CEE 5051: Local Energy Options Research (Fall 2024)

Analysis of Heat Pump and Renewable Energy Integration for Cornell University's Triphammer Cooperative

Advisor

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Acknowledgements

The team would like to extend our sincerest thanks to our advisor, Dr. Francis M. Vanek for his support and guidance throughout our project. His advice, knowledge, and compassion have been invaluable to our team. We would also like to thank the residents of Triphammer Cooperative, especially Vincent Eynon, who permitted us to tour their home and provided ample insight into the amazing community that Triphammer Cooperative fosters. Furthermore, we would like to extend our appreciation to Peter Warner – the Facility Manager of Triphammer Cooperative – whose knowledge of the building history and structure of Triphammer Cooperative was invaluable to our analysis and research. We would also like to thank Bryan McCracken of Ithaca's Landmarks Preservation Commission for his insightful comments on how our project could affect the historic character of Triphammer Cooperative.

Lastly, we would like to thank the Department of Civil and Environmental Engineering at Cornell University for providing us the resources and environment to conduct an extensive study for our project.

Introduction and Motivation

Cornell University plans to achieve carbon neutrality for its Ithaca main campus by 2035. As a key stakeholder and member of the greater Ithaca community, Triphammer Cooperative seeks opportunities to contribute to this important goal and support the City of Ithaca's adopted Green New Deal. This proposal will focus on evaluating the technical and financial feasibility of implementing sustainable technologies at Triphammer Cooperative to reduce on-site energy consumption and greenhouse gas emissions. Specifically, the proposed system would involve the installation of air-source heat pumps and a potential solar photovoltaic array.

Triphammer Cooperative is not only subject to Cornell's Climate Action Plan but also the aggressive Ithaca building code goals for fighting climate change. While the Cornell Climate Action Plan aims for decarbonization by 2035, the City of Ithaca is striving to achieve this by 2030. New building codes developed by the city have indicated that by 2030 old buildings should be retrofitted to support renewable heating systems (like air and ground source heat pumps). This goal was conceived in response to the 2019 passing of Ithaca's Green New Deal. The city wants to become a national leader in renewable energy implementation and the fight against climate change through policies like these goals for their building codes. The pressing need for decarbonization and climate-friendly solutions is paramount, and studies like ours will be necessary to facilitate Ithaca and Cornell University's transition to low-carbon technologies.

In addition, our proposal not only assists Ithaca's Green New Deal but also fits into Cornell's goal of creating a living laboratory in the sustainable energy field. Cornell has already implemented a lake-source cooling system and is in the process of developing a campus-wide ground-source heating system, but smaller-scale air and ground-source heat pumps will be just as important in the future of Cornell's Climate Action Plan. Our proposal in Triphammer Cooperative expands Cornell's on-campus implementation of renewable heating and cooling systems to students who reside off-campus to ensure an equitable energy transition.

Overall, the proposal explores an opportunity for Triphammer Cooperative to play its part in advancing the sustainable development priorities of Cornell University and the Ithaca community at large.

Contributor Background

Xiaodie Chen (xc544@cornell.edu)
Xiaodie (she/her) graduated from Northwest A&F University in June 2024 with a BEng & B.Sc. in Environmental Science and is expected to receive her M.Eng. in Environmental Engineering with a focus in Sustainable Energy Systems in May 2025. After graduation, she wishes to work in the nuclear energy industry, by promoting environmental-friendly practices. She is from Zhejiang, China and likes to ski, watch movies, and write prose in her leisure time.

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Haoran He (he/his) is from China, holding a bachelor's degree in Groundwater Science & Engineering from China University of Geosciences, Wuhan, and a degree in Environmental Engineering from the University of Waterloo. He is currently pursuing a Master of Engineering (MEng) in Civil and Environmental Engineering at Cornell University. After graduation, he plans to work in environmental management, focusing on water and air quality management and sustainable energy. His hobbies include traveling, Chinese chess (Go), and playing basketball.

Lila Rallatos (jar538@cornell.edu)
Lila (they/she) graduated from Cornell University in May 2024 with a B.S. in Environmental Engineering and a minor in Climate Change Studies. They are expected to receive an M.Eng degree in Environmental Engineering with a focus in Sustainable Energy Systems in May 2025. With this degree, she aspires to work on implementing climate change policies such as the Green New Deal with work in solar and wind energy. They are from Albany, New York and are a playwright, screenwriter, director, actor, and guitarist on the side.

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Mia (she/her) is expected to graduate from Cornell University in December 2024 with a B.S. in Environmental Engineering and is expected to receive her M.Eng. in Environmental Engineering in May 2025. After graduation, she hopes to work in the energy sector and help support cleaner energy practices in different industries. She is from Berkeley, California and enjoys spending her time watching Big Red Hockey and solving puzzles.

Maya Yu (mzy3@cornell.edu)
Maya (she/her) graduated from Cornell University in May 2024 with a B.Sc. in Environmental Engineering and is expected to receive her M.Eng. in Environmental Engineering with a focus in Sustainable Energy Systems in May 2025. Upon graduation, she hopes to support the clean energy transition as a solar development engineer. She is originally from Long Island, New York and loves to spend her free time reading (a recent favorite being *A Man Called Ove* by Fredrik Backman).

Project Goals, Objectives, and Scope

Goals

The general goal of this project is to explore the integration of heat pump technology and renewable energy systems at Cornell University's Triphammer Cooperative to contribute towards Cornell's carbon-neutral vision by 2035. To accomplish this general goal, members in this project will:

1. Promote carbon neutrality and support the Sustainable Development Goals: This project aims to drive the energy transition of the Triphammer Cooperative, reduce greenhouse gas emissions, and enhance the building's environmental performance, contributing to Cornell University's goal of achieving carbon neutrality by 2035. By integrating heat pump technology with renewable energy systems, the project seeks to provide a more sustainable and efficient energy solution for campus buildings.
2. Raise energy utilization efficiency of Triphammer Cooperative: The project aims to optimize the energy structure and technology selection to reduce the use of conventional energy sources and improve energy efficiency in the building. The project will explore how to optimize the use of heat pumps and renewable energy systems to optimize energy consumption and environmental impact.
3. Evaluate the technical feasibility of the proposed solutions for Triphammer Cooperative: The project will assess the technical and economic feasibility of integrating heat pump technology with renewable energy systems, exploring the cost-effective system configuration to ensure both environmental benefits and economic sustainability.
4. Enhance the professional and collaboration skills of the project members: Through participation in this project, team members will gain practical experience in sustainable energy technologies and building carbon reduction. Members will develop the skills to analyze and solve complex problems, enhancing their professional expertise and practical abilities in environmental engineering and energy management, laying a solid foundation for future career development.

Objectives

The specific objectives of our project will focus on evaluating the feasibility and effectiveness of heat pumps and solar photovoltaics. Our initial market analysis studied the various heating/cooling, building envelopes, and renewable energy opportunities for Cornell University's Triphammer Cooperative. These initiatives will support the goals of Cornell University's Climate Action Plan and Ithaca's Green New Deal, both of which aim for substantial reductions in carbon emissions and energy consumption. By conducting a comprehensive analysis of these technologies, the project can explore ways in which Triphammer Cooperative can minimize its reliance on traditional energy sources and lower its heating and electricity demands.

Our project emphasizes the importance of stakeholder engagement and collaboration with members of Triphammer Cooperative. By working closely with the cooperative's residents and management, we aim to ensure that the proposed solutions align with their needs and goals. Our team will conduct site visits and interviews, gather energy consumption data, and consult with relevant individuals to gain insights into the building's current energy performance. These engagements will inform our risk and challenges assessment, as well as the feasibility studies for potential system upgrades. Additionally, feedback from the cooperative will be integral in tailoring the solutions to ensure practicality and acceptance by the community. The models and solutions developed for this project could also serve as a prototype for other residential buildings, both on and off campus, that seek to integrate renewable energy systems and enhance energy efficiency.

A key aspect of the project is to assess the compatibility of the cooperative's existing infrastructure with renewable energy technologies, particularly ground and air source heat pumps, and solar energy generation. This involves understanding the architectural and historical constraints of the building, identifying optimal solutions for energy efficiency improvements, and calculating the potential energy savings. Additionally, this project will explore local and state incentives that could help fund the installation of sustainable and/or renewable energy systems, increasing the financial viability for the cooperative to pursue the options outlined in our project.

This project seeks to align the retrofit strategies with Ithaca's progressive climate mandates, which push for the electrification of heating systems and a shift toward net-zero emissions. Through careful analysis and application of these technologies, the project ultimately aims to contribute to the long-term sustainability of Triphammer Cooperative and serve as a model for other residential buildings seeking to reduce their carbon and environmental footprint.

Scope

The project scope will include recommendations for low-carbon technologies to be implemented at Cornell University's Triphammer Cooperative. In particular, we aim to provide potential system sizes for heat pumps and solar photovoltaic solutions. We will aim to examine Triphammer Cooperative's current building envelope to provide recommendations for sustainable retrofitting endeavors. To examine the environmental impacts of our proposed systems, we will estimate the carbon emissions that are saved through enacting these solutions. In addition, we will estimate the financial savings that the owners of Triphammer Cooperative can expect to see through our design. Finally, we will investigate the social sustainability impacts of our system – such as increased equitable energy access and the creation of local jobs.

Our proposal will be limited to designing and providing a recommended system size for the heat pump and solar photovoltaic projects. We will not conduct further in-depth feasibility studies regarding these projects, such as performing geotechnical studies, soil sample analyses, and grid interconnection studies. In addition, this study will not conduct research into other alternative forms of green technology, such as energy storage solutions, small-scale wind, or residential biomass solutions. Furthermore, we will not conduct in-depth building and structural audits. All recommendations for future retrofitting projects will be based on high-level site visits. Similarly, detailed analyses into interconnection costs or permitting will not be explored in this proposal.

Market Analysis: Local Climate Action and Incentive Landscape

Ithaca's Market for Renewable Energy Integration

Building Codes

Ithaca's building codes and regulations are in the process of major renovations spurred on by progressive climate change mandates by the local government. The primary goal is to reach net-zero carbon emissions in building construction by 2030, an ambitious aspiration (Lamb, 2021). This would focus on improving building efficiency of newly constructed buildings in order to retain heat and regulate temperature in a more optimal fashion. Ithaca follows an electrify everything philosophy for improving energy efficiency and fighting climate change. Heat pumps (both ground and air source) are directly cited by Ithaca as recommended methods for building electrification.

Recent legislation has moved the 2030 deadline for new building construction to be carbon neutral up to 2026 (Lamb, 2021). However, cooking and processing energy are exempt from these regulations. These two energy sources are subject to the 2030 deadline.

The retrofitting of older buildings is a more complicated process. The Ithaca Energy Code Supplement (IECS) provides a system where older buildings can earn points (The Easy Path) by fulfilling certain renewable energy standards (Lamb, 2021). A total of six points is required to fulfill The Easy Path. Alternatively, buildings can choose The Whole Building Path, a system where buildings can choose one aspect to be overly "green" in. This allows said building to be less compliant with other environmentally-friendly regulations. The system is similar to carbon offsets and credits in the corporate world. Both IECS paths are regulated by the Green New Deal and operate off of its timeline.

Green New Deal

By 2030, Ithaca, New York plans to achieve carbon neutrality in a way that alleviates historical inequalities and bigotry (*Green New Deal*, 2024). The building codes for retrofitting discussed above are subject to this 2030 deadline. Although the Green New Deal was adopted in 2019, progress on implementing the ambitious plans included within has been behind schedule (Redelmeier, 2024). Student-led organizations such as the Sunrise Movement are responsible for the momentum behind the Green New Deal's original ratification and the mounting pressure to ensure the city makes good on the promises of its climate change policies. The recently adopted Justice 50 framework demonstrates a major victory for this youth-movement. The goal of the framework is not just to reduce carbon emissions, but also to reduce emissions in a way that prioritizes climate justice. Climate justice emphasizes historically marginalized communities and their struggles with environmental issues, such as the zoning of energy plants that produce secondary emissions near historically black neighborhoods. In this way, the Ithaca Green New Deal is as much a social justice policy as it is an environmental one.

Electricity and Natural Gas Rates

According to Energy Sage (2024), the average residential electricity rate in Ithaca is about $0.17 per kilowatt-hour of usage – roughly 31% lower than the national average. However, there is significant discrepancy between sources regarding the national average electricity rate. For instance, Energy Sage (2024) cites an average residential electricity rate of $0.23/kWh. In contrast, according to the latest data available from the Energy Information Agency (EIA), the average residential electricity price in the United States is 16.83 cents per kilowatt-hour (kWh) (Choose Energy, 2020). The EIA also reports that the national average increased 3.4 percent compared with the previous year.

Based on the electricity data provided by Jonathan Hart (expounded upon in *Existing Conditions*), the average electricity rate for the Triphammer Cooperative residence is approximately $0.151 per kilowatt-hour of consumption. However, in 2023, the New York Public Service Commission (PSC) approved electric bill rate increases for NYSEG, translating to a 6.6% increase in 2023, a 7.3% increase in 2024, and an 8.2% increase in 2025 for its customers (Christian, 2023).

Similarly, Triphammer Cooperative spent approximately $0.872 per therm on natural gas during the 2023 heating season. Such rates are expected to increase by 2% in 2024 and 2.1% in 2025 (Christian, 2023).

Cornell University's Climate Action Plan

To lead and guide its sustainability initiatives, Cornell University has implemented a Climate Action Plan to help its Ithaca campus achieve carbon neutrality. Cornell University's Climate Action Plan encompasses the following goals: 1) Reduce Ithaca campus carbon emissions to net zero by 2035, 2) Create a living laboratory for low-impact behaviors, climate education, and research, and 3) Lead by example on campus and exercise climate leadership beyond campus (*Cornell Climate Action Plan,* 2024).

In regards to renewable energy integration, Cornell seeks to optimize campus energy systems through the BIG RED (Building an Integrated Grid for Reliability, Efficiency, and Decarbonization) Energy Transition. This plan calls for the implementation of peak demand and emergency power strategies, the conversion of the campus' heat distribution system from steam to hot water, and to continue ongoing support for the Lake Source Cooling project. In addition, Cornell University aims to heat its campus with renewable energy by developing earth source heating for buildings on the district energy system and transitioning existing buildings that are not connected to the district energy system to heat pumps (*Cornell Climate Action Plan,* 2024).

Cornell's Climate Action Plan also includes Energy Conservation Initiative (ECI) studies – aiming to reduce campus-wide energy consumption to help the Ithaca campus reach carbon neutrality by 2035 through utilizing energy-efficient building infrastructure. Cornell's ECI program started in the early 2020s and since its inception has saved the campus over $75 million dollars, avoided over 235 million tons of CO_2 emissions, and abated over 3.75 trillion BTUs of energy demand (*Cornell Climate Action Plan,* 2024). Through these initiatives, Cornell University's Ithaca main campus has experienced a 42% reduction in its CO_2 emissions since 2008.

Incentive Landscape

Inflation Reduction Act's Investment in Clean Energy Infrastructure and Climate Action

The Inflation Reduction Act (IRA) of 2022 provides a historic level of funding and grant programs that serve to accelerate the clean energy transition. Many of the provisions outlined in the IRA seek to boost economic growth in the United States while ensuring an equitable distribution of clean energy resources – such as through advocating for energy justice in low-income communities, maintaining prevailing wages and apprenticeships, and supporting the domestic manufacturing of sustainable technologies.

In particular, the Investment Tax Credit (ITC) outlined by the U.S. Code Section 28 provides a critical tax credit for projects investing in the development of clean energy and energy-efficient technologies, such as solar photovoltaics and heat pump solutions. The ITC also provides direct pay eligibility for tax-exempt organizations, such as Cornell University.

The ITC currently provides a 30% tax credit if prevailing wage and apprenticeship requirements are achieved. In addition, the IRA also highlights multiple bonus credit adders for the ITC. For instance, the base credit is increased by 10% if the project is located in an energy community – which is defined as a community whose economy historically relied on the fossil fuel industry for employment or tax revenue. According to the Energy Community Mapping Tool by Baker Tilly (2022), it is unlikely that residences in Ithaca would qualify for the Energy Community Adder. However, the IRA also outlines a 10% bonus credit adder if the project meets certain domestic content requirements. In particular, a project may claim the ITC's Domestic Content Adder if it meets the two criteria: 1) "The project must use 100% domestic steel and iron for construction materials that are structural in nature", and 2) "Projects that begin construction before 2025 must use at least 40% domestically manufactured products" (Cooper, 2023).

NY-Sun Megawatt Block Solar Program

The New York State Energy Research and Development Authority (NYSERDA) offers the NY-Sun program to support solar energy expansion across the state. In particular, the Megawatt Block program divides New York State into three regions: ConEdison, Long Island, and Upstate. A certain amount of incentives is allocated toward each of the three regions. From here, each region is divided into blocks that are given a certain allocation of megawatts eligible for incentives. The program will remain open until all of the blocks within a region are fully subscribed to (New York State Energy and Development Authority, 2024). The program is intended to support regions where solar energy development is not financially feasible and allow for the gradual phase-out of fossil-fuel based electricity generation.

Projects located in Ithaca would fall under the Upstate solar incentive block. As of September 28, 2024, the Upstate region's residential block is in Block 12 of 12. The block allocates incentives for 10.16 MW of residential solar photovoltaics and has roughly 2.95 MW of incentives remaining. The block provides $0.20/W of incentives for such projects. This incentive is paid directly to the solar installer of the customer's choice. The contractor must then translate these savings by lowering the customer's upfront capital cost. Though the Upstate NY-Sun incentive program is almost fully subscribed to, it is likely that new incentive programs will be released by NYSERDA to facilitate the development of renewable energy programs.

New York State Solar Energy System Equipment Credit

New York State's Department of Taxation and Finance also provides a tax credit for the installation of residential solar energy systems. The requirements for eligibility include the following: 1) "If the solar energy system equipment produces electricity, [the customer] must enter into a net energy metering contract with [their] electricity corporation or comply with the electric corporation's net metering schedule", and 2) "The complete solar energy system must also be connected to the electric corporation's transmission and distribution facility"(New York State Department of Taxation and Finance, 2023). The incentive provides a 25% tax credit for the solar energy system's expenditures and is limited to a maximum of $5,000.

NYSERDA EmPower+ Incentive

EmPower+ helps low-to-moderate (LMI) households save energy and money toward energy improvements made to their primary residence. Through EmPower+, eligible New Yorkers can receive the following incentives based on their income: Low-income, single-family households are eligible for no-cost energy efficiency improvements capped at $10,000 per project; Moderate-income single-family households are eligible for no-cost energy efficiency improvements capped at $5,000 per project. The total incentive amount a household is eligible to receive is based on the combination of energy efficiency improvements. The maximum incentive limits per improvement are as follows: $1,600 for air sealing, insulation, and ventilation; $1,750 for heat pump water heaters; $8,000 for heat pumps.

Through this program, LMI households in New York can receive the following benefits: 1) No-cost energy assessments and audits to determine sources where energy is being wasted, 2) No-cost plans to reduce energy consumption, 3) No-cost direct installation improvements identified during the audit as long as the customer utilizes a participating program contractor, and 4) Funding toward the cost of energy efficiency improvement solutions (New York State Energy and Development Authority, n.d.).

Green Jobs-Green New York (GJGNY)

NYSERDA offers a suite of loans under the Green Jobs-Green New York (GJGNY) Program to help New York State residents finance energy efficiency improvements, and renewable energy systems. Homeowners could be eligible for up to $25,000 in loans for energy efficiency improvements or renewable energy installations at one-to-four family residential properties. On-Recovery bill loans, Smart Energy Loans, and Renewable tax credit bridge loans (max $25,000) are available. In addition, these methods of financing may be paired together to maximize the available financial incentives. The Smart Energy Loan is a traditional loan that is repaid monthly via check or automatic payment. Renewable Energy Tax Credit Bridge Loan enables applicants to finance federal and state tax credits paired with the Smart Energy or On-Recovery bill Loan (combined total cannot exceed $25,000). Loans over $13,000 are required to have a payback period of less than 15 years.

Existing Conditions

About Triphammer Cooperative

The Triphammer Cooperative has a rich history, evolving through several significant phases. Originally constructed between 1912 and 1913, the house was built for Ora M. Leland, a professor of astronomy and geology at Cornell University. Leland resided at the house until the early 1920s. Afterward, from the 1920s through the 1950s, the building was used as the residence for Sigma Kappa sorority. In the mid-20th century, the house transitioned into a women's dormitory and cooperative residence, becoming part of Cornell University's co-op housing program. Today, Triphammer Cooperative continues to serve as a co-educational, student-run cooperative, located on the university's North Campus.

Triphammer Cooperative is known for its tight knit and collectivist community. Each resident is assigned specific days to cook dinner for the other residents of the house and social events are held often to ensure a strong sense of togetherness. Although rent prices for the co-op are not publicly available, tenants have reported Cornell raising these costs in recent years. The University has additionally refused calls by the tenants to allocate rent prices in each room based on the number of residents living in said room (*Co-Op Residents Face Deteriorating Houses, Increasing Rent Costs - the Cornell Daily Sun*, 2024).

The house is situated at the southwest corner of Triphammer Road and Dearborn Place, overlooking Cornell's North Campus to the east. It is surrounded by a number of other early 20th-century homes and is one of approximately 150 buildings that are part of the Cornell Heights Historic District, a suburban development in the northeastern section of Ithaca (Dulberger, 1987).

Building Information and Details

Triphammer Cooperative not only boasts a rich historical background but also showcases a unique architectural style. This two-and-a-half-story residence is clad in stucco with a high, hipped roof, and features attic lofts with skylights on its north, south, and east facades. The main facade is accentuated by two-story wings with matching hipped roofs and a single-story porch at the central entrance, supported by square wooden columns. The building's windows vary in style, with 8/1 double-hung windows on the first floor and 6/1 double-hung windows on the second. The north facade features multi-pane windows and a side door beneath the second story, flanked by tall brick chimneys that enhance the historic ambiance. Photographs of Triphammer Cooperative are shown in Figure 1.

Figure 1: Exterior of Triphammer Cooperative (Source: Maya Yu)

The building spans approximately 8162 square feet, accommodating 20 students including transfer students, upperclassmen, and graduate students. The building closes during Cornell University's winter break (approximately late December to mid-January, though specific dates vary). Most minor renovations occur during this time, as no tenants reside in the house. The building does not close during the summer; typically up to 15 residents sublet and occupy Triphammer Cooperative during the summer, though this figure may vary significantly depending on the year. Major renovations may require a longer period of vacancy in which the tenants of Triphammer Cooperative may need to vacate the building for several months for the building upgrades to be completed. These concerns are discussed in greater depth below.

Due to the building's historical value and existing structure, space for additional rooftop solar installations is extremely limited. However, Building-Integrated Photovoltaics (BIPV) may be assessed as an option should re-roofing projects take place in the future. Proposals to install solar panels in the yard for a ground-mount solar system might encounter resistance. However, as expounded upon in *Renewable Energy*, there is strong potential for a south-facing carport system. We do not anticipate that the proposed system can meet 100% of the building's electricity demand; hence, purchasing solar offsets is being considered as an alternative.

In terms of construction materials, Triphammer Cooperative utilizes a light wood frame structure covered in stucco. It comprises 5 doors, 57 windows, and 2 chimneys. Despite multiple changes in use over the years, most of the original structure and materials have been well-preserved.

The basement of Triphammer Cooperative houses a Heat Recovery Ventilator, meant to prevent excess heat in the building from being exhausted. It collects and redistributes this lost heat with between 60 and 95% efficiency (Xu et al., 2019).

Triphammer Cooperative is currently planning on major renovations to the building over the next five years. Each renovation and its timescale is documented in the table below:

Table 1: Future Triphammer Cooperative Renovations

When will this renovation occur?	What is the renovation?
Immediately	Sprinkler maintenance The patching of holes in the basement
Within the next two years	Replacement of single pane windows with double panes

	Replacement of window trim Investigation of basement leaks
Within the next three years	Perform upkeep on the staircases Upgrade electricity panel
Within the next four years	Replace electrical infrastructure
Within the next five years	Replace Boiler Improve ventilation via kitchen renovation

Electricity and Heating Demand

Current data and projections for Triphammer Cooperative's heating and electricity demand were provided by Johnathan Hart on 10/1/2024 in the form of the linked spreadsheet.

We observe that between August 2023 and May 2024, electricity consumption at Triphammer Cooperative was 48,872 kWh. The building consumed an additional 9,823.4 therms of natural gas. In total, Triphammer Cooperative spends $8,565.74 on natural gas during this timespan and $7,359.44 on electricity.

To determine the annual usage of electricity and consumption of natural gas, we estimated the values for June 2024 and July 2024. A weighted moving average was used to determine these values, where a weight of 60% was given to the previous time period and a weight of 40% was given for two periods before the current. Figure 2 illustrates the monthly consumption of natural gas and electricity for Triphammer Cooperative. Tables 2 and 3 demonstrate the monthly breakdown of consumption and the electricity and natural gas bills incurred for Triphammer Cooperative by month. In these tables, both June and July are highlighted in blue to signify that a weighted moving average was utilized to determine the monthly consumption and price.

Figure 2: Monthly Consumption of Natural Gas and Electricity

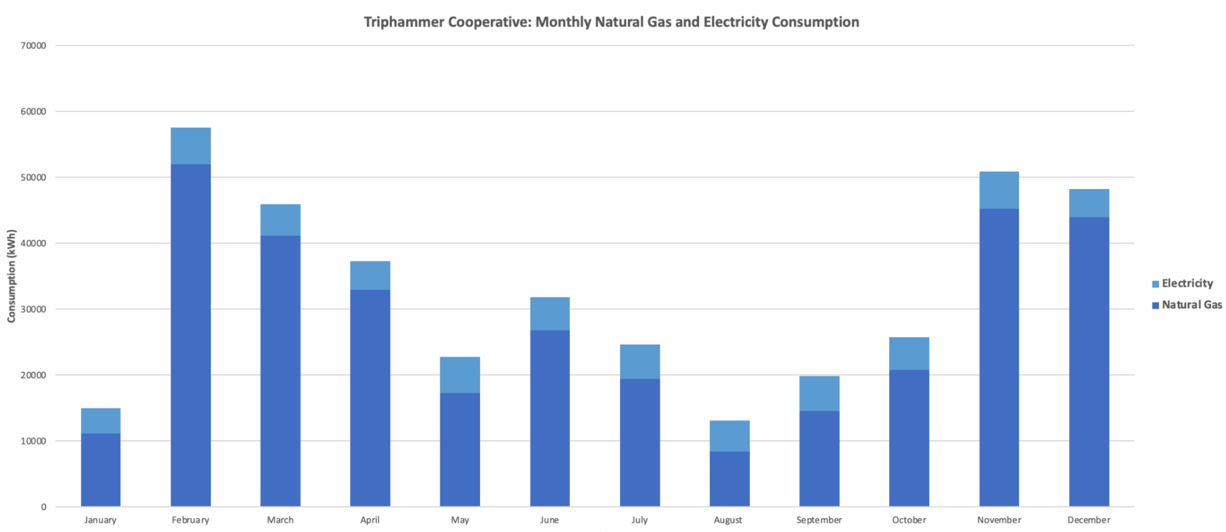


Table 2: Monthly Natural Gas Consumption for Triphammer Cooperative

Monthly Natural Gas Consumption for Triphammer Cooperative					
Month	**Consumption (Therms)**	**Consumption (kWh)**	**Supply Costs**	**Demand Costs**	**$/kWh**
January	380	11134	$808.88	$559.36	$0.12289
February	1775	52007.5	$795.78	$502.96	$0.02497
March	1402.4	41090.32	$699.94	$281.44	$0.02388
April	1123.6	32921.48	$513.58	$215.22	$0.02214
May	589	17257.7	$434.84	$114.52	$0.03183
June	914.36	26790.748	$466.34	$516.79	$0.03670
July	662.696	19416.9928	$453.74	$221.02	$0.03475
August	285.2	8356.36	$81.00	$175.16	$0.03065
September	496.2	14538.66	$143.22	$266.98	$0.02821
October	709.6	20791.28	$394.00	$218.38	$0.02945
November	1544	45239.2	$673.84	$530.96	$0.02663
December	1500	43950	$694.80	$460.88	$0.02630
Sum	11382.056	333494.2408	$6,159.95	$4,063.67	

Table 3: Monthly Electricity Consumption for Triphammer Cooperative

Monthly Electricity Consumption for Triphammer Cooperative				
Month	**Consumption (kWh)**	**Supply Costs**	**Demand Costs**	**$/kWh**
January	3812	$299.48	$324.96	$0.16381
February	5488	$511.60	$425.28	$0.17071
March	4836	$293.54	$408.26	$0.14512
April	4310	$284.82	$363.06	$0.15032
May	5526	$314.42	$562.74	$0.15873
June	5039.6	$302.58	$480.41	$0.15537
July	5234.16	$307.32	$512.95	$0.15671
August	4742	$324.90	$323.54	$0.13674
September	5292	$408.50	$359.54	$0.14513
October	4976	$355.34	$335.30	$0.13879
November	5626	$374.14	$446.42	$0.14585
December	4264	$288.04	$355.56	$0.15094
Sum	59145.76	$4,064.68	$4,898.02	

Based on data obtained from the Commercial Buildings Energy Consumption Survey (CBECS) (U.S. Energy Information Administration, 2021), the estimated energy consumption of a lodging house was calculated using two metrics: energy consumption per square foot and energy consumption per worker. The results of this analysis are shown in Table 4. Using the "per square foot" metric (converted to 0.0255850983 kWh per square foot), the predicted energy consumption for the lodging house was 158,550.85 kWh, which is lower than the actual recorded value of 333,494.24 kWh. Meanwhile, using the "per worker" metric (million Btu per worker), the calculated consumption was 1,523,500.29 kWh, which is higher than the actual value. These differences suggest that while the predicted results show some deviation, the actual data appears to be reasonable and aligns with expectations for similar buildings under comparable conditions. The discrepancies in predictions likely stem from variations in building-specific characteristics, such as energy efficiency measures, worker density, or operational patterns.

Table 4: CBECS Survey on Energy Consumption

CBECS Survey on Energy Consumption					
Principal Building Activity	Mean Square Feet per Building (Thousand)	Mean Square Feet per Worker	Per Building (Million British Thermal Units [MMBtu])	Per Square Foot (Thousand BTU)	Per Worker (Million British Thermal Units [MMBtu])
Lodging	33.1	2388	2892	87.30	216.60

Construction Issues

Given that Triphammer Cooperative is open for tenants eleven months out of the year, with winter break being the only period of zero occupancy, major construction efforts such as the upgrades to be discussed further in this report face a major scheduling issue. The electrification of the entire heating system of the building will take longer than one month to complete. As a result, either construction would need to occur incrementally over an extended period of time such that tenants could continue occupying the building during construction or the building would need to be closed in its totality for a short timespan.

The incremental approach would necessitate vacating one room at a time and providing alternative room accommodations to the ousted tenants. Larger rooms such as the kitchen and dining areas would need to be closed as well. Given the collectivist values of Triphammer Cooperative (e.g. groups of tenants during weekdays are expected to prepare a meal for the entire co-op) closing these group spaces would harm the culture of the Triphammer and likely receive pushback from tenants.

The all-at-once approach would additionally see pushback. Cornell University has a history of closing dorm buildings for entire academic semesters or years to renovate them for future occupants. A recent example includes renovations in Balch Hall on North Campus, where residents were temporarily relocated to Barbara McClintock Hall. This renovation took place from 2021 to late 2024 and included exterior repairs, systems replacement, and reconfigurations to the existing floor plan. However, these dorms lack the culture and consistent occupants of Triphammer Cooperative, where tenants often spend multiple academic years living in the house with the friends they make in the space. As a result, vacating the entire building for an academic semester or year to electrify the building would not only deprive tenants of their housing and culture but also necessitates alternative housing to be organized. Given that co-op tenants often choose this housing option due to lower rent prices compared to alternatives whether on Cornell's campus or Ithaca's Collegetown, alternative housing would need to be organized in such a way that preserves these lower rent prices. It would not be ethical to charge these students more for alternative housing because they have been forced from their cheaper housing option for reasons beyond their control.

Overview of Building Upgrade Technologies

Heating/Cooling

Ground Source Heat Pump

Ground source heat pumps, commonly known as geothermal heat pumps, utilize the earth's stable underground temperature to efficiently transfer heat to and from homes through a network of buried piping. These systems are particularly advantageous during colder months, as they draw heat from the relatively warmer ground, thereby avoiding the inefficiencies associated with air-source heat pumps, which are more susceptible to outdoor temperature fluctuations. While geothermal heat pumps can significantly reduce energy costs over time and provide consistent heating and cooling, they typically involve high upfront installation costs due to the extensive underground work required to establish the system (U.S. Department of Energy, 2017).

In Ithaca, ground source heat pumps are a viable option for residential heating and cooling; however, they require the installation of ground loops, which can vary in configuration based on the available space and soil conditions. Closed-loop system options include horizontal, vertical, and pond/lake configurations, in addition to the open-loop option. Local regulations and incentives may also influence the decision to install these systems (U.S. Department of Energy, 2017). In particular, Cornell University has recently completed the construction of an exterior electric shallow-well vertical ground source heat pump for its Child Care Center (Cornell University Facilities and Campus Services, 2024)

It is worth noting that Triphammer Cooperative lacks access to ponds/lakes that would allow for the closed-loop system configuration. This in conjunction with the installation complexity of ground source heat pump systems makes this option less viable than its alternative heating counterparts.

Air Source Heat Pump

Air source heat pumps extract heat from the outside air to heat or cool the home. They are often relatively affordable and suitable for Ithaca’s climate. One of the significant advantages of air source heat pumps is their relatively affordable installation costs compared to other heating systems, such as geothermal heat pumps. They are particularly suitable for Ithaca's climate, where moderate temperatures can be effectively managed by these systems. However, it’s important to note that the efficiency of air source heat pumps tends to decrease in very cold weather, typically when temperatures drop below freezing. This reduction in performance may necessitate the use of supplemental heating systems during winter months to ensure consistent comfort levels (Department of Energy, 2017).

Homeowners can choose from various configurations, including ductless, ducted, and short-run ducted systems, allowing for minimal construction disruption or the utilization of existing ductwork. Ductless systems require only a small opening for installation, making them ideal for retrofits and additions. In contrast, ducted systems integrate into a home’s existing ventilation, while short-run ducted options serve smaller areas effectively. Additionally, air source heat pumps are available in both split and packaged designs, with split systems housing separate indoor and outdoor components for efficiency. For homes needing tailored climate control, multi-zone configurations enable heating or cooling of individual rooms, enhancing comfort. With advancements in technology, modern air source heat pumps are more efficient than ever, making them a viable option for residents looking to reduce energy costs while maintaining a comfortable living environment year-round (Department of Energy, 2017).

Active Solar Heating

Active solar heating uses solar collectors to capture sunlight and convert it into heat for the home, often used for space or water heating. While this technology can significantly reduce fuel bills and greenhouse gas emissions, it does come with certain requirements and limitations. One key requirement is that effective solar exposure is essential; this can be a challenge in Ithaca, particularly during the more extreme winter climate, where overcast skies can reduce solar gain. The installation costs for active solar heating systems are moderate, and they can be most cost-effective in cold climates with ample sunlight, especially when displacing more expensive heating fuels such as electricity or propane (Department of Energy, 2017).

Active solar systems typically utilize liquid or air as a working fluid to absorb and transfer solar energy. Liquid systems are often preferred for central heating applications and can be integrated with existing heating systems, such as radiant heating or forced air systems. They require proper storage solutions, like water tanks, to maximize efficiency and performance. On the other hand, air systems, while less efficient than liquid systems, can be simpler and more effective for heating individual rooms or pre-heating ventilation air (Department of Energy, 2017).

Furnace Heating

Furnace heating burns fuel (natural gas, oil, propane) to generate heat, which is distributed via ducts. This is common in many homes due to relatively low installation costs and high heating efficiency. However, fossil fuel dependence and emissions are a downside. Most U.S. homes rely on furnaces or boilers, with furnaces distributing heated air and boilers heating water for distribution via radiators or radiant floor systems. While traditional systems can have efficiency ratings as low as 56%, modern high-efficiency furnaces can reach up to 98.5% Annual Fuel Utilization Efficiency (AFUE), significantly reducing emissions and fuel consumption. Upgrading to a high-efficiency model or retrofitting an older system can improve efficiency, but the cost of retrofitting should be carefully weighed against replacing the system entirely. Additionally, choosing a sealed combustion unit can prevent heat loss and the risk of harmful gasses, such as carbon monoxide, entering the home (Department of Energy, 2017).

Window Units

Window units are small air conditioners installed in windows for cooling individual rooms. They are inexpensive and easy to install, which makes them accessible for students who reside in Ithaca. However, they are less efficient for whole-house cooling and can increase energy costs due to their higher electricity consumption (Benningfield, 2022). Additionally, they may not provide the same level of temperature control or air circulation as more advanced cooling systems like central air or ductless mini-splits. Their tendency to cause air leakage around the window can also reduce overall energy efficiency. While they require minimal maintenance – typically just cleaning the filter and coils annually, they tend to have a shorter lifespan compared to central systems.

When using window units, it is essential to properly size them based on room dimensions and other factors like ceiling height and window shading, to avoid overcooling and energy waste. Furthermore, using interior fans in conjunction with window units can help distribute the cool air more effectively throughout the space, improving comfort without significantly increasing energy usage (Department of Energy, 2017).

Central Air Systems

Central air systems use ducts to distribute cooled air throughout the house and are typically powered by an electric air conditioner. These systems, common in newer homes, circulate cool air through supply and return ducts. Supply ducts carry cooled air from the air conditioner to rooms, while return ducts bring warmer air back for cooling. Central air systems are convenient, quiet, and often more efficient than window or portable units. However, a major drawback is the installation cost of ductwork, especially in older Ithaca homes that may not already have ducts. Another consideration is energy efficiency. Newer central air systems can be up to 50% more efficient than older models, with SEER ratings (Seasonal Energy Efficiency Ratio) of up to 26. This can reduce energy costs, but proper sizing and installation are critical to avoid humidity issues or insufficient cooling. If you're installing a new system, factors like adequate space, ductwork sizing, and refrigerant charge must be addressed by a qualified contractor. Additionally, central air conditioners help dehumidify the air, but in very humid conditions or with oversized units, a dehumidifier may be needed, which increases energy use. Modern systems with energy-efficient features like variable-speed motors or automatic-delay fan switches can further enhance energy savings, making central air an appealing option for those upgrading their home's cooling system in Ithaca (Department of Energy, 2017).

Ductless Mini-Split

Ductless mini-splits provide both heating and cooling without the need for ductwork, using individual units for each home. These systems are efficient and versatile and are well-suited for Ithaca homes that lack existing ductwork. These systems consist of an outdoor compressor/condenser and one or more indoor air-handling units, which can be installed in various locations. This offers flexibility in home design. They also allow for zoning, meaning an individual can control the temperature in different rooms independently. This saves energy by only heating or cooling the occupied spaces. One major advantage of mini-splits is their efficiency. Since they don't use ducts, they avoid the energy losses that occur in central air systems, where ducts can lose up to 30% of cooling energy. This makes mini-splits more efficient than central systems, especially for older homes. However, mini-splits tend to be more expensive than window units and can cost about 30% more than central systems (not including ductwork). Proper sizing and placement are essential to ensure efficient operation and avoid issues like short cycling. Additionally, while they are less visually intrusive than window units, some homeowners may find the appearance of indoor units less appealing than built-in central air systems. Despite these drawbacks, their efficiency and versatility make them a strong option for heating and cooling in Ithaca homes (Department of Energy, 2017).

Building Envelope

Passive Solar Heating

Passive solar heating systems utilize a building's architectural design to naturally collect, store, and distribute solar energy as heat without the need for mechanical intervention. Such systems rely on incident sunlight entering through windows, which may then be absorbed and released slowly to warm the space. Through such systems, we may minimize Triphammer Cooperative's reliance on conventional heating systems, thereby improving the building's overall energy efficiency.

For instance, passive solar overhangs may be utilized to help block incident sunlight from entering the building in the summer – thereby reducing the building's energy demand for cooling. Similarly, in the winter, such systems would allow sunlight to enter the building, passively heating the residence. Such passive solar systems help to reduce the need for conventional heating/cooling systems – effectively lowering energy bills and reducing Triphammer Cooperative's environmental impact. In addition, once designed and built, passive solar systems require little to no maintenance or operational costs that may be associated with their conventional counterparts. However, these systems often present limited flexibility. As the design is entirely dependent on the Sun, there is less flexibility in adjusting temperatures during the summer and winter months without an additional source of heating and cooling.

Insulation

As the Triphammer Cooperative residence was first built in the early 1900s and has not undergone any major retrofitting projects, it may be likely that the walls of the residence lack a sufficient insulation system. Proper insulation will act as a barrier to heat flow, keeping heat in during the winter and maintaining cooler temperatures in the summer. As such, insulation reduces the energy demand needed to maintain a comfortable temperature across Ithaca's temperate climate. According to Energy Star (2021), Ithaca falls under the "5A Cool Humid" IECC Climate Zone. As such, it is recommended that uninsulated wood-frame walls utilize one of the following recommended R-values, where CI refers to "continuous insulation" that is applied for the exterior of the wall assembly: 1) R20+R5 CI, 2) R13+R10 CI, or 3) R0+R15 CI (Department of Energy, 2022). While there are many types of insulation options available, we will focus on ones that allow for integration into enclosed existing walls for retrofitting projects: loose-fill/blown-in and sprayed foam insulation.

Loose-fill insulation typically consists of recycling waste materials, such as small particles of fiber and foam made from cellulose, fiberglass, and mineral wool. Cellulose loose-fill insulation is commonly made from recycled newsprint, fiberglass products often contain 40-60% recycled glass, and mineral wool is usually produced from 75% post-industrial recycled content (Norton, 2022). As such, loose-fill is deemed as a sustainable option for insulation. Depending on the type of material used, loose-fill insulation has an R-value that ranges from 2.2 to 3.8 per inch (Washington State University, 2006). This insulation method is very flexible, and may be used for roofs and walls with unique architectural features. Some of the notable advantages of loose-fill insulation include its ease of installation and relatively low upfront cost. However, this installation method often creates an enormous amount of dust when installed, which may require the residents of Triphammer Cooperative to vacate the building during the retrofit process. In addition, cellulose insulation is often susceptible to moisture intrusion – potentially leading to mold and rot (Solar365, n.d.)

Sprayed foam insulation may be blown into walls, attic surfaces, or under floors to reduce air leakage. There are two primary types of foam insulation: closed-cell and open-cell. Both of these options are typically made using polyurethane. Closed-cell foam insulation utilizes high-density cells – pockets of air that create the structure of a foam insulation material to trap air and provide thermal resistance. In contrast, open-cell foam cells are not as dense and provide a more sponge-like texture (Norton, 2022). Closed-cell foam insulation provides an R-value of around 6.5-7 per inch and offers a stronger resistance to moisture and air leakage. In comparison, the R-value for open-cell spray foam is around 3.5 per inch (Mordasky, 2018).

To determine the amount of air leakage present at Triphammer Cooperative, professional auditors may utilize blower door tests. A blower door test is conducted to determine the specific locations where insulation is missing and air is leaking in a home – thereby providing a diagnostic for the air infiltration rate (Department of Energy, 2019). To prevent further air leakage, air sealing techniques such as caulking and weatherstripping may be used as quick, cost-effective ways to reduce the rate of air infiltration at Triphammer Cooperative.

Windows

The main factors that affect the thermal performance of Windows are the type of frame and glass, and the filling material.

Frame Types:

- **Aluminum Frames**: Lightweight and durable but highly conductive, which can lead to significant heat loss, especially in winter. They require thermal breaks to prevent cold air infiltration.
- **Wood Frames**: Aesthetic with good insulation but require regular maintenance to prevent weathering and pest damage.
- **Vinyl Frames**: Affordable and low-maintenance, resistant to UV radiation, and can be customized. They provide excellent insulation.
- **Composite Frames**: Made from recycled materials, mimicking wood with added durability, and offer superior insulation but at a higher cost.
- **Hybrid Frames**: Combine materials, typically wood for interior beauty and aluminum for exterior durability. These tend to be more expensive.

Glass Options:

- **Low-E Glass**: Reduces infrared and ultraviolet light, improving insulation by up to 30% while controlling sunlight entry.
- **Spectrally Selective Coating**: Designed for hot climates, it blocks infrared and ultraviolet rays, letting in visible light and reducing heat absorption.

Filling:

- **Gas Fills & Spacers**: Double or triple-pane windows filled with argon or krypton gas enhance insulation. Argon is cost-effective for larger spaces (1/2 inch), while krypton works better in smaller spaces (1/4 inch) with superior insulation. Sealed spacers maintain consistent distance between panes and prevent moisture infiltration, ensuring effective thermal performance.

Roofs

There are a variety of roofing insulation materials that may be used for potentially insulating the roofing for Triphammer Cooperative. The table below summarizes some key insights for each of the materials:

Table 5: Options for Roofing Insulation Materials

Material	Cost ($/ft^2)	R-Value	Advantages and Disadvantages
Polystyrene Panel	$1-2	3.6-5.7	Suitable for high humidity, high thermal resistance, easy installation. Flammable if not used properly, lower

			durability than other roofing options
Structural Insulated Panels (SIP)	$7-$12	15-67	Provides lasting insulation, suitable for prefab roofing. Susceptible to moisture if installed improperly
Rigid Foam Board	$0.70-$1	5-5.6	High insulation performance, reasonable price Possible failure after 50 year of use
Fiberglass	$0.30-$1.50	3.1-4.3	Suitable for DIY projects, low cost. May need regular replacement to maintain effectiveness.
Hybrid Insulation	$1-$4	2.2-4.3	Provides consistent insulation across different climates Installation requires professional skills
Bromine-Free	$0.45-$0.65	0.45	Environmentally friendly, helps reduce indoor harmful emissions Low R-value, poor insulation performance
Perlite	$0.30-$0.50	2.7	Suitable for humid environments, good moisture resistance Lower R-value may not provide ideal thermal insulation
Fiber Cement Board	$5-$14	~1	Suitable for damp environments, some soundproofing effect Low R-value, may not be suitable for applications requiring high insulation performance

Renewable Energy Generation and Adoption

Rooftop Solar Photovoltaic Systems

Rooftop PV systems are ones in which solar panels are directly installed on the roofs of residential, commercial, or industrial buildings. These systems utilize otherwise unused rooftop space, making them an efficient option for generating renewable energy in more suburban or urban areas that may be space-constrained. Rooftop PV systems are typically more affordable to install compared to parking canopies as they do not require much additional structural support infrastructure, and they integrate seamlessly into the building's electrical system. However, their efficiency is limited by the roof's orientation, angle, available surface area, and age – making them less viable for buildings with complex roof designs or heavy shading.

Parking Canopy Photovoltaic Systems

Parking canopy PV systems include solar panels that are mounted on structures built above parking spaces, providing dual benefits of clean energy generation and shaded parking. These systems are ideal for larger-scale commercial or institutional applications, where parking lots offer ample, unobstructed surface area. Unlike rooftop systems, parking canopy systems allow for optimal panel orientation and tilt to maximize energy production. However, their installation costs tend to be higher due to the additional infrastructure required to support the panels – especially when compared to ground-mounted solar panels where the supporting structure can be optimized to minimize cost. Depending on the ground on which the solar canopy is installed, the foundation will require sufficient strength to support the columns along the edge of the canopy, which will affect the total cost of the project.

Ground-Mounted Photovoltaic Systems

Ground-mounted PV systems are installed directly into the ground using support beams. Such systems are extremely versatile and suitable for large-scale installations, such as utility-scale solar farms. However, even smaller systems may be viable if there is an abundance of open space. As such, these systems are ideal for locations that have ample space with limited spatial constraints. Ground-mount systems often achieve the highest efficiency out of any other solar photovoltaic configuration, as they can be oriented and angles to optimize incident irradiance and may be spaced to reduce inter-row shading between panels. However, these systems may require significant land area and may face more backlash regarding land-use restrictions and community opposition.

Community Solar

Community solar is an accessible form of solar power that enables anyone to benefit from clean energy's electricity savings, whether they own a sunny rooftop or rent their homes. If the energy produced from on-site renewable generation cannot fully meet the demand, complementary solutions like Community Solar and grid-supplied Green Electricity can help achieve higher levels of renewable energy usage. With community solar farms, the energy accrues credits that are applied to the bill, resulting in a zeroed-out electricity bill and additional savings.

Proposed Solutions for Triphammer Cooperative

Note about Historic Preservation

The team's contact on issues related to historic preservation was Bryan McCracken, Secretary of the Ithaca Landmarks Preservation Commission. According to him, the presence of air-source heat pumping technology visible on the exterior of Triphammer Cooperative would violate the historic character of the building, as it is protected as a historically significant building. Therefore, any planning as to the physical location of the heat pumps from the exterior and the inherent visual pollution therein would need to be approved by Bryan McCracken. For the purposes of our project, we will proceed with assuming that any upgrades (on-site heat pumps, renewable energy sources, and building envelope) will be approved by the Ithaca Landmarks Preservation Commission.

It would be possible to construct an enclosure surrounding the installed air source heat pump in such a way that preserves the historic character of the building. Additionally, the side of the building opposite its main entrance has an electricity meter installed. It is possible that more modern electrical components, such as the proposed heat pump, would be allowed to be installed in Triphammer Cooperative so long as they are isolated to the western side of the building where other modern installations are found. The western side of Triphammer Cooperative is less visible from a street view. In addition, commercial heat pump covers are available to help maintain the historic aesthetic of Triphammer Cooperative. Some feature more sleek, minimal metal designs and others feature more natural, cedar styles.

Building Envelope Upgrades

The team analyzed potential upgrades to the building envelope, focusing on improving insulation for walls, replacing windows with double-pane models, and installing a new roof. These upgrades were modeled in Sketchbox to achieve target R-values, with energy efficiency improvements assessed by comparing these values against their U-value counterparts. The findings align with the market analysis section, which examined available upgrade options.

Table 6: R-Value Analysis for Building Envelope

Parameter	Window	Exterior Walls	Roof
Current R-Value	1.61	7.697	2.95
Target R-Value	5	19	49

The team used Sketchbox software to model the building under various scenarios. Initially, the current conditions were recreated in the software using data from Triphammer Cooperative, including wall and window areas, resident density, square footage, material types, and other known variables. By adjusting parameters such as insulation levels and window efficiency, the team assessed the potential impact of upgrades on energy consumption and costs.

The results of the analysis, shown in Table 7, compare the baseline scenario with proposed upgrades. This includes the effects of individual and combined upgrades on electricity and natural gas usage. These results are further visualized in Figure 3, which illustrates a comparison across all modeled scenarios, including air-source heat pump integration.

Table 7: Building Envelope Upgrades

Parameter	Current Scenario (Baseline)	Building Envelope Upgrade: Windows, Wall	Building Envelope Upgrade: Roof, Windows, Wall
Electricity (kWh/year)	59191	56840	55623
Natural Gas (therms/year)	11680	10089	8319
Electricity Equivalent (kWh/year)	401415	352448	299370

The reductions in electricity and natural gas consumption, as shown in Table 7 and Figure 3, highlight the benefits of improved building envelope insulation. The decrease in electricity usage through upgrading the building envelope was a slightly unexpected outcome. After further investigation of the software, this is due to reduced runtimes of indoor fans and air conditioning (AC) units. Enhanced insulation minimizes energy loss, enabling these systems to maintain comfortable indoor temperatures with lower energy input.

The analysis demonstrates that as more upgrades are implemented, total energy consumption declines. Among the improvements, roof insulation yielded the most significant reduction in overall energy use, emphasizing its importance in building efficiency initiatives.

The potential impact of doors, specifically the R-value of a Therma-Tru door, was an area potentially worth exploring further. Based on the U-value of 0.28 found on the manufacturer's website, the R-value for a Therma-Tru door is calculated to be 3.57 (*Performance Data for Professionals*, 2024). However, the model in Sketchbox does not currently support modifying door values.

Air Source Heat Pumps

The team explored the potential of transitioning the heating system to an air-source heat pump (ASHP) powered exclusively by electricity, eliminating natural gas consumption. This change represents a significant shift in energy sourcing, with implications for overall energy efficiency and environmental impact. The ASHP was modeled under three scenarios: the current building envelope, upgrades to windows and walls, and a fully upgraded envelope (roof, windows, and walls).

Table 8: Air-Source Heat Pump Modeled in Various Building Envelope Upgrade Scenarios

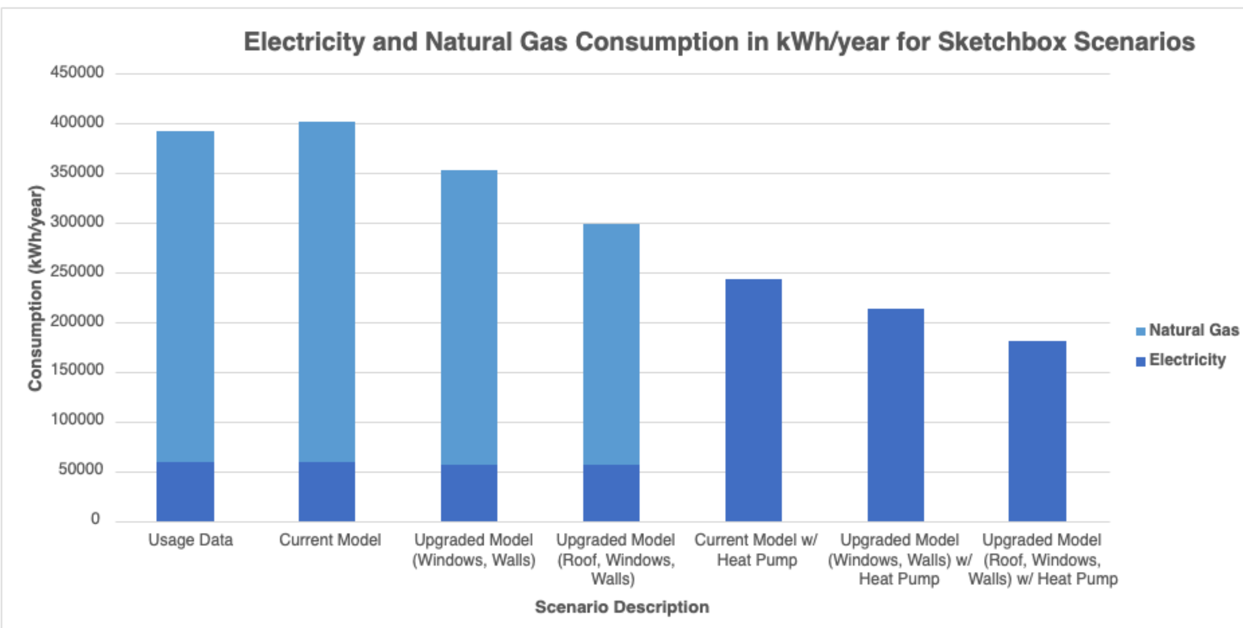
Parameter	Current Scenario (Baseline)	Building Envelope Upgrade: Windows, Wall	Building Envelope Upgrade: Roof, Windows, Wall
Electricity (kWh/year)	243074	212911	180640
Natural Gas (therms/year)	0	0	0

The results, shown in Table 8, highlight a significant reduction in electricity consumption as building envelope upgrades are implemented. Improved insulation and more efficient windows reduce heat loss, thereby lowering the energy demand of the ASHP to maintain comfortable indoor temperatures. The analysis reveals that the combination of ASHP technology with comprehensive building envelope upgrades provides the most energy-efficient outcome. Electricity consumption drops substantially in the fully upgraded scenario, aligning with the goals of reducing reliance on fossil fuels and enhancing sustainability.

The findings are consolidated in Figure 3, which compares electricity and natural gas consumption across all Sketchbox scenarios. The building upgrades in the natural gas models improve insulation, decreasing natural gas usage for heating and electricity needs for cooling. The heat pump further decreases electricity needs with building upgrades.

The combined impact of ASHP installation and envelope upgrades shows the potential for significant energy savings, especially when roof insulation is included as part of the improvements. The comparison also demonstrates the interaction between ASHP systems and an optimized building envelope. By reducing energy demand through envelope enhancements, the ASHP operates more efficiently, further decreasing electricity usage and costs.

Figure 3: Electricity and Natural Gas Consumption in kWh/year for All Sketchbox Scenarios



To estimate the coefficient of performance (COP) of the heat pump, we used the natural gas consumption to represent the heat output of the heat pump. The electricity consumption of the heat pump was treated as the work performed during the compression process. By dividing the heat output (natural gas consumption) by the electricity consumption, we obtained an estimate of the COP for the heat pump.

For the heat pump capacity, we designed it based on the maximum heating demand. Considering cost and weather conditions in Ithaca, we assumed the maximum heating demand occurs when the outdoor temperature is 0°F and the indoor temperature is 65°F. This assumption is grounded in the climate characteristics and historical temperature records of Ithaca. Typically, the minimum winter temperatures in Ithaca do not fall below 0°F. Although extreme temperatures lower than

0°F have occasionally occurred in some years, these events are rare and usually last for only a single day. Designing the heat pump capacity for temperatures significantly lower than 0°F would require additional investment in equipment and installation, as a larger capacity system would be necessary to handle such extreme conditions. However, the benefits of this increased capacity would be minimal, as it would only address rare and short-lived events. Considering the added cost and the limited gains, designing the heat pump capacity based on a minimum temperature of 0°F strikes a reasonable balance between performance and cost. This assumption ensures the system can handle typical winter conditions effectively while avoiding unnecessary oversizing and expense. Using this assumption and the insulation properties of the house, we determined the heat pump capacity to ensure it could meet the peak heating demand under these conditions.

The simulated COP values of the air source heat pump (ASHP) in the table are significantly lower than the expected range for similar systems. This discrepancy may be attributed to two key factors. First, climatic conditions likely play a major role in the observed low COP values. The simulation assumes an outdoor minimum temperature of 0°F during winter. At such low temperatures, the performance of an air source heat pump can drop significantly, as shown in Figure 4 from Langer (2023). Since ASHPs rely on extracting heat from outdoor air, the efficiency of this process diminishes substantially in extremely cold conditions. As a result, the heat pump consumes considerably more electricity to meet the same heating demand, leading to a lower COP. Therefore, the extreme low-temperature assumption of 0°F may have had a significant impact on the heat pump's simulated performance. Second, inaccuracies in the simulation model itself may have contributed to the underestimated COP values. Simplifications in the model, such as the exclusion of advanced heat pump technologies, could have led to an incomplete representation of the system's performance. Additionally, insufficient attention to boundary conditions or the detailed handling of building loads in the simulation could have further skewed the results. Table 9 below summarizes the COP and capacity of ASHP.

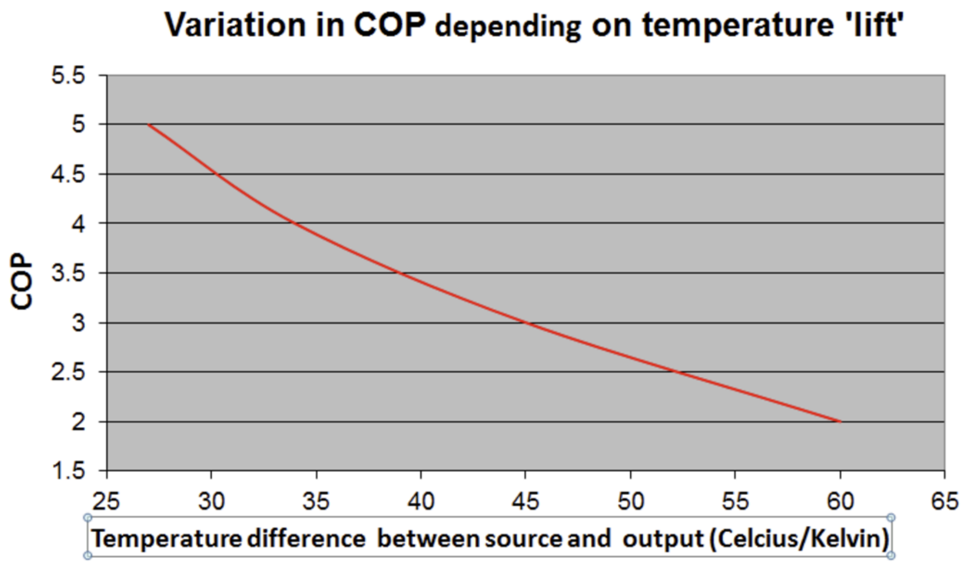
$$\text{Capacity} = [(\Delta T \times A \times U)_{\text{Walls}} + (\Delta T \times A \times U)_{\text{Windows}} + (\Delta T \times A \times U)_{\text{Roof}}] \times 0.000293071$$

Where: (ΔT×A×U) represents the heat loss through walls, windows, and roof, calculated in BTU/h. 0.000293071 is a conversion factor to transform BTU/h into kW.

Table 9: COP and Capacity of Air Source Heat Pump

	Baseline	**Building Envelope Upgrade: Windows, Walls**	**Building Envelope Upgrade: Windows, Walls, Roof**
Heat Pump Capacity (kW)	45	32	11
COP	1.86	1.90	1.95

Figure 4: The Variation in COP depending on Temperature Lift (Langer, 2023)



Solar Photovoltaic Canopy

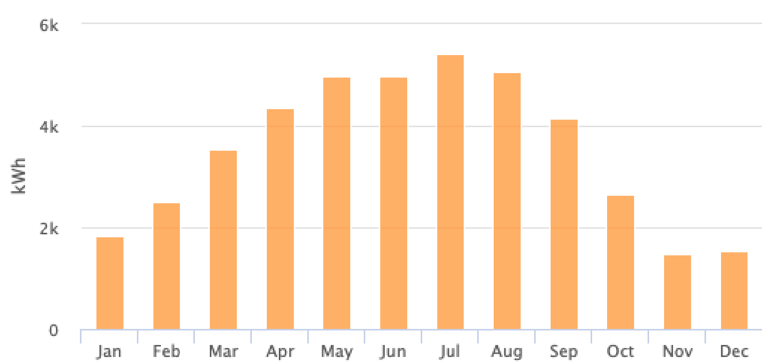
Based on the available area for solar development, we believe that a south-facing solar carport would be the most suitable and viable form of on-site solar generation for Triphammer Cooperative. Figure 5 below shows a preliminary design and layout of a solar canopy for the residents. To create these models and production estimates, the team utilized Helioscope – an industry-standard software in the solar photovoltaic development industry.

Figure 5: Helioscope Design of Solar Parking Canopy

The above system has a nameplate DC system size of 35.4 kW at a tilt angle of 5° and an azimuth of 178.6°. A tilt angle of 5° was implemented as per industry standards, as greater degrees of tilt would increase the wind load incident on the array – leading to a greater need for heavy duty foundation and columns (Lala, 2021). Such structural improvements typically lead to increased costs that outweigh the production gain associated with higher degrees of tilt. Alternatively, the solar canopy designer might choose a standard tilt angle for carport structures in the Ithaca region, namely a 4-in-12 pitch truss angle sloped to the south. This angle implies that for each 12 feet of horizontal run, there is 4 feet of vertical rise. The result is a 18.4-degree tilt angle, which increases productivity per kW of capacity compared to a 5-degree tilt. This choice of angle has the advantage of being familiar to local building inspectors – which may allow for ease in obtaining a building permit for construction.

The system consists of 60 QCells Q.PEAK DUO XL-G11S 590 Watt modules and one Chint Power Systems SCA25KTL-T/EU inverter at 25 kW. This system configuration results in a DC/AC ratio of 1.42. The system is 12 feet tall to allow for sufficient clearance for any vehicles that will park underneath the canopy. Based on Helioscope's estimates, the system is expected to produce 42.45 MWh of electricity per year. As such, the capacity factor of the system (the ratio of the electricity generated over a typical year divided by the installed capacity) is 13.69%. The reported capacity factor is a bit longer than the average capacity factor for solar PV systems installed in New York – approximately 16.8% (Caiazza, 2024). Figure 6 below summarizes the monthly production of the system.

Figure 6: Monthly Production of Solar Parking Canopy



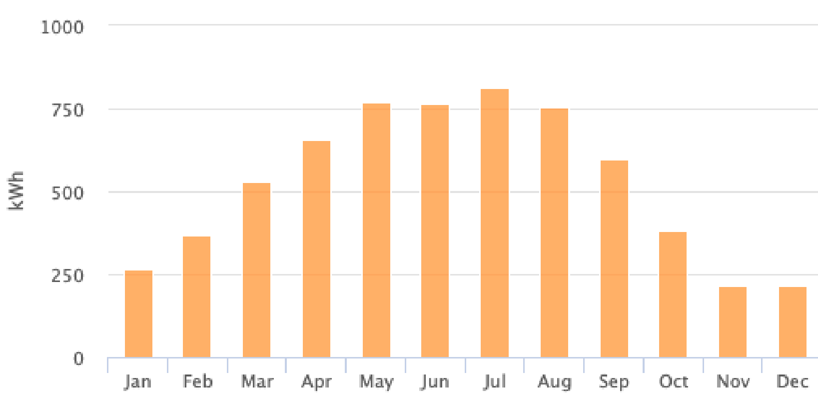
Solar Photovoltaic Rooftop

In addition to the solar parking canopy, we wanted to examine the feasibility of Building Integrated Photovoltaics (BIPV). In BIPV systems, solar modules are utilized as an integral part of the building's envelope – typically by replacing conventional building materials, like roofing shingles, with photovoltaic materials. Figure 7 demonstrates a potential design for a retrofit system utilizing architectural solar shingles:

Figure 7: Helioscope Design of BIPV System

The above design has a DC system size of 6.86 kW using 28 of Bisol's BSO-245 Watt BIPV modules with east-west flush-mounted racking. For this system, three SMA Sunny Boy 2000W inverters were used – resulting in a DC/AC ratio of 1.14. Based on Helioscope's estimate, the proposed system is expected to produce 6.33 MWh per year. As such, the capacity factor of the system is determined to be 11.44%, considerably lower than the state's average of 15.8% (Ciazza, 2024). Figure 8 summarizes the system's expected monthly production:

Figure 8: Monthly Production of BIPV System

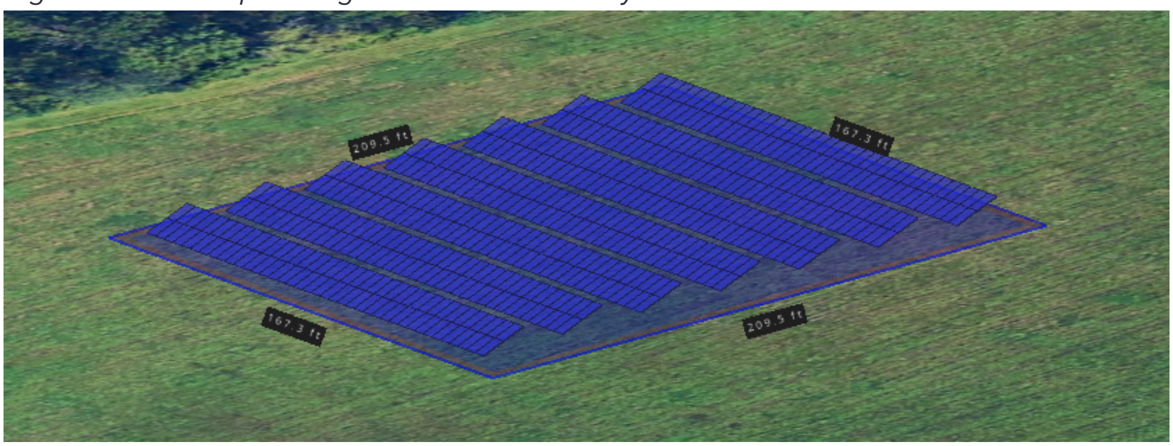


The existing roof architecture limits the available area for efficient solar energy production, thereby reducing the overall viability of the system. In particular, the roof features numerous Dormer windows that present challenges regarding the integration of BIPV materials for Triphammer Cooperative's roof. However, should a re-roofing project be undertaken in the future, modifications to the roof structure could make BIPV integration more attractive.

Offsite Ground-Mount Solar Array

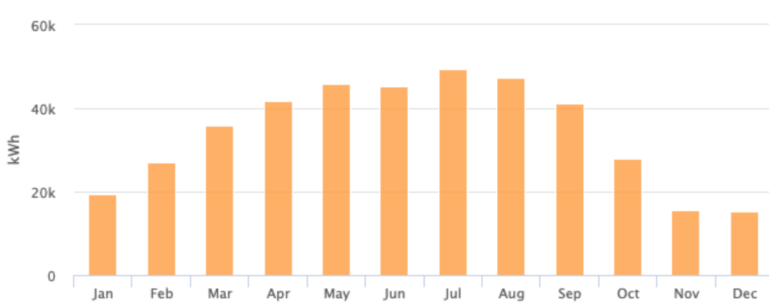
To further our analysis into reducing electricity consumption for Triphammer Cooperative, an off-site ground-mounted solar array was designed to accommodate the current energy load of Triphammer Cooperative – 392.64 MWh/year accounting for both electricity and natural gas consumption. The proposed system has been oversized to ensure that sufficient electricity is produced through the array. While the array's specific location is not the focus of this analysis, its design highlights the scale of solar capacity required for Triphammer Cooperative's energy load. We will assume that the array is located in Ithaca, New York. In addition, we will assume that there is sufficient land available for purchase to install this array. Figure 9 demonstrates a potential design for the off-site ground-mounted solar array:

Figure 9: Helioscope Design of Ground Mount System



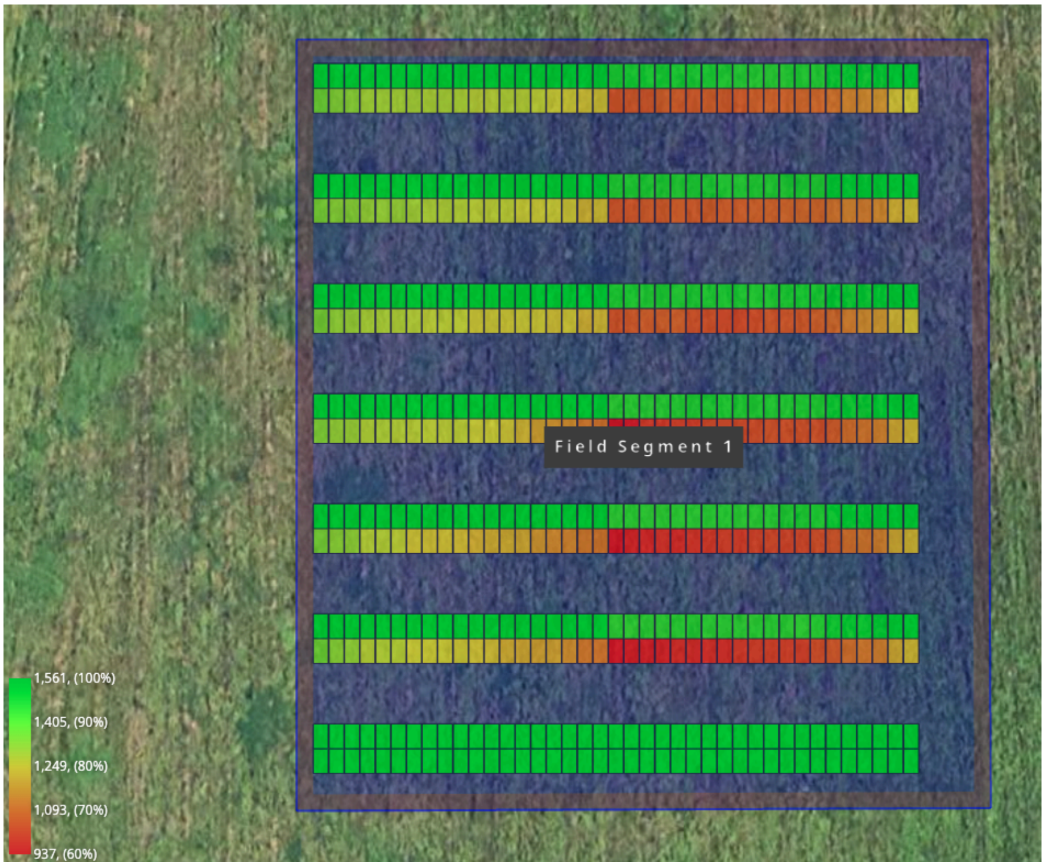
The above design has a DC system size of 322.1 kW using 546 QCells Q.PEAK DUO XL-G11S 590 Watt modules with an azimuth of 180°. For this system, 21 SMA SHP 125-US-20 inverters were used – resulting in a DC/AC ratio of 1.23. The rows of the array are spaced 14.6 feet apart from each other. This inter-row spacing was determined by Helioscope to be the optimal spacing to reduce shading losses. Based on Helioscope's estimate, the proposed system is expected to produce 412.2 MWh per year. As such, the capacity factor of the system is determined to be 14.61%, relatively similar to the state's average of 15.8% (Ciazza, 2024). Figure 10 summarizes the system's expected monthly production:

Figure 10: Monthly Production of Ground-Mount Array



A sensitivity analysis was conducted to evaluate the performance of the solar array at different tilt angles: 10°, 20°, 30°, and 42.4°. The first three tilt angles were chosen as they represent industry-standard values for ground-mounted systems – balancing ease of installation, wind resistance, and sufficient energy production. The 42.4° tilt iteration corresponds to the latitude of Ithaca, New York. This tilt angle is theoretically optimal for maximizing incident sunlight year-round. However, maintaining this tilt angle would result in an abundance of inter-row shading, thereby reducing the total energy production of the system. Figure 11 highlights the areas of inter-row shading for the 42.4° tilt iteration, where some sections of the array experience up to 40% losses associated with inter-row shading.

Figure 11: Inter-Row Shading for 42.4° Tilt



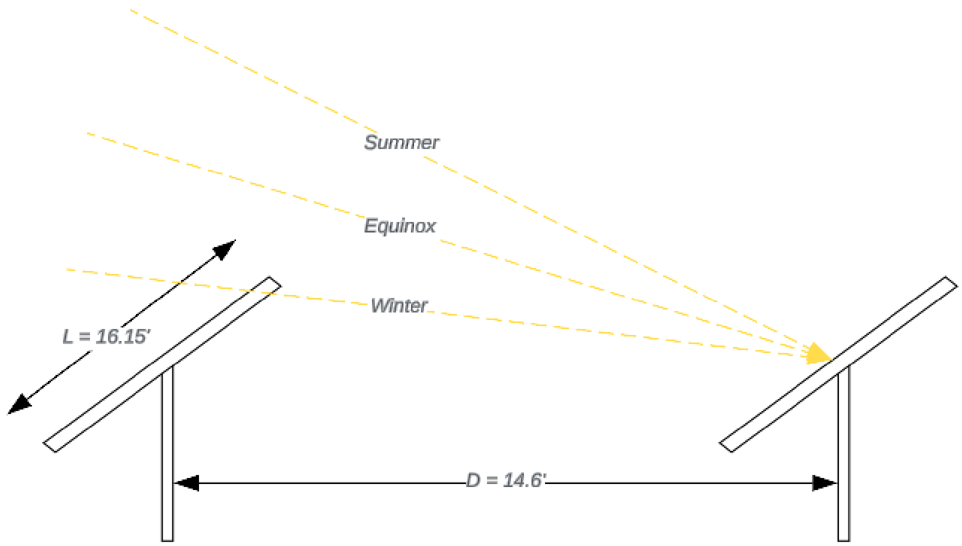
From Table 10, we see that a tilt angle of 20° is the most optimal for this project – providing low overall shading losses while maintaining the highest annual production and capacity factor.

Table 10: Ground-Mount Array Sensitivity Analysis for Tilt Angle

Ground Mount Array Sensitivity Analysis: Tilt				
Parameter	**10° Tilt**	**20° Tilt**	**30° Tilt**	**42.4° Tilt**
Required Area (ft^2)	36907.7	35056.0	33247.9	31200.7
kWh/kWp	1250.1	1279.7	1207.9	1092.9
Shading Losses	0.4%	2.2%	6.7%	12.2%
Estimated Annual Production (MWh/year)	402.7	412.2	389.1	351.8
Capacity Factor	14.27%	14.61%	13.79%	12.47%

However, we do note that there is some loss associated with shading even in the 20° tilt iteration. As such, we may determine the solar altitude angle (α) which is the angle between the horizontal plane of the Earth's surface to the sun's position that will ensure no inter-row shading between panels. Based on the calculated minimum altitude angle, we may determine during which periods of the year the system is anticipated to experience inter-row shading. This concept is visually demonstrated in Figure 12. As the Sun is positioned lower in the sky during the winter months, it is more likely that the photovoltaic system will incur inter-row shading in the winter – thereby reducing the overall efficiency of the system.

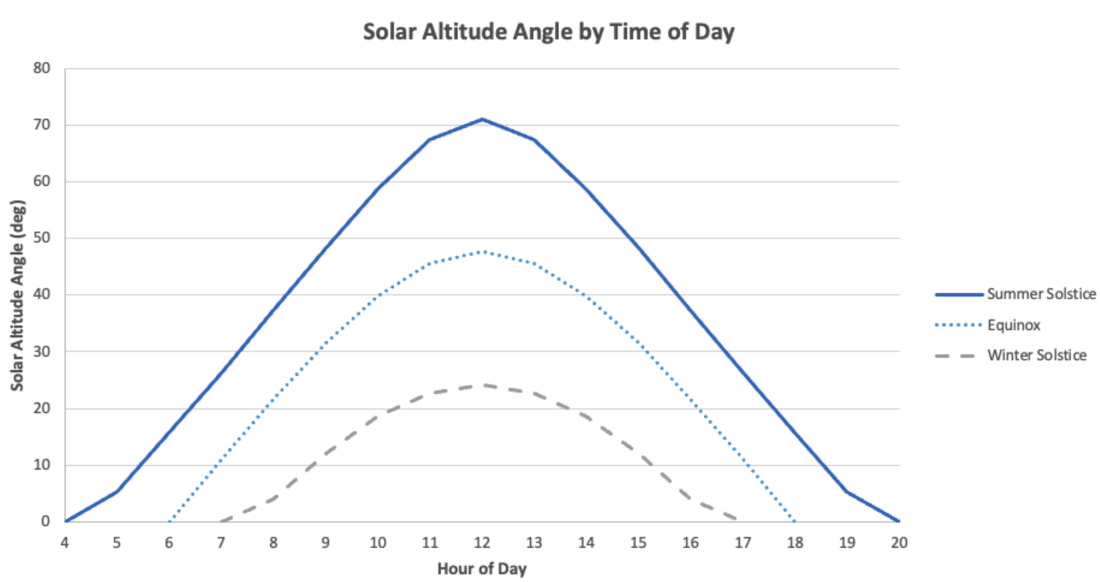
Figure 12: Side View of Ground-Mounted System with Solar Altitude Angles



We will use the following formula to determine the minimum value of α to ensure the system does not experience inter-row shading – where D is the inter-row spacing between the panels (14.6 ft), L is the length of the row (16.15 ft), β is the array's tilt (20°), and γ is the azimuth of the system (180°). $D = \frac{L sin(\beta)}{tan(\alpha)} cos(180 - \gamma)$

From the above formula, we determine the minimum solar altitude angle required to prevent inter-row shading to be $\alpha = 20.723°$. Figure 13 demonstrates the solar altitude angle by time of day between the various seasons. We see that the array may experience far greater inter-row shading in the winter months while in the summer production is not as limited by inter-row shading.

Figure 13: Solar Altitude Angle by Time of Day in Ithaca



Community Solar Adoption

Triphammer Cooperative may wish to explore inclusion in New York's Community Benefit Projects incentive program, and the incentive's purpose is intended to meaningfully increase community solar access for DACs and their residents, while also providing a higher savings rate for eligible subscribers. The incentive is between $0.15 and $0.20/watt for Upstate projects depending on the other adders the project has received.

If Triphammer Cooperative intends to purchase clean electricity from the grid, it will receive 100% clean electricity derived from wind and solar at a rate of $0.139/kWh as a 24-month fixed price (CleanChoice Energy, 2024). Opting into community solar may be advantageous for Triphammer Cooperative, as their average electricity prices from August 2023 to May 2024 were approximately $0.151/kWh.

Overall, Community Solar and grid-supplied Green Power can help the cooperative meet more of its electricity needs with renewable options while realizing cost benefits.

Economic Analysis of Proposed Solutions

The following section will examine the capital and operating costs associated with the proposed solutions. In addition, this section will investigate the Levelized Cost of Heating (LCOH) and Energy (LCOE). These levelized costs help determine the average cost of installing and maintaining the proposed systems over their lifetime. Furthermore, the land acquisition costs associated with the solar photovoltaic ground-mounted system will be examined. Though there is an attractive incentive landscape in Ithaca, the following report will not analyze the anticipated incentives gained for the proposed solutions.

Capital Costs

Building Envelope Upgrades

In this estimation process, we calculated the capital cost required to upgrade the thermal performance of the building envelope based on the current R-values and the recommended R-values. Using insulation material cost data from the document *Guide to Home Insulation* shown in Figure 14, we analyzed each building component (roof, exterior walls, windows, and doors) separately. For each component, we determined the area or quantity and referenced the cost per R-value provided in the guide. We then calculated the cost difference required to upgrade from the current R-value to the recommended R-value and used the following formula to determine the capital costs:

$$Total\ Cost\ =\ \Delta R\ (\frac{Cost}{R})\ (Area)$$

Finally, we aggregated the costs of all components to obtain the total capital cost, providing a basis for optimizing the building's insulation performance. The final capital cost is expected to be about $81248 as demonstrated in Table 11. We would like to note that this approximation of the capital cost associated with the building envelope upgrade is a very rough estimate with huge uncertainty. However, we assert that the estimate should give an approximate level of capital cost of the building upgrades.

Figure 14: Update cost of building envelope from Department of Energy (2010).

Material type	R-value	Cost per square foot	Cost per square foot per R-value
Fiberglass batt (3.5 - 12 inches thick)	13	$0.20 to $0.40	$0.02
	30	$0.60 to $1.00	$0.03
Loose fill such as fiberglass, cellulose, and mineral wool (8 - 23 inches thick)	30	$0.45 to $1.35	$0.03
	50	$0.75 to $2.25	
Open cell polyurethane spray foam (3.5 inches thick)	12.6	$1.70 to $2.50	$0.17
Closed cell polyurethane spray foam (1 inch thick)	6.5	$1.30 to $2.00	$0.25
Expanded polystyrene foam board (1 inch thick)	3.8 – 4.4	$0.20 to $0.35	$0.07
Extruded polystyrene foam board (1 inch thick)	5	$0.40 to $0.55	$0.10
Polyisocyanurate foam board (1 inch thick)	6.5	$0.60 to $0.70	$0.10

Table 11: Capital Cost of Building Envelope Upgrades

Parameter	Window	Exterior Walls	Roof
Current R-Value	1.61	7.697	2.95
Target R-Value	5	19	49
Number/Area	57 Windows	4900 ft^2	3400 ft^2
ΔR	3.39	11.303	46.05
Updated Material	Fiberglass	Spray foam	Fiberglass
Cost per Square Foot/Unit ($/R)	$1100/Window	$0.25/R	$0.03/R
Total Cost($)	$62700	$13851	$4697

Solar Photovoltaic Systems

To assess the financial impact of the proposed solar photovoltaic systems for Triphammer Cooperative, capital cost estimates were obtained using data provided by the National Renewable Energy Laboratory (NREL) (2024). These estimates consider the costs associated with the purchasing of modules, inverters, mourning structures, electrical components, and labor costs. From NREL's (2024) analysis, they detailed that the average cost of solar photovoltaic systems ranging from 2.5 to 10 kW had decreased by 2% between 2023 and 2024 to $4.17/W. Similarly, for systems between 10 and 100 kW, the median capital cost decreased 8% to $3.46/W. However, for systems between 100 to 500 kW, the median capital cost increased by 4% to $2.61/W. Table 12 below summarizes the anticipated capital costs for the various proposed solar photovoltaic systems detailed in the section above.

Table 12: Capital Costs for Solar Systems

Capital Costs: Solar Systems			
System	**System Size (kWdc)**	**Average $/Wdc**	**Capital Cost**
BIPV	6.86	$4.17	$28,606.20
Solar Canopy	35.40	$3.46	$122,484.00
Ground Mount	322.10	$2.61	$840,681.00

Air Source Heat Pump

To estimate the capital cost of air source heat pumps (ASHP), we considered both the fixed cost and the variable cost associated with the system capacity. According to NREL (2024), the fixed cost represents the baseline expenses for equipment purchase and standard installation, while the variable cost is dependent on the nominal heating or cooling capacity of the ASHP. For ducted ASHPs, the fixed cost was estimated to be approximately $3907.01, and the variable cost was calculated as $155.17 per MMBTU/h (approximately $44.30 per kWth). For ductless systems, the total cost per ton (3.5 kWth) was derived based on market data, ranging from $2000 to $10,000 per ton depending on system efficiency and installation complexity. The capital cost of ASHPs is influenced by several key factors. System efficiency plays a significant role, as higher efficiency systems with improved performance metrics, such as higher HSPF or SEER ratings, tend to have increased costs. This reflects the additional investment in advanced technology and enhanced performance. Climate conditions are another crucial factor; in colder regions, high-efficiency cold-climate ASHPs (ccASHPs) are often necessary, resulting in higher costs due to their more robust design and components. Additional installation requirements, such as upgrading electrical panels, sealing ducts, or improving insulation, can also substantially increase overall costs. Furthermore, market and regional variations, including local labor costs, regulatory requirements, and market dynamics, contribute to the variation in ASHP capital costs across different locations. In this project, we assume the most basic case. Table 13 below summarizes the capital costs for ASHP.

Table 13: Capital Costs for Air Source Heat Pumps

	Baseline	Building Envelope Upgrade: Windows, Walls	Building Envelope Upgrade: Windows, Walls, Roof
Heat Pump Capacity (kW)	45	32	11
Fixed Cost	$3907	$3907	$3907
Variable Cost ($44.30/ kW)	$1993	$1417	$487
Total Capital Cost	$5900	$5324	$4394

Operating Costs

Though solar photovoltaic systems do require routine maintenance to ensure optimal performance, these costs are relatively minor compared to the systems' capital costs. As such, we will assume that there are no operating costs associated with the solar photovoltaic systems after installation. In addition, we will assume that there are no operating costs associated with the building envelope upgrades after they have been installed.

We began by collecting the local electricity prices for each month of the year. Using these monthly data, we calculated the annual average electricity price, assuming it remains constant throughout the year. Next, we calculated the electricity consumption attributable to the heat pump by subtracting the electricity consumption without the heat pump from the electricity consumption with the heat pump. Finally, we multiplied the heat pump's electricity consumption by the average electricity price to determine the heat pump's operating cost. This methodology was applied to three different scenarios to evaluate the operating costs of the heat pump under varying conditions.

From here, we determine the impact of net metering revenue from our solar photovoltaic systems. In particular, we examine the electricity costs associated with installing the parking canopy (35.40 kWdc, 42.45 MWh/year), a ground-mount system (322.10 kWdc, 412.2 MWh/year), or purchasing power from the grid. We see that installing a ground-mount solar system presents an excellent opportunity for Triphammer Cooperative to benefit from net metering. As the system generates significantly more electricity than the building consumes, the excess energy can be sent back to the grid, earning credits through net metering. Such credits may help to reduce utility costs during periods when the system produces less energy, such as during the winter season. Additionally, the surplus electricity contributes to the local grid by supporting renewable energy adoption and grid stability. We will proceed by assuming that the net metering revenue on a $/kWh basis is approximately 50% of the annual average electricity price (SunShot, 2014). Table 14 below summarizes the Operating Costs of ASHP and Income from the sale of excess electricity production.

Table 14: Operating Costs of Air Source Heat Pump and Net Metering Income

	Baseline (45 kW)	Building Envelope Upgrade: Windows, Walls (32 kW)	Building Envelope Upgrade: Windows, Walls, Roof (11 kW)
Power Purchase from Grid without Solar	-$27864	-$23652	-$18946
Rooftop Solar	-$26908	-$22696	-$17990
Solar Canopy	-$21434	-$17219	-$12513
Groundmount System: Net Metering Income	+$12811	+$15095	+$17541

Levelized Cost of Electricity

To allow for more informed decision-making between the various solar photovoltaic systems, we will proceed with calculating the Levelized Cost of Electricity (LCOE) of each of the three proposed systems. The LCOE is a metric that allows for an objective comparison between the average revenue per unit of electricity generated to cover the costs of building and operating each system over its lifetime. For our analysis, we will assume that the solar modules have a lifetime of approximately 25 years and an associated interest rate of 5% (Langone, 2024). The formula for determining the Levelized Cost of Electricity is shown below:

$$LCOE = \frac{Capital\ Costs + Operating\ Costs}{Electricity\ Production}$$

As mentioned previously, we will assume that the operating cost for each of the solar photovoltaic systems is negligible. We will annualize the capital cost of the system using the following:

$$A = P(A/P,\ i\%,\ N) = P\left(\frac{i(1+i)^N}{(1+i)^N - 1}\right)$$

We determine the LCOE for each solar photovoltaic system as follows in Table 15:

Table 15. Levelized Costs of Electricity for Solar Photovoltaic Systems

System	Capital Cost	Annual Production	Levelized Cost of Electricity
Rooftop (6.86 kW)	$28,606.20	6.33 MWh/year	$0.320/kWh
Solar Canopy (35.4 kW)	$122,484.00	42.45 MWh/year	$0.205/kWh
Groundmount (322.1 kW)	$840,681.00	412.2 MWh/year	$0.142/kWh

The analysis of the LCOE for the various proposed solar systems reveals distinct trends across the system types. For instance, according to Santos (2023), the average unsubsidized LCOE for residential rooftop solar photovoltaics ranges from $0.117/kWh to $0.282/kWh. In contrast, the

LCOE for the proposed rooftop system is significantly higher at $0.320/kWh. The higher-than-average values for the system's LCOE are likely attributed to the system's low annual production and specific yield. Triphammer Cooperative's rooftop offers very little feasible space for rooftop solar installation, thereby resulting in relatively low levels of production.

In comparison, the solar parking canopy and ground-mounted systems both exhibit LCOE values that align with the United States average unsubsidized LCOE. For parking canopies between 10 and 100 kWdc, the average unsubsidized LCOE ranges from $0.074/kWh and $0.229/kWh. For commercial and industrial solar installations (100-500 kWdc), the average unsubsidized LCOE ranges from $0.032/kWh to $0.155/kWh (Santos, 2023).

Levelized Cost of Heating

The Levelized Cost of Heating (LCOH) is a critical metric to evaluate the economic viability of heating systems, representing the average cost of generating heat over the system's lifetime. To assess the LCOH for the proposed heating systems, we conducted our analysis for the three recommended ASHP system sizes – 45 kW, 32 kW, and 11 kW – as determined by the output of the Sketchbox models. We will also consider the various possible electricity sources: rooftop, parking canopy, and ground-mounted solar systems, as well as grid-purchased electricity. For our analysis, we will assume that the heat pumps have a lifetime of approximately 25 years and an associated interest rate of 5% (Langone, 2024). The formula for determining the Levelized Cost of Heating is shown below:

$$LCOH = \frac{Capital\ Costs + Operating\ Costs}{Annual\ Heat\ Production}$$

We determine the LCOH for the proposed air source heat pumps as follows in Table 16:

Table 16: Levelized Costs of Heating for Air Source Heat Pumps

Electricity Source	Baseline (45 kW)	Building Envelope Upgrade: Windows, Walls (32 kW)	Building Envelope Upgrade: Windows, Walls, Roof (11 kW)
Power Purchase from Grid	$0.153/kWh	$0.153/kWh	$0.153/kWh
Rooftop Solar	$0.148/kWh	$0.145/kWh	$0.146/kWh
Solar Canopy	$0.118/kWh	$0.110/kWh	$0.102/kWh
Groundmount System	-$0.067/kWh	-$0.096/kWh	-$0.137/kWh

The analysis of the LCOH for the various proposed air source heat pump systems reveals significant trends across the system sizes and their associated electricity generation sources. For instance, according to the International Energy Agency (2021), the average unsubsidized LCOH for electric air source heat pumps ranges from $0.118/kWh to $0.208/kWh. We see that the proposed systems are either within this average range or are substantially lower. In particular, the ground-mount systems – due to their net metering benefits – provide a negative LCOH for the air source heat pumps, indicating significant returns for the consumer.

Overall, if the budget of Triphammer Cooperative is limited, it is recommended to pursue a solar canopy installation, especially with building envelope upgrades. For a focus on long-term cost savings and emission reduction, the ground-mount photovoltaic system is the more attractive option, particularly in high-demand scenarios.

However, both systems significantly reduce reliance on fossil fuels and decrease CO_2 emissions. The ground-mount system with its larger energy output, contributes more to mitigating carbon emissions.

Land Acquisition Costs

A 20° tilt system necessitates 35056 square feet (0.805 acres) of available land for construction and maintenance. If we plan on keeping this solar system in Ithaca, NY, then we would need to purchase an open plot of land that a) minimizes the presence of large foliage that obstructs sunlight from reaching the solar photovoltaics and b) is open enough to support a solar grid. A plot of land such as the one present on Hornbrook Road, Ithaca, NY 14850 satisfies these qualifications while also providing 3.69 total acres. The payment plan provided by the real estate company selling this land amounts to $274/month ($3288/year for 30 years) assuming a 20% down payment and 6.616% interest rate on the total $44,900 investment. Depending on the credit/financial status of the University, this interest can vary. However, we will assume that the default down payment and interest rate provided by realtor.com applies. There are a myriad of other plots of land available through various realtors in Ithaca, New York. For the purposes of this report, we will assume that our acquisition for our offsite solar array will derive from the Hornbrook Road listing. As such, the land acquisition costs associated with the installation of the ground-mounted solar system will likely add an additional 0.797 cents per kWh to the LCOE – resulting in a 5.61% greater LCOE for the system at $0.149/kWh.

Ecological Analysis of Proposed Solutions

Avoided Carbon Emissions

Based on the total electricity produced by each of the solar systems that we plan on implementing, we can calculate the number of CO_2 equivalent emissions avoided by each system. Triphammer Cooperative derives its heating from natural gas currently. We will assume that the emissions of CO_2 equivalents will be on the basis provided by the U.S. Energy Information Administration of 0.97 pounds CO_2 equivalents per kWh of electricity produced by natural gas (2023). This will be converted to 0.44 metric tons of CO_2 emitted per MWh of natural gas consumed.

Table 17: Metric Tons of CO_2 Equivalent Avoided From Solar Systems

	Solar Canopy (35.4 kW dc)	**Solar Rooftop (6.86 kWdc)**	**Groundmount System (322.1 kWdc)**
Electricity Produced per year (MWh/yr)	42.45 MWh/yr	6.86 MWh/yr	412.2 MWh/yr
CO_2 Equivalents Avoided (tonnes/year)	18.68 Metric Tons	3.02 Metric Tons	181.37 Metric Tons

It should be noted Triphammer Cooperative's total annual electricity is approximately 392.64 MWh/year. Therefore, we assume that the excess electricity produced by the ground-mount system (which would be 412.2 MWh/year - 392.64 MWh/year = 19.56 MWh/year) will also go to avoiding CO_2 equivalent emissions from natural gas, given that natural gas is a major component of Ithaca's electricity system.

By nearly an order of magnitude, the off-site ground-mount system is the best at mitigating Ithaca's CO_2 equivalent emissions when compared to the solar parking canopy.

We also make the important assumption that every kWh of solar energy produced by each of the solar systems in Table 17 is replacing one kWh of heat produced by natural gas.

Avoided Carbon Emissions by Air Source Heat Pumps and Building Upgrades

Based on the simulation data from Sketchbox, the reduction in natural gas consumption was calculated by first converting the natural gas usage in therms to kilojoules using a conversion factor of 105505.59 kJ/therm. This total energy value was then divided by the energy content of natural gas, assumed to be 45357 kJ/kg, to obtain the avoided natural gas consumption in kilograms per year. For the calculation of the avoided CO_2 emissions, the United States Environmental Protection Agency (EPA) Greenhouse Gas Equivalencies Calculator was used. This tool provided the emissions factor for natural gas, which allowed the conversion of the avoided natural gas in kilograms into equivalent metric tons of CO_2 emissions avoided. The results show significant environmental benefits, particularly in scenarios where the building envelope was upgraded, demonstrating the compounded impact of efficient energy systems and enhanced insulation. The results are shown in Table 18 below:

Table 18: Natural Gas and CO_2 Equivalents Avoided per Year by Building Upgrades

	Baseline with ASHP	Building Envelope Upgrade: Windows, Walls with ASHP	Building Envelope Upgrade: Windows, Walls, Roof with ASHP
Natural Gas Avoided (kilograms/year)	27169 kg/year	23468 kg/year	19351 kg/year
CO2 Equivalent Avoided (tonnes/year)	61.8 tonnes/year	53.4 tonnes/year	44 tonnes/year

Extraction of Raw Materials for Manufacturing Systems

Raw Materials Needed for Solar Panels

Though solar technology is essential in accelerating the clean energy transition, the extraction of the raw materials necessary to produce the solar modules poses significant environmental impacts. The most common type of solar photovoltaic panels is crystalline silicon – composed of 76% glass, 10% plastic polymer, 8% aluminum, 5% silicon, 1% copper, and less than 0.1% silver and other metals (Institute for Sustainable Futures, 2019). The mining and processing of such materials often pose significant environmental consequences, including habitat destruction, soil erosion, water pollution, and the emission of air pollutants. In addition, such rare earth elements are associated with energy-intensive mining practices and the generation of toxic waste byproducts. For instance, silica mining can contaminate water resources during the processing of the silica ore. If the wastewater is not properly handled and discharged, residual chemicals and suspended solids may contaminate surface and groundwater sources – thereby harming nearby aquatic ecosystems and depleting the water quality for nearby communities (Rahiman, 2023). As such renewable energy sources require such vast amounts of critical earth mineral resources, it is vital to ensure the security of the world's mineral supply while also ensuring safe mining practices that serve to protect the surrounding environment.

Raw Materials Needed for Air Source Heat Pumps

The raw material requirements for air-source (ASHP) vary across components and are broken down by Greening and Azapagic (2012). Common materials include low-alloyed steel for evaporators and condensers, reinforcing steel for housing and compressors, and copper for wiring, piping, and expansion valves. Elastomer is used for pipework insulation, while polyvinyl chloride (PVC) is used for wiring insulation. Polyolester oil is required for lubrication. ASHPs use copper for air fans, while GSHPs use HDPE. Refrigerants (R-134a) are needed for all systems, with losses occurring during manufacturing and operation. For assembly, medium-voltage electricity and natural gas are consumed. In addition, under-floor heating systems across all pumps require sand, cement, aluminum, LDPE, and polystyrene. GSHPs and WSHPs use HDPE and ethylene glycol for heat collector pipework and insulation, and various materials like cast iron, brass, and cement for additional components. Installation processes require diesel, and operation uses electricity. Maintenance involves refrigerant replenishment. Decommissioning results in the recycling or waste of various materials like steel, aluminum, copper, and plastics.

Land Use

Solar photovoltaic systems, particularly ground-mounted arrays, can have an impact on land and soil quality. Installing solar photovoltaic (PV) systems on open land may lead to soil degradation, which includes the loss of soil fertility, erosion, compaction, and alteration of natural ecosystems.

Soil Degradation

Removing plants for panel installation exposes soil to direct sunlight, wind, and rain, increasing erosion risks. Removing plants for panel installation exposes soil to direct sunlight, wind, and rain, increasing erosion risks. Changes in surface water flow patterns caused by panel placement and related infrastructure can lead to localized flooding or drought conditions, further stressing the soil.

Solar farms may fragment habitats and affect local flora and fauna. Vegetation removal can reduce biodiversity and disturb natural ecological processes. Soil microbial communities, critical for nutrient cycling, may be also disrupted by construction and prolonged exposure to altered environmental conditions. Decreased soil productivity and increased runoff can lead to downstream impacts, such as sedimentation in nearby water bodies and reduced water quality. Once degraded, soil recovery is slow and may require significant intervention to restore its health.

Social Analysis of Proposed Solutions

The residents of Triphammer Cooperative have already been cited as having dissatisfaction with the process by which Cornell University determines the rent prices for tenants. In this case, the economic effects of our proposal have inherently social consequences. The financial burden of this problem presumably falls upon the tenants. Cornell University and the City of Ithaca, however, are responsible for the renewable energy guidelines that initially drove this project. Therefore, it could be argued that the burden of paying for these renewable renovations to this building should fall upon Cornell and Ithaca.

There are tremendous social implications to the decision of who is financially responsible for the installation of a heat pump system (alongside an offsite solar array and improved insulation) in Triphammer Cooperative. Should tenants be made to pay extra in their rent prices for the sake of electrification and green energy installation within their homes? Or are the decision-makers (Cornell University in this case) being made to front the necessary finances?

The construction of our proposed off-site solar array does imply local economic benefits, creating short-term construction-based green-collar jobs alongside long-term maintenance positions. The same green-collar job principles apply to the electricians and building managers who will be responsible for installing the heat pump system in Triphammer Cooperative and removing the current natural gas heating system.

It is important to note that decarbonizing the heating system of Triphammer Cooperative would serve as an informal pilot project for Cornell University's switch to green heating and electricity. Given Ithaca and Cornell's Green New Deal Commitments, the manner by which the co-op works in tandem with the Ithaca Landmarks Preservation Commission to decarbonize the building will set a precedence for how other Cornell residential centers go about this difficult process, with all of the social and economic sacrifices that are undertaken and benefits that are achieved.

Conclusion

Through analyzing the environmental, economic, and social impacts of the proposed low-carbon technologies, we seek to provide further insight for Cornell University to meet its aggressive and ambitious goal to reach carbon neutrality by 2035. In particular, the report highlighted the energy conservation and carbon emission reduction potential for implementing air source heat pumps, building envelope upgrades, and solar photovoltaics for Triphammer Cooperative. Through our preliminary evaluation, we determine that building envelope upgrades to the windows, doors, walls, and roof of Triphammer Cooperative may significantly reduce the energy demand required for the building's heating and cooling. In addition, the implementation of air-source heat pumps may provide highly efficient heating and cooling while solar photovoltaics would allow for the production of clean energy – reducing Triphammer Cooperative's reliance on the electricity grid.

However, the historic nature of Triphammer Cooperative presents a set of unique challenges and opportunities to investigate further. As Triphammer Cooperative is situated in the Cornell Heights Historic District, the historic charm of the building's exterior must be maintained. The regulations surrounding the historic preservation of Triphammer Cooperative and the Cornell Heights Historic District may inhibit the installation of low-carbon technologies on the building's exterior. In particular, the installation of air source heat pumps and on-site solar photovoltaics may directly conflict with the architectural charm of Triphammer Cooperative. Further collaboration with the Ithaca Landmarks Preservation Commission would be beneficial to determine which exterior changes may be compatible with preserving the historic character of Triphammer Cooperative.

In addition, the team recommends evaluating the feasibility of battery energy storage systems (BESS) as a low-carbon energy solution. Implementing a BESS would allow for reduced dependence on the grid for electricity – protecting Triphammer Cooperative and similar residences from power outages. Additionally, we recommend investigating the interconnection costs of installing solar photovoltaic systems to enhance our economic analysis of each system's capital costs. Lastly, it would be beneficial to explore the economic impact of the proposed technologies on the residents of Triphammer Cooperative. As the co-op strives to provide a welcoming environment and community for Cornell's diverse population, it is vital to ensure that the residents are not inundated with the immense economic burden associated with the proposed solutions. Further collaboration with Cornell University's Student and Campus Life would be necessary to evaluate the impacts on rent for the co-op's residents.

Overall, this project sought to examine and explore the feasibility and effectiveness of air source heat pumps and solar photovoltaics for Triphammer Cooperative to minimize its reliance on traditional energy sources and lower its overall energy demands. We hope this study contributes to advancing the climate action initiatives already in motion at Cornell University. By highlighting the potential of these innovative, sustainable technologies, our report aims to serve as a foundation and inspiration for further exploration into alternative low-carbon strategies.

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