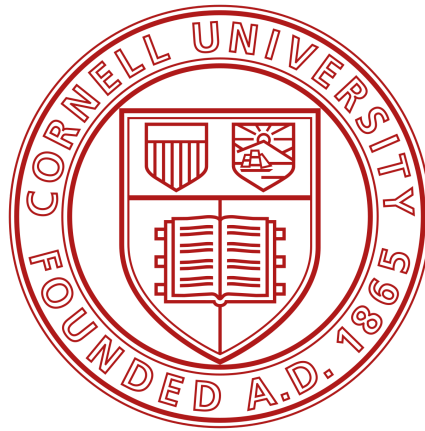


Carbon Neutral Cornell: CEE 5052 M.Eng. Project Final Report

Cornell University



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Team Member Backgrounds

Mateo Aranzazu

Mateo Aranzazu is currently pursuing his M.Eng. in Engineering Management and is expected to graduate from Cornell University in May 2025. Mateo holds a B.S. in Environmental Engineering from Cornell University, which he obtained in December 2024. Mateo is passionate about sustainability and hopes to work in the renewable energy industry to make a great positive impact on the environment and contribute to reducing global carbon emissions. Mateo was raised between Medellín, Colombia and Miami, FL. He loves hiking, nature, and taking care of his plants.

Bailey Belinger

Bailey Belinger (she/her) is from Montague, MI. She is expected to graduate from Cornell University in May 2025 with a B.S. in Environmental Engineering and is expected to receive her M. Eng. in Environmental Engineering in December 2025. Upon graduation, she hopes to work in the clean energy or water sector to help mitigate climate change. In her free time, she enjoys traveling and reading.

Arron Chang

Arron Chang is currently pursuing his B.S. in Environmental Engineering with an expected graduation date of Spring 2025 and an Early M.Eng student in Civil and Environmental Engineering with an expected graduation date of Fall 2025. He is highly interested and involved in the future development and growth of novel technologies to solve global challenges such as in water and air quality. After graduation, he seeks to work in industry for a short term and then transition to non-profit environmental work or starting his own company. In his free time, he enjoys rock climbing, hiking, and photography.

Yiwen Gao

Yiwen Gao (she/her) from Beijing, graduated from the environmental science program at Liverpool University. She is currently enrolled in the environmental engineering M.Eng

program, graduating in May 2025. She is trying to get a job first in the industry as an environmental engineer upon graduation, and eventually get a doctorate degree in environmental-related fields. She is specifically interested in geography, biogeochemistry, transportation, and urban ecosystems.

Shahrin Khan

Shahrin Khan (she/her) is from New York City and completed her undergraduate degree in Mechanical Engineering from The Cooper Union in 2024. She is currently pursuing her Master's Degree in Environmental Engineering with a focus in renewable energy systems from Cornell University and expects to graduate in May 2025. After graduation, she looks forward to designing renewable energy technologies and furthering the development of new, environmentally friendly projects.

Camila Monter

Camila Monter (she/her) is from Washington, D.C. She is expected to graduate from Cornell University in May 2024 with an undergraduate degree in environmental engineering and is currently an Environmental Engineering M.Eng student with a concentration in Sustainable Energy Systems. After graduation, Camila plans to work at the Engineering firm, Langan, in NYC, where she will work to remediate groundwater and soil contamination. Camila is also training for her first half marathon and hopes to continue racing post-grad.

Project Motivation

Climate change mitigation is important for many reasons, including ensuring a livable future, encouraging sustainable innovation, and protecting ecosystems. The increase in greenhouse gases (GHGs) in the atmosphere greatly impacts life on Earth, causing temperatures to rise and extreme weather events. Promoting and implementing carbon-neutral practices is vital for reducing these emissions and improving the quality of life.

The combination of effluent thermal energy recovery (ETER) technologies with solar PV power is important for a variety of reasons, from carbon neutrality to the development of novel technologies. This proposal will focus on evaluating the technical and financial feasibility of using ETER and solar PV systems to power Cornell's campus. Cornell University's commitment to carbon neutrality by 2035 motivates the need for greenhouse gas-free primary energy sources. Heating constitutes one of the largest portions of Cornell's energy consumption, alongside cooling. In 2020, the total building energy consumption for centrally provided commodities was 1,943,000 mmBTU. This highlights the importance of shifting away from conventional sources of energy, particularly for heating and cooling, and demonstrates a need for novel technology to fill this gap in demand. Effluent thermal energy recovery presents itself as the ideal solution; by harnessing thermal energy from wastewater, ETER significantly reduces reliance on fossil fuels

for heating and cooling. Furthermore, since wastewater flow is constant, ETER provides a stable and predictable energy source year-round.

The integration of ETER with solar PV at Cornell is additionally important as this project has the ability to serve as a model for other institutions and municipalities striving for carbon neutrality. By coupling wastewater heat recovery with renewable electricity, this system demonstrates a way to eliminate fossil fuel reliance for heating and cooling. Lessons learned – such as optimizing system sizing, managing intermittent solar generation, and ensuring cost-effectiveness – can inform similar projects elsewhere. The replicability of this project demonstrates a scalable pathway to decarbonized energy systems that can be applied to a variety of different systems such as urban districts, campuses, and wastewater treatment facilities worldwide.

Project Goals

Our project primarily aims to address the feasibility of a new ETER system utilization on campus and the potential of powering ETER with a renewable resource such as solar power. Through this analysis, we expect to research various new ETER solutions based on case studies and determine the pros and cons of each. The new system's feasibility will be analyzed by looking at GHG emissions and costs. We aim to estimate the reduction in carbon emissions when systems are changed and also through being powered by solar. Furthermore, we will estimate the costs of installing a new ETER system and the efficiencies of the components of the system. More specifically, some parameters that we will explore are the amount of heat the ETER system will deliver, the electricity needed to power such a system in various demand conditions, and the size of the renewable energy-powered system to meet this demand.

The levelized cost of electricity (LCOE) and Life Cycle Assessment (LCA) evaluations will be focused on the aspects mentioned above such as including a cost analysis focusing on the reduction of GHG emissions, levelized cost per unit of energy using life cycle costing, cost per ton of CO₂ reduction, and potential greenhouse gas reductions. The Life Cycle Costing and LCA will be carried out based on the general resource costs such as natural gas and electricity, as well as the assumed value of discount rate and other relevant resources.

We will also be conducting research based on different dimensions: the technical, environmental, economic, social sustainability, non-economic dimension, and contribution to diversity/equity/inclusion dimensions. We will examine similar case studies to understand their key findings and explore how their insights can be applied to our project. Relevant policies may briefly be mentioned so that we can explore the future implications of our project. Additionally, we will work with the Cornell facilities to successfully identify the opportunity for solar electricity generation to power the ETER system. More details will be added regarding specifics once we begin interacting with the facilities team.

Scoping Statement and Clarifying Assumptions

The scope of this project encompasses a comprehensive feasibility study on sustainable ETER at Cornell University - Ithaca Campus, focusing on technical, economic, environmental, and social analyses. The study will assess the viability of integrating a solar PV energy component as a low-carbon power source for the proposed ETER system. A preliminary technical design will be developed to support thermal energy recovery and cooling, based on estimated effluent and target usage capacities. The economic analysis will evaluate financial feasibility, considering high initial costs and life cycle costing with discounting to compare existing heating and cooling resource use against potential energy savings. Environmental benefits will be quantified through the reduction of CO₂ emissions compared to conventional methods.

This study focuses on the feasibility and integration of existing, off-the-shelf components without delving into specific hardware design or modifications to existing technologies. The project remains strictly advisory, excluding studies on energy transmission losses, seasonal fluctuations, long-term maintenance, small-scale social impacts and political views, and alternative renewable energy sources beyond solar PV. It assumes all stakeholders act in good faith, with accurate representations of costs and system performance, and it does not investigate stakeholder motives or political dynamics. While the team will highlight potential political or social barriers, addressing them lies outside the project's scope. The environmental analysis will be limited to CO₂ emissions at the end-use stage, excluding other life cycle stages and greenhouse gases coming from manufacturing, transportation, disposal of equipment, etc.

Technical Analysis

ETER System Overview

Effluent Thermal Energy Recovery (ETER) systems harness the otherwise wasted heat found in domestic streams. This wastewater, which is produced by showers, dishwashers, cooking, or industrial processes enters sewer systems at temperatures ranging from 10 °C to over 20 °C. Instead of letting this thermal energy dissipate into the environment, ETER systems capture and reuse it for heating purposes such as space conditioning.

The process begins with the collection of wastewater through a sewer line, where a heat exchanger is installed either directly within or adjacent to the sewer pipe. This device extracts heat from the warm wastewater and transfers it to a closed-loop system filled with a secondary fluid, typically clean water or glycol.

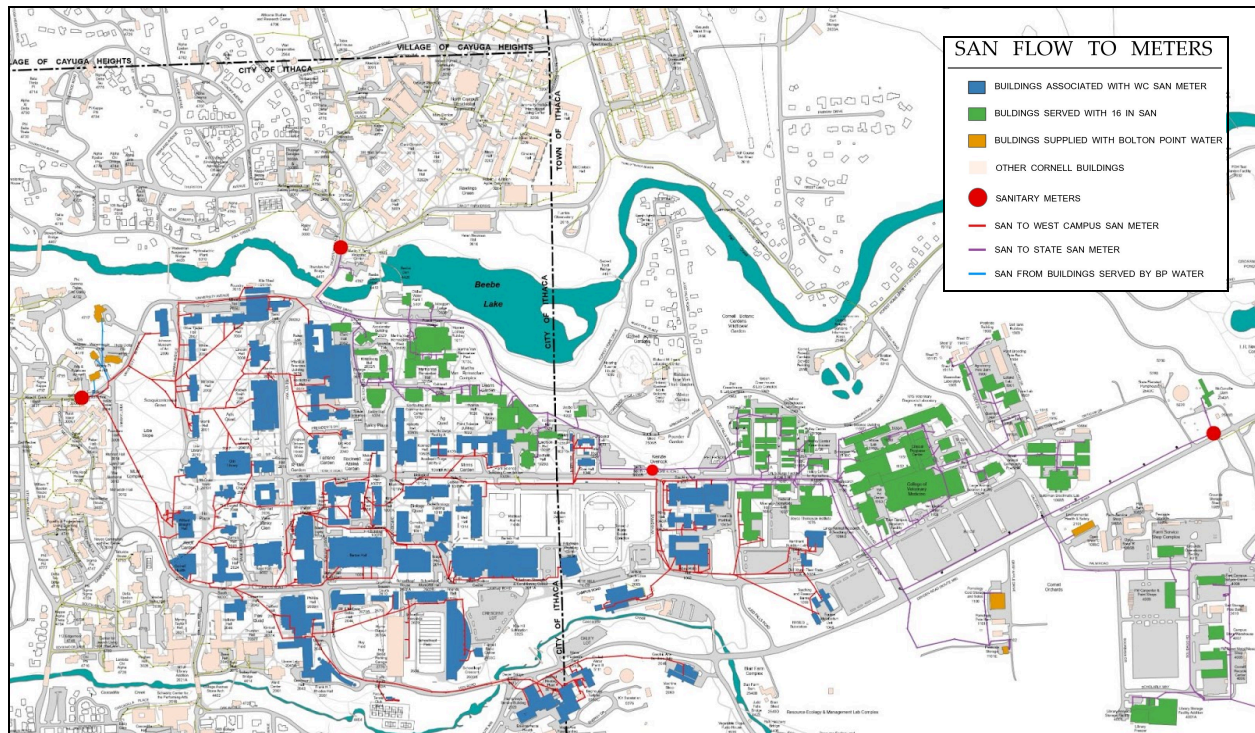


Fig. 2. Sanitary Map of Cornell University.

Cornell currently meets about 20% of their campus electricity needs from renewable sources, while the majority of it is produced by the University's natural gas powered combined heat and power (CHP) plant, which produces both heat and power. Cornell's current heating system consists of steam and hot water lines. The CHP plant supplies steam through a network of underground piping, delivering heat to campus buildings. However, as this steam travels through the system, it experiences a 25% distribution loss. Cornell is currently undertaking long-term transition to circulate hot water instead of steam and prevent distribution losses.

Our proposed ETER system design is the double pipe system as shown in Figure 3. This system allows heat transfer between two concentric pipes containing fluids of different temperatures. The inner pipe will contain a diverted portion of the wastewater from the main pipe, while the outer pipe will contain a colder working fluid or water. The heat will transfer through the wall of the inner pipe and enable the two fluids to exchange thermal energy without direct contact. The dominant form of heat transfer is conduction as heat passes from the inner towards the outer fluid. The pipe materials are often a highly conductive material such as steel or aluminum. The material we chose for our system is carbon steel as it is highly conductive and reflects materials currently in use on campus. The fluids can operate in parallel or counterflow, in our case counterflow is more preferred as it increases heat transfer. After reaching the end of the pipeline, the working fluid or water will pass through a heat pump system as described above and the temperature will be raised even further. The heat will then be extracted and used to heat the

building. Then, the working fluid will return to the pipe system and this process will be repeated in a close loop (Cavallo, 2023).



Fig. 3. Double pipe system (Jansen, 2025).

There are many advantages of using the double pipe system. In terms of construction, the double pipe system is relatively simple and straightforward to produce and repair. They are frequently used so replacement parts are easy to source. The robust design of the pipe system also makes it suitable for high temperatures and pressures. It is also a modular design, so the pipe parameters can be easily adjusted. Furthermore, the double pipe system has a broad range of applications. It can be used in chemical processing, petroleum refining, refrigerating, heating, sterilization, and wastewater treatment (Cavallo, 2023). These benefits make the system suitable for the Cornell Campus as there are already pipe system changes occurring due to the switch from steam to hot water for heating and this system can help reduce infrastructure costs.

ETER Estimation of Heating Capacity and Electricity Demand

Wastewater data taken in the sanitary meters was provided by Samuel V. Fairchild, an Energy & Sustainability Engineer at Cornell. This data ranged from November 28, 2025 until January 29, 2025 and contained the temperature and flow data from the Thurston, University Ave, Tower Road, Pump House sanitary meters. Flow rate data had units of gallons per minute for five minute intervals, and temperature data was collected in five minute intervals in Fahrenheit. The average, maximum, minimum, and variability of both flow and temperature were calculated and can be seen in Tables 1 and 2.

Site Name	Pump House	Thurston	Tower Road	University Ave
Average Flow (gpm)	51.69	269.57	136.03	160.39
Max Flow (gpm)	327.59	760.93	599.75	412.84
Min Flow (gpm)	0.01	76.08	11.86	4.94
Variability (gpm)	327.58	684.85	587.89	407.90

Table 1. Wastewater flow rate data.

Site Name	Pump House	Thurston	Tower Road	University Ave
Average Temp (°F)	49.19	55.18	50.86	56.38
Max Temp (°F)	54.79	63.22	58.27	64.64
Min Temp (°F)	42.49	49.38	43.67	51.78
Variability (°F)	12.30	13.84	14.60	12.86

Table 2. Wastewater temperature data.

Given the proximity of the University Avenue sanitary meter to West Campus, student residencies here were chosen as the buildings that are to be heated by the ETER system. One of these buildings is Boldt Hall, a Collegiate Gothic style building that is part of the Alice Cook House. Gothic buildings in West Campus typically use steam generated by the CHP plant to heat their spaces.

To calculate the energy demand from heating in Boldt Hall, the Energy Management & Control System (EMCS) was used. The EMCS provides access to downloadable real-time energy consumption data for the Cornell campus buildings. To match the timing of the wastewater data that was provided, we looked into the heating demand of Boldt Hall from November 28, 2024 to January 29, 2025.

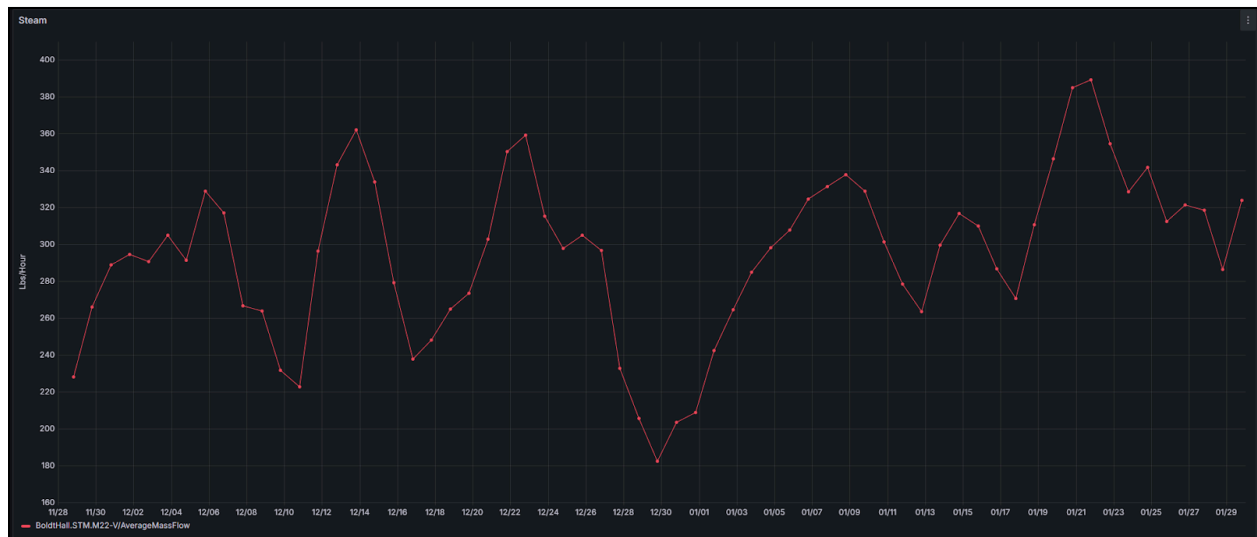


Fig. 4. Average mass flow of steam for heating in Boldt Hall.

Figure 4, shows the steam demand in Boldt Hall for heating, which is in pounds per hour. We decided to calculate the average heating demand throughout this heating season to make sure that the ETER system provides sufficient heating throughout the period. An average of 295 lbs/hr was found.

To have a standard unit for both systems, we converted the mass flowrate of steam into kWh. Given the design standards of the steam piping system used at Cornell, the pressure of the fluid is between 60-75 psig and a temperature of 450°F. We assumed a pressure of 70 psig. To determine the enthalpy of steam under the given conditions, we first converted the pressure from gauge to absolute, resulting in 84.7 psia. Since the corresponding saturation temperature at this pressure is approximately 311°F and the given steam temperature is 450°F, the steam is in a superheated state. We then referred to standard thermodynamic steam tables for superheated steam to find the specific enthalpy at 84.7 psia and 450°F. According to these tables, the enthalpy of superheated steam at these conditions is approximately 1,218 BTU/lb.

To estimate the total thermal energy delivered by the steam system, the average heating load of 295 lbs/hr was used with the enthalpy value of 1,218 BTU/lb. This energy content per pound was multiplied by the mass flow rate and the total duration of operation, assuming continuous flow over a 63-day period. The total energy in BTUs was calculated and yielded approximately 541.49 million BTU. This was then converted to kilowatt-hours (kWh) using the conversion factor of 1 kWh = 3,412 BTU, resulting in a total energy output of approximately 162,876 kWh over the 63-day period for Boldt Hall.

Now, to find the heat available from WW, the specific heat equation (Equation 1) was used.

$$Q = m * C_p (T_{in} - T_{out}) \quad (1)$$

Specific Heat Equation Input Parameters:

Q = rate of heat energy available in the wastewater (kW)

m = mass flowrate of wastewater (kg/s)

C_p = Specific heat capacity of water (kJ/kg*K)

T_{in} = Inlet temperature of wastewater (C°)

T_{out} = Outlet temperature of wastewater after the heat exchanger (C°)

$$Q_{usable} = \eta_{exchanger} * Q_{theoretical} \quad (2)$$

To illustrate the process, we performed a sample calculation using data from December 23, 2024, across three monitored locations: the Pump House, Thurston Ave, and University Ave. A 20°F temperature drop was assumed at each location to represent heat extraction.

Pump House		Thurston		University Ave	
Flow Rate (gal/min)	Temperature (F)	Flow Rate (gal/min)	Temperature (F)	Flow Rate (gal/min)	Temperature (F)
48.12	49.67	202.25	50.10	171.91	57.82

Table 3. Wastewater flow and temperature on December 23, 2024.

The heat available from each site was calculated as follows:

Pump House:

$$Q = 48.12 \times 8.34 \times 20 = 8,030.8 \text{ BTU/min} = 481,848 \text{ BTU/hr} \approx 141.2 \text{ kW}$$

Thurston Ave:

$$Q = 202.25 \times 8.34 \times 20 = 33,716.0 \text{ BTU/min} = 2,022,960 \text{ BTU/hr} \approx 592.5 \text{ kW}$$

University Ave:

$$Q = 171.91 \times 8.34 \times 20 = 28,658.1 \text{ BTU/min} = 1,719,486 \text{ BTU/hr} \approx 503.8 \text{ kW}$$

Summing the theoretical heat potential from all three sites gives a total of approximately 1,237.5 kW. To determine how much of this heat could realistically be recovered and used, we applied a heat exchanger efficiency factor (η) of 0.85. Using the usable heat equation (Equation 2), the total usable heat on December 23 becomes:

$$Q_{usable} = 0.85 \times 1,237.5 \text{ kW} = 1,051.9 \text{ kW} \times 24 \text{ hrs} = 25,245.6 \text{ kWh}$$

This calculation shows the methodology used in the model, which performs the same operation across each day of the 63-day heating season using site-specific flow and temperature data. While only one day is shown here for simplicity, the code computes the total available and usable heat for the entire period. Please refer to the appendix for the code.

Lastly, to compute the energy consumption of the ETER system, a COP of 3 was used. For the 63-days heating used, the compressor, which is assumed to account for 80% of the ETER energy demand, uses 54,292 kWh. Hence, the total electricity needed to power the system during the heating season is 67,865 kWh.

ETER Model

Heat Transfer

For additional proof of concept, the heat transfer losses were considered for our proposed double pipe system compared to the current campus pipe system. The current campus pipe system was assumed to be using hot water in this analysis to reflect future heating plans. This heat transfer model also solely focuses on conduction losses. The below radial heat conduction formula was used assuming a thick walled pipe with insulation in which L represents the length of the pipe, T

represents the temperature, and R represents the thermal resistance in each layer (Conduction Heat Transfer | Engineering Library, n.d.).

$$Q = 2\pi L(\Delta T)/\Sigma R \quad (3)$$

Additionally, the parameters depicted in Table 4 were used for each system's calculations. Our analysis yielded that the current campus system experiences a heat loss value of 1,601.18 BTU/hr while our proposed double pipe system would experience a heat loss value of 426.10 BTU/hr. This reveals how our system would reduce heat losses by a large factor due to how the outer fluid conducts the heat from its inner wastewater pipe.

Parameters	Double Pipe System	Current Campus Piping	
		Hot Water Pipe	Wastewater Pipe
Pipe Material (Cornell University, 2024)	Carbon steel	Carbon steel/ steel alloy	PVC
Insulation Material (Cornell University, 2024)	Polyurethane	Polyurethane	Polyurethane
Length of Straight Pipe (feet) (Cornell University, 2024)	40	40	40
Nominal diameter of pipe (inches) (Cornell University, 2024, map)	Outer: 12 Inner: 10	12	12
Insulation thickness (inches) (ASHRAE, 2022)	2.5	2.5	2.5
$k_{insulation}$ (BTU/h * ft * °F) (Carriço et al., 2017)	0.017	0.017	0.017
k_{pipe} (BTU/h * ft * °F) (Engineering ToolBox, 2005)	24.8	24.8	0.017
Temperature of fluid in the pipe (°F) (Cornell University, 2024)	Outer: 37 Inner: 57	180	57

Table 4. Heat loss analysis parameters.

ETER Data Analysis

For our proposed ETER system, we wanted to develop a model to process and visualize the data given to us to determine whether the wastewater heat recovery could potentially be a viable source of energy for buildings on west campus such as Boldt hall. The model assesses how much of a building's heating demand could be met through calculating heat recovery from flow and temperature data, compares it to building demand, and lastly generates visualizations. The final model visualizations include a comparison of total heating demand vs. wastewater + compressor contributions, usable energy recovered per location, monthly breakdown of recovered heat (with November adjustment), and theoretical vs. usable energy to show system efficiency.

The initial model version only estimated the amount of heat that could be recovered from campus wastewater using passive heat exchangers. The key features of this model included simplified pipe loss calculations, total versus usable energy at all four locations of pump house, thurston ave, university ave, and tower road. It also calculated a basic payback period. This initial model did not account for a compressor which would be used in reality to boost the temperature of the heated nanofluid.

The final model reflects reality as it incorporates the compressor aspect. Some key features include the compressor aspect through the inclusion of a COP of 3 (Cipolla & Maglionico, 2014), a simplified pipe loss model due to negligible impact, temporal filtering to match the 63-day heating season, and a focused source-to-demand setup between University Ave and Boldt Hall. Additional improvements include more detailed plots for better visualization and interpretation.

The inclusion of COP was a key important part of the final model because of the inclusion of the compressor, and translates thermal energy into electrical energy input. Heating season data alignment was also a key change in the final model which allowed for accurate matching between demand and production, increasing the temporal precision of heat availability relative to building heating demands. Additionally, the ultimate choice to model energy production and demand only based on university ave and Boldt hall allowed for a more localized and specific proof of concept. The respective results can be interpreted and analyzed for feasibility for future implementation or even scaling up.

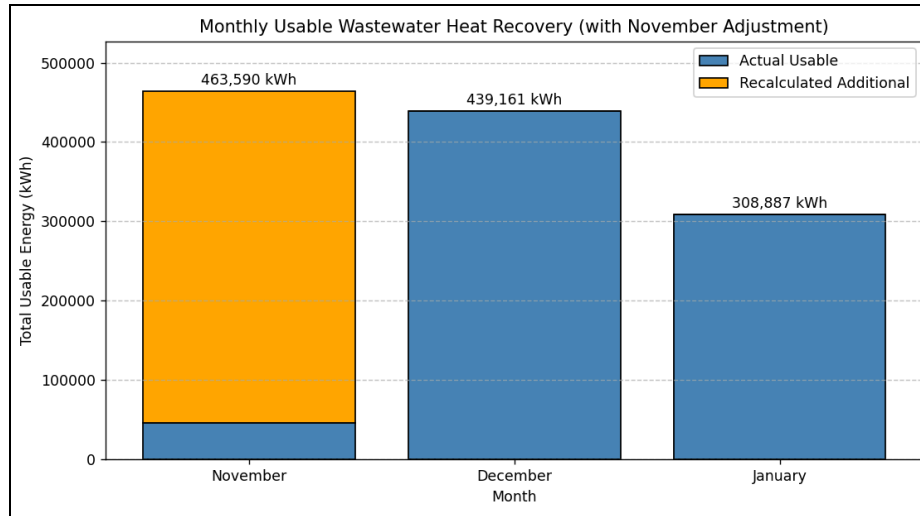


Fig. 5. Estimated monthly wastewater energy generation based on available data.

In Figure 5, energy values were extrapolated using three days of recorded data from November, which yielded a daily average of approximately 15,453 kWh/day. This average was scaled to estimate a full month's generation of 463,590 kWh. The total energy generation over the 63-day period was calculated by summing the estimated November total (463,590 kWh) with available totals from two other months: 439,161 kWh and 308,887 kWh, resulting in a cumulative total of 1,211,638 kWh. Missing data limited the model's input to only three days of November data.

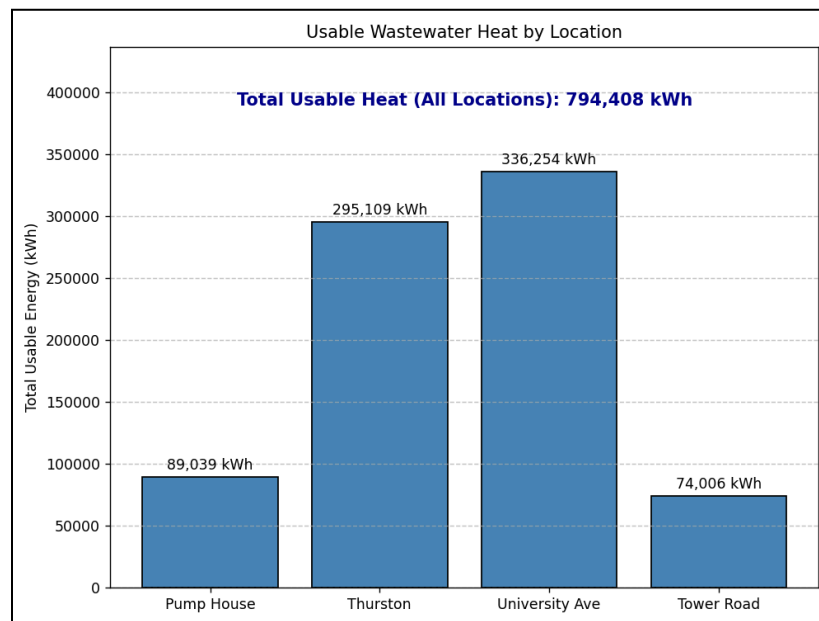


Fig. 6. Wastewater energy generation by location.

Figure 6 illustrates the variation in energy potential across four sites. Pump House and Tower Road exhibit the lowest energy generation, which may be attributed to lower wastewater flow

rates, reduced temperatures, or smaller contributing areas. In contrast, Thurston and University Avenue show the highest energy potential, likely due to greater wastewater volumes, higher temperatures, or increased residential density in those areas.

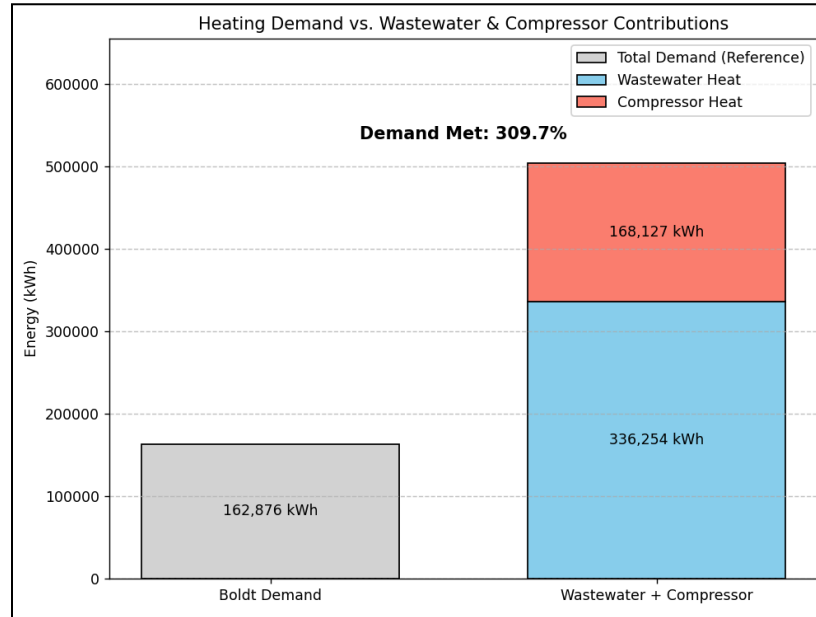


Fig. 7. Comparison of Boldt Hall’s heating demand with projected energy production from wastewater heat recovery and compression (2:1 ratio).

In Figure 7, the left graph displays the seasonal heating demand for Boldt, while the right graph shows the estimated energy output from the University Avenue wastewater site. The analysis indicates that University Avenue alone can supply more than enough energy to meet Boldt’s heating needs, with surplus energy potentially serving additional nearby housing. These results support site prioritization efforts, helping identify optimal locations for heat exchanger installation to maximize building energy offsets.

Some areas of consideration were data gaps, data insufficiency (63 day heating period) , static conditions, physical modeling simplifications (using T_{out} as 4 C), and no thermal storage implementation. When using the 63 day heating cycle due to data limitations, we fail to capture the seasonal variability in wastewater temperatures and flow. This may significantly overestimate or underestimate the reality of the wastewater conditions and would benefit from utilizing more sets of data from multiple years. The static conditions that we are assuming over the large heating period ignores the diurnal and other episodic conditions that affect energy production, and future work to use dynamic time series by the hour would better reveal real world variability. From our modeling simplification of using T_{out} of 4C may not reflect the true outlet temperature which vary with heat exchanger efficiency, which would need laboratory testing to estimate a more accurate value. Lastly, without the thermal storage option, we miss out on operational flexibility of storing energy during low demand periods and using them during high demand

periods. Including this element would better model the temporal matching between heat recovery and building demand by the hour or any other time interval.

Solar PV Integration

Solar PV Integration: Snyder Road Farm Site

The Snyder Road Solar Farm is located in the North of Ithaca, close to the local airport near Lansing. Due to its current location, the Snyder Road farm can be easily set as a critical sample for the BOCES' design. Snyder Road Solar Farm provides energy for the Cornell campus, with an annual generation of 1,925 GWh (*NYSERDA DER Integrated Data System*, n.d.). As the design showed to be effective and provide enough energy support to meet the assumption on campus, the BOCES is similar in location and the general design can be similar with the Snyder Road Solar Farm. According to the latest data retrieved online, with a tilt angle of 17°, and a nameplate capacity of 2067.29 kW, the capacity factor is currently 10.6% (NYSERDA, 2025).

Additionally, there were some parameters that specifically needed validation and analysis. One of those tasks was to verify that the number of solar panels in the aerial view match the plan. After thorough counting, the number of panels was determined to be 6,778 which matched the number of panels from the plan. Additionally, to analyze the Snyder Road Farm performance, we were tasked to compare the site generation across year 1, 5, 10, 15, and 20. Since the solar farm was finished at the end of 2014, we decided to take 2015 as the baseline year for energy generation. Our plot used the real generation data from the NYSERDA website (*NYSERDA DER Integrated Data System*, n.d.), which had complete yearly generation from 2015 to 2021. These years were used to calculate the capacity factor of the system, and then a constant yearly degradation of 0.50% was considered to calculate the losses of the solar panels throughout the years. The electricity generation from the Snyder Rd Farm from 2015 to 2035 can be seen below in Figure 8. Overall, this site was used as a model and basis for the BOCES site due to their similarities.

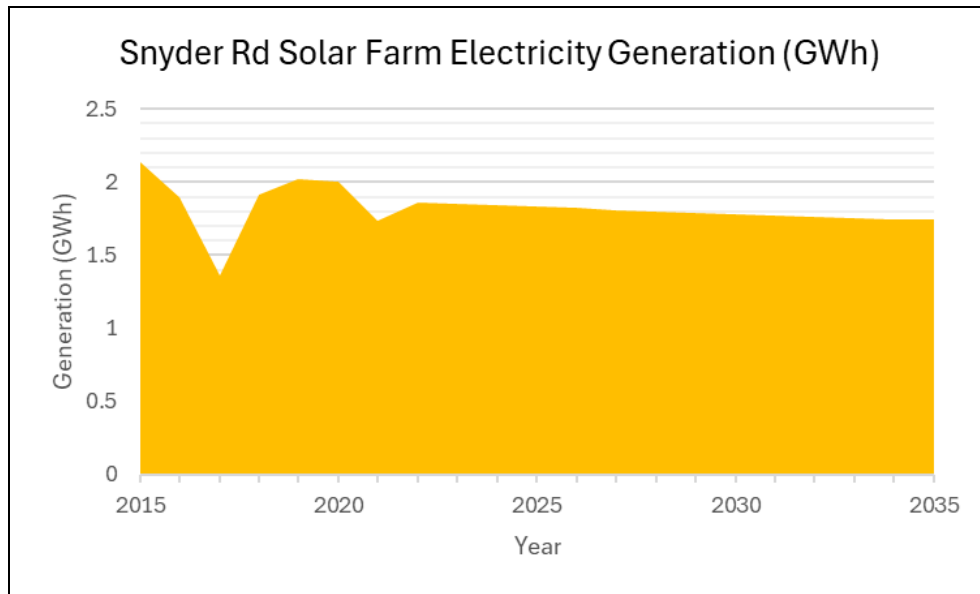


Fig. 8. Snyder Road Farm generation from 2015-2035.

Solar PV Integration: BOCES Site

For the BOCES site, we began by analyzing solar energy generation using PV Watts estimation tools with default parameters. The only parameter change we made was the tilt of the rooftop racking system. We decided to use an angle of 43 degrees, as this is the latitude at the site location. This is a common way to determine the ideal tilt angle that we have used before in the mini-course for this project as well as other renewable energy courses. To further refine our analysis, we modeled our site in Helioscope, which allowed for considerably more detail in terms of panel location, keepouts, and shading factors. Cross-validating the Helioscope simulation with the previous PV Watts estimates, we found that the total annual generation of our farm differed due to variations in system losses. While the PV Watts modeling tool allows the user to manually input the total system losses (with an option to provide more detailed loss information), the Helioscope model only allows for system losses to be input for each specific loss factor. This posed a challenge for us as we had determined the total system loss for our design to be around 43%. This value was extrapolated via the Snyder Farm Road Solar Farm using the annual production data and the nameplate capacity. To overcome this challenge, we decided to put in specific loss values in the Helioscope model, as this software is objectively more accurate than PVWatts. We kept the default AC losses as 0.5% to account for the fact that all the generated electricity will be used, either on-site to power the BOCES buildings, or redirected to our campus ETER system.

Helioscope Results: According to Helioscope modeling, the BOCES site, assuming optimal panel placement and minimal shading, has a nameplate capacity of approximately 2.21 MW. The annual production is 2.067 GWh and the number of modules in the layout is 6,907. This will be discussed more later in the paper.

System Losses and Realistic Output: Recognizing that real-world conditions impose efficiency losses (e.g., inverter losses, shading, soiling, wiring inefficiencies), we estimated total system losses similar to those observed at the Snyder Road Farm (approximately 19.5% losses from theoretical maximum output). Adjusting for comparable losses, the practical annual generation output for the BOCES site would be approximately 820 MWh/year.

Comparison with Heating Demand: The Boldt House, used as a representative building for heating demand calculations, requires approximately 162,876 kWh for the winter heating season (63 days). The BOCES site's annual solar production (even after losses) is more than enough to completely offset the electricity required to power the ETER system for the found seasonal heating demand.

To optimize the solar energy potential at the BOCES site, several integration considerations should be addressed. First, exploring opportunities for additional rooftop installations or the development of nearby ground-mounted arrays could increase energy offsets and enhance overall system performance. Additionally, engaging with NYSEG to negotiate favorable net metering or grid interconnection terms will be critical, particularly to effectively manage seasonal overgeneration and ensure economic viability of the system. In conclusion, the BOCES plays a critical role in meeting net annual electricity requirements for the ETER system, moving Cornell closer to its carbon neutrality goals.

Helioscope Modeling and Simulation

To begin modeling the BOCES site in Helioscope, the potential areas for solar panel and inverter placement was first determined. The BOCES site consists of five buildings and two parking lots (north and south). There is also additional flat land located near the north parking lot. All of these areas were identified as areas for solar implementation. The buildings and flat land contain fixed tilt rooftop solar panels while the parking lots contain carport canopies. The carport canopies were dimensioned to be 12 feet above the ground as this is a standard height that covers most car heights (Solar Carport Canopies Element Energy Systems, 2023). Furthermore, the tilt angle used for all the solar panels was 17° to match the existing Snyder Road Farm. The following default solar panel and inverter type was chosen for the layout: Trina Solar, TSM-PD14 320 (May16) (320W) and Sunny Tripower 24000TL-US (SMA). Additionally, a constant set back of 4 feet from roof edges/ parking lot edges and 2 feet for keep out zones were used throughout the design for simplicity and consistency. The keep out zones included HVAC units, the courtyard within one of the buildings, and any large piping that could be detected from the aerial view. For precise placement, the buildings' heights were determined through Google Earth measurements. Helioscope's default electrical wiring and inverter placement was also utilized. As mentioned previously, the system default values were used for losses. For soiling this

was kept at 2% monthly, the AC derate factor was kept at 0.5%, and the assumed irradiance variation was 5%.

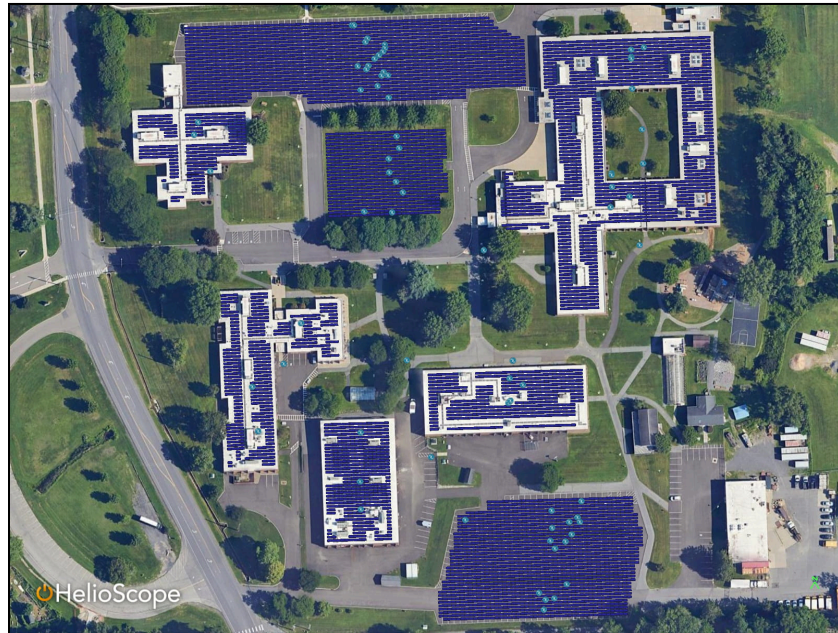


Fig. 9. BOCES site layout in Helioscope.

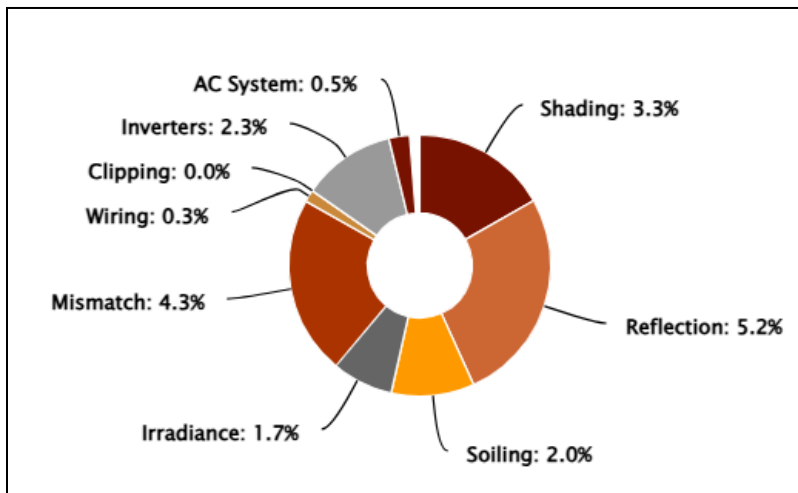


Fig. 10. Helioscope system losses for the BOCES site.

Finally, the site layout results were compiled and analyzed as shown in Figures 9 and 10. The nameplate capacity is 2.21 MW, the annual production is 2.067 GWh, and the number of modules and inverters in the layout is 6,907 and 74 respectively. These results align with the Snyder Road Solar Farm which was used to help us model this new site. The number of panels is fairly similar and the annual generation is also in a similar range. However, the BOCES site yields higher overall results due to its maximized area usage and simplifications. To further

validate the design and its efficiency, the capacity factor was calculated below. The calculated value of 10.6% is on par with what is expected from large solar sites in which the mean capacity factor can range from 10% to 36% (Boretti & Castelletto, 2020). The capacity factor also matches Snyder Farm's value (NYSERDA, 2025). Capacity factors also depend heavily on climate and solar availability, so values above 20% are typically only found in areas that receive a lot of sunlight like Arizona.

$$CF = \frac{2.067GWh}{2.21MW} * \frac{1MW}{0.001GW} * \frac{1}{8760\text{ hours/year}}$$

$$CF = 10.6\%$$

Economic Analysis

Capital and Operating Costs

ETER

According to an economic assessment of a wastewater ETER project, the investment cost is 0.37 €/m³ and the operating cost is 0.29 €/m³ (Munoz et al., 2019). Using the given flow data for each of the meters on campus, we can estimate the cost per year of the ETER portion of the project. These calculations can be shown in Table 5.

Meter	gal/min	m ³ /s	m ³ /d	m ³ /yr	\$/yr
Pump House	51.69	3.26E-03	281.76	102,844.08	90,276.53
Thurston	269.57	1.70E-02	1,469.48	536,358.43	470,815.43
Tower Road	136.03	8.58E-03	741.51	270,649.77	237,576.36
University Ave	160.39	1.01E-02	874.32	319,126.15	280,128.93

Table 5. Annual cost calculations of the ETER system for each meter.

Since our project focuses on West Campus, we will only consider the cost of the University Ave. meter, which is \$280,128.93 annually.

Solar

To estimate the annualized capital cost of the solar PV system, we relied on data from the National Renewable Energy Laboratory (NREL), including capital expenditures (CAPEX), fixed operation and maintenance (O&M) costs, and variable O&M costs. We adopted the moderate cost scenario, which assumes continued research and development investments at current levels and successful achievement of industry technology roadmaps. To select the appropriate NREL technology classification, we used the global horizontal irradiance (GHI) specific to Ithaca, New York. As shown in Figure 11, the GHI for Ithaca is less than 4 kWh/m² per day. Using this we

found that Ithaca corresponds with the NREL technology class 10. A summary of the cost assumptions is provided in Table 6.

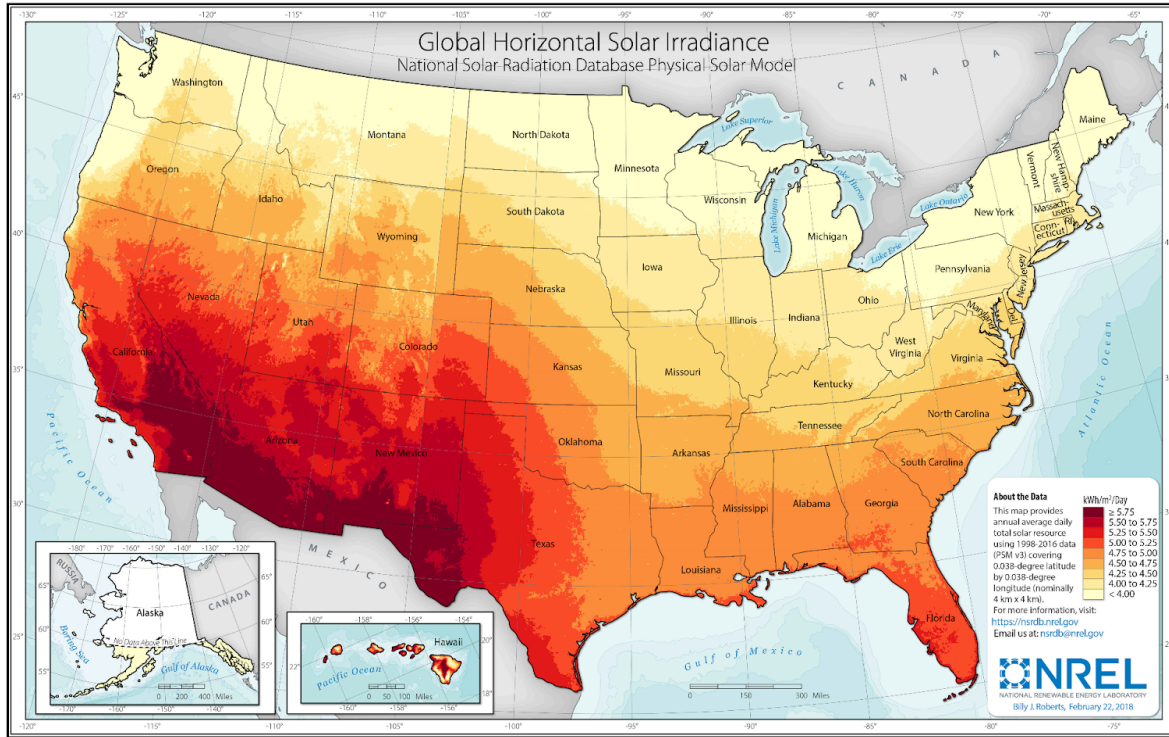


Fig. 11. Global horizontal solar irradiance for the United States (*Residential PV | Electricity | 2024, n.d.*).

Variable	Cost (USD)
CAPEX (\$/kW)	1,744
Fixed O&M (\$/kW-y)	18

Table 6. Capital expenditures, fixed O&M, and variable O&M for solar PV installation.

To evaluate annual costs, I converted the capital expenditure into an annualized value using a capital recovery factor. This calculation incorporates the capital recovery period (N) and the weighted average cost of capital (i, WACC), following the standard equation:

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

For the technology class 10, the capital recovery period is 30 years and the WACC is 3.6%. The result can be found in Table 7.

CAPEX (\$/kW)	Total Cost (\$)	A/P	Annualized Cost (\$)
---------------	-----------------	-----	----------------------

2,519	3,854,240	0.0551	\$212,194
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Table 7. Annualized capital cost calculation.

The total annual cost, including fixed O&M, is \$251,974.

Cost-Benefit Analysis

Comparison with Conventional Heating

Cornell's current heating system relies on centralized steam production, which results in an annual expenditure of \$170,235, a levelized cost of energy (LCOE) of \$0.0922 per kilowatt-hour, and approximately 334 metric tons of carbon dioxide emissions each year. These figures establish the baseline for evaluating alternative heating options. In the ETER-only scenario, the system achieves a LCOE of \$0.0986 per kilowatt-hour, with a payback period of 1.1 years and annual emissions reduced to 100 metric tons of CO₂. By integrating solar PV, the ETER + PV configuration lowers the LCOE significantly to \$0.0297 per kilowatt-hour, further reducing emissions to 33 metric tons of CO₂, with a slightly extended payback period of 2.2 years due to higher initial capital costs.

Levelized Cost of Energy Comparison

From a cost perspective, Figure 15 illustrates the LCOE comparison among the three systems. Although ETER-only marginally exceeds the steam system in per-kilowatt-hour cost, the addition of solar PV dramatically reduces the LCOE, achieving a 68% cost reduction compared to the steam baseline. This demonstrates the significant long-term financial benefits of coupling heat recovery with renewable electricity generation.

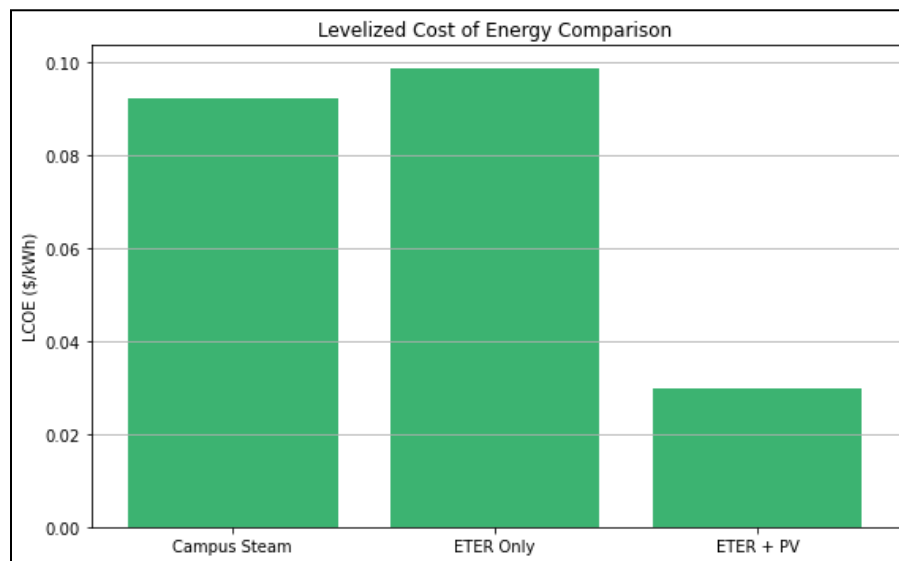


Fig. 12. LCOE comparison of the current campus steam system, the ETER only system, and the ETER and PV combined system.

Payback Period Analysis

When applying a discounted cash flow analysis at a 5% discount rate, the payback periods for both the ETER + PV and Solar Only systems are estimated to occur in approximately 15 years. This reflects the capital-intensive nature of large-scale solar PV installations in regions with relatively low electricity rates and moderate solar resources, such as Ithaca, NY. The longer payback periods underscore the financial reality of such systems, where the bulk of avoided electricity savings accumulates gradually over decades. For the discounted payback period analysis, we used the system-wide PV generation estimate of 2.07 million kWh per year, consistent with our earlier modeling of the BOCES and Snyder Road Solar Farm sites. An avoided electricity cost of \$0.18 per kWh was applied to reflect the behind-the-meter retail rate Cornell might offset with on-site solar generation. This results in an annual avoided electricity cost of approximately \$372,600, which was used as the basis for both the ETER + PV and Solar Only discounted cash flow analyses.

$$\text{Discounted Savings in Year } t = \frac{\text{Annual Savings}}{(1+r)^t}$$

where $r = 5\%$ and t is the project year (1 to 30)

The cumulative discounted savings were compared to the total upfront capital cost of \$3.85 million, and the payback period was identified in Year 15, when the discounted savings exceeded the initial investment. This approach ensures that the payback period reflects the time value of money, which is critical when evaluating the financial viability of capital-intensive energy systems with long project lifespans. These results highlight the need for careful financial planning and the role of incentives or financing structures to make such systems more attractive to investors.

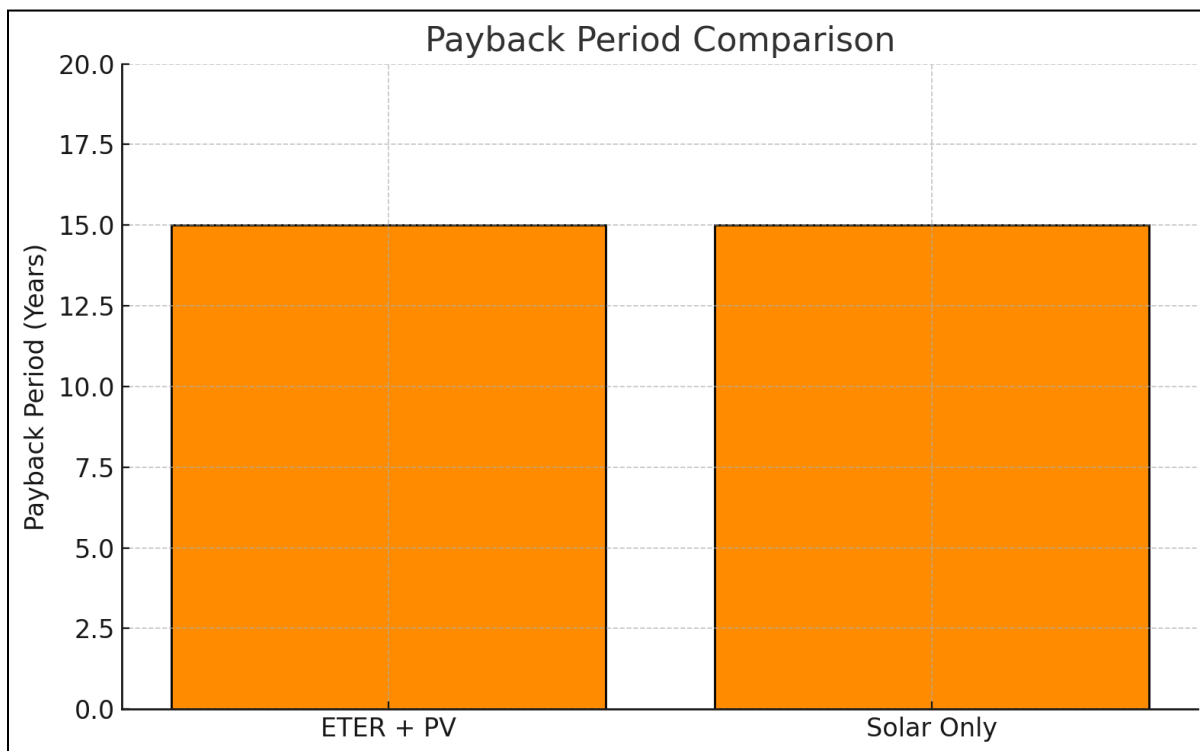


Fig. 13. Comparison of the payback periods for the ETER and PV combined system and solar only system.

Annual Operating Costs

Figure 14 compares the annual operating costs, including O&M and electricity expenses, across all scenarios. Both ETER-based alternatives significantly reduce annual operational expenditures compared to steam, with the ETER-only system achieving the lowest ongoing costs. The ETER + PV system, while incurring higher O&M costs, still represents a considerable improvement over the existing infrastructure.

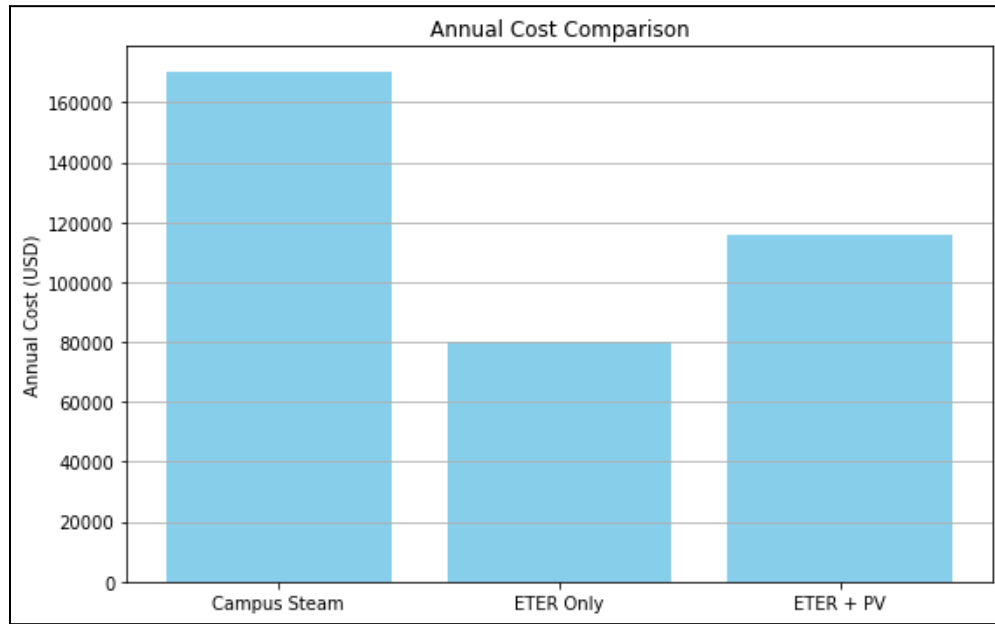


Fig. 14. Comparison of the operating and maintenance costs for the current campus steam system, ETER only system, and ETER and PV combined system.

Sensitivity to Discount Rate

Financial sensitivity analyses were conducted to assess the robustness of these findings. Figure 15 presents the sensitivity of LCOE to discount rates ranging from 3% to 7%. The results indicate minimal variation for both ETER-only and ETER + PV configurations, suggesting that the systems' economic performance is relatively insensitive to changes in financing terms.

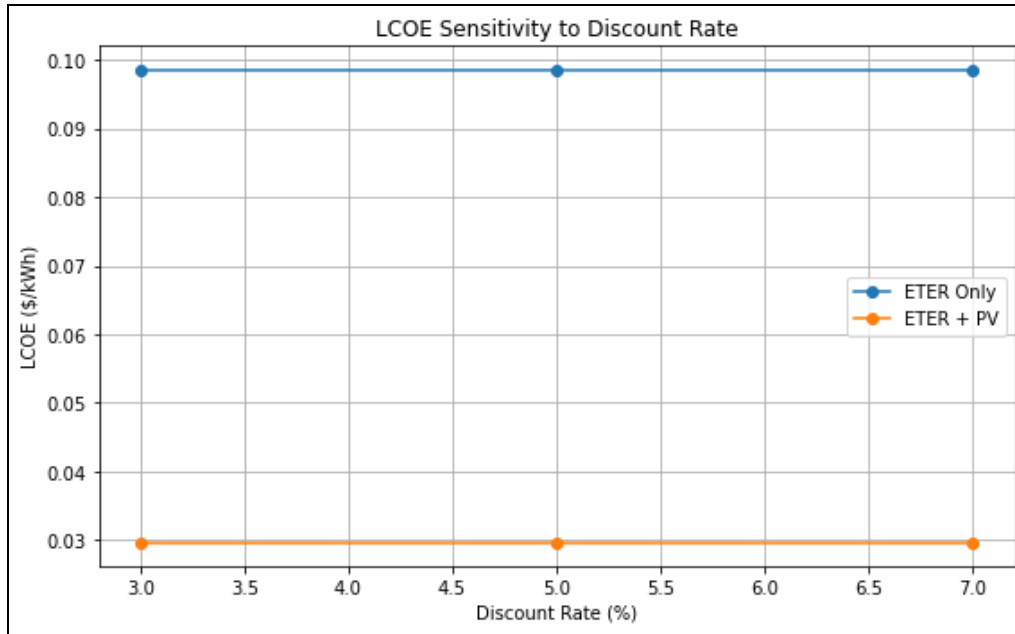


Fig. 15. Sensitivity of LCOE to discount rates running from 3% to 7%.

Sensitivity to Capital Costs

Capital cost variations, however, have a more pronounced impact, as depicted in Figure 16. A $\pm 20\%$ fluctuation in capital expenditures significantly affects LCOE outcomes, particularly for the ETER-only scenario. This sensitivity emphasizes the importance of securing cost-effective procurement strategies and managing installation expenses to ensure favorable economic returns.

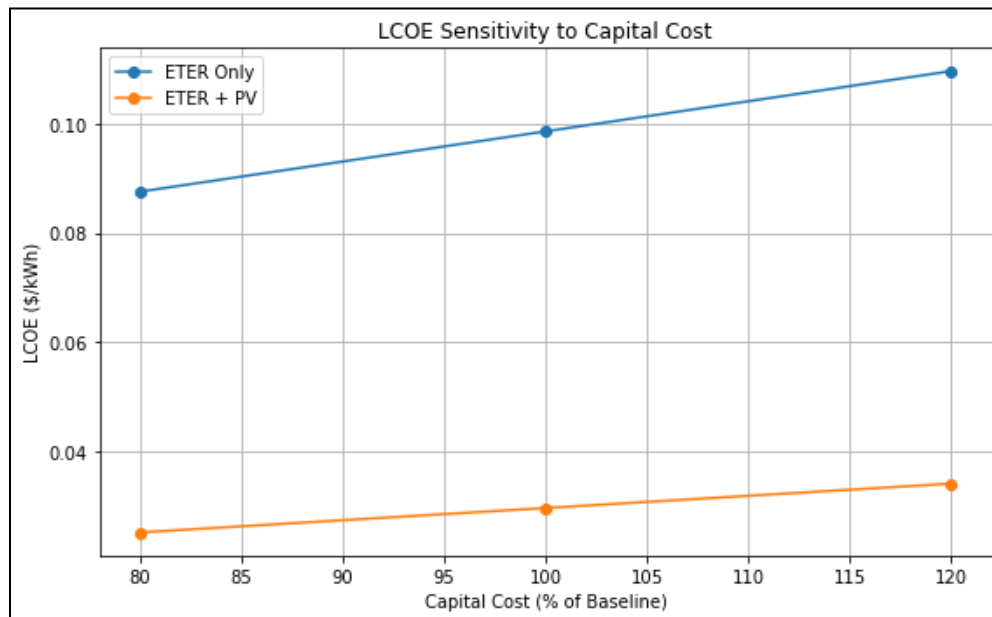


Fig. 16. Sensitivity of LCOE to capital cost variations.

Sensitivity to System Lifetime

The impact of system lifetime assumptions on LCOE is illustrated in Figure 17. Extending the operational lifespan from 20 to 30 years improves the economic performance of both configurations. Nevertheless, ETER + PV maintains a lower LCOE than steam across all lifespan scenarios, confirming its long-term financial viability.

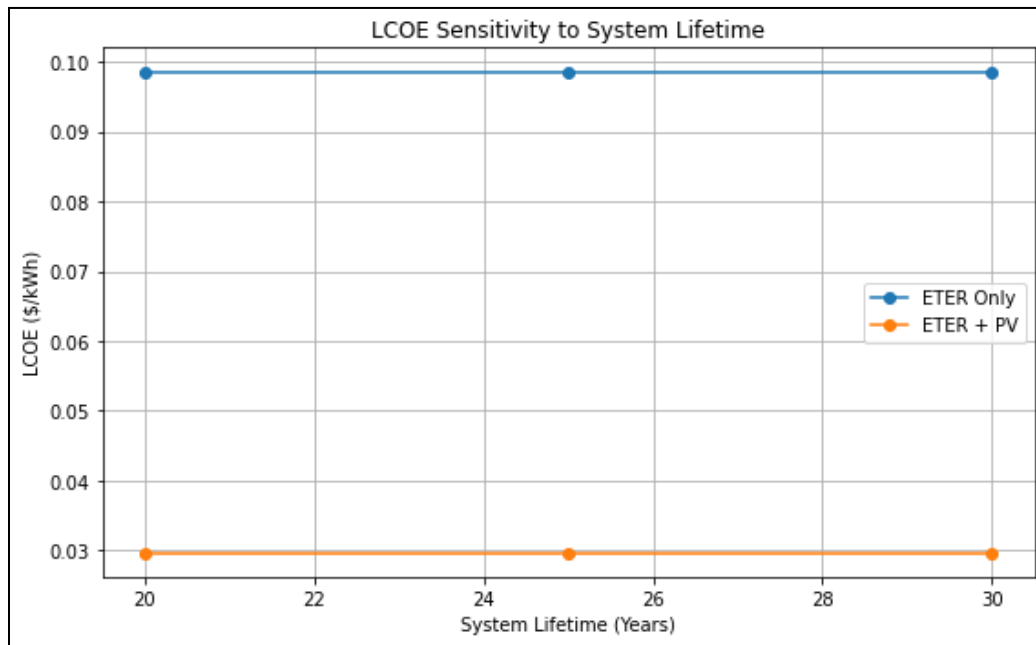


Fig. 17. Sensitivity of LCOE to operational system lifetime, ranging from 20 to 30 years.

Tornado Analysis of LCOE Sensitivity

A tornado diagram presented in Figure 18 summarizes the relative influence of capital costs, discount rates, and system lifetime on the ETER-only system's LCOE. Among these variables, capital cost exerts the greatest impact, followed by system lifetime and discount rate. This visualization underscores the critical importance of managing upfront investment costs and planning for long-term system durability to maximize economic benefits.

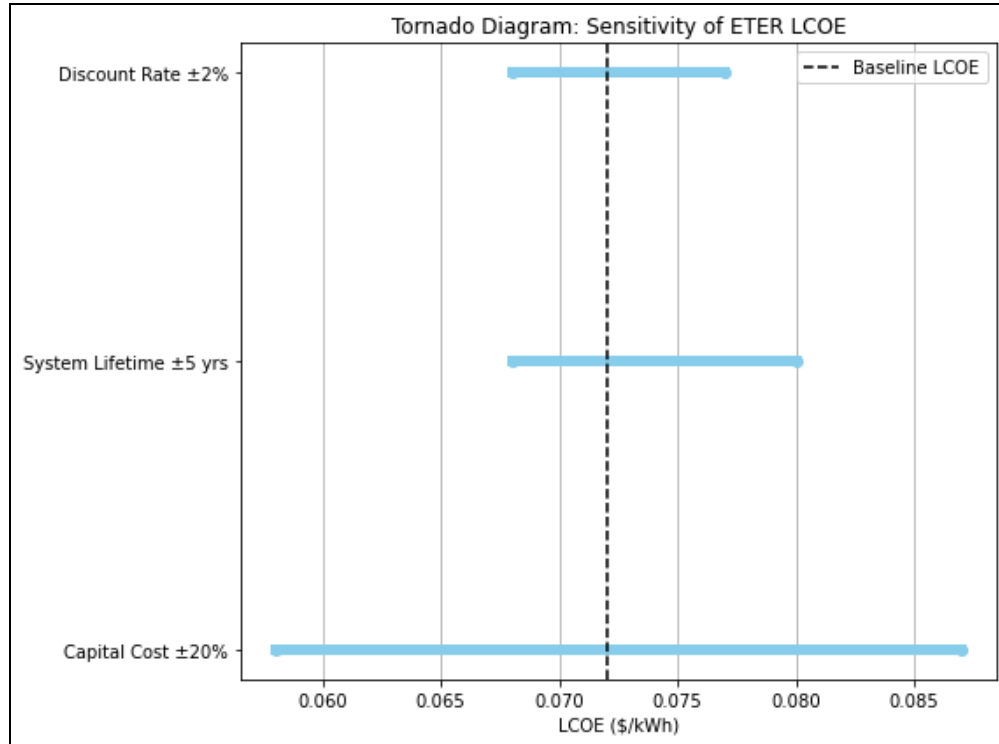


Fig. 18. Tornado diagram summary of sensitivity analysis.

Summary of Findings

The comparative analysis demonstrates that the ETER and solar PV systems offer significant economic and environmental advantages over the current steam-based heating infrastructure. While the ETER-only configuration provides rapid capital recovery and substantial emissions reductions, the integration of solar PV further enhances cost-effectiveness and decarbonization potential. Sensitivity analyses confirm that these benefits are robust across a range of financial assumptions, with capital costs identified as the primary driver of LCOE. Overall, the proposed systems align with Cornell's carbon neutrality goals and represent a viable path toward a more sustainable campus energy future.

Environmental Analysis

Carbon Emissions Reduction

Based on the total heat produced by the ETER system, that would replace the heated steam that comes from the CHP plant and the electricity generated by the solar panels after powering the ETER system, the number of CO₂ equivalent emissions avoided were calculated. It was assumed that the electricity generated to power BOCES would replace electricity coming from the NYS grid, which majority comes from natural gas.

Instead of using CHP steam (from natural gas) to supply 1,845,759.524 kWh of heat to the West Gothic dormitories, the ETER system uses solar powered heat pumps. Assuming a 70% efficiency for the CHP plant, and an emission factor for natural gas of 0.185 kg CO₂/kWh, the emissions from the CHP are as follows (*Emissions From Home Energy Use*, 2025):

$$\text{Natural Gas Input Needed} = \frac{1,845,759.524 \text{ kWh}}{0.70} = 2,637,942.18 \text{ kWh of gas}$$

$$\text{CHP CO}_2 \text{ emissions} = 2,637,942.18 \text{ kWh} * 0.185 \text{ kg CO}_2/\text{kWh} = 487 \text{ tonnes CO}_2$$

Since the ETER system will be completely powered by solar powered heat pumps, there would not be any emissions from this system.

The BOCES Solar project generates 2,067,000 kWh/year, of which 129,300 kWh goes to the heat pumps. The remaining solar electricity is 1,937,700 kWh. It was assumed that 35% of the electricity from the NYS grid comes from natural gas and an emissions factor for natural gas electricity generation of 0.5kg CO₂/kWh (*Fiscal Year 2024 Cornell University Central Energy Plant (CEP) Fast Facts*, 2025) (*Greenhouse Gas Emissions Calculator: User Guide*, 2024).

$\text{CO}_2 \text{ Savings from Solar Project} = 1,937,700 \text{ kWh} * 0.5 \text{ kg CO}_2/\text{kWh} * 0.35 = 339.1 \text{ tonnes CO}_2$
A total of 826.1 tonnes of CO₂ would be saved per year, further helping Cornell achieve its carbon neutrality goals.

Emissions Reduction Benefits

The environmental advantages of the proposed systems are visualized in Figure 19, which compares annual CO₂ emissions across the campus steam, ETER-only, and ETER + PV scenarios. While ETER-only achieves a 70% reduction in emissions compared to steam, the combination with solar PV pushes this reduction to 90%, underscoring the substantial decarbonization potential of integrating renewable technologies into the heating system.

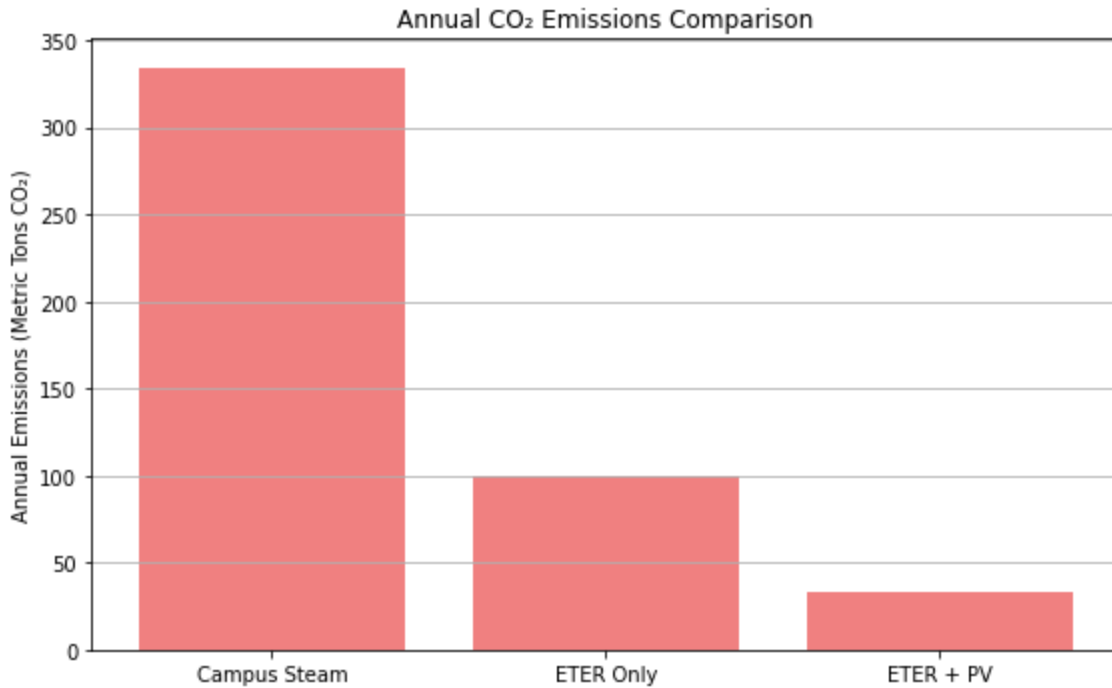


Fig. 19. Annual CO₂ emissions comparison for the current campus steam system, ETER only system, and ETER and PV combined system.

Sustainability Benefits

The integration of wastewater effluent thermal recovery with solar farm energy presents a highly sustainable solution for low-carbon heating and cooling, with substantial benefits across multiple environmental and energy-related dimensions. One of the primary advantages lies in the significant reduction of fossil fuel reliance. By extracting low-grade heat from municipal or industrial wastewater streams and using high-efficiency heat pumps powered by on-site solar PV, the system displaces the need for natural gas or other fossil fuels that are typically used in boilers or chillers. This shift significantly reduces greenhouse gas emissions, as well as encourages practical use of building operations and energy generation which contributes to long-term climate goals. Furthermore, since the BOCES solar farm supplies the energy required to operate the compressor and system controls, the system operates with near-zero operational emissions, effectively decoupling heating and cooling needs from volatile fossil fuel markets and enhancing energy sovereignty.

Alongside these energy benefits, the system also supports water conservation and generates additional environmental co-benefits. Traditional heating systems, such as steam and hot water systems that the Cornell Campus is currently using, often require large volumes of water and result in a significant amount of heat energy losses. In contrast, wastewater energy recovery systems operate in a closed loop and do not consume water in the process, therefore preserving local freshwater resources. This solution also contributes to energy stability by leveraging local,

decentralized renewable energy sources like solar PV and potentially integrating with battery or thermal energy storage, facilities becoming less dependent on centralized grids and more resilient to supply disruptions or peak demand events. This contributes to the broader goals of grid decarbonization and energy democratization. Most importantly, this approach aligns closely with national and international carbon neutrality goals, such as achieving net-zero emissions by 2050.

When appropriately managed, the ETER system can cut energy supply-related carbon emissions up to 97% compared to traditional systems. This level of reduction is critical for jurisdictions and organizations seeking to meet their Scope 1 and Scope 2 decarbonization targets. Finally, the technology offers compelling economic benefits, particularly when viewed over the long term. Although the initial capital investment may be higher than that of traditional systems, especially if pipeline system reconstruction is needed, the significantly reduced operating costs and potential for renewable energy incentives contribute to an extremely short payback period, between 1-3 years, according to our calculations.

Recommendations for Future Research

Key areas are being identified to refine and advance the integrated design of the ETER system in conjunction with solar PV energy supply. The first priority involves refining the system's technical and economic models through more precise calculations and detailed design considerations. On the solar energy side, this includes the selection of appropriate photovoltaic panel and inverter types that align with the site's needs, factoring in proper "keep-out zones" for HVAC units, shading, walkways, or structural limitations. Historical solar irradiance data, particularly from locations like Snyder Farm, should be analyzed in depth, with attention to seasonal variability and long-term degradation curves, especially in comparative sites such as BOCES. To enhance financial modeling, the inclusion of policy-driven incentives like the Investment Tax Credit (ITC) and benefits from the Inflation Reduction Act (IRA) is crucial, as these can substantially improve the return on investment and reduce the payback period.

For the ETER system itself, future work should include the acquisition of higher-resolution and longer-duration wastewater temperature and flow data to improve model accuracy and enable performance optimization over a range of seasonal conditions, as well as eliminating systematic energy loss. The potential to extend thermal energy recovery to additional nearby buildings or facilities should also be explored, which may unlock additional efficiencies and shared infrastructure opportunities. Incorporating battery thermal energy storage technology (BTES) as a significant part of the system, dynamic modeling can better simulate interactions between supply and demand under variable operating conditions, as well as provide an extra supply of energy. This is especially important in ensuring that heat is available during peak periods while avoiding waste during off-peak times. This technology further provides an extra supply as it can further extract thermal energy and transfer the energy into electricity to eliminate system losses.

Beyond ETER and PV, a broader evaluation of alternative renewable energy sources, such as geothermal, biomass, or wind, considering the topography and geological environment in which Ithaca is located, may provide additional flexibility and resilience in the energy system's design. As for policy and market considerations, the detailed assessment of local, state, and federal funding mechanisms, green building certifications, and renewable energy credits (RECs) could reveal valuable financial support and shape the overall deployment strategy. From a societal perspective, the system's impact on energy equity, local job creation, and regional decarbonization efforts should be further examined to strengthen the case for public investment and stakeholder engagement. Ultimately, the next phase of this work will focus on the iterative refinement of system modeling and integrated design, expanding feasibility across multiple scenarios and use cases. This will be accompanied by a comprehensive assessment of viable renewable integrations, BTES strategies, and financing pathways to ensure that the proposed solution is not only technically sound and economically viable but also socially and environmentally transformative.

Conclusion

Summary of Findings

The integration of ETER systems with PV power presents a technically and economically viable strategy to decarbonize Cornell's heating infrastructure. Our analysis demonstrated that wastewater from the University Avenue sanitary line alone could meet the full winter heating demand of Boldt Hall, with surplus capacity to serve additional buildings. Economically, the combined ETER and PV system offers the lowest LCOE at \$0.0297/kWh, compared to the current steam system. Environmentally, the system achieves a 90% reduction in CO₂ emissions compared to the existing infrastructure, contributing an estimated 826.1 tonnes of annual emissions savings. Sensitivity analyses confirm the robustness of these findings, particularly under variations in system lifetime and financing assumptions.

Limitations and Challenges

Key limitations of this study include the short duration of wastewater data (63 days), which constrained our ability to capture seasonal and diurnal variability in flow and temperature. The model also assumes constant system efficiency, a simplified outlet temperature, and no thermal storage, factors that may differ in real-world implementation. Additionally, solar performance estimates rely on assumptions about system losses and irradiance that could vary over time or due to shading and maintenance issues.

Final Recommendations

We recommend that Cornell Facilities pursue a pilot project using the University Avenue wastewater line to heat Boldt Hall or a similar West Campus residence. This site has demonstrated both technical feasibility and significant energy potential. Future work should

include installing real-time monitoring equipment to gather year-round wastewater data and developing dynamic models with hourly resolution. Incorporating thermal storage and considering policy incentives (e.g., the Inflation Reduction Act) can further enhance system performance and financial viability. The proposed ETER and PV system offers Cornell a replicable model for sustainable heating and a meaningful step toward its 2035 carbon neutrality goals.

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Appendices

Appendix A: Model Code

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

wastewater_data = pd.read_csv("C:\\CORNELL WORK\\SP25\\MEng\\Daily Average
Flow and Temp Data.csv")
wastewater_data.columns =
wastewater_data.columns.str.strip().str.lower().str.replace(r'\s+', '_',
regex=True)
wastewater_data["date"] = pd.to_datetime(wastewater_data["date"],
errors="coerce")

flow_conversion_factor = 0.056
temp_locations = ["pump_house", "thurston", "university_ave",
"tower_road"]

BOLDT_DEMAND_kWh = 162876
COP = 3.0
Cp_kJ_kgK = 4.18
eta_ex = 0.85
T_out_C = 4
Q_loss_kW = 0.0

for loc in temp_locations:
    gpm_col = f"{loc}_flow"
    temp_f_col = f"{loc}_temp"
    m_dot_col = f"{loc}_m_dot_kg_s"
    temp_c_col = f"{loc}_temp_C"

    wastewater_data[m_dot_col] = pd.to_numeric(wastewater_data[gpm_col],
errors='coerce') * flow_conversion_factor
    wastewater_data[temp_c_col] =
(pd.to_numeric(wastewater_data[temp_f_col], errors='coerce') - 32) / 1.8

def heat_recovery_kw(m_dot_kg_s, Cp_kJ_kgK, T_in_C, T_out_C, eta_ex,
Q_loss_kW):
```

```

    if (
        m_dot_kg_s is None or np.isnan(m_dot_kg_s) or m_dot_kg_s <= 0 or
        T_in_C is None or np.isnan(T_in_C) or T_in_C < T_out_C
    ):
        return 0.0, 0.0

    Q_in_kW = m_dot_kg_s * Cp_kJ_kgK * (T_in_C - T_out_C)
    Q_usable_kW = max(0.0, eta_ex * (Q_in_kW - Q_loss_kW))
    return Q_in_kW, Q_usable_kW

heating_season_data = wastewater_data[
    (wastewater_data['date'] >= '2024-11-01') & (wastewater_data['date']
<= '2025-01-31')
].copy()

location_kWh = {}
for loc in temp_locations:
    m_dot_col = f"{loc}_m_dot_kg_s"
    temp_col = f"{loc}_temp_C"

    heating_season_data[[f"{loc}_total_kW", f"{loc}_usable_kW"]] =
heating_season_data.apply(
    lambda row: pd.Series(
        heat_recovery_kw(row[m_dot_col], Cp_kJ_kgK, row[temp_col],
T_out_C, eta_ex, Q_loss_kW)
    ),
    axis=1
)

    heating_season_data[f"{loc}_total_kWh"] =
heating_season_data[f"{loc}_total_kW"] * 24
    heating_season_data[f"{loc}_usable_kWh"] =
heating_season_data[f"{loc}_usable_kW"] * 24

    location_kWh[loc] = heating_season_data[f"{loc}_usable_kWh"].sum()

uni_ave_kWh = location_kWh["university_ave"]
compressor_display_kWh = uni_ave_kWh * 0.5
delivered_total_kWh = uni_ave_kWh + compressor_display_kWh

print(f"\nBoldt Hall Heating Demand: {BOLDT_DEMAND_kWh:,.0f} kWh")

```

```

print(f"University Ave Usable Heat: {uni_ave_kWh:,.0f} kWh")
print(f"Compressor Heat: {compressor_display_kWh:,.0f} kWh")
print(f"Total Delivered Heat: {delivered_total_kWh:,.0f} kWh")

# Plot 1: Main demand vs. wastewater + compressor
labels = ['Boldt Demand', 'Wastewater + Compressor']
x = [0, 0.6]
width = 0.4

fig, ax = plt.subplots(figsize=(8, 6))
ax.bar(x[0], BOLDT_DEMAND_kWh, width, label='Total Demand (Reference)',
color='lightgray', edgecolor='black')
ax.bar(x[1], uni_ave_kWh, width, label='Wastewater Heat', color='skyblue',
edgecolor='black')
ax.bar(x[1], compressor_display_kWh, width, bottom=uni_ave_kWh,
label='Compressor Heat', color='salmon', edgecolor='black')

ax.set_ylabel("Energy (kWh)")
ax.set_title("Heating Demand vs. Wastewater & Compressor Contributions")
ax.set_xticks(x)
ax.set_xticklabels(labels)
ax.legend()

ax.text(x[0], BOLDT_DEMAND_kWh / 2, f"{BOLDT_DEMAND_kWh:,.0f} kWh",
ha='center', va='center', color='black')
ax.text(x[1], uni_ave_kWh / 2, f"{uni_ave_kWh:,.0f} kWh", ha='center',
va='center', color='black')
ax.text(x[1], uni_ave_kWh + compressor_display_kWh / 2,
f"{compressor_display_kWh:,.0f} kWh", ha='center', va='center',
color='black')

percent_covered = (uni_ave_kWh + compressor_display_kWh) /
BOLDT_DEMAND_kWh * 100
ax.text(np.mean(x), max(BOLDT_DEMAND_kWh, uni_ave_kWh +
compressor_display_kWh) * 1.05,
f"Demand Met: {percent_covered:.1f}%", ha='center', va='bottom',
fontsize=12, fontweight='bold')

ax.set_ylim(0, max(BOLDT_DEMAND_kWh, uni_ave_kWh + compressor_display_kWh)
* 1.3)

```

```

ax.grid(axis='y', linestyle='--', alpha=0.7)
plt.tight_layout()
plt.show()

# Plot 2: Energy produced per location
total_usable_all_kWh = sum(location_kWh.values())

fig, ax2 = plt.subplots(figsize=(8, 6))
loc_names = [loc.replace('_', ' ').title() for loc in temp_locations]
loc_values = [location_kWh[loc] for loc in temp_locations]

bars = ax2.bar(loc_names, loc_values, color='steelblue',
edgecolor='black')
for i, val in enumerate(loc_values):
    ax2.text(i, val + 0.01 * max(loc_values), f"{val:,.0f} kWh",
ha='center', va='bottom')

ax2.text(len(loc_names) / 2 - 0.5, max(loc_values) * 1.15,
f"Total Usable Heat (All Locations): {total_usable_all_kWh:,.0f}
kWh",
ha='center', va='bottom', fontsize=12, fontweight='bold',
color='darkblue')

ax2.set_ylabel("Total Usable Energy (kWh)")
ax2.set_title("Usable Wastewater Heat by Location")
ax2.set_ylim(0, max(loc_values) * 1.3)
ax2.grid(axis='y', linestyle='--', alpha=0.7)
plt.tight_layout()
plt.show()

# Plot 3: Monthly Recovery
heating_season_data['month'] = heating_season_data['date'].dt.month
november_actual = 46360
november_adjustment = 417230

december_value = heating_season_data[heating_season_data['month'] == 12][
    [f"{loc}_usable_kWh" for loc in temp_locations]
].sum().sum()

january_value = heating_season_data[heating_season_data['month'] == 1][

```

```

    [f"{loc}_usable_kWh" for loc in temp_locations]
].sum().sum()

months = ['November', 'December', 'January']
bottom_values = [november_actual, december_value, january_value]
top_values = [november_adjustment, 0, 0]
fig, ax = plt.subplots(figsize=(9, 5))
bars_bottom = ax.bar(months, bottom_values, color='steelblue',
edgecolor='black', label='Actual Usable')
bars_top = ax.bar(months, top_values, bottom=bottom_values,
color='orange', edgecolor='black', label='Recalculated Additional')

for i in range(len(months)):
    total = bottom_values[i] + top_values[i]
    ax.text(i, total + 0.01 * max(bottom_values + top_values),
f"{total:,.0f} kWh", ha='center', va='bottom')

ax.set_ylim(0, max(bottom_values + top_values) * 1.2)
ax.set_title("Monthly Usable Wastewater Heat Recovery (with November
Adjustment)")
ax.set_ylabel("Total Usable Energy (kWh)")
ax.set_xlabel("Month")
ax.legend()
ax.grid(axis='y', linestyle='--', alpha=0.7)
plt.tight_layout()
plt.show()

# Plot 4: Theoretical vs. usable
total_theoretical_kWh = heating_season_data[[f"{loc}_total_kWh" for loc in
temp_locations]].sum(axis=1).sum()
total_usable_kWh = heating_season_data[[f"{loc}_usable_kWh" for loc in
temp_locations]].sum(axis=1).sum()

fig, ax4 = plt.subplots(figsize=(8, 6))
labels = ['Theoretical Heat', 'Usable Heat']
values = [total_theoretical_kWh, total_usable_kWh]
colors = ['lightgray', 'skyblue']

bars = ax4.bar(labels, values, color=colors, edgecolor='black')
for i, val in enumerate(values):

```

```
    ax4.text(i, val + 0.01 * max(values), f"{val:,.0f} kWh", ha='center',  
va='bottom')  
  
ax4.set_ylabel("Energy (kWh)")  
ax4.set_title("Wastewater Heat Energy: Theoretical vs. Usable")  
ax4.set_ylim(0, max(values) * 1.2)  
ax4.grid(axis='y', linestyle='--', alpha=0.7)  
plt.tight_layout()  
plt.show()
```