Cornell University Heat Pump Study

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CEE 5052 – Final Project Report

Connor Bayne (cb678), Gregory Brumberg (gsb78), Gabrielle D'Arcangelo (gmd79), Harry Fuller (hf245), Nicolaas Justice (nj86), Shreen Sachdev (ss2853), Hanyang Song (hs697), Peter Wise (pbw43)

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List of Authors

1. Connor Bayne (cb678@cornell.edu)
   Connor received his Bachelor of Science degree in Mechanical Engineering from Cornell University in May of 2021. During his undergraduate years, Connor pursued renewable energy through a project team lead role in Cornell University Sustainable Design (CUSD) and through offshore wind energy research under Professor Max Zhang. Connor is currently studying environmental engineering for his M. Eng. degree, with a focus in sustainable energy systems.

2. Gregory Brumberg (gsb78@cornell.edu)
   Greg received his Bachelor of Science in Chemical & Biomolecular Engineering with a with a minor in China & Asia-Pacific Studies in December 2021. During his undergraduate years, he ran Engineers for a Sustainable World: Biofuels, an undergraduate research and engineering team that focuses on implementing bio energy in the Cornell and wider Ithaca community, including converting a campus tractor to run on biodiesel. He is now pursuing a Master of Engineering in Engineering Management.

3. Gabrielle D'Arcangelo (gmd79@cornell.edu)
   Gabby received her Bachelor of Arts in Chemistry from Princeton University in May 2021, with certificates in Sustainable Energy, Technology & Society, and Materials Science. There, her research interests included atmospheric chemistry and sustainable food systems. She is currently pursuing a Master of Engineering in Environmental Engineering.

4. Harry Fuller (hf245@cornell.edu)
   Harry is completing his M.Eng. degree with a focus in Environmental and Water Resources systems. Harry's experiences working on sustainability engineering initiatives through Cornell and internship experiences led him to his passion for renewable energy systems. Harry is particularly interested in resource recovery and the intersection of waste and energy.

5. Nicolaas Justice (nj86@cornell.edu)
   Nicolaas is receiving his Bachelor of Arts degree in Physics with a concentration in Computer Science from Cornell in May 2022. After exploring a range of applications of these two broad fields through various courses, projects, and research, Nicolaas found a passion for renewable energy technology that led him to pursue a Master of Engineering in Civil and Environmental Engineering with a focus on Sustainable Energy Systems.

6. Shreen Sachdev (ss2853@cornell.edu)
   Shreen received her Bachelor of Science degree in Material Science from Rochester Institute of Technology in May 2020. She brings along useful academic and industrial

experiences ranging from manufacturing, processing, sustainable materials, and supply chain. Shreen is currently pursuing her M.Eng. Degree in Environmental Engineering with a focus on Renewable Energy Systems and Engineering Management.

7. Hanyang Song (hs697@cornell.edu)
   Hanyang received his Bachelor of Science degree in Environmental Science and Management from the University of California, Davis in June 2021. During his undergraduate, he accumulated many experiences with environmental planning and impact assessment. He is currently pursuing the Master of environmental engineering at Cornell, with a focus on renewable energy and sustainable water systems.

8. Peter Wise (pbw43@cornell.edu)
   Peter received his Bachelor of Arts in Physics from Goshen College in 2017. He is currently in the M. Eng program studying Civil and Environmental Engineering with a concentration in sustainable energy systems. Peter has worked as an environmental educator and leader in the conservation world. Peter is interested in employing alternative energy systems, improving energy efficiency, educating consumers, and analyzing data to support developments in the energy transition.

Executive Summary

To support Cornell University's climate action plan and meet carbon neutrality by 2035, this project focuses on developing a ground-source mini-district heat pump system for 12 residences on West Campus. The system demand was evaluated using Grafana dashboard which provided access to steam and electricity data of campus buildings. The system design requires 19 heat pumps, implementing a well-field of 74 500' boreholes. This figure is subject to change according to soil moisture, bedrock depth, and other factors which could be determined from a site visit. The economic analysis determined that the total necessary capital cost is around $1,500,000 and the annual operating cost is around $231,500. In addition to reducing emissions, we determined several key environmental and social impacts associated with implementation and found that other potential locations to expand this work would be Cornell's Hungerford Hill Laboratories, Geneva AgriTech campus, and Ithaca airport business park.

Background

Previous Work: Heat Pump Technologies

What Are Heat Pumps?

Ground-source heat pumps (GSHPs) can be thought of like giant refrigerators running in reverse. Ground-source heat pumps work by moving heat from one place to another, using the earth either as a heat sink or heat source. In heating mode, ground-source heat pumps work by moving heat from the ground into conditioned spaces. In cooling mode, ground-source heat pumps move heat from a conditioned space into the ground. GSHPs use the relatively constant temperature of the earth to extract and disperse heat. Ground temperature averages can range from 35-75°F depending on latitude and depth (Naylor and Gustin, n.d). GSHPs take advantage of the "low temperature" heat available in the ground instead of producing heat via combustion of fuels. By moving already available heat from underground to inside a building, they become highly efficient.

Below in Figure 1 is an illustration highlighting the processes and components of a GSHP in heating mode. The ground loop heat exchanger delivers heat to the evaporator. The temperature of the delivery fluid in the ground loop is relatively cool to human senses given that it will be around the ambient temperature of the ground at the depth the ground loop is installed. Even though the ambient ground temperature may feel cool to human senses, thermodynamically, this fluid still possesses a usable quantity of energy. The heat available in the ground loop is exchanged to a cooler refrigerant in the heat pump cycle. This refrigerant is then delivered to the evaporator. The heat pump then compresses the refrigerant, greatly raising the temperature of the refrigerant. While the refrigerant is compressed, another heat exchanger in the condenser absorbs the heat from the refrigerant and delivers it to the house for heating. The cool air in the house is constantly being warmed by the pressurized refrigerant. The heat-tapped refrigerant is then expanded, back to the original pressure in the evaporator. The refrigerant's temperature at this stage is cooler than it was before it was compressed.

This temperature of the refrigerant in the evaporator will remain colder than the ambient temperature of the ground so that the ground can be used to constantly heat the uncompressed refrigerant in the evaporator. A pump will continue to circulate the working fluid in the ground loop, passing heat from the warmer ambient ground loop fluid to the cooler refrigerant in heat pump cycle. If the ground loop is designed and sized properly, it will be able to meet the heating and cooling needs of the house. Ambient ground heat is considered a renewable and sustainable source of heat. Similarly, a GSHP can be used in reverse to deliver cool air to the house for conditioning in summer months. Instead of using the ground as a heat source, the system uses the ground as a heat sink, transferring warm air from the house into the ground and returning cooled air to the conditioned space.

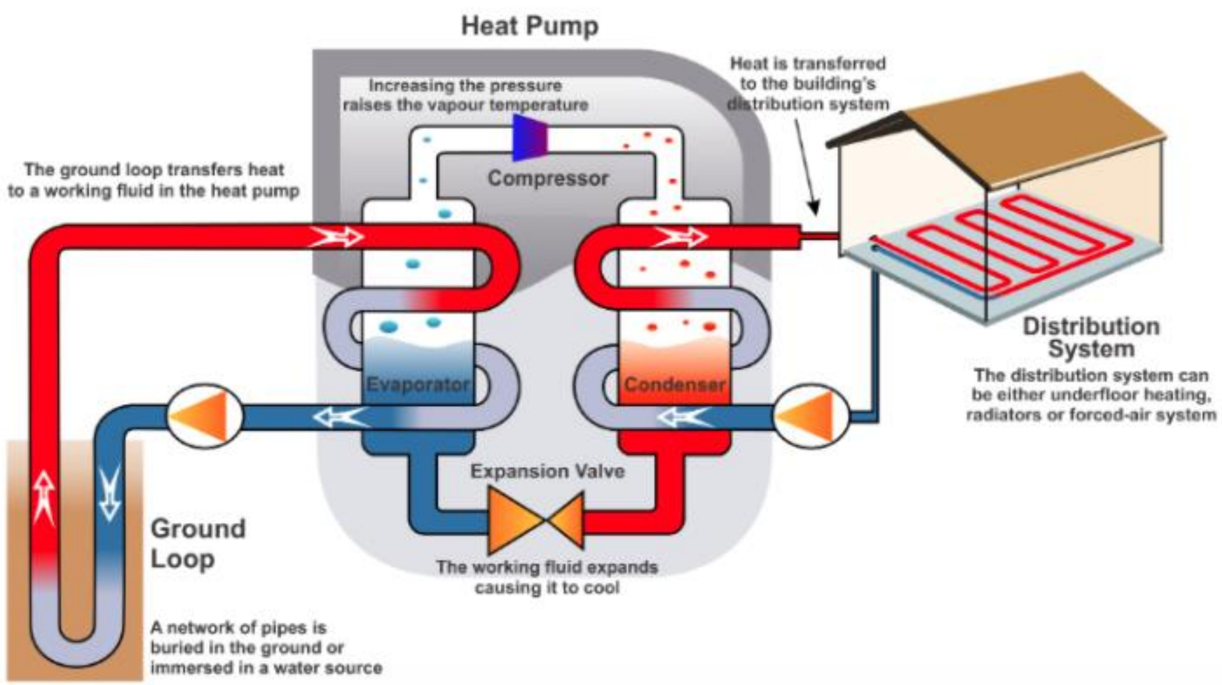


Figure 1: Visualization of GSHP

Air and Ground Source Heat Pumps

The decision of whether to install an air or ground source heat pump depends on the building design, area between buildings, climate, and heating or cooling demand. Air source heat pumps have a lower initial cost due to their simpler installation, but they tend to have a shorter lifespan than ground source heat pumps because more of the machinery is exposed to wind and precipitation due to its being above ground. Air source heat pumps do not require the building to have a large, empty space, such as a yard or parking lot, surrounding it. However, placing air-source heat pumps within a few feet of each other will result in lower performance because they will be competing for the same heat. Depending on the building's existing ventilation system, air source heat pumps may be able to utilize existing ducts. Because they draw heat from a lower-temperature source, air source heat pumps have a higher electricity demand, especially at night when the air temperature is cooler (Violante et al., 2022). This may be a challenge for systems that utilize solar power. It is also harder to predict how efficiently an air source heat pump will operate compared to a ground source since the air temperature is much more variable than the ground.

Because Ithaca has a cold climate, the higher efficiency of a ground source heat pump may be desirable despite several drawbacks. This higher efficiency is a result of the fact that the ground temperature is higher than air temperature in winter months, which means that the pump requires less energy to draw the load heat from the source (Garber-Slaght, 2013). However, installation of a ground source heat pump can be twice as expensive as an air source heat pump and requires either a large yard for horizontal pipes or a drillable ground for vertical pipes. This area cannot be interrupted by tree roots or other pipes or placed too close to another heat pump system (Jaafar & Maragna, 2021). Horizontal pipe systems are commonly buried between four and six feet underground in 2-foot-wide trenches, while vertical pipes are drilled about 20 feet apart and 100 to 400 feet deep. According to the U.S. Department of Energy, the additional installation costs of a ground-source heat pump are recovered within 5-10 years of reduced heating costs (*Geothermal Heat Pumps | Department of Energy*, n.d.).

Overestimating the size of the ground exchange can greatly reduce efficiency when heating demand is low. Thus, in both horizontal and vertical cases, it must be considered that Ithaca demand will vary significantly between seasons. Even though both horizontal and vertical heat exchange systems are closed loops, ground source has a higher risk of undetected refrigerant leakage than air source. The lifetime of a ground-source heat pump itself is over 20 years, while the underground heat exchange pipes can last over 50 years (*Geothermal Heat Pumps | Department of Energy*, n.d.).

District Heating Case Studies

As we carried out our case study research, it was encouraging to find two college campuses have successfully converted their HVAC systems from fossil fuel boilers to ground source heat pumps in regions with comparable to the climate found in Ithaca.

Richard Stockton College of New Jersey

The first of these college campuses is Richard Stockton College of New Jersey, a small public college found in rural New Jersey, with an enrolment of ~9,000 students. Richard Stockton College of New Jersey (Stockton University) completed the construction of a series of 400 closed-loop boreholes in 1994. The project was one of the first of its kind in the world and was co-funded by Atlantic Electric, the primary energy provider for the region, and the NJ Department of Environmental Protection and Energy (Checket-Hanks, 2011).

The 400 boreholes feed into a pump building found on the edge of the borehole field where the water is pumped to 62 rooftop heat pump units on buildings across campus (Checket-Hanks, 2011). In the summer, the borehole field loop acts as a heat sink. In the winter, the borehole field loop acts as a heat source. The heat pump units can generate temperature-controlled water which feeds the HVAC systems found at the served buildings. The multi-site heat pump approach would not be considered the most efficient process, neither in terms of economics nor energy usage. However, due to Stockton University’s historic interest in energy conservation, the arrival at this solution was gradual (Checket-Hanks, 2011). Therefore, several rooftop heat pumps were already present.

One issue which arose in the Stockton University case was a gradual rise in groundwater temperature around the borehole field, caused by the system giving out more heat in the summer than it is taking in through the winter (Epstein & Sowers, n.d.). Some monitoring well locations showed a rise by 11℃ (Epstein & Sowers, n.d.). This is believed to have been caused by irregular groundwater recharge in the area (Epstein & Sowers, n.d.).

Ball State University

Ball State University is another excellent case study to analyze due to its near-identical campus size and enrolment (~23,000 students). Due to federal regulation, Ball State University was forced to permanently shut down the coal-fired boilers responsible for the heating and cooling of campus (anon, n.d.).

The system was replaced by a district ground source heat pump system, through the conversion of the existing pipe network, and the construction of two vertical borehole fields located North and South of campus, each consisting of 1800 400-500ft boreholes. Each borehole field serves a district heating system (heat pump station), where temperature regulated hot or cold water is generated (seasonally dependent) and pumped around campus utilizing the pipe network previously used to deliver steam to campus buildings (anon, n.d.). Finally, individual building interfaces were converted to accept water as opposed to steam. The overall coefficient of performance (COP) of the system is an astonishingly high 7.7 (anon, n.d.).

The project cost a total of $83 million. The State of Indiana initially gave the university $45 million, while the university was awarded $5 million from the federal government through the Recovery Act. Finally, BSU approached the State of Indiana to request an additional $33 million to finish the project. In total, the State contributed $78 million. BSU claims to save $2.2 - $2.5 million annually due to the district ground source HVAC system (anon, n.d.). Furthermore, the University is eligible to claim carbon neutrality and sells carbon credits, providing a capital stream to fund further environmental and energy efficiency projects around campus.

Pollutant	Emissions Saved (tons/yr)
Carbon Dioxide	85,000
Nitrous Oxide	240
Particulate Matter	200
Carbon Monoxide	80
Sulfur Dioxide	1400

Table 1: Annual Emission Savings Generated through the Conversion from Coal-fired Boilers to District Ground Source Heat Pump System

Princeton University Case Study

A seven-person team, consisting of George Pinder (University of Vermont), Cy Yavuzturk (University of Hartford), Thomas Filburn, Metin Ozbek (ENVIRON), Ira Guterman (Princeton Engineering Group), David Van Kamp (Princeton University), and Lou Kagel decided to pursue a "least-cost design tool [called OptGSHP] that would enable [ground-source heat pump] developers to analyze system cost and performance in a variety of building applications to support both design, operational and purchase decisions," back in 2010 (Pinder, Yavuzturk, & Ozbek, 2015). This systems approach was one of the first of its kind and included features such as groundwater drilling sites, flow rate, borehole length and depth, and more. The full project concluded with an 81-page submission to the U.S. Department of Energy in April of 2015 (Pinder, Yavuzturk, & Ozbek, 2015).

In this final report, the study of the Lawrence Apartments Complex at Princeton University is thoroughly explained. The goal was to estimate the savings that would have been achieved had the project used the OptGSHP program instead of the current design implemented in 2001. The wellfield consisted of 160 wells with each of the wells having a depth of 450 feet, and 20 feet spacings maintained between each borehole. Groups of wells were then combined to pipe to a central pumping facility. This central facility, Building 6 in Figure 2, contains the central pump and heat exchangers and distributes heated water to 6 nearby apartment buildings. One of OptGSHP's most notable features is its design to determine the feasibility of a design through inputs. If OptGSHP is unable to find a solution, it will conclude that the system cannot be designed with the current input parameters. Another feature is the ability to account for heat transfer due to groundwater in OptGSHP. This benefits the designer by ensuring the system is not overdesigned and requiring more capital than necessary (Pinder, Yavuzturk, & Ozbek, 2015). Unfortunately, the researchers ran into more difficulties integrating the groundwater model to the ground heat exchanger model. Though the project stalled in 2015, the submission to the Department of Energy for funding remains a hopeful sign.

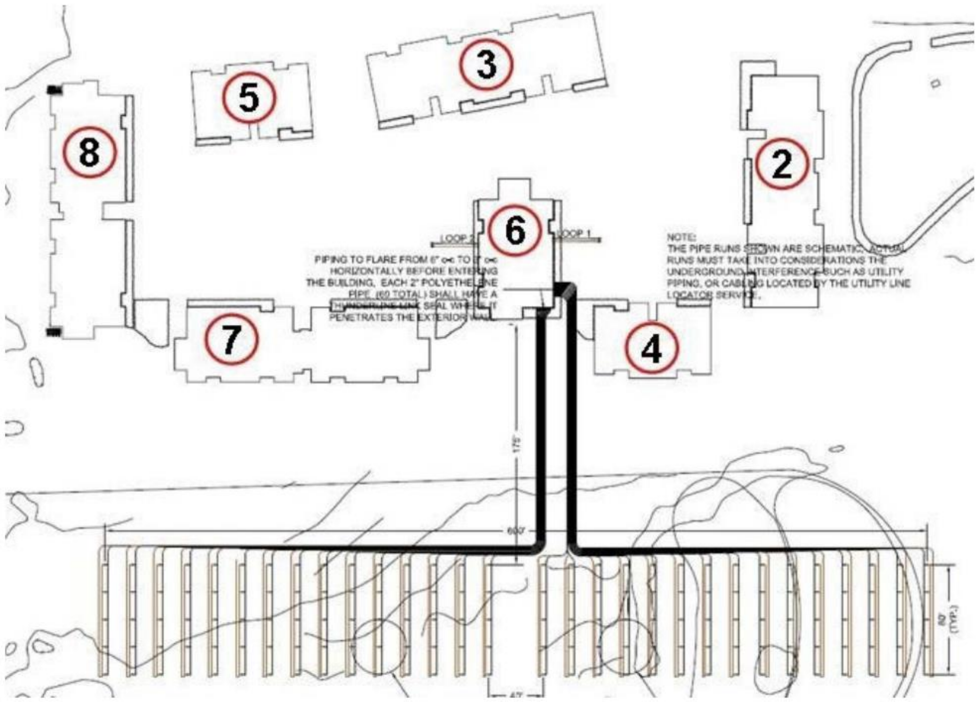


Figure 2: Princeton Lawrence Apartments District Heat Pump System (Pinder, Yavuzturk, & Ozbek, 2015)

Water remains the most popular heat source for heat pumps, but other supplies exist such as humid air for the Skjern Paper Factory and waste heat cycled from data centers. Industrial heat pumps have the potential to drastically decrease emissions, yet obstacles such as high initial capital costs and stipulations about their efficacy remain. Another hindrance to widespread heat pump usage is the current, popular steam system. If this was to remain in use, heat pumps would only be a step towards reaching 100°C and producing steam. Heat pumps alone are almost never used to reach boiling temperatures. To replace steam heating systems, more investment and longer installation time is required.

Project Motivation

Cornell seeks to reduce its total carbon footprint to zero net emissions by 2035 from the 2008 baseline. They have already achieved roughly 30% net emissions in 2020 and continue to follow an emission-reducing trajectory. The goal is to replace the Combined Heat and Power Plant (CHPP), which currently runs on natural gas, with a renewable energy array for electricity generation and earth source heating for the campus heating load. However, there are a few additional buildings that are not particularly amenable to a centralized earth source heating district. If Cornell wants to heat these buildings without natural gas, then they will need to

Transitioning to heat pumps could reduce the overall energy consumption needed for heating and cooling and allow the electrical input for the heat pump operation to be sourced from renewable energy. By investigating the use of heat pumps on campus, we hope to contribute to Cornell's efforts to achieve long-term carbon neutrality in a financially, ecologically, and socially sustainable manner. Furthermore, we hope to add to a growing collection of knowledge around large-scale heat pumps and have Cornell serve as an example for other institutions.

System Location and Demand

Mini-District Selection

After an examination of buildings on and off Cornell's main campus, we concluded an effective mini-district could be installed on West Campus at Cornell University. This mini-district would consist of a well-field, centralized heat pump and heat exchange station, and a distribution system to buildings within the mini-district. While we also examined locations on North Campus, East Hill Plaza, and Hungerford Hill, we lacked sufficient data on buildings in these areas. The location of West Campus was chosen for not only its data but also its suitability as a mini-district location.

West Campus is on the periphery of Cornell's centralized steam heating system network. Peripheral locations require greater costs of infrastructure to support their operation due to their greater distance from the center of the network. In the map below, the location of the 12 buildings the mini-district would serve is shown along with the Central Heating and Power Plant, which is in the southeast corner of the map. This more remote location makes this conglomeration of 12 buildings attractive for a min-district development.

We were able to obtain heating and electrical use data from Graphana for the 4 northern-most buildings in the district. These buildings included:

1. Delta Tau Delta
2. Sigma Phi
3. Psi Upsilon
4. Phi Kappa Psi

While these are mainly Greek life residences, they are connected to the steam network on Cornell and are billed by Cornell utilities for their steam heat and electricity use. In addition to these 4 residences, we chose 8 other residences in the area to be part of the mini-district.

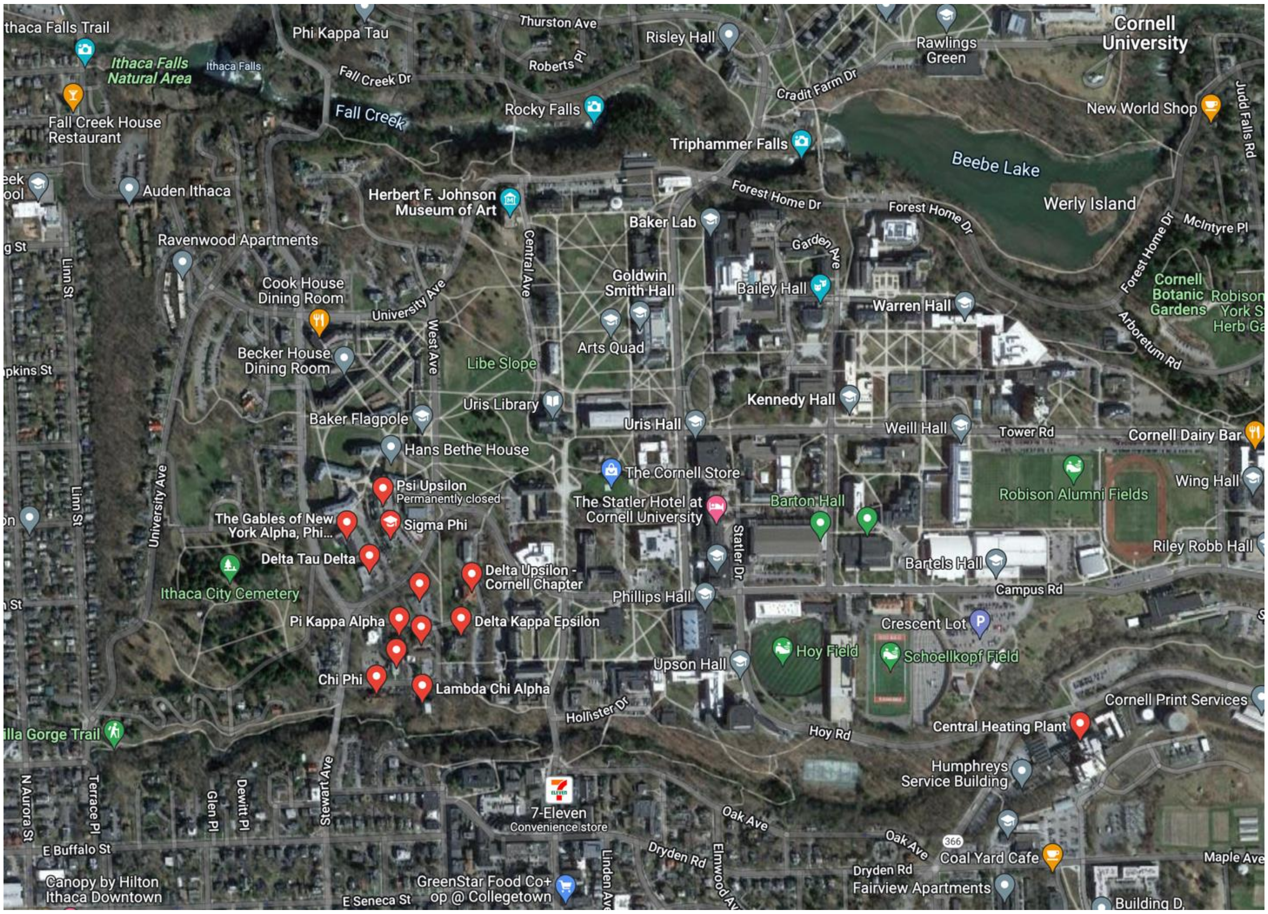


Figure 3: Satellite Image of Cornell's Campus and Mini-district

These additional 8 buildings include:

1. Chi Phi
2. Phi Sigma Sigma
3. Delta Kappa Epsilon
4. Delta Upsilon
5. The Center for Jewish Living
6. 112 Edgemoor Lane Residence Hall
7. Lambda Chi Alpha
8. Pi Kappa Alpha

Since Cornell does not have data on heating and electricity use for these buildings, we chose to estimate their energy use by calculating an energy consumption per square foot for the 4 buildings we have data for and applying that energy intensity to the other buildings. We also assumed Lambda Chi Alpha and Pi Kappa Alpha have an average square footage of the 4 other Greek life houses numbered 1-4 in the list of 8 buildings without heating data. Both these buildings are not owned by Cornell and did not have data on the net area of the residence. The average net area of the 4 buildings with data was calculated to be 17,159 sq ft while the average of the 8 buildings without heating data was calculated to be 13,015 sq ft. We used these square footages to find that the total energy demand of the district is 10.07 times greater than the average energy consumption of the 4 buildings for which we have heating and electrical data.

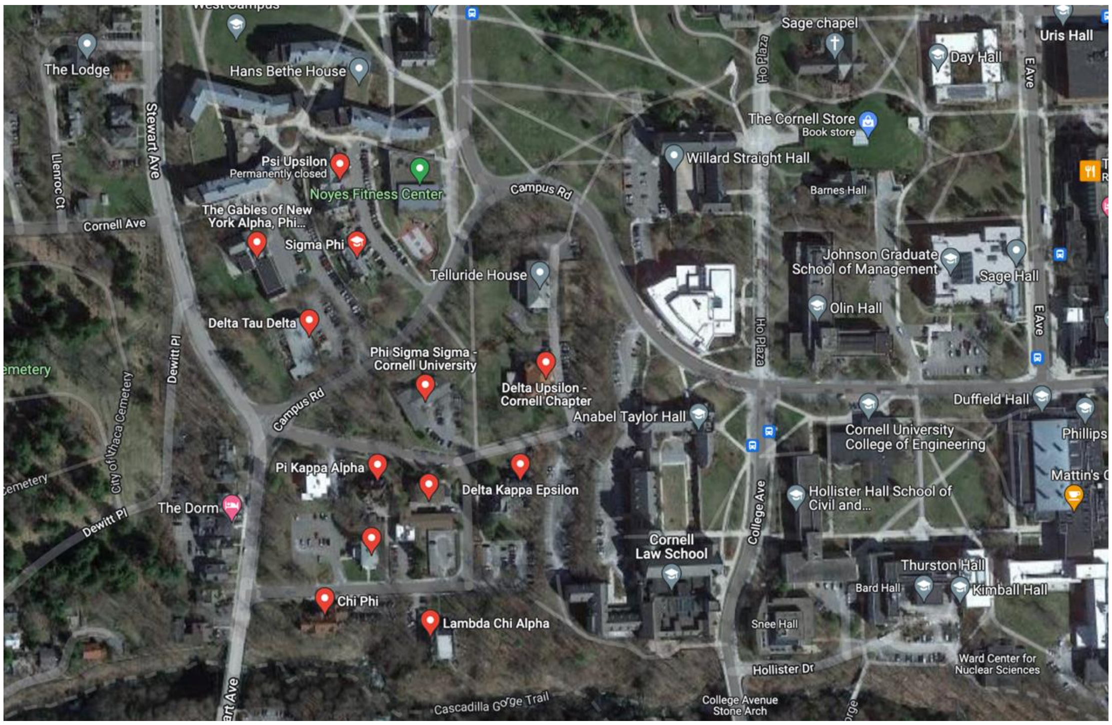


Figure 4: Satellite Image of Mini-district

To better optimize our system for the portion of the year that it will be active, we choose to design our system around the 75th percentile of the average daily heat load over one year. This gives us a target steam demand for the four houses in the Grafana of 184 pounds per hour. Using an industry standard of 1,194 BTUs per pound of low-pressure steam (Decker, 2018), we find our target heating load of the four Grafana house to be 220,000 BTU per hour, and the total target heating demand for the district to be 2.22 million BTU per hour. Figure Nic_1 below plots the average daily heat load of the four houses in the Grafana system compared against the effective 75th percentile of the distribution that we design our system around.

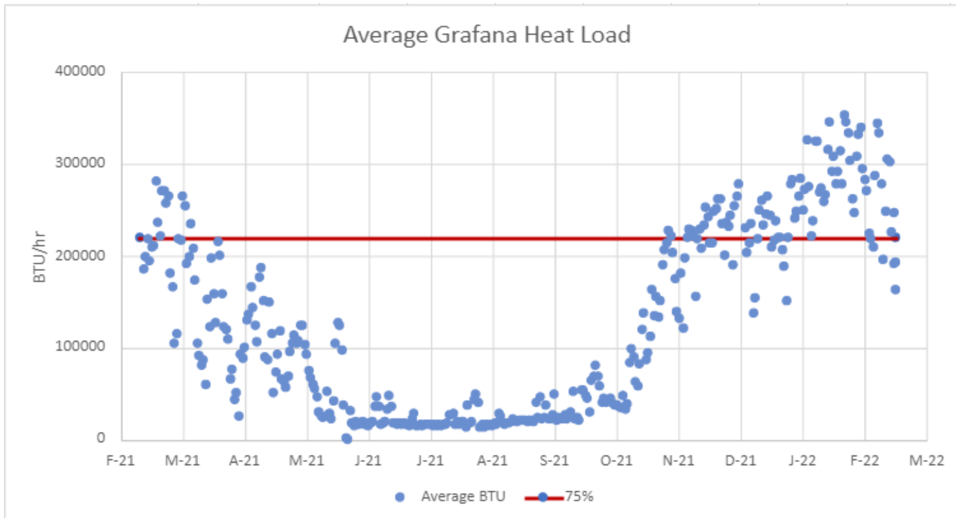


Figure 5: Average Grafana Heat Load

Cooling Demand Estimates for Fraternity and Sorority Houses

As explained earlier in the section How Heat Pumps Works, heat pumps can operate in reverse, delivering cool air instead of warm air to conditioned spaces. We examined the cooling needs of the mini-district in two ways. One way of estimating cooling demand is by examining cooling demand for other residences in New York. The 2009 Residential Energy Consumption Survey shows that the average New York State residence's energy need for space cooling averages about 1% of total residential energy consumption and energy demand for space heating averages 56% of total energy consumption (EIA, 2009).

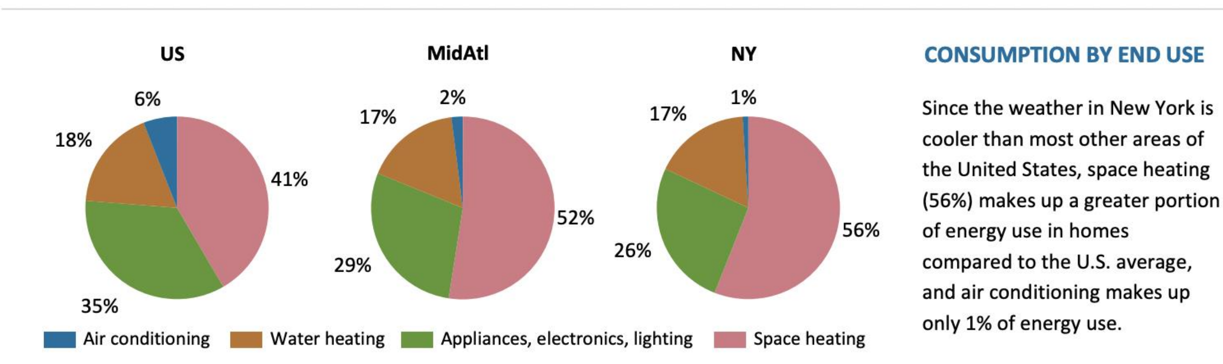


Figure 6: Energy Consumption by End Use in Residential Buildings (EIA, 2009)

The first method using the New York State average assumes that the buildings have similar characteristics and cooling demands as the rest of the state. This approach ignores differences in resident behavior and building characteristics that could change energy consumption for air conditioning. By looking at actual consumption data from buildings within the district, we can attempt to characterize energy use for air conditioning.

The second way we estimated the cooling demand was by comparing the electrical use during the cooling season and during the heating season. The underlying assumption is that the additional electrical use during the cooling season is used for air conditioning purposes. This method presumes that the calculated additional electrical consumption during the cooling season is an accurate estimation of space cooling needs. One of the concerns in this methodology is that these are student residences, being partially or completely unoccupied during the cooling season. Figure y below shows the electricity rate of use in kW over the year for the 4 residences for which data was available. Note the gap in usage during the summer months when Cornell is not in regular session.

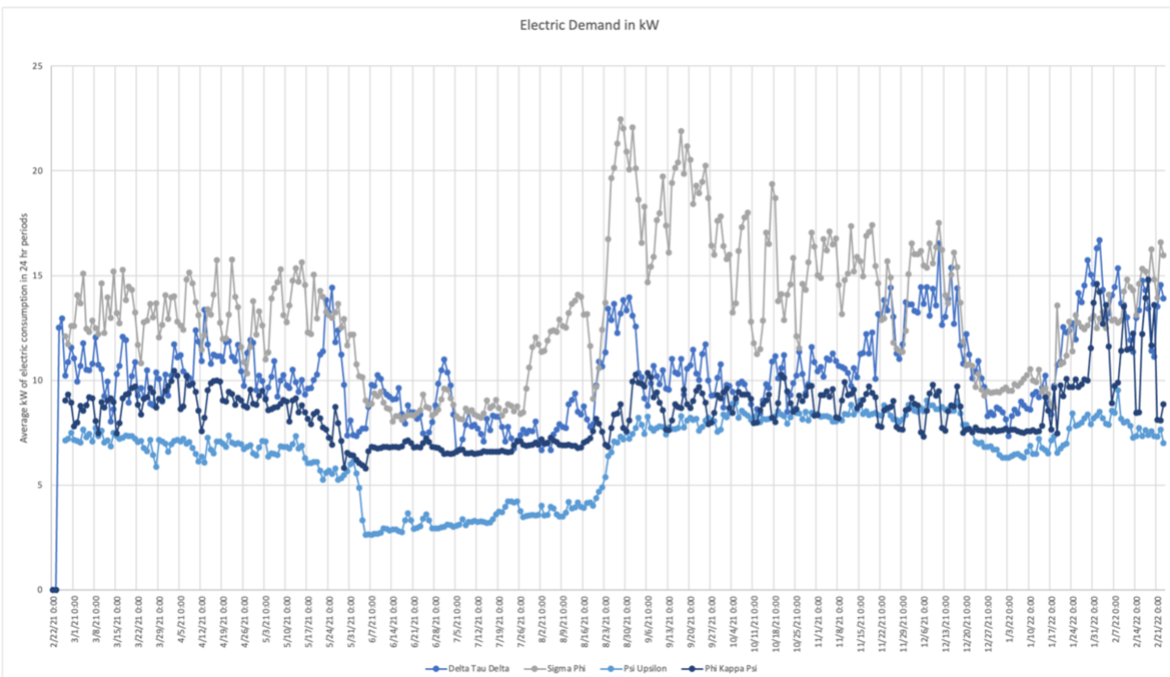


Figure 7: Electrical Demand for Delta Tau Delta, Sigma Phi, Psi Upsilon, and Phi Kappa Psi

Since the prior assumption of comparing cooling season use to heating season use would be a poor assumption knowing this gap of use in the summer, we instead decided to compare the rate of electrical use during the cooling season when school was in session to the rate of electrical use during the heating season while school was in session. The dates of the heating season were selected to be from 10/21 through 5/21. These dates were selected by visually inspecting graphs of the steam deliveries to the residences. The dates of the cooling season were chosen by visual inspection of figure y and set to the dates of the Cornell academic calendar for the start and end dates of the regular school session. The cooling season was defined from 5/22 through 10/20, excluding the gap in the summer, which was defined to be from 5/29 through 8/25.

After finding the rate of electrical consumption during this attenuated cooling season and the heating season baseload rate of consumption for the total of the 4 residences, we calculated the difference in these electrical rates to estimate the energy consumption for air conditioning during the attenuated cooling season. This resulted in 2.52 kW or 8611 Btu/hr continuously as an estimation for air conditioning energy demand during the attenuated cooling season. Similarly, we calculated energy need for heating by finding the difference of heat use between the heating and attenuated cooling season. This assumes that the buildings use heat for purposes other than space heating, such as hot water, dryers, etc. The average rate of heat use for space heating during the heating season was then calculated to be 182 kW or 621,000 Btu/hr. We then compared these rates of consumption for AC and space heating for the attenuated cooling season and the heating season. The average rate of energy consumption for cooling is 1.4% of the energy consumption for heating.

If the need for space heating in these residences aligns with the average consumption of 56% of total energy demand in the 2009 RECS study, the energy need for cooling of these 4 residences is 0.78% of total energy demand for the 4 observed buildings in the mini district.

A major critique of this second approach in methodology is the critical assumption that the increased electric load in the attenuated cooling season is an accurate way of characterizing energy need for AC. Additionally, the gap in the summer leaves out times when cooling needs could be greatest. However, the data we have leaves us with an inability to make comparisons to the summer months as the residences empty for the summer. One observation from the electrical data is that air conditioning needs may be lower than state averages if some spaces are not occupied and not receiving cooling as if they were occupied.

Regardless of the methodology chosen, the energy demand for cooling is insignificant compared to the energy demand needed for cooling. The heat pump mini-district system could be configured to also operate in cooling mode, providing valuable cooling for the cooling season when school is in session. For simplicity of the analysis, we have chosen to exclude technical and economic impacts of providing air conditioning as the results of the cooling demand analysis show cooling demand to be insignificant compared to the heating energy demands for the mini district. Energy demands for cooling are estimated to be at 1% or less of the total energy use of the buildings and 56 to 72 times less than the energy demand for space heating.

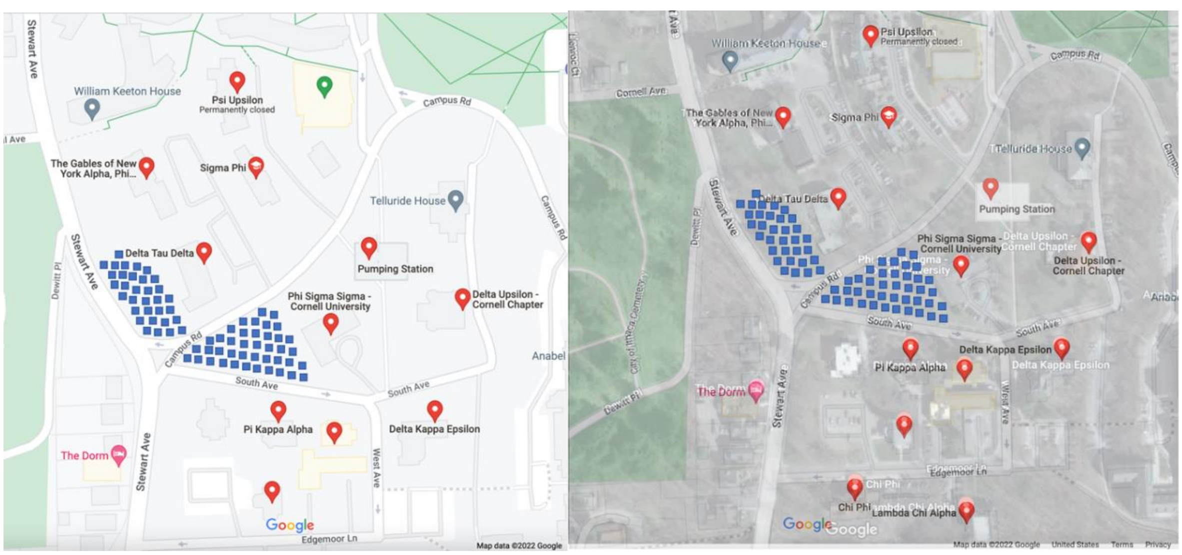
Proposed Technologies

Heat Pumps

To select the correct heat pump(s) to install for this project, we first needed to gauge the heating demand for the buildings being studied. We pulled this data from Grafana, selecting a BTU rate which is 75% of the maximum demand throughout the year. This number totaled around 220,000 BTU/hr. Most commercially available heat pumps operate on a smaller scale than this high demand, so our system must implement a series of heat pumps. To maximize financial viability, we searched for the largest available ground source heat pump on the market. Our search led us to the Bosch Greensource CDI TW 120 model, operating at a maximum capacity of ~120,000 BTU. At this capacity, we require 19 units to meet the demand. At lower demands, it will be possible to shut some units off, maximizing energy efficiency.

Wellfield Estimates

To avoid drawing heat from each other, vertical exchange pipe pairs are typically buried in grouted 4-inch diameter holes which are drilled at least 20 feet from one another. Thus, a field of 74 boreholes will have a minimum area demand of 29,600 square feet depending on the shape of the field (*Geothermal Heat Pumps | Department of Energy*, n.d.). Suitable locations for such a field in proximity to the fraternity and sorority housing district are displayed on the figures below.



Figures 8 & 9: Spacing of Wellfield using Google Maps Images

The cost estimations for the necessary wellfield stem from the Northeast Geo Water Energy Director of Commercial Design and Sales. Stated Closed Loop Well Field estimates included the following:

- 500’ boreholes provide 2.5 tons of heat transfer
- Each 500’ borehole would cost an average of $16,200

Knowing each borehole’s cost and production gives us the ability to better speculate wellfield cost and therefore total capital cost. While these numbers are heavily reliant on bedrock date, moisture content, soil type, water static levels etc., the wellfield portion of capital cost remains too substantial to neglect.

Soil & Bedrock Information

The team was able to gain bedrock depth knowledge through a meeting with a Cornell Earth & Atmospheric Sciences (EAS) professor. In this meeting, a program with bedrock information was discussed and used. A screenshot of the program is seen in the figure below. By hovering the cursor over potential wellfield sites, we could take note of areas with significant topsoil depth. The depth to bedrock is seen in the lower left of the figure below, listed after the zone. More information regarding rock type was found in a dissertation by Koenraad Becker in May of 2016. At the Varna site under consideration by Becker, the geology was found to be “Quaternary unconsolidated alluvial and glacial deposits topping Devonian shale” (Beckers, 2016). Thermal conductivity of the soil and rock also has a substantial influence on the number of and depth of boreholes. Thermal conductivity including effects of groundwater is estimated to be 4 W/m*K at the Varna site (Beckers, 2016).

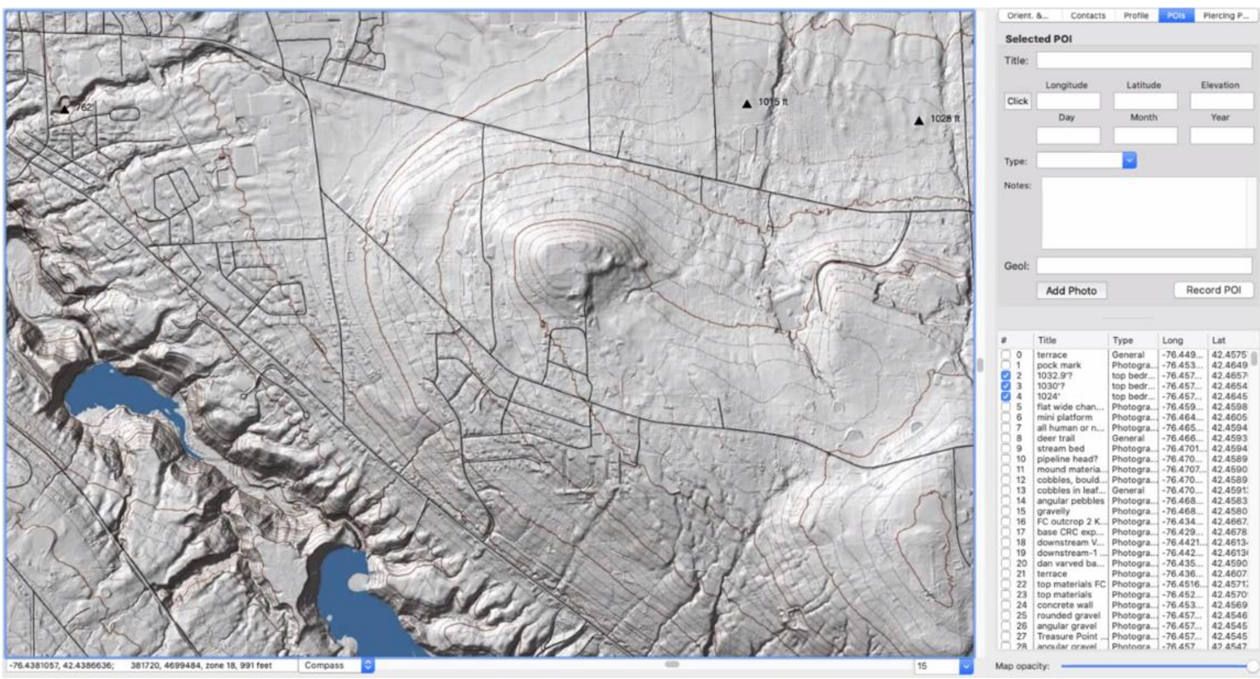


Figure 10: Bedrock Simulation Software provided by Cornell EAS Department

Economic Analysis

Installation Costs

An estimation of installation costs was adopted from a well-documented Toronto heat pump project. The Toronto project attributed 30% of capital required for the heat pumps to construction costs (Joksimovic, Fung, Kwiatek, & Sohail, 2019). Since we required 19 heat pumps, with a total cost of around $200,000, the installation cost is 30% of that total pump capital, or about $60,000. Regarding the wellfield installation costs, we were able to directly use a vendor estimate with the given information we provided. The installation of new piping and the central pumping facility were not accounted for in this project.

Total wellfield costs are estimated to be $1,200,000 using the pricing estimates from Northeast Geo and implementing a system of 74 500’ boreholes. This figure is subject to change according to soil moisture, bedrock depth, and other factors which could be determined from a site visit.

Operating Costs

Operation costs stemmed from the electricity needed to run the installed heat pumps. Using the specifications from Bosch, we found the required kWh usage from running each pump according to 75% coverage. Using a coefficient of performance of 3.7, stemming directly from the specifications sheet of the Bosch heat pump. This COP allowed the team to determine the electricity needed from the kWh supplied to the district through heating.

$$\frac{Heat\ Demand\ (kWh)}{COP} = Electricity\ Needed\ (kWh)$$

After an in-depth analysis of the number of fully active heat pumps during each hour of a calendar year, the team found a total power requirement of around 3,000,000 kWh per year. This figure divided by the COP gave the total electricity demand from the designed system. This yearly demand required to operate the heat pumps is 814,000 kWh. This number was used in an overall electricity cost and operating cost analysis of the pumps.

Using the above total and NYSEG electricity and natural gas prices, our team calculated the annual operating cost of the system, including the boiler’s additional costs. Another method we implemented was the use of NYSEG’s Catch the Wind Program, that allows customers to purchase clean wind energy for an extra monthly charge of $2.50 per 100 kWh of demand. Both the standard grid costs and Catch the Wind operating costs were studied and can be seen in more detail in the Appendix.

For the calculations that follow, a few more assumptions were made. These assumptions include an annualized capital cost associated with installing a new 5-ton boiler to supplement the heat pump system. This boiler would supply the necessary 25% of demand that the heat pump system is unable to support. Using this assumption and the delivery and service charges of natural gas, the cost of the boiler system that supplements the heat pumps totals $7,500 annually. The pump system was also annualized over a 20-year lifetime with a discount rate of 5%. With the added cost of the Catch the Wind program for electricity and the annualized capital cost, the total cost of the designed system is $224,000 from the heat pumps and $7,500 from the boiler totaling $231,500 annually. This includes the annualized capital cost of the wellfield and heat pump system, operating electricity cost of the pumps, and the added annualized cost of the boiler. If the Catch the Wind program is not used, the total annual cost is $203,000 from a lower $/kWh electricity cost.

Status Quo Operating Cost Comparison

The status quo cost of heating from the Cornell cogeneration plant was reported by Mark Howe to be about $22 per million BTU. For several buildings of interest, the cost of heating was calculated to be between $15 and $22 per million BTU during high-heating months based on steam consumption trends and utility bills, so $22 per million BTU is taken to be the status quo cost of heating buildings which receive power and steam from Cornell's cogeneration plant. For March 2021 to February 2022, the cost of heating a fraternity house using steam from the cogeneration plant was $20,928 assuming that heating is the primary use of steam. The status quo cost of heating from NYSEG, which applies to university buildings that are not on the heating distribution loop, was calculated to be $87,300 for the remaining 8 fraternity houses based on historical (February 2021 to February 2022) gas prices and distribution fees available through NYSEG as well as installation cost of natural gas boilers. The $87,300 total results in around $11,000 operational cost per house. That is significantly lower per house in comparison to the steam from cogeneration cost. Natural gas prices allow boilers to remain a cost-effective form of heating, as seen in the lower per-house cost of the buildings not included in Cornell's steam loop. Altogether, these figures result in an annual district heating cost of $171,000 under the current system.

Steam Cost					
Fiscal Yr	Degree Days	4741	4747	4776	4777
2021	7493	$22,263.94	$24,345.86	$14,708.17	$17,348.40
2022	6355.8590	$21,234.75	$26,425.06	$15,380.50	$16,515.98
Overall	13849	$43,498.69	$50,770.92	$30,088.67	$33,864.38

Table 2: Steam costs for Psi Upsilon, Sigma Phi, Delta Tau Delta, and Phi Kappa Psi

The $171,000 cost is heavily dependent on the excessive price of Cornell's steam system operation. Had the mini district studied contained 12 buildings all reliant on the steam system, an annual heating cost of $209,000 would be expected. This number stems from the known buildings' steam costs listed on the Cornell database and scaling according to square footage. In this analysis, the heat pump system is an economically attractive investment.

Carbon Free Electricity

The best low-impact electricity source for heat pumps at Cornell is likely to change over upcoming years as the state of New York and the City of Ithaca both work towards ambitious goals for an emissions-free future. Because New York State plans to invest heavily in large-scale renewable energy, there is legislation in place to prevent competitive private projects (Carson, 2022). Thus, it should be expected that Cornell's renewable capacity, provided by solar farms and hydroelectric plants, will remain constant in the future.

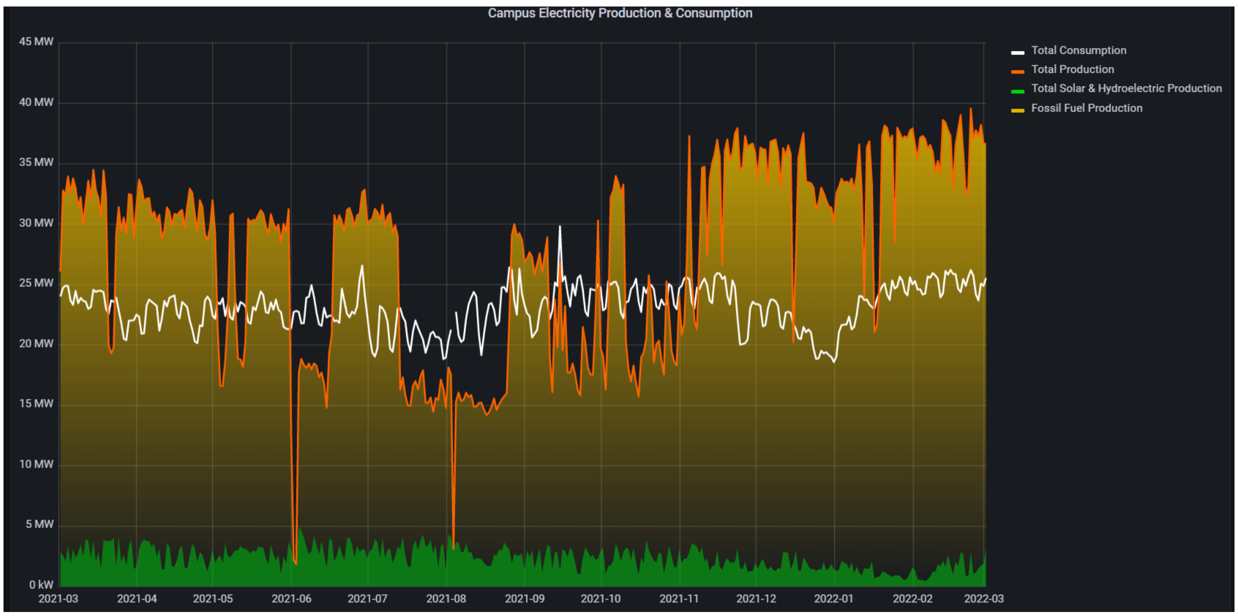


Figure 11: Campus Electricity Production and Demand from Grafana

Instead of building new renewable capacity, it can be assumed that the University will eventually rely on the NYSEG grid, which must be 100% emissions-free by 2040 according to the Climate Leadership and Community Protection Act (Climate Act, n.d.). It is not yet clear how this transition will affect the price of energy from the grid because the capital cost of renewable energy projects depends on variables such as tariffs on foreign-made technologies and installation restrictions. However, supplying New York residents with energy at a consistent price is one of the main goals of the renewable energy transition. According to NREL, the LCOE of utility scale renewable energy generation is projected to range from $30-50/MWh in the year 2050 if NYS CAC goals are met with a mix of hydropower, wind, and solar energy with battery storage (*New York State Climate Action Council*, 2021). The LCOE is calculated over a 20-year period and depends on technological innovation that takes place between now and 2050

(*Technologies | Electricity | 2021 | ATB | NREL*, n.d.). If NYSEG supply costs change to reflect LCOE and delivery costs remain the same as they are currently, the cost of operating heat pumps with renewable electricity in 2050 will be between \$64,000 – 83,000 per year to meet the 856,000-kWh demand.

Cornell's cogeneration plant is an efficient use of fossil fuels and not near the end of its lifetime, so it will likely continue to operate until NYSEG can provide cleaner energy. While future heat pumps are powered by either the cogeneration plant or by a non-renewable grid, such as NYSEG before 2040, the funding of some carbon management strategy will be necessary to offset the impacts of the heat pumps' emissions. Because it can be difficult to assess the true impacts of third-party carbon offsets, reliable carbon management strategies are an active area of research at Cornell. Currently, Cornell's Office of Sustainability has a working group with the College of Agriculture and Life Sciences to investigate ways in which Cornell's land uses and management strategies could be manipulated to reliably sequester atmospheric carbon (Carson, 2021). The team recommends that, while the heat pumps rely on a fossil-powered grid, corresponding action is taken to sequester atmospheric carbon through land management practices. To be cost-competitive with third-party offsets, these carbon management strategies would need to cost less than the previously mentioned \$0.03820 per kWh.

To minimize carbon emissions from the system without installing more large-scale renewable capacity, the University could also consider installing solar panels on site to generate clean energy. Excess energy generated throughout the year could be exported to NYSEG and bought back with RECs when needed. At the residential scale, we could see levelized costs of \$147 - \$221 per MWh and capital costs of \$2475 - \$2850 per kW. Commercial and utility scales systems would see lower rates of \$67 - \$180 per MWh or \$28 - \$41 per MWh levelized costs and \$1400 - \$2850 per kW or \$800 - \$950 per kW respectively (Ray & Douglas, 2021). EnergySage provides a local residential average of \$2760 per kW, indicating that solar costs in Ithaca are above the national average (*Solar Panels in Ithaca, NY: 2022 Cost and Companies | EnergySage*, n.d.).

Levelized Cost of Energy (LCOE)

By determining the number of heat pumps required during each hour of the calendar year using demand data, we were able to determine the total amount of BTUs supplied by the 19 Bosch heat pumps. This number appears in the denominator of the LCOE calculation, once multiplied by the expected life of the heat pump system. Progressing through the calculation, the total capitalized cost of the wellfield and heat pumps (installation cost section) is used in the numerator of the calculation. Lastly, the operating cost of the pumps in the form of dollars per kilowatt hour is added. Maintenance costs over the course of the project's lifetime were not considered in this LCOE calculation; this aspect remained out of scope.

$$LCOE\ (\frac{\$}{kWh}) = \frac{Total\ Capital\ Costs}{Total\ Lifetime\ Production} + Operating\ Cost\ (\frac{\$}{kWh})$$

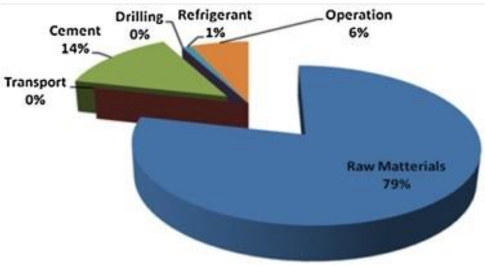
Two separate calculations were done and can be viewed in more detail in the Appendix. The LCOE for a 20-year projection is $0.124/kWh using grid electricity and $0.149 using NYSEG's Catch the Wind program. Both instances heavily rely on the cost of electricity to run the pumps themselves. This operating cost per kWh is derived above in the operating cost section. Implementing a 30-year lifetime leads to an LCOE of $0.116 using grid electricity and $0.141 using NYSEG's Catch the Wind program. This decrease is caused by the larger total lifetime production from the pumps.

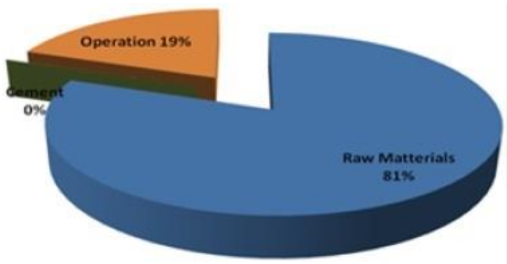
LCOE is an important aspect of any energy project as it is designed to bring all capital costs, production, and operating costs into one key metric. It is commonly used to compare different generation sources and their respective economic viability. In this case, the LCOE is heavily impacted by the expensive electricity costs from the grid and NYSEG. Future scenarios with higher renewable generation within the grid could see this LCOE metric decrease for a heat pump project of this magnitude.

Environmental & Social Impacts:

Lifecycle Emissions

The widely accepted method to measuring the environmental impacts of heat pumps is by using the life-cycle assessment (LCA) which is a validated, consolidated methodology that identifies and quantifies the potential environmental impacts associated with a product, process, or activity, throughout its life cycle (Fortes et al., 2018). The environmental impacts analyzed include greenhouse effects, ozone depletion, acidification, eutrophication, cancerogenic effects, heavy metals, and winter smog (Christopher & Evanthia, 2016). In the following three figures, Koroneos & Nanaki (2016) have shown that the raw materials production and extraction would be the greatest contributor to all three types of air pollutants.





Figures 12 & 13: (left) CO2 Emissions from all Stages during the GSHP System Life Span (right) SO2 Emissions from all Stages during the GSHP System Life Span (Koroneos & Nanaki, 2016)

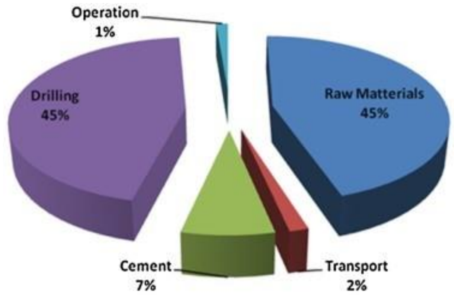


Figure 14: NOx Emissions from all Stages during the GSHP System Life Span (Koroneos & Nanaki, 2016)

According to Koroneos & Nanaki (2016), the total carbon dioxide emission throughout the life of a 265.4-kW (for heating capacity) ground source heat pump (GSHP) is around 6,592.5 tons. In this study, our total capacity is around 670 kW. As mentioned above, the team has proposed using existing sustainable energy sources, such as solar, to provide electricity to run heat pumps. Therefore, the operational release will be reduced to very low, close to zero. Therefore, as we assume the amount of lifecycle emission is proportional to the size of the whole heat pump system, we can estimate its lifecycle carbon footprint to be approximately: ((670 kW * 6592.5 tons) / 265.4 kW) * 0.94 = 15,644 tons. This figure represents the entire life cycle emissions related to the manufacturing and operation of the heat pumps. It cannot be accurately compared to yearly emissions explored in the following section.

While there are emissions throughout the heat pump life cycle, heat pumps are still considered sustainable. According to a Natural Resources Defense Council (NRDC) study, over its lifetime, a new air-source heat pump can reduce greenhouse gas emissions by 46 to 54 percent compared to natural gas alternatives. Besides, emissions of the ASHP are 40% lower than the emissions of the direct electric heating and, in the case of the ground source heat pump, this reduction is up to 70% (Juan-Ignacio Latorre et al., 2018).

Status Quo Emissions & Carbon Emission Reduction

To estimate how many carbon emissions are avoided by this GSHP implication, the team first calculates the carbon emissions per unit energy value (in unit of MmBtu). The chemical reaction equation of the combustion of natural gas is as follows:

$CH_4 + 2O_2 == CO_2 + 2H_2O$

In which 1 mole of CH_4 could generate 1 mole of CO_2 after full combustion. Based on the molecular mass of the CH_4 (16 g/mol) and CO_2 (44 g/mol), we could infer that 1 kg methane could produce 2.5 kg CO_2. In this study, we make several consumptions about the efficiencies: 1. the natural gas boiler efficiency is 95% (GoldsWorthy et al., 2013); 2. the steam turbine efficiency is 90% (EPA, 2015); 3. the energy transmission efficiency is 95% (EIA, 2021).

The energy content of methane is in the range of 50 – 55 MJ/kg. In this study, we assume the natural gas is 100% methane by volume, so its energy content is set at 50 MJ/kg.

Then, we estimate the energy produced per kg CO_2 emission to be 17,236.36 Btu (the unit conversion between MJ and Btu is: 1 MJ = 948 Btu). Thus, we could infer that for 1 MmBtu produced, 127.93 lb of CO_2 would be emitted. The number is valid and logical because it is close to the EIA official number (116.7 lb of CO_2/MmBtu). After we considered the natural gas boiler efficiency, we could get 134.7 lb-CO_2-emitted / MmBtu.

	Heating demand	Fraction of heating demand
4 houses with data	4080.91 MmBtu	39.7%
8 houses without data	6190.30 MmBtu	60.3%
Total	10271.1 MmBtu	100%

Table 3. Heating Demand According to Building Grouping

As shown in the table above, the current energy consumption of the four frat houses on the Cornell steam network is 4080.81 MmBtu, and the current energy consumption of the eight frat houses off the network is 6190.3 MmBtu. Therefore, we estimate the status quo emission by summing up the emissions from four frat houses with data and the emissions from eight frat houses without data. Since those 4 houses are heated by steam, we need to take the efficiency of the steam turbine into account. Thus, the emission from the 4 frat houses is:

(4080.81 MmBtu * 134.7 lb-CO_2-emitted / MmBtu) / 0.95 / 0.9 = 642716.7 lb.

The emission from the 8 frat houses is:

(6190.3 MmBtu * 134.7 lb-CO_2-emitted / MmBtu) / 0.9 = 877460.2 lb.

The total status quo emission is 1520176.9 lb, which is equivalent to 689.42 metric tons CO_2/year. As mentioned before, we assume that there would be no emissions during the operating of heat pumps given that they will run on 100% renewable electricity. However, there remains about 42 metric tons of emissions from operating the supplement natural gas boilers for times when the heat pump system capacity is maxed out and additional heating is needed. This occurs only in the months of January and February and emits 6% of the estimated annual emissions of the current heating infrastructure. We could estimate the amount of CO_2 emission reduced by the heat pump application is roughly 647 metric tons of CO_2/year.

Soil Thermal Balance

Soil thermal imbalance is the main obstacle during the operation of the ground source heat pump (GSHP) system (Xu et al., 2021). For heating dominated GSHP, long-term heat extraction from the ground causes a drop in soil temperature. Furthermore, the outlet temperature of the working fluid leads to the deterioration of GSHP performance. During cooling-dominated GSHP, heat accumulates in soil and the soil temperature rises year by year, which breaks heat balance of the subsurface environment (Xu et al., 2021).

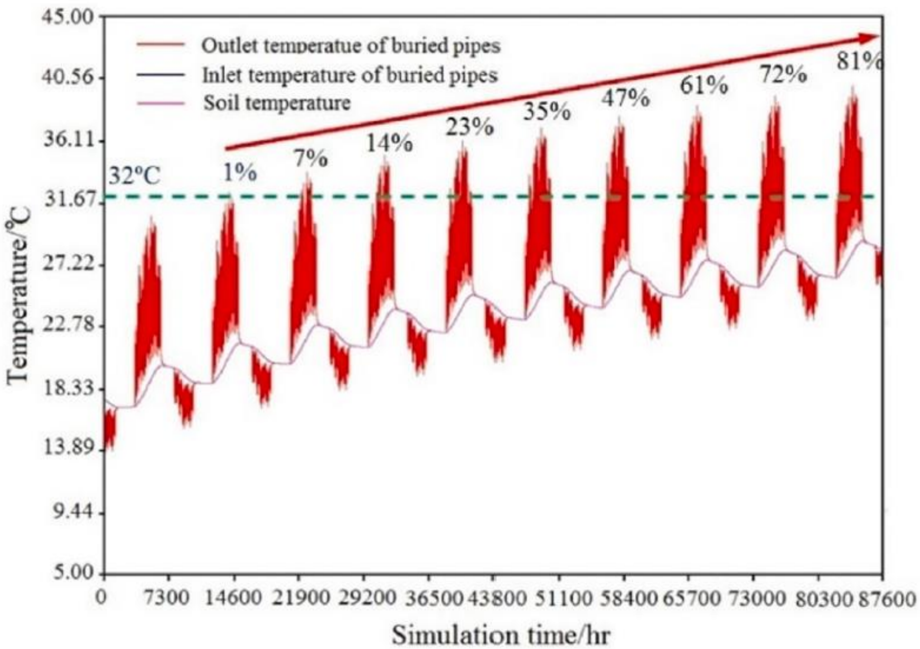


Figure 15. Soil Temperature Increases as the GSHP Works (Xu et al., 2021)

The alternative heat pump system which could be used to solve this soil temperature problem and improve system performance is the Hybrid Ground Source Heat Pump (HGSHP) (Xu et al., 2021). This type of heat pump was not considered in this project, but its potential application could serve as a research pathway in the future.

Refrigerant Use

An important environmental impact of heat pumps is their use of refrigerants, which can be ozone-depleting or have high global warming potential (GWP). In 1987, the United Nations Environmental Programme passed the Montreal Protocol, which banned the use of ozone-depleting chemicals like chlorofluorocarbon refrigerants (UNEP, 2020). Since then, hydrofluorocarbons (HFCs) like R134a have been the main group for commercial refrigeration purposes. While they are not ozone-depleting, these molecules do have a high global warming potential. The 2015 Kigali amendment to the Montreal Protocol calls for the reduction of HFC production by 80% by 2050 (UNEP, 2018). If successful, this policy could reduce the global temperature in the year 2100 by up to half a degree Celsius (Xu et al., 2013).

The goal of this project is to contribute to a "Carbon Neutral Cornell," but in doing so, we should also reduce Cornell emissions of other, especially more potent, greenhouse gases when possible. The UNEP and the USEPA both recommend the use of alternative refrigerants which have a lower global warming potential than R134a. The global warming potential (GWP) of R134a over a 100-year period is equivalent to 1430 tons of CO_2, whereas alternative refrigerants have a GWP lower than 6 (USEPA, n.d.). Many of these refrigerants have not been used for heat pump applications but have been used in other large-scale or commercial settings like grocery store refrigeration systems or vehicle air conditioning (UNEP, 2014). They include popular refrigerants such as R744 (CO_2) and R717 (ammonia) as well as other less-commonly used fluids like R290 (propane), R1234YF or R1233zd (hydrofluoroolefins), and propylene glycol.

Previous studies have focused significantly on CO_2 and found that GSHPs, with CO_2 as the working fluid, have a COP between 2.24 and 3.8. This range is caused by CO_2 having an internally low critical point of 30.98 degrees Celsius and 7377 kPa. Furthermore, a heat pump may run subcritical or transcritical cycles depending on configuration (Wu et al., 2021). Though CO_2 and ammonia both have relatively low capital costs, their high operating pressure demands result in higher maintenance costs and more expensive equipment demands. Ammonia requires extra care due to its toxicity and corrosiveness to copper, which is a common material in heat pumps. While assessing alternatives, one group has proposed a method of quantifying the compromise between energy efficiency, GWP, leakage rate and ease of detection, and other operating considerations of refrigerants. The best refrigerant choice was found to depend on heat pump cycle boiling point, condensation temperature, and compressor efficiency as well as the CO_2 emissions associated with electricity use (Il'in et al., 2021).

Social Impact

The main social impact is related to the employment which is both on a short-term basis during construction and continually over the life of the project (Oliker, 2022). This effect can be seen within the plethora of GSHP projects around the world. For instance, the employment enhancement of GSHP application each year in China is around 1 person/100 m^2 (Huang & Mauerhofer, 2015). Based on the reports of the GE Association of USA, the total direct, indirect, and induced employment effects of geothermal energy are calculated to be 4.25 full-time positions and 16 person-years per MW (Soltani et al., 2021).

Estimation of Employment Effects

The total power of the whole GSHP system in this study is approximately 0.67 MW. Using the calculation mentioned above, the estimated employment enhancement would be around 3 full-time positions and 11 person-years. It should be noted that since we are targeting only 12 buildings for this project, our social impact will seem minimal. Given that Cornell will be applying heat pump systems to most or all its campus facilities in the future, the estimated numbers could be magnitudes higher. The exact numbers are significantly influenced by several variables, including the education of the local workforce in Ithaca, the development of actual construction, and the actual availability of the surrounding (within or out of the Tompkins County) workforce, etc.

Recommendations for Future Action and Research

Additional Locations for District Heating Systems

There are multiple other locations that Cornell University and Tompkins County could consider for the installation of ground-source district heating systems. When starting this report, the team investigated the animal health labs on Hungerford Hill Road as a potential focus area due to their distance from central campus. However, their separation from the cogeneration plant meant that we could not access information about these buildings' heating demands or electricity costs through the Grafana Dashboard. If Cornell Utilities chooses to implement heat pumps in the future, we recommend analyzing the potential of this area for district heating. Satellite locations like Cornell AgriTech in Geneva or some of Cornell's cooperative extensions may also be viable locations. Since the whole City of Ithaca is also working towards decarbonization, local business parks like the one near Ithaca Tompkins International Airport could be good sites for ground-source heating districts.

Incorporation of New Data

There are several efforts currently underway that could contribute to future heat pump projects. Presently, Cornell is initiating two other campus heating innovations: earth source heat and the switch of the campus heat distribution loop from steam to hot water. An exploratory well broke ground in April 2022, which will test the compatibility of campus's geology with geothermal heat production (*Heat: Earth Source Heat | Sustainable Campus*, n.d.). As the University moves forward with its Earth Source Heat project, significant information about the subsurface condition of Ithaca will be collected. Understanding more about local geology, temperature, and groundwater flow will help optimize wellfield design for future projects.

Additional information about New York State's climate action will also help by specifying the cost of renewably generated electricity. Currently, it is not known how utility companies will change their supply or delivery costs to reflect new electricity sources, but this information will have to be released as the transition to renewable energy begins over the next several years. Having more accurate values for future electricity prices will result in better estimates of operating cost and LCOH. Knowing the sources of this electricity will also help to determine the exact environmental impacts of the heat pump system, since renewable electricity generation methods have different environmental impacts other than CO_2 emissions.

Alternative technologies

In pursuing a carbon-neutral campus this report has looked at the employment of ground-source heat pumps to provide heating. Heat pumps themselves can help reduce carbon emissions by reducing the amount of energy needed to deliver the same amount of heat but are dependent on energy sources for their operation. These energy sources can come with varying degrees of cost and carbon intensity. This project has looked at a specific application of ground-source heat pumps with a renewable source of electricity. There exist many other alternative technologies that could be employed to both reduce cost and carbon emissions associated with heating buildings on campus.

Air-source heat pumps could be used to provide heat. This study tentatively discarded the notion of using air-source heat pumps due to the sheer number of units and installation space it would require. Moreover, air-source heat pumps suffer in productivity in colder climates making ground or water-source heat pumps a wiser option. Beyond other heat pump technologies and employments, other alternative means of providing heat exist. In the future, Cornell could look at reducing costs and carbon emissions from heating by using primary or supplemental boilers that run on biomass. Alternatively, Cornell could also turn to solar hot water heaters for providing heat needed for hot water demands in its residences and buildings.

The employment of biomass, solar hot water, and alternative uses of heat pumps lie outside the scope of this investigation. It is worth mentioning that amongst ground-source heat pumps many alternative technologies exist for providing heat. Future studies can help determine the costs and emissions associated with these other alternative technologies.

Hot Water Booster Application

Since 2001, Cornell's combined heat and power plant has increased the efficiency of the campus's fossil fuel use, resulting in a 25% carbon emissions reduction over the entire campus energy system. Known as a cogeneration plant, this system uses the waste heat from electricity generation to vaporize water to high temperature steam which circulates around the campus in a distribution loop (*District Energy & Combined Heat and Power | Facilities and Campus Services*, n.d.). From this distribution loop, heat from the steam can be transferred to water that runs through individual buildings to control internal temperature.

Regardless of the success of Earth Source Heat, the University plans to convert the steam distribution system to hot water. Doing so will reduce maintenance costs and increase reliability. Hot water may be supplied by the existing cogeneration plant or large-scale heat pumps if earth source heat is unsuccessful. Some of the newest buildings on campus are already connected to a hot water loop that extends from the main steam circulation. However, the cost of conversion of existing buildings to be compatible with hot water instead of steam is a large investment, as it would require significant reconstruction of each building's internal heat distribution.

Heat pumps could help to reduce the cost of this conversion by reducing the reconstruction requirement. In this role, a given building could be fitted with a heat pump that would transfer heat from the return line of the distribution loop to the supply line, raising its temperature. At this higher temperature, the hot water would deliver the same energy to the building that the steam does currently. This would mean that the internal circulation infrastructure of the building would not need to be renovated to accommodate a different incoming heat energy.

Conclusion

This project aims to provide potential renewable energy solutions for Cornell University's climate action plan to meet carbon neutrality by 2035. The primary focus of our study was to evaluate the implementation of a mini-district heat pump system for residential housing on Cornell University's West Campus. This location was chosen given the availability of existing electrical and heating data as well as its suitability as a mini-district location. Considering the capacity of existing infrastructure and remote location, we determined that our heat pump system would power 12 residences, 4 buildings currently on cogeneration steam and the remaining 8 currently on NYSEG gas boilers.

To gauge the heating demand for the buildings being studied, we pulled existing data from Grafana and determined that to successfully meet the heating demand while maximizing financial viability, it is best to install the Bosch Greensource CDI TW 120 model, operating at a maximum capacity of ~120,000 BTU. At this capacity, it was determined that we would need 19 units. To support the heat pumps, the system design also consists of a well-field with (74) 500' boreholes which would be distributed between the Phi Sigma Sigma and Delta Tau Delta due to the vast amount of unused greenspace between these buildings.

To further understand the feasibility of the designed system, we did an in-depth economic analysis of the installation and operating costs. Given an annual electricity usage of 856,000 kWh, it was estimated that the total capital cost would be roughly $1.5 million with an annual cost of $231,500. This cost included the annualized capital cost of the heat pump system, operating cost, and annualized capital cost of the small boiler working in conjunction with the new heat pump system. Given a 20-year period, this leads us to an LCOE of $0.15/kWh.

For future work, the team recommends additional systems to adopt district heating systems. These locations include Cornell's Hungerford Hill Laboratories, Geneva AgriTech Campus, and various locations in collaboration with Tompkins County. It is also beneficial to consider hot water boosting application for its many added benefits. Additionally, we recommend inclusion of ESH CUBO findings into the wellfield design and a more detailed calculation of refrigerant compatibility with heat pump models.

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Appendix A—Additional Heat Pump Case Studies

Utilizing Waste Heat for Higher Efficiency

In addition to the district heating case studies examined in the Background section, we also investigated several other uses of industrial-size heat pumps in literature. A report by Kosmadakis et. al. performed a techno-economic analysis on large-scale heat pumps applied to situations of recovering waste heat. Many of the examples given in the overview of the European Heat Pump Association (EHPA) make use of waste heat from industrial processes. Waste heat recovery has high economic viability as there is abundant heat available for transfer into heating applications. Kosmadakis et. al. looked at applications of heat pumps where source temperatures of heat ranged from 40-100 degrees Celsius and supply temperatures ranging from 100-150 degrees Celsius.

They examined single and two-stage cycles, refrigerants, as well as source and supply temperatures to optimize economic performance of high temperature heat pump applications.

The authors observed that changes in source/supply temperature, the size of the system, the refrigerant, and the cycle configuration all had large effects on economic performance. The specific cost of capital ranged from 200-800 Euros/kW (Kosmadakis, et. al, 2020). In some instances, the discounted payback period was a short as 3 years. Overall, the single stage heat pump with an internal heat exchanger yielded best economic performance, but with temperature lifts of 50℃ or more, the efficiency of two-stage heat pumps led to the best economic performance of the scenarios examined.

The economic performance of a given configuration depends largely on the technical performance of the heat pump, which can be measured by a coefficient of performance (COP), the ratio of units of heat output per unit of input energy. Figure 1 shows the COP of three different cycle configurations: a single stage heat pump, a single stage heat pump with an internal heat exchanger, and a two-stage heat exchanger. These scenarios were configured with their highest performing refrigerant—R1234ez(Z).

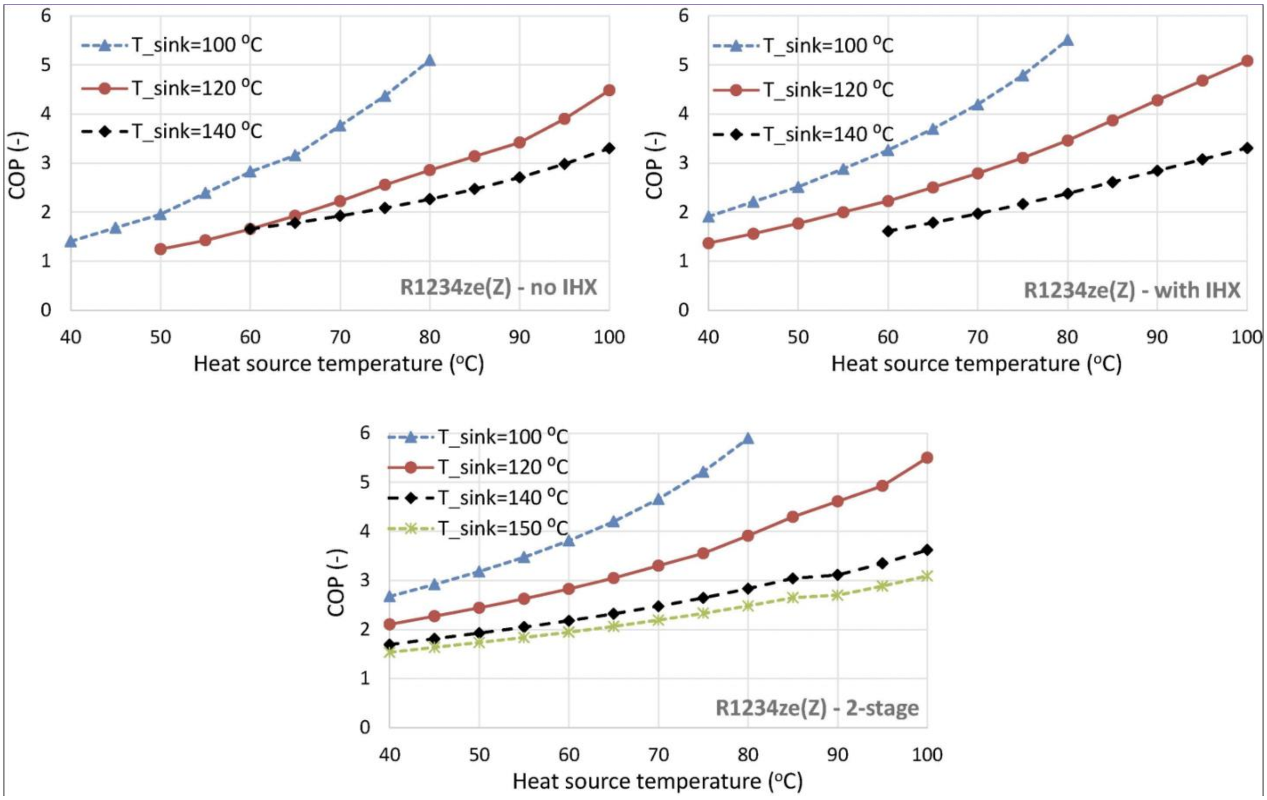
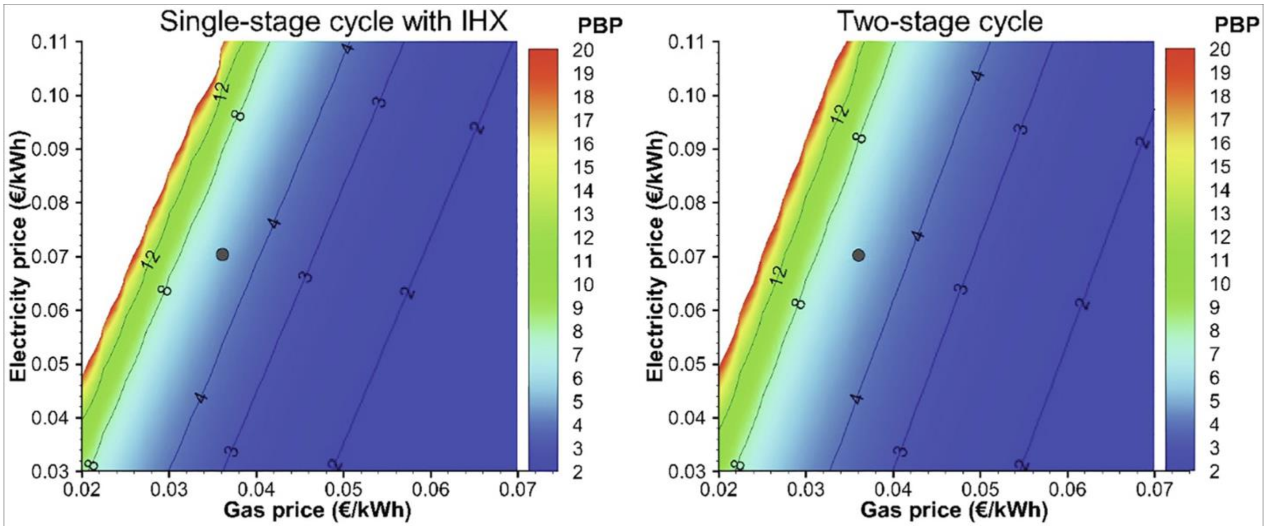


Figure 1: COP of single-stage, single-stage with internal heat exchanger, and two-stage heat pump configurations (Kosmadakis, et. al. 2020).

In executing their economic analysis, Kosmadakis et. al. make several economic assumptions in their model. They assume a capacity factor of 80%, which they argue is a conservative value for waste heat recovery projects. They assume a discount rate of 5%. While they vary the source and supply temperatures in the study, the base model assumes 80 and 120 degrees Celsius for reference source and supply temperatures, respectively. Kosmadakis, et. al. also investigated the effect of electricity price and natural gas on payback period. They argue one of the largest impacts on economic performance is the cost of electricity relative to natural gas. If electricity costs are high compared to gas, it makes heat pumps relatively expensive to operate when compared to systems that combust natural gas. Geographies that possess a low electricity to natural gas price ratio have better economic performance for heat pumps. Here, they assumed an average electricity and gas price of 0.07 Euros/kWh and 0.036 Euros/kWh, respectively. In US dollars this amounts to 7.8 cents/kWh and 4.0 cents/kWh. These prices are plotted in figure 2 below.

In this figure, Kosmadakis, et. al. set the source and supply temperatures at 80 and 120 degrees Celsius and compare their best performing high-temperature heat pump configurations. This model uses the assumptions stated above to calculate a discounted payback period allowing electricity and gas price to vary. These two scenarios are considered as they represent the highest economically-performing systems examined in this study. The gray dots on the figure represent the electricity and gas rates assumed by the authors. These prices happen to correspond to payback periods of about 6 years.



Figures 2 & 3: Discounted payback period of a single-stage heat pump with an internal heat exchanger and a two-stage heat pump.

Ambient Water Heat Pumps

While many heat pumps take advantage of waste heat, it is also worth giving attention to the performance of heat pumps in situations with access only to heat in the ambient environment. Trabert, et. al. examined the economic performance of two-stage industrial heat pumps for applications in district heating systems in Germany. They look at applications where cities are positioned next to rivers and can take heat out of the ambient-temperature river water. They used energyPRO software to produce 3 different models of the technical performance of proposed systems.

The model is run over a simulation period of 15 years with hourly intervals. The model accounts for variables of ambient temperature, river temperature, delivery and source temperature, heating demand, and spot prices on the electricity market. The model is run on 4 different heat pump configurations summarized in the table below. These configurations are sized to provide the district with 50% of the heat required to meet annual demand and storage systems large enough to shift peak heating loads.

Trabert, et. al. used the energyPRO software to create a predictive model of an expected river temperature for later use in the techno-economic model. The results are shown below.

Table 1: Dimensions of HP and storage in the compared simulation models

Component	Basis	HP10	HP20	HP30
HP	4.70 MW_{th}	5.17 MW_{th}	5.64 MW_{th}	6.11 MW_{th}
Storage	600 m³	900 m³	1,200 m³	1,500 m³

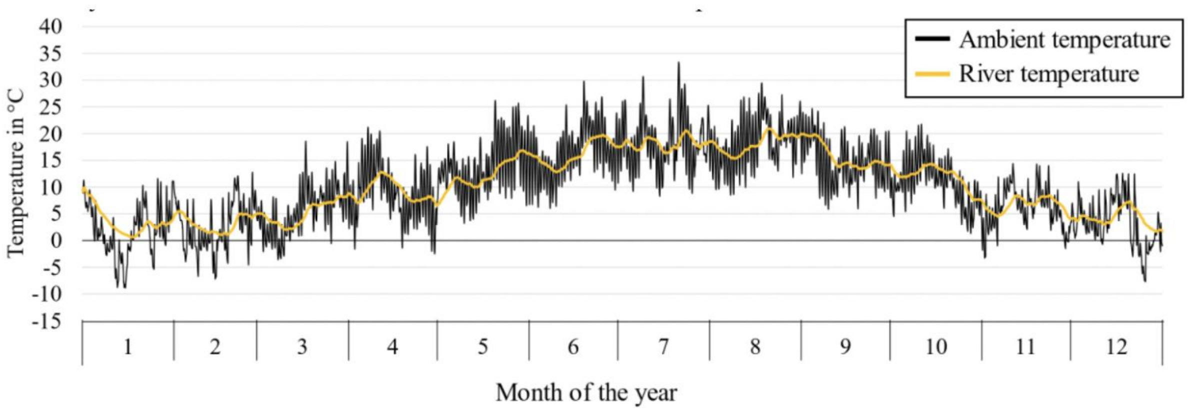


Figure 4: Annual River Temperature Fluctuations (Trabert, et. al. 2021)

Using energyPRO software, they modeled the COP performance of the base model using 3 modeling methodologies. These methodologies are poorly compared and explained by the authors. However, each of the models was restricted to using a minimum river temperature of 3 degrees Celsius and a maximum delivery temperature of 90 degrees Celsius. Cost-efficient operations of district heating systems rely on supply temperatures in the range of 65-70 degrees Celsius (Trabert, et. al. 2021). As shown in figure 4 below, the model of all 3 methodologies of predicting COP fluctuate with the season. When subjected to lower river temperatures in the winter months, the COP sags accordingly. While it is not elaborated on, delivery temperature in the winter months is allowed to be raised about the baseline delivery temperature of 75 degrees Celsius. This is likely to accommodate higher demand as this heat pump system is sized to provide only half of the total district demand. The storage of these systems would also be employed during these times.

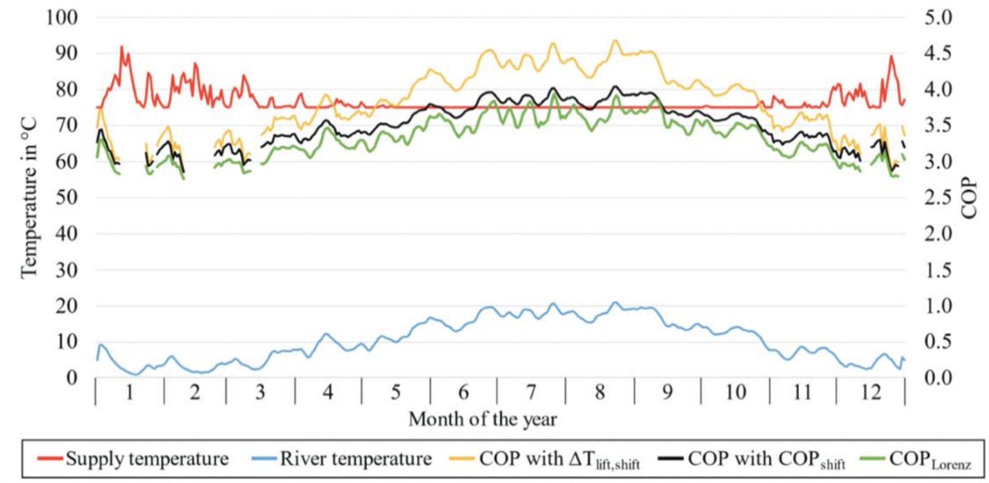


Figure 5: COP vs. time by modeling methodology (Trabert, et. al. 2021)

Even amongst the lowest of the estimates of the predictive models, the COP stays above 2.75 in the coldest times. COP in the wintertime could be expected to range from about 3-3.5 while summertime COP could be as high as 4-4.5. It is likely that the wintertime COP is a more accurate reflection of the economic performance of the heat pump as that is when heating demands are largest.

Trabert, et. al. go on to summarize the levelized cost of heating (LCOH) in their work for two of their predictive methodologies. The authors make the economic assumptions of an 8% discount rate and 30% government subsidy available for financing the initial capital cost. The results of the LCOH modeling are shown in figure 5 below. While these methodologies yield slightly different results, it is important to note the costs of the system. Well over half of the costs of the proposed heat pumps are fuel costs in the form of electricity. Interestingly, there is also not an economy of scale in the increased size of the systems installed.

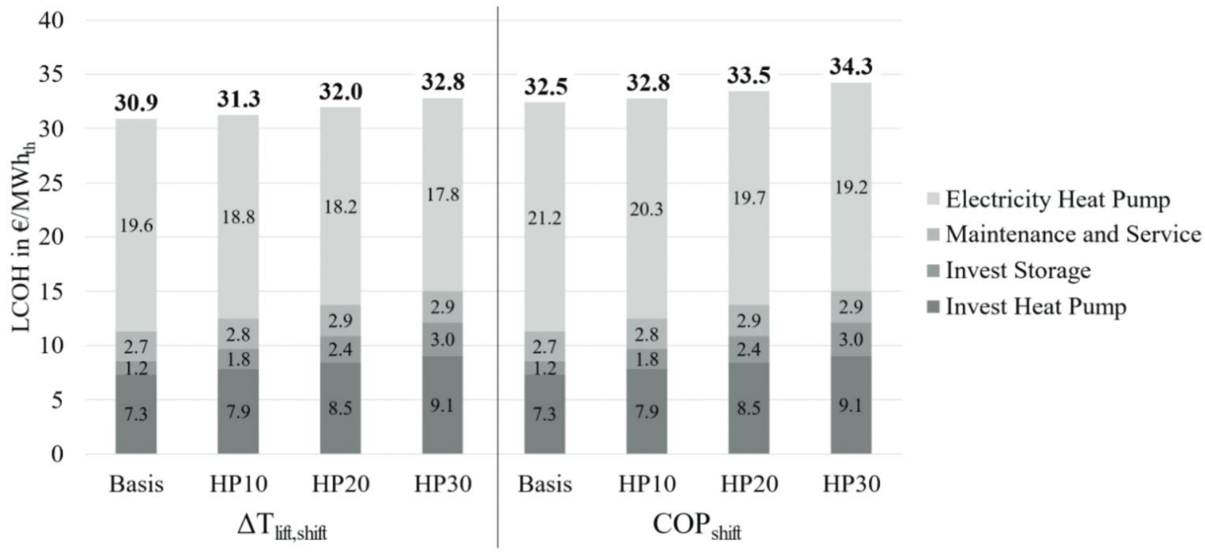


Figure 6: Comparison of LCOH of 4 different heat pump and storage size scenarios and 2 different modeling methodologies.

In USD, the LCOHs shows in this figure translate to $34/MWh to $38/MWh. The authors conclude that these LCOHs can be obtained, however, the outcome and performance of a specific applied situation will be highly dependent on the specifications of the heat pump as well as river temperature. Currently, the simulated conditions have the modeled heat pumps operating only 89% of the year. This downtime is due to low temperature of the river water. This raises serious questions about the usefulness of a heating system in the wintertime that is out of operation due to cold temperatures.

Ground Source Heat Pumps in Europe

On a global scale, large heat pumps have slowly gained traction in commercial and industrial applications, with Europe leading the charge. These pumps reduce emissions and do not degrade air quality during use. Two documents released by the EHPA were of interest. The summaries included any pump above 100kW and included COP, source heat, and temperature output. The majority of said pumps were found in the chemical, paper, food/tobacco, and wood industries (Large Scale Heat Pumps in Europe, 2020).

In West Jutland, Denmark, the Skjern Paper Factory houses three giant heat pumps totaling a capacity of 5.2 MW. These pumps use waste heat from their own facility to heat 60% of the town of Skjern, home to around 8,000 people. The humid air enters at 55 degrees Celsius and leaves the heat exchanger at 30 degrees. In 2015 alone, the plant produced and sold 40GWh. The plant recorded a COP of between 6.5 and 7, thanks to a contribution from direct surplus heat distribution (Large Scale Heat Pumps in Europe, 2020).

In Lausanne, Switzerland, two 4.5 MW heat pumps were built in 1985. These heat pumps use lake Leman, with a flow of 260 liters per second, as their heat source and are designed to minimize the number of pump start-ups required with storage tanks. The lake temperature is around 6–7°C, while the pumps supply the average temperature network with 28-65°C. If the temperatures are extreme, two gas turbines will turn on to work in conjunction with the heat pumps to supply necessary heat. The pumps supply the local university and school with reliable heat, use ammonia as a refrigerant, and maintain a coefficient of performance of 4.8 (Large Scale Heat Pumps in Europe, 2020).

Europe has found a way to encourage significant heat pump penetration into the heating market, with a conservative model estimating heat pumps alone could supply 15% of Europe's heating needs (Large Scale Heat Pumps in Europe, 2020). Scenarios in which waste heat is used by heat pumps lead to more efficient use of energy and less waste. Snellman Meat Refinement noticed the wastewater from washing surfaces could easily supply heat to the building, if properly used. The installation of heat pumps ended up saving the factory 580,000 Euro on an annual basis (Large Scale Heat Pumps in Europe Volume 2, 2020). Europe has also seen incredibly short payback periods, like in Kronoterm and Lust Brand's case in Slovenia when the return on investment was less than one year (Large Scale Heat Pumps in Europe, 2020). Addressing the reliability aspect of heat pumps, some companies constructed storage tanks to supply hot water for hours in the case of an emergency. Furthermore, gas boilers are sometimes used in combination with heat pumps to meet rare, extremely high demand. In these cases, new boilers are not installed. Instead, when restructuring the system to use heat pumps, a few of the boilers previously in use are not removed and left to support the new system.

Appendix B—Calculations

Operating Costs and Levelized Costs

Operating Costs & LCOE			
Heat Pump Required Electricity	856000	kWh/yr	Computed using spec sheet required voltage
Monthly kWh for Heat Pumps	71333.33333	kWh/month	
Monthly Charge for all Wind	$ 1,783.33	$/month	
Clean Energy Operating Cost	$ 0.125	$/kWh	From NYSEG Catch the Wind & Cell D68
Operating Cost (grid)	$ 0.10	$/kWh	Estimate using NYSEG delivery and service charge
LCOE Numerator	$1,460,620.00		Total wellfield and heat pump cost
Provided power from heat pumps	3010164.644	kWh/yr	From monitoring hourly heat pump use
Assume 20 yr lifetime	60203292.87	kWh	Lifetime Output (Cell D70*20)
Overall LCOE (w/ Oper. Cost)	$0.124		
Overall LCOE w/ Clean Energy	$0.149		

Table 1: Heat Pump Cost Calculations for a 20-year Lifetime

	Heat Pump Required Electricity	856000	kWh/yr	Computed using provided power and COP of 3.7
	Cost per year of operating pumps	$107,000.000		
	Annualized capital cost	$117,203.928		
	Boiler cost w/ heat pumps			
	Total yearly cost of new system	$224,203.928		$202,803.928
on system:	4 buildings cost	$83,713.00	steam	
20 year, 5%	8 buildings cost	$87,329.74	assumptions include building new boilers (no ducts) and no maintenance	
	Yearly cost of current system	$171,042.74		
Operational cost of our pumps and boiler system		$114,526.132	assumptions include having to install one 5 ton boiler	
		Assuming all 12 Building on Steam		
	12 building cost on steam	$209,282.50	using each 1 of the 4 buildings on network is 10% of total square feet	

Table 2: Heat Pump Cost Calculations