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CARBON NEUTRAL CORNELL: ENVIRONMENTAL SUSTAINABILITY IMPROVEMENTS AT THE LLENROC HOUSE

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RESUMEN DEL PROYECTO

El trabajo *Carbon Neutral Cornell: environmental sustainability improvements at the Llenroc house* es un estudio de viabilidad realizado con el objetivo de proporcionar a la fraternidad Delta Phi de Cornell un plan para renovar energéticamente su casa principal, llamada Llenroc. Actualmente, el edificio alberga a 19 alumnos de Cornell y pretende sustituir sus tecnologías actuales por otras respetuosas con el medio ambiente. En este documento se explicará la decisión dada a la organización. Dicha solución consiste en sustituir la caldera de gas de Llenroc por una bomba de calor geotérmica de 80 kW que calentará y enfriará la casa cuando sea necesario, así como un sistema de paneles solares de 101 kW de capacidad que suministrará electricidad limpia a Llenroc. El coste inicial total de este proyecto sería de 298.511 dólares. Aunque pueda parecer caro, el coste de no realizar estas reformas sería más elevado. Esta solución se presentó a la junta directiva de Delta Phi en mayo de 2023 en Ithaca, Nueva York.

Palabras clave: energía renovable, bomba de calor, geotermia, Cornell, Llenroc, Delta Phi, paneles solares, gas natural.

1. Introducción

Este trabajo de fin de grado combina la línea de acción de la universidad de Cornell con las necesidades energéticas de la casa Llenroc.

Cornell University es una Universidad que se encuentra entre las Ivy League. Fue fundada en 1865 por Ezra Cornell y se encuentra en el pueblo de Ithaca, en el estado de Nueva York. En 2008, la Universidad lanzó su Climate Action Plan. El objetivo de este proyecto es el de conseguir que el campus sea neutral en carbono antes de 2035.

Llenroc es una casa victoriana de estilo gótico construida por piedra del siglo XIX que fue construida como hogar para Ezra Cornell. Actualmente, la casa acoge a la fraternidad Delta Phi, con 19 miembros de la hermandad viviendo en ella. Debido a su arquitectura y antigüedad, Llenroc tiene el estatus de Casa Hisórica. Esto significa que tanto el exterior como los alrededores de la vivienda no pueden sufrir cambios significativos sin la aprobación de un comité externo a la fraternidad. Aun así, Delta Phi, con Mr. Bruce Bucholz, antiguo miembro de la fraternidad e ingeniero con amplia experiencia en el sector energético, al mando, pretende renovar la villa. Delta Phi pretende que Llenroc alcance su máxima capacidad de residentes, la cual es de 30 personas. La idea es sustituir el sistema de calefacción actual, a la vez que se mejora la eficiencia energética de la casa, de manera que Llenroc cumpla el Climate Action Plan de Cornell. Por eso, la renovación también busca que toda la electricidad consumida por la casa sea renovable.

Con estas premisas, este trabajo se centrará en tecnologías renovables como bombas de calor, sistemas de energía solar, y mejoras energéticas. Es un estudio preliminar con el objetivo de sustituir el sistema de calefacción de la vivienda sin alterar los alrededores de Llenroc significativamente.

El trabajo original fue realizado en Cornell por un grupo de 6 alumnos dirigidos por Francis M. Vanek, profesor de Cornell y doctor en Sistemas de Ingeniería por la Universidad de Pennsylvania. Este documento solo recoge mi aportación al proyecto.

2. Definición del proyecto

Este proyecto buscará la forma más eficiente de mejorar energéticamente el edificio de Llenroc. Tras analizar distintas tecnologías, el objetivo es dimensionar y ubicar una bomba de calor geotérmica y un sistema de placas solares. Estas dos tecnologías combinadas deberían ser suficientes para calentar la casa en invierno, refrigerarla en verano y suministrar suficiente electricidad al edificio de forma que no haya emisiones de CO2.

3. Metodología

La metodología seguida para determinar la capacidad de la bomba de calor y el sistema de paneles solares ha consistido en analizar el consumo histórico de Llenroc y de viviendas similares, con el fin de poder predecir el consumo futuro y los sistemas necesarios para proveer a la casa con energía limpia. Además, el proyecto ha buscado que la producción de esta energía sea óptima.

4. Resultados

Los resultados principales de este proyecto han sido tres. En primer lugar, se ha descubierto que se necesitaría una bomba de calor geotérmica de 80 kW para satisfacer las necesidades energéticas de Llenroc. La mitad de los tubos necesarios para extraer el calor para la bomba serían horizontales y requerirían zanjas, mientras que la otra mitad serían bucles verticales y necesitarán que se excavasen agujeros profundos, como se muestra en la **Figura 1**.

Figura 1: Area destinada a los tubos para la extracción de calor

Lo siguiente descubierto en el proyecto fue que un sistema solar de 101 kW bastaría para alimentar la casa y la bomba de calor con energía renovable. Además, habría un exceso de producción que se vendería a la red. Esto permitiría a Llenroc generar ingresos cada año. El conjunto de los paneles solares se dividiría en dos. Se propone que la mitad de los paneles se ubiquen en la pista de tenis cercana y que la otra mitad formará parte de una marquesina solar situada en el aparcamiento de la villa.

En tercer lugar, se ha podido predecir el consumo anual de energía de Llenroc. La

Tabla 1 y la **Figura 2** resumen esta información de manera cuantitativa y cualitativa, respectivamente.

Tabla 1: Resumen del flujo de energía en Llenroc a lo largo de un año

Consumo de gas natural	67.390 kWh
Electricidad generada por las placas solares	100.644 kWh
Electricidad demandada para la casa	27.886 kWh
Electricity demandada para la bomba de calor	37.072 kWh
Electricidad vendida a la red	35.686 kWh
Calor producido por la bomba de calor	104.624 kWh
Frío producido por la bomba de calor	25.123 kWh

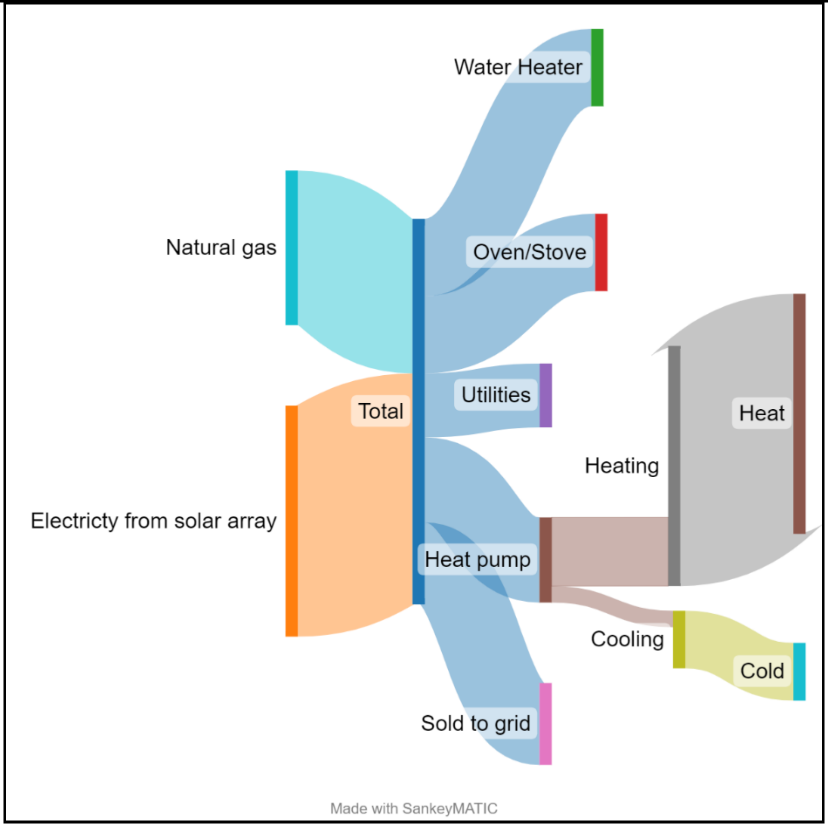

Figura 2: Diagrama de Sankey del flujo de energía propuesto

Por último, un análisis económico concluyó que sería necesaria una inversión inicial de 298.511 dólares para llevar a cabo el proyecto. Sin embargo, debido al bajo coste de mantenimiento de las tecnologías propuestas, Llenroc sería capaz de generar 1.577 dólares de ingresos cada año durante los 50 años de vida útil del sistema.

5. Conclusión

El objetivo del Proyecto Llenroc era encontrar la manera de renovar la Casa Llenroc para que cumpliera con el plan Climate Action Plan de Cornell. La solución que se ha dado a la junta directiva de la fraternidad Delta Phi ha consistido en sustituir la caldera de gas por una bomba de calor de 80 kW e instalar un sistema de producción energética solar de 101 kW, compuesto por placas solares y una marquesina solar. Este conjunto alimentaría tanto las necesidades eléctricas de la casa como las de la bomba de calor. Además, se ha calculado que la electricidad producida por los paneles solares sería más que suficiente para cubrir la demanda de Llenroc. Así, el remanente podría venderse a la red para obtener beneficios. Gracias a su tecnología, la bomba de calor geotérmica podrá calentar la casa durante el invierno y enfriarla durante el verano. La posibilidad de enfriar la casa en verano debería hacer que Llenroc fuera apta para acoger eventos veraniegos de la Universidad, lo que también proporcionaría ingresos adicionales a Delta Phi.

Aunque la inversión inicial del proyecto, estimada en 298.511 dólares, sea elevada, debería acabar amortizándose antes de que finalice su vida útil de 50 años. Por si fuera poco, en el trabajo se ha descubierto que las emisiones de CO_2 de Llenroc disminuirían en un 76% si se instalase esta tecnología.

Lo expuesto en este informe, así con las aportaciones del resto del equipo, fue presentado a la junta directiva de Llenroc en mayo de 2023. El proyecto completo original era un estudio de viabilidad, y pretendía proporcionar a Delta Phi indicaciones sobre cómo continuar con la renovación en el futuro. Este estudio preliminar demuestra que el proyecto es viable, si bien se requieren más análisis ingenieriles para desarrollar un diseño más detallado y obtener estimaciones de costes más precisas. Sin embargo, esos análisis estaban fuera del alcance del estudio.

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Collaborating Entity: Cornell University

ABSTRACT

The *Carbon Neutral Cornell: environmental sustainability improvements at the Llenroc house* is a feasibility study conducted with the objective of providing Cornell's Delta Phi Fraternity with a plan to renew energetically their main house, named Llenroc. The building currently hosts 19 Cornell students and is seeking to replace its current technologies with others that are eco-friendly. Therefore, this document will explain the decision given to the organization. This solution consists in replacing Llenroc's gas boiler with an 80 kW geothermal heat pump that will heat and cool the house when needed and a 101 kW solar array that will provide Llenroc with clean electricity. The total initial cost of this project would be $298,511. Although it might seem expensive, it was found that the cost of not undergoing these renovations would be more expensive. This solution was presented to the board of directors of Delta Phi.

Keywords: renewable energy, heat pump, geothermal, Cornell, Llenroc, Delta Phi, solar panels, natural gas.

1. Introduction

This project combines Cornell University’s line of action regarding carbon emissions with the energetic needs of the Llenroc House.

Cornell University is an Ivy League University founded in 1865 by Ezra Cornell and located in Ithaca, New York. In an effort to address climate change, the University launched the Climate Action Plan in 2008. The objective of this program is to achieve carbon neutrality on campus by 2035 by bringing together students, faculty, and staff in different projects.

Llenroc is a nineteenth century Victorian Gothic stone villa built as Ezra’s Cornell home. It is located on campus, at 100 Cornell Avenue, Ithaca, New York. Today, the house hosts Cornell’s Delta Phi Fraternity, with 19 brothers living in it. Due to its architecture and antiquity, Llenroc possesses the status of a Historic Home, which means that the exterior of the building, as well as its surroundings, can’t be significantly altered. However, Delta Phi, led by Mr. Bruce Bucholz, a graduated Cornell Engineer with vast experience in the energy sector and ex-member of the Fraternity, has been trying to renew the house in the past years, as they seek to fit 30 brothers in the house. As a part of this transition, Llenroc is looking to renew the building energetically. Primarily, the house seeks to replace its current heating system and improve its overall energy efficiency, as they want to meet Cornell’s Climate Action Plan. To meet the carbon neutral policy, they also expect to only consume CO2 free electricity.

With this knowledge in hand, this project focuses on technologies such as geothermal heat pumps, solar PV systems, and high-performance building upgrades. It is a feasibility study focusing on upgrading the building's current heating system while maintaining its historical integrity.

The study has been conducted by 6 Cornell alumnus, including myself, and directed by Francis Vanek, PhD in Systems Engineering by the University of Pennsylvania, and Cornell Professor. In this document, I will only report my contribution to the project.

2. Project definition

This project will look for the most efficient way to energetically upgrade Llenroc’s building. After analyzing different technologies, the objective is to size and locate a geothermal heat pump and a solar array. Those two technologies combined should be enough to heat the house in the winter, cool it in the summer and give enough electricity to the building in a ecofriendly manner.

3. Methodology

The methodology followed to size the heat pump and the solar array effectively consisted in analyzing Llenroc’s historical energy usage. Then, the best locations for these technologies were determined so that the production of energy was optimized.

4. Results

There were three main results found in this project. Firstly, it was found that an 80 kW geothermal heat pump would be needed to meet Llenroc’s energetic needs. Half of the loops needed for the pump will be horizonal loops that will require trenches, while the other half will be vertical loops and will need wells, as shown in **Figure 1**.

Figure 2: Areas of trenches and wells for the heat pump in Llenroc's yard

The next thing discovered was that a 101 kW solar array would be enough to power the house and the heat pump with clean energy. Moreover, there would be an excess of production that would be sold to the grid. This would allow Llenroc to generate income every year. The array would be divided in two. Half of the panels will be located in the tennis court nearby, while the other half will be part of a solar canopy situated in Llenroc’s parking lot.

Thirdly, it was possible to predict Llenroc’s yearly energy usage. **Table 1** and **Figure 2** summarize this information quantitatively and qualitatively.

Table 1: 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

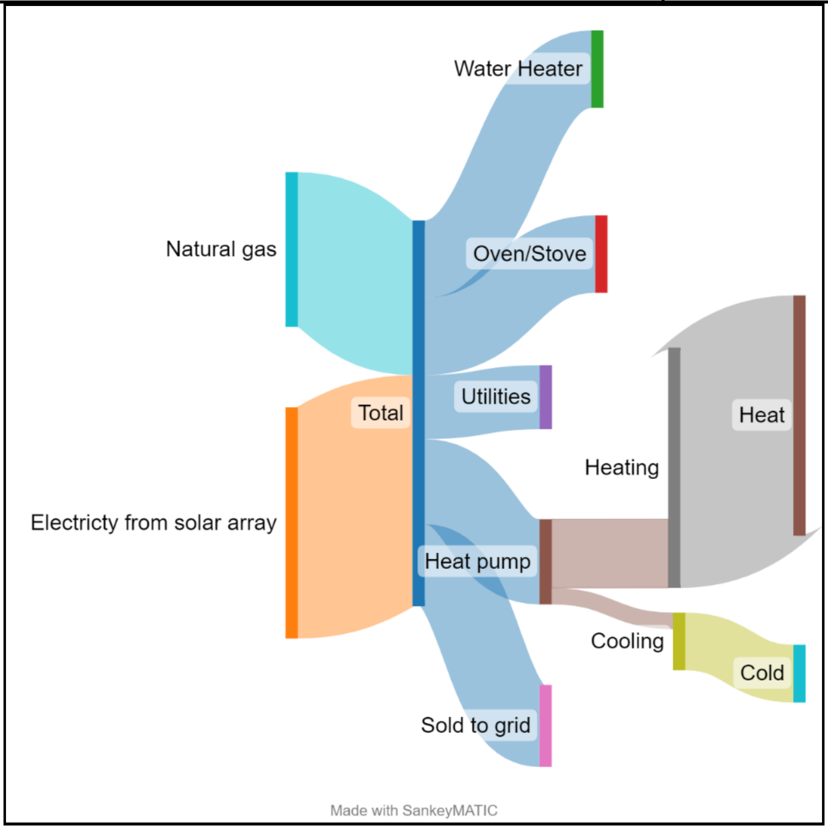

Figure 2: Sankey diagram of the proposed energy flows for the Llenroc House

Finally, the economic analysis concluded that an initial investment of $298,511 would be necessary to conduct the project. However, due to the low maintenance cost of the proposed technologies, Llenroc would be generating $1,577 of income every year during the 50 year lifetime of the system.

5. Conclusión

The aim of the Llenroc Project was to find a way to renew Llenroc's House so that it met Cornell's Climate Action plan. The solution given to the board of directors of the Delta Phi Fraternity consisted in replacing the gas boiler with an 80 kW heat pump and to install a 101 kW solar system, which would consist in a solar array and a solar canopy. This array would both power the house's electrical needs and the heat pump. Moreover, it was calculated that the electricity produced by the solar panels should be more than enough to cover Llenroc’s demand. Hence, the remanent could be sold for profit to the grid. Thanks to its technology, the geothermal heat pump will be able to heat the house during the winter and cool it during the summer. The possibility of cooling should make the house eligible for hosting summer events in the University, which would also provide Delta Phi with additional income.

Even if the project’s initial investment, estimated at $298,511, is elevated, it should end up paying off before its 50-year lifetime ends. As if that wasn’t enough, Llenroc’s CO2 emissions would decrease by 76%.

What was explained in this report, along with the contributions of the rest of team, was presented to the board of directors of Llenroc in May 2023. The project was a feasibility study, and it should provide Delta Phi with directions on how to continue with the renovation in the 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. However, those analyses were out of the scope of the study.

Memory index

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I am also deeply thankful to my esteemed professors, Francis M. Vanek at Cornell University and Mercedes Fernandez at ICAI. Their guidance, expertise, and unwavering belief in my abilities have been instrumental in shaping the direction of my project. Their mentorship and dedication to academic excellence have inspired me to push boundaries and strive for innovation.

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Figure 1: Llenroc House seen from the outside.

2. STATE OF THE ART

This section aims to cover two areas. Firstly, it intends to go through the current situation of the different players of the project: Cornell and Llenroc. Secondly, it aims to review the possible technological solutions available for the problems proposed by Llenroc.

Cornell's energetic situation

Since the launch of the Climate Action Plan in 2008, Cornell has already reduced its total CO2 emission by 54%, currently emitting 147,124 MT of CO2. However, the University is still far from achieving the goal it set for itself. As it was noted in the introduction, Cornell intends to be carbon neutral by 2035. Being carbon neutral means achieving a balance between the amount of CO_2 emitted into the atmosphere and the amount of CO_2 removed or offset from the atmosphere. Carbon neutrality can be attained by the following three strategies: improving energy efficiency, reducing emissions and offsetting carbon emissions.

In relation to this plan, a variety of green energy projects are being developed around the campus. Two of them are of special importance due to their relationship with what will be analyzed in Llenroc:

1) **Cornell Cubo**: the University drilled a 2-mile-deep hole to analyze if the heat from the Earth's core can be extracted and used for heating purposes.
2) **Vertical Closed-Loop Geothermal System**: this project will replace the current gas heating system of Cornell Day Care Center with a ground-source heat pump. There is a great resemblance between this program and the solution proposed to Llenroc.

Llenroc House

After one year unoccupied, Llenroc currently fits 19 Delta Phi members. The building is powered by electricity bought from the grid and heated by a gas boiler, which is run by natural gas. The Brotherhood is supplied by Nyseg, which is owned by Avangrid, property of the Spanish multinational Iberdrola. As of 2022, the average daily consumption billed by Nyseg reflected 200 kWh of electricity and 47 therms (4,958 MJ) of natural gas. As it stands now, Llenroc doesn’t have any kind of air conditioning to cool the house during the summer months. However, they have also asked for one, as it would serve two purposes. Firstly, it would improve the quality of living of the residents. Secondly, it would allow the Fraternity to rent the property for private events during the summer months in which the house is not occupied.

Llenroc’s property consists of one house with a parking lot and the land surrounding it. The house has a basement, which includes a crypt, and three floors, with a total space of around 9,000 square ft (836 m2). The third floor of the house doesn’t have natural gas radiators. Instead, it is heated with strip heater radiators. Also, the insulation of the house is poor, with old windows leaking cold air during the winter. That is why one part of the team focused on upgrading the efficiency of the building. Although I was not included in that task, I will comment on their results, as they are an important piece in the puzzle.

The area surrounding the house consists of mainly grass. The parking lot is situated on the East side of the property, while the majority of the land is in the North and West part. Moreover, there is a tennis court adjacent to the property. Even if the court belongs to Cornell now, it could be loaned to Llenroc if the space was needed.

Finally, Llenroc’s historical status means that any visual change in the property must be approved by the board of directors of the house and NY State, so that it complies with the regulation.

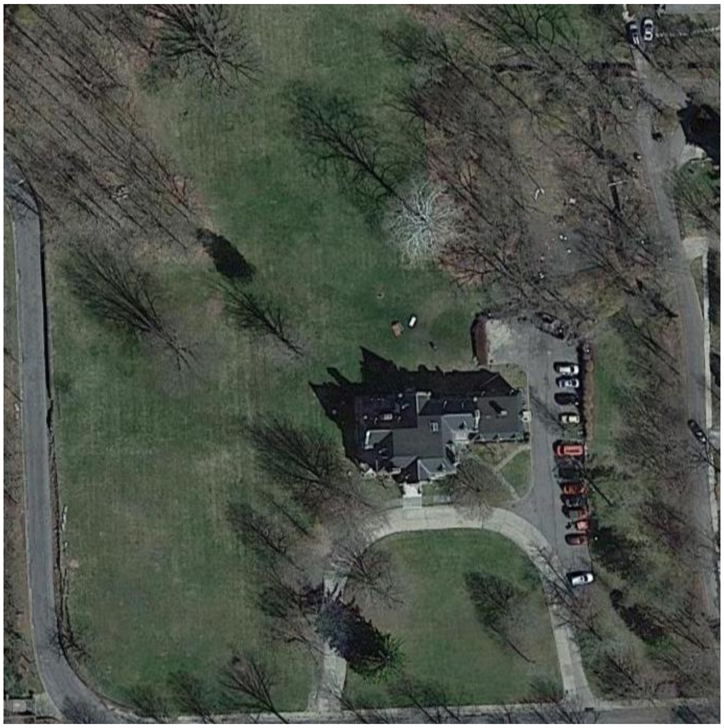


Figure 2: Llenroc House seen from the air

Possible solutions

Out of the major challenges proposed in the project, I focused on replacing the heating system and providing the building with green electricity. There are three technologies that can provide heating to a house without polluting CO2. All these three are being implemented all around the world nowadays. Let's look at them:

a) ELECTRIC HEATING WITH RESISTORS

This solution would be the simplest, as it would only require replacing all the radiators with electrically powered ones, like the house is already doing on the third floor. Electrical radiators work by converting electrical energy into heat energy by heating up a resistance.

However, this technology has a COP of 1. This means that for every unit of electricity that enters the system, the output is also one unit of heating. In other words:

1 kWh of electricity consumed = 1 kWh of heat as output

Given the large energy demand of Llenroc, this option is unviable, as it would require producing or buying an incredible amount of electricity, which would be too expensive.

Moreover, Llenroc is also looking to cool the house in the summer, something that would not be accomplished with this technology. For those reasons, electric heating was disregarded.

b) SOLAR HEATING

Solar heating technologies consist of using the sun’s energy to heat a house. It can be done in two different ways:

- **Active solar**: which consists of implementing solar collectors that capture energy from the sun and use it to heat a fluid in a water tank. This fluid can later be distributed throughout the house according to the needs of the owner to heat it. The solar collectors would have to be located in the roof of the house.
- **Passive solar**: this technology implies redesigning the building so that it maximizes the energy from the sun. Typical solutions related to solar heating usually include replacing walls with large crystal windows that let the sun come in or using materials that are more efficient to capture the heat. Overall, it would consist in redesigning the house so that it reaches its maximum efficiency.

Both solutions would require major aesthetic changes in Llenroc. Passive solar demands for a large redesign, while active would alter the roof. Because of this, neither of them can be taken into consideration, as they would never meet regulation codes for Historic houses. Nevertheless, less-aggressive energy improvements, such as substituting the windows will be considered in the project.

c) HEAT PUMPS

With the impossibility of implementing electric radiators and solar heating, we arrive at the third option, heat pumps. This will be the technology used to solve the problem, which is why I have conducted an extensive market analysis that could show the state of the art of this technology.

Heat pumps have been used as a renewable energy solution for several decades. 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. The first and third will be analyzed later.

How do geothermal heat pumps work?

Heat pumps can be used for both heating and cooling purposes, which is one of their main advantages. They are based on the second law of thermodynamics: heat moves from a warmer to a cooler item. Hence, the main idea of heat pumps is to transfer heat from one location to another using a refrigeration circle. Because they use electricity to move heat rather than generate it, their COP is between 3 and 5, which makes them one of the most energy-efficient systems available today.

Geothermal (or ground-source) heat pumps take advantage of the earth's relatively stable temperature beneath the surface. They either take or deposit energy from the ground, which makes it a renewable energy source, as the surface's heat is endless and is constantly being renewed. The first challenge, then, is how to extract this heat from the earth. In a ground-source heat pump, this is done with a loop system. There are two types of systems:

1) **Open loop systems.** They 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.

   Llenroc doesn't have close access to water, which is why this option is not viable for the project.
2) **Closed loop systems.** They circulate an antifreeze solution through a closed loop of tubes that must be buried underground. An antifreeze solution is made of water with chemicals that lower its freezing temperature. Unlike open loop systems, in this case the solution that runs through the loops is always the same. Depending on the arrangement of the loops, two types of closed-loop systems prevail:
   a) **Horizontal loops.** In this array, the pipes are placed horizontally. Therefore,

they require a larger amount 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, as it is not needed to drill deep into the earth. This 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 3** shows how, the deeper the loops are installed, the more stable ground temperature is.

b) **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 with 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.

With the natural resources available, the idea is to implement horizontal trenching in the Llenroc House, if it is possible.

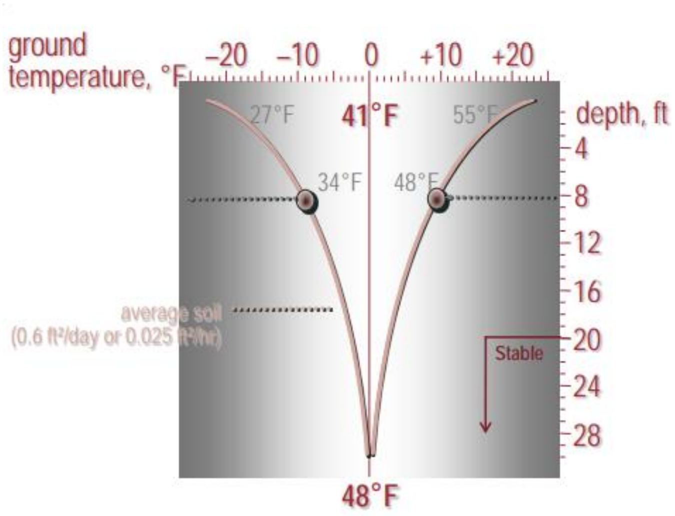


Figure 3:Ground temperature swing depending on depth (Sakry, 2012)

Once the heat is extracted or deposited into the earth, the next step comes in. This step takes place into the heat pump itself, which is connected to the loop system. A heat pump is a machine made of a compressor, a reversing valve, an evaporator, a condenser, and an expansion valve. Tubes filled with a refrigerant run through these elements. In heating mode, cool antifreeze solution coming out of the evaporator absorbs heat from the ground in the ground loops and the following process takes place:

1) This warm water circulates into the heat pump's evaporator again, where it exchanges heat with the refrigerant, warming it and causing it to boil and turn into vapor. As will be explained in the **Refrigerant** section later, refrigerants have very low boiling points.
2) Next, the refrigerant goes into the compressor, leaving it as a high-pressure, high-temperature vapor. The compressor functions with electricity.
3) From there, the refrigerant heads into the condenser, where it exchanges its heat with the cold liquid that runs through the radiators of the house, making it warmer and ready to heat the house. As heat is removed, the refrigerant condenses into a liquid, leaving the condenser as a high-pressure, not-so-high-temperature liquid.
4) After that, the refrigerant comes to the expansion valve, where it is expanded in volume. Hence, a low-pressure, even cooler liquid reaches the evaporator again, where the process is back at point one.

It is important to understand that the refrigerant and the antifreeze solution never come in contact with each other, they just exchange heat between themselves. **Figure 4** helps understand the process, as it shows a heat pump in heating mode.

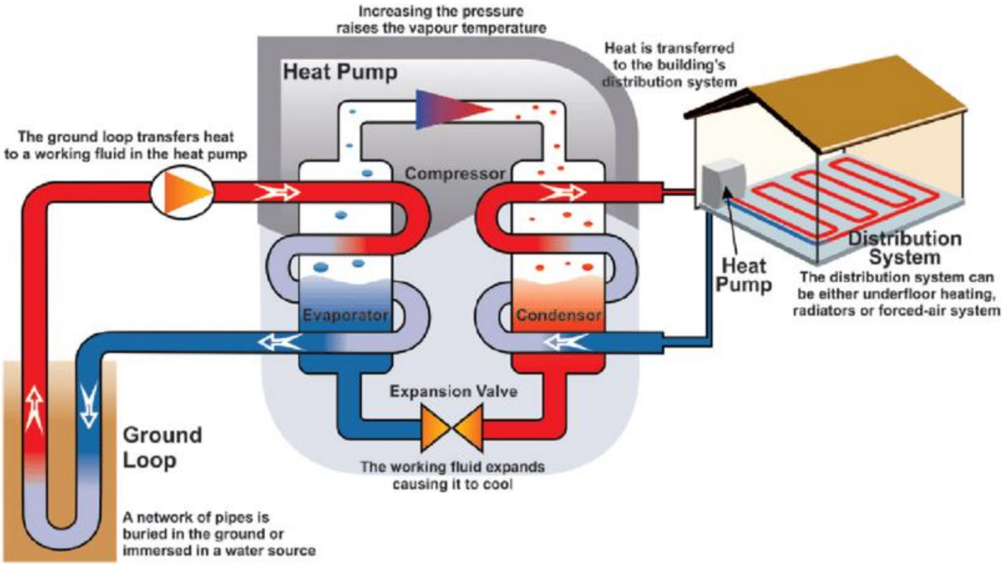


Figure 4: Schematic of a heat pump

In cooling mode, the opposite process occurs. Warm air from the building is brought into the heat pump. The warm air is then absorbed by the refrigerant (which is in liquid state) in the evaporator, causing it to boil and turn into a gas. This would be point 1 in **Figure 4**. The gas goes into the compressor, where it is turned into a high-pressure, high-temperature superheated vapor. Next, the refrigerant circulates through the system and it exchanges heat with the cooler antifreeze solution from the ground loop in the evaporator, causing the refrigerant to turn into liquid and lower its temperature. Moreover, the heat that came from the house is rejected to the cooler ground thanks to the loops. The liquid refrigerant is now ready to be expanded in the expansion valve, where it comes out as a low-pressure, low-temperature liquid. Now, it exchanges heat with the warm solution coming from the house, causing it to cool and be ready to cool the whole house. The process is then back at the starting point. **Figure 5** shows the entropy diagram of the cooling process that takes place in a heat pump. The same diagram applies for the heating cycle but working backwards.

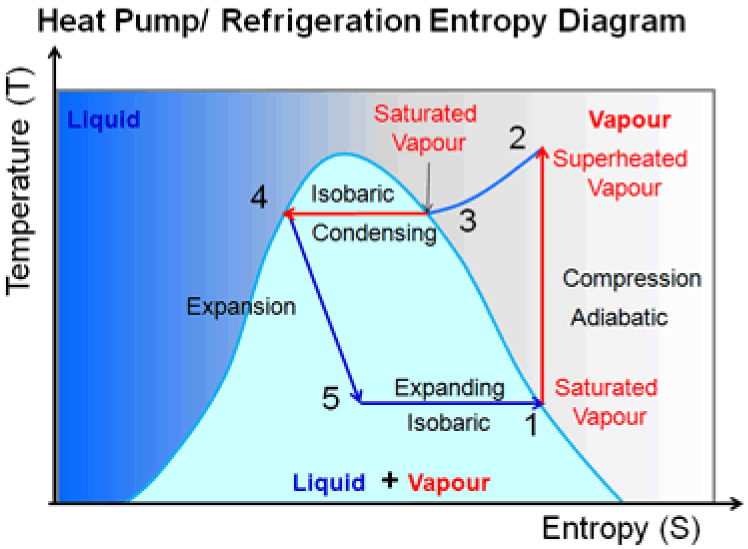


Figure 5: Heat pump refrigeration entropy diagram

Unlike gas boilers, who create heat by burning a gas, heat pumps only move the heat from one place to another. By doing so, they don't emit gases into the atmosphere. They do use electricity, mainly to power to compressor. The generation of electricity can also be a cause of pollution if it is not renewably generated, which is why the electricity that powers the house and the pump will have to be green.

Heat pump market

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. In fact, as **Figure 6** 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) The 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, 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.

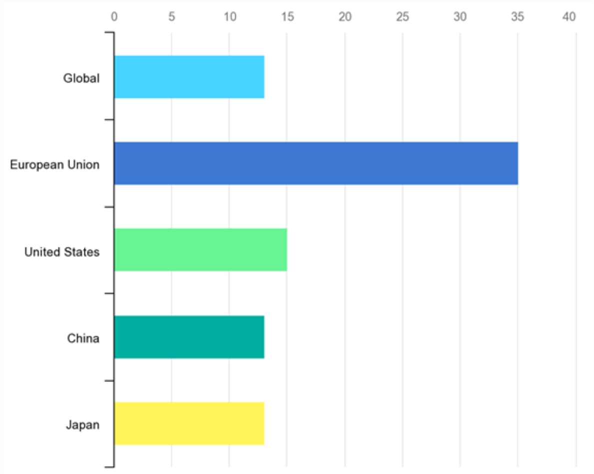


Figure 6: Increase in heat pump sales (2020-21)

Currently, the heat pump market is valued at $79.9B. Air-source represents 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

As was mentioned earlier, there are three main types of heat pumps: air-source, water-source, and ground-source. In this study, we focus on ground source heat pumps instead of air or water source. This is 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 and these would violate the appearance of Llenroc as a historical building, and thus not be 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 are also noisy while running in defrost mode. Geothermal heat pumps save more energy (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 because they require excavation and drilling (the site needs to be suitable for drilling). There is also a risk of groundwater contamination during the drilling and excavation process, although this can be mitigated by following proper procedures and regulations.

Moreover, air-source heat pumps are visually disruptive because they need to have a heat exchanger outside of the building. Then, they are not suitable for Llenroc. Meanwhile, geothermal heat pumps extract the heat from loops installed in the ground through trenches or dwells, which means there is no visual impact. Because of that, the proposed technology for this project will be a ground-source heat pump.

3. PROJECT MOTIVATION

The motivation of the project is to offer Llenroc a carbon neutral solution for their house. Following Llenroc's advice and requirements, the project will focus on the feasibility of installing a geothermal heat pump to heat and cool the house, as well as a solar array to meet the building's electric demand. The projected outcome of the report should be a clear guideline of what size they should be and why to install these technologies, together with an economic analysis that supports their utilization.

4. PROJECT GOALS

Given my personal knowledge and situation inside the group I worked with, the needs of Llenroc and Cornell's policies, the objectives of this project are the following:

1. Design a system that is capable of both heating and cooling the house. This is the main goal of the project. It will be crucial to consider Ithaca's geography and climate, as the winters are cold and long. In the past ten years, there are records of temperatures reaching -32ºC. We can't forget that this is a real project in which the customers are college students. Their comfort and satisfaction with the proposed solution is the number one priority of the study.
2. 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. The combination of these renewable energies and technologies was the chosen solution to tackle Llenroc's requirements. Therefore, I hope to fully understand their correct functioning and maintenance. This project intends to size the systems correctly in order to provide the most cost-effective renewable solution. To do that, it is necessary to comprehend how geothermal and solar energy can be combined and optimized.
3. Execute the 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). As mentioned earlier, this project is done not only under the belief that renewable energy is better for the environment, but also thinking that it is a cheaper solution in the long term. Hence, I hope to explore all the viable options and prove that the chosen one was the ideal for the house. Furthermore, it is within the scope of the report to provide Llenroc with organized deliverables that are useful and can have tangible benefits, as well as to produce clear "next steps" for Llenroc's management team after the conclusion of the project.
4. I 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. The project has two major constraints: Cornell's 2035 Carbon Neutral Plan and Llenroc's Historic Building condition. Regarding the first one, as Cornell thrives into a green future, this project hopes to set an example on how to transition to cleaner energies. Moreover, it wishes to help discover geothermal energy to those that were not aware of it. About the historic condition, I intend to preserve Llenroc's beautiful image untouched. The visual impact of the technology implemented aims to be the minimum possible.

5. Finally, throughout this project, I have and will continue to interact with experienced professionals. I hope to learn from them, ask questions to help grow my intuition, and interact professionally with them.

5. SCOPE AND ASSUMPTIONS

Throughout this project, the team was 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. Assumptions made for the research and calculations are outlined below.

Llenroc Building

1. The design of the technology was for thirty residents (compared to the 19 at Llenroc in 2022).
2. The design looked at a time horizon of 50 years and interest rate of 6%.
3. It was assumed that the Llenroc basement has enough physical space to install all of the proposed machinery.
4. The abandoned tennis court area near Llenroc is technically Cornell's property (rather than Llenroc's), but it was assumed that Cornell would sell or rent the land to Llenroc for solar array space.

Solar PV and Battery System

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

Out of the Project's Scope

1. Replacing the natural gas used by the water heater and the cooking with a renewable source of energy was not considered.
2. All modifications on the property would need to be approved by Llenroc's Historical Building association.
3. A geotechnical study was not available, so it was assumed that installing trenches and drilling wells for the heat pump was feasible.

4. 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.
5. The main benefits and drawbacks of different refrigerants were discussed, but none in particular was chosen. Choosing what refrigerant would be a decision made further along in the engineering design process rather than in this feasibility study.
6. Only the 30% IRA tax credit was considered in the financial model. The other credits and subsidies were left out because their ability to apply to this project is much more convoluted.

6. 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.

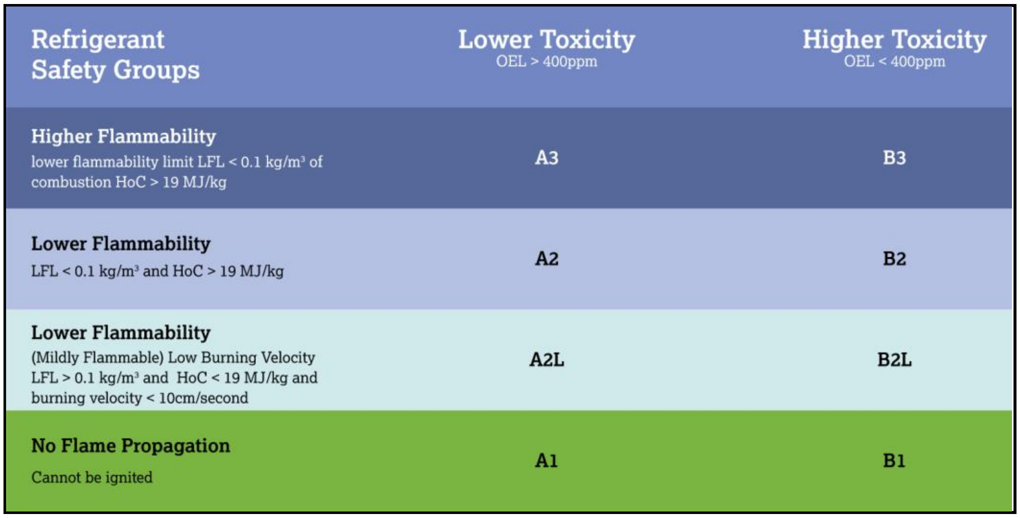
This can be done thanks to their low boiling temperature and by manipulating their pressure and temperature inside the heat pump.

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 7** shows the different classification they can be attributed based on safety:

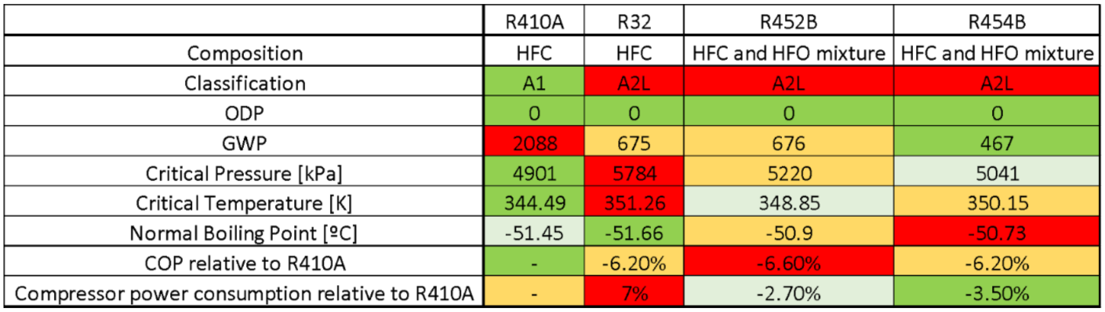


Refrigerant Safety Groups	Lower Toxicity OEL > 400ppm	Higher Toxicity OEL < 400ppm
Higher Flammability lower flammability limit LFL < 0.1 kg/m^3 of combustion HoC > 19 MJ/kg	A3	B3
Lower Flammability LFL < 0.1 kg/m^3 and HoC > 19 MJ/kg	A2	B2
Lower Flammability (Mildly Flammable) Low Burning Velocity LFL > 0.1 kg/m^3 and HoC < 19 MJ/kg and burning velocity < 10cm/second	A2L	B2L
No Flame Propagation Cannot be ignited	A1	B1

Figure 7: 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 R454 refrigerants

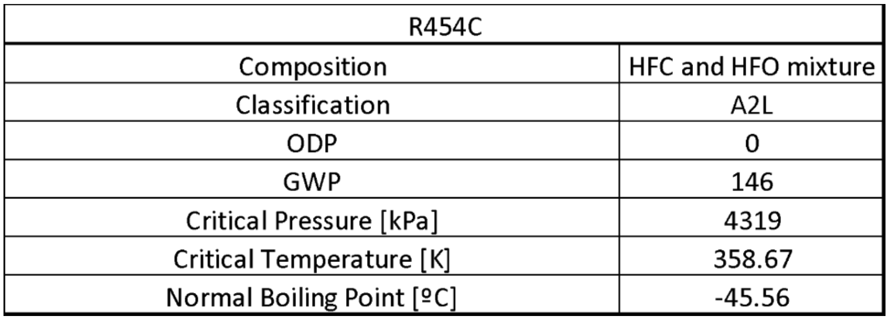


	R410A	R32	R452B	R454B
Composition	HFC	HFC	HFC and HFO mixture	HFC and HFO mixture
Classification	A1	A2L	A2L	A2L
ODP	0	0	0	0
GWP	2088	675	676	467
Critical Pressure [kPa]	4901	5784	5220	5041
Critical Temperature [K]	344.49	351.26	348.85	350.15
Normal Boiling Point [ºC]	-51.45	-51.66	-50.9	-50.73
COP relative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

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 suggested 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.

7. METHODOLOGY

The method used to estimate the size of the heat pump 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 Llenroc's 2022 NYSEG invoice. Note that NYSEG electricity billing is on a 2-month basis. Subsequently, considerations 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. As was found by other members of the team, 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.

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 8**. 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 8** 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:

$$Boiler\ average\ output\ (December) = \frac{41{,}390\ kWh}{1\ month} * \frac{1\ month}{31\ days} * \frac{1\ day}{24\ hours} = 62\ kW$$

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 8**. 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.

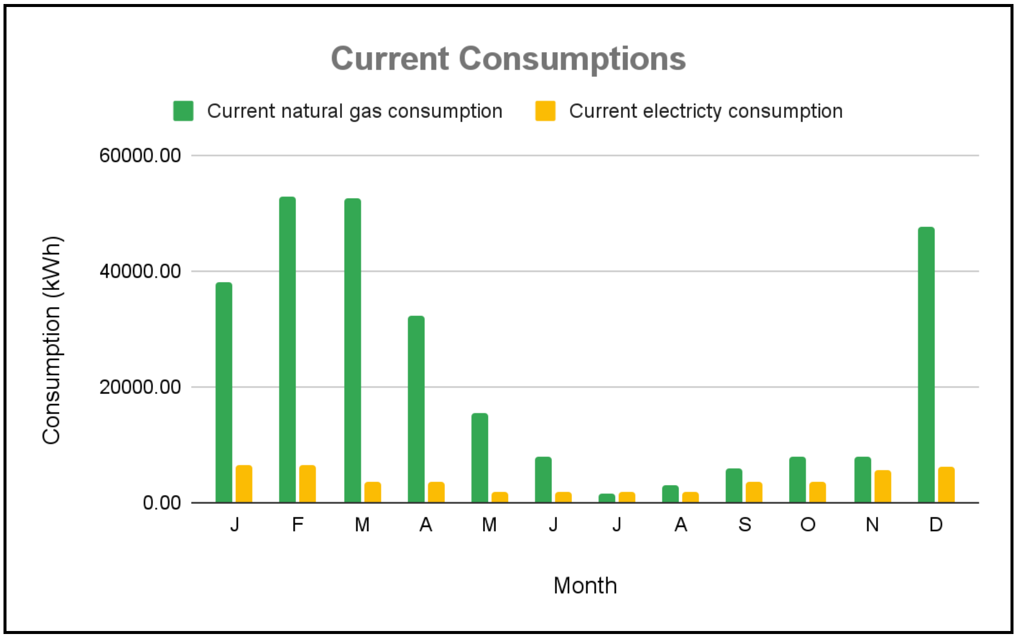


Figure 8: Current natural gas and electricity consumption per month

- **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 9** shows how much electricity is allocated per month to the radiators. The total kWh values are the same as in **Figure 8**, 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.

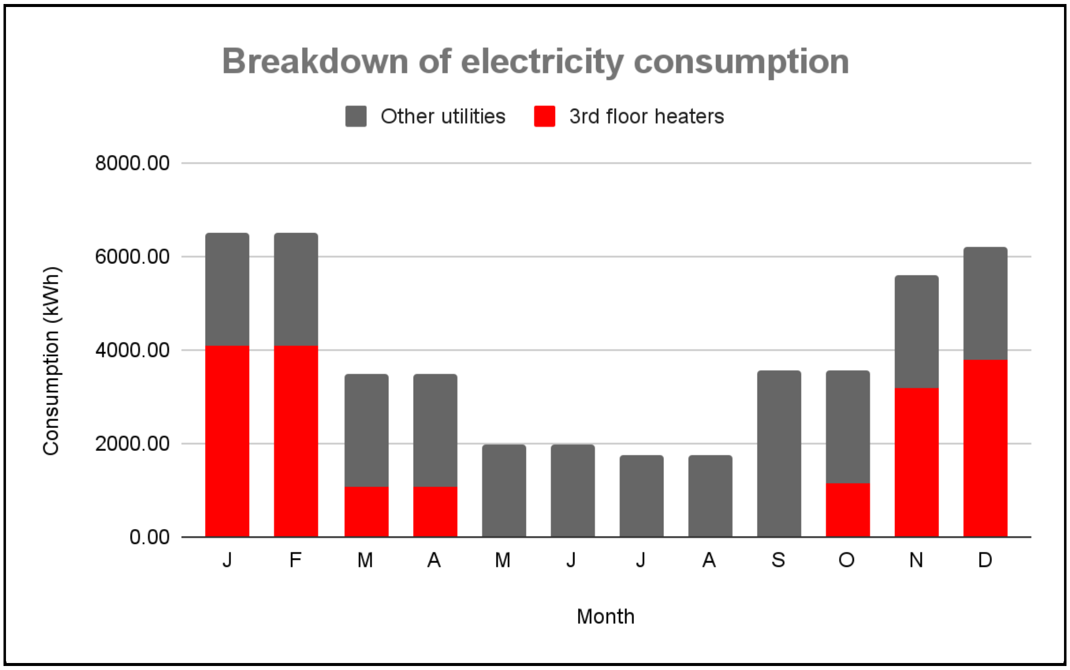


Figure 9: Breakdown of electricity consumption per month

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 10** shows the electric consumption over a year of four different buildings: three of them are fraternity houses, while the fourth 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.

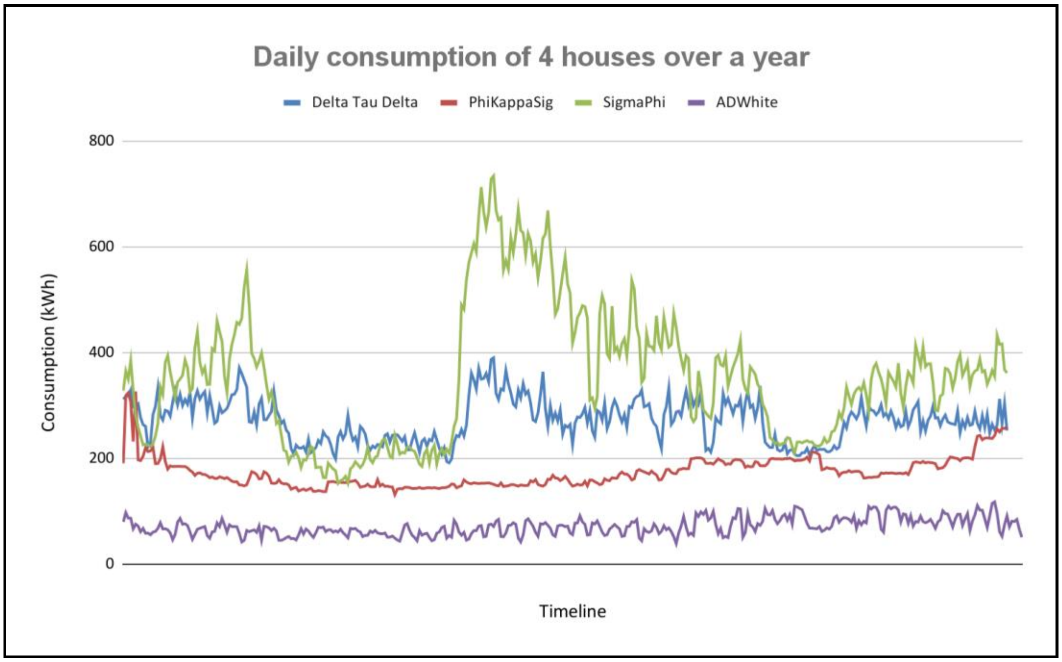


Figure 10: Daily consumption of 4 similar buildings

Figure 11 illustrates Sigma Phi's monthly electricity consumption. The dotted line represents the average consumption. It seemed clear 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:

$$Maximum\ cooling\ load\ needed = (Highest\ consumption\ in\ one\ day - Average\ consumption) * 30\ days$$

It wasn't necessary 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, scaling it for the cooling season (mid-May to the end of September) was the next step. As Llenroc intends to host events during June and July, using data from Sigma Phi would not be accurate. It was assumed that 11,990.74 kWh would be the highest monthly consumption and, from there, it was scaled according to the calculations done by other members of the team. **Appendix A** shows a column with the estimated cooling load needed according to that method. 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 by the other members of the team.
3) The final estimation of the cooling load per month can be seen in the cooling column in **Appendix A**.

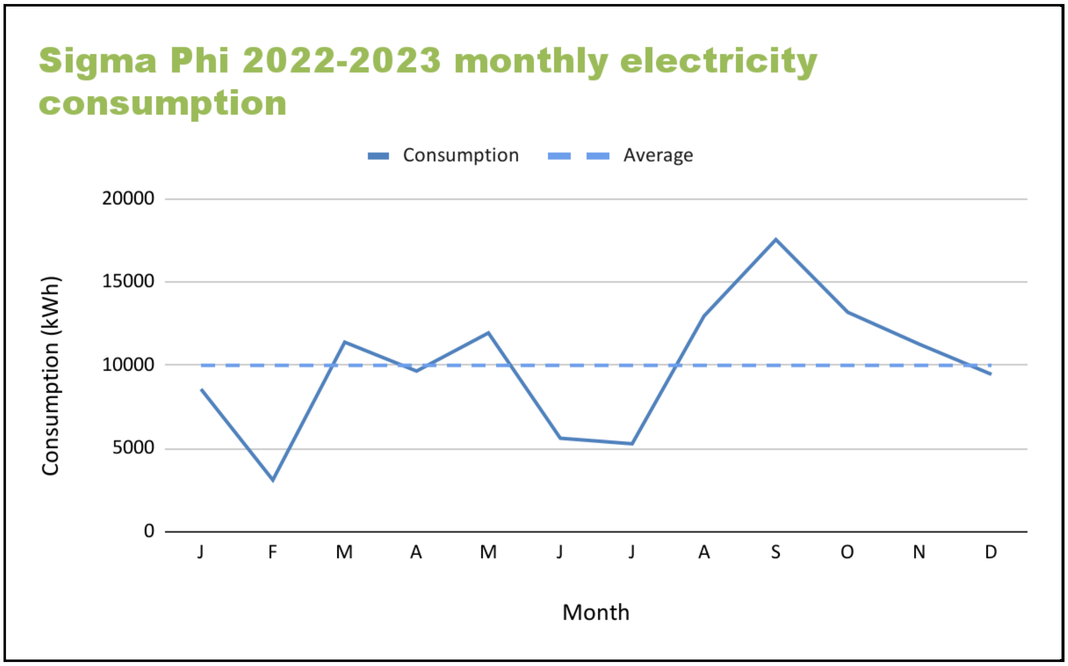


Figure 11: Sigma Phi Monthly Electricity Consumption

Finally, a yearly cooling load of 25,123 kWh was reached, 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.

Future Estimated Energy Outputs

Once the current energy distribution of the house had been modeled, it was necessary 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 B** and will be explained in this section.

- **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:

  $$Heat\ pump\ output = \ (Energy\ used\ for\ heating\ with\ natural\ gas * Boiler\ efficiency * 1.2\ loss\ factor + Energy\ used\ by\ strip\ heater + Energy\ needed\ for\ cooling) * Efficiency\ improvement\ factor$$

  The efficiency improvement factor is the one calculated by other members of the team. 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, it was 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:

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

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 was rounded to 80 kW. This is very similar to the number that was found by other colleagues who followed another method (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 12** 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.

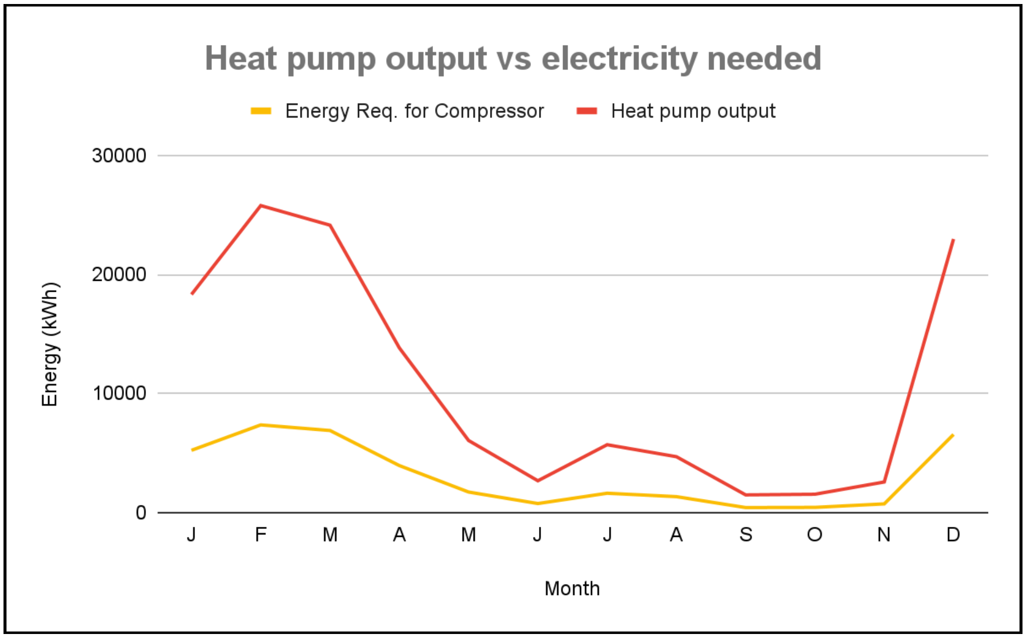


Figure 12: Energy input vs Energy output for the heat pump

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

$$Future\ electrical\ needs = Current\ electricty\ conusmption - Electricity\ needed\ for\ strip\ heaters + Electricty\ required\ for\ heat\ pump$$

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 13 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.

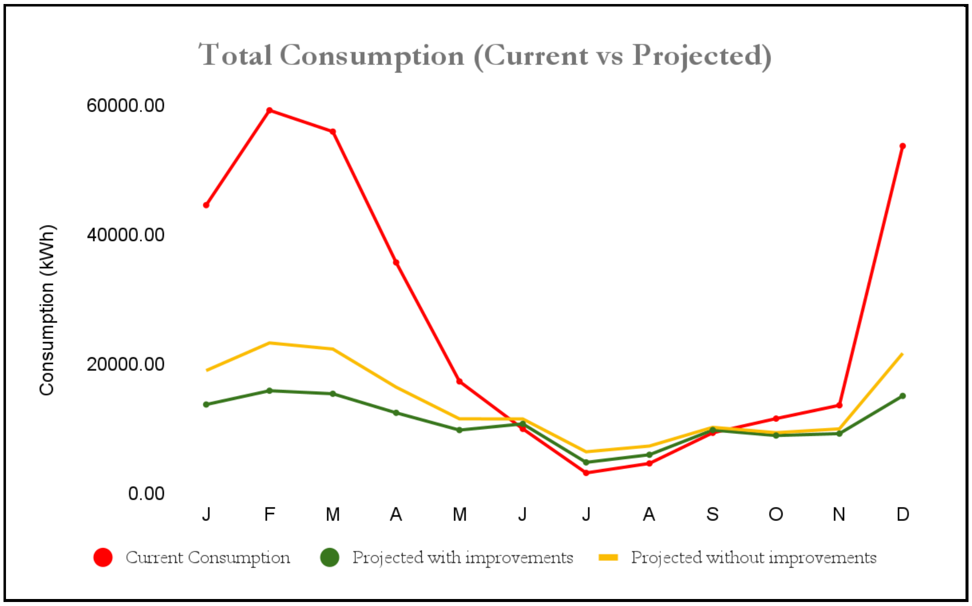


Figure 13: Total energy consumption comparison

Finally, **Figure 14** 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.

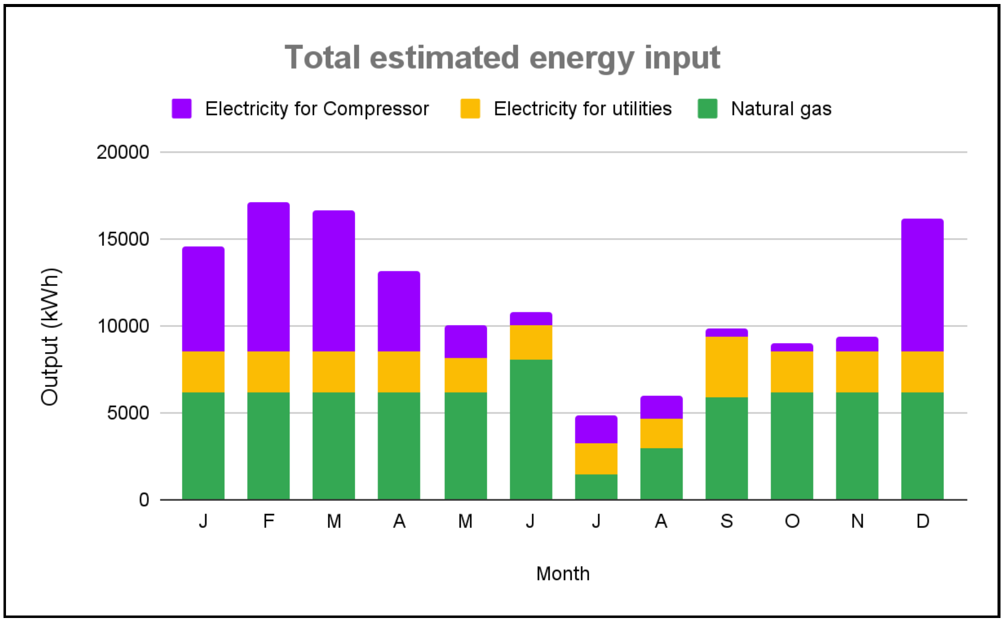


Figure 14: Future energy needs given improvements

The last two columns in the table in **Appendix B** were calculated to analyze the viability of installing Tesla Power Walls (other members decided that it was not feasible) 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, the hourly electricity consumption of the four buildings shown in **Figure 10** was analyzed and it was observed that 50.23% of the total would be consumed at night.

8. DISCUSSION

In the past section, it was found that the heat pump size needed to heat and cool the house was 80 kW. This section will discuss the required space and measurements for the heat pump's loops, as well as the installation of the solar array that will power the pump and the electricity for the whole house.

Trenches and wells areas

The **State of the Art** section showed how the loops required for a geothermal heat pump could be horizontal or vertical. The horizontal arrangement is preferable since it only requires trenches. However, it also occupies more space. There are two areas available for drilling inside Llenroc's property: the slopes facing west and south. Their areas are 2,180 m^2 and 620 m^{2,} respectively.

Other members of the team determined that the only feasible system consisted in implementing trenches on the west slope and wells in the south one, as shown in **Figure 15**.

Figure 15: Areas of trenches and wells for heat pump in Llenroc's yard

Solar PV system

In the planning of the photovoltaic (PV) system for the project, two areas were taken into consideration. The current tennis court and the installation of a solar canopy over the parking area to the east of the house, shown in **Figure 17**.

Given the available space, it was found that total capacity of the solar PV system needed for Llenroc with efficiency improvements was 104 kW. Calculations will be explained in detail in this section.

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 m^2. A 25% increase in space due to renovations consisting in removing trees and vegetation surrounding the court and leveling the surface was assumed. Based on a Jinko panel size and the required spacing between rows, 96 panels fit this area, 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, as can be seen in the equation below, 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:

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

The software PVWatts showed that the total output of this array in one year would be 59,000 kWh. It was 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). **Figure**

16 shows how the array would look like.

Figure 16: Visual impact of the solar array suggested for the tennis court.

The Solar Canopy

In addition to the solar array, a second 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 it would be 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.

Total production

Both arrays combined would produce around 100,000 kWh per year. Monthly production can be seen in **Appendix C**.

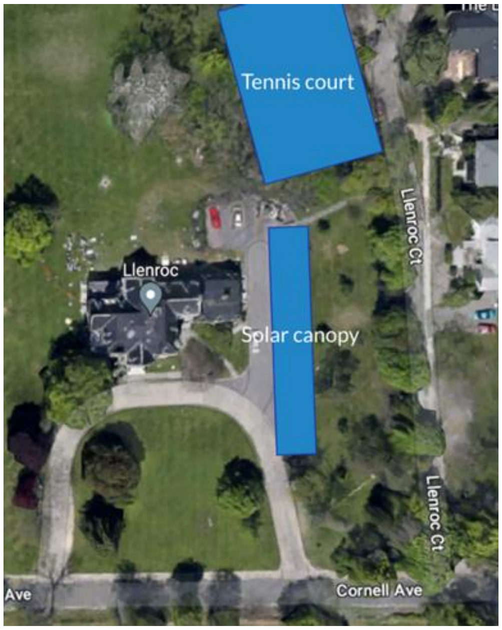


Figure 17: Placement of the solar arrays

Local grid

The table in **Appendix C** shows that the electricity generated by the solar panels exceeds the electricity needed by the house. Even if the cooler months like January or February produce less electricity than they consume, the yearly total is positive. 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. Other members of the team used the analysis provided in the **Discussion** section to prove that it was not necessary to purchase a battery system. Instead, it would be better to sell the remanent production during the summer months to the grid in exchange for credit. Those credits could be used either to purchase electricity when the output from the arrays is not enough or to generate income for the house. This would involve joining a net metering program. 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. There is a $0.72/kW array fee that must be paid per month to join the program. In Llenroc's case, as the system would have 101 kW of power, the monthly fee would add up to $73.

Summary

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

Table 3: 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.

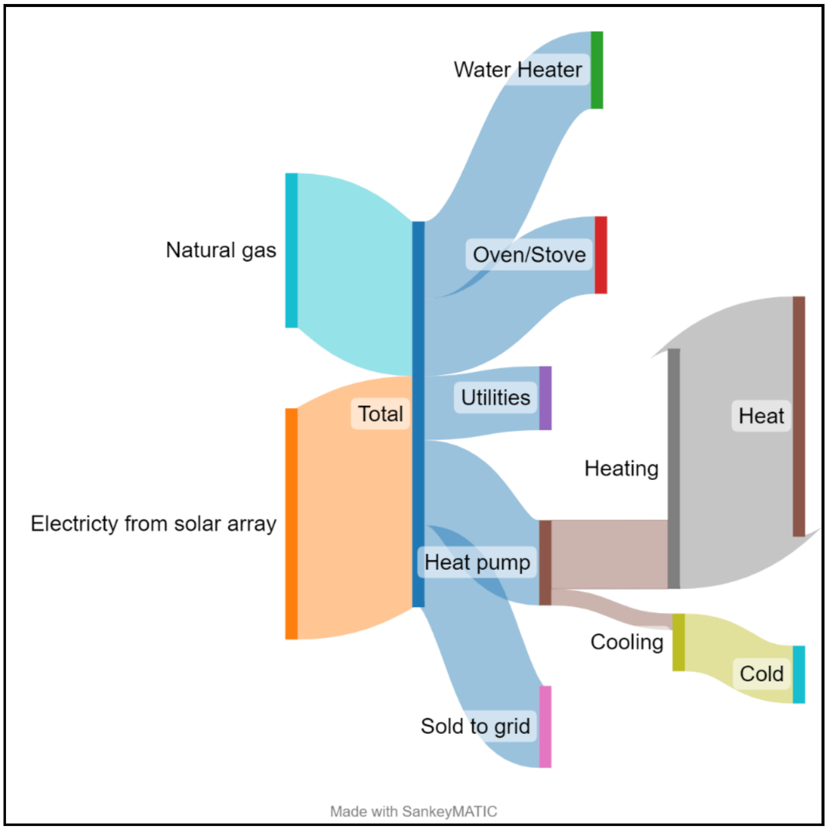


Figure 18: Sankey diagram of the proposed energy flows for the Llenroc House

9. ECONOMIC ANALYSIS

Llenroc management didn’t specify a budget for the project, as long as it yielded benefit in the long term and the objectives were met. Therefore, it was necessary to conduct an economic analysis that was presented to the Fraternity. Note that the analysis considers some costs that weren’t mentioned in this report, as they were discussed by other members of the team. The analysis took into account:

1) **Initial costs**. Costs that would be incurred at the beginning of the process. The prices were estimated after calling companies and doing research. Further detail about each cost and the useful life of each item can be seen in the **Appendix D**. The items considered the following, as **Table 4** shows:
    a) Heat pump and everything related with it, such as the trench system, its installation, labor, piping inside the house, etc.
    b) Solar array and solar canopy.
    c) Efficiency upgrades.

Table 4: Initial costs

Item	Cost
Heat pump system	$146,955
Solar system	$117,389
Efficiency upgrades	$31,168

2) **Annual costs.** Costs in which Llenroc would incur annually:
    a) The heat pump’s operation and maintenance.
    b) The solar system’s operation and maintenance.
    c) Net metering program. As Llenroc is projected to generate more electricity than it will consume, this should be a benefit, not a cost. The average price at which the grid pays for the electricity was estimated to be $0.23/kwh.
    d) Natural gas. The same prices from the **Current Natural Gas and Electricity**

Consumption were used.

Table 5 displays the annual costs:

Table 5: Annual maintenance costs

Item	Cost
Heat pump maintenance	$2,210
Solar system maintenance	$2,000
Natural gas cost	$1,512

The total reimbursement obtained from the net metering was calculated as **Table 6** shows:

Table 6: Total reimbursement from net metering every year

Net metering item	Data
Electricity cost	0.23 $/kWh
Solar system production	100,644 kWh
Llenroc’s demand	64,957 kWh
Annual net metering fee	$873
Total benefit	$7,300

With this information, a multiyear model with a 50-year time horizon was conducted. The discount rate chosen was 6% and tax credit benefits were applied were possible, as Llenroc might be able to qualify for them.

Moreover, the Levelized Cost of Electricity (LCOE) was calculated. 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:

$$LCOE = \frac{Total\ costs\ over\ lifetime\ of\ the\ system}{Total\ output\ over\ lifetime\ of\ the\ system}$$

In our case, the team 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 during the 50 years lifetime. 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.

All these considerations gave birth to **Table 7**:

Table 7: Multi-year model

6 % discount rate in a 50-year lifetime	
Total initial investment	($298,511)
Total annual maintenance costs	($5,722)
Net metering reimbursement	$7,300
Net annual cost after the first year	$1,577
Lifetime present worth sum	($260,371)
Lifetime energy production	11,519,700 kWh
LCOE	$0.0226/kWh

Comments about the analysis

Some observations can be made about the economic analysis:

1) With all the recommended improvements, Llenroc’s net annual cash flows for these improvements would be positive. Because of the low maintenance costs of the heat pump and the solar array, as well as the reimbursement from the extra production of electricity, the fraternity will be making money every year after the initial investment. **Table 7** shows how the net difference between costs and income will be $1,577.
2) The initial investment is high. We are aware that $298,511 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 was found

by another member of the team the lifetime present worth sum associated with not implementing the green upgrades would be $450,959, which is considerably higher. Therefore, the investment will end up paying off.

3) The average LCOE for solar energy is $24/MWh. As the calculations include the natural gas and the energy from the heat pump, the value for Llenroc is lower. This is coherent, as natural gas prices are cheaper and tax credits were included.
4) All these costs are estimates. They are meant to provide an idea of the costs that Llenroc would be incurring with these upgrades.

10. ENVIRONMENTAL IMPACT

In 2015, the United Nations published the 2030 Agenda for Sustainable Development. At the core of this agenda are the 17 Sustainable Development Goals (link), which encompass global priorities for progress and well-being. Two of those goals are of special importance in this project:

Goal 11: Sustainable cities and communities.

The aim of this objective is to promote inclusivity, safety, resilience, and sustainability in cities and human settlements. The Llenroc project focused on the sustainable side of the goal. By transitioning from buying electricity from the grid and obtaining heat from a natural gas boiler to installing solar energy and a heat pump, Llenroc's sustainability will increase. In fact, the only CO_2 emissions coming out of the house in the near future will be those coming from the water heater and the kitchen, as both of them will continue to function with natural gas. However, replacing the water boiler and the oven once their useful life comes to an end is strongly suggested.

Goal 13: Climate action

This goal encourages individuals to actively address climate change and its consequences. This project will help tackle this issue in many ways. Firstly, the emissions of CO_2, which is a greenhouse gas that contributes to global warming, will be cut to almost zero. This will be thanks to the solar panels and the heat pump, as they are both renewable sources of energy. Moreover, the **Refrigerants** section recommended using the refrigerants that have the least Global Warming Potential. It would not make sense to install a heat pump if the liquid running through it was harmful for the environment.

From 2022's NYSEG invoice, it was noted that 272,842 kWh of natural gas were used in the whole year, while the electricity usage came to a total of 46,344 kWh. The CO_2 produced when burning natural gas is 0.185 kg/kWh. For electricity, the factor used is 0.371 kg/kWh. Therefore, the total CO_2 emitted by Llenroc in 2022 was about 68,000 kg.

After the proposed improvements, natural gas consumption per year would be reduced to 67,390 kWh and the solar panels would produce up to 101,000 kWh. The estimated carbon footprint of solar panels is 0.041 kg/kwh. As the natural gas factor doesn't change, the resultant carbon footprint for Llenroc would be 16,600 kg, which is only 24% of what is being polluted right now. **Figure 19** helps understand this improvement.

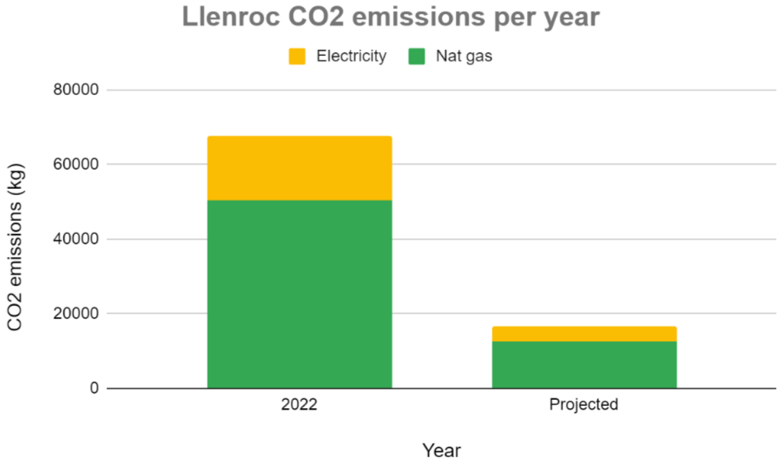


Figure 19: Annual carbon emissions before and after the proposed solutions

11. CONCLUSION

The aim of the Llenroc Project was to find a way to renew Llenroc's House so that it met Cornell's Climate Action plan. The solution given to the board of directors of the Delta Phi Fraternity consisted in replacing the gas boiler with an 80 kW heat pump and to install a 101 kW solar system, which would consist in a solar array and a solar canopy. This array would both power the house's electrical needs and the heat pump. Moreover, it was calculated that the electricity produced by the solar panels should be more than enough to cover Llenroc's demand. Hence, the remanent could be sold for profit to the grid. Thanks to its technology, the geothermal heat pump will be able to heat the house during the winter and cool it during the summer. The possibility of cooling should make the house eligible for hosting summer events in the University, which would also provide Delta Phi with additional income.

Even if the project's initial investment, estimated at $298,511, is elevated, it should end up paying off before its 50-year lifetime ends. As if that wasn't enough, Llenroc's CO_2 emissions would decrease by 76%.

What was explained in this report, along with the contributions of the rest of team, was presented to the board of directors of Llenroc in May 2023. The project was a feasibility study, and it should provide Delta Phi with directions on how to continue with the renovation in the 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. However, those analyses were out of the scope of the study.

Finally, the study also explored heat pump technology, a renewable energy source that is expected to grow in the future. 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.

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13. 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

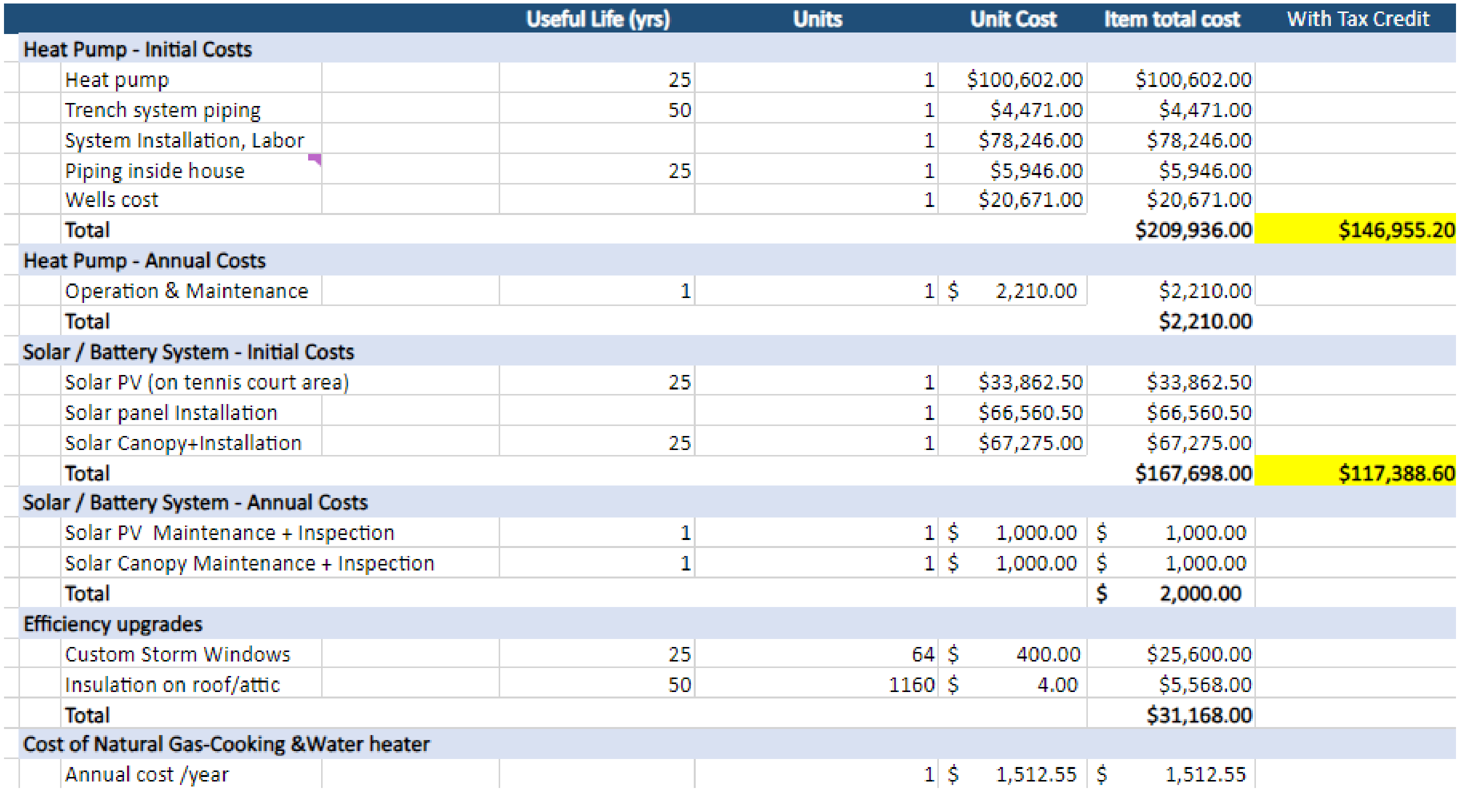
Appendix B: Table of future consumption and outputs with efficiency improvements

Month	Heat pump output (w efficiency improvements)	Electricity required for the heat pump	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	129,749.74	37071.36	64957.69	178.89	89.86

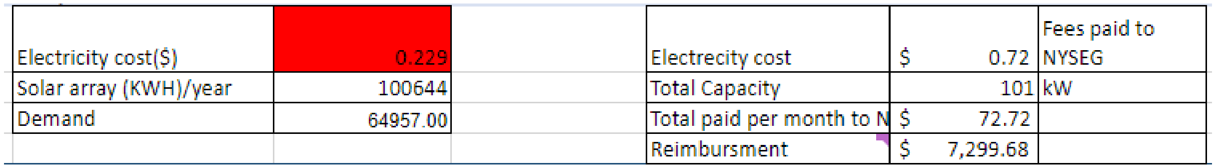
Appendix C: Evaluation of amount of energy that could be bought or sold each month

Month	Output from 52.32 kWh solar array	Output from solar canopy (facing east)	Output - E. Req.	Extra electricity every day	Sell/buy
	(kWh)	(kWh)	(kWh)	(kWh/day)	(kWh/month)
January	3,474	1683	-2,490	-80.33	-2,490
February	4,425	2409	-2,944	-105.15	-2,944
March	5,637	3641	-30	-0.96	-30
April	5,773	4357	3,764	125.46	3,764
May	5,751	4940	6,993	225.58	6,993
June	5,708	5381	8,356	278.54	8,356
July	5,964	5078	7,663	247.19	7,663
August	5,755	4509	7,173	231.37	7,173
September	5,921	3921	5,867	195.55	5,867
October	4,525	2702	4,371	140.99	4,371
November	3,455	1618	1,923	64.11	1,923
December	2,756	1262	-4,959	-159.96	-4,959
TOTAL/AVERAGE	59,143	41501	35,686	1162.40	35,686

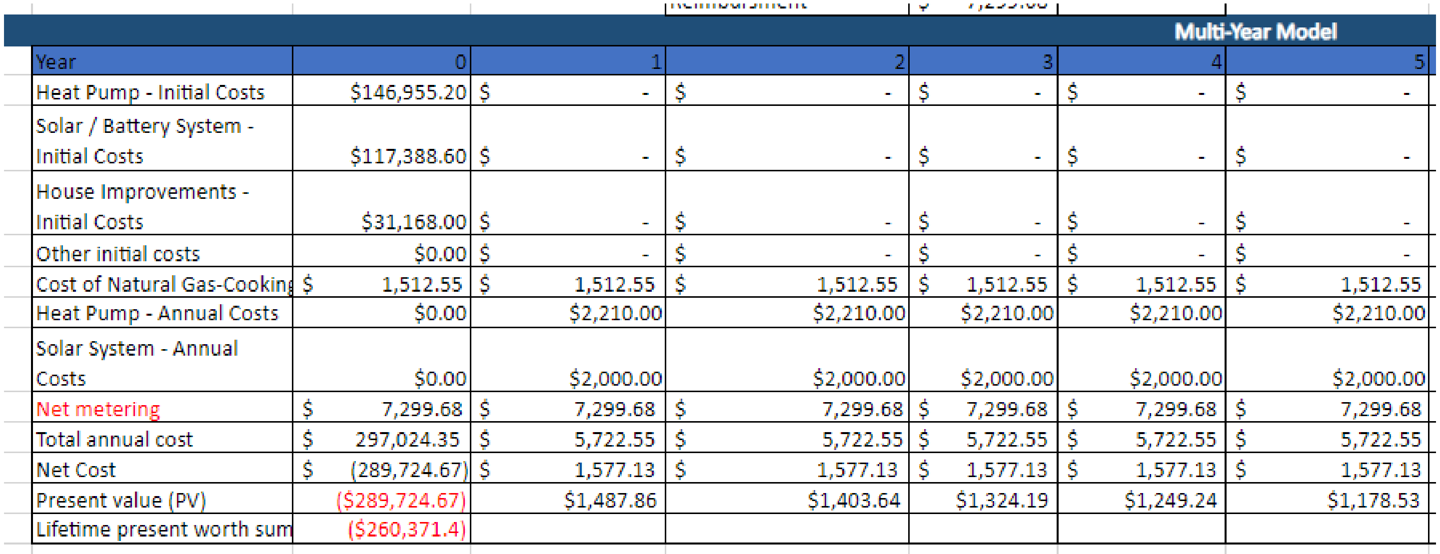
Appendix D: Financial model with detail



	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		1	$20,671.00	$20,671.00	
Total				**$209,936.00**	**$146,955.20**
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	
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	



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	



Multi-Year Model

Year	0	1	2	3	4	5
Heat Pump - Initial Costs	$146,955.20	$ -	$ -	$ -	$ -	$ -
Solar / Battery System - Initial Costs	$117,388.60	$ -	$ -	$ -	$ -	$ -
House Improvements - Initial Costs	$31,168.00	$ -	$ -	$ -	$ -	$ -
Other initial costs	$0.00	$ -	$ -	$ -	$ -	$ -
Cost of Natural Gas-Cookin	$ 1,512.55	$ 1,512.55	$ 1,512.55	$ 1,512.55	$ 1,512.55	$ 1,512.55
Heat Pump - Annual Costs	$0.00	$2,210.00	$2,210.00	$2,210.00	$2,210.00	$2,210.00
Solar System - Annual Costs	$0.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00	$2,000.00
Net metering	$ 7,299.68	$ 7,299.68	$ 7,299.68	$ 7,299.68	$ 7,299.68	$ 7,299.68
Total annual cost	$ 297,024.35	$ 5,722.55	$ 5,722.55	$ 5,722.55	$ 5,722.55	$ 5,722.55
Net Cost	$ (289,724.67)	$ 1,577.13	$ 1,577.13	$ 1,577.13	$ 1,577.13	$ 1,577.13
Present value (PV)	($289,724.67)	$1,487.86	$1,403.64	$1,324.19	$1,249.24	$1,178.53
Lifetime present worth sum	($260,371.4)					