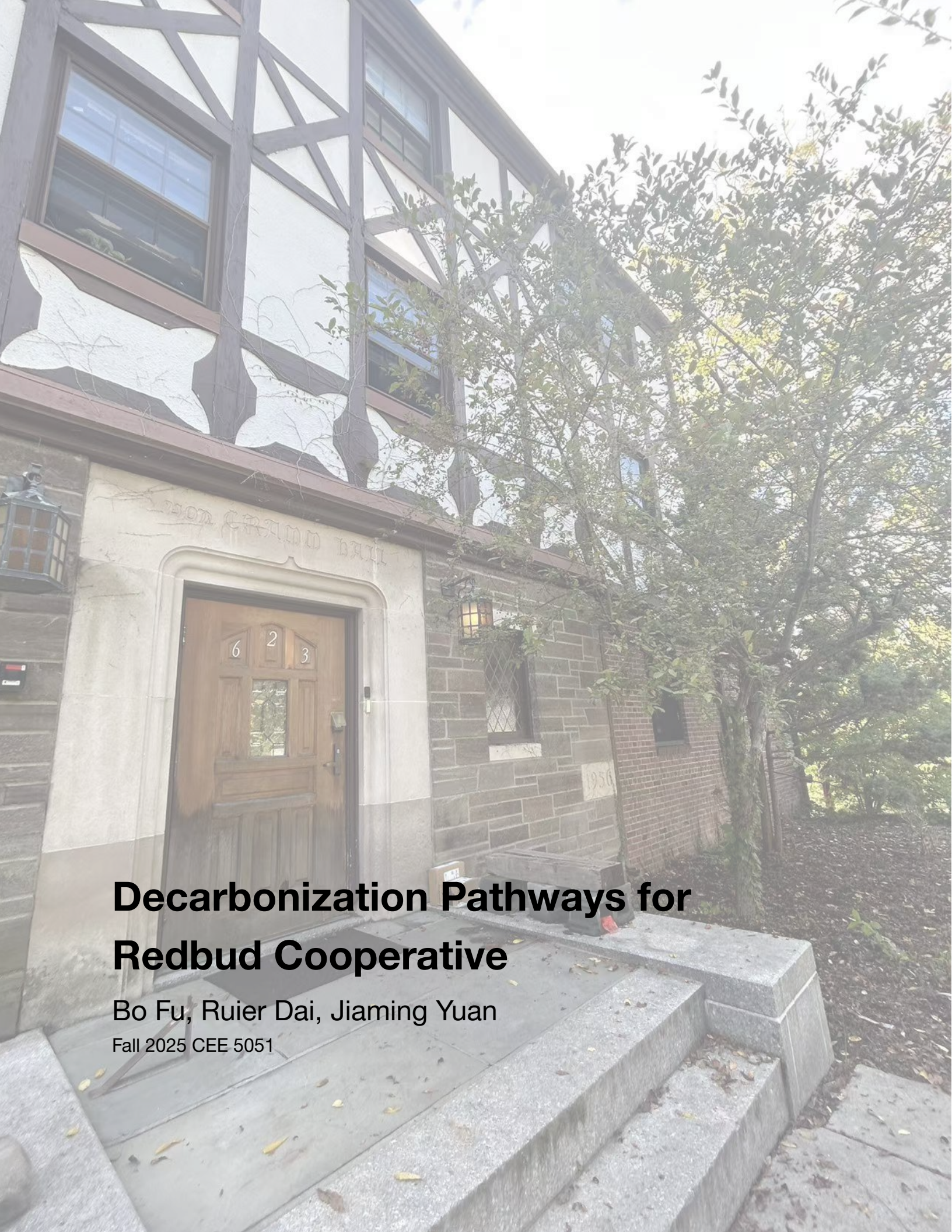




Decarbonization Pathways for Redbud Cooperative

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Team Member Introduction

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Ruier Dai

Ruier is currently pursuing a Master's degree in Civil and Environmental Engineering at Cornell University, starting in Fall 2025. She completed her undergraduate studies at Southeast University in China, where she participated in a water purification project in Nanhua, Yunnan, providing low-cost clean water solutions for local residents. During her exchange studies in Stockholm, Sweden, she developed a strong interest in sustainable urban planning. At Cornell, Ruier is focusing on water resources management and enhancing her modeling and analytical skills.

Jiaming Yuan

Jiaming is currently a Bachelor of Science and Master of Engineering student from San Francisco, California in Cornell University's Environmental Engineering program. She has an interest in water treatment processes and design. She has also helped develop a building proposal standard for the City of Ithaca's existing buildings in Cornell Engineering's Leadership Program. Her career objectives after graduation are to contribute to water treatment and resource management projects in the western United States in order to help build resiliency for small communities and climate change.



Project Motivation

Anthropogenic climate change, driven by the overconsumption of fossil fuels, is one of the most pressing issues affecting countries globally. The impacts of climate change can endanger human livelihood, ecosystem services, and infrastructure. To proactively address the challenges that climate change poses, Cornell University has committed to a climate action plan and net carbon neutrality by 2035 (Climate Action Plan, n.d.). This commitment has made Cornell a leader among universities in the nation in campus sustainability.

In order to achieve net carbon neutrality, fossil fuel usage in campus buildings must be reduced or offset. Some of the biggest challenges to fossil fuel reduction on campus lie in the university's historic buildings, which were not built with energy efficient systems or carbon neutrality in mind. Residential buildings are the second sector with the second largest natural gas usage in the United States, accounting for about 14% natural gas usage in 2023 and over 40% energy consumption by residential buildings being natural gas (USEIA, 2021). Especially in Ithaca, the largest areas of natural gas consumption are in heating systems and end-use electricity consumption. Decarbonizing Cornell's older buildings through seamless integration with scheduled maintenance or upgrades would greatly reduce the amount of fossil fuels, natural gas in particular, that is consumed by the campus. Previous projects at Cornell include a decarbonization plan for residential housing such as Triphammer Cooperative.

This decarbonization plan for Redbud Cooperative continues the efforts of Cornell's cooperative housing groups in contributing to a carbon neutral campus. Ideally, the building can achieve 100% decarbonization through the upgrade of heating systems, cooking units, and switch to electricity supplied by renewable energy sources. However, full decarbonization is ambitious and often infeasible given time and cost constraints. Therefore, the proposal seeks to assess several carbon-saving actions, provide estimated carbon dioxide (CO₂) emissions savings, and outline two decarbonization pathways – full and partial decarbonization pathways – for the upcoming decade in order to inform the residents and administration of Redbud Cooperative of the most feasible and impactful upgrades to prioritize.

Project Goals

The general goal of this project is to provide two pathways for the decarbonization of the Redbud building: a fully net zero retrofit and a list of alternatives to achieve partial decarbonization. The fully decarbonized pathway would likely involve air-source heat pump (ASHP) technology with solar photovoltaic (PV) power. This initiative aligns with Cornell University's commitment to carbon neutrality by 2035 and aims to demonstrate the feasibility of 100% renewable energy heating systems for campus buildings. To accomplish this general goal, this project:

1. Promotes carbon neutrality and support the Sustainable Development Goals:
This project seeks to reduce the Redbud building's dependence on fossil fuels by replacing conventional gas boilers with a solar-powered ASHP system. The retrofit will contribute to Cornell's carbon-neutral vision by lowering direct greenhouse gas emissions and improving the building's overall sustainability performance.
2. Reduces energy consumption and operating costs:
By optimizing system design and control strategies, the project aims to enhance energy utilization efficiency and minimize long-term operational expenses. Through full electrification and renewable energy integration, the building will achieve lower lifecycle energy demand compared to traditional heating systems.
3. Demonstrates the technical feasibility of a 100% renewable energy solution:
The project will evaluate the technical performance, stability, and scalability of the proposed ASHP + PV configuration. The outcomes will serve as a reference model for future campus-wide low-carbon building retrofits and provide data-driven insights into system design and performance optimization.
4. Enhances the professional and collaborative skills of project members:
Participation in this project will provide team members with hands-on experience in sustainable building systems and low-carbon design.

Scoping Statement and Clarifying Assumptions

Limitations

This study is limited to the Redbud Cooperative, which means the results may not be generalized to the entire campus. This study does not include detailed design drawings or construction logistics. The analysis is primarily based on available official energy data and reasonable assumptions based on existing reports and past campus projects. Additionally, no energy audit or residential type units were considered for technology and building upgrades.

The economic calculations are simplified, which means the results are provided for informational purposes only and are not guaranteed to be accurate. Energy prices and incentive programs are assumed to remain stable during the analysis period, which may not be the case in reality. The policy, behavioral, and maintenance aspects of the project, particularly those related to historic building preservation, are discussed at a conceptual level rather than a technical level. Due to these limitations, the results of this study should be considered a preliminary assessment in order to guide future feasibility and implementation efforts.

Assumptions

To maintain consistency and controllability in the process of our analysis, several assumptions should be made at the beginning. The building's current energy consumption is considered typical for a normal year. Building envelope upgrades, such as insulation and window improvements, are expected to reduce heating demand by approximately 25% to 30% (USDOE, 2023). The seasonal coefficient of efficiency (COP) for the air-source heat pump system is projected to be between 3.0 and 3.2, which is similar to typical values from cold-climate models used by New York State (NYSERDA, 2023).

In terms of solar photovoltaic systems, module efficiency is assumed to be approximately 18%, with 0.5% of an annual degradation rate, which could be found in long-term monitoring results reported by the National Renewable Energy Laboratory (NREL) (NREL, 2012, 2024). As recorded, average solar radiation in Ithaca is approximately 3.6 kWh/m²/day (NREL, 2020). Electricity and natural gas prices are assumed to be \$0.15/kWh and \$0.87/kcal, with an average annual increase of approximately 2% (USEIA, 2025). Additionally, a 5% discount rate is used for the lifecycle cost analysis.

In terms of the equipment lifespan, the ASHP units was assumed to be 20 years, the photovoltaic systems was assumed to be 25 years, which are published by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (ASHRAE, 2021). Besides, routine maintenance and occupant behavior were assumed to remain relatively stable throughout the study period.

Emission factors are based on data from the U.S. Environmental Protection Agency. The report states that grid electricity emits approximately 0.35 kg of CO₂ per kilowatt-hour (kWh), and natural gas emits approximately 5.3 kg of CO₂ per kWh (EPA, 2022, 2023). All estimated CO₂ emissions were calculated using the USEPA online calculator (EPA, 2024), and no further calculations or literature review was done. Additionally, all percentage estimates for CO₂ reductions from building upgrade implementation assume the use of 100% clean electricity source for operation of new units. For example, the 86% of current CO₂ emissions can be reduced by electrifying space heating and domestic hot water use assumes that electricity the new air-source heat pump uses will be from 100% clean electricity sources, not the standard fuel mix that Redbud currently uses.

Historic Energy Usage and Considerations

Background on the Redbud Cooperative Building

Redbud Cooperative was built around 1952–1956, and is used as a residential dormitory. Although not a designated historic building, it is located within a historic neighborhood among Cornell's other residential cooperatives. Thus, it is required to preserve the fidelity of the building's outer appearance to remain compatible with its original Tudor Revival style. Historical preservation codes may require further consideration of large-scale upgrades that may be visible from Redbud's exterior.

The heating system of the house is typical for its location. The house currently relies on natural gas boilers for space heating and domestic water heating. There are two aging units from 2002 that are low efficiency and past their service life, as well as one new unit installed in 2024, which is higher efficiency but still uses natural gas. Space heating is achieved by circulating hot water through radiators throughout the building. The existing heat conveyance infrastructure would be intensive to replace, so upgrades that adhere to the current system are noted to be preferable.

There is also a low-efficiency commercial cooking range that can serve around sixty meals per day. The gas on these cooktops burn perpetually, even when the

cooktop is not in active use. A neighboring cooperative, 660 Stewart Avenue, upgraded a similar cooktop to an induction cooktop several years ago, so Redbud building management is familiar with the process of making such an upgrade.

Baseline Energy Usage and CO₂ Emissions

Natural Gas Usage

Redbud Cooperative currently relies on natural gas and electricity for its building uses. The primary use for direct natural gas burning is for space heating, domestic hot water (DHW), cooking, and the drying machine. Due to Ithaca's climate, space heating contributes the most significant natural gas use, and also the greatest equivalent CO₂ emissions.

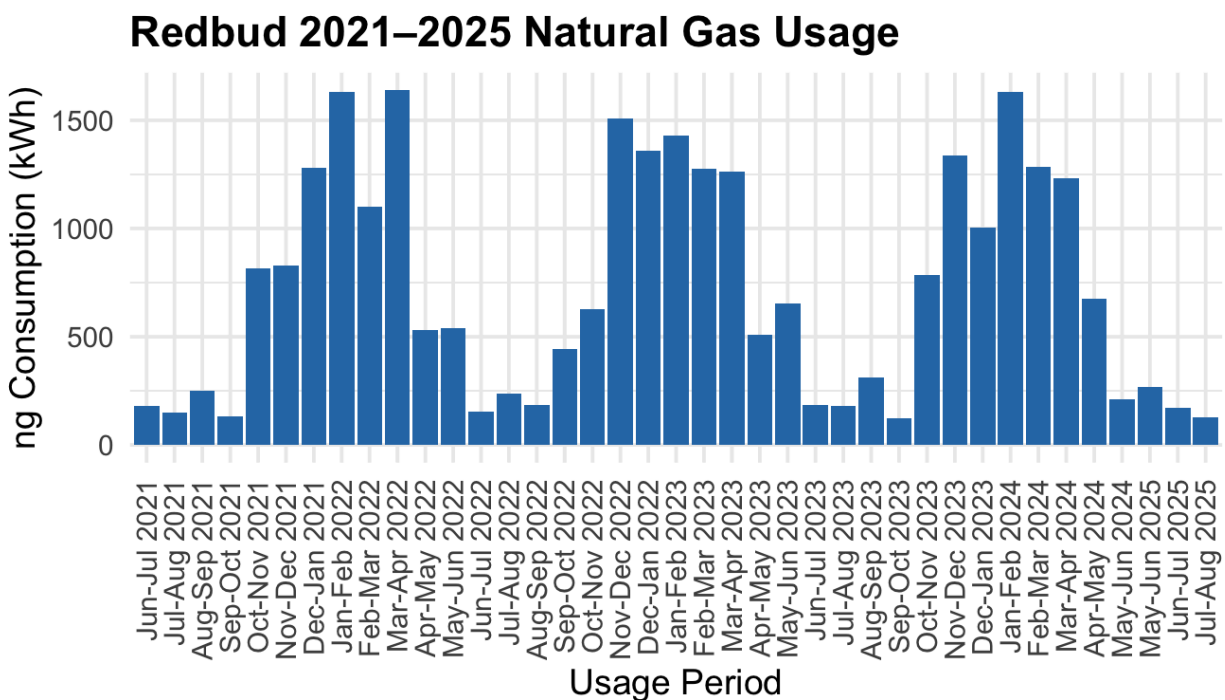


Figure 1. Graph of current Redbud building natural gas usage for the past five years. Peaks during November through March represent the heating season.

Currently, emissions from natural gas usage is the greatest contributor to Redbud's total CO₂ footprint. The average total natural gas for 2022 and 2023 – which are the only two full years of data available – is 9,958.6 THM per year. Baseline natural gas usage is 305.66 THM per month, assuming that natural gas is not being used for heating from April through October, which is the non-heating season. This number is

then multiplied by twelve to obtain the baseline natural gas consumption for the whole year of 3667.9 THM per year. Subtracting the baseline energy usage from the total usage per year yields the total natural gas used for the five-month heating season, which is 6290.7 THM. To get the natural gas usage for heating per month of the heating season, divide by twelve to get approximately 1,258.12 THM per month. Thus, out of the total 1564 THM per month of natural gas used during the heating season, about 80% is used for heating and 20% for other uses. This value is within the feasible range and compares well with Ecovillage at Ithaca's ratio of 75% to 25%. The slightly larger gap in the ratio suggests that Redbud's heating system is slightly less efficient and requires more energy for heating during the cold season.

An estimated breakdown for natural gas usage is shown in the figure below. Because there is no submetering available at Redbud, percentages for natural gas usage between space heating and DHW were estimated while calculating current gas usage for the cooktop and air-source heat pump. Additionally, we assumed that natural gas used for other purposes is negligible. As expected, space heating takes up the highest percentage of natural gas usage, followed by domestic water heating.

Estimated Natural Gas Usage Breakdown

* values are in THM/yr

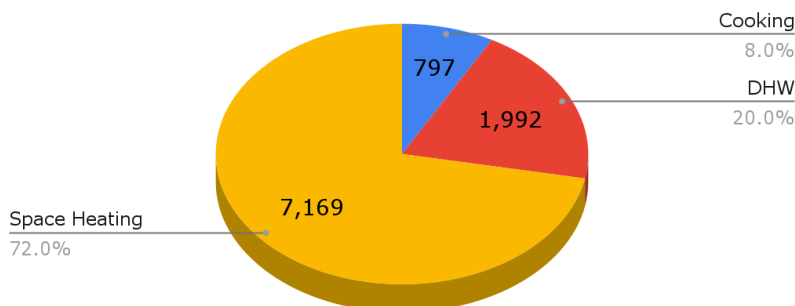


Figure 2. Pie chart illustrating the estimated breakdown of current natural gas usage. Percentages for space heating versus DHW were taken from commonly accepted values used in practice.

This suggests that implementing upgrades that target space heating and DHW will lead to the largest CO₂ emissions reductions. The EPA calculator estimated CO₂ emissions due to the average annual natural gas usage of 9,958.6 THM to be approximately 52.9 metric tons per year. Assuming the rough breakdown of natural gas shown in Figure 2, space heating accounts for 68.66% CO₂ emissions, followed by DHW at 19.02%. Additional upgrades to reduce natural gas from cooking or the drying

machine make up the remaining approximately 12.28% of the building's current total carbon emissions.

Electricity Usage

In addition to natural gas, Redbud utilizes electricity for all remaining building operations, such as lighting and home appliances. Assuming no seasonal impacts to electricity consumption, the average annual electricity usage is approximately 32,816 kWh per year. Note that this number is skewed by the values in 2022, which were a result of NYSEG's billing error. The current average electricity usage is likely to be slightly lower.

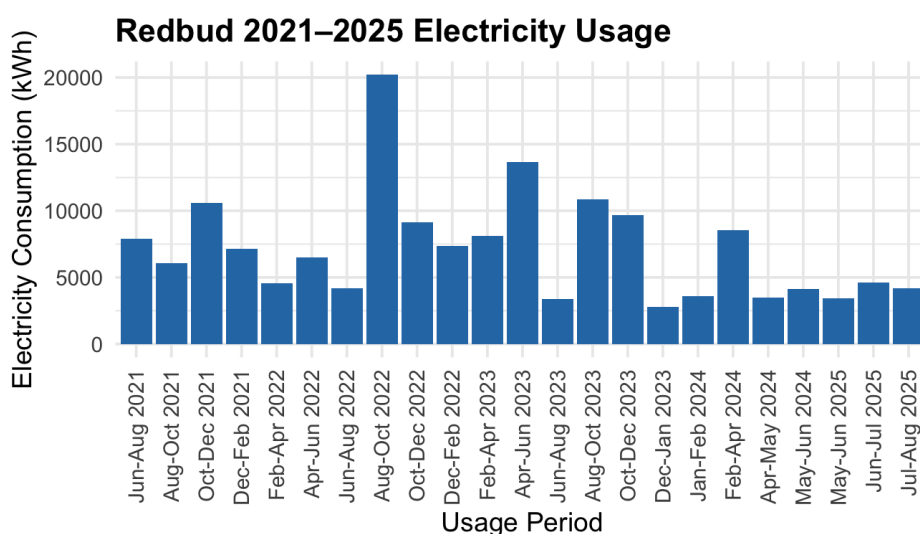


Figure 3. Graph of current Redbud electricity consumption. Note that NYSEG billed electricity incorrectly during 2022, so data from that year may be unreliable.

The current electricity consumption was also analyzed to estimate CO₂ emissions from the New York State Electric and Gas (NYSEG) standard fuel mix. Real-time data collected in five-minute intervals by New York State Independent System Operator (NYISO) for the most recent year of October 2024 through 2025 were averaged to obtain a general estimate for the percentage of the fuel mix from fossil fuel (dual fuel, natural gas) and clean energy sources (nuclear, hydropower, wind, solar and other renewables). The results are that on average, 52.78% of electricity is from fossil fuel sources and 47.22% is from clean energy sources.

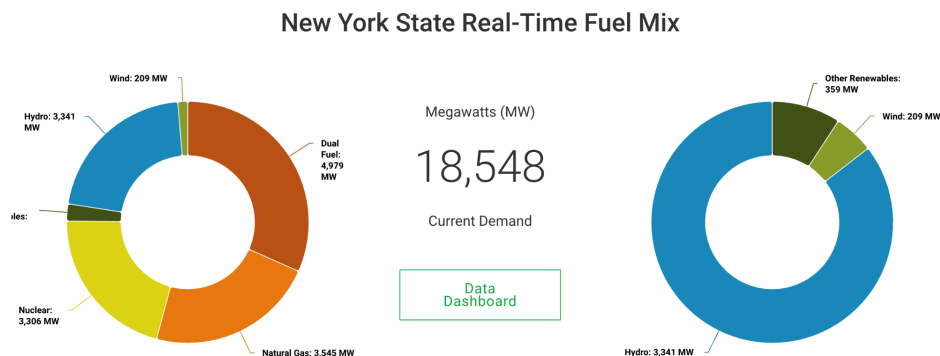


Figure 3. Screenshot of New York State fuel mix from October 2025 to display an example breakdown of electricity sources.

Assuming that the same percentage directly translates to the percentage of kWh provided by either fuel source, it is estimated that approximately 17,320.285 kWh per year of electricity is from fossil fuels. Again, using the EPA calculator, the estimated annual CO₂ emissions from the standard electricity fuel mix is 2.3 metric tons. This adds up to a total of 55.2 metric tons of CO₂ emitted per year.

Although the estimates for current electricity consumption are relatively low compared to the CO₂ emitted by natural gas, the transition to renewable electricity is crucial for Redbud's carbon neutral building goals. As natural gas systems are replaced with electric counterparts, the electricity consumption of the building will significantly increase. Thus, it is important to switch to a clean electricity source in order to fully offset the emissions from the existing natural gas systems.

Current Conditions

Space Heating & DHW System

During the walkthrough, we confirmed that Redbud Cooperative relies on a centralized natural-gas boiler for space heating. The heating room is located in the basement of the apartment. The boiler distributes hot water through a hydronic loop that feeds into baseboard radiators in each room. These radiators provide steady, convection-based heating and continue to function reliably despite their age. The boiler typically operates at a fixed setpoint of around 70–80 °C. While this ensures sufficient heating during Ithaca's winter months, it also results in noticeable distribution losses along older pipes and insulation. These losses become more apparent during mild weather in the shoulder seasons, when high-temperature operation is unnecessary but still maintained due to the system's design.

Overall, the existing hydronic layout remains functional, and its structure is consistent with many radiator-based systems found in cold-climate buildings. Many

retrofits in similar contexts have successfully operated radiators at lower supply temperatures using air-to-water heat pumps. This suggests that Redbud's distribution system itself is generally compatible with future electrification efforts. However, the current boiler remains the key limitation, as it relies entirely on combustion and contributes significantly to the building's annual natural-gas use.

Domestic Hot Water (DHW) System

Redbud's domestic hot water is also produced by the central natural-gas boiler. Heated water is stored in a central tank before being distributed to sinks and showers throughout the cooperative. The tank appears to be an older unit, with aging insulation and piping that reflect long-term use. While the system is still operational, its design predates modern efficiency standards. Because DHW production is tied directly to the boiler, it follows the same high-temperature operating conditions used for space heating. This simplifies system control but increases standby and distribution losses, especially in an older storage tank. Although DHW represents only a small portion of Redbud's total natural-gas demand—part of the approximately 20% not used for space heating—it still contributes to the building's overall carbon footprint.

The current centralized DHW layout is generally compatible with heat-pump-based hot-water systems, which operate using gradual heating cycles and stratified storage. Therefore, shifting to an ASHP-driven DHW system in the future is feasible, and the existing distribution configuration does not present a major obstacle to electrification.

Cooktop

During the Redbud Cooperative Walkthrough in September, the project team observed that cooking in the shared kitchen is supported by a natural gas-fired commercial cooktop. The stove is a large, 8-burner unit typical of a medium-duty institutional kitchen and is connected to the building's natural gas supply (Figure 4). The standing gas cooktop is low efficiency due to the pilot light remaining on 24-hours, and this is especially inefficient for residential units like Redbud because cooking hours are much fewer and concentrated at specific times, unlike commercial cooking facilities.



Figure 4. The current natural gas stove.

Based on on-site observations and a follow-up market comparison, the existing cooktop is most consistent in size and configuration with a medium-duty commercial gas range, similar to a U.S. Range U48-series open burner model (Figure 5). Representative specifications for this class of equipment—including dimensions, weight, total heat output, and fuel type—are summarized in Table 1. These reference values indicate a high-capacity appliance with a total heat output on the order of 320,000 BTU and natural gas as the sole energy input.



Figure 5. U.S. Range U48-series open burner stove

Table 1. The key specifications of the natural gas stove

WxDxH	47 ¼" × 34 ½" × 57"
Weight	572 lb
Power Output	320,000 BTUs

Power Input Type	Gas-Natural
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The identified model is used as a representative reference only. The exact brand, model, age, and performance of the installed cooktop could not be confirmed during the site visit, and no manufacturer label was observed. Therefore, actual operating efficiency and gas consumption may differ from the reference specifications listed in Table 1.

Despite this uncertainty, the observed cooktop represents a direct-combustion cooking system and contributes to Redbud's overall natural-gas use and carbon emissions. While cooking demand is smaller than space heating, the commercial scale of the appliance makes it a relevant component in evaluating future decarbonization pathways such as induction-based retrofit options.

Results and Recommendations

Decarbonization Pathways

This report contains two decarbonization pathways for Redbud to consider when informing future building upgrades. The first pathway is the full decarbonization pathway, which includes three relatively cost and time intensive building upgrades to reach near net zero carbon emissions:

- Install an air-source heat pump for space heating and DHW
- Replace the gas cooktop with an induction cooktop
- Switch to a 100% renewable electricity source

Because these upgrades to achieve net zero emissions may require a substantial financial and time investment, several other energy efficiency upgrades are outlined in the second pathway, the partial decarbonization pathway.

- Implement smart lighting controls
- Buy into a 100% solar electricity source through community solar or another energy services company
- Improve building insulation

The recommendations for both the full and partial decarbonization pathways are included in this report to provide Redbud options for reducing the building carbon emissions. Sizing and cost estimates are included for the full decarbonization pathway actions, as well as impact estimates of the building upgrade on the building's total CO₂ emissions. The findings of this report can be used as a preliminary feasibility and

impact assessment, and all proposed actions should be studied in greater depth for future implementation.

Regardless of which pathway is Redbud's preferred course of action, there are several general actions to do in advance of implementing any upgrades. Firstly, the electric service to the Redbud building must be upgraded to receive sufficient electricity to power future heating or cooking appliances. From the Redbud walkthrough, it is known that the building currently receives a maximum of 200 Amp from NYSEG. To prepare for electrification efforts, which will reduce natural gas usage, this electric service must be increased. Another residential building on Cornell's campus has already implemented this electric service upgrade, and now has a box capable of receiving 500 Amp and the space to potentially upgrade further to service 1200 Amp if needed in the future. It is recommended to complete this electrical upgrade prior to future decarbonization building upgrades so that the building is able to service enough electricity to maintain the system.

An energy audit is also recommended for Redbud. Energy audits are crucial to understanding the inefficiencies of the current building so that a targeted improvement plan can be formed. The specific actions recommended in this report are made using given knowledge from Cornell Residence Life and general trends in literature and case studies, but an energy audit will be able to identify the most impactful energy efficiency upgrades based on the building's current energy consumption and infrastructure. This is especially important when assessing actions recommended in the partial decarbonization pathway, which are general ideas not necessarily the most effective for Redbud specifically.

Full Decarbonization

This section includes several high-impact building upgrades that target the heating and cooking systems in Redbud in order to reduce the building's carbon emissions to zero. Preliminary sizing and cost calculations are also provided for these actions to provide more information about the feasibility or considerations associated with implementation.

Air Source Heat Pump (ASHP)

ASHP System Concept Overview

The retrofit project of Redbud Cooperative suggests a complete switch in heating with air-source heat pumps (ASHPs). The existing natural-gas boiler will be replaced by 2 independent heat-pump units, one for space heating and the other for

domestic hot water (DHW). This is Plan A, which aims at reaching full low-carbon transformation by providing all thermal energy, space heating, and hot water through electricity. This will eliminate on-site burning and use ASHPs and on-site solar energy to meet the building's annual energy requirements. We can reduce capacity competition by isolating the two loads and so designate each system to operate in a specific manner.

The two heat pumps work on separate loops. This decision comes from the way the building actually uses heat throughout the day. Heating rises and falls with outdoor temperature and moves slowly, almost like a background rhythm. Hot-water use is nothing like that; it comes in sharp peaks when people shower or wash dishes. Combining both loads in a single system makes the equipment react in ways that aren't always efficient. Two independent units avoid this kind of tug-of-war, and each one can run more steadily without being pushed outside its ideal operating range.

To facilitate this change, the current cold-climate ASHPs can be used to provide the effective solution that would guarantee the stable performance under the problematic temperatures. They continue extracting heat even when it's well below freezing and can still produce water temperatures that radiators can use. Typical seasonal COP values in climates like Ithaca fall around 2–3. That's not perfect, but it's good enough to stand in for a gas boiler. There are already real buildings in the Northeast running on similar systems, so the technology isn't experimental at this point. Another advantage for Redbud is that the hydronic distribution system is already in place. Radiators, piping, and the general layout all remain usable. Most of the work stays in the mechanical room, keeping the retrofit from becoming a major construction project. Residents hardly notice anything different, but the building ends up with an all-electric heating system that's far cleaner than before.

Working Principles

Air-source heat pumps operate by transferring heat from outdoor air into the building through a vapor-compression cycle. The basic sequence is shown in Figure 6. The refrigerant absorbs heat in the outdoor coil and evaporates into a low-pressure vapor. The compressor then raises the vapor to a higher pressure and temperature, creating a usable heat source for the building.

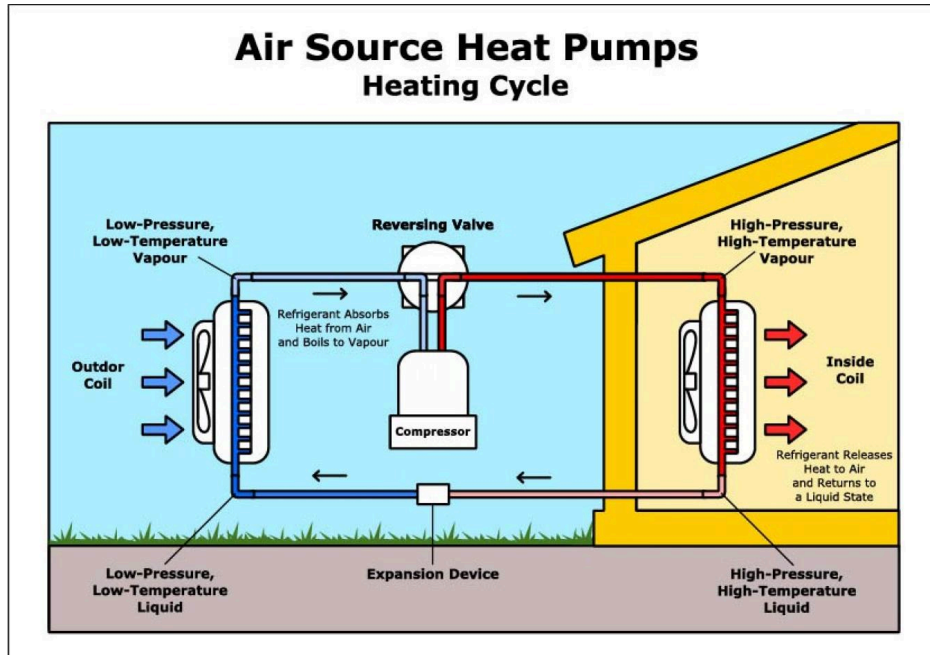


Figure 6. Air-source heat-pump cycle.

The hot vapor propagates to the coil on the indoor side and transfers its heat, thus condensing back to liquid. This is a very important part where the system heats the water of the building through an air-to-water system, as in our case. After the refrigerant has given out its heat, it is now taken through an expansion device, which decreases the pressure as well as the temperature of the gas, taking it back to a condition when it can again absorb heat. The process repeats itself thereafter. It is worth noting that nothing is burned in this process, and the other significant energy input will be the electricity required to drive the compressor.

Since the system uses heat transfer rather than producing it, it can provide more thermal energy than it consumes in electricity. It is especially useful in cold weather, when even the model that has not yet been invented can remain effective in sub-freezing conditions, serving as a source of water temperature and allowing not only space heating but also DHW (IEA, 2022). These are noteworthy operating features that support the system configuration presented in the following section and further illustrate the feasibility of this approach.

System Configuration

The retrofit uses two independent air-to-water heat pump loops. One unit supplies space heating (ASHP-SH), and the other produces domestic hot water (ASHP-DHW). Figure 7 below illustrates the separation of the two circuits and the main components connecting them to the building.

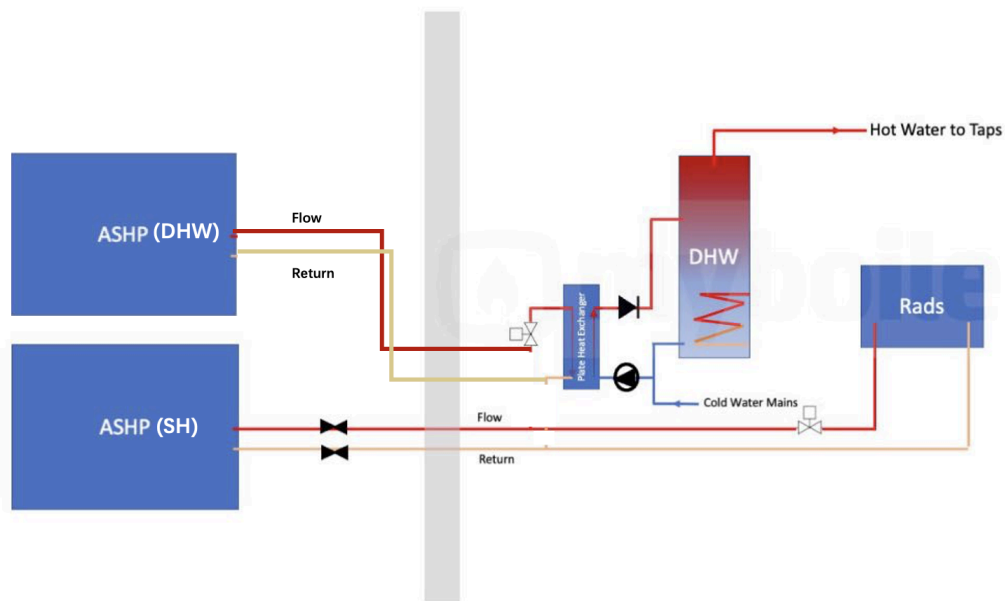


Figure 7. Two-loop ASHP for space heating and domestic hot water

The heating loop is a simple, closed hydronic loop. The ASHP-SH provides moderate-temperature water to the radiator network that already exists, which in a typical air-to-water cold-climate environment is in the 45-55 °C range (IEA, 2022). There is no change in the radiators, distribution pipes, or the source of heat. Flow and return lines are directly linked to the flow and return loop connecting the heat pump and the radiator loop. Isolation valves are also installed, which makes it easier to maintain and balance the system.

Nevertheless, the space heating system is not dependent on the DHW loop. The ASHP-DHW warms a domestic hot water tank with a plate heat exchanger, which ultimately supplies hot water to fixtures. The cold water from the building's mains is pumped into the tank, where it is slowly warmed by the heat pump. The design minimizes the peaks in demand at the short-run of DHW and compressor cycling, which have been found to be better in multi-family ASHP-DHW systems (Guo and Goumba, 2018). It also makes sure that the demand for domestic hot water does not conflict with space heating at the time of maximum demand, as compared to combined systems.

This is achieved by keeping the DHW loop independent of the heating circuit; therefore, there is no competition for capacity, and each heat pump can run at an optimal temperature transfer ratio. This, in addition to boosting the system's efficiency, also increases overall stability. System reliability is also an important design

consideration. Incorporating multiple ASHP units—for example, two units dedicated to space heating—provides built-in redundancy. If one unit fails or requires maintenance, the remaining unit can continue supplying partial heating, preventing loss of service during winter conditions. This redundancy improves operational resilience and supports uninterrupted heating for residents.

Integration with the Existing Hydronic System

A combination of the two heat pump loops is located in the mechanical room. The space-heating unit is linked to the radiator network by a small buffer tank, which prevents working with fluctuating supply temperature and minimizes cyclic operation in the event of light loads. A special circulation pump keeps the flow, and a small number of isolation valves enable the loop to be serviced whilst the rest of the system remains unaffected. The existing radiators and distribution piping remain unchanged. The overall integration arrangement is shown in Figure 8.

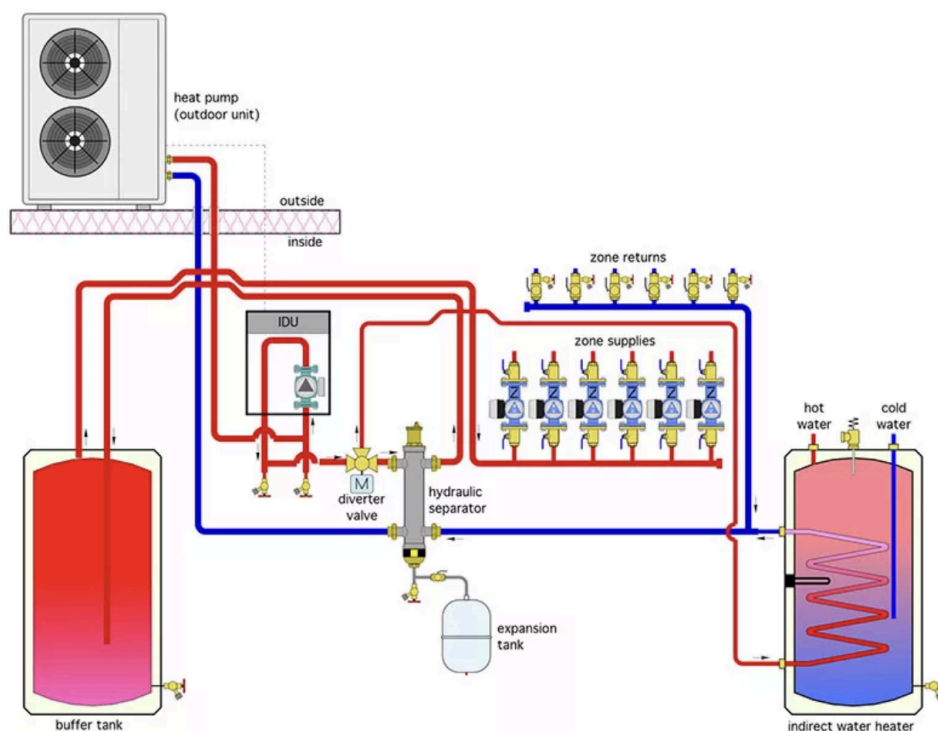


Figure 8. ASHP heating–DHW integration with buffer and storage tanks

The DHW unit ties into the building’s hot-water lines through a stratified storage tank. The heat pump charges the lower part of the tank, and the upper part supplies fixtures at a stable temperature. A recirculation line is kept where required, and simple check valves prevent interaction with the heating loop. All new equipment stays within

the mechanical room, so the integration does not disturb occupied areas and keeps the existing hydronic layout intact.

Energy Performance Analysis

The cold climate air-source heat pumps have an average range with which they are expected to operate consistently within the typical season of the Ithaca heating season. Empirical studies have shown that existing units do not lose their ability under freezing conditions, and it is possible to raise the temperature of the water required to heat hydronic floors (IEA, 2022). Also, the variable-speed compressors are more efficient at partial load. With these performance characteristics, it is possible to estimate the yearly consumption of electricity in the building in heating and hot-water based on the existing thermal requirements of the building.

Heating and DHW Load Breakdown

The natural-gas-average consumption per year of the building is estimated as 9,958 therms per year, indicating that the heating and hot-water loads of the building are calculated. Approximately 8% of natural gas is used for cooking, which is not electrified in Plan A. The remaining 92% is attributed to space heating and domestic hot water. Table 2 summarizes the load distribution and corresponding thermal demand.

Table 2. Estimated heating and DHW load distribution based on natural-gas usage.

Use	Percentage	Energy Demand (kWh/yr)	Energy Demand (therms/yr)
Cooking	8%	23,341	797
DHW	20%	58,354	1,992
Space Heating	72%	210,074	7,169
Total	100%	291,769	9,958

These thermal loads form the basis for estimating electricity demand across different COP scenarios.

COP Scenario Analysis

Heat-pump performance changes with outdoor temperature. To represent this variation, three COP values are used: 2.5, 3.0, and 3.5. Each value is applied to both

the space-heating load and the DHW load. An additional 5% is included to account for pumps and basic controls. Table 3 shows the electricity needed under each scenario.

Table 3. Electricity required for SH and DHW under different COP scenarios.

Use	COP	Heating Demand (kWh/yr)	Required Electricity (kWh/yr)	+5% Auxiliary (kWh/yr)
Space Heating	2.5	210,074	84,030	88,231
	3.0	210,074	70,025	73,526
	3.5	210,074	60,021	63,022
DHW	2.5	58,354	23,342	24,509
	3.0	58,354	19,451	20,423
	3.5	58,354	16,673	17,507

These scenarios illustrate the range of possible electricity demand depending on seasonal operation and system performance.

Seasonal Weighted COP

To represent Redbud's climate more accurately, a seasonal-weighted COP method is used. Each season is given a COP based on its average outdoor temperature, and a share of the annual heating load is assigned to that season. Table 4 shows the values used in the calculation.

Table 4. Seasonal weighted COP based on Redbud's outdoor temperature profile

Season	Months	Avg Outdoor Temp (°C)	Assumed COP	Share of Annual Heating Load	Qi/COPi
Winter	Dec–Feb	–3	2.2	45%	0.2045
Spring	Mar–May	6	2.9	25%	0.0862
Fall	Sep–Nov	9	2.8	25%	0.0893

Summer (DHW only)	Jun–Aug	19	3.4	5%	0.0147
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The weighted seasonal COP is calculated as: $COP_{avg} = \frac{1}{\sum(Q_i / COP_i)}$

Using the seasonal distribution above, the weighted average COP is approximately 2.5, which is adopted as the representative performance value for the ASHP system.

Applying the weighted COP of 2.5 to the total heating and DHW load yields an annual electricity demand of approximately 112,740 kWh/yr. This value represents the expected electrical consumption of both heat-pump units under full electrification and serves as the design basis for the solar-generation analysis that follows.

ASHP Implementation Feasibility

The heat-pump refurbishment is fully feasible within the current Redbud design and hydronic system. New-generation cold-climate ASHPs can provide water at 45 - 55°C to the system's radiators, and there is no need to modify the interior heating terminals or distribution piping. Moreover, the mechanical room is large enough to house the buffer tank, DHW tank, pumps, and controls. The great majority of the new equipment will fit within the existing footprint, causing minimal disturbance to occupied space.

Regarding the outdoor units, they may be located in the backyard, where there is sufficient clearance to ensure adequate airflow and allow for regular maintenance. Cold-climate ASHPs have moderate sound levels, and rear-yard positioning helps reduce the potential noise impacts on residents.

Although electrical upgrades will be necessary to accommodate both heat pumps, the existing capacity will be able to sustain the predicted load after the upgrades are implemented. The system can be mounted without requiring significant building modifications, provided the new equipment is properly positioned and the intended electrical upgrades are implemented.

Conclusively, the current air conditioning and plumbing system within the building provides a strong foundation for achieving the complete-electrification route in the full decarbonization pathway.

Induction Cooktop

Reference Case and Feasibility

Following the September 2025 site visit to Redbud Cooperative, the project team visited 660 Stewart Cooperative, a nearby student housing facility with similar occupancy and kitchen use patterns. At 660 Stewart, two commercial induction cooktops have already been installed in a shared kitchen and were observed to be fully operational during daily use. The systems appeared to meet cooking needs without operational issues.

This site visit provided a relevant reference case and demonstrated that induction cooking is technically feasible in cooperative-style student housing. The successful implementation at 660 Stewart supports the applicability of a similar electrification strategy at Redbud.

Proposed Induction Cooktop Option

Based on observed cooking demand, equipment availability, and cost considerations, the proposed replacement option for Redbud is the Garland GME36-i14C commercial induction cooktop. The proposed configuration includes two units, each with four cooking zones, providing a total of eight burners comparable to the existing commercial gas range.

Key specifications of the selected induction cooktop, including dimensions, weight, rated electrical power (19 kW per unit), and unit cost, are summarized in Table 5, with a representative product image shown in Figure 9. This equipment was selected as a practical replacement that maintains cooking capacity while eliminating on-site natural gas combustion.



Figure 9. The Garland GME36-i14C commercial induction cooktop

Table 5. The key specifications of proposed induction cooktop

WxDxH	35 ½" × 35 ½" × 39 ½"
Weight	200 lb
Total power	19 kw
Price	\$23,719.85 /each

Cooking Gas Baseline

To evaluate the impact of replacing the existing gas cooktop, a baseline estimate of natural gas consumption for cooking was required. However, Redbud's available utility data only provide whole-building natural gas consumption, with no submetering by end use. As a result, cooking-related gas use could not be directly measured.

An assumption-based estimation approach was therefore adopted. The existing cooktop was assumed to be a medium-duty commercial gas range with a rated heat input of approximately 320,000 BTU/h, consistent with on-site observations and market comparison. Cooking operation was assumed to occur for an average of 4 hours per day over 300 days per year, reflecting shared kitchen usage in student housing. A natural gas heating value of 1,038 BTU/ft³ was applied.

An initial calculation assuming continuous operation at full rated input produced an unrealistically high estimate, accounting for more than one-third of total building natural gas consumption. This result reflects the fact that rated heat input represents instantaneous maximum capacity, which is rarely sustained in practice.

To account for intermittent burner use, a load factor approach was introduced. Under a 20% load factor, which is considered representative of shared cooperative kitchens, cooking-related gas consumption is estimated to 768 therms per year, accounting for approximately 7 – 8% of Redbud's annual natural gas use. This value is adopted as the baseline for subsequent electrification and cost analysis.

Retrofit Cost

To estimate the total retrofit cost, several parts associated with replacing existing gas stoves with commercial induction cooktops are calculated: capital cost, operating cost, and levelized cost of cooking (LCOC). All costs are normalized to deliver the same amount of useful cooking energy, which enables a comparison between gas stove and induction cooktop. One thing to note is that the cost estimation

presented here is intentionally conservative and expected to represent a higher scenario in real electrification retrofits.

Capital Cost

The induction cooktop retrofit cost includes equipment, electrical upgrades, installation, and gas line decommissioning. Based on commercial induction equipment pricing and conservative assumptions for partial electrical upgrades, total capital cost is estimated at \$53,700 – \$62,400. The induction cooktop unit chosen for this cost analysis is of high quality, and costs can be lower if a standard residential induction cooktop unit is chosen for Redbud similar to the ones installed at 660 Stewart Ave. The capital and installation cost for the two induction cooktops at 660 Stewart Ave cost around \$15,000 total.

Operational Cost

Annual gas consumption for cooking is estimated at 768 therm/year, taking approximately 7.7% of total building gas use. This is converted to thermal energy using the standard conversion of 29.3 kWh per therm and adjusted by an assumed gas cooktop efficiency of 45%, yielding an annual useful cooking energy of approximately 10,126 kWh-useful/year. This useful cooking energy is held constant across all scenarios. Using a gas price of \$1.40 per therm, the annual operating cost of gas cooking is approximately \$1,075 per year. For induction cooking, an efficiency of 90% is assumed, requiring approximately 11,251 kWh of electricity per year to deliver the same useful cooking energy. At an electricity price of \$0.23 per kWh, the annual operating cost of induction cooking is approximately \$2,588 per year.

Annualized Cost

To allow life-cycle comparison, capital costs are converted to equivalent annual values using a 15-year equipment lifetime and a 5% discount rate. Under these assumptions, the estimated capital cost range corresponds to an annualized capital cost of approximately \$5,200 – \$6,000 per year. As shown in Figure 10, this annualized capital burden dominates the total annual cost of induction cooking, even under the low-capital-cost scenario.

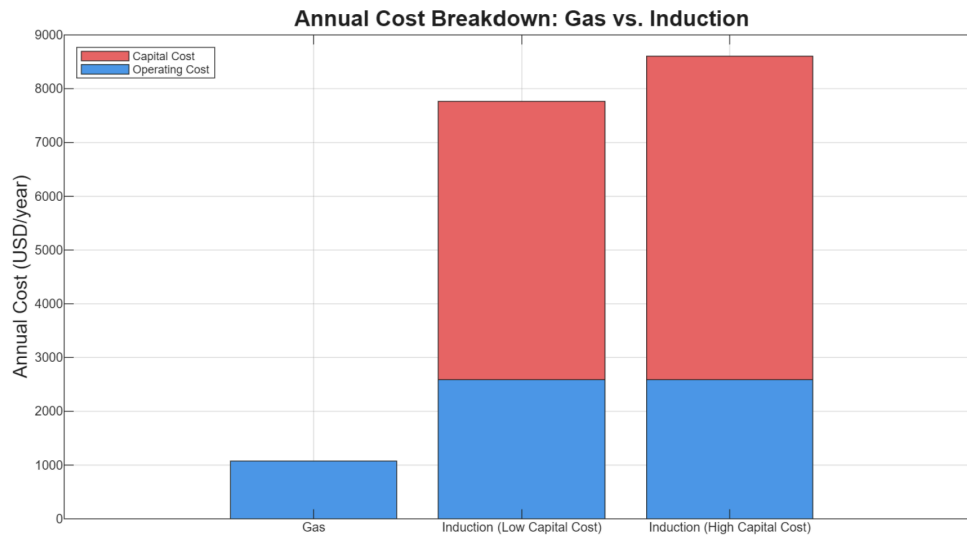


Figure 10. Annual Cost Breakdown of gas stove and induction cooktop

Levelized Cost of Cooking

The levelized cost of cooking (LCOC) is calculated as the sum of annualized capital cost and annual operating cost divided by annual useful cooking energy. Table X summarizes the results. The existing gas system has an LCOC of approximately \$0.11 per kWh-useful, reflecting low operating costs and zero new capital investment. In contrast, the induction retrofit yields an LCOC of \$0.77 – \$0.85 per kWh-useful, depending on whether low or high capital cost assumptions are applied.

Table 6. Cost breakdown for gas stove and induction cooktop

System	Annualized Capital Cost (\$/yr)	Annual Operating Cost (\$/yr)	Annual cooking energy input (kWh/yr)	LCOC (\$/kWh)
Gas(current system)	0	1,075	10,126	0.106
Induction (Low Capital Cost)	5,177	2,588	10,126	0.77
Induction (High Capital Cost)	6,018	2,588	10,126	0.85

Sensitivity analysis

Figure 11 presents a tornado sensitivity analysis of induction cooking LCOC. Electricity price and annualized capital cost are the dominant drivers of cost variability, while parameters such as burner efficiency have a comparatively smaller influence.

Useful cooking load also has a meaningful impact, indicating that induction cooking becomes more cost-effective in higher-utilization environments. Overall, the results show that the higher cost of induction cooking in this analysis is driven primarily by conservative capital cost assumptions and local electricity prices rather than technical performance. Consequently, the reported induction costs should be interpreted as conservative, upper-bound estimates rather than expected average costs.

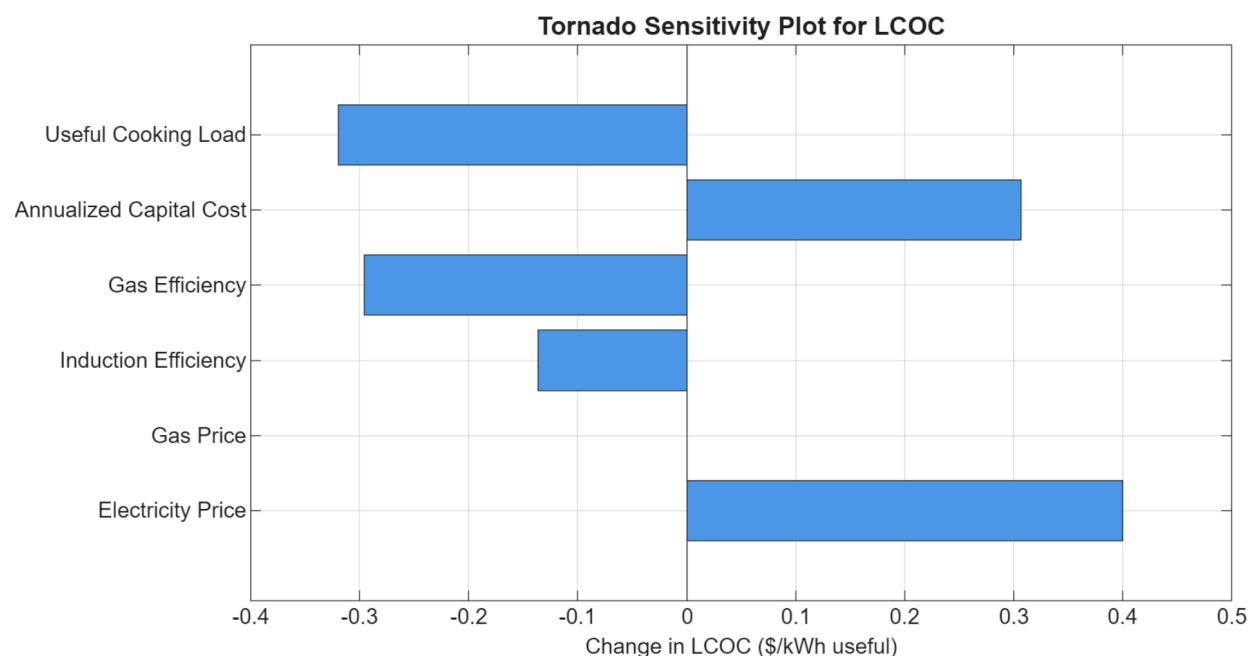


Figure 11. Tornado Sensitivity Plot for LCOC

Renewable Electricity

Solar Farm Sizing and Integration

The solar farm is selected as the renewable electricity source for supporting Redbud's full-electrification pathway. The system is sized to offset the annual electricity demand of the heat-pump retrofit developed in Section 9.6. Using a seasonal weighted COP of 2.5, the combined space-heating and DHW system requires about 112,740 kWh per year. This value defines the load that a solar installation must offset under Plan A. The following analysis evaluates PV system capacities that can meet most of this demand while considering land area, technical feasibility, and the performance differences between fixed-tilt and tracking configurations.

Fixed-Tilt PV Sizing

Fixed-tilt photovoltaics serve as the primary design option for offsetting the heat-pump electricity demand. This configuration is simple to install, requires less land per kilowatt than tracking systems, and represents the most common approach for small ground-mounted arrays in upstate New York. To evaluate the system size needed for Redbud's annual load of 112,740 kWh, several candidate capacities—70 kW, 80 kW, and 100 kW—were assessed using PVWatts runs representative of Ithaca's solar resource.

Table 7 shows the annual AC output, capacity factors, and the share of ASHP demand covered by each system. An 80 kW array produces about 92,846 kWh per year, which offsets roughly 82% of the load. A 100 kW system produces more than the required amount, while a 70 kW system falls short of the desired coverage.

Table 7. Annual generation and ASHP load coverage for fixed-tilt PV systems

PV DC Size (kW)	Annual AC Energy (kWh/yr)	Capacity Factor (%)	Energy Coverage of ASHP Load (%)
70 kW	81,250	13.3%	72.1%
80 kW	92,846	13.2%	82.4%
100 kW	116,044	13.2%	103.0%

Land-area needs and reference installed costs are listed in Table 8. Fixed-tilt arrays typically require around 8 m² per kW, which corresponds to about 640 m² for an 80 kW system and 800 m² for a 100 kW system. These values provide the basic footprint requirements for potential siting.

Table 8. Fixed-tilt PV system land requirements and reference costs

Capacity (kW)	Tilt	Annual Output (kWh/yr)	Land Area (m ²)	Total Installed Cost (USD)
80 kW	36°	92,846	~640 m ²	\$120,000

100 kW	36°	116,044	~800 m ²	\$150,000
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Figure 12 illustrates how annual coverage and installed cost change with system size. The results show that an 80 kW fixed-tilt array provides a practical balance between coverage, land use, and system cost.

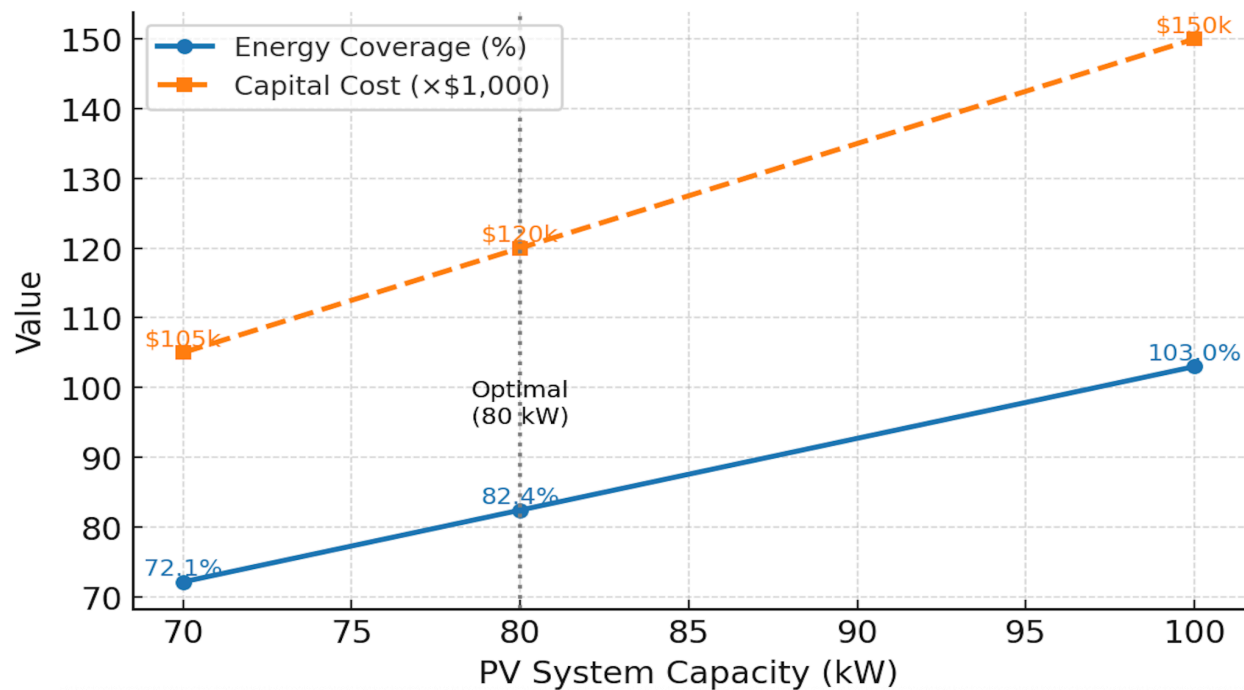


Figure 12. Fixed-tilt PV coverage and cost

Tracking System Comparison

Tracking systems were also evaluated as an alternative to increase annual PV generation. Single-axis tracking increases panel exposure to direct sunlight and can improve annual output. In many U.S. locations, this gain ranges from 20–35%. For Ithaca, the expected increase is smaller, about 12–14% above a fixed-tilt system of the same size.

Table 8 lists the annual output, land-area needs, and reference costs for 80 kW and 100 kW tracking arrays. Tracking systems require more space because of wider row spacing. They also have higher installed costs due to their moving components.

Table 8. Annual generation and land requirements for tracking PV systems

Capacity (kW)	Tracking Type	Annual Output (kWh/yr)	Land Area (m ²)	Total Installed Cost (USD)
80 kW	Single-axis	104,430	~960 m ²	\$160,000
100 kW	Single-axis	130,538	~1,200 m ²	\$190,000

An 80 kW tracking array generates about 104,430 kWh per year, which offsets close to 93% of the ASHP load. A 100 kW system produces more than 130,000 kWh annually and exceeds the building's electricity demand. However, both systems require more land and introduce additional mechanical complexity compared to fixed-tilt arrays.

Because this analysis focuses on feasible system sizes rather than selecting a specific design, tracking results are included for comparison only. Although tracking systems provide higher output, their larger footprint and more complex equipment make them less suited to small ground-mounted installations.

Solar Farm Integration Feasibility

The potential of the solar system integration in Redbud is measured based on land area, seasonal production, and alignment with the ASHP electric consumption. A fixed-tilt array has an area of approximately 8m²/kW or approximately 640m² (80 kW) and 800 m² (100 kW). Tracking systems use more area, with a broader row spacing of approximately 12m² per kW.

Figure 13 indicates the results of the monthly output of an 80 KW fixed-tilt array in AC. In upstate New York, generation is expected to have a seasonal trend, whereby summer has more output than winter. This trend does not correspond to the distribution of heat-pump loads, yet Plan A is made by annual energy offset, but not hourly coincidence. According to conventional net-metering or campus-level accounting criteria, summer oversupply can offset winter undersupply.

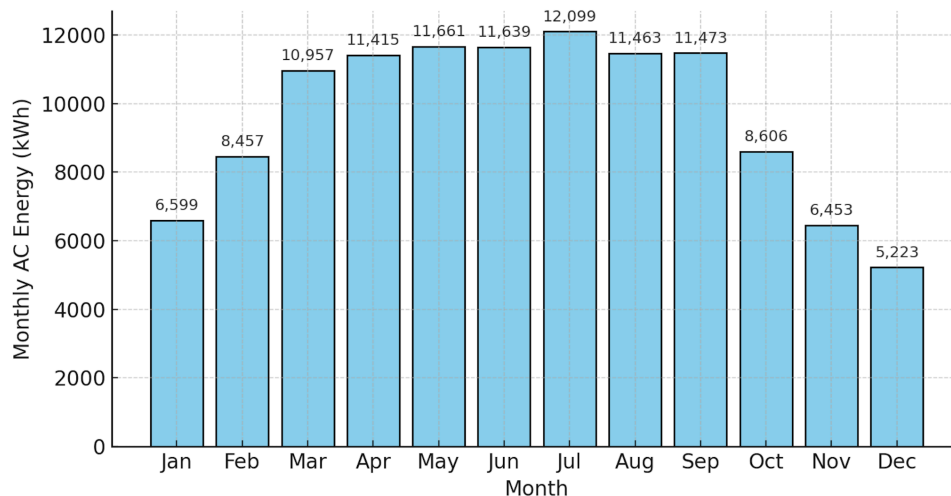


Figure 13. Monthly AC output of an 80 kW fixed-tilt PV system (data generated by PVWatts)

Altogether, the fixed-tilt system represents the easiest way of integration due to the moderate terrain and reduced installation process. An 80 kW array provides a significant annual offset without matching the building load or exceeding the footprint. More electricity is generated with tracking systems, but they require more land and more mechanical parts. Technically, the systems between 70 and 100 kW, particularly around 80 kW, are capable of being integrated properly within the electrification plan of Redbud.

Partial Decarbonization

The partial decarbonization pathway provides lower-impact alternatives that may be feasible to implement in the near term. These actions can be stepping stones used to gradually reduce the net carbon emissions of the building as larger upgrades such as the air-source heat pump or induction cooktop are being discussed.

Solar Electricity from Community Farms or ESCOs

An alternative to a dedicated solar farm to supply renewable electricity for Redbud is to opt into an ESCO or community solar source. According to Peter, there have already recently been discussions about switching all university cooperatives to an ESCO that provides 100% solar electricity. A community solar option that services upstate New York as well is Nexamp Community Solar, which advertises a 10% discount on electricity prices. This option is both feasible and does not substantially impact the electricity cost for the building, and can be used during the transition period between NYSEG's standard fuel mix and Cornell-owned renewable electricity.

Smart Lighting Systems

Another way to improve the building's energy efficiency is to implement smart lighting systems. Lighting can be a substantial use of electricity, especially when common areas such as stairwells, hallways, and common rooms may be required to maintain a minimum lumen level. Implementing occupancy or temporal setbacks can reduce the amount of energy used for lighting by reducing or turning off lights during certain times of the day when natural lighting is sufficient or when rooms are not being used. Smart lighting systems are an important energy saver for commercial buildings especially, and may not be as impactful in a residential building such as Redbud, which may have frequent foot traffic in shared spaces. An energy audit would help to inform whether smart lighting is worth considering for Redbud.

Building Insulation

Improvements to building insulation is another way to reduce natural gas consumption for space heating without changing the heating source. Effective insulation will retain heat inside the building, reducing the amount of heat loss to the outdoors, and thus reducing the amount of energy spent on heating the building. Better building insulation has potential for significant natural gas consumption and CO₂ emissions reductions because of the percentage of energy spent for space heating. Additionally, Figure 13 shows that the second and third floors of Redbud are primary avenues for heat loss from the building. Those two floors have 3 inches of poor performing insulation inside stucco walls, and is likely less insulated than the masonry construction walls used for the first floor. The insulation type currently being used is unknown. Knowing this, the second and third floors as well as the roof are potential priority areas for building insulation installation.

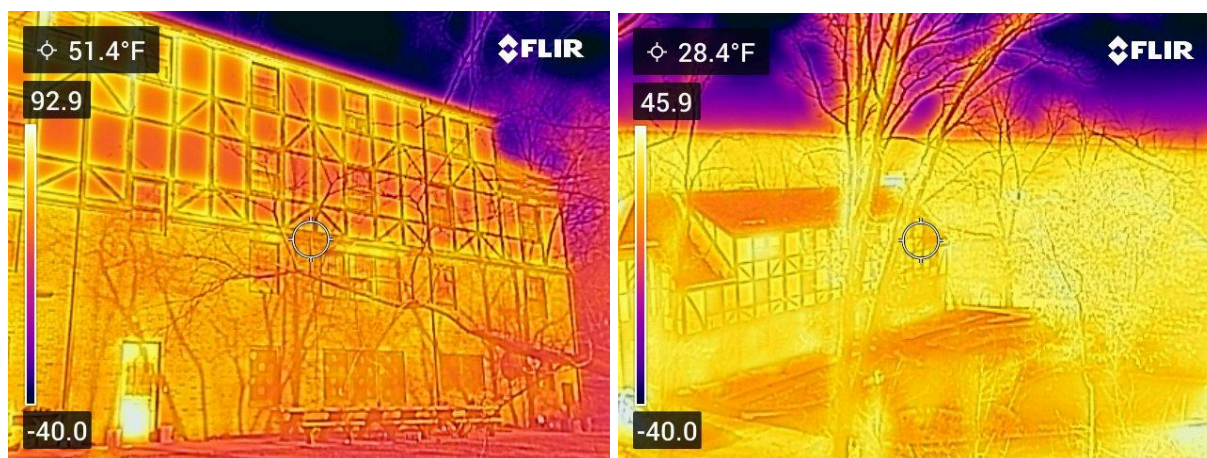


Figure 13. Photographs showing heat transfer from Redbud. Darker red areas show hotspots for heat loss from the building.

Energy savings from improving building insulation can be estimated from utilizing the R-values of building walls, roof, and insulation in a simple heat transfer model of Redbud. In this model, Redbud is simplified as a box with dimensions given from the gross square footage of the building and number of floors. Heat loss from the walls, roof, windows, and doors are estimated by the number of each dimensional component and the heat transfer coefficient to calculate the heat loss per day. The following table shows the results of the heat transfer model calculations with estimates of the current insulation of Redbud. The R-values used for each dimensional component from the appendix of Deer et al. (2008) is listed below:

- Walls: R6 for synthetic stucco and 3” insulation (assumed to be rock wool blown)
- Roof: R13 for thinly insulated roof
- Windows: R2, double of single-pane R1 windows due to treatment
- Doors: R4, maintained value from 2022 Llenroc study

Table 9. Breakdown of estimated heat loss from walls, roof, windows, and doors given current Redbud construction and insulation. A more detailed list of calculations and assumptions for this model is included in the appendix.

Component	Area	Flow	Heat loss	Per day
Units:	ft ²	Btu/ft ² -F-h	Btu/F/h	Btu/F/Day
Walls	6500	0.310	2012	48297
Roof	3805	0.154	585	14049
Windows	1035	0.5	518	12420
Doors	880	0.25	220	5280

Applying a 1.25 multiplier for other losses and accounting for 80% efficiency of converting natural gas to delivered heat, the estimated total natural gas consumption currently is 1,238.58 THM/month, which is slightly lower than the observed amount of 1280 THM/month during the heating season as mentioned in the Current Conditions section but comparable. Note that due to the varying winter conditions, there is no expectation that the heat transfer model will match the observed energy consumption, but the model is useful for providing a qualitative comparison between adding insulation or not. Table 9 also shows that the area for which improved insulation would be most impactful is the wall area, which has the highest heat loss due to the largest area and the largest estimated heat flow rate.

A brief overview of building insulation research was conducted to provide further recommendations on insulation type and potential CO₂ savings. The U.S. Department of Energy recommends minimum R-values for buildings based on region, of which New York State is Alaska climate zone 6 (DOE, 2022). The recommended insulation to add for walls and the roof are estimated below:

- Walls: add R10 for insulated wooden frame wall
- Roof: add R49 for attic with 3-4” of existing insulation

Additionally, recommendations are provided for types of insulation. Building on a previous M.Eng project work with Triphammer Cooperative and the information provided on the U.S. Department of Energy (DOE) website, two types of insulation to consider are sprayed foam and loose-fill or blown-in insulation, which are both suitable for existing walls.

Loose-fill or blown-in insulation is made of recycled materials and made into mineral wool, fiberglass, or cellulose foam blends. It is suitable for enclosed existing walls and unfinished attics, which are applicable to Redbud and blown in place (DOE, 2022). Because of its flexible and easy installation, this type of insulation is suitable for buildings such as Redbud, which may have obstructions or unique architectural features. This type of insulation has R-values ranging from 2.2-3.7 per inch, and is a relatively low-cost and easy installation option.

Sprayed foam insulation is generally made from polyurethane, and is similarly flexible like loose-fill and blown-in insulation. This method is very effective for creating air barriers to improve insulation, and can be applied to large and small areas. The R-value for sprayed foam insulation ranges from 3.5-6.75 per inch, making this an option for greater energy savings but more involved installation and cost investments.

As a case study, the heat transfer model was modified by adding blown-in cellulose insulation (R=3.7) to the total wall and roof area for Redbud. The heat transfer model with a wall R-value updated to 9.73 and roof R-value updated to 9.63 results in a substantial 48% reduction in total natural gas consumption to 768.92 THM/month.

Table 10. Updated heat transfer model showing reduced heat loss with added insulation. Notice the lower heat loss from walls and roof where insulation was applied.

Component	Area	Flow	Heat loss	Per day
Units:	ft²	Btu/ft²-F-h	Btu/F/h	Btu/F/Day
Walls	6500	0.144	938	22511
Roof	3805	0.104	395	9483
Windows	1035	0.5	518	12420
Doors	880	0.25	220	5280

This reduces estimated CO₂ emissions from natural gas by 25%, from 52.9 to 39.7 metric tons per year. This is likely to be an overestimate for the total CO₂ emissions reduced from implementing better building insulation, since it's unlikely that the entire roof and wall area can add new insulation, but it still provides convincing evidence that building insulation is an impactful decarbonization strategy for Redbud to consider in its partial decarbonization pathway.

Future Work

Economic Feasibility and Overall Assessment (ASHP + Solar)

Capital Cost and Solar LCOE Assessment

The full decarbonization capital will cover the air-source heat-pump retrofit and an on-ground PV system between 70 and 100 kW. Small New York multifamily buildings incur moderate ASHP costs, provided outdoor units, hydronic components, storage tanks, and electrical upgrades are installed. The PV system is the more significant portion of the overall cost and thus serves as the basis for economic comparison.

Coarsely speaking, an 80 kW fixed-tilt system can cost about 120,000 US Dollars, and a 100 kW system can cost about 150,000 US Dollars. The 80 kW tracking mount is more expensive, approximately \$160,000, because of extra structural and mechanical hardware.

A levelized cost of energy (LCOE) analysis was conducted for representative fixed-tilt and tracking systems over a 25-year lifetime, a 5 percent discount rate, and an operating cost of 0.004 USD/kWh. The usual capital-recovery approach was taken:

$$LCOE = \frac{capex \cdot CRF + O\&M}{E}, \quad CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Using annual generation estimates from Section 9, the LCOE for the 80 kW fixed-tilt system is about 0.096 USD/kWh. The equivalent tracking system yields roughly 0.113 USD/kWh. Both values fall within the typical range for small ground-mounted PV in New York, where modest capacity factors lead to LCOE values near 0.10–0.15 USD/kWh.

Economic performance is also influenced by the size of the system. A 70 kW array has the least investment, but only terminates approximately 72 percent of the load of the ASHP. The 100 kW alternative would not match up with the annual demand, and it would also need more land without a proportional benefit attached to it. The 80 kW fixed-tilt system offers the most balanced cost-to-benefit ratio, annual offset

(approximately 82%), land efficiency, and long-term stability, making it the preferred economic point of reference for the full decarbonization pathway.

Operational Cost Considerations

The full decarbonization pathway affects operating costs due to the heat pump system's efficiency and the yearly contribution of on-site solar generation. The heat pumps also use much less electricity than the equivalent thermal load, with the seasonally weighted COP averaging around 2.5, making them less expensive to heat than natural gas. Solar power also helps reduce costs by offsetting a large share of the electricity used by the heat pumps. The proposed 80 kW fixed-tilt solar array will reimburse approximately 82 percent of annual electricity consumption, reducing vulnerability to irregular retail electricity charges and helping even out operating costs in the long term.

Even though winter loading will still have to be purchased off-grid, the efficient heating and large solar offset would guarantee a more predictable and potentially cheaper overall operating cost profile than the existing gas-based model. This twofold advantage of low power use and built-in solar energy endows Plan A not only with economic benefits but also with resilience against unpredictable prices.

Overall Feasibility and Recommendation

Redbud can technically and economically make the full decarbonization pathway work. The heat pumps can be fitted directly into the existing hydronic system, which will require relatively small upgrades, and it is indicated in the solar analysis that a fixed-tilt array of 80 kW can cover approximately 82 percent of annual ASHP electricity consumption without having land requirements that are overwhelming. This size also offers the best LCOE among the considered options and prevents the increased cost and larger footprint associated with tracking systems or oversized fixed-tilt arrays.

The existing state incentives, such as the ones offered in the Clean Heat Program of NYSERDA, can also reduce the initial electrification expenses, provided that the work is done by the listed contractors. These are further reasons to abandon fossil-fuel heating. Collectively, the technical and economic analysis shows that the full decarbonization pathway, with decarbonizing a cold-climate ASHP retrofit and an 80 kW fixed-tilt solar array, has an effective and balanced route to Redbud decarbonization and should be implemented.

Conclusion

Decarbonization of Redbud Cooperative is an important step for Cornell to achieve a carbon neutral campus. Residence Life has experience implementing electrification upgrades to decarbonize other cooperative housing units, such as Triphammer Cooperative and 660 Stewart Ave. This report provides a big-picture outline of two decarbonization pathways to identify potential building upgrades for Redbud to achieve full or partial decarbonization.

The full decarbonization pathway includes several cost and time intensive building upgrades that target the current largest uses of natural gas in the building. Installing an air-source heat pump will decarbonize both the building's space heating and DHW, reducing the largest source of CO₂ emissions. Additionally, replacing the current natural gas stove with an induction cooktop at the end of its lifetime will decarbonize gas usage for cooking. Finally, these are both electrification upgrades that will increase Redbud's future electricity consumption, so it is crucial for the building to switch to a 100% clean electricity source, such as purchasing solar electricity from an ESCO or community solar farm, in order to completely offset any CO₂ produced by the heating, DHW, and cooking in the building. Together, these four actions represent a reduction of approximately 99.5% the current building's CO₂ emissions – equivalent to full decarbonization with a small margin of error.

Alternatives outlined in the partial decarbonization pathway are primarily energy efficiency upgrades that can reduce the building's current energy consumption and thus indirectly reduce CO₂ emissions. A short description is provided for each of these actions – community solar, smart lighting, and building insulation – with a focus on building insulation as a potential improvement with the greatest impact on energy and CO₂ savings by reducing heat loss during the winter.

Overall, this report provides Redbud with options for next steps and a preliminary cost, feasibility, and impact assessment for several actions for decarbonization. Future work will be needed by Cornell Residence Life and building residents to determine the best pathway forward to achieving net zero emissions for Redbud Cooperative.

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Appendix A

Heat Pump

A1. Heating and DHW Load Derivation

Annual natural-gas consumption averaged 9,958.6 therms/year (2022–2023).

Baseline non-heating use was estimated from April–October data (305.66 therms/month).

Subtracting this baseline from winter totals yields approximately 7,265 therms/year of heating + DHW load.

A standard 80/20 heating – DHW split was applied, and thermal energy was converted using: 1 therm=29.3 kWh(th).

Total annual thermal demand used for ASHP modeling: $Q_{total} \approx 268,428 \text{ kWh(th)}$

A2. Seasonal COP and Electricity Demand

COP scenarios of 2.5, 3.0, and 3.5 were evaluated using cold-climate performance data (IEA, 2022; EnergizeCT). A weighted seasonal COP of 2.5 was selected based on Ithaca’s winter-dominated load profile.

$$E(total) = \frac{Q_{total}}{COP}$$

Including a 5% auxiliary factor: $E(annual) = 112,740 \text{ kWh/year}$.

This value forms the basis for solar sizing.

Appendix B

Solar PV

B1. PV Sizing Inputs

PVWatts simulations assumed:

- Tilt: 36° fixed;
- Tracking: single-axis;
- Derate: 0.86;
- Sizes: 70, 80, 100 kW

System	Annual Output (kWh)
70 kW fixed	81,250
80 kW fixed	92,846
100 kW fixed	116,044
80 kW tracking	104,430

These values were used for coverage and LCOE evaluation.

B2. LCOE Calculation

LCOE was computed using a 25-year lifetime, 5% discount rate, and 0.004 USD/kWh O&M:

$$LCOE = \frac{capex \cdot CRF + O\&M}{E}, \quad CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Results:

System	LCOE (USD/kWh)
80 kW fixed	0.096
80 kW tracking	0.113

B3. Land-Use Assumptions

Standard area allowances:

- 8 m²/kW fixed-tilt
- 12 m²/kW tracking

Footprint estimates:

System	Area
80 kW fixed	~640 m ²
100 kW fixed	~800 m ²
80 kW tracking	~960 m ²

These values were used solely for feasibility evaluation and do not represent a specific site.

Appendix C

Induction Cooktop Cost Calculation

C1. Estimation of Gas Consumption for Cooking

The average total building natural gas consumption for 2022–2023 is:

$$G_{\text{total}}=9,958.6 \text{ therm/year}$$

This value serves as the reference against which cooking-related gas use is evaluated.

Cooking gas consumption is first estimated using rated appliance capacity to establish an upper bound. The shared kitchen is equipped with a US Range U48-8 U-Series 48-inch open burner range, with a combined rated heat input (burners and ovens) of:

$$Q_{\text{rated}}=320,000\text{BTU/hour}$$

Assuming typical student apartment usage of 4 hours per day over 300 days per year, the annual operating hours are:

$$H=1,200\text{hours/year}$$

Annual thermal energy input at full rated capacity is therefore:

$$E_{\text{rated}}=320,000\times1,200=3.84\times10^8 \text{ BTU/year}$$

Using a natural gas heating value of approximately 1,038 BTU/ft³, and the standard conversion of 1 therm = 100,000 BTU, the corresponding gas consumption is:

$$G_{\text{cook},100\%}=3.84\times10^8/100,000=3,840 \text{ therm/year}$$

This value corresponds to approximately 38.6% of total building gas consumption, which is unreasonably high for shared student kitchens. This result reflects the fact that rated heat input represents instantaneous maximum capacity when all burners and ovens operate simultaneously at full power, a condition that rarely occurs in practice.

To account for realistic operating conditions, a load factor is introduced to represent the fraction of rated input used on average during cooking activities. Shared kitchens in student apartments typically experience intermittent, partial-load operation rather than sustained full-capacity use.

The resulting cooking gas consumption under different load factor assumptions is summarized below:

Load factor	Gas for cooking (therm/yr)	Share of total building gas (%)
100% (full rated input)	3,840	38.56
25% (moderate use)	960	9.64
20% (realistic shared kitchen)	768	7.71
10% (occasional use)	384	3.86

A 20% load factor is selected as the most representative scenario for shared student kitchens, reflecting partial burner usage, short cooking durations, and low simultaneity across appliances. Under this assumption, annual cooking gas consumption is estimated as:

$$G_{\text{cook}}=768 \text{ therm/year}$$

This value corresponds to 7.71% of total building gas use and is consistent with expectations for shared residential cooking facilities.

Gas consumption is converted to thermal energy using the standard conversion factor:

$$1 \text{ therm}=29.3 \text{ kWh}_{\text{thermal}}$$

$$E_{\text{thermal}}=768 \times 29.3=22,502.4 \text{ kWh}_{\text{thermal}}/\text{year}$$

Assuming a gas cooktop efficiency of:

$$\eta_{\text{gas}}=0.45$$

the annual useful cooking energy is:

$$E_{\text{useful}}=E_{\text{thermal}} \times \eta_{\text{gas}}=22,502.4 \times 0.45 \approx 10,126 \text{ kWh}_{\text{useful}}/\text{year}$$

This useful cooking energy is held constant across gas and induction scenarios.

C2. Gas Cooking Operating Cost

The unit price of natural gas is assumed to be:

$$P_{\text{gas}}=1.40 \text{ \$/therm}$$

The annual gas operating cost is therefore:

$$C_{\text{op,gas}}=G_{\text{cook}}\times P_{\text{gas}}=768\times 1.40=1,075 \text{ \$/year}$$

C3. Induction Cooking Electricity Requirement and Operating Cost

Induction cooktop efficiency is assumed as:

$$\eta_{\text{ind}}=0.90$$

The electricity required to deliver the same useful cooking energy is:

$$E_{\text{elec}}=E_{\text{useful}}/\eta_{\text{ind}}=10,1260.90\approx 11,251 \text{ kWh/year}$$

The electricity price is assumed to be:

$$P_{\text{elec}}=0.23 \text{ \$/kWh}$$

Thus, the annual operating cost for induction cooking is:

$$C_{\text{op,ind}}=E_{\text{elec}}\times P_{\text{elec}}=11,251\times 0.23\approx 2,588 \text{ \$/year}$$

C4. Capital Cost Assumptions

Total capital cost for the induction retrofit includes:

- Commercial induction cooktop equipment (2 units)
- Electrical upgrades (partial replacement)
- Installation
- Gas line decommissioning

The resulting capital cost range is:

$$C_{cap}=53,739\text{--}62,439 \$$$

This range reflects conservative assumptions for commercial-grade equipment and electrical upgrades.

C5. Capital Annualization

Capital costs are annualized using the capital recovery factor (CRF), defined as:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1}$$

where:

- $i=0.05$ (discount rate)
- $N=15$ years (equipment lifetime)

$$CRF=0.09634$$

The annualized capital cost is then:

$$C_{ann}=C_{cap}\times CRF$$

$$C_{ann,low}=53,739\times 0.09634\approx 5,177 \$/\text{year}$$

$$C_{ann,high}=62,439\times 0.09634\approx 6,018 \$/\text{year}$$

C6. Levelized Cost of Cooking (LCOC)

The levelized cost of cooking (LCOC) is calculated as:

$$LCOC = \frac{C_{ann}+C_{op}}{E_{useful}}$$

For each scenario:

Gas (existing system):

$$LCOC_{gas}=1,075/10,126\approx 0.106 \$/\text{kWh}_{\text{useful}}$$

Induction (low capital cost):

$$\text{LCOC}_{\text{ind,low}} = (5,177 + 2,588) / 10,126 \approx 0.77 \text{ \$/kWh}_{\text{useful}}$$

Induction (high capital cost):

$$\text{LCOC}_{\text{ind,high}} = (6,018 + 2,588) / 10,126 \approx 0.85 \text{ \$/kWh}_{\text{useful}}$$

Appendix D

Heat Transfer Model for Insulation

D1. Heat Transfer Model for Insulation

The simplified heat transfer model used to estimate heat loss from Redbud was made assuming a uniform box with a length of 111.21 ft, width of 44.16 ft, and height of 26.98 ft. The building footprint is known to be 3359 GSF. Areas of walls, roofs, doors, and windows are shown in the following table. Wall and roof area are known, whereas the area of doors and windows is estimated from the known number of each and values from literature. Redbud has a total of 44 doors, an average of 20 square feet each, and 69 windows, an average of 15 square feet each (Redd 2025, American Home 2025). R-values for each component are found in cited sources (Zabbo n.d.) and the appendix of a building manual linked here by Deer et al. (2008).

Dimensional components	
Roof	3805.0 ft ²
Walls	6500.0 ft ²
Window	0.3 ratio
Doors	880 ft ²
Windows	1035.0 ft ²
Net Walls	4585.0 ft ²

The heat loss per dimensional component is calculated by multiplying the heat transfer rate, obtained through the R-values for each component, by the total area of each component. Then, the heat loss per month is calculated by multiplying heat loss per day by the number of heating degree-days in each month of the heating season, which was assumed to be all of November through March. The following table shows the temperatures used for the heating degree-day estimates.

Target	65 DegF				
Month	Target (F)	Temp, F	Degrees	Days	HDD
Nov	65	41.5	23.5	30	704.9
Dec	65	29.6	35.4	31	1097.2
Jan	65	27.2	37.8	31	1172.0
Feb	65	26.5	38.5	28	1078.2
Mar	65	36.0	29.0	31	899.1
					4951.4

Finally, applying a 1.25 multiplier to account for other losses and an efficiency factor of 0.8 for natural gas conversion to delivered heat, the total gas consumption in mmBtu per season is obtained and converted into units of THM/month for easy comparison with observed data of natural gas consumption for space heating.