Integration of Food, Energy, and Water Systems in Affordable Housing

A Major Qualifying Project
Submitted to the Faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
Degree of Bachelor of Science in Architectural Engineering

Date:
March 20, 2019

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Table of Contents

Abstract

Proper integration of food, energy, and water (FEW) systems creates a sustainable means of decreasing energy consumption. 126 Chandler Street, a low income apartment building, was used as a case study to highlight the impact of different FEW systems. A building energy model was created in Revit and Green Building Studio to analyze the efficiency and feasibility of the systems. Based on the results from the energy model and the project's budget, various design strategies are recommended including solar panels, water conservation and reuse systems, improved insulation, and a rooftop greenhouse into the design of 126 Chandler Street.

Authorship

Nicole Collucci, Yasmeen Logan, Shealyn Musumeci, and Christina Skavicus worked together to successfully complete this project. All members participated equally in major project decisions. The break down of larger responsibilities is as follows: Yasmeen took responsibility for the Building Energy Model. Starting with a base model, she added components throughout the project to produce a final energy model. Shealyn took the lead for the greenhouse design, creating the Revit model and detail drawings. Christina was responsible for the structural calculations and analysis. Nicole took responsibility for many of the FEW systems put in place, such as the rainwater reuse and composting systems. All members co-edited the report and worked together to create the final drawing set.

Acknowledgements

Our team would like to thank our advisors, Professor Leonard Albano and Professor Soroush Farzin-Moghadam from Worcester Polytechnic Institute, for their guidance and feedback throughout the project. This project would not have been successful without their constructive criticism and expert advice. We would like to thank Cynthia Bergeron and Maryann Watts in the Civil and Environmental Engineering Department for scheduling our meeting spaces.

We would also like to thank our sponsor, Yvette Dyson from Worcester Common Ground for being constantly involved and committed to our project. She connected us with key resources such as Davis Square Architects and Struble Engineering who assisted in providing information concerning the existing design. We would like to thank Yvette for being engaged in our project and being available to answer our questions and concerns. She worked with us to produce a successful project that fulfills Worcester Common Ground's goals.

Capstone Design Statement

The goal of this Major Qualifying Project (MQP) is to provide a solution that successfully integrates food, energy, and water (FEW) systems to create a more sustainable design for the proposed case study. This project included creating designs of various FEW systems and specifying adjustments to the structural design of the existing building and the proposed addition. The integration of multiple engineering disciplines, such as architecture, structural and mechanical, was required.

This project satisfies the Capstone Project requirement set by the Accreditation Board for Engineering and Technology (ABET). All students who contributed to this utilized a variety of coursework in order to show design competence in their selected curriculum areas. The team was comprised of four architectural engineering majors with design concentrations in building structural systems.

An architectural considerations for the MQP includes the rooftop greenhouse designed to provide fresh food and green space to residents in the building. The structural design aspects include the greenhouse structural system and modifications to the structural system of the new addition. The structural integrity of the existing building was as verified through structural calculations. Other architectural considerations include the design of the greenhouse HVAC system, spacing of planting beds, floor plan layout, facade, egress, interior finishes, and furnishings. The space was designed to be accessible to all therefore, handicap and disability provisions were taken into consideration.

A building energy model was constructed to analyze the combined efficiency of all selected FEW systems. This model helped to highlight the reduction of energy use from the original design. Other factors, such as integration, building performance and sustainability, constructability, economic, and ethics, were considered when designing the FEW systems and greenhouse.

Integration

The newly designed rooftop greenhouse along with the integration of the FEW systems into the buildings required extensive coordination. The team worked to fully integrate the FEW systems into the proposed building design, while changing as little as possible. Interdisciplinary coordination was required between the team members to maximize the energy efficiency and minimize the structural modifications of the building.

The integration of the building was done by fully coordinating the teams collaborative efforts towards the project. This was done by creating regular weekly meetings, online file sharing, and constant communication between student team members and faculty advisors.

Building Performance and Sustainability

The sustainability and building performance was the primary factor in the assessment and re-design of the building. The original building performance was assessed and used as a baseline. The newly designed building was then compared to the original design in order to analyze the proportion of improvement. The recommended products in the new design are more sustainable than their industry standard counterparts.

The systems investigated in this paper include a rooftop greenhouse, composting systems, high-efficiency appliances, vampire load switches, insulation, solar cooling, water conservation and rainwater reuse. All FEW systems were researched to determine if they work with the current design while also improve its effectiveness. Each additional system was found have a positive benefit on the building, while also being realistic and feasible for the project.

Constructability

Constructability was considered through the selection of materials and system types. The team consulted the Massachusetts Building Code Ninth edition when designing the structural loading. The code was used to look up certain factors and design equations. The Steel Construction Manual by the American Institute of Steel Construction was used to design the steel structures. The National Design Specification made by the American Wood Council was used to verify the current building structure that stands on 126 Chandler Street. Both Allowable Stress Design (ASD) and Load Resistance Factor Design (LFRD) were used. ASD was used for the existing building structural calculations and LRFD was used of the additional building and greenhouse. AutoCAD and Revit softwares were used to show the architectural design and details of the building, as well as to clearly portray the suggested design changes.

Economic

The cost of each FEW system was considered when constructing a final list of recommendations in order to stay within Worcester Common Ground’s budget. The payback period of each system was calculated to help offset the initial costs. A cost-estimate of the proposed design changes and systems is provided, as well as a price estimate of the rooftop greenhouse.

Ethics

Professional engineers assume responsibility for the health, safety, and wellbeing of the public when designing any systems. This project demonstrates those standards and followed the principles outlined by the American Society of Civil Engineers and Massachusetts State Building Code. All risks and dangers were discussed thoroughly by the team with all decisions being made with ethics in mind.

Professional Licensure Statement

Professional Licensure is an essential step in the process of becoming an engineer. Obtaining a professional license allows individuals the ability to review and certify civil documents and drawings. Professional Engineers (PE) are a vital part of any civil engineering firm and are a big part of the building of all civil infrastructure around the world. Professional engineers are charged with holding paramount the safety, health, and welfare of the public and all designs that are implemented must be first approved by a PE.

PE’s have a big responsibility to the public, firm, and themselves to be fully aware of the implications of their designs. The process of getting a PE shows that all state licensure boards take this process very seriously. The process for obtaining a PE license does vary slightly from state to state but the main core requirements hold true for all states. First is the completion of a four-year college engineering program accredited by ABET. Following graduation from this program, individuals must pass the Fundamentals of Engineering (FE) exam. This exam is online and consists of 110 questions completed in about six hours. There are seven different disciplines available to take the FE chemical, civil, electrical and computer, environmental, industrial and systems, mechanical, and other. Topics covered within the exam vary based on the specific discipline of FE that was chosen. After passing the FE an individual earns the designation Engineer-in-Training (EIT). The EIT’s then have to work under the supervision of a PE for four years to be able to sit for the Principles and Practice Engineering Exam. The time worked under the supervision of a PE varies depending on the state where the PE is being attained. In some cases, it can be reduced if a higher degree of education was received, like a masters or doctorate degree. After working under a PE for the specified amount of time the Principles and Practice Engineering Exam can be taken. The Principles and Practice Engineering Exam is an 8-hour long test consisting of 80 questions, questions on this exam vary based on which PE exam is taken. After the PE exam is passed the individual can apply for a PE in their state of practice.

Obtaining a professional license is a big moment in the career of an engineer and takes a lot of hard work and dedication to the profession to obtain the license. Even after obtaining the license these engineers are now responsible for any designs they sign and are deemed responsible for any junior engineers under their charge.

Relating to this project, multiple Professional Engineers from different disciplines such as structural, civil, and mechanical engineering would be required to sign off on the final plans and designs listed in this report. The addition of the rooftop greenhouse along with the structural modifications to the new building has the potential to negatively impact the public if they were to fail. For these reasons, a professional engineer would need to approve the designs and calculations of the drawings shown in this report.

Executive Summary

To counteract the rise in city populations, city planners, designers and legislators must consider sustainable opportunities not only for individual buildings but for communities as a whole. The path to creating net zero neighborhoods is rooted in providing sustainable solutions to food, energy, and water (FEW) systems. This paper asses ways to provide energy conscious affordable housing using a case study of a proposed 31 unit complex located at 126 Chandler Street in Worcester, Massachusetts. FEW systems are evaluated with respect to this building to see which systems will best integrate with the building's structure, energy consumption, and environmental impact. By integrating appropriate systems, this multi-family residential complex will be able to function as a cohesive unit with minimal waste.

Current Conditions

By analyzing the history, building structure, and energy use of the existing building, systems were tailored to improve its performance. 126 Chandler Street was originally an old mill building. In later years the building become a retail establishment, a tire shop, and garage (Davis Square Architects, 2019). The original structure is intact and consists of a reinforced concrete perimeter frame and timber framing in the interior (Struble, 2018). The biggest issue with the existing structure is that the building does not have a code-compliant lateral system. Consequently, the building needs to be reinforced in both the north-south and east-west directions (Struble, 2018). The addition will have a separation joint between the two buildings to allow the loads to zero out (Struble, 2018).

Recommended FEW Systems

Recommended food systems include a rooftop greenhouse and a small scale composting system. Energy systems include high efficiency appliances and solar harnessing systems. Water systems include systematic water conservation, rainwater harvesting, and permeable surfaces.

The greenhouse and compost system comply with goals set by the American Planning Association, the goals of Worcester Common Ground, and in general, will reduce environmental impacts and costs. The rooftop greenhouse will reduce the building's environmental impact on the community, as well as provide valuable resources and knowledge for the low-income families residing in the building. A small scale composting system within the 126 Chandler housing complex will reduce the waste that the residents produce as well as provide fertilizer for the greenhouse.

The two solar systems recommended for implementation into 126 Chandler Street are solar panels, including a solar canopy, and high efficiency appliances. There is sufficient space for 100 panels on the roof of the old building and 18 panels on the solar canopy. The proposed solar panels will collect 531 kW per panel, providing 20.6% of the building's prospective energy needs.

The recommended water conservation system includes a number of low-flow fixtures, water efficient appliances, and educational resources. Rainwater harvesting will help offset the water usage in the building. It will include two distinct systems: one will reuse rainwater from the gutters of the greenhouse and direct it back into the greenhouse for irrigation, the other will redirect rainwater accumulation on the entire roof to the first level laundry room to be reused for in washers. Permeable interlocking concrete pavers (PICPs) will be used to construct the surface of the parking lot. The stormwater that is collected through the PICPs will be stored underground and used for landscape irrigation.

Architectural Considerations

The rooftop greenhouse will be supported by a structural steel frame with a mixed material facade, mostly made up of triple-layer polycarbonate panels. Proper ventilation and cooling, such as windows and fans will be installed as well as radiant heating integrated in the concrete slab floor. The greenhouse will not be visible from the front of the building on Chandler Street, unless the viewer is approximately 300 feet from the building. The greenhouse is almost completely visible from the south side of the building, from Jaques Ave., which will maintain the historical front facade while allowing the public to see the advances in sustainability from the back.

Analysis and Discussion

Some structural modifications are necessary in order to successfully implement the suggested FEW systems. For example, the sizes of some structural members in the additional building will need to be increased to support the additional loads associated with the greenhouse. The building was also analyzed in terms of its energy efficiency through various combinations of the FEW systems. This was done by creating a Building Energy Model (BEM) for three different scenarios. The first scenario includes the FEW systems that were the lowest cost options such as the low-flush toilet systems, solar panels, and improved insulation. The second scenario includes all the applicable FEW systems irregardless of budget, resulting in the maximum energy efficiency and lowest EUI for the complex. The third scenario includes the systems that provide the lowest EUI but also stay within a reasonable budget. This scenario includes the implication of low-flush toilets, solar panels, the greenhouse with its rainwater harvesting system, and improved insulation. The integration of FEW systems into the current design of 126 Chandler Street will greatly improve the building performance and will positively affect the tenants and their surrounding community.

List of Tables

List of Figures

1. Introduction

The populations in cities are rising, with 68% of the world's population being projected to live in cities by 2050, making already overpopulated areas even more crowded (United Nations, 2018). This increase in population escalates the need for resources such as transportation, food, water, and housing, which are already in short supply. Providing these resources to more people puts further strain on the city and its surrounding environment with resource consumption predicted to be 8 to 17 tons per person by 2050 (UN Environment, 2017). Currently, cities use copious amount of energy to ensure the comfort of the city's population. According to the UN Habitat (2012), cities currently consume 75% of the worlds primary energy, and emit 50% to 60% of the world's total greenhouse gases. With the increase in populations, cities will be forced to use even more energy to provide a reasonable living standard for its residents. This increased need for energy further impacts the environment, as cities use more of the world's resources at an alarming rate.

Solving these problems requires a very complex solution. Simply creating and constructing green buildings or energy efficient homes is not enough; instead, people need to implement energy efficient systems at a larger scale. Achieving a net-zero status across all building types requires the whole community to be considered instead of just the individual buildings (Kallushi, 2012). The International Resource Panel (2018) states that cities which become more efficient in transportation, commercial infrastructure, and building heating and cooling can save 36% to 54% in energy use, emissions, and resources. One example of this concept is eco-cities, which aspire to be an ecologically healthy city that has no negative impact on the surrounding environment (Berthold, & Wetterwik, 2013). Another is Net Zero Neighborhood (NZN) which looks to integrate food, energy, and water (FEW) systems of multiple buildings to reduce the total energy consumed (Farzinmoghadam, et al., 2019). By integrating these resources, it is believed that reduced energy consumption can be achieved, as well as increased quality of life for the residents.

Many studies on the subject of future sustainable cities either focus on the entire city or on individual homes. This research paper asses ways to provide affordable apartment housing while being energy conscious. A case study was used to model the recommended systems and investigate the effects of these strategies on a neighborhood scale. A new development on 126 Chandler Street in Worcester, MA was used as case study. A local non-governmental organization, Worcester Common Ground, is planning on renovating an existing structure and building a new addition. FEW systems were evaluated with respect to this building to see which best integrated with the infrastructure, decreased energy consumption, and reduced environmental impact. A building model was then used to investigate the impact of energy efficient systems across the entire apartment complex. A list of recommended systems was produced by compiling this information and considering monetary restrictions.

2. Literature Review

The path to creating net zero neighborhoods is rooted in providing sustainable solutions to FEW systems. *Net Zero Neighborhood (NZN): A Nexus of Food, Energy, and Water for Smart Cities* summarizes how net zero neighborhoods create an economical and sustainable means of decreasing energy consumption in cities (Farzinmoghadam, et al., 2019). This literature review summarizes different food, energy, and water systems that can be integrated into a building's infrastructure in order to decrease the energy consumption. Food systems researched include urban farming techniques and composting. Energy systems investigated were high-efficiency appliances, vampire loads, insultation, and solar cooling. Lastly water systems studied included water conservation systems and rainwater reuse. By integrating the appropriate systems, any building type will be able to function as a cohesive unit with minimal waste.

2.1 Food

Food systems are important to consider in urban planning because of the impacts they have on the environment. The American Planning Association's Policy Guide on Community and Regional Food Planning (2007) lays out several reasons why food systems are important to consider in urban planning. One primary reason is that the "food Americans eat takes a considerable amount of fossil fuel to produce, process, transport, and dispose of" (American Planning Association [APA], 2007). A shorter journey from production to consumption leaves less of an environmental impact. Low income homes usually purchase the least expensive food available, which tends to be unhealthy, processed food (APA, 2007). The general health and wellbeing of low income households improves by bringing healthier foods closer and making them more obtainable. In general, many benefits emerge from stronger community and regional food systems (APA, 2007).

2.1.1 Greenhouse

In 2010, Brooklyn Grange, the first commercial urban rooftop farm (URF) began operations in New York City. Since then, rooftop greenhouses and open-air rooftop farming have become increasingly popular in urban areas as a solution to urban agriculture (Buehler & Junge, 2016). URFs are used for innovation, corporate image, commercial use, education/social use, and improvement of life quality (Buehler & Junge, 2016). URFs that are aimed at improving life quality offer a healthy alternative to the low cost, unhealthy food commonly available in grocery stores. They offer affordable and accessible vegetables and greens, while giving residents the opportunity to learn the skills associated with the maintenance of small-scale agriculture. URFs strengthen the sustainability of a community's food system and have countless social impacts on the surrounding area by introducing green space in the midst of an urban setting.

The two most common methods used for URFs are soil-based and hydroponic farming (Buehler & Junge, 2016). Hydroponic farming can produce a larger quantity of plants, but is limited in the types of vegetables that are grown successfully (Buehler & Junge, 2016). Hydroponic farming methods tend to be successful with leafy greens, tomatoes, and herbs (Buehler & Junge, 2016). Soil-based farming is more flexible, allowing growers to harvest a wide variety of produce including root vegetables, fruits, and grains (Buehler & Junge, 2016).

While URFs have many benefits, there are obstacles that come with designing such structures, especially in colder climates. The biggest issue to overcome is how to control the temperature for year-round plants. Greenhouses allow for more control and the possibility for farming over the winter months, whereas open air farms are completely inactive during winter months in colder climates. Schiller (2016) suggests that the best method for overcoming the cold climate is to cover the south wall of the structure and roof with glazing, tilt the roof to a 17^{o} angle, and insulate the north wall. This design allows for the maximum amount of sun in the winter and prevents the greenhouse from overheating in the summer (Schiller & Plinke, 2016). There are many different types of glazing to choose from including glass, polyethylene film, and polycarbonate panels (Schiller & Plinke, 2016). In climates where temperature is not an issue for plants, glass or film are the best option, but in colder climates, triple-layer polycarbonate is the best option because of the need to balance sunlight and temperature. Triple-layer polycarbonate glazing helps to control overheating in the summer by reducing the amount of direct sunlight that penetrates through the three layers of material (Schiller & Plinke, 2016). The addition of an insulated wall helps maintain a warm interior in the winter months and a cool interior in the summer months, but in continental climates this is not adequate to keep a greenhouse at the desired temperature at all times. Therefore, in colder climates, greenhouses often require additional HVAC systems.

Some popular types of heating for greenhouses are radiant heating, under-bench heating, or overhead heating. Radiant heating involves hot water pipes that run under the flooring system (GGS Structures, 2016). This provides evenly distributed heating throughout the greenhouse, reduced condensation on roofing panels, and prevents pipes from freezing in the winter months (GGS Structures, 2016). The advantage of radiant heating is that the majority of the heat is delivered at the ground level, where it most benefits the plants. Under-bench heating is a similar system to in-floor heating; however, the hot water pipes are only installed under the planting beds. This type of system only provides direct heating to the plants, allowing the majority of the greenhouse to be a cooler which reduces heating costs (GGS Structures, 2016). However, for some plants, under-bench heating does not create a sufficient growing environment (GGS Structures, 2016). The third option is overhead heating, which is most effective in colder climates because it provides a snowmelt protection system for the roof (GGS Structures, 2016). The disadvantage to this system is that it does not provide direct heating to the plants which can increase energy costs as more heat is needed to raise the temperature to the desired levels.

2.1.2 Compost

Composting is “the natural process of decomposition of organic matter by microorganisms under controlled conditions” (Roy & Misra, 2003). It provides rich, organic fertilizer for a variety of farming needs. Using organic fertilizer from composting produces higher yield and reduces the amount of inorganic fertilizer used (Roy & Misra, 2003).

Three main types of composting are anaerobic, aerobic, and vermicomposting (Roy & Misra, 2003). Anaerobic composting occurs when there is little to no oxygen (Roy & Misra, 2003). While there is little maintenance work required for this type of composting, many nutrients and toxins are left behind and the process takes considerably longer (Roy & Misra, 2003). Aerobic composting occurs when there is plenty of oxygen (Roy & Misra, 2003). The heat generated during the breakdown of organic matter allows for an expedited process that is faster than anaerobic composting (Roy & Misra, 2003). Although more nutrients are lost during aerobic composting, less toxic elements are left behind. For aerobic composting to be successful, factors such as aeration, moisture, nutrients, temperature, lignin content, polyphenols, and pH value must be regulated (Roy & Misra, 2003). An alternative type of composting is vermicomposting, which includes the addition of worms to assist in the transition from organic materials to compost (Roy & Misra, 2003). Food scraps go into a bin containing worms, which turn leftover food into rich soil, that is then used for fertilizer (Ross, 2013).

Small-scale community composting has many benefits including offsetting carbon dioxide emissions due to food waste, lowering greenhouse maintenance costs, and educating the community on food waste (Institute for Local Self-Reliance, 2019). The Institute for Local Self-Reliance (2019) lays out six guiding principles of successful community composting:

- Reduce food waste
- Keep organic materials as a community asset
- Enhance local soil using organic materials
- Scale composting system to meet the needs of the self-defined community
- Engage, empower, and educate the community
- Align with community goals and support the community's social, economic, and environmental well-being

Composting systems that value these principles are most successful in engaging its participants and successfully generating shared compost.

2.2 Energy

Energy systems are an important consideration of FEW systems and urban planning because of their impact on the environment, economic development, and human wellbeing. These systems provides the energy needed to power the building, allowing any system that needs energy such as lighting, appliances, and heating the ability to run. This energy normally comes from non-renewable resources which have harmful environmental impacts such as pollution and climate change (Carreón & Worrell, 2018). The sustainable development of cities and proper planning of energy systems can limit the damage caused to the environment(Carreón & Worrell, 2018). By implementing more energy-efficient products, using renewable resources, and designing different renewable systems presents sustainable ways of providing power for the community can be achieved. Some examples of these products include different types of solar systems, high efficiency appliances, and vampire load switches.

2.2.1 High-Efficiency Appliances

High-efficiency appliances reduce both energy and water used in common household appliances and fixtures. The average dishwasher uses 6.1 gallons of water per load, whereas a high-efficiency dishwasher can use as little as 3.07 gallons per load (Water Research Foundation, 2018). As a result, replacing a regular dishwasher with its high-efficiency alternative can save an average of 3,870 gallons of water per year (Energy Star, n.d.). A refrigerator is another appliance that can be easily replaced with a more effective version. The average refrigerator uses about 1,400 kWh per year while a high-efficiency refrigerator only uses about 370 kWh per year. Table 1 depicts this by comparing the US Federal Standard of regular appliances to their high efficiency counterpart.

Table 1: ***High Efficiency Appliances*** (Energy Star, n.d.)

	Efficient Annual Energy Usage (kWh/yr)	*US Federal Standard (kWh/yr)*
Refrigerator	345	426
Dishwashers	220	307
Dryers	149	399

2.2.2 Vampire Loads Switch

Vampire loads, also known as standby or idle power, refer to the energy that is wasted when appliances are left plugged in when not being used (Delforge, Schmidt, & Schmidt, 2015). According to Hyrkas (2014), 75% of electricity consumption in the U.S. is due to idling electrical devices which can cost homeowners between \$100 to \$200 per year. A study done by the National Resources Defense Council shows that electronic devices cause 51% of residential wasted energy while kitchen and laundry appliances cause 6% of residential wasted energy (Delforge, et al., 2015). Tables 2 and 3 summarize which appliances use the most energy and money while on standby.

Table 2: ***Appliances with High Vampire Loads*** (Meier, 2018)

Appliance	*Vampire Load (watts)*
Set-top Box, DVR	36.68
Set-top Box, Cable with DVR	43.46
Set-top Box, satellite with DVR	27.8
Computer, desktop	21.13
Computer, laptop	15.77
Game Console	23.34

Table 3: ***Money Lost Due to Vampire Loads*** (Meier, 2018)

Appliance	*Money Spent/Year*
Television	$ 160
Video Game Consoles	$ 75
Desktop Computer	$ 40
Laptop	$ 19
Kitchen Appliances	$ 15+

To combat this issue switches can be installed to minimize vampire loads so that the largest consumers of idle power can be shut off. This solution works for more permanent appliances such as televisions and kitchen appliances. Residents should be encouraged to switch off portable devices to help reduce vampire loads.

2.2.3 Insulation

Insulation is one of the easiest methods to make a building more energy efficient. Proper insulation provides moisture, mold, and sound control as well as many other additional economical and environmental benefits. Insulation reduces energy loss in the summer and winter months. This lessens the amount of HVAC needed to provide a stable internal temperature. Proper insulation materials will pay back both the environment and building owner by reducing energy usage and the associated cost (Tingley, Hathway, & Davison, 2015).

Some popular forms of insulation include expanded polystyrene (EPS), mineral wool, wood fibre board, and phenolic foam (Tingley, et al., 2015). Of these materials, EPS has the least environmental impact and wood fibre board has the lowest carbon impact due to carbon sequestration (Tingley, et al., 2015). If 5 million homes were renovated with woodfibre board, it would save 3 million tons of CO_2 (Tingley, et al., 2015). In the United States, Maynard (2015) writes that fiberglass, cellulose, and foam are the most popular form of insulation. Fiberglass is a common choice due to the wide range of products and low costs (Maynard, 2015). However, fiberglass insulation is commonly installed incorrectly which leads to its poor performance in the building (Maynard, 2015). Cellulose and high-performance foam both spray into the cavity creating a vapor and air barrier for the wall as well as providing insulation (Maynard, 2015). The

Building Science Institute (2013) found that any insulation can deliver the same performance level as long as they are installed properly. The problem with spray foam insulation, however, lies with its environmental impact because it prevents future recycling of the building materials.

Another method for controlling interior temperature is to install eaves (Bekkouche, et al., 2011). This improves interior temperatures by reducing direct solar gain and keeping conditioned air inside. The study done by Bekkouche (2011), found that in warmer climates, south is the most favorable orientation because of the ability to control solar gain through the walls and windows. The study also found the building has to be insulated to reduce heat loss in order to fully take advantage of these benefits (Bekkouche, et al., 2011).

2.2.4 Solar Cooling

Solar cooling is a method of conditioning a space by utilizing the effects of direct sunlight. There are two effective methods of solar cooling: light shelves and trombe walls. Light shelves reduce the solar heat gain of individual rooms (Chan, Riffat, & Zhu, 2010). They also decrease lighting expenses on sunny days by reflecting natural light deep into a building (Chan, Riffat, & Zhu, 2010). However this technology is limited by window height, floor-to-ceiling ratio, and sprinkler systems (Chan, et al., 2010). In order to have a successful system the windows should be positioned to decrease direct light in the summer months and increase it in the winter (Chan, et al., 2010).

Trombe walls feature a glazing system separated from the exterior wall by a layer of air (Chan, et al., 2010). As shown in Figure 1, the air between the glazing and the exterior wall will flow naturally by convection (Chan, et al., 2010). As the warm air travels through the exterior wall, it rises and leaves the upper vent while cooler air is brought in through the lower vent (Chan, et al., 2010). The cool air is then warmed by the air coming through the exterior wall and the cycle repeats (Chan, et al., 2010). This provides a sustainable and simple way of passively heating and cooling a building (Chan, et al., 2010).

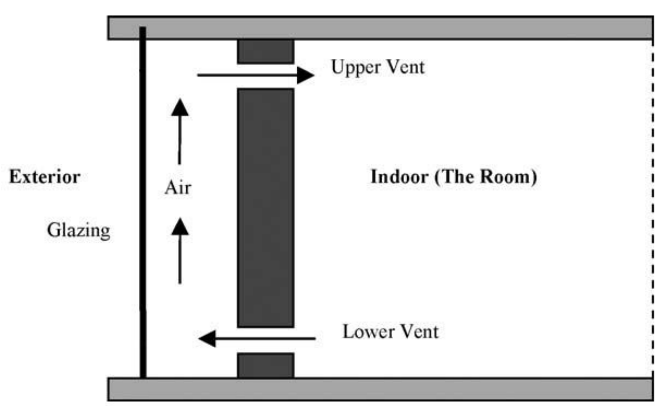

Figure 1: ***Schematic Design and Airflow Pattern in Trombe Wall*** (Chan, et al., 2010)

2.2.5 Solar Systems

Solar systems are used to either integrate renewable and efficient systems with solar power or utilize solar power to provide energy for different facilities. These systems increase renewable energy integration in the built environment and create a more efficient system (Ramos, Chatzopoulou, Guarracino, Freeman, & Markides, 2017). In turn, this helps reduce the reliance on fossil fuels and increases affordable deployment (Ramos, et al., 2017). Some solar systems investigated include solar panels, solar windows, and solar blinds. Other innovative, integrated solar systems researched include greywater systems and a hybrid photovoltaic-thermal panel.

This greywater reuse system was studied at the University of South California and funded by the National Science Foundation. It has grey water flowing through panels and throughout the day these panels filter and heat the water (O'Brien & Tobin, 2017). The panels then pass it through the floor where it gets used as thermal energy (O'Brien & Tobin, 2017). The water is filtered using gold nanoparticles, which release molecules to kill E. Coli and other microbes (O'Brien & Tobin, 2017). This water, while unsafe to drink, is available to wash clothes and flush toilets (O'Brien & Tobin, 2017). This system is best located on the south facing facade of the building, where the sun exposure is optimal (O'Brien & Tobin, 2017).

A hybrid photovoltaic-thermal panel studied by Alba Ramos and her team uses water or a fluid to produce thermal and electrical power (Ramos, et al., 2017). It has an overall efficiency of 70% or higher, as compared to a electrical system which is 15-20% efficient or a thermal system which is 50% efficient (Ramos, et al., 2017). This system provides power to appliances and HVAC systems (Ramos, et al., 2017). The main system used is the PV-T system that is connected to a thermal storage unit and a heat pump, this provides the maximum amount of efficiency (Ramos, et al., 2017). This system covers more than 60% of the heating and an average of 50% of the cooling demands for an urban household (Ramos, et al., 2017). The photovoltaic panel is connected to a thermal storage unit that provides heating and a heat pump to help with cooling as shown in Figure 2. The PV-T also provides electrical power to the housing unit.

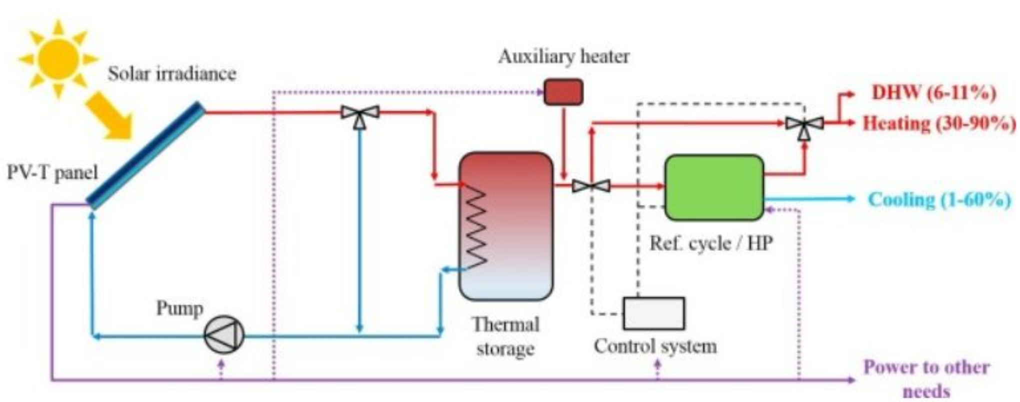

Figure 2: ***Schematic Design for PV-T System*** (Ramos, et al., 2017)

Solar windows harness the power of the sun using two different methods. The first method utilizes tiny solar panels along the edges of glass panes to produce energy; however, this approach does not produce a lot of power (Marsh, 2018). The second method generates power from the glass itself by using quantum dots (Marsh, 2018). The quantum dots absorb the light and refract it as infrared light which powers the solar panels located at the edge of the windows (Marsh, 2018). Consequently, this makes the window opaque, causing it to look more like a traditional solar panel rather than window (Marsh, 2018). Similarly, solar blinds are window blinds with solar panels attached to the vane savers that rotate with the sun to obtain optimal light (Marsh, 2018). However, they provide very little power, only enough for some small appliances and cell phones.

Solar panels are generally used to harness renewable energy from the sun. They are widely used across the country for their affordability and limited constraints which include weather, days of sun, and space. However, this problem can be solved by adding solar panels to a steel structure known as a solar canopy (Big Dog Solar Energy, 2017). Canopies are normally placed over parking lots and help prevent heat island effects created by parking lots, reducing unnecessary heat gain (Big Dog Solar Energy, 2017).

2.3 Water

In 2015, the average person in the United States used about 81 gallons of water per day ("Water Use Data for Massachusetts," 2018). While the current United States' average is lower than in previous years, methods such as water conservation and rainwater reuse, along with an increased amount of education can help to further decrease consumption and reduce wasted water.

2.3.1 Water Conservation

One way to conserve water is replacing current appliances to low-flow appliances. A study by Lee, Tansel & Balbin (2013) in the *Water Resource Management* journal, found that by replacing all water appliances with their low-flow counterpart, a residential home's water demand can decrease by 35%. Toilets use the most water in the average single-family household; therefore, installing an efficient toilet is the best way to decrease water usage (Staff, 2006). Other appliances such as landscaping fixtures, showers, laundry, faucets and dishwashers can improve water efficiency (Staff, 2006). Water usage for landscaping can also be reduced by using native plants and grasses that can survive off the natural rainfall in the area (Staff, 2006).

Table 4 provides a list of various appliances and fixtures as well as their corresponding water usage and possible savings (Appendix A for more detailed calculations). As presented in Table 4, based on an average apartment building, a one-time additional cost of about $22,000 was calculated to finance low-flow fixtures and water efficient appliances as opposed to regular models. The implementation of low-flow appliances in the building will have around an eight year payoff with an annual savings of about $2,700 due to decreased water consumption.

Table 4: Water Savings Calculations

	Regular Water Usage (gal/yr)	*Low Flow Water Usage (gal/yr)*	*Total Water Savings (gal/yr)*	*Regular Price*	*Low Flow Price*	*Additional Expenditures*
Toilet [1]	246,375	82,125	164,250	$4,500	$11,250	$6,750
Sink [2]	264,990	144,540	120,450	$7,600	$7,600	$0
Shower [2]	408,800	245,280	163,520	$1,170	$1,170	$0
Dishwasher [3]	31,000	9,517	21,483	$9,300	$21,700	$12,400
Washer [3]	304,668	225,680	78,988	$4,800	$7,800	$3,000
Total			548,691			$22,150

[1] (Moloney, 2014)
[2] (U.S. Department of Energy, n.d.)
[3] (Energy Star, n.d.)

Education plays an important role in the effort to conserve water in a residential building. Studies found that bathrooms signs, which encourage tenants to turn the water off when brushing their teeth, led to a decrease in water usage (Staff, 2006). The typical 8 minute shower uses around 18.4 gallons of water (Staff, 2006). Shower timers can be installed to help residents visualize how many gallons of water they are using in just one shower. These timers can also work to limit the time in the shower. In addition to education, the building can offer rebates to tenants for using less than a certain amount of water (Staff, 2006). Furthermore, tenants who pay for their own water bills will directly benefit from water conservation.

2.3.2 Rainwater Reuse

There are two methods of harvesting rainwater for reuse: rainwater collection and permeable surfaces. Rainwater collection involves collecting the rainwater from a roof, using gutters and storing the water in a collection tank for later use (Domènech & Saurí, 2011). This system has low maintenance costs, with gutters needing an annual cleaning and the collection tanks requiring a cleaning every four to five years (Domènech & Saurí, 2011). Once the water is collected, it should be used in the most effective way possible. For residential buildings, the best use of the water would be a combination of irrigation and laundry services, as these two uses require the least amount of treatment (Domènech & Saurí, 2011). The water can also be used for showers, toilets, and sinks but this would require extensive treatment methods (Domènech & Saurí, 2011).

The second method of harvesting rainwater is through permeable surfaces, which absorb rainwater and store or redirect it. There are multiple types of porous materials that can be used to create permeable surfaces such as porous asphalt and permeable interlocking pavers. Porous asphalt is not regularly used because it easily clogs and can lead to hydrocarbon leaching (Nichols, Lucke, & Dierkes, 2014). Nichols, Lucke, and Dierkes (2014) found the best material to use for sidewalk and parking lot applications is permeable interlocking concrete pavers (PICP). PICP work by allowing the rainwater to infiltrate through the paver and its joints. The water is naturally filtered as it travels through multiple layers of rock and is collected in a rainwater drainage system underground (Nichols, et al., 2014). The water is then pumped into the collection tank to be stored for future use (Nichols, et al., 2014). For this type of rainwater collection the surface area of the PICP determines how much water can be harvested. In both cases, the system's effectiveness depends on the amount of rainfall in the specific building location (Nichols, et al., 2014). The conservation and reuse of water in a building is one of the many FEW system that can be integrated into a building. However, other aspects need to be considered when creating an efficient building such as type of occupancy, the type of construction, and the customer's budget.

3. Research Methods

This project focuses on a building located at 126 Chandler Street in Worcester, Massachusetts. It was originally an old mill building, but is being redesigned to serve as a multi-use building. For this specific building, the design recommendations include implementing a rooftop greenhouse, insulation, composting system, solar panels, water saving appliances, high efficiency appliances, permeable surfaces, and a rainwater harvesting system. These systems were chosen because they are cost effective and work with the existing structure of the building. Other methods that were considered to create a sustainable building were alternative solar cooling and solar systems, various composting and farming methods, and rainwater harvesting for toilets and sinks. These types of systems were not chosen because they would not work in an apartment-style building or because they would not be worth the cost.

3.1 Current Conditions

Extra steps can be taken during the design or restoration phase of a building in order to make a building as energy efficient as possible. By analyzing the history, building structure, and energy use of the existing building, systems can be tailored to the building to improve its performance. The client's goals of providing a monetary and environmentally friendly space that the community will be using must be considered when creating the design.

3.1.1 The Location

Chandler Street is located right outside of the canal district of Worcester, providing tenants with a variety of restaurants, bars, stores, and activities in walking distance to their apartment. The location of the building will promote healthy living by making it easy for people to walk or bike to their destinations. There is also a bus station right outside the building, allowing for easy transport to more distant locations. The building is situated between the local food pantry, The Mustard Seed, and a Salvation Army (Dyson, 2018). These services tend to attract the homeless community, creating a hotspot of increased crime and safety issues, which can make residents uneasy (Dyson, 2018). One of the goals in the design of the new apartment building is to create a fun and safe place for the tenants to live. Many families moving into these affordable housing units are single mothers with two or three children, therefore the building should feature safe places to play, both in and outdoors (Dyson, 2018).

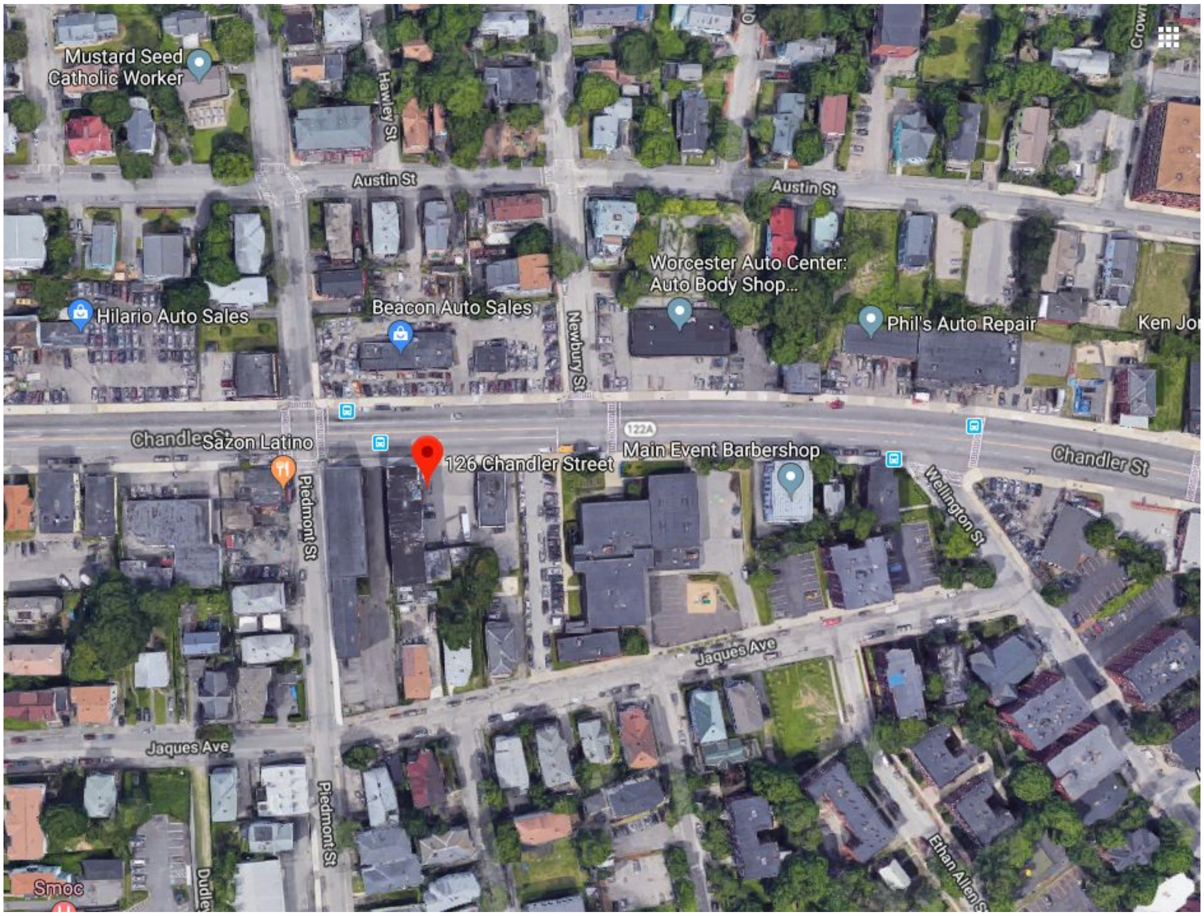

Figure 3: ***Aerial View of 126 Chandler Street*** (Google, 2018)

3.1.2 History of the Building

There are two existing structures on 120 and 126 Chandler Street. On 120 Chandler Street, there is a small, abandoned, two-story office building built in the 1970s that will be demolished. The building on 126 Chandler Street, shown in Figure 3, was built in 1883 and housed the J.R. Torrey Razor Company. This company was founded by Joseph Rice Torrey, and existed from 1858 to 1963, it sold razor strops and straight razors (Manah, 2009). In later years, the building become a retail establishment, and a tire shop and garage (Davis Square Architects, 2019). The building does not have enough history to merit a full restoration, but its fire red brick facade will be restored to its original detailing (Davis Square Architects, 2019). According to Struble Engineering (2018), the structural engineer hired by Worcester Common Ground, the structural system for the existing building is in good condition, and only needs some small adjustments to comply with the current building code. The original structure is intact and consists of a reinforced concrete perimeter frame and timber framing in the interior with timber columns at the center (Struble, 2018).

Figure 4: ***Picture of 126 Chandler Street*** (Google, 2018)

3.1.3 Building Structure

The existing building has a functional structural system with wood girders carrying the load to the concrete perimeter frame, which then disburses the load into the ground. However, given the building's age, it does not comply with all of the current code requirements. According to Struble Engineering (2018), the biggest issue with the existing structure is that the building does not have a code-compliant lateral system. Consequently, the building needs to be reinforced in both the north-south and east-west directions (Struble, 2018). The existing reinforced concrete perimeter frame has been sufficient to maintain the stability of the building, but more lateral resistance will have to be added for the building to be code compliant (Struble, 2018). Additionally, the interior foundations will either have to be upgraded or replaced for compliance with current standards (Struble, 2018). Other parts of the structure will be fixed depending on conditions on the site and areas of the building that are being removed or fixed throughout construction (Struble, 2018).

Added to the existing building will be an addition that will provide more community and residential space. The structural system of the new addition was designed by Struble Engineering. The addition will have a separation joint between the two buildings to allow the loads to zero out (Struble, 2018). This will allow each of the two buildings to have separate structural systems. The new building's structural system uses two major materials, steel and wood. On the first floor, steel columns and framing will be used to support the building. On the upper floors, lightweight wood construction will be used as the structural material. Lateral bracing is placed strategically within the walls of the building to mitigate all lateral loading in the two lower floors, while the upper floors rely on vertical diaphragms for lateral load resistance. The new building also includes two separate staircases and an elevator, allowing people to access both buildings.

3.1.4 Energy use of the Building

The first floor of the building will be used for commercial, retail, and office space. The anticipated electrical usage was estimated by splitting the entire level based on its classification of the space, commercial, retail, or office, and then estimating the electrical usage per area. Using the square footage devoted to each type of space and the corresponding average annual energy usage, the estimated annual energy cost for the first floor was calculated. A summary of this information is shown in Table 5 and further calculations can be found in Appendix B.

The residential space is composed of one, two, and three bedroom units on four different floors of the building. In order to calculate the energy cost, the average kilowatt hours (kWh) in an apartment unit per year in Massachusetts was used and multiplied by the number of units of each floor. These values as well as their annual cost and energy usage are shown in Table 6; further calculations can be found in Appendix C.

Table 5: ***Building Energy Usage - First Floor Mixed Use Space***

	Square Footage of Area (ft^2)	*Average kWh per sq.ft. per year*	*Total Energy (kWh/yr)*	*Total Cost ($/yr)*
Commercial Space	1,730	14[1]	24,220	$3,390.80
Retail Space	1,020	17[1]	17,340	$2,427.60
Community Space	1,474	17[1]	25,058	$3,508.12
Total	4,224	-	66,618	$9,326.52

[1] (Sun Power, 2019)

Table 6: ***Building Energy Usage - Residential Space***

	# of Residential units	*Average kWh in a Residential Apartment Unit per household per year*	*Total Energy (kWh/yr)*	*Total Cost ($/yr)*
Second Floor	9	7.656[1]	68,904	$9,646.56
Third Floor	9	7,656[1]	68,904	$9,646.56
Fourth Floor	9	7,656[1]	68,904	$9,646.56
Fifth Floor	4	7,656[1]	30,624	$4,287.36
Total	31	-	237,336	$33,227.04

[1] (Electric Choice, 2017)

3.2 Recommended FEW Systems

The integration of the FEW systems outlined in the literature review are limited by Worcester Common Ground's budget. In this section, different strategies are proposed to make the most impact in terms of Worcester Common Ground's goals given this restriction. Recommended food systems include a rooftop greenhouse and a small scale composting system. Energy systems include high efficiency appliances and solar harnessing systems. Water systems include systematic water conservation, rainwater harvesting, and permeable surfaces. The integration of these systems into 126 Chandler Street will allow for a more sustainable building and community.

3.2.1 Food Systems

The two main food systems to be implemented into 126 Chandler Street are a rooftop greenhouse and a composting system. These systems comply with goals set by the American Planning Association, the goals of Worcester Common Ground, and in general, will reduce environmental impacts and costs.

A rooftop greenhouse will reduce the building's environmental impact on the community, as well as provide valuable resources and knowledge for the low-income families residing in the building. These families will learn how to make their food system more sustainable, save money, and live a healthier lifestyle (APA, 2007). Any residential unit that wants a plot in the greenhouse will be provided with the education and tools they need to successfully grow vegetables for themselves.

A small scale composting system within the 126 Chandler Street housing complex will reduce the waste that the residents produce as well as provide fertilizer for the greenhouse. This will minimize the costs of fertilizer and waste management. Composting buckets will be provided by residential management of the building. Each residential unit will fill these small buckets and add their contents to a large collection bin located next to the dumpster. Once the large collection bin is full, it will be transported to the greenhouse by building management and become available for public use.

The more engaged the residents and community are in the food systems for 126 Chandler Street, the more successful the systems will be. For example, if residents wish to get more involved in the greenhouse, building management can consider compensating residents to help with day-to-day tasks.

3.2.2 Energy Systems

Massachusetts is the third highest state for solar energy savings (Solar-Estimate, 2018). Citizens of the state have saved an average of $33,380 per year after the payback period. They provide an annual power production 2745 kWh for the state (Solar-Estimate, 2018). With the adoption of solar energy systems, the cost of energy also decreases to about 9 cents per kWh as opposed to 13 cents per kWh provided by Worcester County (Solar-Estimate, 2018).

The two solar systems recommended for implementation into 126 Chandler Street are solar panels, including a solar canopy and high efficiency appliances. These systems are able to provide significant energy needs and cost savings, thereby fulfilling Worcester Common Ground's mission of promoting and developing permanent and sustainable improvement (Worcester Common Ground, n.d.).

The solar panels and solar canopy are included in the design because they produce a large amount of energy. The solar canopy will reduce heat island effects in the parking lot by absorbing the solar rays instead of being absorbed into the the ground. There is sufficient space to place 100 panels on the roof of the old building and 18 panels on the solar canopy. The proposed solar panels will collect 531 kW per panel, providing 20.6% of the building's prospective energy needs. The specific panel used for these calculations is the 5.03 kW Grid-Tied Solar System with Enphase IQ7+ Microinverters and 15x Astronergy 335w Panels. These panels were chosen because of their high efficiency and low cost (Appendix D for energy calculation).

The high efficiency appliance systems offer considerable savings in energy and water, improving the sustainability of 126 Chandler Street. The appliances that will be used are Energy Star appliances, which are known for their savings in energy and water as well as their monetary savings, which is separate from their reduced operating costs.

3.2.3 Water Systems

Three main systems recommended for 126 Chandler Street to help minimize the amount of water used includes water conservation, rainwater harvesting and permeable surfaces. The first is a conservation system, which includes a number of low-flow fixtures, water efficient appliances, and educational resources. Residences will be educated on water conservation, to ensure they are conscious about how much water they are consuming. In addition, there will be signs installed in the bathrooms relating to water conservation and small timers installed in all showers. Table 7 below lists the types of fixtures that are currently specified for the building. All of the fixtures currently planned are efficient, except for the toilets which are recommended to be changed to a low flow model.

Table 7: ***Recommended Plumbing Fixtures*** (Environmental Protection Agency, 2019)

	Regular Fixture	*WaterSense Standard*	*WCG*	*Suggested Model*	*Water Usage*	*Price*
Toilet	1.6 gpf	1.28 gpf	1.28 gpf	Niagara-77001WHCO1	0.8 gpf	$283.00
Sink	2.2 gpm	1.5 gpm	1.2 gpm			
Kitchen Sink	2.2 gpm	1.5 gpm	1.5 gpm			
Shower	2.5 gpm	2 gpm	1.75 gpm			

The second recommended system is rainwater harvesting which will help offset the water usage in the building. It will include two distinct systems: one will collect rainwater through the gutters of the greenhouse, and the other will incorporate roof drains. The greenhouse gutter system will store accumulated water in a 1000 gallon rooftop collection tank, which was sized according to the calculations in Appendix E. The gutter connection is detailed in the attached drawing set on sheet A110. This water will then be reused for irrigation in the greenhouse.

The second system will include roof drains on both the existing building and the addition. The collected water will be transported through a piping system to a collection tank on the ground floor of the building near the laundry room. This water will be used in the washing machines located in the communal laundry room because it will require little to no treatment. The reuse of this water will save about 79,000 gallons of water per year for the building's six washers (Appendix F for calculation).

The last recommended system is to install permeable surfaces on all exterior hardscapes. Permeable interlocking concrete pavers (PICPs) will be used to construct the surface of the parking lot. The water that is collected through the PICPs will be stored underground and used for landscape irrigation. The PICPs will not only work to decrease the impact on the water supply, but will also decrease the heat island effect caused by dark, hardscape surfaces. In addition, these pavers will reduce stormwater runoff and pollution by absorbing the water into the ground (Nichols, et al., 2014).

3.3 Architectural Considerations

The building will feature a rooftop greenhouse as a component of the food systems, which will contain floor level, raised planting beds, and a vertical garden on the north wall, as seen in Figure 5. The greenhouse will be supported by a structural steel frame with a mixed material facade. The south, east, and west walls as well as the roof will be enclosed with triple-layer polycarbonate panels, fastened by a mullion system. The north wall will be insulated in order to reduce the heat loss in the winter. The greenhouse will feature a shed roof oriented to optimize sunlight in the winter. For proper ventilation and cooling, there will be fans on the east and west walls of the greenhouse as well as manually operated windows. Figure 6 demonstrates the northeast exterior perspective of the greenhouse.

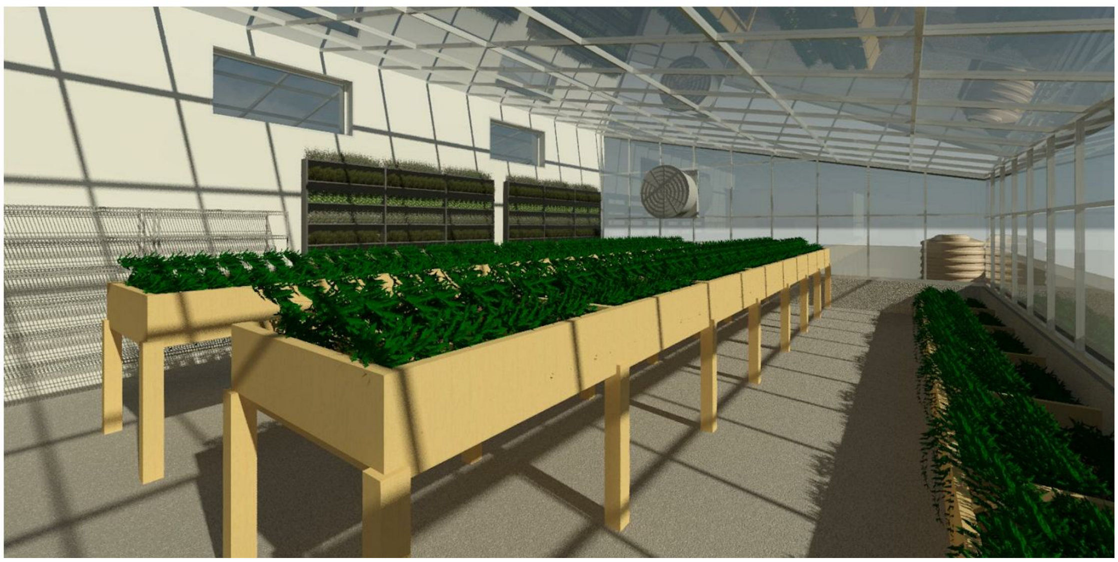

Figure 5: ***Interior Perspective of the Greenhouse***

Figure 6: ***Exterior Perspective of the Greenhouse***

Radiant heating will be installed under a raised flooring system. The radiant heating will decrease the chance of water pipes freezing in the winter and allow for a consistent, warm internal atmosphere, especially closer to the ground, where the plants will benefit most from it. The building will benefit from a closed, radiant heating system as opposed to an open system, meaning the source of energy will be a completely separate circuit than the rest of the building. A 38 gallon, solar powered hot water heater with gas backup will be placed on the roof in a closet attached to the greenhouse. A closed system will need less water treatment and protect the health of the residents by keeping unwanted chemicals out of the energy system of the building (N., 2006). The radiant heating layout and hot water heater placement is detailed in the drawing set on sheet M103.

The greenhouse will not be visible from the front of the building from Chandler Street, unless the viewer is approximately 300 feet from the building. The greenhouse is almost completely visible from the south side of the building, from Jaques Ave., which will maintain the historical front facade while allowing the public to see the advances in sustainability from the back.

4. Analysis and Discussion

For 126 Chandler Street, some structural modifications are necessary in order to successfully integrate the suggested FEW systems. For example, the sizes of some structural members in the addition will need to be increased to support the additional loads associated with the greenhouse. After the structural adjustments were finalized, the building was analysed in terms of its efficiency. The selected FEW systems were integrated into the building energy model (BEM), which was used to analyze the effects on building performance. The BEM shows which FEW systems have the largest impact on the building's energy usage.

4.1 Structural System

The structural system of the building is split into two components, the existing building and the new addition. As mentioned above, each building has a separate structural system and separate load paths. To investigate the structural system for the existing building, similar buildings built and renovated in Worcester were investigated. This showed loads and beam sizes used in similar, nearby buildings. Because of the property's age, some general deficiencies were already known, such as the lack of a lateral-load resisting systems and insufficient support for the roof. Using this information, the live and dead loads acting on the building were estimated. The ninth edition of the Massachusetts Building Code was used to obtain snow and wind loads (Appendix G) (Office of Public Safety and Inspections, 2017). These loads were then used to determine whether the existing roof structure has sufficient capacity (Office of Public Safety and Inspections, 2017). All of the timber beams and columns in the existing building were investigated using Allowable Stress Design, and they are all able to carry the required loading to fully support the structure. These calculations are shown in Appendix H.

The structural system for the proposed greenhouse is a structural steel frame with mullions to support the polycarbonate cladding. A rafter system was chosen to support the roof of the greenhouse to provide more height to the building, and the rest of the structural system is steel framing supported by girders, beams, and columns (Figure 7). Further details on the greenhouse structure can be seen in drawings S101 and S102. The design of the structural steel members was based on Load Resistance Factor Design, and the calculations are shown in Appendix I. Hollow Structural Steel (HSS) ASTM A1085 sections were selected for the roof purlins and supporting rafters, and they were sized using the 15th edition of the AISC Steel Construction Manual (2017). The end beams for the greenhouse are HSS 5x3 with a thickness of ½ inches. The interior beams are HSS 6x4 with a thickness of ½ inches. The column sizes were determined using a 1st-order analysis of the greenhouse to address the effects of combined lateral and gravity loads acting on the columns (AISC, 2017). The end columns for the greenhouse are HSS ASTM 1085 steel and are 4x3 with a ⅛ inch thickness. The interior columns are of the same grade of steel with a size of 4x3 with a 3/16 inch thickness.

The mullions were designed to make sure they could support the weight of the polycarbonate panels, and it was assumed that the mullions would not take any loading from the roof or beams. A first-order analysis was used because while the mullions will be subjected to both bending and flexure, the forces were small enough to meet the exception in the *AISC Specification* to allow the use of first-order analysis (AISC, 2017). Rectangular tube aluminium with grade 6061, and sized to 2x2 with a thickness of 0.65 inches was found to be adequate to support the polycarbonate panels. This calculation in shown in Appendix J.

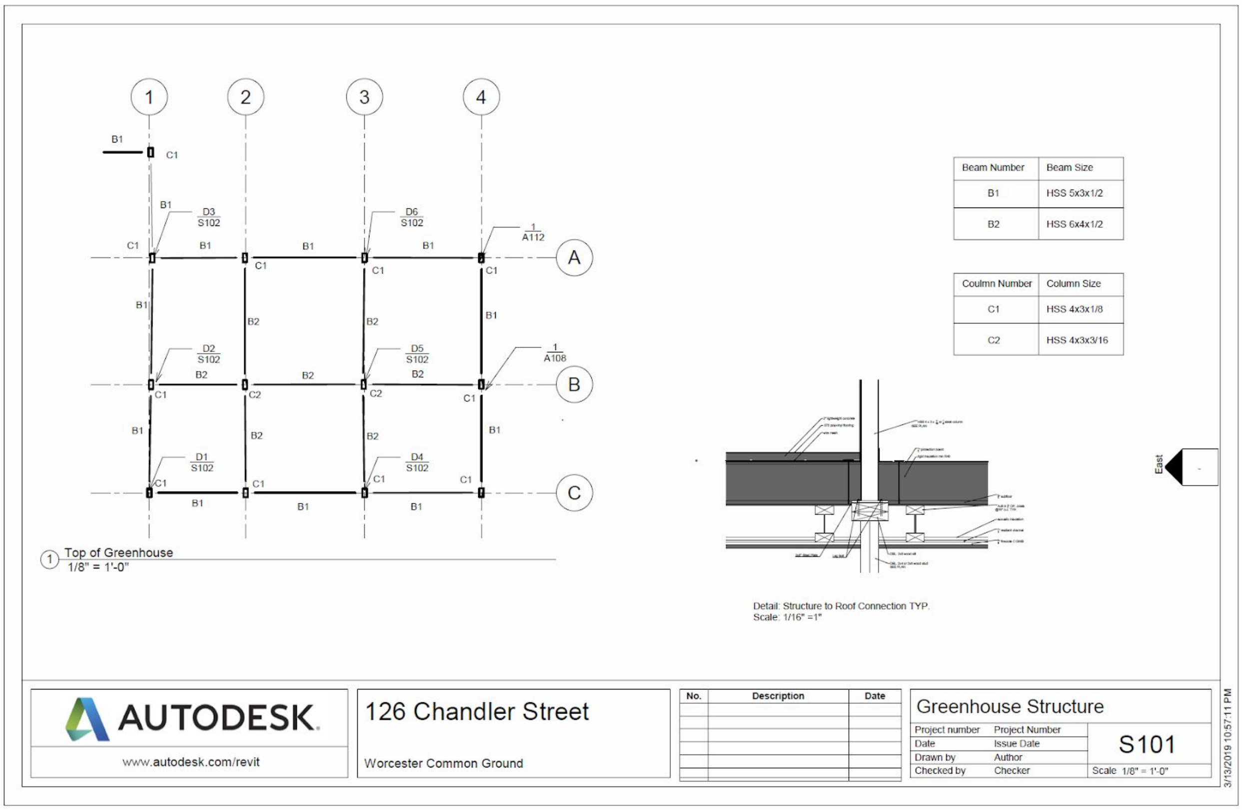

Figure 7: ***Greenhouse Structural System***

The structural system of the new addition then had to be checked using Load Factor Resistance Design to determine whether it would withstand the added loading from the greenhouse. To check this, the total loads acting on the roof of the new building were calculated by summing the total weight of the greenhouse structure, soil in the greenhouse, and the rainwater collection system. The calculation for the total loads can be seen in Appendix K. Considering these loads, a simplified load path was pursued allowing the load to flow from the superimposed greenhouse to the wood-framed bearing walls beneath to avoid adding extra loading to the wood beams. This process will be continued for all the subsequent floors of the new addition to make sure they can handle the new loads added to the building. This was deemed necessary because the proposed rooftop greenhouse added an extra 50,000 pounds. This extra load, if added within the span of the beams on the lower floors, would expand the function of the beams to act as transfer girders, conveying the loads within their span lengths to the supporting columns. After a load path was established from the proposed greenhouse through the underlying building structure, the strength of the beams supporting the roof of the new building was calculated to determine whether they can support the new loads added to the structure. Following this procedure, the roof beams were checked to ensure that they could hold the required loads. This calculation is shown in Appendix L. All beams except two remained unchanged. The wood beam under the column at the bottom left of the greenhouse had to be switched for a W10x39 to support the greenhouse loads because there was no load bearing wall at that point. The wood beam under the water tank also had to be switched to a W10x39 to support the additional load of the water which can be seen in Figure 8. Further detail of the structural modifications can be seen in drawings S103 and S104.

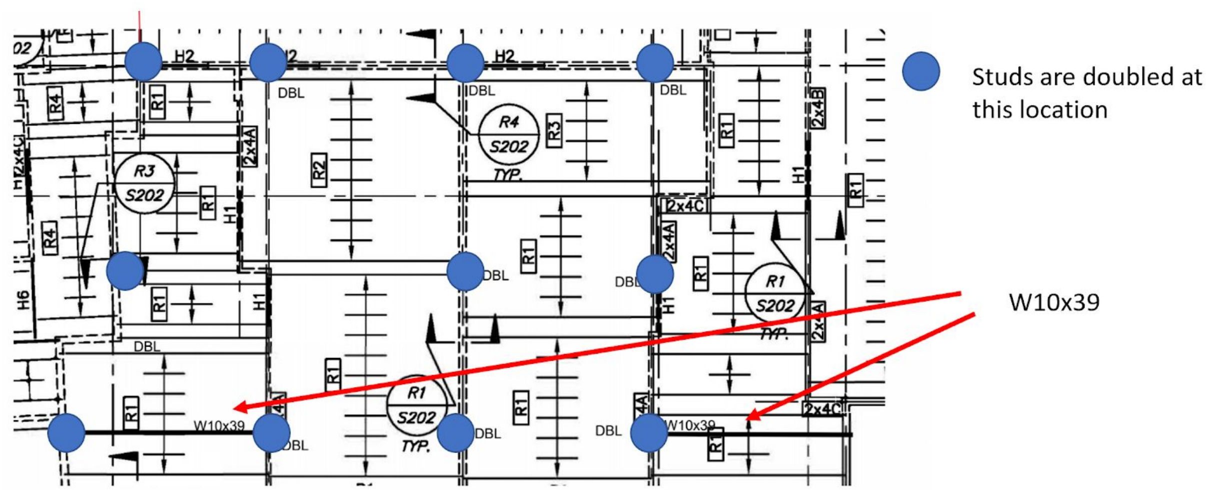

Figure 8: ***Modification of Below Greenhouse Roof Framing***

The wood structural system of the new addition was analyzed using Load Resistance Design and wood properties in the National Design Specification for Wood Design (AWC, 2018). The calculation can be seen in Appendix L. The load supporting stud walls need to be doubled up underneath the greenhouse columns on every level to provide sufficient strength. All the steel columns and beams on the first floor were found to be adequate except two beams that can be seen in Figure 9 and drawing S105. The beam on the left was revised to a W16x57 while the beam on the right was changed to a W16x67. A connecting beam of W10x12 between the W16x67 and an adjacent beam was also added to increase the lateral torsional buckling capacity of the W16x67 beam. All upgraded steel beams were sized not only to sustain the load, but also to fit within the ceiling height, which created unusual sizes but allowed the architect to retain the desired ceiling height.

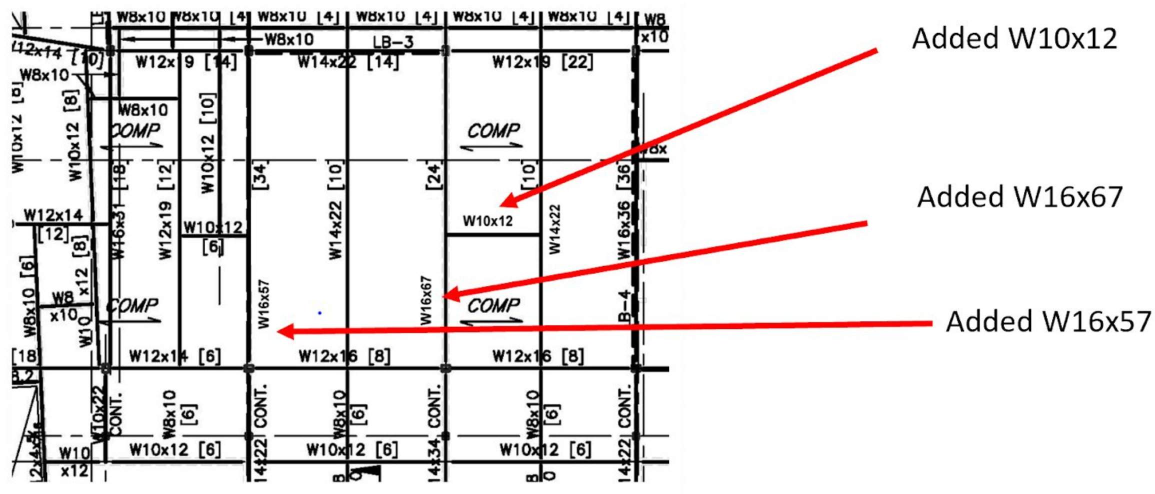

Figure 9: ***Modification of Steel Framing***

4.2 Energy Analysis

An energy analysis of 126 Chandler Street was performed in order to establish the sustainability of the current design, and to give an understanding of how the FEW systems implemented would improve the energy usage of the building. This was accomplished by establishing a baseline EUI (Energy Use Intensity) for the building and testing how these different systems improve the EUI for the entire complex.

4.2.1 Energy Model

Autodesk Revit 2018 and Green Building Studio were used to develop the energy model and calculate an EUI for 126 Chandler Street. Revit allowed for the specification of each space and calculate the heating and cooling loads for the unit. Each space was classified based on its condition type, space type, and construction detail, which pertained to the floor it was on was. The full list of room inputs including space types and construction specifications are in Appendix M and N as well as the construction specifications set for calculation in Green Building Studio. Each space was specified Green Building Studio calculated the EUI, as well as the total annual cost for fuel, electricity, and energy. The results present monthly and annual distribution of the energy use of the system (Appendix O-Q), as well as create alternatives that present the lowest EUI for the complex.

4.2.2 Scenarios

In order to understand the effects of implementing FEW systems, three different scenarios were tested.

The first scenario includes the FEW systems that were the lowest cost options such as the low-flush toilet systems, solar panels, and a change in the insulation. These were basic improvements, which did not provide substantial changes in the EUI.

The second scenario includes all the FEW systems applicable such as low-flush toilets, solar panels, a change in the insulation, the addition of the greenhouse with its own rainwater harvesting system, an additional rainwater harvesting system for the entire complex, and a solar panel canopy for the parking lot. This scenario has no regard for budget, but gives the maximum energy efficiency and lowest EUI for the complex.

The third scenario includes the recommended systems that provide the lowest EUI for the budget. This scenario includes the implementation of low-flush toilets, solar panels, the greenhouse with its rainwater harvesting system, and a change in the insulation. These FEW systems provide the maximum benefit for budget.

4.2.3 Results

Table 7 shows a summary of the data obtained by the energy analysis. The baseline EUI for the building overall is below the average for standard US apartment complexes of this size, which is 70.0 kBtu/ft^2/yr. As the FEW systems are added into the building the EUI decreases except for scenario 1, which as mentioned above is an insulation change, solar panels, and low-flush toilets. For scenario 1, there is a slight increase in every aspect with the exception of water, which may be due to the addition of the insulation. The insulation changed to the sprayed foam insulation mentioned above. This keeps more heat in the building during the winter and summer months causing more potential energy lost and increase use of the cooling system which raises the EUI. Scenario 2 which includes all the recommended systems decreases the most in terms of water usage with a total net savings of 20.6%. Our recommendation systems (Scenario 3) provide the same results as scenario 2 except a slight increase in water usage due to the lack of a full scale rainwater harvesting system. Appendix O, P, and Q have the full set of calculations for Scenario 1, 2, and 3 respectively. This proves that the recommended systems provide value because they are effective in reducing annual cost whilst staying within the project budget.

Table 8: ***Energy Analysis Summary***

	EUI ($kBtu/ft^2/yr$)	*Annual Electricity Usage (kWh)*	*Annual Fuel Usage (Therm)*	*Annual Energy Cost*[1]	*Annual Peak Demand (kW)*	*Total Water Usage (gal/yr)*
Baseline	65.6	255,499.5	10,859.25	$49,280.25	63.75	2,951,123
Scenario 1	66.0	255,565.5	10,868.25	$49,299.75	63.75	2,345,243
Scenario 2	64.0	251,031.7	10,518	$48,243	62.93	2,328,954
Scenario 3	64.0	251,031.7	10,518	$48,243	62.93	2,330,108

[1] Includes Electricity and Fuel

5. Conclusion

This report outlines the process of creating an environmentally conscious building that aligns with the client's goals. In the case of 126 Chandler Street, there are not enough funds to implement all of the suggested particular and costly systems. Some systems, such as solar panels, have government rebates that allow projects with tight budgets to include sustainable designs. The integration of FEW systems into the current design of 126 Chandler Street will greatly improve the building performance and will positively affect the tenants and their surrounding community. The building energy model shows that the best combination of FEW systems are solar panels, water conservation and reuse systems, improved insulation, and a rooftop greenhouse. These systems work in conjunction with the existing building, Worcester Common Ground's goals, and the community of Worcester to create a collection of affordable housing units that are environmentally friendly.

The systems that were not chosen to be included in the design of 126 Chandler Street may be more feasible in projects with larger budgets or different goals. As technology advances, there is a possibility for FEW systems and net-zero strategies to become mainstream systems. This will decrease the costs associated with the design, implementation, and maintenance of the systems. The design of 126 Chandler Street is one step in expanding the idea of net zero beyond building scale, and into an inclusive idea of 'net zero neighborhoods'.

This idea could promote broader research that focus on multiple buildings working together to achieve net zero. How could buildings with different functions play into this concept and contribute to an entire community, in order to reach a higher standard of energy efficiency? This concept encourages further investigation of net-zero communities in various climates, using different materials and different combinations of FEW systems. While expectation for building performance continue to evolve, how can projects involving affordable housing be included in smart growth policies? Local communities, as well as state and federal agencies, who provide funding for affordable housing must consider this in their development of future financial models.

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Appendices

Appendix A: Calculations for Table 4

This example will show all calculations for the first line item (toilet) found in Table 4.
Step One: *Calculate the amount of each fixture in the building*

	Number of Fixtures
Toilet	45
Sink	76
Shower	39
Dishwasher	31
Washer	6

Step Two: *Research the average water usage for both regular fixtures and low flow fixtures. Multiply this number (gallons per a year) by the number of fixtures in the building.*
An average person flushes the toilet 5 time per a day (Water Research Foundation, 2019). A regular toilets uses 3 gallons per a flush and a low flow toilet uses 1 gallon per a flush (Water Research Foundation, 2019).
Regular Toilet: 45 * 3(gpf) * 5(flushes/day) * 365(days/year) = 246,375 gallons per a year
Low Flow Toilet: 45 * 1(gpf) * 5(flushes/day) * 365(days/year) = 82,125 gallons per a year

Step 3: *Subtract the 'low flow water usage' toal from the 'regular water usage' total to get total water savings.*
Total Water Savings: 246,375 - 82,125 = 164,250 gallons per a year

Step 4: *Research the average price of the fixture and its low flow counterpart. Multiply this number by the amount of fixtures in the building*
An average toilet costs $100 and a low flow toilet costs around $200.
Cost of Regular Toilet: $100 * 45 = $4,500.00
Cost of Low Flow Toilet: $200 * 45 = $11,250.00

Step 5: *Subtract the price of low flow fixture from the price of regular fixture to get the additional expense of implementing low flow fixtures.*
Additional Expense: $11,250 - $4,500 = $6,750.00

Appendix B: Calculations for Table 5

Step One: *Calculate the square footage of each space in the building from the floor plan*

Space Type	Square Footage of Area (ft^2)
Commercial Space	1,730
Retail Space	1,020
Community Space	1,474

Step Two: *Research the average kilowatt hours per square foot per year. Multiply this number by the square footage of the area.*

The average number of the average kilowatt hours per square foot per year for commercial space is 14 ft^2/yr (Sun Power, 2019)

14 kWh/ft^2/yr * 1730ft^2 = 24,220 kWh/yr

The average number of the average kilowatt hours per square foot per year for retail space is 17 ft^2/yr (Sun Power, 2019)

17 kWh/ft^2/yr * 1020ft^2 = 17, 340 kWh/yr

The average number of the average kilowatt hours per square foot per year for community space is 17 ft^2/yr (Sun Power, 2019)

17 kWh/ft^2/yr * 1474ft^2 = 25,058 kWh/yr

Step 3: *Research the cost per kWh for energy in Worcester* (Electricity Local 2018) *and multiply this number by the total energy per year, calculate in Step 2.*
The average cost for energy in Worcester is 14 cents per kWh (Electricity Local 2018)

Commercial Space: 24,220 kWh/yr*$0.14 = $3,390.80
Retail Space: 17, 340 kWh/yr*$0.14 = $2,427.60
Community Space: 25,058 kWh/yr * 0.14 = $3,508.12

Appendix C: Calculations for Table 6

Step One: *Calculate the number of residential units in the building from the floor plan*

Space Type	# of residential units
Second Floor	9
Third Floor	9
Fourth Floor	9
Fifth Floor	4

Step Two: *Research the average kWh in a Residential Apartment Unit per household per year. Multiply this number by the number of units per floor.*

The average number of the average kWh in a Residential Apartment Unit per household per year is 7,656 (Electric Choice, 2017)

Second Floor: 7656 * 9 = 68,904 kWh/yr
Third Floor: 7656 * 9 = 68,904 kWh/yr
Fourth Floor: 7656 * 9 = 68,904 kWh/yr
Fifth Floor: 7656 * 4 = 30,624 kWh/yr

Step 3: *Research the cost per kWh for energy in Worcester* (Electricity Local 2018) *and multiply this number by the total energy per year, calculate in Step 2.*
The average cost for energy in Worcester is 14 cents per kWh (Electricity Local 2018)

Commercial Space: 68,904 kWh/yr*$0.14 = $9,646.56
Third Floor: 68,904 kWh/yr*$0.14 = $9,646.56
Fourth Floor: 68,904 kWh/yr * 0.14 = $9,646.56
Fifth Floor: 30,624 kWh/yr*0.14= $4,287.36

Appendix D: Solar Panel Calculations

Number of Panels needed					
	Average Residential Apartment Unit per household per month	**# of Residential units**	**# of kWh needed per year**	**# of kW Generated per solar panel**	**# of solar panels needed**
Residential Apartment Units Only	638	31	237336	531	447
Energy Star Appliances/ Stoves & Commercial Space		31	132119	531	249
	Average kWh per sq.ft. per year	**Square Footage of Area**			
First Floor only			66618	531	125
Commercial Space	14	1730	24220		
Residential Management	17	1020	17340		
Community Space	17	1474	25058		
Refrigeration Only			3330.9		
Total Solar Panels Needed					374

Space Requirement for Solar Panels								
Area	**Square Footage of Area**	**Setback**	**Area Availabl e**	**Square Footage of Solar Panel**	**# of Solar Panels that fit in area**	**# of kW generated per solar panel**	**Hours of full sun per year**	**kWh provided by the Solar Panels per year**
Roof Area	4725	0.75	3543.75	20.8	170	531	1722	143567.8
					100	531	1722	53100.0
Parking Lot	486	0.75	364.5	20.8	18	531	1722	9305.3
								62405.3

Savings for Solar Panel System					
System Savings	**Cost of Energy in Worcester**		**Savings**	**Total Energy of the System**	**Cost of Energy**
62405.0	0.14	8736.7	$8,736.70	303954	$42,553.56

Solar Panels Cost and Savings						
Type	**Cost per Panel**	**Cost of Inverter**	**Cost of Accessories**	**# of Panels**	**Cost**	**Cost w/ Tax Incentives**
Parking	$165.00	159	80	18	$7,272.00	$4,090.40
Rooftop	$165.00	159	80	100	$40,400.00	$27,280.00
Total					$47,672.00	$32,370.40

Weight of the Solar Panels:
Each solar panel weighs 3 pounds per square feet, and the square feet of each panel is 17.6 ft^2 . Since there are 100 hundred panels, the total weights becomes 5280 pounds.

3 lb/ft^2 * 17.6 ft^2 *100 panels = 5280 pounds

Appendix E: Sizing of Rainwater Collection Tank

Potential Rainwater Collection on Roof of the Greenhouse (U.S. Climate Data, 2019)						
Worcester, MA	Average Rainfall (in)	Average Rainfall (ft)	Area of Greenhouse Roof (ft^2)	Volume of Rainfall on Greenhouse (ft^3)	Volume of Rainfall on Greenhouse (gal)	Volume of Rainfall on Greenhouse per a Day (gal)
annual	*48.02*	*4.00*	*700*	*2801.17*	*20952.73*	*57.40*
Jan	3.50	0.29	700	204.17	1527.17	49.26
Feb	3.25	0.27	700	189.58	1418.08	50.65
Mar	4.00	0.33	700	233.33	1745.33	56.30
Apr	3.80	0.32	700	221.67	1658.07	55.27
May	4.00	0.33	700	233.33	1745.33	56.30
Jun	4.00	0.33	700	233.33	1745.33	58.18
Jul	4.00	0.33	700	233.33	1745.33	56.30
Aug	3.50	0.29	700	204.17	1527.17	49.26
Sep	3.75	0.31	700	218.75	1636.25	54.54
Oct	4.50	0.38	700	262.50	1963.50	63.34
Nov	4.00	0.33	700	233.33	1745.33	58.18
Dec	3.75	0.31	700	218.75	1636.25	52.78
Average					1674.43	55.03

The greenhouse contains about 300 ft2 of planting surface. At 0.3 to 0.4 gallons/ft2 needed to sufficiently water the plants, the greenhouse will require about 90 gallons per a day.
A 1,000 gallon collection tank was selected to allow for extra storage to be utilized during dry days.

Appendix F: Amount of Water Collected on Entire Roof

Potential Rainwater Collection on Entire Roof (U.S. Climate Data, 2019)						
Worcester, MA	Average Rainfall (in)	Average rainfall (ft)	Area of Roof (ft^2)	Volume of Rainfall on Roof (ft^3)	Volume of Rainfall on Roof (gal)	Volume of Rainfall on Roof per a Day (gal)
Jan	3.50	0.29	4,725	1,378.13	10,308.38	332.53
Feb	3.25	0.27	4,725	1,279.69	9,572.06	341.86
Mar	4.00	0.33	4,725	1,575.00	11,781.00	380.03
Apr	3.80	0.32	4,725	1,496.25	11,191.95	373.07
May	4.00	0.33	4,725	1,575.00	11,781.00	380.03
Jun	4.00	0.33	4,725	1,575.00	11,781.00	392.70
Jul	4.00	0.33	4,725	1,575.00	11,781.00	380.03
Aug	3.50	0.29	4,725	1,378.13	10,308.38	332.53
Sep	3.75	0.31	4,725	1,476.56	11,044.69	368.16
Oct	4.50	0.38	4,725	1,771.88	13,253.63	427.54
Nov	4.00	0.33	4,725	1,575.00	11,781.00	392.70
Dec	3.75	0.31	4,725	1,476.56	11,044.69	356.28
Average				1,511.02	11,302.40	371.45
Annual	48.02	4.00	4,725	18,907.88	141,430.91	387.48

Appendix G: Wind Load Calculations

The wind force on the existing building and new addition were calculated using the excel sheet below, obtained from the ASCE website. To calculate the wind force on each building all factors remained the same except for building height which was adjusted in order to find wind loads in the various sections of the building.

FLSMIDTH	**MWFRS Wind Loads** *ASCE 7-10* *Enclosed & Partially Enclosed Buildings of All Heights*	Job No: 11054 Designer: DCB Checker:
	Notes: Grinding Building (+/- Z Direction)	Date: 3/16/2019

Basic Parameters		
Risk Category	II	Table 1.5-1
Basic Wind Speed, V	100 mph	Figure 26.5-1A
Wind Directionality Factor, K_d	0.85	Table 26.6-1
Exposure Category	C	Section 26.7
Topographic Factor, K_{zt}	1.00	Section 26.8
Gust Effect Factor, G or G_f	1.122	Section 26.9
Enclosure Classification	Enclosed	Section 26.10
Internal Pressure Coefficient, GC_{pi}	+/- 0.18	Table 26.11-1
Terrain Exposure Constant, α	9.5	Table 26.9-1
Terrain Exposure Constant, z_g	900 ft	Table 26.9-1

Wall Pressure Coefficients		
Windward Wall Width, B	27 ft	
Side Wall Width, L	39 ft	
L/B Ratio	1.44	
Windward Wall Coefficient, C_p	0.80	Figure 27.4-1
Leeward Wall Coefficient, C_p	-0.41	Figure 27.4-1
Side Wall Coefficient, C_p	-0.70	Figure 27.4-1

Roof Pressure Coefficients

Roof Slope, θ	4.8°	
Median Roof Height, h	65 ft	
Velocity Pressure Exposure Coef., K_h	1.16	Table 27.3-1
Velocity Pressure, q_h	25.2 psf	Equation 27.3-1
h/L Ratio	1.67	
Windward Roof Area	0 ft²	
Roof Area Within 33 ft of WW Edge	0 ft²	

Location	*Min/Max*	*Horiz Distance From Windward Edge*			
		0 ft	*33 ft*	*65 ft*	*130 ft*
Windward Roof Coefficient Normal to Ridge, C_p	Min	-1.30	-1.30	-0.70	-0.70
	Max	-0.18	-0.18	-0.18	-0.18
Leeward Roof Coefficient Normal to Ridge, C_p	Min	-1.30	-1.30	-0.70	-0.70
	Max	-0.18	-0.18	-0.18	-0.18
Roof Coefficient Parallel to Ridge, C_p	Min	-1.30	-1.30	-0.70	-0.70
	Max	-0.18	-0.18	-0.18	-0.18

Figure 27.4-1

Structure Pressure Summary (Add Internal Pressure q_zGC_{pi} or q_hGC_{pi} as Necessary)

Height, z	*K_z*	*q_z*	*Walls*				*Roof*			Internal	
							Normal to Ridge		*Parallel*		
			WW	*LW*	*WW + LW*	*Side*	*WW*	*LW*	*to Ridge*	Positive	Negative
0 ft	0.85	18.5 psf	16.6 psf	-11.6 psf	28.2 psf	-19.8 psf	Min: -36.7 psf	Min: -36.7 psf	Min: -36.7 psf	4.5 psf	-4.5 psf
7 ft	0.85	18.5 psf	16.6 psf		28.2 psf					4.5 psf	
13 ft	0.85	18.5 psf	16.6 psf		28.2 psf					4.5 psf	
20 ft	0.90	19.5 psf	17.5 psf		29.1 psf					4.5 psf	
26 ft	0.95	20.7 psf	18.6 psf		30.2 psf					4.5 psf	
33 ft	1.00	21.7 psf	19.5 psf		31.1 psf		Max: -5.1 psf	Max: -5.1 psf	Max: -5.1 psf	4.5 psf	
39 ft	1.04	22.6 psf	20.3 psf		31.9 psf					4.5 psf	
46 ft	1.07	23.3 psf	20.9 psf		32.5 psf					4.5 psf	
52 ft	1.10	24.0 psf	21.5 psf		33.1 psf					4.5 psf	
59 ft	1.13	24.6 psf	22.1 psf		33.7 psf					4.5 psf	
65 ft	1.16	25.2 psf	22.6 psf		34.2 psf					4.5 psf	

Appendix H: Old Building Structural Calculations

Step One: *West Beams*

Calculate the strength of the beams on the west side of the building to see if they can hold the new loading conditions. Repeat this process for the beams on the first, second, third and roof levels. Use allowable stress design and values from the National Design Specification for Wood Design in this calculation (AWC, 2018).

Wood Beams 71/2 x 11 3/4 at ROOF Assuming White Oak No. 1							
Loads							
dead-beam	28.15104167	psf	Load combin	=	64.35	D+S	
solar panel wie(	5280	lbs	wu	=	664.93		
sq ft old roof	4405		Mmax	=	109920.45		
dead-load solar	1.198637911	psf	Mmax	=	9160.037799	lbs-in	
live roof	25	psf	V	=	5651.86		
snow	35	psf				lbs	
wind	28	psf	Deflections				
Trib Area**	10.333	ft	Live	1.133333333	>		
Fb	1200		Snow	1.133333333	>	0.000549191215	
Ft	575		Dead+Live	1.7	>	0.000768867701	
Fv	205					0.000635431398	
Fc_	1000		Stress of beam				
Fc	775		Bending Stress	fb =	664.9755		
E	1000000						Fb
Emin	400000		Design Strength of Beam			Cd	1.15
Length	17	ft	Fb'	1104		Cm	1
Inertia XX	950.5	in^4	E'min	380000		Ct	1
b	7.5	in				Cl	1
d	11.5	in				Cf	1
A	86.5	in^2				Cfu	1
Sxx	165.3	in^3				Ci	0.8
						Cr	1

Wood Beams 71/2 x 11 3/4 at 3rd, 2nd, 1st Floors Assuming White Oak No. 1

Loads							
dead-beam	28.15104167	psf	Load combin	=	88.15	D+L	
Live Load	60	psf	wu	=	910.86		
Trib Area**	10.333	psf	Mmax	=	150577.32	lbs-in	
Fb	1200	psf	Mmax	=	12548.11025		
Ft	575	ft	V	=	7742.35	lbs	
Fv	205						
Fc_	1000		Deflections				
Fc	775		Live	1.133333333	>	0.001318058916	
E	1000000		Dead+Live	1.7	>	0.000875702554	
Emin	400000						
Length	17	ft	Stress of beam				
Inertia XX	950.5	in^4	Bending Stress	fb =	910.9336		Fb
b	7.5	in				Cd	1
d	11.5	in	Design Strength of Beam			Cm	1
A	86.5	in^2	Fb'	960		Ct	1
Sxx	165.3	in^3	E'min	380000		Cl	1
						Cf	1
						Cfu	1
						Ci	0.8
						Cr	1

Step Two: *East Beams*

Calculate the strength of the beams on the east side of the building to see if they can hold the new loading. Repeat this process for the beams on the first, second, third and roof levels. Use allowable stress design and values from the National Design Specification for Wood Design in this calculation (AWC, 2018).

Wood Beams 71/2 x 11 3/4 at ROOF Assuming White Oak No. 1							
Loads							
dead-beam	28.15104167	psf	Load combin	=	64.35	D+S	
solar panel wie	5280	lbs	wu	=	664.93		
sq ft old roof	4405	ft^2	wt	=	1200.19		
dead-load solar	1.198637911	lbs	Mmax	=	109920.45	lbs-in	
live roof	25	psf	Mmax		9160.04	lbs-ft	
snow	35	psf	V	=	5319.40	lbs	
wind*	28	psf					
Trib Area	10.333	ft	Deflections				
Fb	1200		Live	1.066666667	>	0.000430931088	
Ft	575		Snow	1.066666667	>	0.000603303524	
Fv	205		Dead+Live	1.6	>	0.000498600736	
Fc_	1000						
Fc	775		Stress of beam				
E	1000000		Bending Stress	fb =	664.9755		
Emin	400000						
Length	16	ft	Design Strength of Beam		ASD		
Inertia XX	950.5	in^4	Fb'	864			Fb
b	7.5	in	E'	1174351.356		Cd	0.9
d	11.5	in	E'min	380000		Cm	1
A	86.5	in^2				Ct	1
Sxx	165.3	in^3				Cl	1
CT	1.236159322					Cf	1
Le	60.58					Cfu	1
						Ci	0.8
						Cr	1

Wood Beams 71/2 x 11 3/4 at 3rd, 2nd, 1st Floors Assuming White Oak No. 1							
Loads							
dead-beam	28.15104167	psf	Load combin	=	88.15	D+L	
Live Load	60	psf	wu	=	910.86		
Trib Area**	10.333	psf	Mmax	=	150577.32		
Fb	1200	psf	Mmax	=	12548.11025	lbs-in	
Ft	575	ft	V	=	7286.92		
Fv	205					lbs	
Fc_	1000		Deflections				
Fc	775		Live	1.066666667	>	0.001034234613	
E	1000000		Dead+Live	1.6	>	0.000687133087	
Emin	400000						
Length	16		Stress of beam				
Inertia XX	950.5		Bending Stress	fb =	910.9336		Fb
b	7.5	ft				Cd	1
d	11.5	in^4	Design Strength of Beam			Cm	1
A	86.5	in	Fb'	960		Ct	1
Sxx	165.3	in	E'min	380000		Cl	1
		in^2				Cf	1
		in^3				Cfu	1
						Ci	0.8
						Cr	1

Step Three: *Girders*

Calculate the strength of the girders in the building to see if they can hold the new loading. Use a live load reduction factor for the girders to help reduce the loading on the girders. Repeat this process for the girders on the first, second, third and roof levels. Use allowable stress design and values from the National Design Specification for Wood Design in this calculation (AWC, 2018).

Wood Girders 71/2 x 11 3/4 at ROOF Assuming White Oak No. 1							weight
Loads							
dead-beam	28.15104167	psf	Load combin	=	64.35	D+S	
solar panel wie	5280	lbs	wu	=	1093.94		
sq ft old roof	4405	ft^2	Mmax	=	180842.71	lbs-in	
dead-load solar	1.198637911	lbs	Mmax	=	15070.23	lbs-ft	
live roof	25	psf	V	=	5650.22	lbs	
snow	35	psf					
wind*	28	psf	Deflections				
Trib Area	17	ft	Live	0.6886666667	>	0.000074873680	
Fb	1200		Snow	0.6886666667	>	0.000104823152	
Ft	575		Dead+Live	1.033	>	0.000086631188	
Fv	205						
Fc_	1000		Stress of beam				
Fc	775		Bending Stress	fb =	1094.0273		
E	1000000						
Emin	400000		Design Strength of Beam		ASD		
Length	10.33	ft	Fb'	1656			
Inertia XX	950.5	in^4	E'min	380000		Cd	Fb
b	7.5	in				Cm	1.15
d	11.5	in				Ct	1
A	86.5	in^2				Cl	1
Sxx	165.3	in^3				Cf	1
						Cfu	1.5
						Ci	1
						Cr	0.8
							1

Wood Girders 71/2 x 11 3/4 at 3rd, 2nd, 1st Floors Assuming White Oak No. 1							
Loads							
dead-beam	28.15104167	psf	Load combin	=	68.15	D+L	
Live Load	40	psf	wu	=	1158.57		
Trib Area**	17	psf	Mmax	=	191525.72		
Fb	1200	psf	Mmax	=	15960.47702	lbs-in	
Ft	575	ft	V	=	5984.00		
Fv	205					lbs	
Fc_	1000		Deflections				
Fc	775		Live	0.6886666667	>	0.000119797888	
E	1000000		Dead+Live	1.033	>	0.000100670003	
Emin	400000						
Length	10.33	ft	Stress of beam				
Inertia XX	950.5	in^4	Bending Stress	fb =	1158.6553		Fb
b	7.5	in				Cd	1
d	11.5	in	Design Strength of Beam			Cm	1
A	86.5	in^2	Fb'	1200		Ct	1
Sxx	165.3	in^3	E'min	380000		Cl	1
						Cf	1
						Cfu	1
						Ci	1
						Cr	1

Step Four: *Columns*

Calculate the strength of the columns in the building to see if they can hold the new loading. Repeat this process for the columns supporting the first, second, third and roof levels. Use allowable stress design and values from the National Design Specification for Wood Design for this calculation (AWC, 2018).

Wood Columns 7 1/2 x 7 1/2 at 4th Floor to Roof Assuming White Oak								
Loads								
dead-column	18.359375	psf	Load combin	=	54.56	D+S		
sq ft old roof	4405	ft^2	wu	=	9580.93	lbs		
dead-load solar	1.198637911	lbs						
solar panel wie	5280	lbs						
live roof	25	psf	Deflections					
snow	35	psf	Live	0.8	>	0.000491467576		
wind*	28	psf	Snow	0.8	>	0.000688054607		
Trib Area	175.61	ft	Dead+Live	1.2	>	0.000424274744		
Fb	1200							
Ft	575		Stress of beam					
Fv	205		Comp. Stress	fc =	170.3276915			
Fc_	1000		Comp. Stress Par	fc_ =	170.3276915			
Fc	1000							
E	1000000		Design Strength of Beam		ASD			
Emin	400000		Fc'	810.1760288			Fc	Emin&E
Length	12	ft	E'	950000		Cd	1.15	
Inertia XX	263.7	in^4	E'min	380000		Cm	1	1
b	7.5	in				Ct	1	1
d	7.5	in				Cf	1	
A	56.25	in^2				Ci	0.8	0.95
Sxx	70.31	in^3				CT		1
Ke	0.65					Cp	0.8806261183	
Le	7.8					Fc*	920	
c	0.8					Fce	2005.516519	
						sqrt	1.225044245	

Wood Columns 7 1/2 x 7 1/2 at 3rd to 4th Floor Assuming White Oak

Loads								
dead-column	18.359375	psf	Load combin	=	115.42	D+L		
live load	60	psf	wu	=	20268.45			
load up. Flrs	37.06	psf	Mmax	=	1425125.21	lbs-ft		
Trib Area	175.61	ft	Mmax	=	118760.43			
Fb	1200		V	=	121610.68	lbs		
Ft	575							
Fv	205		Deflections					
Fc_	1000		Live	0.8	>	0.001179522184		
Fc	1000		Dead+Live	1.2	>	0.000639291808		
E	1000000							
Emin	400000		Stress of beam					
Length	12	ft	Comp. Stress	fc =	360.3279554			
Inertia XX	263.7	in^4	Comp. Stress Par	fc_ =	360.3279554			
b	7.5	in						
d	7.5	in	Design Strength of Beam		ASD			
A	56.25	in^2	Fc'	719.4929154			Fc	Emin&E
Sxx	70.31	in^3	E'	950000		Cd	1	
Ke	0.65		E'min	380000		Cm	1	1
Le	7.8					Ct	1	1
c	0.8					Cf	1	
						Ci	0.8	0.95
						CT		1
						Cp	0.8993661442	
						Fc*	800	
						Fce	2005.516519	
						sqrt	1.670410552	

Wood Columns 9 1/2 x 9 1/2 at 2nd to 3rd Floor Assuming White Oak

Loads								
dead-column	29.45659722	psf	Load combin	=	204.87	D+L		
live load	60	psf	wu	=	35977.92			
load up. Flrs	115.42	psf	Mmax	=	5141094.94	lbs-ft		
Trib Area	175.61	ft	Mmax	=	428424.58			
Fb	1200		V	=	215867.52	lbs		
Ft	575							
Fv	205		Deflections					
Fc_	1000		Live	0.8	>	0.000458220388		
Fc	1000		Dead+Live	1.2	>	0.000311914039		
E	1000000							
Emin	400000		Stress of beam					
Length	12	ft	Comp. Stress	fc =	398.6473189			
Inertia XX	678.8	in^4	Comp. Stress Par	fc_ =	398.6473189			
b	9.5	in						
d	9.5	in	Design Strength of Beam		ASD			
A	90.25	in^2	Fc'	683.1713911			Fc	Emin&E
Sxx	209.4	in^3	E'	950000		Cd	0.9	
Ke	0.65		E'min	380000		Cm	1	1
Le	7.8					Ct	1	1
c	0.8					Cf	1	
						Ci	0.8	0.95
						CT		1
						Cp	0.9488491543	
						Fc*	720	
						Fce	3217.739837	
						sqrt	6.097579721	

Wood Columns 9 1/4 x 11 1/4 at 1st to 2nd Floor Assuming White Oak No. 1								
Loads								
dead-column	35.65798611	psf	Load combin	=	300.53	D+L		
live load	60	psf	wu	=	52776.42			
load up. Flrs	204.87	psf	Mmax	=	11051162.34	lbs-ft		
Trib Area	175.61	ft	Mmax	=	920930.19			
Fb	1200		V	=	316658.52	lbs		
Ft	575							
Fv	205		Deflections					
Fc_	1000		Live	0.8	>	0.000258338870		
Fc	1000		Dead+Live	1.2	>	0.000195878945		
E	1000000							
Emin	400000		Stress of beam					
Length	12	ft	Comp. Stress	fc =	5810.248015			
Inertia XX	1204	in^4	Comp. Stress Par	fc_ =	5810.248015			
b	9.5	in						
d	11.5	in	Design Strength of Beam		ASD			
A	109	in^2	Fc'	695.9022165			Fc	Emin&E
Sxx	209.4	in^3	E'	950000		Cd	0.9	
Ke	0.65		E'min	380000		Cm	1	1
Le	7.8					Ct	1	1
c	0.8					Cf	1	
						Ci	0.8	0.95
						CT		1
						Cp	0.9665308563	
						Fc*	720	
						Fce	4715.192171	
						sqrt	14.07388658	

Appendix I: Greenhouse Structural Calculations

Step One: *Exterior Beams*

Calculate the size of the exterior beams needed to support the greenhouse roof and panels. Use the biggest size calculated for all exterior beams in order to reduce the variations of beam sizing. Follow the sample of the calculation for all beams. Change the loading, length, and tributary area to match the properties of the given beam in order to see if it can support the loads at that given size. Use load resistance factor design and values from the Steel Construction Manual for this calculation (AISC, 2017).

Beam- "1" HSS 5x2.5, 1/4 thickness									
Loads									
dead-beam	11.36		Load combinations	=	75.8920				
dead plastic	0.54999		wu	=	531.2439				
live roof	25		wt	=	356.3699				
snow	28		Mmax	=	2069.8517		ft-lbs		
wind	21								
Es	29000000								
Iy	3.13		Zx	=	0.5520	<	4.83		
Tribitary Area	7								
Length	5.583								
Fy	50				Deflections				
Ix	9.4		wL	=	7.2917				
							L/360		
			Delta L	=	0.0211	<	0.1861	<	1
							L/240		
			Delta T	=	0.029	<	0.27915		

Beam "4"- HSS 5x3, 1/2 thickness									
Loads									
dead-beam	0	Load combinations	=	88.2160					
dead plastic	0.54999	wu	=	617.5119					
dead-girder	21.63	wt	=	253.2599					
live roof	25	Mmax	=	13894.4161					
snow	28								
wind	21								
Es	29000000	Zx	=	3.7052	<	8.83			
Iy	7.18								
Tribitary Area	7	Deflections							
Length	13.4166	wl	=	7.2917					
Fy	50						L/360		
Ix	16.4	Delta L	=	0.3064	<		0.4472	<	1
		live load (cracking)							
							L/240		
		Delta T	=	0.3882	<		0.67083		
		dead, snow							

Step Two: *Interior Beams*

Calculate the size of the interior beams needed to support the greenhouse roof and panels. Use the biggest size calculated for all interior beams in order to reduce the variations of beam sizing. Follow the sample calculation below for all beams. Change the loading, length, and tributary area to match the properties of the given beam in order to see if it can support the loads at that given size. Use load resistance factor design and values from the Steel Construction Manual for this calculation (AISC, 2017)

Beams-"6"- HSS 6x4, 1/2 thickness									
Loads									
dead-beam	0	Load combinations	=	96.3760					
dead plastic	0.54999	wu	=	1192.4601					
dead-girder	28.43	wt	=	531.7914					
live roof	25	Mmax	=	29215.2724					
snow	28								
wind	21								
Es	29000000	Zx	=	7.7907	<	23.5			
Iy	17.8								
Tribitary Area	12.373	Deflections							
Length	14	wl	=	12.8885					
Fy	50						L/360		
Ix	34	Delta L	=	0.2590	<		0.4667	<	1
		live load (cracking)							
							L/240		
		Delta T	=	0.4662	<		0.70000		
		dead, snow							

Step Three: *Exterior Columns*

Calculate the size of the exterior columns needed to support the greenhouse roof and panels. Use the biggest size calculated for all exterior columns in order to reduce the variations of beam sizing. Follow the sample calculation below for all columns. Change the loading, length, and tributary area to match the properties of the given column in order to see if it can support the loads at that given size. Use load resistance factor design and values from the Steel Construction Manual for this calculation (AISC, 2017)

Columns-1- HSS 4x3, 1/8 thickness					
Loads					
dead-plastic	0.55		Load combinatioı	120.9040	
dead-beams	43.26	lbs	wu	2040.2550	lbs
dead-column	5.61	lbs		2.0403	kips
Live Load	25		Lc	14.5	
Snow load	28				
Wind Load	21	ksi			
Es	29000	kips	KLx/rx	120	
Tribitary Area	16.875		KLy/ry	150	
Length y	14.5				
Fy	50	kips	Fe	12.70792889	
K	1		Fcr	9.633196762	
Length x	14.5		oFcr	8.669877085	
rx	1.45		oPn	13.35161071	kips
ry	1.16				
Ag	1.54				
rx/ry	1.25				

Step Four: *Interior Columns*

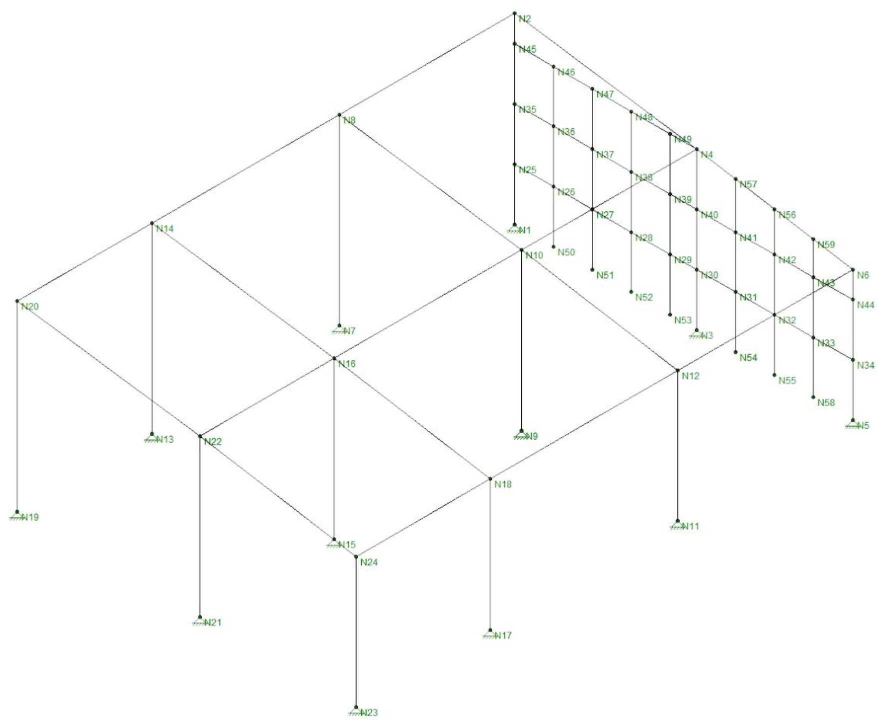
Calculate the size of the interior columns needed to support the greenhouse roof and panels. Use the biggest size calculated for all interior columns in order to reduce the variations of beam sizing. Follow the sample calculation below for all columns. Change the loading, length, and tributary area to match the properties of the given column in order to see if it can support the loads at that given size. Use load resistance factor design and values from the Steel Construction Manual for this calculation (AISC, 2017)

Columns-7- HSS 4x3, 3/16 thickness					
Loads					
dead-plastic	0.55		Load combinatioı	123.9520	
dead-beams	43.26	lbs	wu	22049.3255	lbs
dead-column	8.15	lbs		22.0493	kips
Live Load	25		Lc	12.5	
Snow load	28				
Wind Load	21	ksi			
Es	29000	kips	KLx/rx	100.8403361	
Tribitary Area	177.886		KLy/ry	126.0504202	
Length y	12.5				
Fy	50	kips	Fe	17.9956981	
K	1		Fcr	15.62864143	
Length x	12.5		oFcr	14.06577729	
rx	1.4875		oPn	31.50734112	kips
ry	1.19				
Ag	2.24				
rx/ry	1.25				

Appendix J: Mullion Calculations

Step One: *Second Order Analysis*

Complete a second order analysis of the structural system because the members are experiencing forces along two different axes. Construct a RISA model (as seen below) of the greenhouse to model the forces on the mullions in order to obtain the Pnt, Mnt, Mr, and Pr.



Using the values obtained from RISA conduct a second order analysis is shown below:

P_{nt}=.004^{k}, M_{nt}=.009$^{ft\text{-}k}$, M_1=.009$^{ft\text{-}k}$, M_2=0, P_{lt}=.916^{k}, M_{lt}=1.181$^{ft\text{-}k}$, α=1.0

Assume B_2=1

Cm=0.6+0.4(M1/M2) =.6+0.4(0)=0.6

Pr=Pnt +B2Plt= .004+1(.916)=.92 kips

Pel=2EI/(K1L)2=2*10,000*.036/(1.0*48)2=74.02 kips

B1=Cm/(1-(Pr/Pel))=$_{.6}$/(1-1.0(.92/74.02))=.61 so B_1=1

After finding B_1 and B_2, re-solve for second-order P_r and M_r

Pr=Pnt+B2*Plt=.004+1.0*0.916=0.92kips

Mr=B1*Mnt+B2*Mnt=.009*1.0+1.181*1.0=1.19 foot-kips

Step Two: *Use Appendix 7 in the AISC Steel Construction Manual equation (A-7-1) which states that if the member can pass this test then a first-order analysis can be used (AISC, 2017).*

Pr0.5Pns

Pns=Ag*Fy=0.243*30=7.29

1.0*.920.5*7.29

.923.645

The test shows that the mullions can be analyzed by using a first-order analysis (shown below) (AISC, 2017).

Mullions: Aluminum 6061					
Mullions: Columns RT 1x1x.65					
Loads					
dead-plastic	0.55		Load combinatioı	19.1400	
dead-beams	0.56	lbs	wu	76.5600	lbs
dead-column	0.84	lbs		0.0766	kips
Live Load	0		Lc	4	
Snow load	0				
Wind Load	21	ksi			
Es	10,000	kips	KLx/rx	126.3157895	
Tribitary Area	4		KLy/ry	126.3157895	
Length y	4				
Fy	40	kips	Fe	6.179367361	
K	1		Fcr	2.663226515	
Length x	4		oFcr	2.396903864	
rx	0.38		oPn	0.5608755041	kips
ry	0.38				
Ag	0.234				
rx/ry	0				

Mullions - side walls RT 1X1X.65									
Loads									
dead-beam	0	Load combinations	=	17.7960					
dead plastic	0.54999	wu	=	71.1840					
dead-girder	0.28	wt	=	3.3200					
live roof	0	Mmax	=	142.3679					
snow	0		=	0.1424					
wind	21								
Es	10000000	Zx	=	0.0475	<	23.5			
Iy	0.036								
Tribitary Area	4	Deflections							
Length	4	wl	=	0.0000					
Fy	40						L/360		
Ix	0.036	Delta L	=	0.0000	<		0.1333	<	1
		live load (cracking)							
							L/240		
		Delta T	=	0.0531	<		0.20000		
		dead, snow							

Mullions - roof RT 2X2X.65									
Loads									
dead-beam	0	Load combinations	=	62.5960					
dead plastic	0.54999	wu	=	250.3840					
dead-girder	0.28	wt	=	59.3200					
live roof	0	Mmax	=	500.7679	lbs-ft				
snow	28		=	0.5008					
wind	21								
Es	10000000	Zx	=	0.1669	<	0.7156			
Iy	0.7156								
Tribitary Area	4	Deflections							
Length	4	wl	=	0.0000					
Fy	40						L/360		
Ix	0.7156	Delta L	=	0.0000	<		0.1333	<	1
		live load (cracking)							
							L/240		
		Delta T	=	0.0477	<		0.20000		
		dead, snow							

Appendix K: Soil Weight Calculations

The table shows the calculation used to determine the total added weight of the soil in the planting beds of the greenhouse. This was used in the calculations for the structural modifications of the addition. The specific beds used can be seen in the bill of materials.

	Number of Beds	Volume per Bed (cubic feet)	Weight of Beds	Total Volume (cubic feet)	Weight of Wet Soil (pounds)	Weight of Beds	Total
Raised Beds 4.5'x4'x1'	14	18.00	33	252.00	19,656	462	20,118
Floor beds 2.75'x4.75'x1'	9	13.06	20	117.56	9,170	180	9,350
Vertical Planter	6	4.5	42	27	2,106	252	2,358
Total	29	35.56	95	396.56	30,932	894	31,826
	Will need about 400 cubic feet of soil to fill all the beds.						
	Wet soil will be 31,306 pounds.						
Added Weight	**30.38936372**	**lbs/sq.ft**	**avg. 31**				
			total designed for: 32,643lbs				

Appendix L: New Building Structural Calculations

Step One: *Wood Joists*

Check the size of the wood joists on the roof to see if they can support the greenhouse load in the case of the greenhouse columns not aligning with a load bearing wall. Below is a sample of the calculation used for all beam loading with loading and length changed to match the given beam. Find the capacity of the wood joist on the manufacturer's site (Boise Cascade, 2013). Use load resistance factor design and values from the Nation Design Specification for Wood Design for this calculation (AWC, 2018).

Wood Joists AJS 9 1/2 at ROOF Wood I-beam					
Loads					
dead-flr	20				
dead-beam	7.751736111	psf	Load combin	=	82.90
solar panel wie	5280	lbs	LL	=	49.6
sq ft old roof	4405		wu	=	110.26
dead-load solar	1.198637911	psf			
live roof	25	psf			
Grn-lds	31	psf			
snow	0	psf			
Trib Area**	1.33	ft			
b	2.5	in			
d	9.5	in			

Wood Joists AJS 9 1/2 at 3rd, 2nd, 1st Floors Wood I beam					
Loads					
dead-flr	20				
dead-beam	7.751736111	psf	Load combin	=	129.30
Live Load	60	psf	LL	=	96
Trib Area**	3	psf	wu	=	387.91
b	2.5	in			
d	9.5	in			

Step Two: *Wood Stud Joists*

Check the size of the wood joists on the roof to make sure they can support the greenhouse load when the greenhouse columns do not align with a load bearing wall. Below is a sample of the calculation used for all beam loading with loading and length changed to match the given beam to see if it could hold the loads at that given size. Use load resistance factor design and values from the Nation Design Specification for Wood Design for this calculation (AWC, 2018).

Wood Joists 2 x 8 at ROOF Assuming Spruce pine

Loads							
Dead-roof	56	psf					
dead-beam	2.265625	psf	Load combin	=	139.92		
live roof	25	psf	wu	=	174.90		
snow	35	psf	Mmax	=	1071.25	lb-ft	
wind	28	psf	Mmax	=	12855.03516	lb-in	
Trib Area**	1.25	ft	V	=	612.14	lbs	
Fb	875						
Fv	70		Deflections				
Fc	1150		Live	0.4666666667	>	0.000225041990	
E	1400000		Snow	0.4666666667	>	0.000315058786	
Emin	510000		Dead+Live	0.7	>	0.000085621444	
Length	7	ft					
Inertia XX	47.63	in^4	Stress of beam				
b	1.5	in	Bending Stress	fb =	978.3132		Fb
d	7.25	in				Cm	1
A	10.88	in^2	Design Strength of Beam			Ct	1
Sxx	13.14	in^3	Fb'	1919.6352		Cl	1
			E'min	484500		Cf	1.2
						Cfu	1.15
						Ci	0.8
						Cr	1.15
						Kf	2.16
						Lambda	0.8

Step Three: *Load Bearing Stud Walls*

Check the size of the load bearing stud walls make sure they can support the greenhouse load. Below is a sample of the calculation used for all stud wall loading with loading and length changed to match the given stud wall to see if it could hold the loads at that given place. Use load resistance factor design and values from the Nation Design Specification for Wood Design for this calculation (AWC, 2018).

Stud Wall 2 x 6 4th Floor to Roof Assuming Spruce Pine Fir								
Loads								
gre-hse lds	26000							
dead-column	6.875	psf	Load combin	=	89.69			
Dead Jts&Flr	20	psf	wu	=	27789.28	lbs		
sq ft old roof	4405	ft^2		=	51.19			
dead-load solar	1.198637911	lbs						
solar panel wie	5280	lbs						
live roof	25	psf						
snow	35	psf	Stress of beam					
wind*	0	psf	Comp. Stress	fc =	842.0995			
Trib L -y	1.33	ft						
Trib L-x	15	ft					Fc	Emin&E
Trib Area	19.95	ft	Design Strength of Beam		LRFD	Cm	1	1
Fc	1150		Fc'	1468.34104		Ct	1	1
E	1400000		E'	1330000		Cf	1	
Emin	510000		E'min	726750		Ci	0.8	0.95
Length	10	ft				Cr		1
Inertia XX	10.718	in^4				CT		1.5
b	3	in				Kf	2.16	
d	11	in				Lambda	0.8	
A	33	in^2				Cp	0.9236243457	
Sxx	6.12	in^3				Fc*	1589.76	
Ke	1					Fce	5019.722813	
Le	10					sqrt	2.805072337	
c	0.8							

Stud Wall 2 x 4C 3rd Floor to 4th Assuming Spruce Pine Fir								
Loads								
gre-hse lds	26000							
dead-flr&jts	20							
dead-column	6.875	psf	Load combin	=	179.44			
Live Load	60	psf	wu	=	29364.47	lbs		
Up. Fl Load	51.19	ft^2						
Trib L -y	1.25	ft						
Trib L-x	15	ft	Stress of beam					
Trib Area	18.75	ft	Comp. Stress	fc =	889.8324			
Fc	1150							
E	1400000						Fc	Emin&E
Emin	510000		Design Strength of Beam		LRFD	Cm	1	1
Length	10	ft	Fc'	1468.34104		Ct	1	1
Inertia XX	10.718	in^4	E'	1330000		Cf	1	
b	3	in	E'min	726750		Ci	0.8	0.95
d	11	in				Cr		1
A	33	in^2				CT		1.5
Sxx	6.12	in^3				Kf	2.16	
Ke	1					Lambda	0.8	
Le	10					Cp	0.9236243457	
c	0.8					Fc*	1589.76	
						Fce	5019.722813	
						sqrt	2.805072337	

Stud Wall 2 x 4B 2nd Floor to 3rd Assuming Spruce Pine Fir								
Loads								
gre-hse lds	26000							
dead-Flr&jts	20							
dead-column	6.875	psf	Load combin	=	307.69			
Live Load	60	psf	wu	=	30615.33	lbs		
Up. Fl Load	179.44	ft^2						
Trib L -y	1	ft						
Trib L-x	15	ft	Stress of beam					
Trib Area	15	ft	Comp. Stress	fc =	927.7371			
Fc	1150							
E	1400000						Fc	Emin&E
Emin	510000		Design Strength of Beam		LRFD	Cm	1	1
Length	10	ft	Fc'	1468.34104		Ct	1	1
Inertia XX	10.718	in^4	E'	1330000		Cf	1	
b	3	in	E'min	726750		Ci	0.8	0.95
d	11	in				Cr		1
A	33	in^2				CT		1.5
Sxx	6.12	in^3				Kf	2.16	
Ke	1					Lambda	0.8	
Le	10					Cp	0.9236243457	
c	0.8					Fc*	1589.76	
						Fce	5019.722813	
						sqrt	2.805072337	

Step Four: *Steel beams*

Check the size of the steel beams on the 1st floor to make sure they can support the greenhouse load after it passes through the upper floors. Below is a sample of the calculation used for all beam loading with loading and length changed to match the given beam to see if it could hold the loads at that given size. Use load resistance factor design and values from the Steel Construction Manual for this calculation (AISC, 2017).

Steel Beams- W16x67, c,										
Loads										
grn-hse weight	26000									
Load above	40									
dead-flrs	20									
dead-beam	67		Load combinations	=	168.4000					
Live Load	40		wu	=	27148.5772					
Es	29000000		wt	=	26087.0000					
Iy	45		Mmax	=	410622.2302					
Tribitary Area	6.583									
Length	11									
Fy	50		Zx	=	109.4993	<	130			
Ix	954									
			Deflections							
			wl	=	10.9717					
								L/360		
			Delta L	=	0.0332	<		0.3667	<	1
			live load (cracking)							
								L/240		
			Delta T	=	0.3106	<		0.55000		

Step Five: *Steel Columns*

Check the size of the steel columns on the 1st floor to make sure they can support the greenhouse load after it passes through the upper floors. Below is a sample of the calculation used for all column loading with loading and length changed to match the given column to see if it could hold the loads at that given size. Use load resistance factor design and values from the Steel Construction Manual for this calculation (AISC, 2017).

C1- HSS 4x4, 3/8 thickness					
Loads					
dead-floor	10		Load combinatio	466.2240	
dead-beams	40	lbs	wu	93136.2560	lbs
dead-column	17.27	lbs		93.1363	kips
Live Load	40		Lc	10	
Snow load	35				
Grn-Hse	26000				
Es	29000	kips	KLx/rx	81.63265306	
Tribitary Area	144		KLy/ry	81.63265306	
Length y	10				
Fy	50	kips	Fe	42.90713053	
K	1		Fcr	30.7006294	
Length x	10		oFcr	27.63056646	
rx	1.47		oPn	132.0741077	kips
ry	1.47				
Ag	4.78				
rx/ry	1				

Appendix M: Space Specification

	Construction Type	Space Type	Condition Type
Retail Space	Proposed Construction First Floor	Personal Service Sales Area	Heated and Cooled
Office Space	Proposed Construction First Floor	Office - Enclosed	Heated and Cooled
Community Space	Proposed Construction First Floor	Office Common Activity Areas - Inactive Storage	Heated and Cooled
Water Closet	Proposed Construction First Floor	Electrical/Mechanical	Cooled
Mechanical Storage	Proposed Construction First Floor	Electrical/Mechanical	Cooled
Electrical Storage	Proposed Construction First Floor	Electrical/Mechanical	Cooled
Bike Storage	Proposed Construction First Floor	Bike Storage	Cooled
Laundry Room	Proposed Construction First Floor	Laundry- Iron and Sorting	Unconditioned
Bathrooms (First Floor)	Proposed Construction First Floor	Restrooms	Heated and Cooled
Vestibule	Proposed Construction First Floor	Lobby	Naturally Vented
Hallways	All Floors	Corridors	Unconditioned
Stairways	All Floors	Stairways	Unconditioned
Bedrooms	Residential Floors	Dormitory Bedroom	Heated and Cooled

Bathrooms (Residential Units)	Residential Floors	Restrooms	Heated and Cooled
Kitchen	Residential Floors	Food Preparation	Unconditioned
Living Room	Residential Floors	Living Quarters - Dormitory	Heated and Cooled
Closets	Residential Floors	Closet	Unconditioned
Pantry	Residential Floors	Pantry	Unconditioned

Appendix N: Construction Specifications

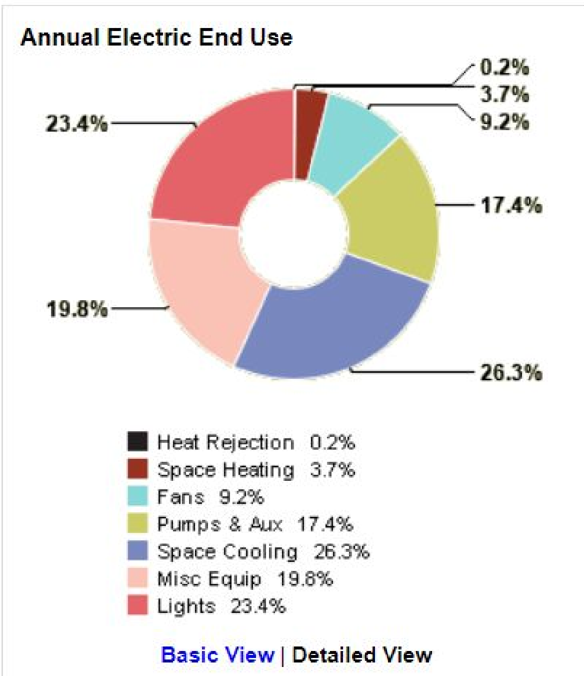
Scenario 1 Specifications	
Roof	Flat Roof C
Exterior Walls	Metal Curtain Wall w/ 2 in. Insulation
Interior Walls	Frame construction R-15 insulation
Ceilings	4 in lightweight concrete with false ceiling
Floors	Timber flooring, Batting Gypsum
Slabs	Standard Slab Construction
Doors	Metal
Exterior Windows	¼ single panes ⅜ in cavity
Interior Windows	¼ single panes ⅜ in cavity

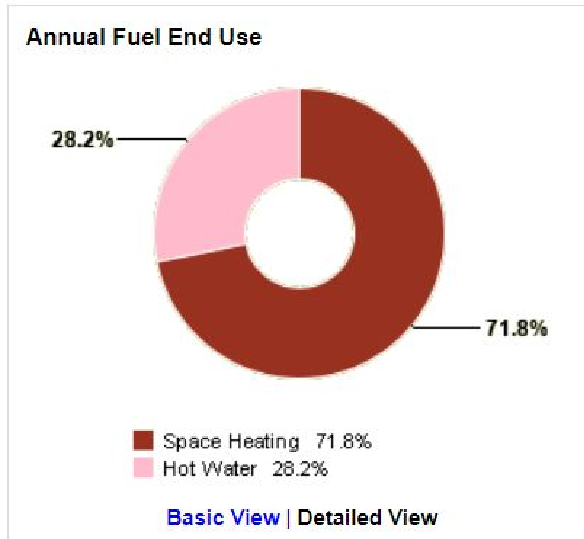
Scenario 2 and 3 Specifications	
Roof	Flat Roof C
Exterior Walls	Metal Curtain Wall w/ 2 in. Insulation
Interior Walls	Frame construction R-21 plus R-6 insulation
Ceilings	4 in lightweight concrete with false ceiling
Floors	Timber flooring, Batting Gypsum
Slabs	Standard Slab Construction
Doors	Metal
Exterior Windows	¼ single panes ⅜ in cavity
Interior Windows	¼ single panes ⅜ in cavity

Appendix O: BEM- Scenario 1

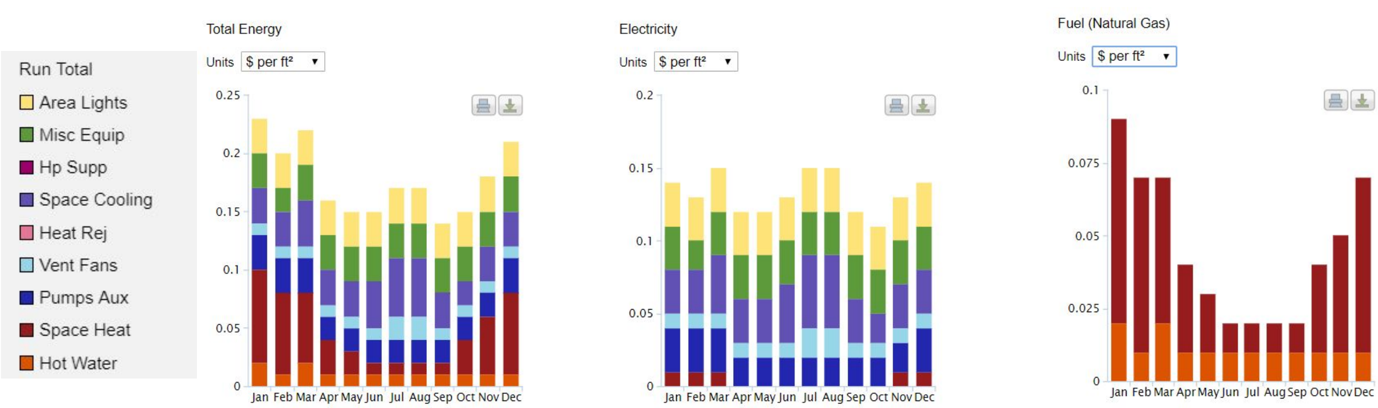
Due to the error while calculating square footage, energy values displayed in Table 7 are all multiplied by 0.75 to ensure the most accurate EUI.

Annual Energy Usage Charts





Annual Energy Cost Charts



Annual Water Usage and Cost

Water Usage and Costs

Total:	**2,951,123 Gal / yr**	**$17,323 / yr**
Indoor:	2,940,224 Gal / yr	$17,295 / yr
Outdoor:	10,899 Gal / yr	$28 / yr
Net Utility:	**2,951,123 Gal / yr**	$17,323 / yr

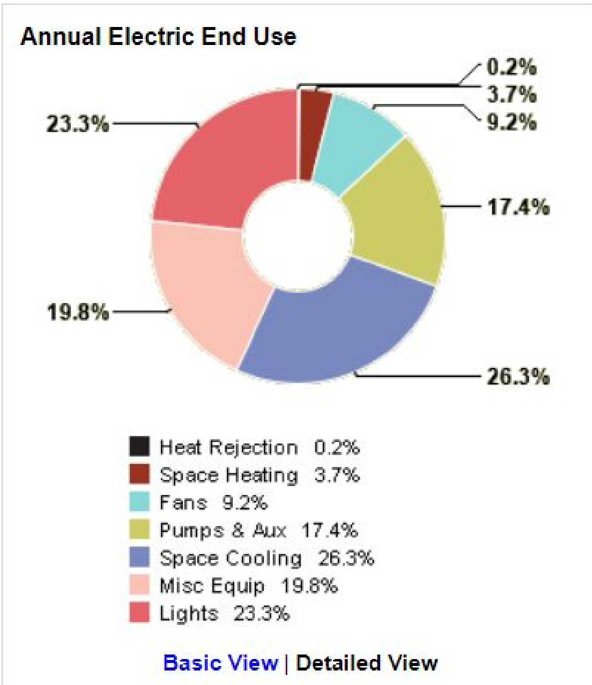
Source: AWWA Research Foundation 2000 Residential / Commercial and Institutional End Uses of Water.

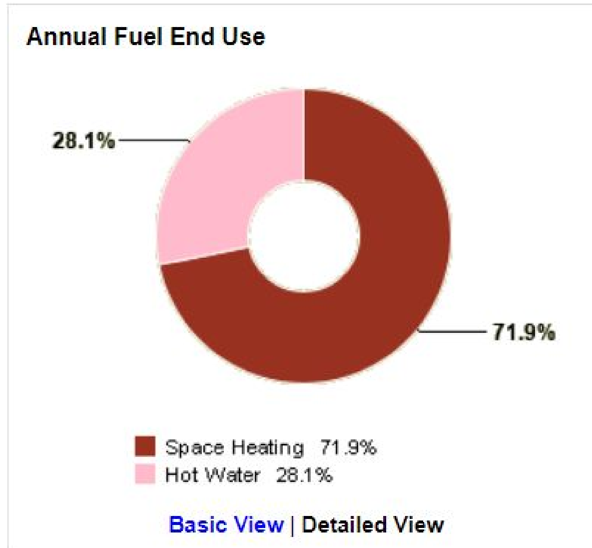
Building Summary						**Efficiency Savings**		
	Total	Male	Female	Employee Only	Efficiency	Percent of Indoor Usage (%)	Gallons per Year	Annual Cost Savings ($)
Toilets:	41	3	3	0	Standard	0	0	0
Urinals:	0	0		0	Standard	0	0	0
Sinks:	41	3	3	0	Standard	0	0	0
Showers:	31	0	0		Standard	0	0	0
Clothes Washers:	0				Standard	0	0	0
Dishwashers:	31				Standard	0	0	0
Cooling Towers:	1				Standard	0	0	0
☑ Include cooling tower blowdown in sewer costs					**Total Efficiency Savings:**	**0%**	**0**	**$0**

Source: 2000 Uniform Plumbing Code of the IAPMO, Tables 4-1 and 4-3.

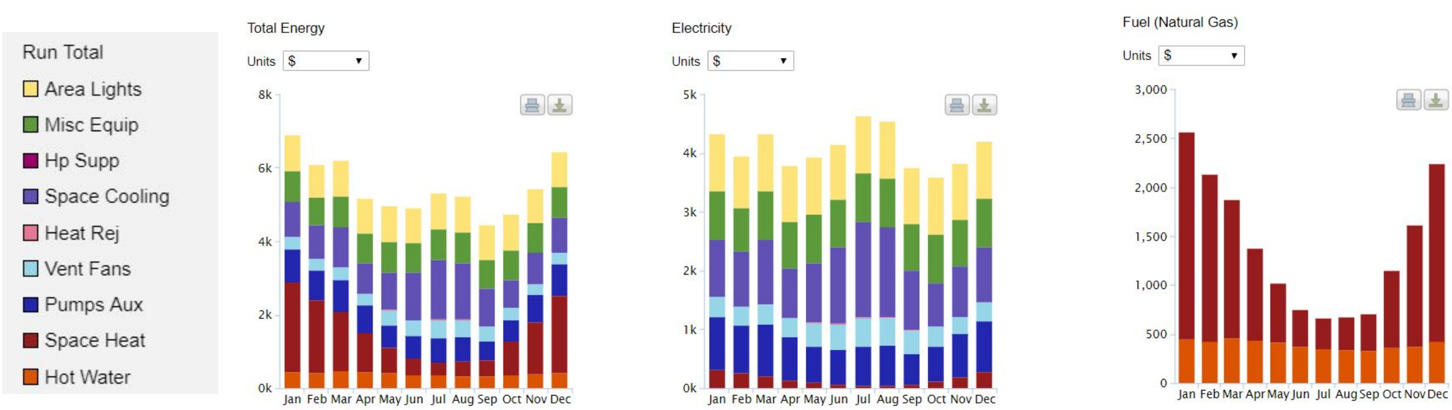
Appendix P: BEM- Scenario 2

Annual Energy Usage Chart





Annual Energy Cost Charts



Annual Water Usage and Cost

Water Usage and Costs

Total:	**2,345,243 Gal / yr**	**$13,640 / yr**
Indoor:	2,334,344 Gal / yr	$13,611 / yr
Outdoor:	10,899 Gal / yr	$28 / yr
Net Utility:	**2,345,243 Gal / yr**	$13,640 / yr

Source: AWWA Research Foundation 2000 Residential / Commercial and Institutional End Uses of Water.

Building Summary / **Efficiency Savings**

	Total	Male	Female	Employee Only	Efficiency	Percent of Indoor Usage (%)	Gallons per Year	Annual Cost Savings ($)
Toilets:	41	3	3	0	Low-Flow	13.5	395,061	2,402
Urinals:	0	0		0	Standard	0	0	0
Sinks:	41	3	3	0	Low-Flow	1.5	44,145	268
Showers:	31	0	0		Low-Flow	5.6	163,068	991
Clothes Washers:	0				Standard	0	0	0
Dishwashers:	31				Standard	0	0	0
Cooling Towers:	1				Standard	0	0	0
☑ Include cooling tower blowdown in sewer costs					**Total Efficiency Savings:**	**20.6%**	**602,274**	**$3,662**

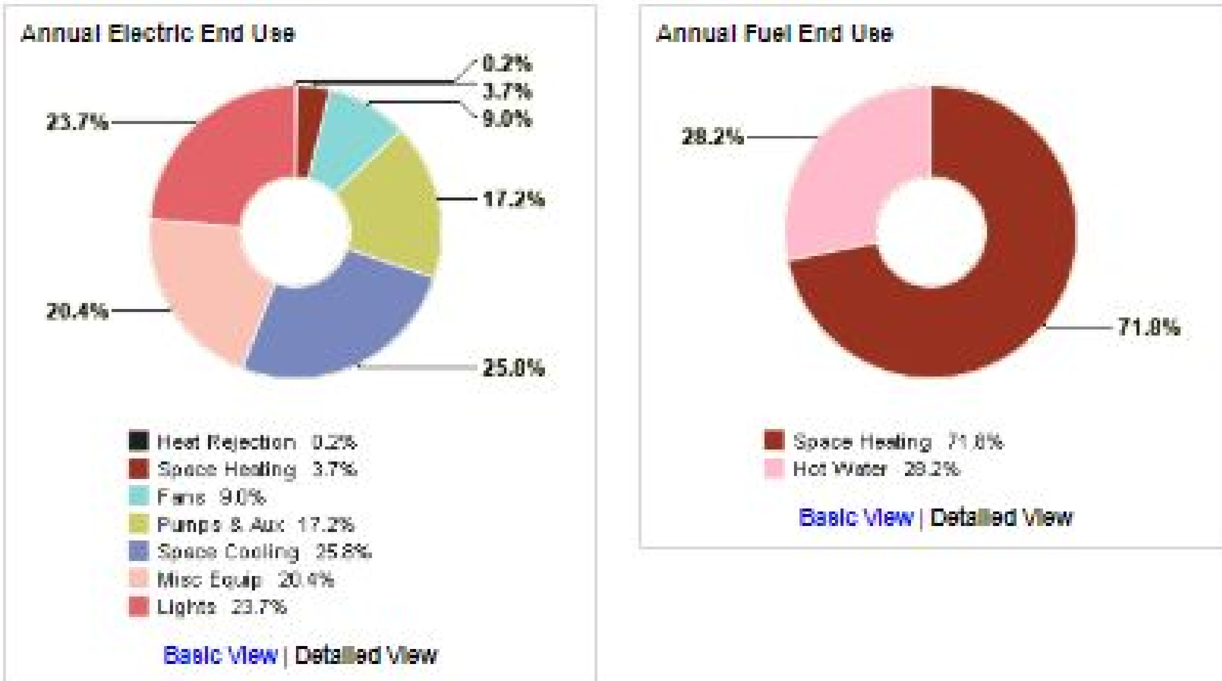
Source: 2000 Uniform Plumbing Code of the IAPMO, Tables 4-1 and 4-3.

Net-Zero Measures / **Net-Zero Savings**

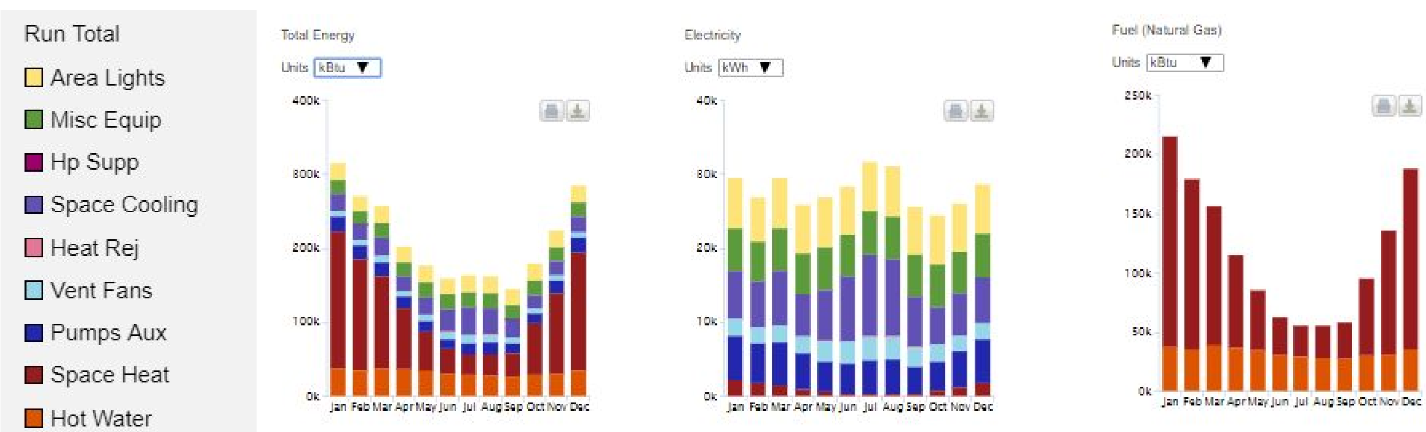
		Annual Rainfall (in)*	Catchment Area (ft²)	Surface Type	Gal / yr	Annual Cost Savings ($)
Rainwater Harvesting:	Yes	46.6923	7650	Concrete/Asphalt	200,387	521

Appendix Q: BEM- Scenario 3

Annual Energy Usage Chart



Annual Energy Cost Charts



Annual Water Usage and Cost

Water Usage and Costs

Total:	**2,330,108 Gal / yr**	**$13,548 / yr**
Indoor:	2,319,209 Gal / yr	$13,520 / yr
Outdoor:	10,899 Gal / yr	$28 / yr
Net Utility:	**2,330,108 Gal / yr**	$13,548 / yr

Source: AWWA Research Foundation 2000 Residential / Commercial and Institutional End Uses of Water.

Building Summary						**Efficiency Savings**		
	Total	Male	Female	Employee Only	Efficiency	Percent of Indoor Usage (%)	Gallons per Year	Annual Cost Savings ($)
Toilets:	41	3	3	0	Low-Flow	13.5	395,061	2,402
Urinals:	0	0		0	Low-Flow	0	0	0
Sinks:	41	3	3	0	Low-Flow	1.5	44,145	268
Showers:	31	0	0		Low-Flow	5.6	163,068	991
Clothes Washers:	6				Standard	0	0	0
Dishwashers:	31				Efficient	0.1	2,553	16
Cooling Towers:	1				Standard	0	0	0
Include cooling tower blowdown in sewer costs					**Total Efficiency Savings:**	**20.7%**	**604,827**	**$3,677**