Carbon Neutral Cornell:
Environmental Sustainability Improvements at the Llenroc House

CEE 5052 M.Eng Project
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Executive Summary

In an effort to become a carbon-neutral campus by 2035, Cornell University is making many investments in energy efficiency and renewable energy. This project focused on one such investment, namely upgrading a historic building owned by the Delta Phi Association near Cornell University, the Llenroc House at 100 Cornell Avenue. Llenroc was constructed beginning in 1869 for Ezra Cornell's family estate and is now a house for the Delta Phi fraternity. To design the upgrade for Llenroc, we propose using geothermal heat pumps, solar PV systems, and energy-efficiency building upgrades like installing storm windows and adding additional roof insulation. These energy efficiency upgrades would help reduce Llenroc's heating load by half. The designed project is a feasibility study focusing on upgrading the building's current aging heating system while maintaining its historical integrity. As will be discussed throughout the paper, we have found that a geothermal heat pump and solar PV system, paired with energy efficiency upgrades is feasible at Llenroc.

Given these energy efficiency upgrades, Llenroc would need to replace their existing HVAC system with a 80 kW geothermal heat pump, with the heat pump loops being split equally between trenches and wells. While the upfront costs of these upgrades seem steep, they would provide "greener" heating and provide cooling in the summer months (which Llenroc does not currently have). Also, we found that a 52-kW solar array on the property and a 48-kW solar canopy over the parking area would help Llenroc run on renewable energy during the year. We considered a battery for this solar energy which could store enough energy for the residents overnight in the summer months, although we found that this expense may not be cost-effective in Ithaca. In total, we calculated that the initial investment would be $457,194 for these recommended changes. The "business-as-usual case" where Llenroc replaces their HVAC system with the same system type, but new, would have a lifetime present-worth value of $450,959, while the recommended upgrades would have a lifetime present worth of $420,541. Although these costs are similar, our recommendations are much more environmentally sustainable.

Project Motivation

There are many initiatives in the Ithaca area and in the Cornell community aimed at improving energy efficiency and switching to renewable energy. Ithaca's Green New Deal outlines the city's ambitious goal of becoming carbon neutral by 2030 (City of Ithaca, 2019). Similarly, Cornell University's Ithaca campus intends to be carbon neutral by 2035 (Cornell University, 2023). These initiatives aim to reach carbon neutrality by avoiding carbon-intensive activities, reducing energy usage, switching from fossil-fuel based energy to renewables, and offsetting the remaining carbon.

The management at Llenroc would like to pursue similar initiatives to increase their environmental sustainability. Bruce Buchholz, our partner at Llenroc for this project, has asked us to perform a preliminary analysis to see if sustainability updates could be implemented at Llenroc. He hopes that Llenroc will eventually be able to use geothermal heat pumps to heat the building in the winter and cool it in the summer. This is largely motivated by the decline of Llenroc's existing heating system, as he showed us that the heating system and radiators are deteriorating and would need to be replaced soon anyway. A heat pump system would also provide cooling during warm days, which Llenroc does not currently have. This would make the building more comfortable during the summer months and even allow for summer events to take place on the property (thereby providing an additional potential revenue stream).

Additionally, Mr. Buchholz is interested in installing solar PV with a battery system so that the house could use its own renewable energy and store any additional energy created. If Llenroc's average electricity usage was all from solar PV instead of conventional electricity (which is shown in the electricity generation mix for New York State below in **Figure 1**), its carbon footprint would be significantly reduced.

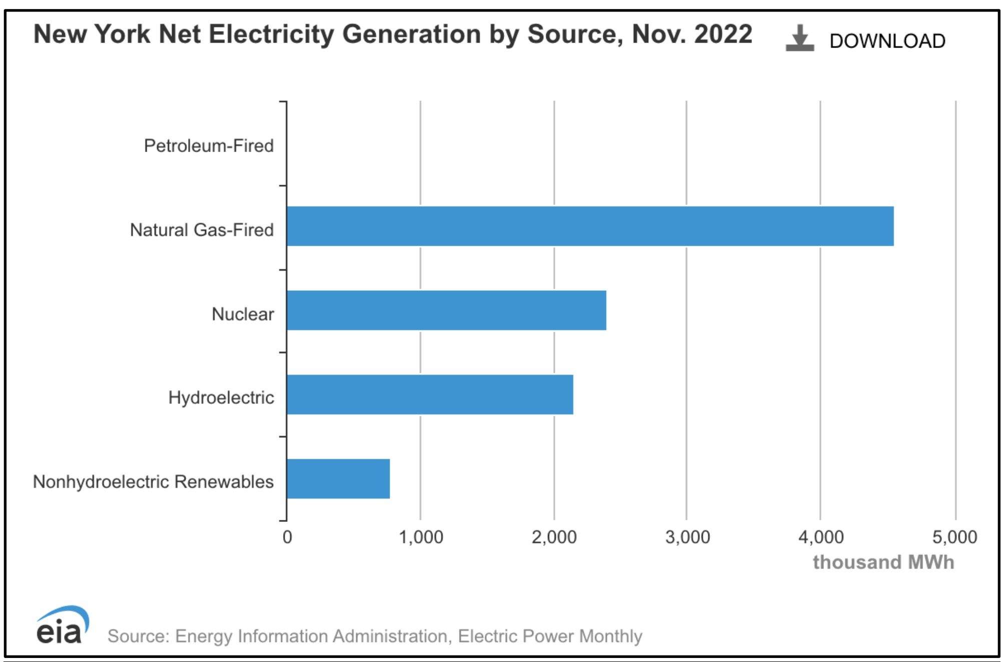

Figure 1. New York's Electricity Generation in November 2022

In addition to these renewable energy-based technologies, Mr. Buchholz also asked us to look into other upgrades that would be made around the same time as the technology installations. These include increasing the house's occupancy, improving the energy efficiency of the house, and adding a retaining wall along the slope of Llenroc's property. These details are further outlined in our **Scope and Assumptions** section.

Project Goals

As a group, we would all like to do the following:

1. Gain a greater understanding of geothermal heat pumps, their integration with HVAC systems, solar PV and battery systems, and how green upgrades can be made to older residential buildings.
2. Take in constructive feedback proactively and respond well to it.
3. Throughout this project, we have and will continue to interact with experienced professionals. We hope to learn from them, ask questions to help grow our intuition, and interact professionally with them.

For Llenroc house specifically, we would like to:

4. Execute our project in a way that explores multiple avenues of reducing Llenroc's operating energy usage and carbon emissions (compared to the status quo and compared to the alternative new gas heating system option).
5. Create organized deliverables for Llenroc that are useful and can have tangible benefits, and produce clear "next steps" for Llenroc's management team after the conclusion of our project.
6. Present deliverables to Professor Vanek and Llenroc management that are polished and professional.
7. Last, we hope that this project sets a good example for how others (ie. Cornell buildings, residential buildings, historical buildings, etc.) can make worthwhile green upgrades to increase energy efficiency and reduce carbon emissions.

Our Team

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Anna received her Bachelor of Science degree in Environmental Engineering from Cornell University. She is currently studying Civil Engineering with a focus on Transportation for her M.Eng degree, and she will graduate in May 2023. She is interested in smart cities, renewable energy, and urban transportation systems.

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Marie Rose is currently pursuing her masters degree in Environmental Engineering specialization in Sustainable Energy Management at Cornell University. She holds a Bachelor degree in Civil & Environmental Engineering from Notre Dame University, Lebanon. She has four years of experience in the wastewater treatment and water treatment sector which she led multiple projects from planning to execution. Additionally, she co-founded a startup called "Reborn" with the purpose of providing innovative sustainable solutions in the production and material of activewear for female athletes. Furthermore, she assisted startups and small to medium enterprise (SMEs) in the MENA region in their validation and acceleration phases.

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Katelyn is currently finishing her Bachelor of Science in Environmental Engineering at Cornell University from the College of Engineering with intended graduation in May 2023 as well as starting her M.Eng in Environmental Engineering with a concentration on renewable energy systems, with intended graduation in December 2023.

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Santiago is an exchange student from the Universidad Pontificia de Comillas ICAI, in Spain. Santiago is currently finishing his Bachelor of Industrial Engineering, as well as a Bachelor of Business Administration with intended graduation in May 2023. He is particularly interested in all forms of renewable energy, having working experience in the solar photovoltaic industry.

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Jason is currently finishing his Bachelor of Science in Environmental Engineering from Cornell University with intended graduation in May 2023. He is also starting his M.Eng in Environmental Engineering with a concentration in renewable energy systems. He has experience with renewable energy systems from working as Sustainability Engineering Intern at Shoals Marine Lab.

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Faria received her Bachelor of Science degree in Environmental Science and Geography from the University of California, Los Angeles in June 2022. She is currently completing her M.Eng in Civil and Environmental Engineering from Cornell University with intended graduation in May 2023.

1. Market Analysis

In this section, we will explore our initial findings concerning heat pump systems, solar photovoltaic (PV) and battery systems, as well as other key factors within these markets.

1.1. Heat Pump Systems

Heat pumps have been used as a renewable energy solution for several decades. Heat pumps work by transferring thermal energy from one place to another using a refrigeration cycle. They are powered by electricity (instead of natural gas, like Llenroc's current system), and they can remove or add multiple units of heat for one unit of electricity. **Figure 2** shows a general diagram of how geothermal heat pumps work. In a heating scenario in the winter, heat is absorbed by the liquid in loops in the ground, an evaporator transfers that thermal energy to the separate liquid used in the heat distribution system, and a compressor is used to increase the pressure and thereby raise the temperature in the fluid. From there, the fluid is circulated around the house where it releases thermal energy and heats the rooms.

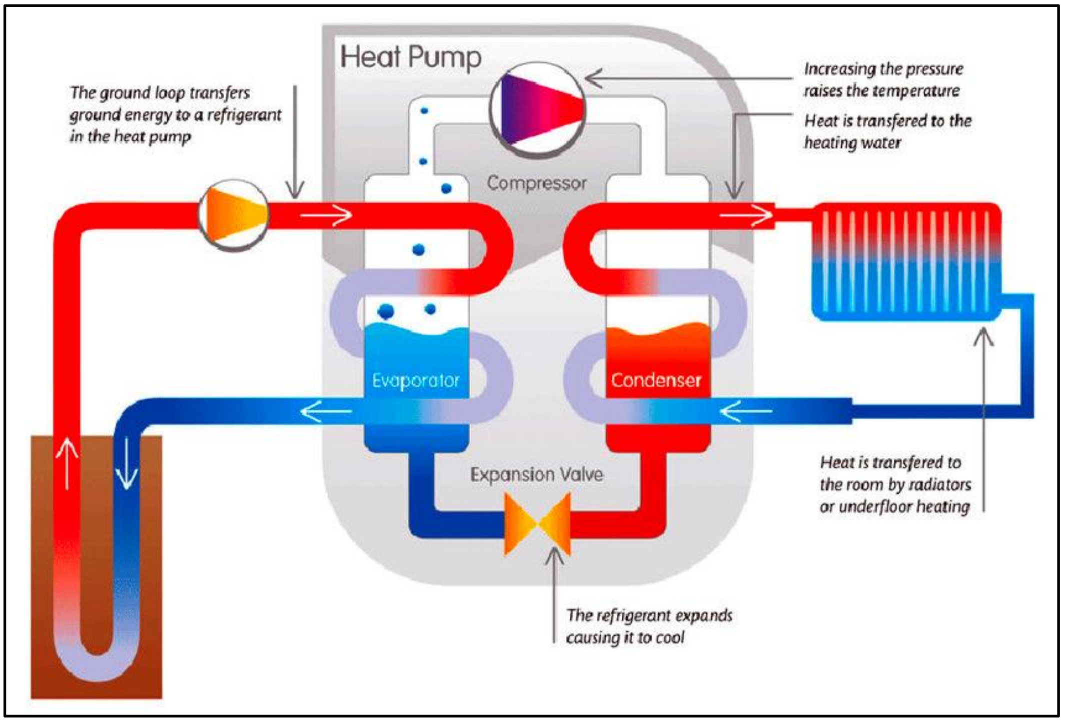

Figure 2: Schematic of Heat Pump

The first heat pump was invented by Lord Kelvin in the 1850s, but it was not until the 1940s that heat pumps began to be used for heating and cooling buildings. Early heat pumps were primarily used in industrial settings, but over time, they became more common in residential and commercial buildings as well. There are three main types of heat pumps connected by ducts: air-to-air, water source, and geothermal, also known as ground source. Air-to air and ground source will be analyzed later.

The heat pump market has experienced significant growth in recent years, driven by increasing demand for energy-efficient and sustainable heating and cooling solutions. According to a report by the International Energy Agency (IEA), the global heat pump market has been growing at an average annual rate of around 10% since 2010, with Europe leading the race (IEA, 2022). In fact, as **Figure 3** shows, there was a 35% increase in heat pump sales in Europe from 2020 to 2021. In the United States, the increase was 15%, which is also significant. The market is growing for several reasons:

1) Lifetime cost of heat pumps is now cheaper than oil and gas for heating in several countries.
2) Policies to support the heat pump market are currently being developed. In the US, a 22-30% tax credit is available for those who wish to install a heat pump.
3) Several manufacturers are expanding heat pump production and new business models are emerging.
4) According to the Net Zero Scenario, heat pumps should represent more than half of total heating sales by 2030.

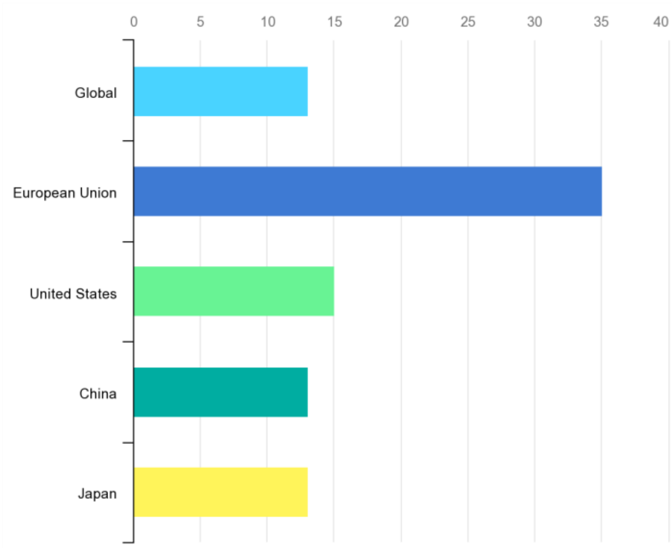

Figure 3. Global Increase in Heat Pump Sales (2020 to 2021)

Currently, the world's heat pump market is valued at $79.9B. Air-source heat pumps represent 81% of the market share, leaving geothermal with a valuation of $9.5B (12.5%). Both of them are growing at the 10% rate mentioned above. At that rate, the heat pump market size is expected to surpass $139B by 2030.

Ground Source vs. Air Source

In this study, we focus on ground source heat pumps instead of air or water source heat pumps. Water source heat pumps were not evaluated for this study because there is not a water source near the Llenroc house to exchange heat with. Also, air source heat pumps would require mechanical exchangers to be placed near some windows which would significantly alter the appearance of Llenroc. Since Llenroc has historical preservation status, this is not allowed. Despite this, we believe that it is important to recognize the various pros and cons of the two most common types of heat pumps: air source and ground source.

Air heat pumps cost less in moderate climates and can give a better return on investment. However, they need more maintenance than geothermal heat pumps (GHPs) because they are exposed to air, snow, and environmental conditions. Air source heat pumps also are noisy while running in defrost mode. Geothermal heat pumps are more energy efficient (because there are consistent temperatures below the surface of the earth) and are not affected by bad weather or storms. Furthermore, according to the EPA, geothermal heat pumps can reduce energy consumption—and thereby carbon emissions—by up to 44% compared with air-source heat pumps and up to 72% compared with electric resistance heating with standard air-conditioning equipment. Geothermal heat pumps would be a good option for Llenroc because they would be more reliable in extreme weather conditions, like in Ithaca's winters. However, GHPs have high installation costs from excavation and drilling (also, the site must be suitable for drilling). There is also the risk of groundwater contamination during the drilling and excavation process, although this can be mitigated by following proper procedures and regulations.

There are many factors that affect geothermal heat pump installation: size and capacity, location, brand, labor, efficiency rating, permits, and duct installations. The major efficiency ratings are the Heating Seasonal Performance Factor (HSPF) and the Seasonal Energy Efficiency Ratio (SEER). HSPF measures the heating efficiency over the heating season, while SEER measures the cooling efficiency over the cooling season. The required permits include mechanical and/or building permits to install, alter, replace or repair any heating pump, air conditioner, or duct system. There are many geothermal heat pump brands such as Nibe, Bosch, and Trane.

The main drawback of geothermal heat pumps is their high upfront cost. Even if the investment ends up being profitable after 5-10 years, it demands a considerable initial investment. The typical installation cost of the heat pump itself ranges from $3,000 to $22,000 for residential buildings, with an average of $12,378, not including the underground loops. Therefore, in addition to that, horizontal loops cost between $14,000 and $35,000, while vertical loops cost between $20,000 to $38,000. Moreover, the implementation of a vertical loop needs a drill test to ensure the feasibility of the installation. These tests can cost up to $15,000. After taking into account the cost of landscape repairs, permits and regulations, and heating costs, the total initial cost for a heat pump that will power a residential building of five people will be between $40,000 to $50,000. Further, these costs can vary by a wide margin based on the location and soil composition where the piping for geothermal heat pumps is placed.

Types of Geothermal Loop Systems

Geothermal heat pumps, which serve as the focal point of our study, can be divided into two categories: open and closed loop.

Open loop heat pumps use water as the heat exchange fluid. Once the water has circulated, it returns to the ground. These heat pumps only account for less than 15% of the geothermal market share, as they need to meet two requirements to be installed. Firstly, a supply of clean water must be accessible next to the site. Secondly, they need to meet local environmental and safety codes regarding groundwater.

Therefore, closed-loop systems are the preferred solution to move heat. They circulate an antifreeze solution through a closed loop that must be buried underground. Depending on the arrangement of the loops, two types of closed-loop systems prevail:

1) **Horizontal loops**: In this array, the pipes are placed horizontally. Therefore, they require a larger horizontal area of land. They are typically 500 ft long and are buried 6-12 ft deep. When the land is available, they are more cost-effective than vertical loops, which makes them ideal for residential installations. Although the temperature of the antifreeze solution is more likely to be subject to seasonal variance, the temperature fluctuation shouldn't affect the heat pump's performance. **Figure 3A** shows how, the deeper the loops are installed, the more stable ground temperature is.
2) **Vertical loops**: This is the preferred system when the size of the system is larger or there is not enough space to implement a horizontal system, which is the case of larger buildings. The tubes are laid vertically into the ground 20 ft apart and 200-800 ft deep. At this depth, the temperature is more consistent year-round, which is an advantage for heat exchange. As they require drilling equipment, their costs are higher than horizontal trenching costs.

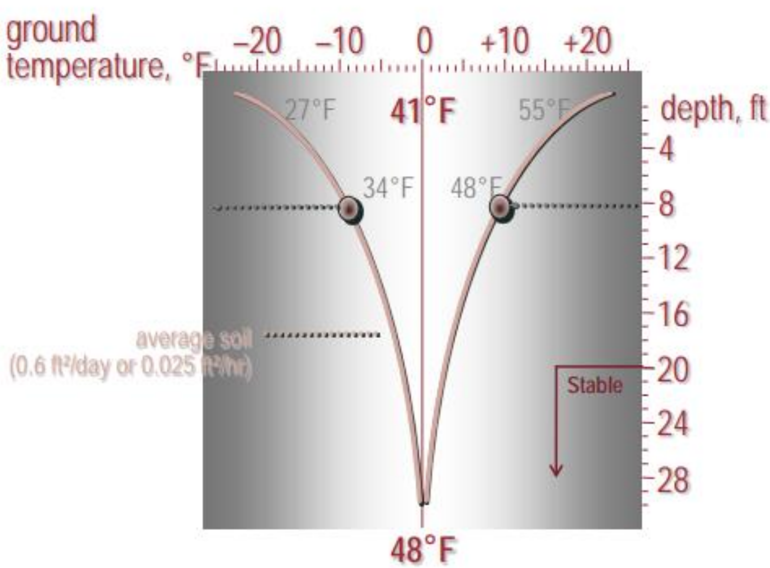

Figure 3A: Ground temperature swing depending on depth *(Sakry, 2012)*

1.2. Solar PV and Battery Systems

Globally, the amount of solar photovoltaic capacity has steadily increased in the last decade. This trend is also seen in the United States, with the amount of installed capacity of solar PV increasing over time, although this growth is predominantly at the utility scale (Mercure, 2020). Residential-scale solar PV can help reduce the load that regular electricity providers experience.

And, since residential solar panels are typically applied to roofs or other unused surfaces, residential solar reduces the amount of land required for renewables generation. Further, residential solar paired with battery systems would help reduce the non-renewable energy load required at peak demand times (like at the beginning and end of the day, when solar energy production is low). This is because a solar PV and battery system would ideally overproduce electricity during daylight hours and the excess would be stored in the battery for later use when the solar panels are not producing. We researched how solar PV and battery systems work, what they typically look like, what they cost, and what external factors might apply to our project at the Llenroc House in Ithaca, NY.

Solar PV systems primarily vary by size, tilt (tracking vs. fixed tilt), and cell type (monocrystalline silicon, polycrystalline silicon, or thin film). Further, the output of the panels depends on a variety of factors (besides just the panel's capacity factor). For example, panels deteriorate and become less efficient over time, and the environmental conditions (i.e. snow or dust on panels) can affect the output. Also, the cost of the solar system varies with system size and type (as the costs vary for hardware, inverter, battery size, electrical work, installation costs, labor, etc.). The price of residential solar systems has decreased over time, and was $2.71/Watt on average in the United States in 2020 (Feldman et al., 2020).

The cost of backup battery systems also greatly varies. The pricing differs with the chemical makeup of the battery (lead vs. lithium-ion), the type of input power, the usable storage capacity, the load capacity, the power rating, and the physical size and compactness of the battery. Although the prices of battery systems have decreased over time, batteries are still relatively expensive. Further, when figuring out what type and size battery Llenroc should use, we must also consider what appliances are running off of the battery and when they are running.

In Ithaca specifically, there are no large-scale programs to help install solar PV and battery systems for large residential buildings like Llenroc. However, Ithaca's Green New Deal outlines a framework for the city to become carbon-neutral by 2030 through energy efficiency improvements, renewable energy, and energy use reduction. Also, Cornell University has many sustainability efforts aimed at switching to renewable energy sources to power its campus buildings. For example, Cornell's Ithaca campus already has six solar farms totaling 28 MW. Therefore, it would be unlikely for Cornell of Ithaca to take issue with the changes that we propose here.

At Llenroc, there are many different factors that we need to consider when planning a solar PV and battery system. We need to ensure that there is enough land area for the solar panels, since they must be visually unobtrusive to Llenroc due to its historical nature. The solar panels must also be placed in a location where their tilt angles can be optimized (usually facing south) and with very minimal shade. Also, there are many different regulations about where large residential batteries should be placed (because of fire risks), so we would need to plan where in the Llenroc building a battery system could be located, or if an external structure would need to be built to house the battery. Last, our goal is to size the solar PV and battery system so that it would offset the annual electricity costs at Llenroc, and this is a very complicated goal, since the electricity usage is hard to forecast given our assumptions and available information. The system would ideally work by over-producing solar energy in the summer, storing some for use when the solar arrays aren't producing at night, and selling the excess back to the grid in return for credits. Then, the solar system would not produce enough electricity in the winter to power the whole house daily, but the credits would make up for this.

1.3. Other Considerations

In this section, we discuss how historical buildings have gotten "green" upgrades in the past, the type of tax credits available to Llenroc with these upgrades, and other important considerations.

1.3.1. Historical Buildings

All kinds of housing are moving towards improving indoor air quality and adding more sustainable, energy-efficient features, and historic homes are no exception. This movement towards sustainability is essential for historic homes, which are often inefficient in terms of energy usage and can contribute to environmental degradation. Despite their historical value, these homes require high levels of heating and cooling to maintain a comfortable living environment, resulting in high greenhouse gas emissions. Fortunately, there are examples of successful upgrades to historic buildings through LEED certifications (Benjamin, 2020).

For instance, the African American Library in Houston, Texas, built in 1926, has implemented green housekeeping strategies and achieved exemplary accomplishments in green power. They have also implemented heat island reduction strategies; this can come in the form of green roofs that can provide shading building surfaces, deflect radiation from the sun, and release moisture into the atmosphere (US EPA, 2015). Another historical building is the Energy Innovation Center in Pittsburgh, Pennsylvania. It was constructed in 1930 and is an example of adaptive reuse done sustainably while advancing clean energy goals through its programs. During its renovation, 95% of construction waste was diverted from landfills, and the structure was designed to save over 50% in energy costs compared to a conventional building of the same size. It became a prime example of how renovations can adhere to historic preservation guidelines, showing that energy efficiency and stewardship of our historic places are not incompatible. Additionally, the Fay House in Cambridge, Massachusetts, built in 1807, is the oldest building in the United States with a LEED certification. The building's restoration included the implementation of geothermal energy, occupancy sensors, and the use of salvaged materials, while also restoring the facade and adding accessibility features to bring the historical integrity of the structure in line with 21st-century needs.

1.3.2. Tax Credit Considerations

While the initial costs of equipment and installation can be high, there are tax credits available that can reduce these costs. There are three potential tax credits that the Llenroc may be eligible for, but this would have to be confirmed with the IRS or the New York State Parks, Recreation and Historic Preservation Office. The first incentives that may be available are

Residential Clean Energy credits under the Inflation Reduction Act of 2022. Under this tax credit, up to 30% of solar PV panels, geothermal heat pumps, and battery storage systems can be claimed as federal tax credits (IRS, 2023). Additionally, there are state and federal tax credits which apply specifically to buildings with historical status through the New York State Office of Parks, Recreation and Historic Preservation (NY OPRHP, 2023). The first is the New York State Historic Homeownership Rehabilitation Credit which offers a state income tax credit equal to 20% of rehabilitation costs. For this tax credit to be claimed, the homeowner must live in the home. Since the fraternity owns the house and the members reside in it, it is unclear whether the Llenroc would qualify. If not, there is also the New York State Historic Preservation Tax Credit Program for Income Producing Properties which gives a 20% federal rehabilitation tax credit along with an additional state credit of 20% or 30% of the qualified rehabilitation expenditure up to $5M. In this case, the residents could be viewed as tenants, making the Llenroc an incoming producing property. Some additional considerations are that state rebates for heating system upgrades vary by state and program, and utility companies offer rebates to reduce upfront costs and energy costs. Additionally, homeowners can also take advantage of low-interest loans to spread out the cost of upgrades over time. Overall, these incentives and programs offer homeowners a range of options to make energy-efficient upgrades more accessible and cost-effective but the appropriate agencies must be contacted to confirm eligibility.

1.3.3. Psychrometric Considerations

To design HVAC equipment and size systems, the sensible heat load and the additional cooling load must be taken into account; in other words, we must consider extreme temperatures in the heat pump system. If Relative Humidity (RH) exceeds 70%, toxic mold can form. In this project, latent conditions of 35°C dry bulb, 25°C wet bulb, and 82% RH were given by the lead engineer, Mr. Buchholz. Ideally, the goal is to achieve a RH between 40-60% for comfort and health. To achieve this with vapor compression systems, the air must first be subcooled below to the desired set point (10°C), then additional moisture must be condensed out and collected, and finally, it must be warmed back up to the desired temperature which will allow for a comfortable RH level (**Figure 4**).

This energy-intensive process was not incorporated when calculating the maximum cooling load in the design for this project. This is due to the fact that the maximum cooling load was less than the heating load, so it should not affect the size of the heat pump. However, it is still essential to keep in mind that dehumidification for the system will be needed.

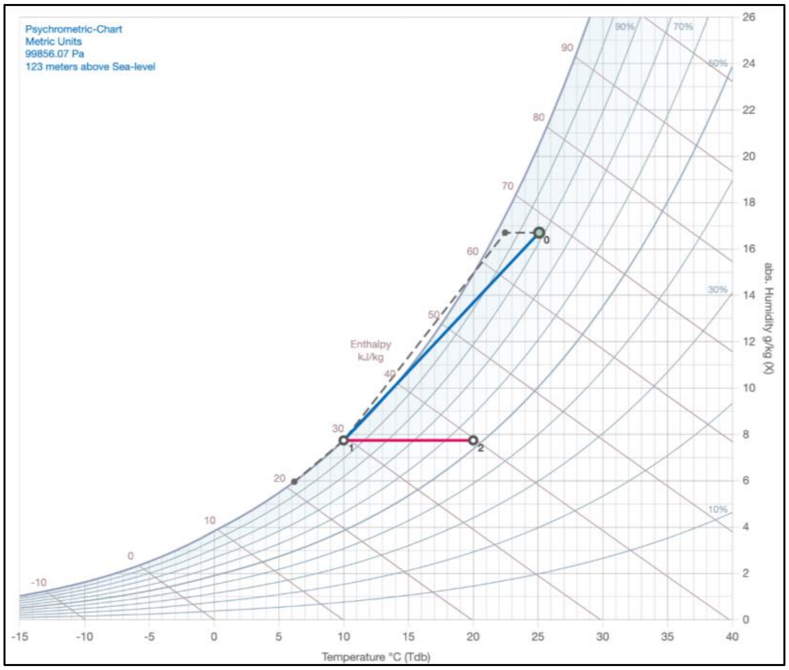

Figure 4: Subcooling and reheating shown using psychrometric chart (*Psychrometric Chart Calculator*)

1.3.3. Other Improvements

The focus on window efficiency and different types of insulation is important when it comes to reducing energy consumption and heating costs in homes. This is because windows can be a significant source of heat loss, particularly if they are old or not properly sealed. While insulation can also cause higher energy consumption.

Energy-efficient windows with low U-values (thermal transmittance) can help prevent heat loss and reduce energy consumption. Additionally, measuring solar heat gain coefficients (SHGC) can give an understanding of how the heat is coming through the window given different climates. The Department of Energy recommends that homeowners look for windows with these characteristics to improve the energy efficiency of their homes. In fact, windows account for around 10% of residential energy consumption in the Northeastern US (U.S. Energy, 2023).

Proper insulation is also essential for keeping homes in the Northeast warm during the cold winter months. This can significantly reduce energy consumption and heating costs. Further, 90% of homes in the Northeast are heated with oil, natural gas, or propane, so insulation plays a crucial role in keeping these homes warm and energy-efficient (U.S. Energy, 2023). There are two main types of insulation commonly used in homes: fiberglass and spray foam (Good Life Energy Savers, 2018). Fiberglass insulation is relatively inexpensive upfront and easy to install, but it is less effective at insulating. On the other hand, spray foam insulation, such as Icynene, is more resistant to moisture and mold. There are two types of spray foam insulation: closed cell and open cell. Closed-cell spray foam completely blocks airflow from the outside, while open-cell spray foam is usually less expensive and can also be used for sound reduction in addition to insulation.

2. Scope and Assumptions

Throughout this project, we were limited by the availability of information (whether it be about specifics of the Llenroc building or specifics about the technology we were looking into). To finish the project in a reasonable amount of time, we also limited the scope of our research. Further considerations that we recommend be taken are outlined in the **Future Research** section of the paper, while assumptions made for our research and calculations are outlined below.

Llenroc Building

- Our design was for thirty residents (compared to the ~19 at Llenroc in 2022).
- Our design looked at a time horizon of 50 years and interest rates of 6% and 10%
- We are assuming that the Llenroc basement has enough physical space to install all of the proposed machinery.
- The abandoned tennis court area near Llenroc is technically Cornell's property (rather than Llenroc's), but we assume that Cornell will sell or rent the land to Llenroc for solar array space.

Heat Pump System

- Temperatures: indoor and outdoor extreme temperatures
    - Desired indoor air temperature of 70°F
    - Extreme temperature of -15°F in the winter
    - Extreme temperature of 95°F in the summer
- R-values:
    - Ignored heat escape through the ground
    - Windows are old and have the low R-value of 1
    - Doors are standard and have R-value of 4
    - R-value of walls estimated as 18 inches of limestone
- We ignored any additional dehumidification equipment that would need to be installed to meet humidity requirements in the summer.

Solar PV and Battery System

- Cooling loads were considered by analyzing other buildings, which could lead to over or underestimations.
- We assumed that there would be similar energy consumption behaviors between buildings similar in age and size to Llenroc.

Out of Our Scope

- We are not considering replacing the natural gas used by the water heater and the cooking with a renewable source of energy.
- All modifications on the property would need to be approved by Llenroc's Historical Building association (we accounted for this as best we could).

- We did not have a geotechnical study, so we assumed all installing trenches and drilling wells for the heat pump was feasible.
- We also worked under the assumption that all the heat-pump related wells and trenches would be on Llenroc's property, but in the future Llenroc could try to work with Cornell to use the empty property nearby for this too.
- We discussed the main benefits and drawbacks of different refrigerants and VRV vs. hydronic heat pump systems, but we did not definitively choose specifics. Choosing what refrigerant and the type of heat distribution system (hydronic vs. VRV) would be a decision made further along in the engineering design process (rather than in this feasibility study). Also, decisions related to the piping for the heat distribution system (for example a two-pipe versus a four-pipe system) would also be made later.
- We only considered the 30% IRA tax credit in the financial model, but left out the other credits and subsidies because their ability to apply to this project is much more convoluted.

2.1. Heat Distribution in Building

One of the major considerations in installing a geothermal heat pump system is how to move the heat throughout the building. **Figure 5** below shows how heat can be distributed throughout a building in conjunction with geothermal heat pumps. The final schematic of how Llenroc would distribute heat depends on the building itself, the system that they choose, and whether they choose to distribute heat with a VRV or hydronic system. Further, there are many configurations for heat distribution in terms of where the consoles (the machinery used to convert the thermal energy in the distribution fluid to the air in the house) can go throughout the house: they could be on every floor, every room, or some combination of this. We did not choose a specific configuration as this would be left to Llenroc's management and the piping and ductwork limitations in the house.

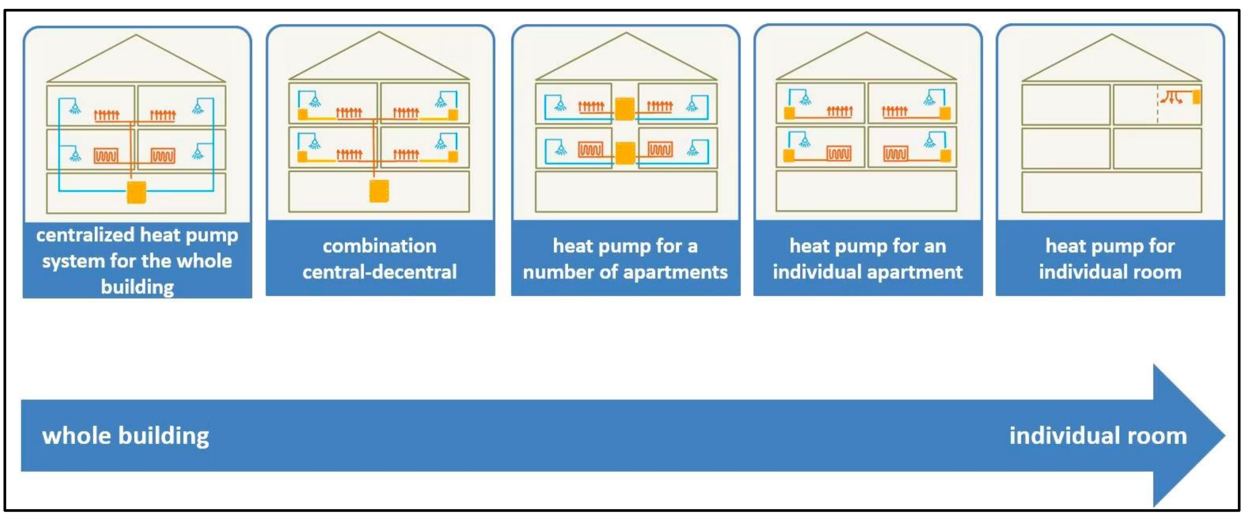

Figure 5: Potential Heat Distribution Schematics

Further, geothermal heat pumps are compatible with either hydronic systems or with VRV systems. VRV systems circulate refrigerants to each indoor unit in every room to distribute heat, while hydronic systems circulate water. Each one has its own advantages and disadvantages, outlined below (Siegenthaler, P.E., 2016).

Main advantages of the hydronic systems are:

- Allows for simpler future modifications, specifically for older commercial or institutional buildings to be upgraded, their existing hydronic distribution system, or portions of that system, may be reusable in combination with a new central plant for producing heated and chilled water.
- Hydronic distribution systems are not dependent on the type of refrigerant used because it is water-based and therefore it is not subjected to changes with time.
- Reduces the risk associated with leakage and it is easier to detect the leaks.
- Hydronic systems have less global warming potential since they use water instead of the refrigerants which tend to contain many chemicals.
- They can use traditional piping systems, lowering initial cost.

Main advantage the VRV system are:

- VRV systems are more energy efficient in the long run
- VRV systems are most commonly used in historical buildings due to limits on pipe length.

Main disadvantages of the VRV systems:

- Existing hydronic piping and all hydronic terminal units must either be decommissioned in place or removed from the building. All new copper piping and refrigerant-based terminal units must then be installed to each conditioned space. This can be highly disruptive to the normal use of the building.
- Dependent on the type of the refrigerant where some refrigerants were phased out because of their negative impact on global warming. In this case replacement of the refrigerant is a must because refrigerant will remain acceptable for not more than 20 years.
- High initial investment because of the copper piping system needed.
- Risk of leakage which sometimes causes the evacuation of the building.

2.2. Refrigerants

The refrigerant is the fluid that runs through the geothermal heat pumps to transfer the heat through the building. Refrigerants can be easily boiled from a liquid into a vapor and condensed from a vapor back into a fluid. For example, at ambient pressure, water has a boiling point of 100ºC, while a commonly used refrigerant such as R134a boils at -26.3ºC. Refrigerant R410A, which will be discussed later, has a boiling point of -48.5ºC. When refrigerants boil, they carry away thermal energy that can be extracted rapidly. This is the main principle used in heat pumps and is the reason why refrigerants are compressed or expanded inside the machine to the heat from one place to another. During a heat pump cycle, the refrigerant undergoes four states:

1) High pressure, high temperature, superheated vapor.
2) High pressure, slightly cooler, liquid.

3) Low pressure, low temperature, vapor mixture.
4) Low pressure, low temperature, superheated vapor.

This can be done thanks to their low boiling temperature and only by manipulating their pressure. Main composition of the refrigerants are hydrofluorocarbons (HFCs) or chlorofluorocarbons (CFCs) which are the main cause of the air pollution when released into the atmosphere and impact global warming. Older refrigerants frequently contained CFCs, which were discovered to be the cause of the ozone layer's thinning. The ozone layer is not damaged by HFCs, which are frequently used in newer refrigerants to replace CFCs, although they do contribute to global warming. HFCs can trap heat when they are released into the atmosphere, which can result in temperature increases and other climate change effects. Two terms are used to evaluate the polluting effects of these fluids:

- Ozone Depletion Potential (ODP): this offers a relative indication of the substance's effect on the depletion of the ozone layer. For all HFCs, this value is 0.
- Global Warming Potential (GWP): this offers a relative indication of the amount of heat trapped in the atmosphere by a certain mass of the gas in question relative to the amount of heat trapped by a similar mass of carbon dioxide. It is represented as a ratio to carbon dioxide, which has a standardized global warming potential of 1. Even if there are no specific GWP targets at the federal level yet, some states are already implementing their own regulations. The California Air Resources Board, for example, stated that, starting in 2022, large refrigerant systems (those using more than 50 lbs of refrigerant) must use refrigerants with a GWP of 150 or less.

Moreover, refrigerants can also be classified depending on their flammability and toxicity. **Figure 6** shows the different classification they can be attributed based on safety:

Refrigerant Safety Groups	Lower Toxicity OEL > 400ppm	Higher Toxicity OEL < 400ppm
Higher Flammability lower flammability limit LFL < 0.1 kg/m³ of combustion HoC > 19 MJ/kg	A3	B3
Lower Flammability LFL < 0.1 kg/m³ and HoC > 19 MJ/kg	A2	B2
Lower Flammability (Mildly Flammable) Low Burning Velocity LFL > 0.1 kg/m³ and HoC < 19 MJ/kg and burning velocity < 10cm/second	A2L	B2L
No Flame Propagation Cannot be ignited	A1	B1

Figure 6: Refrigerant safety classification from ASHRAE Standard 34 (*Toxicology and Safety*, 2014)

In recent years, R410A had been the preferred choice for manufacturers due to its low boiling point, as well as the fact that it had zero ODP. However, R410 is an HFC fluid with GWP of 2,088, which is still harmful for the environment. Because of this, it has been phased out and old systems that operated with it are looking for suitable replacements. That is why Panato, Marcucci and Bandarra (2022) explored R32, R452B and R454B as alternatives. They evaluated the different properties of the three of them. The outcome of their study is summarized in the following table:

Table 1: Comparison of R410A, R32, R452, and R454B refrigerants

	R410A	R32	R452B	R454B
Composition	HFC	HFC	HFC and HFO mixture	HFC and HFO mixture
Classification	A1	A2L	A2L	A2L
ODP	0	0	0	0
GWP	2088	675	676	467
Critical Pressure [kPa]	4901	5784	5220	5041
Critical Temperature [K]	344.49	351.26	348.85	350.15
Normal Boiling Point [ºC]	-51.45	-51.66	-50.9	-50.73
COP relative to R410A	-	-6.20%	-6.60%	-6.20%
Compressor power consumption relative to R410A	-	7%	-2.70%	-3.50%

Legend:

Best

Second Best

Medium

Worst

Looking at the table, R410A would be the best option in terms of performance, if it wasn't for its high GWP. As we are moving towards a carbon neutral environment, it must be replaced by one of the other three. Out of the remaining options, R454B is clearly the most attractive. Not only does it have the lowest GWP, but also it consumes even less compressor power than the others, which means that less electricity will be needed to power the heat pump, even if its COP is higher. The only concern that R454B poses is that it is classified as A2L, which means that it is lowly flammable. Despite this, along with the direction in which the industry is moving, R454B will be the choice of refrigerant for this project. Nowadays, some A2L fluids like R454B are considered to be safe in residential buildings (Menale et al, 2021). In fact, 2023 was the year marked by HVAC manufacturers to start implementing this refrigerant.

There is still another alternative that was not considered by Panato, Marcucci and Bandarra. This is the refrigerant R454C, that has the following properties:

Table 2: R454C properties (Panato, 2021)

R454C	
Composition	HFC and HFO mixture
Classification	A2L
ODP	0
GWP	146
Critical Pressure [kPa]	4319
Critical Temperature [K]	358.67
Normal Boiling Point [ºC]	-45.56

Inspecting the properties and the existing research done, the main benefit of this refrigerant as a replacement of R410A is its low GWP. However, it showcased the lowest COP values and the highest mass flow rates values when it was tried as a substitute for R410A in a ground source heat pump (Kapicioglu, 2022). It was also classified as a non-viable refrigerant for a 10.5 kW residential heat pump, as it decreased performance around 8% in terms of COP (Burns et al, 2022). Nevertheless, the fact that R454C is not a viable substitute for an existing heat pump does not mean that it would not be adequate for a new one. In fact, it is being used by Mitsubishi in its newest pumps.

In conclusion, the final decision of refrigerant will be between R454B and R454C. While the first one will perform better in terms of efficiency and has been proved to be an effective refrigerant, the second one has a lower GWP, which could be beneficial in the case that further regulations were implemented in the future. If following California's example, a threshold of 150 in terms of GWP was implemented in NY State, the heat pump would have to be designed for R454C. As the thermodynamic properties of the refrigerant affect the sizing and performance of the heat pump, the final decision will be taken once the final estimation of the needed load is done.

3. Methodology

In this section we outline the methods used to size the heat pump and the energy efficiency improvements that we recommend for Llenroc. We note the assumptions that we have made and the values used.

3.1. Method 1

The first method that we used to estimate the heating capacity needed was an engineering analysis based on the physical materials and structure of Llenroc. The external "shell" or "envelope" of the building consists of the walls, roof, windows, basement, and any other outward facing surfaces that heat could escape from in the house. Thus, the model would be based on maintaining the internal temperature of the house just given that heat loss through those surfaces. Then, the amount of heat lost would equal the amount of heat that the heat pump would need to replenish.

To start our model, we found the total areas of Llenroc's walls, windows, doors, and roof surfaces from the architectural drawings of Llenroc. Next, through our discussions with Mr. Buchholz and Llenroc's architect, we approximated the R-values for each surface. An R-value expresses how well a surface resists conductive flow of heat; therefore, a high R-value implies the surface acts as a good insulator for the home. Once we had the envelope areas and their R-values, we approximated the heating capacity needed using **Equation 1**, where Q expresses the estimated heating load. We did this for two temperatures: the heating load at the extreme temperature of -15°F in the winter, and the cooling load for the extreme temperature of 95°F in the summer. While these temperatures may seem somewhat extreme since Tompkins County only requires new buildings to handle -2°F, (Sirt et. al., 2017), since there are very few days where Ithaca will be sustain those temperatures, "overdesigning" the system has some benefits. If the heat pump is sized to the extreme temperatures, it will not struggle with capacity if the extreme temperatures are surpassed (which they could be in the future). Also, with time the system will begin to become less efficient, so installing higher capacity initially can help avoid future issues with load capacity.

For the cooling load, we also approximated that each of the thirty residents in Llenroc produce the body heat of 600 BTU/person (average of active and inactive body heat) (Conditioned Air Solutions, 2018).

$$Q = \frac{1}{R\text{-}value} Area \cdot (T_{indoor} - T_{outdoor}) \qquad \textbf{(1)}$$

Given the desired indoor temperature of 70°F, we found that this model predicted a heating load of 88 kW and a cooling load of 31 kW. To see how realistic the model predictions are, we compared them to the actual natural gas consumption data provided through utilities invoices. To estimate the heating/cooling load over a given period of time, we used available hourly temperature data to calculate how much energy would be required to heat the space given different outdoor temperatures. Looking at the month of March 2022, the model predicted a total heating load of approximately 22,700 kWh while the actual natural gas consumption for that month was around 56,600 kWh. There are a couple ways heat can be lost that the model prediction does not include. There may be infiltration from cracks or gaps in sealing of the home, allowing for cold air to come into the home. Ventilation for fresh air may also allow for hot air to escape. For this reason we believe it is reasonable to double the predicted loads in order to better reflect the actual natural gas consumption and to add a factor of safety. Therefore, to design for extreme peak conditions, we assume a heating and cooling load of 175 kW and 78 kW, respectively.

Once we estimated the model and checked its accuracy, we looked at how the building envelope could be upgraded to reduce the heating load required at Llenroc, and thus be more energy efficient. We considered multiple different residential housing upgrades, but ultimately found that window upgrades and roof insulation would be the best given our prior knowledge of Llenroc House. Regular or historic residential homes also often get upgrades by replacing or adding to the insulation in the walls, but because we knew very little about Llenroc's walls, and because Llenroc has lots of molding on its walls, we decided against considering this option.

When considering what window upgrades could make a building more energy efficient, there are many options. In a typical home, replacing the existing windows with EnergyStar Rated windows is one of the most effective window upgrades. While this is a possibility that Llenroc management could consider, we believe that it would be much too expensive to be feasible, since almost all of Llenroc's windows would need to be custom-made. A much cheaper alternative would be to apply window films to each window that are specifically designed to better insulate the house. Additionally, it would be prudent to also fill in any gaps of cracks near the windows with sealants. This alternative would be much cheaper but may not be as effective. The resulting R-value increase would be difficult to predict, and thus the change in energy efficiency would be difficult to model. The last alternative that we considered was increasing insulation by adding interior storm windows. We included this alternative in our model for multiple reasons. First, it achieves a predictable change in the R-value (whereas adding window films and sealants does not), and second, it would likely be a more affordable option compared to the custom Energy-Star rated windows. However, it is important to note that the storm windows would likely still need to be custom-made, which has the potential to also be expensive. We also note that storm windows can be designed to be operable (can open and close) for ventilation when the residents desire it. In reality, Llenroc management could choose to go with any combination of these options for these windows, but for the simplicity of our model, we treated the improvement as if storm windows were added to all of Llenroc's window area. We also choose to analyze interior storm windows since they seemed less likely to disturb the exterior appearance of Llenroc, but exterior storm windows are also viable options.

The other consideration that we made was to decrease heat lost through Llenroc's roof. This can be done by applying additional insulation to the attic space. Based on conversations with those familiar with the building, we assumed that the R-values for the roof at Llenroc had the same values as typical roofs made of membrane and shingles. Additional insulation would significantly improve the heat retention in the house. The R-values of the existing house and of the energy efficiency improvements are shown in **Table 3** below.

Table 3: R-Values with and without energy efficiency improvements

Component	R-value (ft^2*°F*h/Btu)	R-value with Improvements (ft^2·°F·hr/BTU)
Walls	1.944	(Same as current)
Windows	1	3.85
Doors	4	(Same as current)
Roof	0.75	4

Given the estimated heating and cooling loads of Llenroc at its current state and adjusted to actual consumption, we can estimate the heating and cooling loads if these energy efficiency improvements are made. Then, we would use the greater of the two loads with energy efficiency improvements to size the heat pump going forward. As can be seen in **Table 4** below, the heating loads are more than the cooling loads, so the recommended heat pump will be sized to the 78.62 kW heating load.

Table 4. Current and Improved Heating/Cooling Loads

Heating Load (Current)	175.96 kW
Cooling Load (Current)	44.50 kW
Heating Load (Improved)	**78.62 kW**
Cooling Load (Improved)	33.67 kW

3.1.2. Check Against Boiler

In order to verify that our results are reasonable, we compared our values to Llenroc's current boiler. The current boiler has a higher capacity than what the house needs or uses, with a maximum capacity of 223 kW. However, the actual highest monthly average output for 2022, according to natural gas consumption, was around 80 kW. So, the maximum output of the boiler is more than the peak heating load of 175 kW, which accounts for the safety factor of two.

3.2. Method 2

The project's second method comprises several steps. Firstly, the analysis of historical data on natural gas and electricity consumption from the previous year is conducted to get heating loads, from the 2022 NYSEG invoice. Note that NYSEG electricity billing is on a 2-month basis. Subsequently, consideration of the cooling loads were estimated by looking at the consumption data for four Cornell buildings that were similar in age or size due to Llenroc's lack of a cooling unit at present. Next, the energy produced and needed by the solar system and heat pump output are consolidated. Finally, a comparison is made between the current and projected energy consumption and production, while noting potential improvements. In addition, it is worth noting that the natural gas consumption includes the steam boiler, water heater, and cooking/stove, while the electricity consumption comprises all electric utilities, including the strip heaters on the third floor, as well as lighting. This process aims to provide a comprehensive understanding of the energy requirements and possibilities for optimization for the project.

All the calculations needed to understand previous consumptions and forecast future energy consumption and production per month will be explained in this section. Firstly, the table in **Appendix A** comprises data from Llenroc's current consumption. Then, two scenarios were analyzed. The table in **Appendix B** contains the calculations needed if the house didn't undergo any efficiency improvements, while **Appendix C** analyzes the case in which the improvements are done. As it was mentioned in Method 1, efficiency improvements would reduce Llenroc's heating and cooling needs by a factor of 2. To help better understand the process followed, different charts will be displayed.

3.2.1. Current Natural Gas and Electricity Consumption

This section will explain how we analyzed the current natural gas and electricity consumption from the table in **Appendix A**.

- **Natural gas consumption (therms) →** this column refers to the current natural gas usage of the house. The data was extracted from Llenroc's 2022 NYSEG invoice. Currently, the Delta Phi fraternity is using its natural gas for the steam boiler, the water heater, and the cooking. The aim of this project is to remove the steam boiler, which should decrease natural gas consumption considerably.
- **Natural gas consumption (kWh)** → to unify criteria, energy units chosen for this section were kWh. Therefore, this column shows monthly natural gas consumption in kWh. The factor used was 29.3001 kWh per therm. Consumption per month can be seen in **Figure**

7. It is worth noticing that the value for November is lower than expected. This is due to the way in which NYSEG measures consumption. The company takes measures every two months and estimates the remaining months. In this case, November is an estimate based on September's consumption, while December is a real measure. Moreover, **Figure 7** shows how consumption during the summer months is almost negligible, as there are no heating needs, which require most of the natural gas usage.

- **Water heater and cooking (kWh)** → as it was mentioned before, once the geothermal heat pump is installed, natural gas will still be used for cooking and boiling water. This column estimates the amount of gas that will be needed in the future for these purposes. To get this estimation, we looked at the months in which there is no heating. According to Ithaca's location and needs, those months range from mid-May to the end of September. Hence, we assumed that the amount of natural gas used for the water boiler and the cooking would be the average of the consumption during those months in the heating season and that it would remain constant during the cooling season. In other words:

Water Heater + cooking natural gas consumption in one month = Minimum(average consumption during the summer period, natural gas consumption during that month)

- **Water boiler and cooking (therms) →** this column shows the consumption from the last column in therms. It is needed to calculate the future yearly cost of natural gas, as this cost comes in $/therm.
- **Price of natural gas (2022, $/therm)** → the average price of natural gas per month was recorded here in $/therm (National Grid USA Service Company, Inc. 2023). We used the values from 2022 adjusted for inflation, which is 3.5% (Allioth 2023). That way, we were able to predict a future annual cost of $1,512.55. This cost would increase yearly according to inflation.
- **Heating (kWh)** → this column displays the amount of natural gas that is being used for heating purposes every month. It was obtained subtracting the natural gas used for the water heater and the cooking from the total natural gas consumption. As we have already mentioned, this energy would be provided by the heat pump in the future. Note that because of the efficiency of the boiler, only 85% of this natural gas will transform into heat.

Moreover, this analysis helped us compute the maximum capacity needed from the boiler under the current circumstances. By inspection, we observed that December was the month in which the most gas was required for heating, with a total of 41,390.05 kWh in the whole month. Then:

$$Boiler\ average\ output\ (December) = \frac{41390.05\ kWh}{month} * \frac{1\ month}{31\ days} * \frac{1\ day}{24\ hours} = 62.64\ kW \quad \textbf{(2)}$$

The total capacity of the boiler is 223 kW (760,000 Btu/hr). This means that the boiler was over designed. However, the order of magnitude is not that big (around four times) and this method is looking at average consumptions per month, it doesn't consider daily peaks, which probably increase the maximum capacity.

- **Current electricity consumption (kWh)** → like natural gas consumption, this data was extracted from Llenroc's 2022 NYSEG invoice and it is also shown in **Figure 7**. However, NYSEG only provided total consumption every two months, which is why we had to assume that it would be divided evenly between them. The only exception was December and November, where the numbers were accurate. Because natural gas usage is significantly greater than electricity consumption, **Figure 8** gives a better understanding of Llenroc's utilization of electricity. We can observe how Delta Phi's electricity consumption goes up during the colder months. This indicates three things:
  1) There is no AC in the house.
  2) Some electricity is diverted into heating during the winter.
  3) Lighting needs during the winter are greater than during the summer.

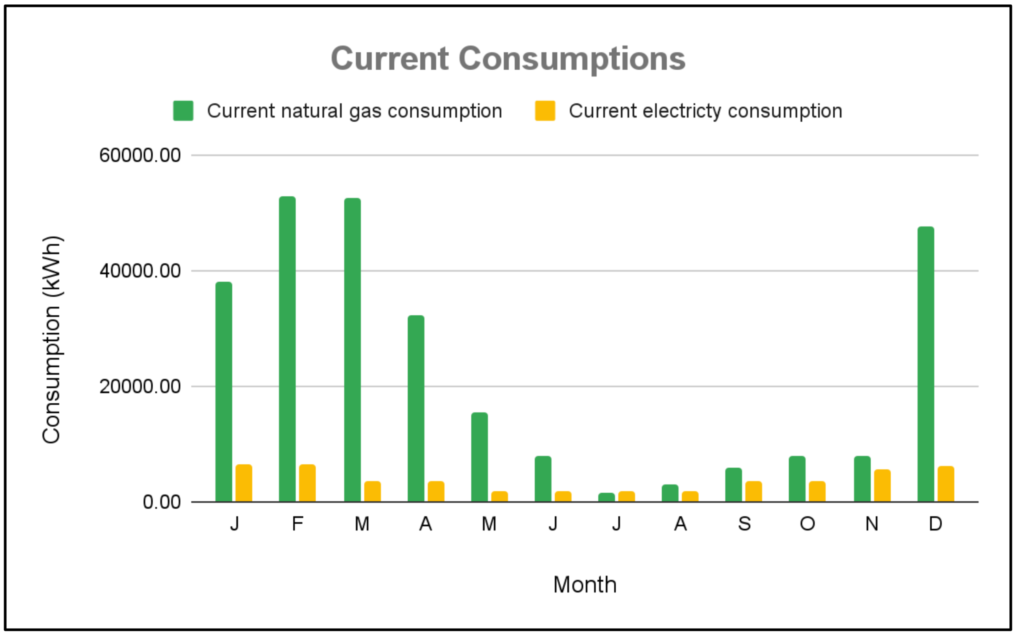

Figure 7: Current natural gas and electricity consumption per month

- **Electricity used for 3rd floor heaters** → Llenroc does not currently have radiators on the third floor, which is why the fraternity currently uses electric heaters there. **Figure 8** shows how much electricity is allocated per month to the radiators. The total kWh values are the same as in **Figure 7**, they have just been enlarged to provide more detail. As electric heating is a costly and non-environmentally-friendly way of heating, the heat pump will cover this heating needs. Strip heaters have a COP of 1, they deliver 1 kWh of heat for every kWh of electricity that goes into them. To calculate how much electricity is spent in the electric heaters, we distinguished two cases:

1. Cooling season: where no electricity is used for heating.
2. Heating season: where the electricity used for 3rd floor heaters every month is equal to the electricity used during that month minus the average electricity used during the cooling season. Here, we assumed that the average electricity consumption during the cooling season would all be used for lighting and utilities and that that amount would remain constant during the heating season.

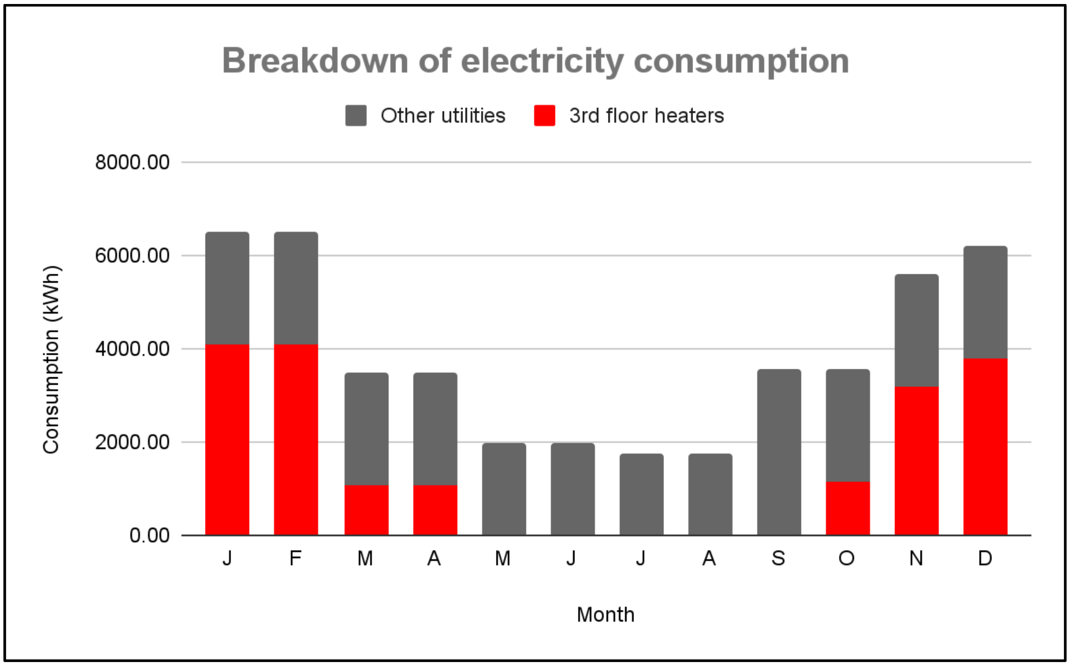

Figure 8: Breakdown of electricity consumption per month

3.2.2. Cooling

Right now, the Llenroc House doesn't have AC. However, one of the many benefits of heat pumps is that they can work in reverse mode. Hence, the same initial investment could provide the house with a device capable of cooling and heating. The fraternity wants to gain advantage of this and use the AC to host events during the summer months. Hence, in this method, we needed to estimate what the cooling consumption of the house would be, as it could affect the optimal heat pump size.

As we could not extract cooling consumptions from the NYSEG Invoice, we had to look at similar buildings in Ithaca. **Figure 9** shows the electric consumption over a year of four different buildings: three of them are fraternity houses, while the forth one is AD White House, another historical building at Cornell. We were looking for a spike in consumption during the summer months, as that would mean that the building is using AC. We noticed that only Sigma Phi seemed to match this requirement, so we focused on their consumption.

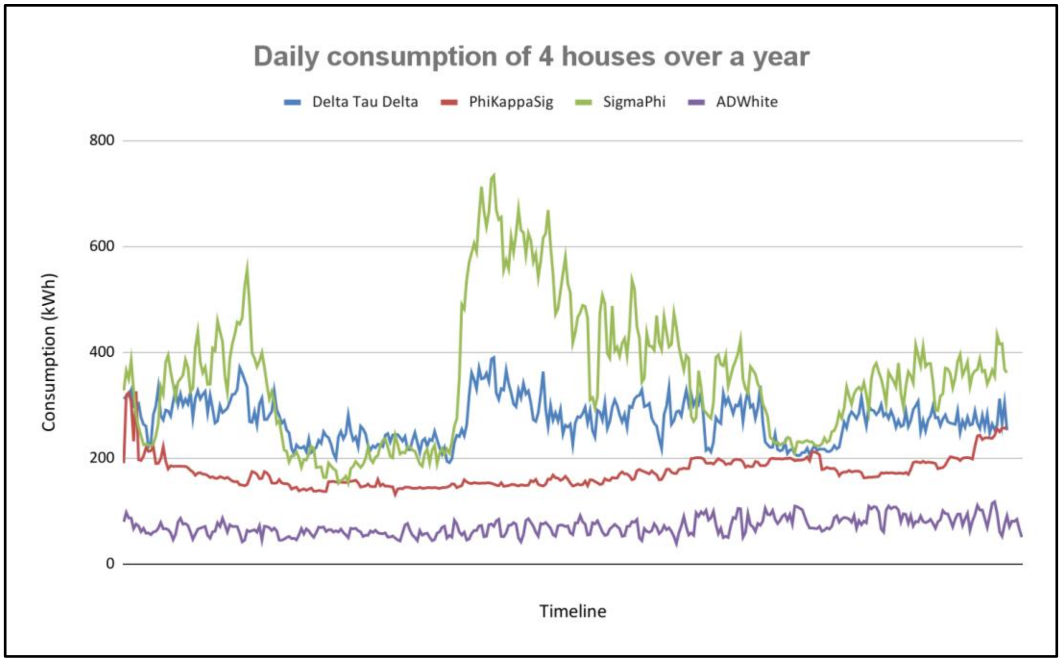

Figure 9: Daily Consumption of 4 Similar Buildings

Figure 10 illustrates Sigma Phi's monthly electricity consumption. The dotted line represents the average consumption. It seemed clear to us how their electricity consumption was higher during Ithaca's cooling season (records from June and July are low because there are no residents living there). We checked with the Fraternity and they use window box a/c units. In order to calculate the cooling needs from Llenroc per month we followed the subsequent approach:

1) The maximum cooling needed per month would be equal to the day with the highest consumption minus the average monthly consumption (not considering June and July, as they are not representative) times the number of days in the month:

   $Maximum\ cooling\ load\ needed\ =$ *(Highest consumption in one day - Average year consumption)*30 days = (734.225 kWh - 334.534 kWh)*30 = 11,990.74 kWh* **(3)**

   We didn't have to scale this number according to the number of people living in the house because Sigma Phi currently hosts 30 brothers, which is the desired number at Llenroc.

2) Once we had the highest consumption, we had to scale it for the cooling season (mid-May to the end of September). As Llenroc intends to host events during June and July, we couldn't keep on using data from Sigma Phi. We assumed that 11,990.74 kWh would be the highest monthly consumption and, from there, we scaled it according to the calculations in Method 1. **Appendix A** shows a column with the estimated cooling load needed according to Method 1. July is the month with the highest consumption, as the column "Percentage of maximum cooling" displays. Therefore, we assigned 11,990.74 kWh to the month of July and, from there, we scaled that value for every month in compliance with the percentages that were calculated in Method 1.

3) The final estimation of the cooling load per month can be seen in the cooling column in **Appendix A**.

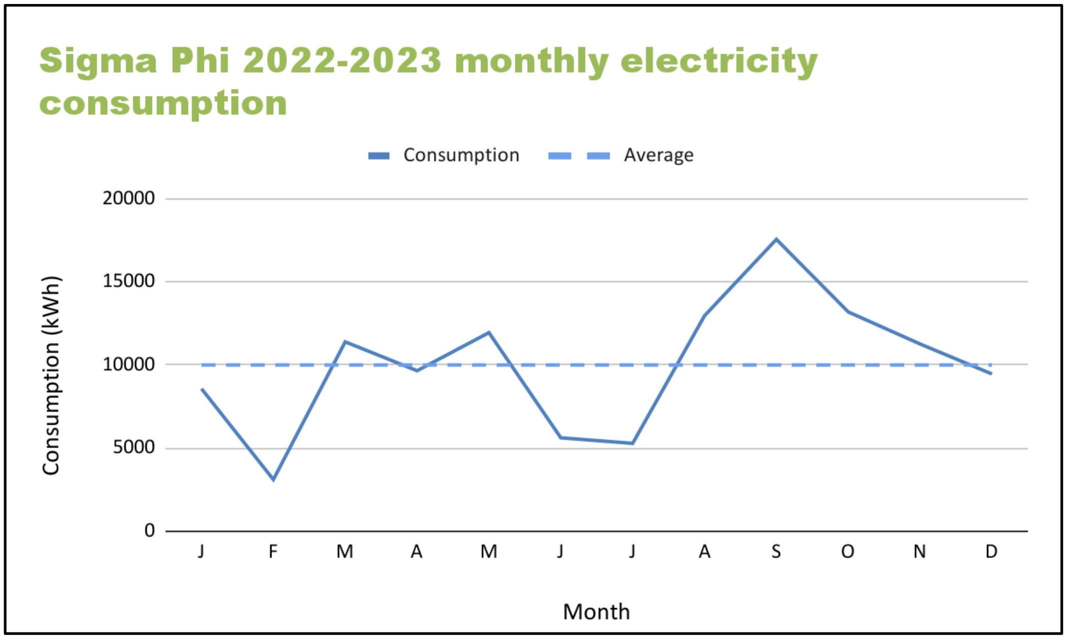

Figure 10: Sigma Phi Monthly Electricity Consumption

Finally, we were able to get to a yearly cooling load of 25,123 kWh, which is four times smaller than the heating load. Also, the requirements under peak conditions are not as demanding as those for heating. Therefore, the size of the heat pump will not be affected by the cooling needs.

3.2.3. Future Estimated Energy Outputs

Once we had modeled the current energy distribution of the house, we had to analyze how that would change with the installation of the heat pump. In this report, we will focus on energy outputs and inputs if efficiency improvements are indeed installed in the house. That information is in **Appendix C** and will be explained in this section. **Appendix B** shows the same table if efficiency upgrades were not made.

- **Heat pump output** → the heat pump will be in charge of both heating and cooling the house. Hence, the energy output from it (this is, the amount of energy that the residents will feel during the year) will be:

*Heat pump output = (Energy Used for Heating with Nat Gas*Boiler efficiency*1.2 loss factor + Energy Used by Strip Heaters + Energy needed for cooling)*Efficiency improvement factor* **(4)**

The efficiency improvement factor is the one calculated in Method 1. It has a value of 0.499 and it indicates that, if the house underwent the proposed changes, it would only need half of the heat that it needs today, as insulation would improve. The yearly total output from the heat pump would add up to 129,750 kWh (259,786 kWh without improvements).

Moreover, we observed that the month with the highest output would be February, with 25,774 kWh. That means that, under these assumptions, the size of the heat pump should be:

$$Heat\ pump\ size\ = \frac{25{,}744\ kWh}{1\ month} * \frac{1\ month}{28\ days} * \frac{1\ day}{24\ hours} = 38.35\ kW \quad \textbf{(5)}$$

Given a safety factor of 2 to account for extreme temperatures, the suggested size of the heat pump in this method is 76.7 kW which we have rounded to 80 kW. This is very similar to the number that was found in Method 1 (which was 78.62 kW).

- **Energy required for the heat pump**→ Thanks to the 3.5 COP of the heat pump, it only needs 1 unit of electricity for every 3.5 units of heating/cooling that it gives. This will allow Llenroc to cut down its energy usage. Moreover, all the electricity that is used will come from a solar array, which eliminates CO_2 emissions. **Figure 11** shows this graphically. We can see how the heat pump transforms the electrical energy from the yellow line into heat or cool in the red line. Most of the electricity is used in the compressor, although the heat pump also draws electricity for other parts such as pumps or controls.

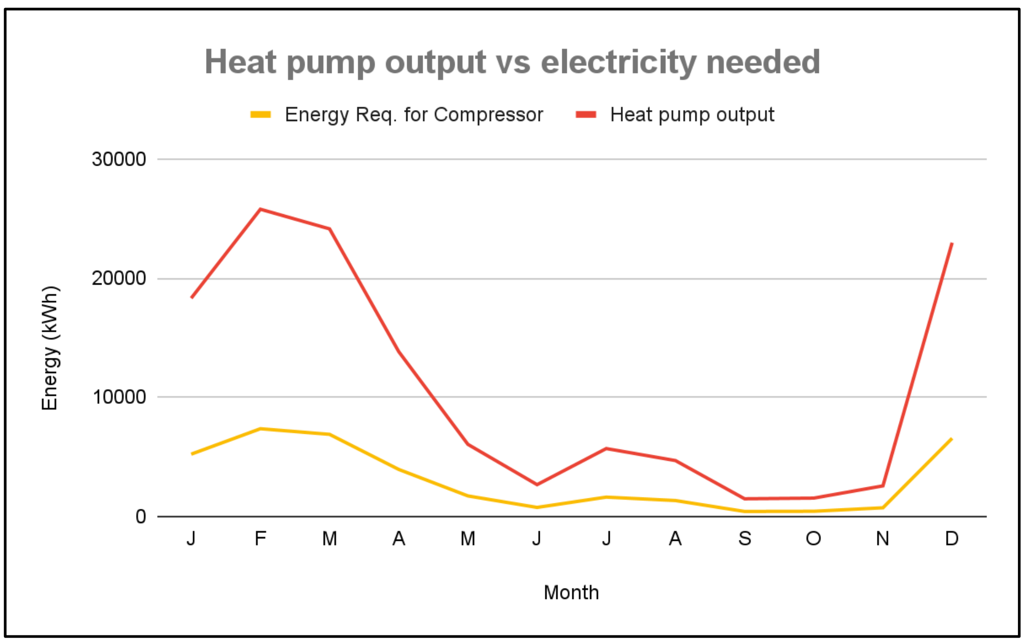

Figure 11: Energy input vs. energy output for the heat pump

- **Total future electricity consumption** → after all the consideration made, the electricity that Llenroc will need in the future will be:

Future electrical needs = Current Electricity Consumption - Electricity needed for Strip Heaters + Electricity required for Heat Pump **(6)**

The total electricity that Llenroc will require per year will total 64,958 kWh (102,136 kWh without improvements). Note how, even after considering the electrical needs of other utilities, this number is still lower than the heat pump output. It will all be powered by the solar array.

Figure 12 provides a comparison of the total energy needed (natural gas + electricity) to power Llenroc. The red line represents the status quo, while the green and yellow reflect the consumption that will be required if the heat pump is installed. Except for the summer months, in which consumption will slightly increase due to the installment of the AC, the difference is enormous and it is all thanks to the geothermal heat pump. Llenroc will see a drastic decrease in its natural gas consumption that will turn into a slight increase in electricity usage.

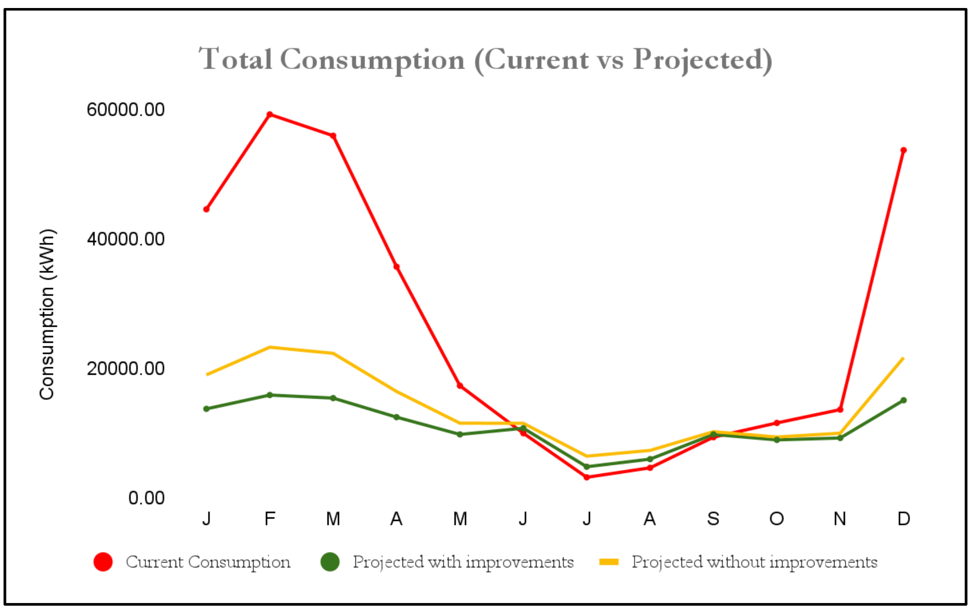

Figure 12: Total energy consumption comparison

Finally, **Figure 13** breaks down future consumption needs into the main players: natural gas used for the water heater, cooking and electricity, which is also broken down between electricity to power the heat pump and electricity to power other utilities such as lights or home appliances.

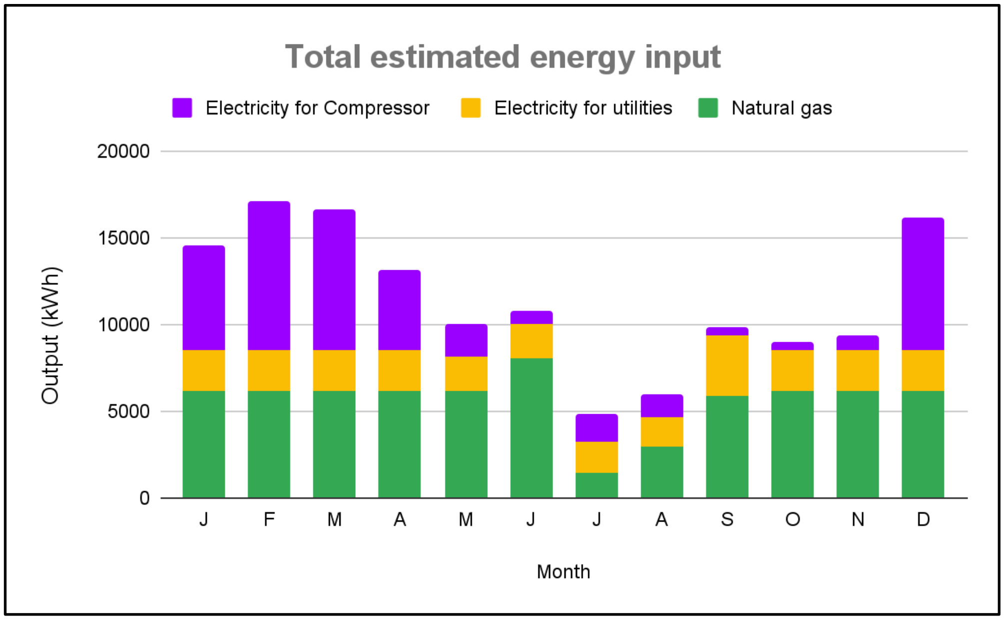

Figure 13: Future energy needs given improvements

The last two columns in the table in **Appendix C** were calculated to analyze the viability of installing Tesla Power Walls as a backup and can be explained as follows:

- **Daily consumption (kWh)** → it intends to show the electric consumption of Llenroc per day. It was computed dividing the consumption in the given month by the number of days in the month.
- **Daily consumption at night (kWh)** → we wanted to see how much electricity would be consumed by Llenroc at night, which is when the solar array wouldn't generate any power. To do that, we analyzed the hourly electricity consumption of the four buildings shown in **Figure 9** and we observed that 50.23% of the total would be consumed at night.

4. Discussion

In this section we outline the rest of our process in the feasibility study. We roughly define where the trenches and wells needed for the heat pump would be located and how large they would need to be for the different scenarios. We also discuss how we size the solar PV system and the battery system.

4.1. Trenches & Wells Areas

With the 80-kW required for the heat pump, half will be implemented in trenches and half in wells. There is not enough room in the yard of Llenroc to implement the full 80 kW in trenches, which would require 48,000 ft^2. Trenches are much cheaper, so we maximized the amount of energy that could be put in trenches, while still allowing for room for the remainder of the piping to be in wells. This came to a total of 24,000 ft^2 of trenches for 40 kW, and 8,000 ft^2 in wells. A scale size of these areas on the Llenroc property are shown in **Figure 14** below. Additionally, there is a possibility of reaching an agreement with Cornell to install the trenches beneath their land located north of Llenroc.

Figure 14: Areas of trenches and wells for heat pump in Llenroc's yard

4.2. Solar PV System

In the planning of the photovoltaic (PV) system for the project, three areas were taken into consideration were the current tennis court area, the slope—which would require a retaining wall along Cornell Avenue, and a solar canopy over the parking area to the east of the house, shown in **Figure 15**. We considered three different brands of solar panels: Sunpower, Jinko, and Longhi. The brands were then compared by energy production efficiency, taking into account the size of the panels and the specific energy in kilowatts that they produced. Additionally, potential energy generated by the solar canopy was evaluated using three different brands of solar panels suitable for the task: REC, Silfab, and Canadian Solar. The direction and angle of the solar panels and canopy were taken into account during the evaluation process. The team also calculated the energy capacity of the Tesla Powerwall+ Battery System, which is further detailed in **Section 4.3**. Finally, the excess energy was noted, to be either sold or bought to or from the local power grid.

By using this methodology, the team determined the most productive and efficient brands and the optimal areas for installing the solar panels. It was found that total capacity of the solar PV system needed for Llenroc with efficiency improvements was 104 kW (without solar array on the slope), with up to 158 kW available otherwise (includes all three areas).

The Tennis Court

The first area that was considered for the installation of the PV system was the tennis court next to the house, covering an area of 840 square meters, which includes the original size of the tennis court. The team assumed a 25% increase in space due to renovations: removing trees and vegetation surrounding the court and leveling the surface. Following the methodology, the team focused on the Jinko panels, taking into account their efficiency. Based on the panel's size and the required spacing between rows, the team was able to comfortably fit 96 panels, which would produce 52 kW of power.

The size of a single Jinko panel that produces 0.545 kW is 2.274 x 1.134 square meters. The distance between the rows was determined to be 2.32 meters (**Equation 7**) to avoid shading other panels, making it feasible to install 12 rows of 8 panels each. Thus, a total of 96 solar panels could be installed, generating 52.32 kW of power. This renovation of the tennis court represents the first step in the implementation of the PV system for the project.

$$Module\ row\ spacing\ = \frac{sin(\beta)*Module\ Width}{tan(solar\ elevation\ angle)}$$, where: **(7)**

- β = Tilt angle = 42.5º
- Module Width = 1.05 m
- Solar Elevation Angle = 17º

PVWatts showed that the total output of this array in one year would be 59,143 kWh. We assumed that the panels would be tilted 42.5º to match Ithaca’s latitude. This tilted angle was designed to make the production optimal, according to *Energy Systems Engineering: Evaluation and Implementation, Third Edition* (Albright et al., 2021).

The Slope

The second area considered for the installation of the PV system is the slope adjacent to the building which would duplicate the tennis court solar array design: 840 square meters in size and the same capacity of 52.32 kW. However, it is important to note that this array is only necessary if the management decides not to proceed with efficiency improvements. Space is not an issue in this area, but there are some obstacles to overcome. Firstly, a historical tree stands in the area, which would shade the panels and decrease their efficiency. Additionally, the slope is tilted facing west, which further reduces the panels' efficiency. Finally, there is the aesthetic concern, as the panels' visual impact from the street may not be desirable. Solutions to these problems include seeking approval from the board to remove the tree or cut its branches, using a 219 MW plant in Alcoutim, Portugal as a precedent, and increasing the height of the wall to block the visual impact. The plant in Alcoutim managed to tilt towards south panels located in slopes facing west.

The Solar Canopy

In addition to the two solar arrays, a third solar system location was decided, the solar canopy. This would act as an overhead structure above the parking area. The solar canopy installation would be about 225 m^2 (2,500 ft^2). The average solar energy would be 20 W/ft^2, with a total possible output of just under 50 kW. Since this installation would be facing east, it would not be as optimal as facing south. Generally, solar panels facing east produce about 20% less electricity than those facing south (Marsh, 2022). In Llenroc's case, the total electricity generated in one year if the panels face east would be 42,000 kWh, compared to 55,000 kWh if they face south, according to PVWatts simulator. Despite this efficiency loss, this installation is still feasible and would add to Llenroc's solar production. Some additional benefits that the solar canopy would provide include improved energy with the added amount of solar, reduced parking lot maintenance costs due to protection of cars and pavement from harsh weather, and easy electric vehicle charger integration if Llenroc decides to install EV chargers in the future. The solar canopy installation would require approval from a historical standpoint, since it would visually alter the building from the outside; however, Llenroc has historically had other vehicle coverings in the anticipated solar canopy location, so gaining approval is feasible.

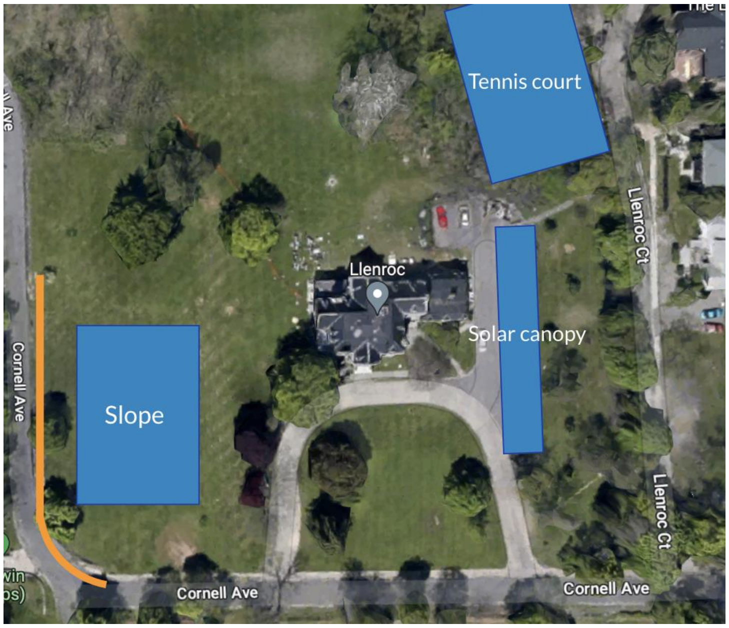

Figure 15: Placements of the three arrays

4.3. Storage and Local Grid

Battery Storage System

The battery storage system was evaluated for its feasibility to provide backup power for 1-3 days in case of a power failure. It was decided that the cost of implementing such a system would be too high. As an alternative, 7 Tesla Powerwall+ batteries were selected to store the electricity generated by the solar panels especially during the summer months. It was found that 23 batteries would be needed to provide a backup power supply for just 1 day. The daily consumption of energy was calculated to be an average of 178.89 kWh. The total energy capacity of 7 batteries was determined to be 94.5 kWh, which would support 53% of the daily electricity usage. However, it was noted that in order to fully charge the batteries in the days in which there was not enough solar energy, energy would need to be purchased from the local grid which would further increase the cost of implementing the system. It is also important to note that the self-discharge rate of the batteries is negligible at 1-2% per month.

Each Tesla battery costs $8,400. Therefore, purchasing 7 of them would mean an extra cost of $58,800. Moreover, the output from the solar array should be more than enough to cover the electricity needs of Llenroc throughout the year. Thanks to a net metering program that will be further explained later, the house wouldn't need to pay for electricity from the grid at night. Then, the only benefit that the batteries could provide would be as an energy backup in case there was a blackout. Even if that happened, the batteries could only support electric energy consumption for half a day if everything was running as normal. If powering the heat pump were given priority, the Tesla batteries could power it for 56% of one winter day or 2.4 summer days.

Considering that the maximum cost for a diesel generator is $24,000, the recommendation from the team is to not purchase the batteries. A gas generator may be ideal, as well. It is not economically beneficial to purchase the batteries as opposed to the generator especially considering the cost per use ratio. However, as it was requested from Llenroc Management, they will be included in the economic analysis.

Buying and Selling to the Local Grid

Selling to the local grid is a possibility for Llenroc given our estimated calculations in **Appendix E**. By subtracting the total future energy consumption from the sum of outputs from the tennis court solar array and canopy, we calculated that the total amount of energy that could be sold to the grid is just over 30,000 kWh/year. Net metering would allow Llenroc to receive full retail for solar. The customer benefit contribution charge for net metering is ~$0.69–$1.09 per kW of solar and would add up to about $71.76–$113.36 per month, or $861.12–$1360.32 per year. This would still allow for a profit for Llenroc and enable them to buy back the energy they sold to the grid in their positive summer months for the negative winter months.

4.4. Summary

After all the calculations done, the projected energy flows of the Llenroc in one year time can be summarized like this:

Table 5: Summary of energy flows in one year

Natural gas consumption	67,390 kWh
Electricity produced by solar array	100,644 kWh
Electricity for utilities	27,886 kWh
Electricity for the heat pump	37,072 kWh
Electricity sold to the grid	35,686 kWh
Heat produced by the heat pump	104,624 kWh
Cold produced by the heat pump	25,123 kWh

The Sankey diagram below provides a qualitative visual aid to help understand how Llenroc's energy's flow would look like under the proposed renovations. Note how the electricity used to power the heat pump gets transformed into a greater output in the form of heat or cold.

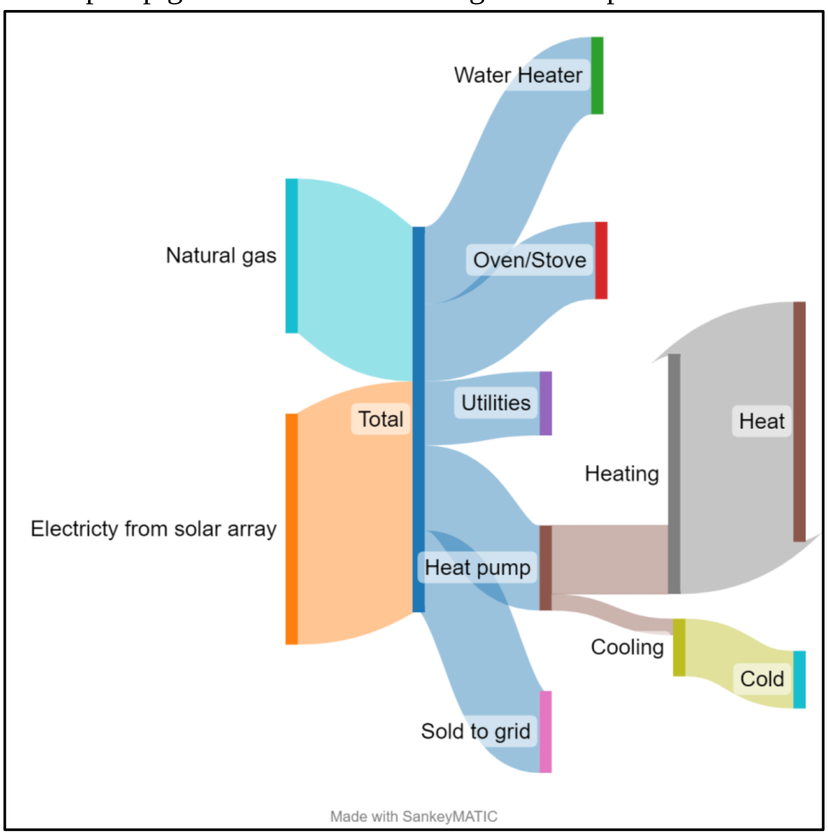

Figure 14: Sankey Diagram of the proposed energy flows for the Llenroc House

Using the figures of projected natural gas and electricity consumption we can compare the associated carbon emissions between the improvement scenario and business-as-usual case. We assume burning natural gas emits 117 pounds of CO_2 per million British thermal units which is equivalent to .18 kg CO_2 per kWh based on a figure from the U.S. Energy Information Agency (U.S. EIA, 2022). For electricity for business-as-usual case, we assume that electricity consumption has .71 kg CO_2 emissions per kWh consumed based on value the EPA cites as the U.S. national weighted average marginal emission rate from 2019 data (U.S. EPA, 2023). Under the improvement case, electricity consumed is from PV solar generation. We assume this electricity has no associated carbon emissions. This means we are ignoring the emissions associated with mineral extraction, manufacturing, and transportation for the solar panels. Additionally we do not take into account the emissions from drilling bore holes for the heat pump.

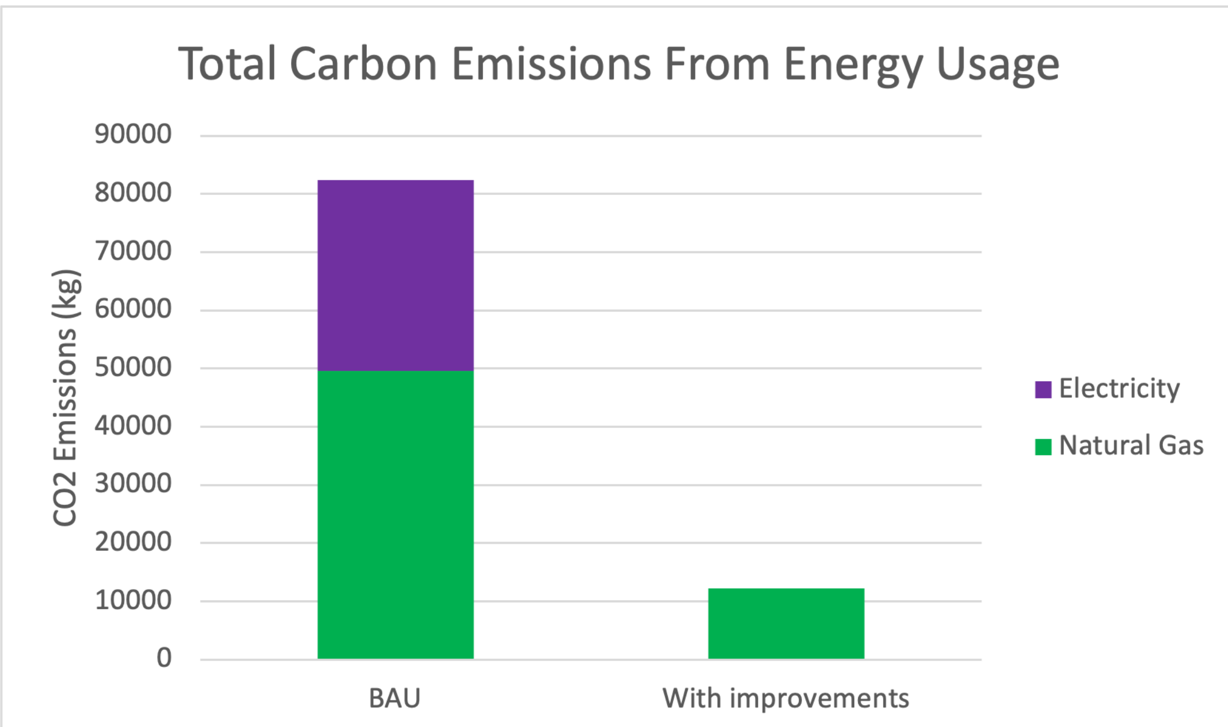

Figure 15: Chart showing the annual carbon emissions associated with energy usage including natural gas and electricity consumption

Figure 15 shows the annual equivalent carbon emissions associated with energy usage including natural gas and electricity consumption. The total annual emissions from the business-as-usual case is 82395.95 kg CO_2 while the heat pump, solar, and energy improvements lead to 12235.56 kg CO_2 emissions. In other words there would be an approximately 85% reduction in annual carbon emissions from energy consumption, again not taking into account the life-cycle emissions of the heat pump or solar arrays.

5. Multi-Year Financial Model

The team also conducted a thorough budget and cost of life analysis for a time horizon of 50 years. This analysis took into account:

1. Initial Costs:
    a. Heat pump (heat pump itself, trench system piping, heat pump system installation, labor, piping inside house, wells)
    b. Solar and battery system (solar PV panels on tennis court area, solar PV installation, solar canopy and its installation, and Tesla Powerwalls+)
    c. Home improvements: custom storm windows, insulation in attic crawl space
    d. Other: retaining wall along Cornell Ave.
2. Annual Costs:
    a. Heat pump (operation and maintenance)
    b. Solar system (solar PV maintenance and inspection, solar canopy maintenance and inspection)
    c. Net metering (electricity usage, selling back to the grid from solar PV system)
    d. Other (cost of natural gas for cooking and hot water)

Please note calculations are estimates based on several different sources and averages.

As shown in **Table 8,** investing $31,000 by improving the windows and insulation of the roof would significantly decrease heat loss in the house, although the true costs could vary greatly from our best estimates. Specifically, the window improvement cost would be unpredictable, this is just an estimate. However, the improvement overall would decrease the size of the heat pump needed, considerably decreasing the total costs.

Based on the initial investment needed to install the heat pump and solar panels system and all needed adjustments we conducted a multiyear model for a 50-year time horizon using two discount rates: 6 and 10%. Discount rates affect the present value of investing in this project where we can see the present worth (PW) of the cost is lower for the 10% interest rate. In our PW take into account the total and operational cost.

We calculated the Levelized Cost of Electricity (LCOE) for the two different scenarios and under the two different discount rates. LCOE is a measure used to estimate the average cost of producing electricity from a power generation technology over its entire lifetime, taking into account all costs including initial investment, operation and maintenance costs, fuel costs, and financing costs:

$$LCOE = \frac{Total\ costs\ over\ lifetime\ of\ the\ project}{Total\ output\ over\ lifetime\ of\ the\ project} \quad \textbf{(8)}$$

In our case, we wanted to analyze our whole system, which includes a heat pump and a solar array. That is why the total output will be the sum of the energy generated by the heat pump and the electricity generated by the solar array. Rather than electricity, LCOE in this project will be used to compare the cost of every unit of energy that is generated in the house. Units for LCOE are $/kWh.

The following tables will breakdown the initial and operation costs of the project, which will be used to calculate the final LCOE. Further detail regarding totals cost can be found in **Appendix F** and **Appendix G**.

Table 6: Total initial cost for the heat pump system & solar panel installation

Initial Cost	WO improvements	With improvements
Heat Pump (heat pump, trenches, wells, system installation and labor)	$450,556	$189,256
Solar / Battery System (solar PV on tennis court and slope area and installation, solar canopy & installation, battery system-tesla powerwalls)	$377,237	$226,498
Retaining Wall along Cornell Ave	$8,750	$8,750

Table 7: Total operation and maintenance cost per year

Annual Operational Cost	WO improvements	With improvements
Heat Pump	$4,812	$2,210
Solar system	$2,000	$2,000
Cost of Natural Gas (cooking & water heater)	$1,512	$1,512

Table 8: Total initial costs for house improvements

House Improvements	
Custom Storm Windows	$25,600.00
Insulation on Roof/Attic	$5,568.00
Total	$31,168.00

Table 9: Total reimbursement from net metering

Net metering	WO improvements	With improvements
Electricity Cost ($/kWh)	0.23	0.23
Solar array production (kWh/year)	159,787	100,644
Demand	102,136	64,957
Total	$11,880	$7,300

Table 10: Multi-Year Model

Interest Rate	6%		10%	
	W/O Improvements	**With** Improvements	**W/O** Improvements	**With** Improvements
Total Initial Investment	($838,055)	($457,194)	($838,055)	($457,194)
Total Annual Cost	($8,325)	($5,723)	($8,325)	($5,723)
Net metering	$11,880	$7,300	$11,880	$7,300
Net annual cost	$3,556	$1,577	$3,556	$1,577

Lifetime present worth sum	($760,00)	($420,541)	($782,286)	($430,426)
Lifetime (kWh)	20,983,100	11,519,700	20,983,100	11,519,700
LCOE	($0.0362)	($0.03651)	($0.0373)	($0.03736)

Based on the economic analysis, these are our comments:

1. We **highly recommend doing the efficiency upgrades on the house**. The biggest costs are the ones related to the heat hump (**Table 6**), whose size would be reduced by half with these upgrades. As size decreases, so do its initial costs, from $450,556 to $189,256. This difference is not linear because of the space available on Llenroc's property for trenches and wells. Llenroc's available land is not infinite, which means that if the heat pump was bigger, we would need to install more wells than trenches, which are significantly more expensive.
2. The **retaining wall in Cornell Ave** from **Table 6** will have to be installed even if the array on the slope is not installed because the ground is starting to slide down the slope. The $8,000 is a placeholder but the actual price of this wall can go uptowards $600,000 due to material and size.
3. With all of the recommended improvements, **Llenroc's annual cash flows for these improvements would be net positive**. Because of the low maintenance costs of the heat pump and the solar array (**Table 7**), as well as the reimbursement from the extra production of electricity, the fraternity will be making money every year after the initial investment. **Table 10** shows how the net difference between costs and income will be $1,577 (with improvements).
4. The **initial investment is high**. We are aware that $457,194 is an elevated sum of money. However, as it was mentioned in the last point, that would almost be the only expense required during the lifetime of the system. Moreover, as it will be shown later, our calculations show that the costs of not doing anything are even higher.
5. **LCOE is slightly higher if improvements are done** ($0.0365 vs. $0.362 under 6% interest rate). However, the total kWh produced during the lifetime of the system is almost half in the efficiency upgraded scenario, which means that, even if Llenroc would be paying a little bit more per kWh, the total kWh would be drastically reduced.
6. This method included the Tesla Powerwall+ batteries in the analysis, although we do not recommend them.
7. Furthermore, tax credit was not considered previously.

In a scenario with efficiency upgrades, without the batteries and in which Llenroc is eligible for a 30% tax credit, the costs would change according to the values in **Table 11** below.

Table 11: 6% interest rate with efficiency improvements

6% interest rate & efficiency improvements	
Total Initial Investment	($291,305)
Total Annual Cost	($5,723)
Net Metering	$7,300
Net Annual Cost	$1,577
Lifetime Present Worth Sum	($254,652)
Lifetime (kWh)	11,519,700
LCOE	($0.02211)

Last, we note that all of these costs are **estimates**. They are meant to provide an idea of the costs that Llenroc would be incurring with these upgrades.

5.1. Business-As-Usual Analysis

We wanted to compare these different potential investments to the costs of business-as-usual operations where no energy efficiency improvements are done and the current HVAC system is maintained. For this we use the same 50-year time horizon. We assume that the current boiler and radiators will be initially replaced in year one and then additional replacements will be done every 20 years. For costing we assumed $10,000 and $75,000 for boiler and radiator replacements respectively as we took values from the higher end of ranges cited due to the larger size of the home (Moore, 2023; Ogletree, 2023). We also use the current consumption data for natural gas and electricity to estimate the yearly utilities cost.

Table 12: 6% interest rate for business-as-usual

6% interest rate & business-as-usual	
Total Initial Investment	($85,000)
Total Annual Cost	($16,809)
Lifetime Present Worth Sum	($450,959)
Lifetime (kWh)	15,959,300
LCOE	($0.02826)

Although the initial investment is higher if there is an investment in renewable energy, the lifetime present worth sum of not doing so is greater than installing the heat pump and the solar array. With or without tax credits, the investment will end up paying off.

6. Results

The results of our research and analysis of this feasibility study show that the Llenroc House would benefit from several additions. First, added insulation to the roof in the attic crawl space and custom storm windows to improve the R-value of the house. Next, for solar generation we recommend a 52-kW solar array on the tennis court area and a 48-kW solar canopy over the parking area. While we did include calculations in the cost model for the addition of Tesla Powerwall+ batteries for overnight storage of summer electricity, we do not recommend going forward with these due to the costs outweighing the benefits. Lastly, for the geothermal heat pump to heat and cool the house, we recommend installing an 80-kW heat pump. For the loops from which the heat pump would obtain the energy, we estimated that trenches should provide 40 kW and wells should account for the remaining 40 kW. The team remains impartial regarding the choice between the 2-pipe and 4-pipe hydronic system as well as the difference between interior and exterior storm windows, as the final decision will be determined by the next detailed engineering study of Llenroc.

The initial investment costs are high, but compared to the business-as-usual case, the costs for the energy efficiency improvement case are similar to the business-as-usual case. This is because the energy efficiency improvement drastically reduces the heating and cooling loads. Additionally, the heat pump allows for much more efficient heating and cooling compared to the current boiler and radiators. And of course, our proposed improvements increase environmental sustainability. Therefore, we recommend these investments because the present worth for both cases are similar, but the renovations and upgrades are much more environmentally sustainable.

7. Conclusions

This project holds immense significance for achieving a carbon-neutral future at Cornell University, in Ithaca, and beyond, despite the high initial investments. If these renovations and upgrades were performed, they would serve as an exemplary model for other historical and small commercial size buildings that aspire to use smart renewable energy technologies for a sustainable future. This preliminary study demonstrates that the project is feasible, but further engineering analyses are required to develop a more detailed design and obtain more accurate cost estimates. By showcasing the possibilities of green energy and sustainability, this project can inspire and motivate others to take similar steps towards a cleaner environment. If the project goes through, besides the small amount of natural gas used for water heating and cooking, there would be no CO_2 emissions from Llenroc.

8. Future Research

Due to the limited scope and availability of information, our feasibility study was not able to account for all factors related to these improvement projects at Llenroc. There are many additional considerations that Llenroc management and design engineers would need to make going forward; these are listed below.

- We estimated the heat pump size, pricing, and specifications in our study. However, heat pumps that are not made for regular sized residential homes do not have listed prices or specifications online. We tried calling lots of different manufacturers, but all of them wanted more information about the house and their ability to be the contractors before they could give pricing or sizing quotes. There are a lot of factors relevant to sizing a heat pump that we did not fully account for, so we would also recommend that further analysis be performed. It would be very problematic to install a heat pump that is too small as it would not be able to keep up with heating and cooling demands, but there could also be some problems associated with heat pumps that are much larger than necessary (McCabe 2022).
- The ground under Llenroc's property is incredibly important to the feasibility of the entire project. The type of soil and rock under Llenroc, the depth of these soil compositions, and the water table height will all influence how and what type of geothermal heat pump piping can be performed on the property. For example, if there is hard shale (which is common in the Ithaca area) at a shallow depth, it will be very difficult to drill wells on the property—and it will be far more expensive. We did not have a geotechnical survey of the property, so it was very difficult to estimate the exact cost of the drilling (instead we used more general estimates for areas in the Northeastern United States). We would highly recommend a geotechnical study be performed before any detailed planning of the heat pump system is done.
- Due to the complex combinations of installations and renovations that have been done at Llenroc, we did not have fully up-to-date detailed plans of Llenroc, particularly the walls of the building. As such, we did not design specific or precise outlines of how any new ductwork and piping would go through the building. This would be left to future contractors.
- We ignored end-of-life and disposal costs. This includes the disposal costs of the current HVAC system—which could be substantial given the complex network of pipes, ducts, and radiators currently in the house. It also includes the end-of-life costs related to disposing of the recommended systems at the end of their 50-year time horizon.
- We didn't suggest replacing the water heater because it was relatively new. However, we recommend looking for a green alternative once the heater's lifetime comes to an end.

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10. Appendices

Appendix A: Consumption table

Month	Natural gas consumption	Natural gas consumption	Water heater + cooking	Water heater + cooking	Price of natural gas (2022)	Heating	Current electricity consumption	Electricity used for 3rd floor heaters	Cooling (Method 1)	Percentage of max cooling	Cooling
	(therms)	(kWh)	(kWh)	therms	($/therm)	(kWh)	(kWh)	kWh	Btu		(kWh)
January	1300.00	38090.13	6134.71	209.38	0.49	31955.42	6500.00	4085.67	0.00	0.00	0.00
February	1800.00	52740.18	6134.71	209.38	0.56	46605.47	6500.00	4085.67	0.00	0.00	0.00
March	1790.00	52447.18	6134.71	209.38	0.46	46312.47	3500.00	1085.67	0.00	0.00	0.00
April	1100.00	32230.11	6134.71	209.38	0.56	26095.40	3500.00	1085.67	0.00	0.00	0.00
May	525.00	15382.55	6134.71	209.38	0.67	9247.84	1968.00	0.00	2589749.1	0.24	2693.94
June	275.00	8057.53	8057.53	275.00	0.77	0.00	1968.00	0.00	5149727.6	0.47	5356.91
July	50.00	1465.01	1465.01	50.00	0.70	0.00	1750.00	0.00	10978091	1.00	11419.75
August	100.00	2930.01	2930.01	100.00	0.92	0.00	1750.00	0.00	9040057.9	0.82	9403.75
September	200.00	5860.02	5860.02	200.00	0.97	0.00	3550.00	0.00	2865944.6	0.26	2981.24
October	275.00	8057.53	6134.71	209.38	0.60	1922.82	3550.00	1135.67	0.00	0.00	0.00
November	275.00	8057.53	6134.71	209.38	0.59	1922.82	5608.00	3193.67	0.00	0.00	0.00
December	1622.00	47524.76	6134.71	209.38	0.76	41390.05	6200.00	3785.67	0.00	0.00	0.00

Appendix B: Table of future consumption and outputs with efficiency improvements

Month	Heat pump output (w efficiency improvements)	Energy Req. for Compressor	Total Future Electricity Consumption	Daily consumption	Daily consumption at night
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
January	18313.63	5232.46	7646.80	246.67	123.90
February	25774.37	7364.10	9778.44	349.23	175.42
March	24127.32	6893.52	9307.85	300.25	150.82
April	13831.49	3951.86	6366.19	212.21	106.59
May	6054.62	1729.89	3697.89	119.29	59.92
June	2674.59	764.17	2732.17	91.07	45.75
July	5701.63	1629.04	3379.04	109.00	54.75
August	4695.09	1341.45	3091.45	99.72	50.09
September	1488.47	425.28	3975.28	132.51	66.56
October	1546.24	441.78	2856.12	92.13	46.28
November	2573.75	735.36	3149.69	104.99	52.74
December	22968.56	6562.45	8976.78	289.57	145.45
TOTAL / AVERAGE	129749.74	37071.36	64957.69	178.89	89.86

Appendix C: Table of future consumption and outputs without efficiency improvements

Month	Heat pump output (w/o efficiency improvements)	Energy Req. for Compressor	Total Future Electricity Consumption	Daily consumption	Daily consumption at night
	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
January	36680.20	10480.06	12894.39	415.95	208.93
February	51623.25	14749.50	17163.83	612.99	307.91
March	48324.39	13806.97	16221.30	523.27	262.84
April	27702.98	7915.14	10329.47	344.32	172.95
May	12126.74	3464.78	5432.78	175.25	88.03
June	5356.91	1530.54	3498.54	116.62	58.58
July	11419.75	3262.79	5012.79	161.70	81.22
August	9403.75	2686.79	4436.79	143.12	71.89
September	2981.24	851.78	4401.78	146.73	73.70
October	3096.94	884.84	3299.17	106.42	53.46
November	5154.94	1472.84	3887.17	129.57	65.08
December	46003.52	13143.86	15558.20	501.88	252.09
TOTAL / AVERAGE	259874.6	74249.89	102136.22	281.49	101.89

Appendix D: Evaluation of amount of energy that could be bought or sold each month without improvements

Month	Output from 104.64 kWh solar array	Output from solar canopy (facing east)	Output - E. Req.	Extra electricity every day	Energy that can be stored in Batteries (this would be used at night)	Sell/buy
	(kWh)			(kWh/day)		(kWh/month)
January	6,947	1683	-4,264	-137.56	0	-4,264
February	8,850	2409	-5,905	-210.89	0	-5,905
March	11,274	3641	-1,306	-42.14	0	-1,306
April	11,546	4357	5,574	185.78	94.50	5,574
May	11,502	4940	11,009	355.14	88.03	11,009
June	11,415	5381	13,297	443.25	58.58	13,297
July	11,928	5078	11,993	386.88	81.22	11,993
August	11,510	4509	11,582	373.62	71.89	11,582
September	11,842	3921	11,361	378.71	73.70	11,361
October	9,050	2702	8,453	272.67	53.46	8,453
November	6,910	1618	4,641	154.69	65.08	4,641

December	5,512	1262	-8,784	-283.36		-8,784
TOTAL/AVERAGE	118,286	41501		1876.79		57,651

Appendix E: Evaluation of amount of energy that could be bought or sold each month with improvements

Month	Output from 52.32 kWh solar array	Output from solar canopy (facing east)	Output - E. Req.	Extra electricity every day	Energy that can be stored in Batteries (this would be used at night)	Sell/buy
	(kWh)			(kWh/day)		(kWh/month)
January	3,474	1683	-2,490	-80.33218214	0	-2,490
February	4,425	2409	-2,944	-105.1584939	0	-2,944
March	5,637	3641	-30	-0.9629749215	0	-30
April	5,773	4357	3,764	125.4603743	94.5	3,764
May	5,751	4940	6,993	225.5841744	59.91775628	6,993
June	5,708	5381	8,356	278.5444066	45.74559622	8,356
July	5,964	5078	7,663	247.1923115	54.75132128	7,663
August	5,755	4509	7,173	231.3724615	50.09152227	7,173
September	5,921	3921	5,867	195.5574213	66.55939392	5,867

October	4,525	2702	4,371	140.9962897	46.27827656	4,371
November	3,455	1618	1,923	64.110312	52.73632028	1,923
December	2,756	1262	-4,959	-159.9606014		-4,959
TOTAL/AVERAGE	59,143	41501		1162.403499		35,686

Appendix F: Financial model calculations without improvement

Heat Pump - Initial Costs			
Heat pump	25	1	$225,153.00
Trench system piping (same size as 11.18 ton)	50	1	$4,471.00
Wells system piping (remaining 38.86 ton)	50	1	$25,142.00
Additional wells drilling	50	1	$20,671.00
System Installation, Labor		1	$175,119.00
Piping inside house	25	1	
Refrigerant			
(ADD IN TAX CREDITS)			
Total			
Heat Pump - Annual Costs			
Operation & Maintenance	1	1	$ 4,812.00
Total			
Solar / Battery System - Initial Costs			
Solar PV (on tennis court area)&slope area	25	1	$67,725.00
Solar panel Installation (2 arrays - 104 kW)		1	$183,437.00
Solar Canopy+Installation	25	1	$67,275.00
Battery System - Tesla Powerwalls	10	7	$8,400.00
Total			

Solar System - Annual Costs				
Solar PV Maintenance + Inspection	1	1	$ 1,000.00	$ 1,000.00
Solar Canopy Maintance + Inspection	1	1	$ 1,000.00	$ 1,000.00
Total				$ 2,000.00
Cost of Natural Gas-Cooking &Water heater				
Custom Storm Windows	25	64	$ 400.00	$25,600.00
Insulation on roof/attic	50	1160	$ 4.00	$5,568.00
Total				$31,168.00
Cost of Natural Gas-Cooking &Water heater				
Annual cost /year		1	$ 1,512.55	$ 1,512.55
Other Costs				
Retaining wall along Cornell Ave	50		8750	$ 8,750.00
Total				$8,750.00

Appendix G: Financial model improvements with improvements

Heat Pump - Initial Costs				
Heat pump	25	1	$100,602.00	$100,602.00
Trench system piping	50	1	$4,471.00	$4,471.00
System Installation, Labor		1	$78,246.00	$78,246.00
Piping inside house	25	1	$5,946.00	$5,946.00
Wells cost				
(ADD IN TAX CREDITS)				
Total				$189,265.00
Heat Pump - Annual Costs				
Operation & Maintenance	1	1	$ 2,210.00	$2,210.00
Total				$2,210.00
Solar / Battery System - Initial Costs				
Solar PV (on tennis court area)	25	1	$33,862.50	$33,862.50
Solar panel Installation		1	$66,560.50	$66,560.50
Solar Canopy+Installation	25	1	$67,275.00	$67,275.00
Battery System - Tesla Powerwalls	10	7	$8,400.00	$58,800.00
Total				$226,498.00
Solar / Battery System - Annual Costs				
Solar PV Maintenance + Inspection	1	1	$ 1,000.00	$ 1,000.00
Solar Canopy Maintenance + Inspection	1	1	$ 1,000.00	$ 1,000.00
Total				$ 2,000.00

Solar / Battery System - Initial Costs			
Solar PV (on tennis court area)	25	1	$33,862.50
Solar panel Installation		1	$66,560.50
Solar Canopy+Installation	25	1	$67,275.00
Battery System - Tesla Powerwalls	10	7	$8,400.00
Total			
Solar / Battery System - Annual Costs			
Solar PV Maintenance + Inspection	1	1	$ 1,000.00
Solar Canopy Maintenance + Inspection	1	1	$ 1,000.00
Total			
Efficiency upgrades			
Custom Storm Windows	25	64	$ 400.00
Insulation on roof/attic	50	1160	$ 4.00
Total			
Cost of Natural Gas-Cooking &Water heater			
Annual cost /year		1	$ 1,512.55
Other Costs			
Retaining wall along Cornell Ave	50		8750
Total			

Appendix H: Financial model with improvements, no batteries and tax credit

		Useful Life (yrs)	Units	Unit Cost	Item total cost	With Tax Credit
Heat Pump - Initial Costs						
Heat pump		25	1	$100,602.00	$100,602.00	
Trench system piping		50	1	$4,471.00	$4,471.00	
System Installation, Labor			1	$78,246.00	$78,246.00	
Piping inside house		25	1	$5,946.00	$5,946.00	
Wells cost						
(ADD IN TAX CREDITS)						
Total					**$189,265.00**	**$132,485.50**
Heat Pump - Annual Costs						
Operation & Maintenance		1	1	$ 2,210.00	$2,210.00	
Total					**$2,210.00**	
Solar / Battery System - Initial Costs						
Solar PV (on tennis court area)		25	1	$33,862.50	$33,862.50	
Solar panel Installation			1	$66,560.50	$66,560.50	
Solar Canopy+Installation		25	1	$67,275.00	$67,275.00	
Battery System - Tesla Powerwalls		10	0	$8,400.00	$0.00	
Total					**$167,698.00**	**$117,388.60**
Solar / Battery System - Annual Costs						
Solar PV Maintenance + Inspection		1	1	$ 1,000.00	$ 1,000.00	
Solar Canopy Maintenance + Inspection		1	1	$ 1,000.00	$ 1,000.00	
Total					**$ 2,000.00**	
Efficiency upgrades						
Custom Storm Windows		25	64	$ 400.00	$25,600.00	
Insulation on roof/attic		50	1160	$ 4.00	$5,568.00	
Total					**$31,168.00**	
Cost of Natural Gas-Cooking &Water heater						
Annual cost /year			1	$ 1,512.55	$ 1,512.55	
Other Costs						
Retaining wall along Cornell Ave		50		8750	$ 8,750.00	
Total					**$8,750.00**	
Electricity						
Electricity cost($)	0.229		Electrecity cost	$ 0.72	Fees paid to NYSEG	
Solar array (KWH)/year	100644		Total Capacity	101	kW	
Demand	64957.00		Total paid per month to N	$ 72.72		
			Reimbursment	$ 7,299.68		