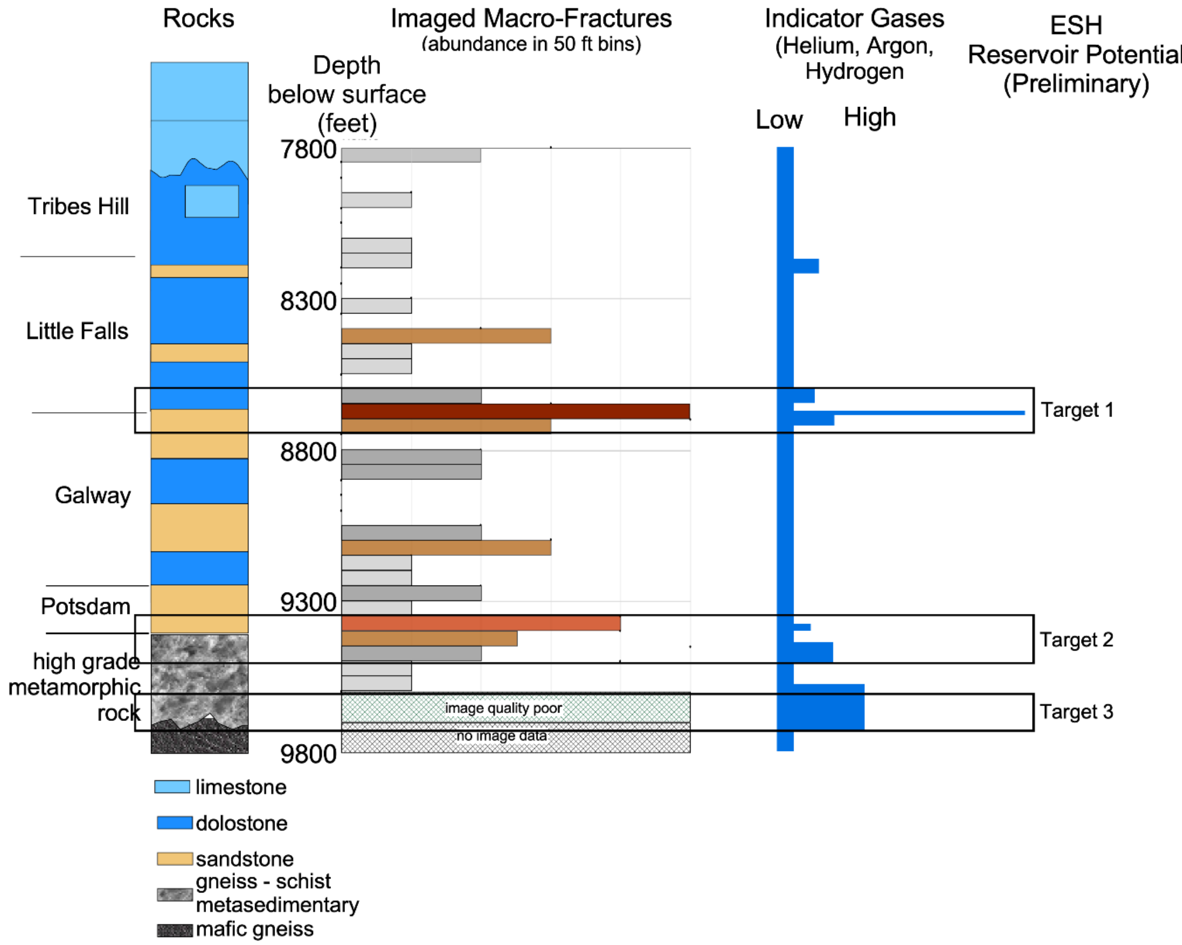


Figure 15: Summary of relative abundance of fractures identified in borehole image logs and spikes in inorganic gases observed in online gas monitoring during drilling. Intervals with gas spikes correlate with areas with higher fracture density providing an indication of permeability and connectivity. The noted targets for ESH reservoirs are current but likely to be adjusted as analysis continues. See Fulcher et al. (2023) for fracture details.

5.3 In Situ Stresses and Fractures

Fracture characterization based on borehole image logs reveal abundant fractures that are largely focused within particular stratigraphic intervals (see companion paper by Fulcher et al., 2023 and in Figure 15). In general, these fractures have a NE strike and NW dip direction. Basement directions vary a bit more. The depth distribution of fractures largely agree with downhole logs. However, analysis of 3D far-field sonic logs largely observe a secondary orthogonal set of fractures away from the borehole within a NW trending orientation (see Figure 16). Together these data and ongoing analysis on fracture characterization within 25 sidewall cores from the open-hole section characterize the existing subsurface fracture networks and their ability to flow water or be stimulated to enhance overall permeability and connectivity.

The susceptibility of fractures to respond to hydraulic stimulation or to slip in general is related to their present day stress state governed by its orientation within the 3D stress field. Understanding the state of stress is therefore important to guide stimulation strategies, establish the direction of potential future wellbores, and assess induced seismicity hazards.

A variety of observations and techniques have been used to characterize the stress state at depth within CUBO (see Pinilla et al. 2023 companion paper). Dual-packer mini-frac tests along with integration of density logs at multiple depths within the open hole section constrain stress magnitudes. Interpretation of borehole breakouts observed in both 4-arm caliper and borehole image data describe stress orientation as a function of depth. In general, stress orientation is roughly NE trending with little variation with depth. Stress magnitudes reveal a strike-slip / transpressional setting at depths of 8,000 ft or more with the overburden stress being σ_2 yet relatively close to σ_3.

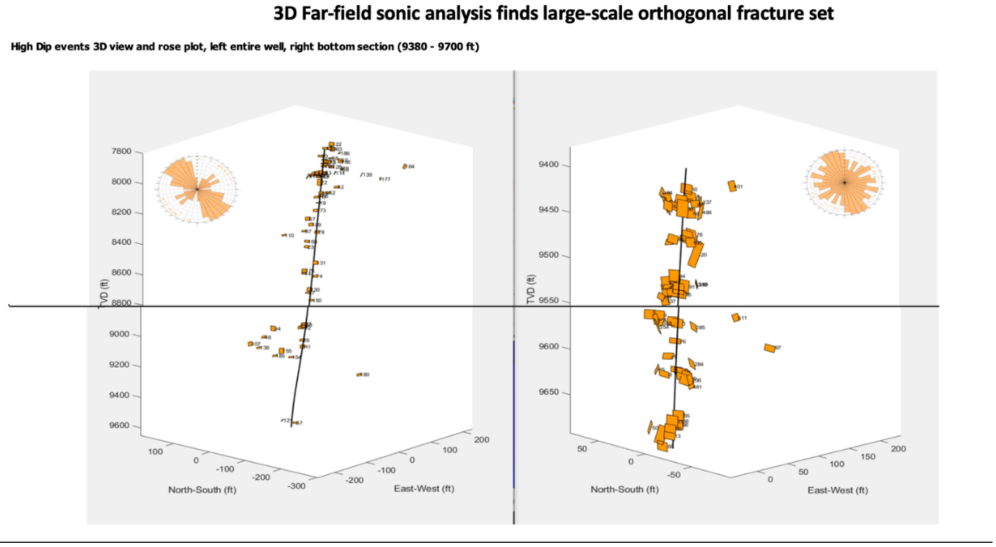


Figure 16: Large scale fractures imaged away from the borehole using active downhole sonic tools.

6. CONCLUSIONS AND PLANS FORWARD

This paper provides the context and rationale behind Cornell's effort to decarbonize its campus energy system. A key objective of Cornell's Climate Action plan is to develop carbon neutral heating by using the thermal energy stored in rocks at depths of about 3 km (10,000 ft.) in the subsurface under its main campus in Ithaca, NY. The first phases in evaluating if a multi-well direct use geothermal district heating system is feasible using a technical approach Cornell has labelled Earth Source Heat have been carried out over the past few years. The main topic of this paper describes the progress made to design and drill the first exploration well — Cornell University Borehole Observatory (CUBO) — and to perform preliminary testing and modeling of target rock formations with temperatures above 80°C that look promising for sustained heat extraction. We encourage those interested in learning more about the analysis of the testing of CUBO that was carried out in July and August of 2022, to attend the four companion presentations and papers in this workshop: Clairmont and Fulton (2023), Fulcher et al. (2023), Pinilla et al. (2023) and Purwamaska and Fulton (2023).

The next phase of the ESH project aims to develop a doublet injection and production well pair system in our target reservoir region capable of supplying about 10-15 MW_{th} (20%) of Cornell's base heating load. The design of the Phase 2 system will utilize the knowledge and experience gained by drilling and testing CUBO to lower the technical risks and costs relative to the exploration well. While the preliminary results of CUBO are encouraging with respect to developing a viable ESH system, further field testing is needed to prove that sufficient reservoir connectivity and size between injection and production wells can be created to insure heat production at economic levels. In the coming years we look forward to being able to report on our progress towards achieving that goal.

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