Developing a Net-Zero Framework for the WPI Campus

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Joseph Howell, Aidan Mayer, Erika Wentz
Advisors: Soroush Farzin, and Leonard Albano
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Abstract

Climate change is causing many people globally to consider their energy consumption and how it could be decreased. To achieve this goal, many buildings are being designed as net-zero energy by implementing various energy saving strategies. This project investigates this goal on the Worcester Polytechnic Institute (WPI) campus. Campus-wide energy consumption was analyzed for developing baseline energy models. These models were created based on existing building plans, and energy analysis was conducted by implementing strategies and determining the energy savings across the WPI Quadrangle (Quad). From this analysis, recommendations were given for which strategies to implement at WPI, and a modular solar canopy was designed to be implemented across campus.

Acknowledgments

We would like to thank our advisors Professor Soroush Farzin and Professor Leonard Albano for their feedback and continual support during the completion of this project. The help and insight they provided throughout the project were imperative to our success. Additionally, we would like to give a big thank you to William Spratt of WPI Facilities for all of the information he was able to provide toward our project. Bill was always willing to help and meet with us at a moment’s notice to supply necessary information, and we are grateful for all his help and guidance.

Design Statement

For this Major Qualifying Project (MQP) the architectural design process was utilized to fulfill the requirements needed to perform building energy analysis as well as structural design and analysis. Autodesk Revit, Autodesk Insight, Sketchup's Sefaira, RISA-3D, and AutoCAD-3D were all used to complete these goals.

For the architectural design of the case study, construction documents from WPI Facilities and aerial map images from Google Earth were imported into Revit and utilized to create mass models of each of the case study buildings. Each case study building was then separated into individual Revit models, and detailed building elements were added through examining the given construction documents.

For the energy analysis of the case study, the two Revit plugins Autodesk Insight and Sketchup's Sefaira were used. Autodesk Insight was used to perform a solar analysis of the case study as well as to investigate solar energy potential. Both Insight and Sefaira were then used with each of the individual building Revit models to perform a baseline energy analysis, and four separate energy improvement analyses.

For the structural design and analysis, RISA-3D was used to perform structural calculations and member sizing. RISA was able to simulate multiple load cases on the structure so that the design could be proven to sustain all possible conditions. AutoCAD-3D was then used to develop an architectural model of the structural system which was then imported into the Revit model.

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Executive Summary

With buildings producing up to 39% of energy-related emissions, the concept of net-zero energy has grown. Net-zero energy is defined as a building generating all of its own energy resources, or only consuming the amount of energy that it is able to produce. This project examines the feasibility of implementing net-zero energy strategies on the Worcester Polytechnic Institute (WPI) campus. WPI has begun to implement sustainability goals and focus on energy savings strategies across the entire campus. With the buildings across the campus greatly ranging in age (from being built in 1868 to 2018), the systems in place vary, and the information available for each individual building's usage is limited. Many buildings on the main campus are linked together through a main electricity and steam loop, which limits analyzing the usage and areas to improve. While it is a complex and expensive process to bring everything to net-zero energy, the building proximities, combined with their existing connections, make WPI a prime candidate to analyze energy-saving strategies and conduct a net-zero case study.

Seven buildings were selected for a case study of the WPI campus. This case study was composed of buildings around the Quadrangle (Quad) with varying occupancies, ages, and energy consumptions. In order to conduct the energy analysis of these buildings, a baseline energy model was created using mass modeling in Autodesk Revit. The model of each building was then updated to show the realistic building elements and produce an accurate energy analysis when conducted. Baseline energy analysis was the essential step in determining the net-zero energy potential on the WPI campus. Using Autodesk Insight and SketchUp Sefaira, the energy consumption of each building was matched to the measured data from WPI.

In analyzing the available strategies that could be implemented within the case study on the WPI campus, solar energy production was at the top of the list. With the large open areas and

the terrain of the quadrangle area of campus, the solar potential is very high. To analyze the solar potential, PV panels were modeled on all the available roof surfaces, and a full-year PV panel analysis was conducted. Additionally, to utilize the solar availability elsewhere on campus a modular solar canopy was designed. This system would follow the sun's path throughout the day and year on a 2-axis system to generate the maximum amount of solar energy possible.

Four scenarios were investigated within the energy analysis, and the highest impact is from Scenario 3 – Mechanical and Electrical Upgrades, saving 39% of the case study's energy usage: rounding out to about $322,776 saved per year. Scenario 1 – Insulation Upgrades, saved the case study about 18%, equating to about $145,131 saved per year. Scenario 2 – Window and Shading Improvements, saved 6%, totaling about $51,366 saved per year. Integrating all scenarios showed about 65% reduction in total energy usage and $533,693 in savings per year. Adding solar panels to all available roof surfaces in the case study generated 563,357 kilowatts per year, which provides about $84,504 in energy savings each year. Implementing all scenarios and the solar arrays totals a 75% decrease in energy of the buildings around the quad (the case study).

Based on our analysis, the following recommendations for WPI have been developed:

1) *Sub-Metering:* WPI could invest in sub-metering all the buildings in order to have a strong understanding of the energy usage within each individual building. In order to move towards a net-zero energy goal, having an accurate picture of the existing conditions is essential to determine the optimum strategies and suitable technologies.
2) *Strategy Implementation*: WPI could implement the strategies outlined in Scenarios 1, 2, and 3 within the energy analysis in order to achieve goals for the sustainability plan. By

implementing these strategies through a phased approach, the school can optimize the benefits and costs of each strategy.

3) *PV Implementation:* WPI could invest in the roof-mounted PV panels and a Modular Solar Canopy outlined in this study. This would allow WPI to work towards their sustainability goal to implement renewable energy systems to produce a 25% increase of renewable energy production by 2025. The roof-mounted panels are optimized to produce the maximum amount of renewable energy for the selected buildings. For the modular canopy, an extensive cost analysis is recommended.

As institutions of higher education continue to work towards sustainability across their campuses, it is important to focus on energy reduction before energy production. To achieve this goal, many strategies including wall, roof, floor, and window insulation; lighting improvements; and window shading can reduce energy consumption up to the 75 percent as shown in this study. By first reducing energy with these strategies, the amount of energy that a community needs to generate is lower, making it easier to achieve net-zero energy. With further research and analysis, the last 25% of energy consumption could be offset through additional strategies or future innovations.

1.0 Introduction

Climate change has been an increasingly important issue across the world and many different agencies have started to combat this crisis. One of the biggest causes of climate change is the effects of society's carbon emissions, causing the average global temperatures to slowly increase. With humans across the world spending so much time indoors and the built environment growing, it is important to consider the design and construction process in the battle against climate change. In order to decrease the energy use and emissions produced by buildings, various "net-zero" technologies are being implemented through both active and passive energy saving or creating strategies. Within residential, commercial, or municipal construction these technologies are imperative to help the entire world work towards decreasing emissions and negative impacts around the globe.

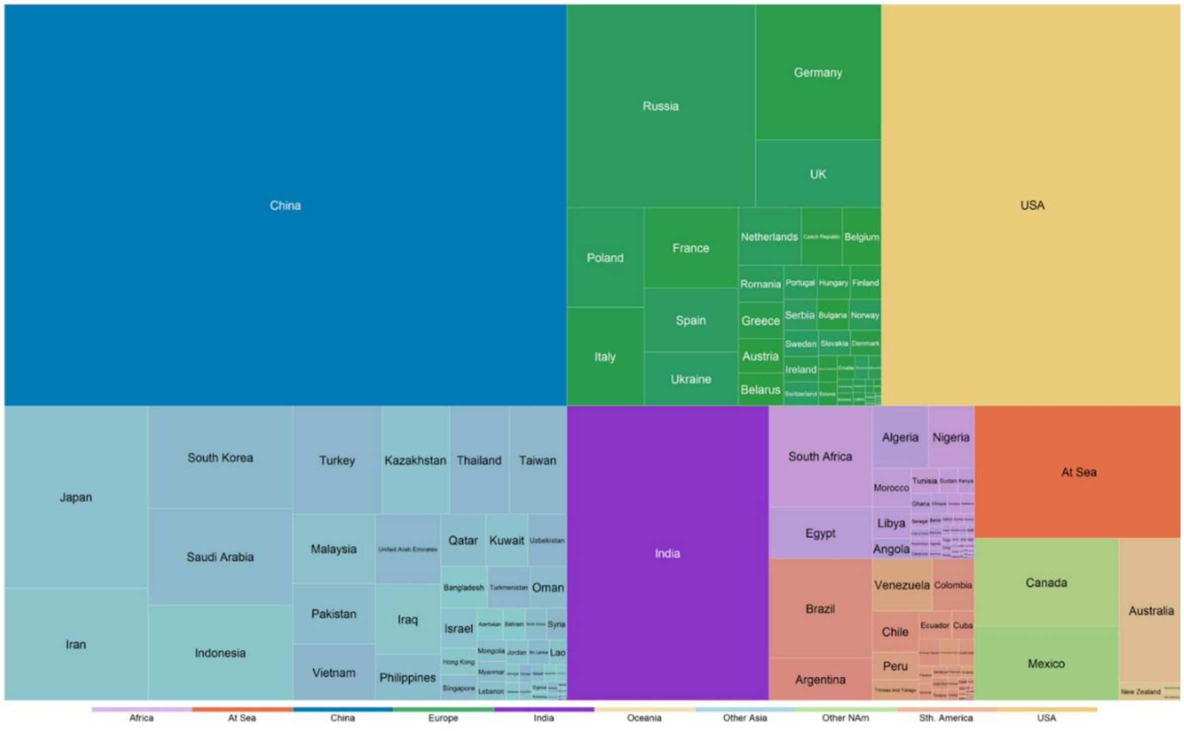
With a continuous effort from students and donors in higher education, many universities have begun transitioning to greener strategies for their buildings. The rise of Leadership in Energy and Environmental Design (LEED) certifications as well as net-zero has encouraged many universities to move their new construction in a sustainable direction and WPI has been following suite. Since 2006, any new construction on WPI's campus has been LEED certified, totaling five new energy efficient buildings in the past 15 years. However, the older buildings on WPI's campus are still higher energy users. In order to make an impactful change, WPI could explore the opportunities for energy efficient renovations within these older buildings.

Since 2014, WPI has been able to reduce its energy usage through many smaller projects focused on renovations. Through lighting updates and the additions of various occupancy sensors, WPI has begun the process of reducing its energy demand. With a more thorough energy analysis, WPI will be able to make a larger decrease in the campus's total energy consumption. By exploring where the most energy is being used and for what processes, WPI can identify the aspects of the campus that need attention and begin to decrease the energy usage.

2.0 Background

Humanity has known about climate change since the 19th century, and it continues to impact the world we live in today (Weart, 2020). In a 2017 study, experts found that the global temperature of the Earth has increased by 1.8 °F (1.0 °C) over the past 115 years. This is the warmest the planet has been during the known data of man (Wuebbles et al., 2017). This increase in global temperature has correlated to a rise of global challenges including melting polar ice caps, changing precipitation patterns, increasing heat waves and droughts, more frequent and devastating hurricane seasons, forest fires, and rising ocean levels (NASA, 2020).

Among the multiple causes of climate change, the most prominent contributor to the rising average global temperature is the greenhouse gases that originate from society's carbon emissions, and different agencies are beginning to take steps to combat this crisis. Figure 1, highlights the major contributors of carbon emissions broken down by country during 2018.



Source: Global Carbon Project

Figure 1: Breakdown of 36.6 Billion Tons of Carbon Dioxide Contributors in 2018 (Roberts, 2020)

As the president of one of the largest carbon dioxide contributors, China’s president, Xi Jinping, announced at the United Nations General Assembly, “Humankind can no longer afford to ignore the repeated warnings of Nature and go down the beaten path of extracting resources without investing in conservation.” Jinping then released China’s plan to completely achieve net-zero carbon emissions by 2060 (Pike, 2020). In the US, which is the second largest contributor to carbon emissions, California Governor, Gavin Newsom, announced an executive order that implements measures to eliminate emission from the transportation sector, including requiring all new car sales to be zero-emission by 2035 (The Office of Governor Newsom, 2020). With countries beginning to develop legislation and plans to become more sustainable, the next question is *how will they begin to achieve these goals?*

2.1 Built Environment and Climate Change

With countries around the world growing rapidly, it is important to monitor the sources of the world’s emissions and work to decrease it. A study done by CAIT Climate Data Explorer (Figure 2) identifies the number one sector contributing to greenhouse gas emissions is heat and electricity, at 30% of the total (Roberts, 2020).

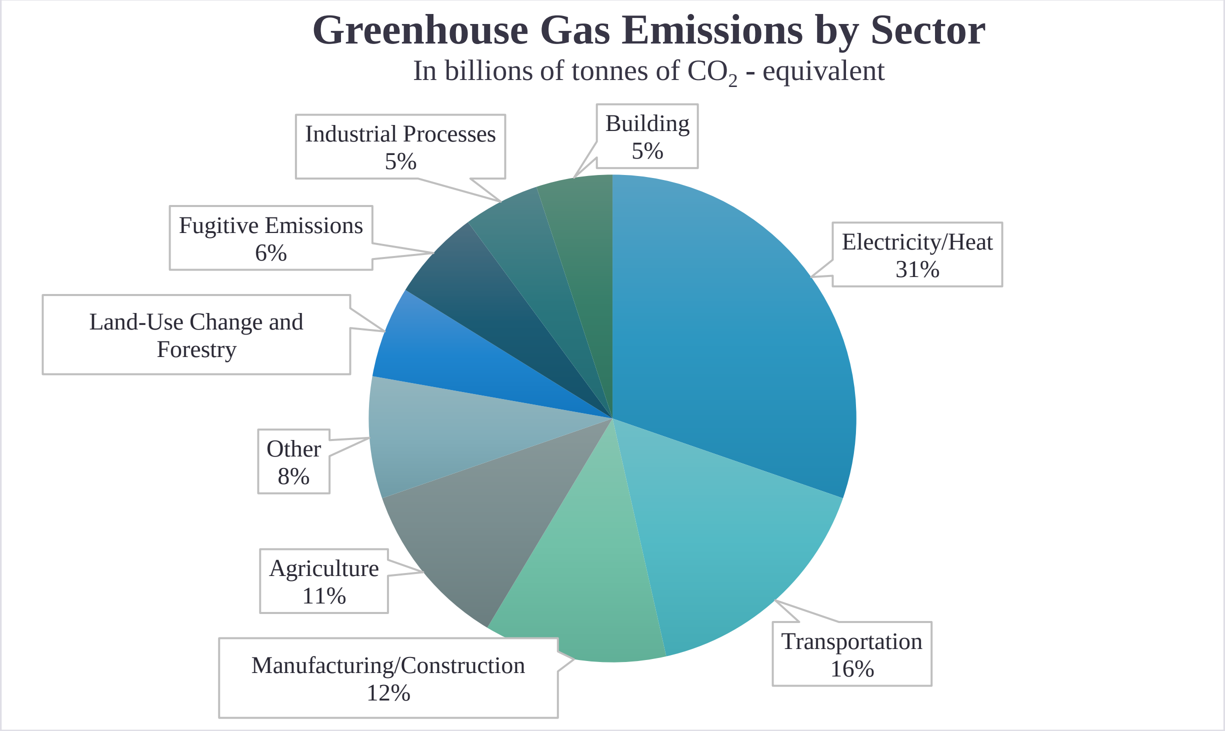


Figure 2: World Greenhouse Gas Emissions by Sector (Roberts, 2020)

On average, humans spend 90% of their lives indoors (US Environmental Protection Agency, 2018), and these buildings require a tremendous amount of energy to sustain this operation in addition to their initial construction. This includes the 12% manufacturing/construction, 6% land-use change and forestry, as well as 5% building, which adds up to a large portion of greenhouse gas emissions originating from buildings (Roberts, 2020). Within the last century, cities have become the forefront of human activity and it is estimated that 4 billion people currently live-in cities. This accounts for nearly 55% of the global population living in urban areas (Ritchie & Roser, 2018), which has huge impacts on the environment as buildings from design to completion account for 36% of global energy use, and 39% of energy-related emissions (Budds, 2019). Therefore, it is important to reconsider the design and construction process of our built environment by developing and implementing “Net-Zero energy” strategies as an essential solution for battling climate change.

2.2 Defining Net-Zero

Net-zero buildings are a way to reduce the impact that buildings have on climate change. Net-zero buildings generate all their own resources while reducing the overall energy consumption through different passive and active strategies. Passive strategies do not have any input from users; these can be site-specific strategies like the building orientation and landscape design, or building-specific strategies such as high thermal mass, passive shading, or window design (Steven Winter Associates Inc., 2016). Passive strategies do not need maintenance or operational energy to function. Active strategies, however, need some form of operational energy or maintenance to function. Some examples of active strategies are photovoltaic panels, wind turbines, or graywater reuse. Together these strategies can create a net-zero building or community.

There are many different approaches towards defining a net-zero building. Buildings can be categorized as net-zero energy, net-zero water, or net-zero emissions. This project focuses on the net-zero energy aspect of a net-zero community. The World Green Building Council defines a net-zero building as "*a building that is highly energy efficient and fully powered from on-site and/or off-site renewable energy sources*" (World Green Building Council, n.d.) while the National Renewable Energy Laboratory focused on four basic categories: net-zero site energy, net-zero source energy, net-zero energy costs, and net-zero energy emissions (Torcellini et al., 2006). These definitions, however, are only structured for individual buildings, not towards net-zero communities. In 2014, the U.S. Department of Energy Building Technologies Office in collaboration with the National Institute of Building Sciences defined a net-zero community as "*An energy-efficient community where, on a source energy basis, the actual annual delivered* *energy is less than or equal to the on-site renewable exported energy*" (Peterson et al., 2015). This was the definition used in this project.

2.3 Existing Net-Zero Buildings and Communities

Across the world architects and planners have shown the effect of net-zero technology by their implementation in numerous buildings. At Oberlin College, they constructed the Adam Joseph Lewis Center for Environmental Studies, an academic building designed to promote the growing field of ecological design, in which various strategies were implemented towards making the building net-zero. The architect's inspiration for the design was a tree, and not just the physical object, but the biological and chemical processes of a tree living off the light of the sun. The design philosophy looked at the biodiversity of nature, photosynthesis, and the use of waste to value other parts of the environment. The original construction of the building included the implementation of a 60kW photovoltaic roof which resulted in the production of over 100% of the building's required electricity. Additionally, the landscape within and around the building works to produce food for occupants and stimulate native ecosystems. Specifically, in the center of the building there is a Living Machine that filters water from the plants and other landscaping and recycles it throughout the building for non-potable uses. All these different systems within the building allow the occupants to continually study the science of ecosystems in addition to analyzing the ecological data of the building's performance (Oberlin College and Conservatory, 2020). Since the building's construction in 2000, there are continually renovations happening as building energy performance is more understood and analyzed. This includes the addition of a 100 kW PV roof over the adjacent parking lot which brought the building's net exports to the grid to 16,853 kWh per year (Zeiler & Boxem, 2013). These renovations allow the building to maintain its net-zero status.

The implementation of these net-zero systems within individual buildings yields great benefit but extending resources across multiple buildings can have an even larger impact. In recent years, net-zero technologies have expanded to residential, commercial, and even educational buildings. One example of this expansion is the planning and construction of Kaupuni Village in Oahu, Hawaii. This community is the first of its kind in Hawaii and is part of the Hawaii Clean Energy Initiative that was launched in 2008. The village consists of 19 single-family homes all designed for maximum efficiency and energy performance by the implementation of various features within each home's construction. There are many passive strategies in these homes including Solatube lights, insulated roofs, and shaded glazing, in addition to multiple active systems. The main system in each home is the PV panels on the roofs that power the high efficiency appliances, water heater, and an electric car plug-in. With the production of solar energy and the use of aquaponics for fish and vegetables, the members of this community are able to benefit from these features while also helping the State and Country as a whole. Within this project, the State of Hawaii has committed to achieving 70% clean energy by 2030, and this can be achieved through their aggressive energy goals and further implementation of neighborhoods like this (*Kaupuni Village: A Closer Look at the First Net-Zero Energy Affordable Housing Community in Hawai'i (Brochure)*, 2012). This community and the Adam Joseph Lewis Center are key examples of how resources can be used in various ways within a building to achieve net-zero status.

2.4 Existing Net-Zero Higher Education Campuses

Interdependencies and connections between buildings to share resources within a community can be applied to many other settings, including higher education campuses. Having buildings with a variety of usage categories, a campus is an ideal place to implement net-zero concepts: one building could benefit from the underutilized resources in another. The close proximities between buildings and shared schedules allow for the interconnection and sharing of resources between buildings even further. For example, if one building is in direct sunlight all day and does not use all the power generated by its PV panels, the power can then be redirected to a building that is within campus and may not have enough sunlight to generate its own electricity. In order to implement a net-zero campus there must be a significant amount of planning and coordination in addition to the necessary money and resources.

A study at the University of Basque Country, in Spain, investigated the ability to retrofit the School of Architecture in San Sebastian to be net-zero. This study examined the thermal comfort of the rooms in the building and used net-zero strategies to increase the student comfort in the room while decreasing the energy used. The heating demand in the building at the beginning of the study was measured within the range of 36.8 to 76 kWh/m^2 year (Irulegi et al., 2017). As the School of Architecture is an academic building, it sees much less activity during the summer months of June to August. With modifications to the natural ventilation in the summer as well as implementation of air-to-air heat recovery, elimination of thermal bridges, and addition of window improvements, the heating demand of the entire building decreased from 38.4 kWh/m^2 to 16.1 kWh/m^2 (Irulegi et al., 2017). Through using these net-zero strategies, the school was able to decrease the overall heating load while still ensuring the comfort of the occupants remained the same. This reduction is an important concept when looking at net-zero construction, and it shows the importance of energy reduction as a first step in achieving a net-zero campus.

The University of California (UC) has developed their Davis West Village campus to be net-zero by utilizing extensive planning and considering the different building uses. Through funding from the US Department of Energy, UC was able to develop a “130-acre West Village campus that provides housing for approximately 3,000 people in 662 apartments and 343 single-family homes,” in addition to both educational and research facilities (US Department of Energy, 2020). The residential facilities across campus contain many occupants who all use vastly different amounts of energy. To reduce the impact of residential energy use, individual net energy metering was investigated in order to provide residents with financial incentives, (Irulegi et al., 2017). The buildings within this campus follow energy saving design guidelines including building envelope construction and HVAC system design. But these systems are only saving energy, not producing any of their own, which is where the active strategies implemented on the West Village campus come into play. Across the entire campus, there is over 10 megawatts of solar-generated energy (UC Davis, 2020) as well as a campus Biodigester that uses campus waste to produce both gas and electricity to be redistributed and utilized in the buildings (*UC Davis West Village*, 2012). This campus is home to the University’s first Energy Hub in which energy research centers utilize the living laboratory of UC Davis West Village while working with the private sector. This provides the opportunity for innovation in the field of sustainability and inspiration for other campuses across the country and world. The incorporation and use of these different strategies across can not only help to decrease energy consumption but also provide additional benefits for the community around it. By looking at these case studies and examples of net-zero higher education, the campus of Worcester Polytechnic Institute can be examined to determine its net-zero feasibility.

3.0 Methodology

This project analyzed the WPI campus in terms of its energy usage and potential for implementing renewable energy. In this paper, various strategies were examined and applied to the selected buildings to show the impacts on reducing the campus' energy usage. The performance of a higher education campus varies greatly depending on the buildings' usage, occupancy, and age of buildings (Khoshbakht et al., 2018). By developing strategies and a framework for net-zero energy campuses, higher education buildings can utilize specific strategies that will benefit their campus while allowing for better energy coordination.

Multiple software tools were used for modeling and analysis including Autodesk Revit, Autodesk Insight and Sketchup's Sefaira. Revit was used to create mass models of different campus buildings and the built-in tool; Insight, was used for solar and energy analysis. To conduct a more thorough energy analysis, Sefaira was used for its analysis properties and recommendations properties. For the modular solar panel system, RISA 3D was used to model and design the structure, perform load analyses, and complete the structural analysis.

3.1 WPI Campus Background

Looking at the potential for sustainability on the WPI campus, the history of the campus was considered in order to create a wholistic view. The oldest building at WPI, Boynton Hall, was built in 1868 while the newest building, Foisie Innovation Studio, opened in 2018. Over these 150 years, WPI has seen various building projects that renovate or replace parts of existing buildings along with new building construction. Throughout this time, WPI has become more environmentally conscious, with the newer buildings earning Leadership in Energy and Environmental Design (LEED) certifications. The general trend has been towards sustainability, but not all WPI's building are energy efficient.

When certain buildings were built, many of them were added to the existing electricity main that sits in Washburn Shops. Over the years, about 23 separate buildings were added to this main, with only 11 buildings sub-metered. Additionally, there is a similar style steam-distribution system around campus that heats 23 buildings. Table 1 shows a breakdown of the buildings that are on the steam loop and the electrical loop. It also indicates whether the building is sub-metered for electricity or not.

Table 1: WPI Campus Steam and Electricity Distribution by Building

Building Name	Year Built	Electricity from Main	Electrical Sub-meter	Heat from Steam Plant
Alden Memorial	1940	X	X	X
Atwater Kent Laboratories	1906	X	X	X
Bartlett Center	2006	X		X
Boynton Hall	1868	X	X	X
Campus Center	2001	X		X
Daniels Hall	1963	X	X	X
Foisie Innovation	2018	X	X	
Fuller Laboratory	1990	X	X	X
Goddard Hall	1965	X	X	X
Gordon Library	1967	X		X
Harrington Auditorium	1968	X	X	X
Higgins House	1923	X		X
Higgins Laboratory	1941	X		X
Kaven Hall	1954	X		X
Morgan Hall	1958	X	X	X
Olin Hall	1958	X	X	X
Powerhouse		X		X
Project Center	1902	X		X
Sports and Recreation Center	2012	X	X	X
Sanford Riley Hall	1926	X		X

Salisbury Labs	1889	X		X
Skull Tomb	1886	X		X
Stratton Hall	1894	X		X
Washburn Shops	1868	X		X

The buildings at WPI vary in occupancy and function; some serve as laboratories and others house students, but they all have something to offer to a community. The geographical location, close proximity between the buildings on the main campus, combined with their existing connections, make WPI a prime candidate to analyze energy saving strategies and conduct a net-zero case study. By first analyzing the current status of the WPI campus, a baseline model of the area around WPI's Quadrangle (Quad) was developed (Figure 3).

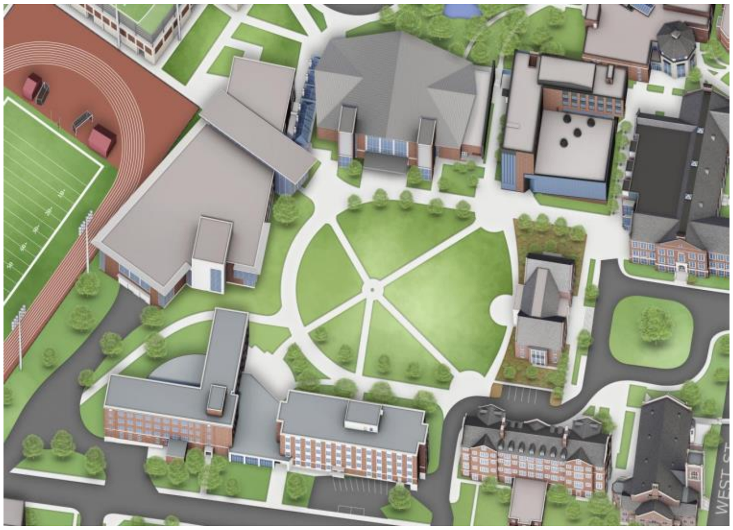


Figure 3: WPI Quadrangle Building Layout Diagram

Seven buildings were used as case studies to examine the feasibility of implementing net-zero energy strategies to the rest of the campus. The baseline model was used as a basis for implementing applicable net-zero energy strategies and measuring the impacts on the energy performance.

3.1.1 WPI Campus Energy Data

Campus energy data was examined from 2012 to 2019 while excluding the year 2020 in the analysis due to the coronavirus pandemic altering the regular energy loading patterns. When examining the total campus data, it was found that the energy usage of campus peaked in 2014 (Figure 4), which highlights a decline in energy usage since 2014 at a rate of 1-2% per year. In 2014, WPI began implementing energy management systems such as lighting retrofit projects and installation of occupancy sensors. This shows that a school can make an impactful change in their energy usage by implementing smaller systems.

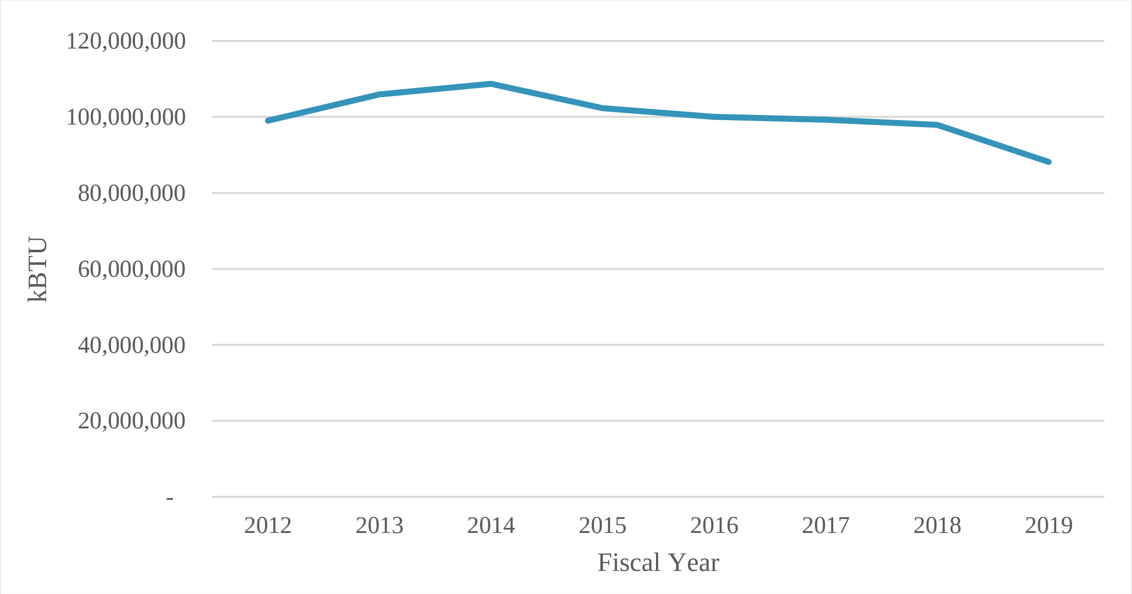


Figure 4: WPI Campus Yearly Energy Usage

Further, these values for total energy usage can be translated to the energy use intensity, or EUI, which represents how much energy the campus uses per square foot. Figure 5 shows the total campus EUI, compared to the total square footage per year. WPI has been able to decrease EUI by an average of 3% each year while campus square footage increased.

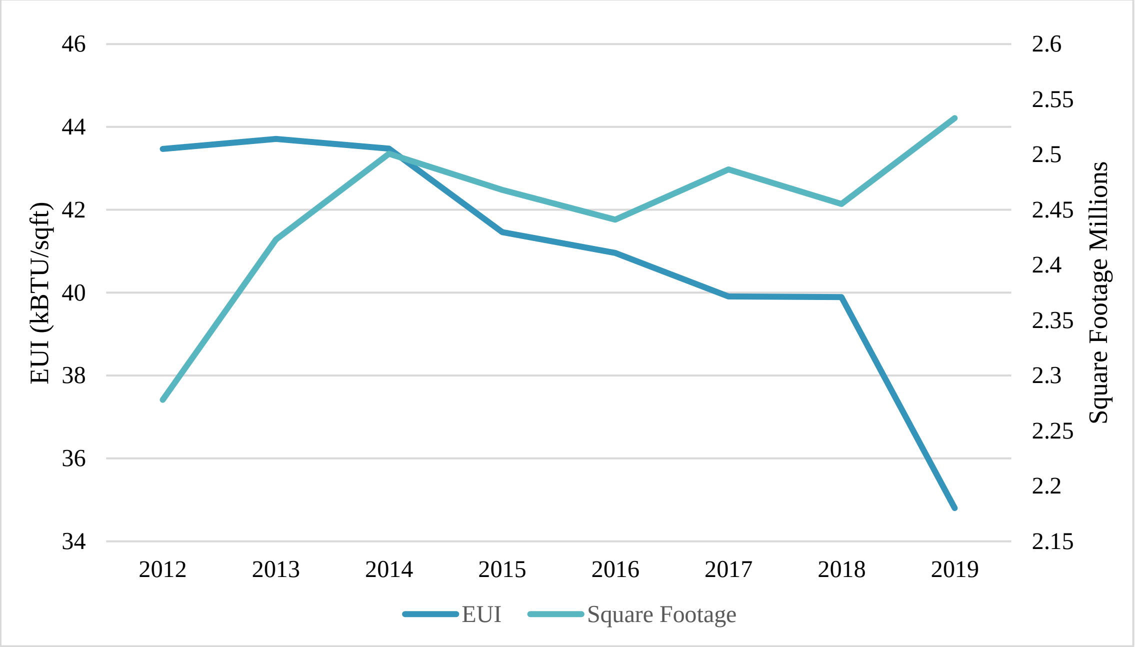


Figure 5: Total Campus EUI vs Square Footage per Year

In outlining the existing conditions of WPI's campus, an understanding of campus' area of improvements can be seen. This helps to determine where to apply net-zero energy strategies and outlines which buildings within the case study need the most help. By looking at the data of the whole campus in different ways, it helps set the stage for the analysis of the seven buildings in the case study.

3.1.2 WPI Case Study Energy Data

To begin looking at the WPI campus, a case study of select buildings needed to be chosen. Through evaluating different sections of campus, the Quad area was determined to be the best for this analysis because it consists of seven buildings with varying purposes and sizes. These seven buildings serve as an example of the campus to analyze the energy usage, evaluate potential net-zero energy strategies, and examine the coordination within various features. The selected buildings surround the Quadrangle (Quad): Harrington Auditorium, the Sports and

Recreation Center, Morgan Hall, Daniels Hall, Riley Hall, the Bartlett Center, and the Foisie Innovation Studio.

When examining the data from these seven buildings, there were various challenges, including limited energy data available and sub-metering. The energy usage for the remaining buildings was determined from other buildings with similar occupancy, age, and building assembly. Detailed information about the extrapolation can be found in Appendix A. With the energy usage per building determined through extrapolation, the EUI for each building was regenerated for the data collected in 2019 (Figure 6). With this comparison, the building with the highest energy consumption per square foot was identified as the Sports and Recreation Center. This data helped outline the current state of the buildings within the case study and highlighted which buildings need the most attention regarding net-zero energy strategies.

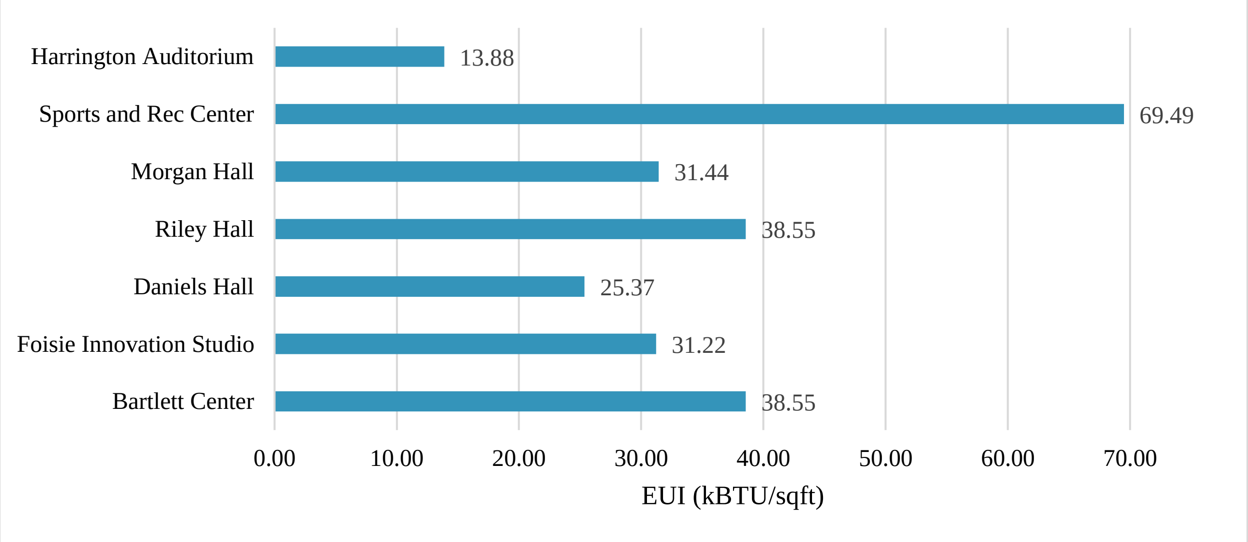


Figure 6: EUI Values for Case Study Buildings Based on 2019 Energy Data

When analyzing these EUIs, many of them fall well below the national average based on each building's occupancy classification (Energy Star, 2018). The Sports and Recreation Center, however, is the only building within the case study that is above the average. This shows that overall, the buildings within the case study have done well with reducing the energy usage but

WPI still has work to do to become net-zero energy. Table 2 outlines the current case study EUI compared to the national averages for each building.

Table 2: Case Study Buildings EUI Compared to National Average EUI

WPI Building	Occupancy Category	National Avg. EUI (kBTU/ft^2)	Actual EUI (kBTU/ft^2)
Harrington Auditorium	Public Assembly Recreation	50.8	13.88
Sports and Rec Center			69.49
Riley Hall	Residential Dormitory	57.9	38.55
Morgan Hall			31.44
Daniels Hall			25.37
Foisie Innovation Studio	Education College/University	84.3	31.22
Bartlett Center	Office	52.9	38.55

3.2 Baseline Energy Model

In order to complete an energy study of the WPI campus, a model was created in Autodesk Revit to conduct energy simulations and visualize the different features of the campus. Existing building energy data was used to verify the results from the energy simulations. The energy analysis programs used were Autodesk Insight and Sefaira, and both were used to utilize the various features and functions.

3.2.1 Create Baseline Energy Model

Autodesk Revit was used to create conceptual masses of the buildings. This simplified the creation of individual building models through a sketch and extrusion method, which can then be joined to other geometries and form the overall building shape. This method allowed for a simple analysis by creating spaces and general usage categories for the buildings rather than defining detailed specifications (e.g., wall types, floor types, mechanical systems). To begin modeling, all buildings within the case study, excluding the Foisie Innovation Studio and the

Sports and Recreation Center was created based on the plans and details provided by the WPI Facilities Office. The Foisie and Sports and Recreation Center models were formed from existing Revit models received from WPI Professor Sergio Alvares-Romero. These models were full models including all building and architectural elements, so it was imperative they were simplified to walls, windows, floors, and roof to conduct the energy analysis.

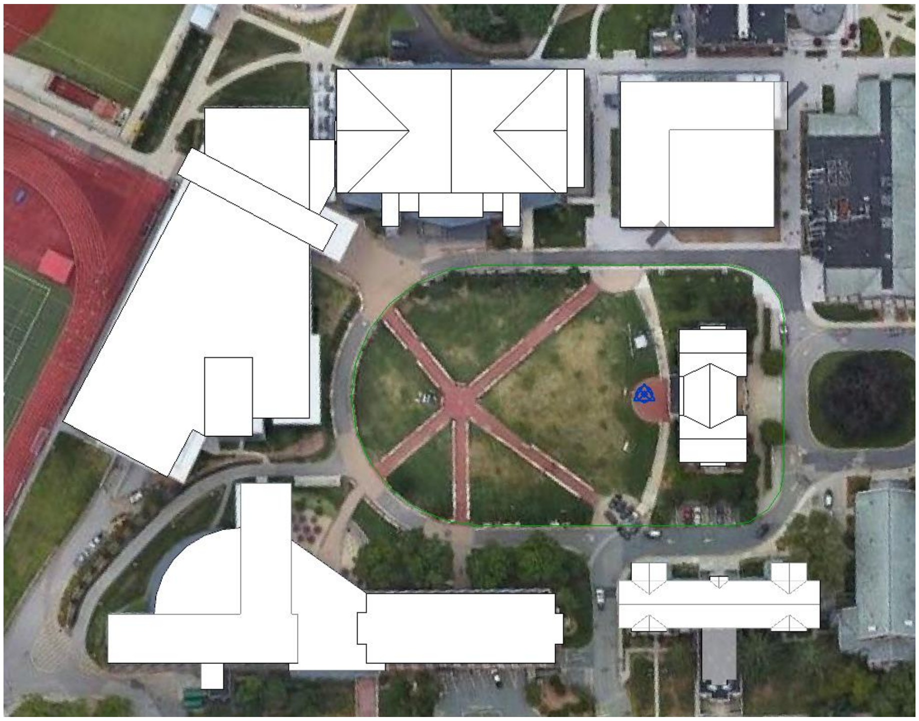


Figure 7: Site View of WPI Quadrangle Base Model

With all these models, a central file was created by linking the buildings and creating the campus model based on online satellite views (Figure 7). This model included the site and topography of the Quad, which was imported from Massachusetts GIS information, and using online maps the buildings were laid out across the site in their approximate relative locations to one another.

3.2.2 Implementing Existing Conditions into Model

In order to start the energy analysis and produce accurate results, it is imperative that the existing conditions of the campus and each respective building are put into each building model. To do this, the campus model (Figure 7) was divided into separate building models in order to accurately define the elevation heights, building materials, and floor plans. To conduct the energy analysis, each individual model needed to be updated. Each of these models specified the various wall, floor, and roof types, for each building, the interior spaces and their uses, and the HVAC system being used in the building. This workflow was followed for Daniels Hall, Morgan Hall, Riley Hall, Harrington Auditorium, and the Bartlett Center. For the Foisie Innovation Studio and the Sports and Recreation Center, models were provided as BIM models, transferred to Revit, and simplified for the energy analysis.

3.3 Net-Zero Strategies

Multiple strategies for energy reduction and production help to achieve the goal of net-zero energy, and they can be described on a spectrum of passive to active. Passive strategies are methods to save/conserve energy without any user input. Examples of these are building orientation and architectural design of walls or windows. Passive strategies exist on their own to create better energy efficiency without maintenance or alternative energy input. Active strategies, however, require maintenance or operational energy to function. Examples of common active strategies are wind turbines and photovoltaic panels. The strategies in between can be described as hybrid. They are more self-sustaining than many active strategies but still need some form of input, albeit lesser than some active strategies. Therefore, the hybrid class sits somewhere in the middle. As there are a variety of methods and strategies to develop net-zero energy buildings, the focus is to reduce the building’s load.

3.3.1 Strategies Matrix

In order to understand the available types of net-zero strategies and to organize them more clearly, six categories were defined: Solar, Flora & Fauna, Wind, Mechanical/Electrical Load Reduction, Water, & Geothermal. These groupings allowed for net-zero best practices to be categorized and within each category the strategies were placed into one of three subsections: passive, hybrid, or active. Through this separation, each strategy can be placed onto a matrix, using the subsections, that can then be implemented into a project. All these strategies, outlined in Appendix B, have unique features and may not be able to add value to all projects. The goal of this matrix is to show all the potential scenarios a project can take through providing a structure for selection of the optimized solution. Considering the WPI case study, there are multiple factors to consider: location, weather patterns, current energy data, building use, and sun exposure. Each of these elements had to be analyzed in order to pick suitable strategies. This matrix can be used by any project trying to achieve net-zero energy. A project can examine the six categories on the left side of the matrix and determine which they want to focus on. They follow the horizontal line to a gradient of active and passive strategies the project could implement. A project can pick one or more of these strategies as they will have differing impacts depending on the type of project.

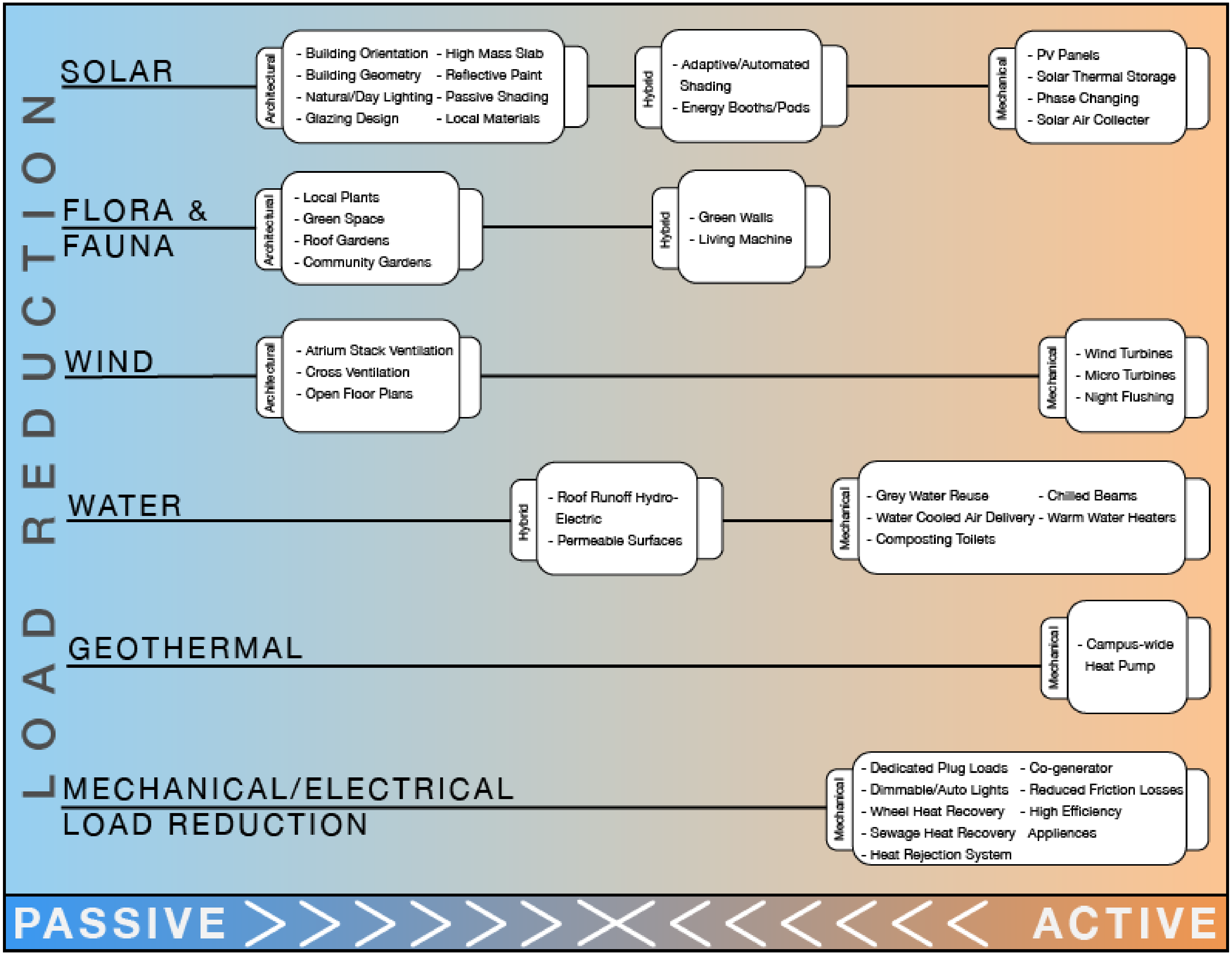


Figure 8: Active and Passive Energy Strategies

3.3.2 Applicable Strategies

Based on the research and data previously discussed, the net-zero energy strategies that will be focused on will be Natural/Day Lighting, Glazing Design, Passive Shading, Adapted/Automated Shading, Photovoltaic Panels, Ventilation, Dedicated Plug Loads, Dimmable/Auto Lights, Efficient HVAC Systems, and Photovoltaics were selected to explore on WPI case study.

Different design scenarios were explored using Insight and Sefaira for each building of the case study based on an initial optimization comparison created in each software. Within each building energy model, a variety of net-zero energy strategies from the above strategy matrix were implemented. A breakdown of the design enhancements that can be utilized within Insight and Sefaira are shown in Table 3.

Table 3: Energy Analysis Tools Comparison

Platform	Sefaira	Insight
Net Zero Design Strategies ****bolded** indicates utilized strategies	Envelope Design **Façade Glazing**, ***Walls***, ***Floors***, **Infiltration**, *Roof Glazing*, ***Roofs***, *Orientation* Shading **Horizontal Shading, Vertical Shading, Automated Blinds & Shades** Space Use **Design Loads, Design Temperatures, Ventilation & Outside Air, HVAC Schedule, Day Schedule** Air-Side **Central Outdoor-Air Handling Unit, Fan Coil Unit (Each Zone)** Water-Side **Chilled Water Loop, Heating Hot Water Loop, Condenser Water Loop** Natural Ventilation **HVAC Integration, Openness (Excludes Fixed Glazing), Window Control Options** Photovoltaic **PV Panel Efficiency, PV Panel Orientation, PV Panel Tilt, PV Panel Area** Zoning *Zoning Strategy*	Building Orientation Window to Wall Ratio *North, South, East, West* **Window Shades** **North, South, East, West** **Window Glass** **North, South, East, West** **Wall Construction** **Roof Construction** **Infiltration** **Lighting Efficiency** **Daylighting & Occupancy Controls** **Plug Load Efficiency** **HVAC System** Operating Schedule **PV Panel Efficiency**

3.3.3 Solar Energy Potential

A solar study was conducted to determine suitable roof surfaces for PV panel installation and solar power production. Using the local solar angle and the corresponding panel placement allowed for the most sunlight utilization throughout the whole year. The solar azimuth angle that was used was 48° (the angle in the Spring and Fall), to ensure maximum solar coverage throughout the year. The PV panels were then placed on all the available roof spaces (Figure 9) and Autodesk Insight's solar analysis feature evaluated the solar potential for all panels within a Full-year PV analysis.

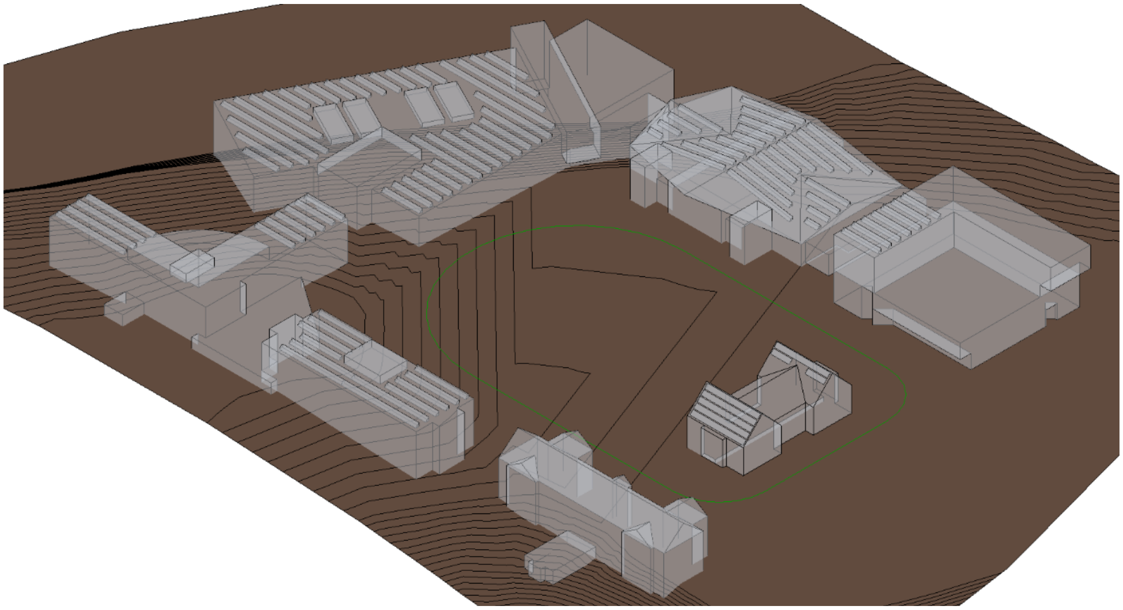


Figure 9: Campus Model with PV Panels Modeled on Available Roof Surfaces

3.3.4 Design of Modular Solar Canopy System

Due to the uneven terrain of the WPI campus, it was determined that a modular solar canopy system that could be placed in various locations would be the optimal solution. By having this design, the school will be able to construct it in any location they would like based on building locations, outdoor space usage, and shading. This modular solar canopy is designed on a two-axis system to follow the sun's path based on the azimuth and altitude throughout the day and year to ensure maximum solar efficiency and energy gain through the PV panels. The motor selection and mechanical assembly of the canopy are not described within this report but recommendations for the purpose and the needs are stated. The single column structural design allows this system to have a small footprint, and provides space underneath for various purposes, up to the school's discretion.

Looking into the structural design of this system, the main frame was derived from the Top-of-Pole Mounts, which is engineered and sold by Preformed Line Products (Preformed Line Products, 2021). These systems are not only listed with specifications, but the company provides a design tool to help isolate the specific mount that would be best for our panel configuration and the local conditions. Through this tool, the TPM4 Type H mount was identified, but due to the orientation given, the members needed to be rearranged to follow the landscape design of our canopy. Following the layout and structural configuration of this mount, a model was created with the structural analysis software, RISA-3D, and within this program the dead loads of the structure and panels, in addition to the live loads of snow, wind, etc. were used to assess the structural integrity of the canopy according to LRFD provisions. RISA provided sizing constraints for the members, and they were then sized accordingly, and a final structural model was created (Figure 10).

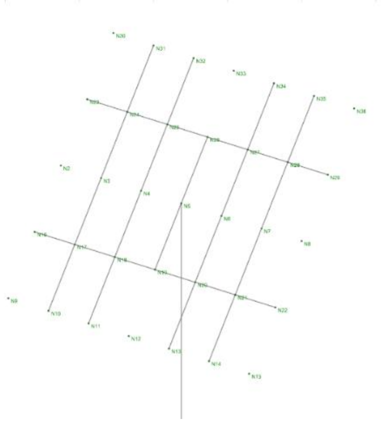


Figure 10: Canopy Structural Model

A focus within the design of the canopy was the architectural appeal for the community as it would be placed in open areas, which are limited in the Worcester area. In order to incorporate this modular system into the community, a tree-like design was implemented to surround the structural base. This was composed of zero-force telescoping members to ensure that the load path was restricted to the evaluated core structure, and the canopy could still move along the sun’s path as designed. With all this in mind, the final design for the canopy was produced and modeled in AutoCAD 3-D, and then imported to the Revit Model.

3.4 Conclusion

Each element of this analysis provided important results and, when incorporated into the WPI campus, created a framework for how the campus can achieve net-zero energy. By utilizing the base model created, a complete energy analysis of the buildings, various implemented net-zero energy strategies including a solar analysis of PV panels on the roof surfaces, and data comparison with strategy implementation, meaningful results bringing the seven studied buildings towards net-zero energy were discovered.

4.0 Results

After analyzing the campus model and the solar canopy, the following results were obtained. The energy analysis performed in Sefaira and Autodesk Insight highlights the places where the WPI campus could improve its energy efficiency. A solar study examined the solar potential of the campus case study. A modular solar canopy was designed, and a structural analysis investigated the structural capabilities of the design along with a high-level finical analysis.

4.1 Energy Analysis

To begin the energy analysis of the buildings, baseline data was modeled in Insight and Sefaira. This baseline data was adjusted to match the data measured by WPI Facilities so that energy improvements could be estimated using Sefaira. The resulting energy data from the simulations of each individual building were then summed together to form the total energy of the selected WPI campus buildings. This data was used to calculate the dollar cost and savings if the strategies were implemented.

4.1.1 Baseline Energy Analysis

In order to establish the baseline energy use, the available data from WPI Facilities was imported into each individual model. The goal for the accuracy of the modeled energy vs the measured energy was a five percent error. However, when importing the individual models into both programs, a notable discovery was found. With Sefaira, this goal was achieved through matching all known building type information about each individual building. The identical building information imported into Insight, resulted in drastically different energy data (Figure 11).

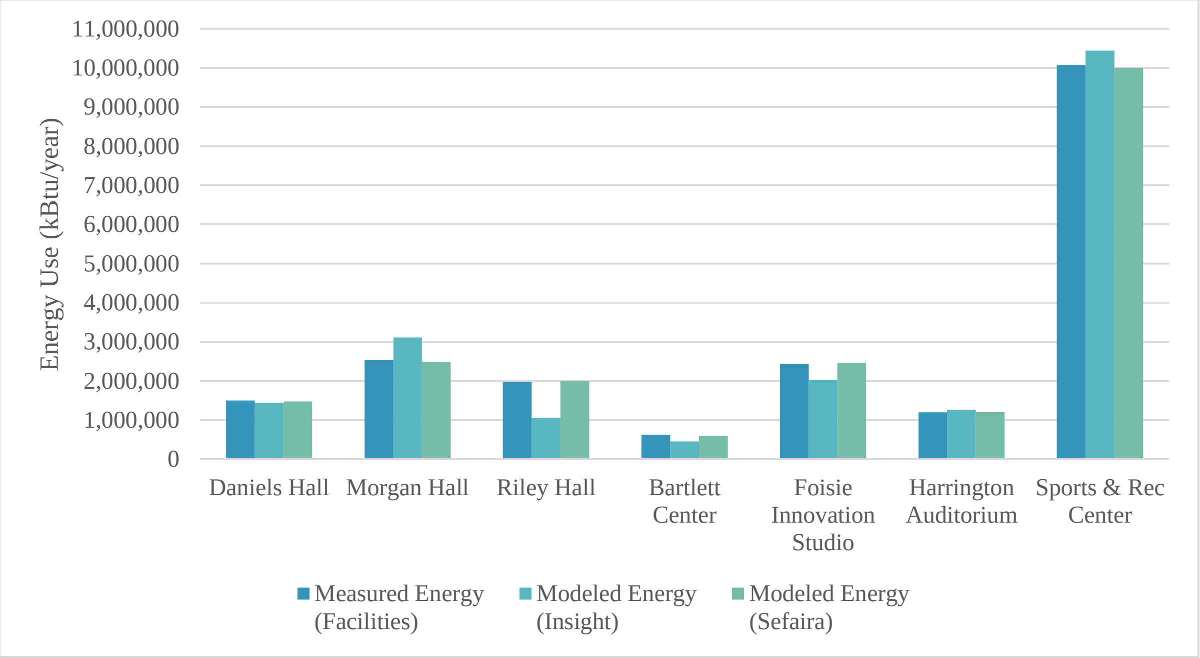


Figure 11: Measured vs. Modeled Baseline Energy Usage

When these results are summed together to form the final measured versus modeled baseline data for the selected portion of the campus, the average percent error that Insight produced was 18.1% whereas the average percent error of Sefaira was 1.5% (Table 4).

Table 4: Energy Analysis Percent Error in Insight and Sefaira for each Case Study Building

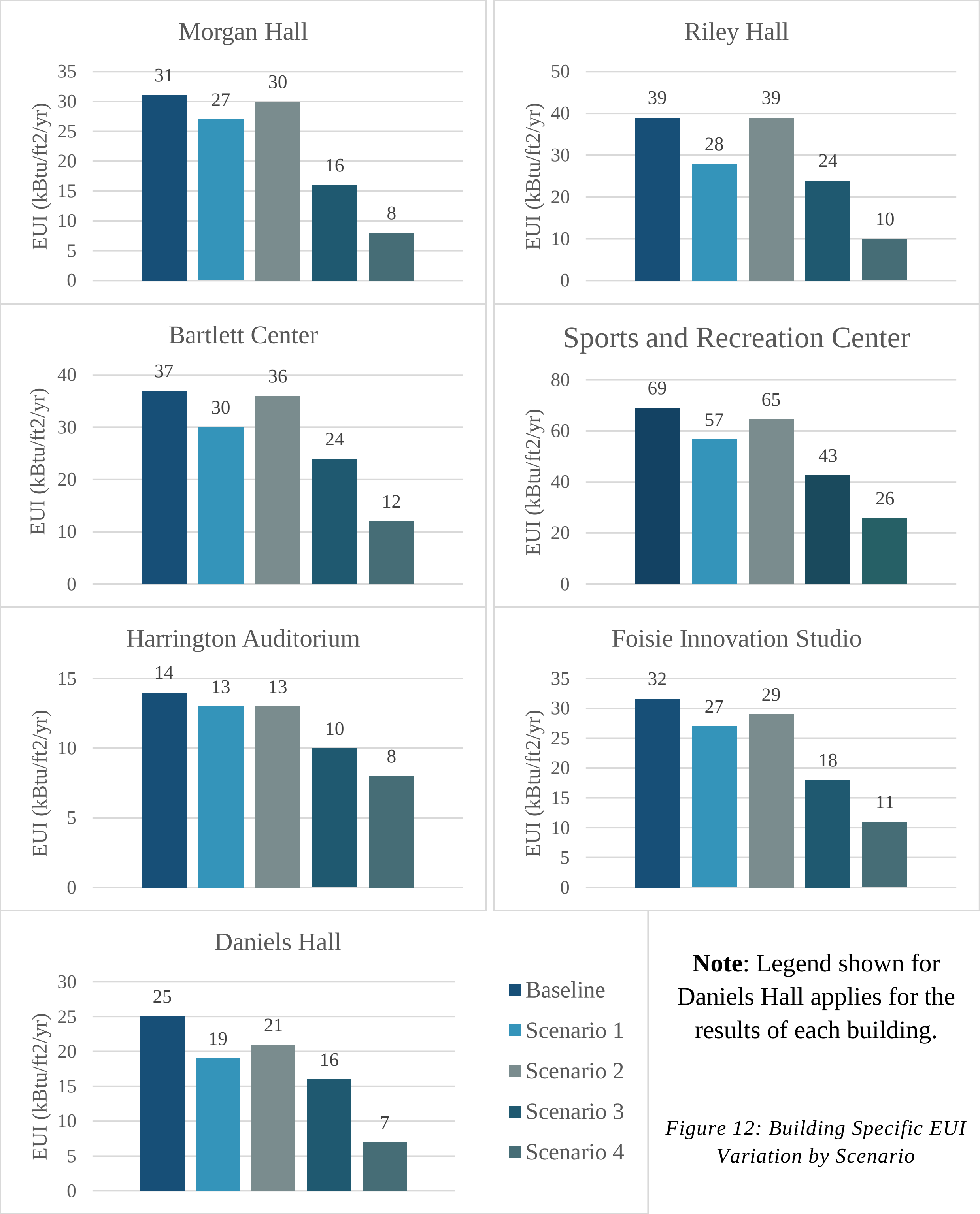
Modeled Building	Percent Error (Insight)	Percent Error (Sefaira)
Daniels Hall	3.9%	1.5%
Morgan Hall	22.9%	1.5%
Riley Hall	46.4%	0.7%
Bartlett Center	27.3%	4.0%
Foisie Innovation Studio	16.8%	1.2%
Harrington Auditorium	5.7%	0.5%
Sports & Rec Center	3.6%	0.8%

4.1.2 Individual Building Model Improvements

As result of a baseline model error in Insight, individual building energy improvements were investigated solely through Sefaira. In order to provide multiple forms of results, four scenarios for energy improvements were studied:

Scenario 1: Wall, Roof, & Floor Improvements
Scenario 2: Window and Shading Improvements
Scenario 3: Lighting and Energy Improvements
Scenario 4: Combination of Scenarios 1, 2, and 3

By implementing these scenarios on an energy model, the impacts of each set were measured (Figure 12). Through this, each scenario has its own results that identify how their implementation will decrease the total energy use. The strategies implemented within Scenario 3 result in the greatest decrease in EUI when implemented by itself in each building. With the major mechanical upgrades that come with Scenario 3, the buildings can actively decrease the energy that is being wasted by mechanical systems. But when all scenarios are combined (Scenario 4), the EUI is the lowest, as expected. With higher efficiency mechanical systems, better window, wall, roof, and floor insulation and more proactive shading, the buildings can dramatically decrease in EUI. The average decrease in EUI for all of the buildings in the case study was about 66%. These results for each individual building's EUI with each scenario's implementation are as follows:



Note: Legend shown for Daniels Hall applies for the results of each building.

Figure 12: Building Specific EUI Variation by Scenario

4.1.3 Total Campus Model Improvements & Savings

Combining the results for the individual buildings, the total potential decreases for the case study were determined. Each of the 4 scenarios allowed for a variety of solutions that all lead to reductions in total energy use. The total baseline energy for the selected portion of the case study is 20,226,036 kBTU/year. Figure 13 outlines the total energy savings generated from each scenario. Table 5 highlights the percentage decrease each scenario had on the case study. Scenario 1, the case study shows an 18% energy use reduction through insulation improvements. For Scenario 2, there is a 6% energy use reduction through implementing newer window systems and shading techniques. For Scenario 3, the case study shows a 39% energy use reduction through updating the efficiency of lighting and mechanical loads. Scenario 4, (combination of Scenarios 1-3), the selected portion of campus would see a 65% energy use reduction to 7,068,271 kBTU/year.

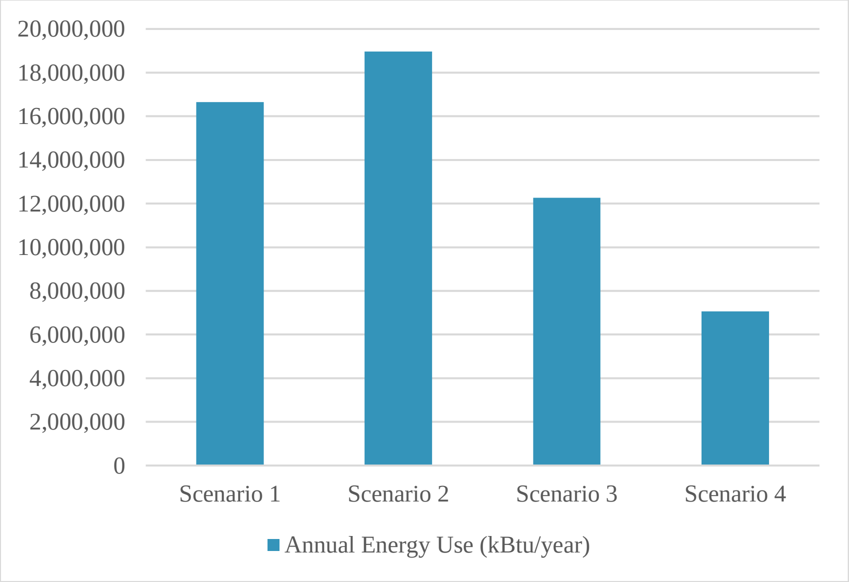


Figure 13: Final Energy Use for Each Scenario

Table 5: Percent Decrease in Energy for Each Scenario

Scenario	**Energy Percent Decrease**
1	18%
2	6%
3	39%
4	65%

Using this data alongside Worcester, MA electricity rates, a dollar cost savings for each scenario was calculated. Currently, WPI pays approximately $820,389 per year on electricity for the case study buildings. Figure 14 displays how much the energy of the case study would cost once the corresponding scenario is incorporated. Of Scenarios 1, 2, and 3, Scenario 3 would decrease the total energy costs of the case study buildings the most. Figure 15Scenario 3 would save WPI $322,776 per year (Figure 15). Through implementing Scenario 4 (combination of Scenarios 1-3) on each building, WPI would only pay $286,696 per year and save a total of $533,693 per year.

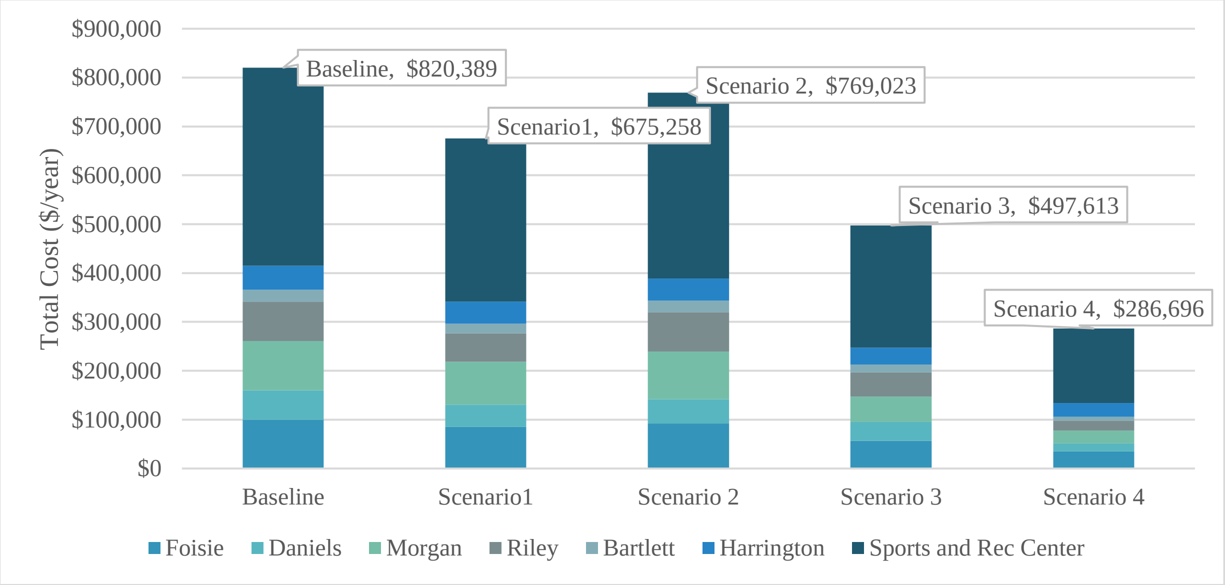


Figure 14: Yearly Costs per Scenario with Building Breakdown

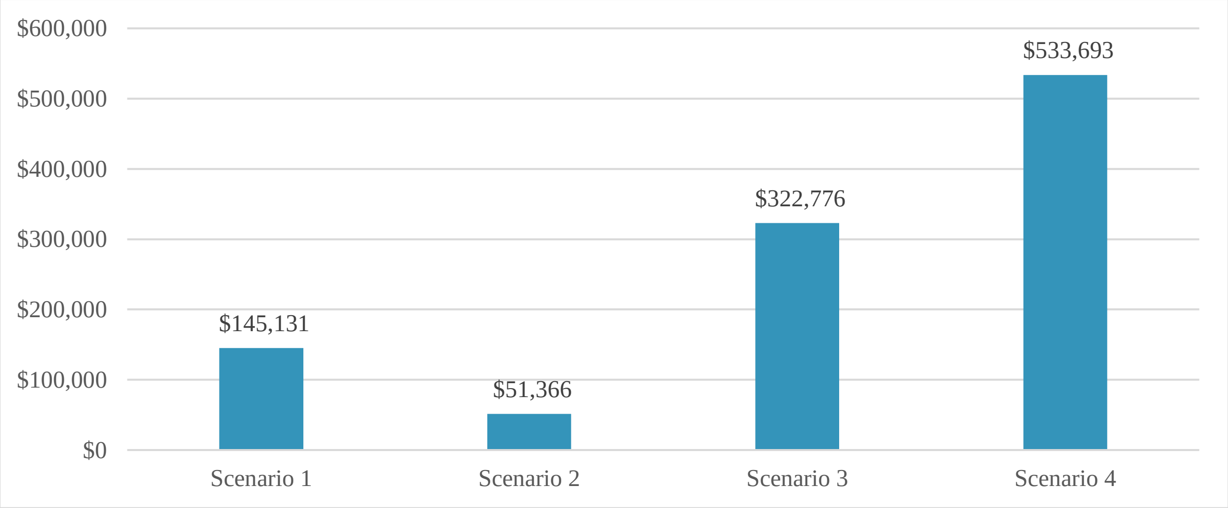


Figure 15: Yearly Campus Savings per Scenario

4.2 Solar Analysis

To begin the solar analysis, masses were created to model solar panels, and they were placed on the available roof surfaces of all the buildings in the area of focus. Figure 16 shows the solar potential of the panels in the case study analyzed on a gradient of kilowatt hours per square meter (kWh/m^2) of surface. This analysis showed that the panels generated a total of 563,357 kWh per year, which would provide about $84,504 in energy savings based on the cost of electricity in Worcester, generated by Autodesk Insight. This energy savings correlates to about 9.45% of the total electric energy usage for the buildings in the case study.

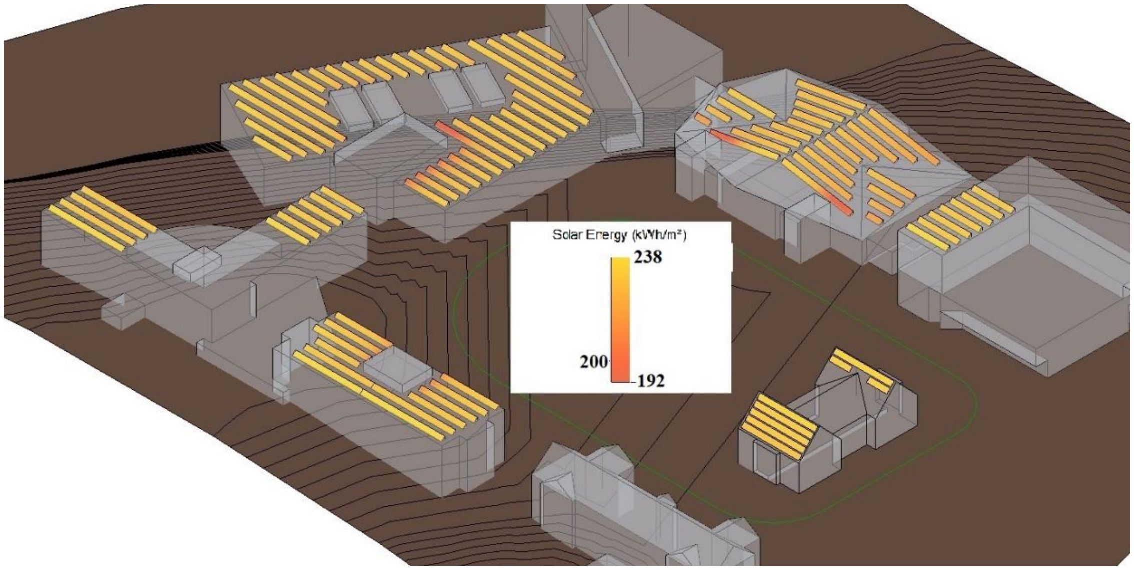


Figure 16: Solar Study Results Showing a Gradient of Potential Solar Energy

Despite producing such a small percentage of the electricity needed to make the buildings in the study net-zero energy, the panels still provide a lot of power comparatively. For reference, the average house uses between 10,000 and 12,000 kWh annually. This means the total energy produced in this solar study generates the electricity for roughly 50 homes. The results from this analysis are represented on a gradient (Figure 16), showing the solar energy produced per square meter from 238 kWh/m^2 represented by bright yellow and 192 kWh/m^2 represented in dark orange. The dark orange side of the gradient shows the shaded regions of the roof surfaces that would not receive as much solar energy, but they are able to produce a significant amount of energy. Despite the overall limited impact of PV panels on the WPI energy analysis, it is still a very valuable energy source and can be highly utilized in working towards a net-zero energy community or campus.

4.3 Modular Solar Canopy

To utilize the solar potential of the WPI campus, a modular solar canopy was designed to be placed in any location across the campus and produce electricity. This system will move with the sun throughout the year so analyses at the maximum summer and maximum winter angles were completed to determine the largest structural members needed for the canopy. The design of the canopy was focused on integration into the campus architecture while also producing energy for the campus.

4.3.1 Structural Design and Analysis

The focus for the design of the canopy was to provide a supporting structure for the PV panels in order to withstand the strong wind and snow loads present in the Worcester area. The structural frame of the canopy is outlined in Figure 17, in which the PV panels are mounted to the module rails, the loads are then transferred to the cross bars, and then to the main strongback. From the strongback, the loads are transferred to a single post, fixed in the ground to a footing.

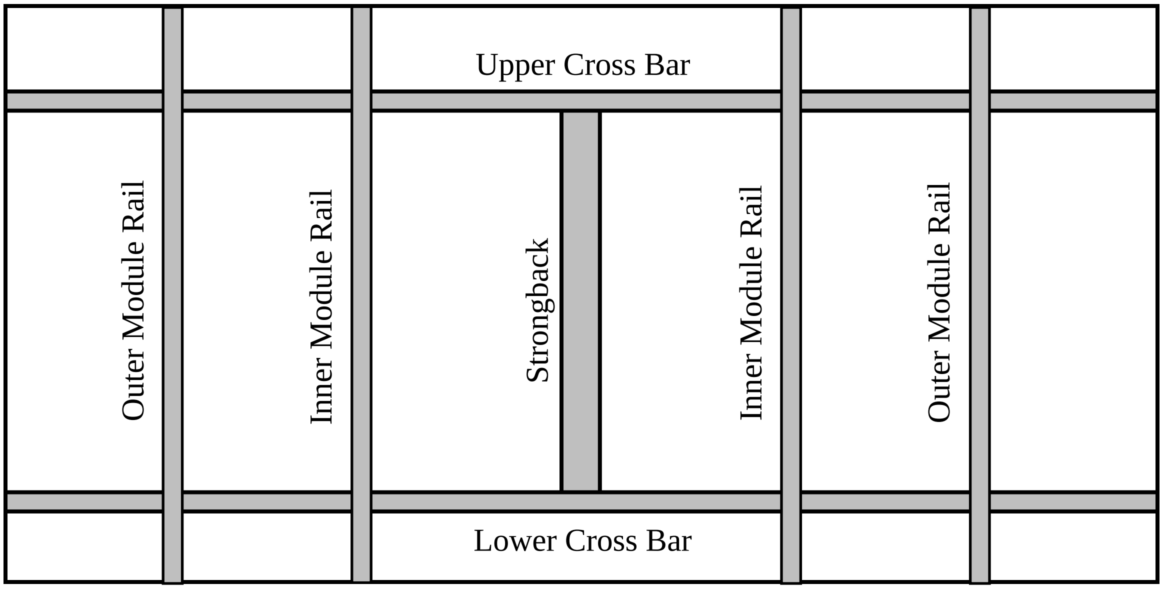


Figure 17: Structural Frame Sketch for Solar Canopy

The structural analysis for all these members was completed using RISA-3D and incorporated the following multiple load cases:

- Dead load of PV panels (DL) = 2 lbs/ft^2 (Matasci, 2020)
- Wind load (WL) = 16 lbs/ft^2 (analyzed both laterally and vertically, found in ASCE 7)
- Snow load (SL) = 50 lbs/ft^2 (Worcester ground snow load)

The load combinations used for this analysis followed the Load and Resistance Factor Design (LRFD) guidelines; they were the following:

1.2*DL + 1.6*SL + 0.5*WL 1.2*DL + 0.5*SL + 1.0*WL 0.9*DL + 1.0*WL

A batch analysis was conducted within RISA-3D to determine the most restrictive load combination, and the member sizes were determined for both the summer and winter based on this maximum loading. An HSS round pipe, sized at 6.625” x 0.188”, was defined for the main structural column for both the winter and summer load conditions. The sizes for all other members in each configuration are listed in Table 6 below, in addition to the maximum size required for the structure. The variation in sizing between the summer and winter angles is due to the different distribution of loads. For example, in the winter there is a heavy snow load with the panels at the steepest angle, so the Upper Cross Bar is sized to have a larger surface area (of 7”, compared to the 5” sized in the summer) to transfer the necessary loads through the structure. All members, excluding the column, were designed as HSS tubes, and the column to be an HSS pipe, to decrease maintenance necessary and reduce exposed surface area for both weather and wind concerns.

Table 6: Structural Members Sizes

	Summer	**Winter**	**Max Bar Needed**
Strong Back	5" x 2.5" x 2"	3.5" x 1.5" x 2"	5" x 2.5" x 2"
Upper Cross Bar	5" x 5" 2"	7" x 3" x 2"	7" x 3" x 2"
Lower Cross Bar	6" x 5" x 2"	6" x 4" x 2"	6" x 5" x 2"
Inner Module Rail	2" x 1" x 2"	2" x 1" x 2"	2" x 1" x 2"
Outer Module Rail	2" x 1" x 2"	2" x 1.5" x 2"	2" x 1.5" x 2"

A footing was designed to support the loads of the canopy at the ground, using the reactions at the base of the column. The controlling factor in the beginning of this analysis is the soil bearing pressure, and this was determined to be 5 tons per square foot for glacial till, per the Massachusetts Building Code, 9th edition. To calculate the base reactions, Allowable Stress Design standards were used, using the load following load combination: 1.0*DL + 1.0*SL + 0.75*WL. The reactions at the base of the column were a maximum vertical force (P) of 5.904 kips, a maximum lateral force of 0.838 kips, and a maximum moment (M) of 8.874 kip-feet. With these values, a footing was sized to ensure the both the soil bearing pressure and the footing would be able to support the loads. The minimum area of the footing, to not exceed the soil bearing pressure, would be about 0.59 square feet. Through the calculations, the eccentricity of both the force and moment was solved to be 1.503 ft (Figure 18). To keep this eccentricity within the kern of the footing’s base, the minimum size of the footing must be 9’x9’. To check the maximum compression, stress the beneath the base of the footing, the following equation was used: $q_{max} = \frac{P}{BL} * \left(1 + \frac{6e}{L}\right) \leq q_{allowable}$

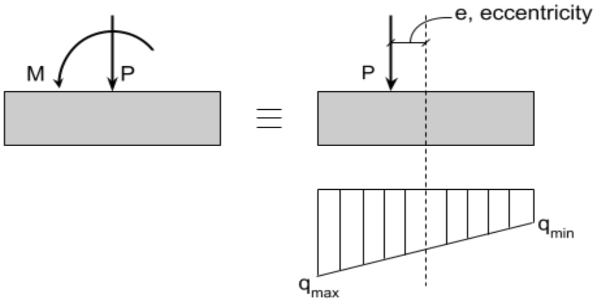


Figure 18: Footing Structural Analysis Diagram

Based on these calculations, the maximum soil stress under the 9’ x 9’ footing would be 0.146 kips per square foot, well under the allowable 10 kips per square foot defined by the local soil bearing pressure.

4.3.2 Architectural Concept

The solar canopy was designed based on the concept of a tree to ensure it would blend in with and be well incorporated into the WPI campus. With the flat surface of panels on the top of the structure, it was important to make the column and supporting structure follow the concepts in design (Figure 19). Using telescoping members and free-movement connections, branch-like members were added to the structure that will allow the panel to move freely along the lateral axis. These members were designed to be structurally negligible and have zero force within them as to ensure their movement would not hinder the canopy’s ability to follow the sun as designed.

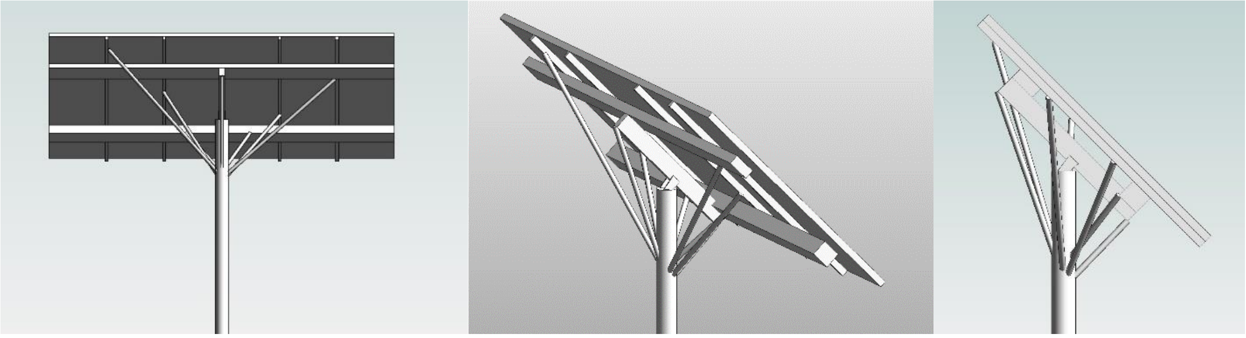


Figure 19: Views of Modular Canopy Architectural Model from Different Angles

4.3.3 Financial Analysis

The elements of the solar canopy are the footing, the steel support, the panels, and the zero-force members. Table 7 outlines the estimated cost of each element without labor costs. More information about how these prices were estimated can be found in Appendix C.

Table 7: Price Estimate of Solar Canopy

Component	Footing	Structural Steel	Solar Panels	Telescoping Members	TOTAL
Price	$1,352	$150	$608	$152	$2,262

With one solar canopy generating 1863 kWh each year, this translates to about $280 in energy savings that the single canopy will generate each year. With the entire system costing around $2,262, it will take just over 8 years for this solar panel to offset its initial cost. With the installation of multiple panels, there would be a reduction in the cost per unit because the university would be buying and manufacturing materials in bulk so the price of each component will decrease. This means that with less expensive units, the panels will be able to generate more savings per year and offset the initial cost earlier.

5.0 Recommendations

Based on the results and the analyses completed throughout this study, the following recommendations have been made. Understanding that the first step to move toward a net-zero energy goal is reducing energy usage, WPI can improve in a variety of ways.

First, WPI could invest in sub-metering all the buildings on the campus. In moving towards net-zero energy, the campus must understand the buildings that are the highest energy users before they invest in energy-saving strategies. To best understand electric energy consumption, having consistent annual data for every building on campus will help the school determine priorities for investment. Based on the data received from WPI Facilities, many of the miscellaneous buildings around campus that house a variety of student and faculty services are sub-metered in contrast to the largest academic and residential buildings. Only 11 of the 25 buildings (see Table 1 for details) on the campus electricity loop are sub-metered. With more reliable annual data from these buildings, WPI will be able to identify the highest energy users and can respond accordingly.

Second, WPI could implement Scenarios 1, 2, and 3 (4.1.2 Individual Building Model Improvements) into the WPI Green Revolving Fund to help achieve the goals of the WPI Sustainability Plan: 2020-2025. It is recommended that WPI phase in the different improvement scenarios over time in order to distribute the initial costs of implementation and optimize the necessary payback period. Based on the analysis, they could be implemented in the following order: Scenario 3 – Window and Shading Improvements, Scenario 1 – Wall, Roof, and Floor Improvements, and then Scenario 2 – Lighting and Energy Improvements. This order will allow WPI to implement the strategies that will provide the maximum energy saving as first step.

These stages will allow for WPI to work towards achieving two of the goals outlined in the WPI Sustainability Plan: 2020-2025:

- "WPI will continue energy efficiency projects producing a 10% reduction in KWH/FTE by 2025," (Worcester Polytechnic Institute, 2019).
- "WPI will reduce computing energy consumption producing a 20% reduction in KWH/FTE by 2025" (Worcester Polytechnic Institute, 2019).

If all three scenarios are implemented across campus, the total kWh/FTE of the campus could decrease from 3,500 kWh/FTE to 2,614 kWh/FTE, addressing both the goals outlined in the WPI Sustainability Plan. These values are based on the Full Time Equivalent (FTE) being equal to the number of hours worked by a single employee/student per week.

Third, it is recommended that WPI invest in the roof-mounted PV panels outlined by 4.2 Solar Analysis, as well as the modular canopy system outlined by 4.3 Modular Solar Canopy to contribute towards the renewable energy production goal in the WPI Sustainability Plan: 2020-2025:

- "WPI will implement additional renewal energy systems on campus producing a 25% increase in KWH of renewable energy production by 2025, " (Worcester Polytechnic Institute, 2019).

The roof-mounted PV panels shown in Figure 16 will produce the maximum amount of solar energy for the selected buildings on WPI. For the modular canopy system, it is also recommended that the cost and payback period are analyzed when constructing multiple at one time.

6.0 Conclusions

As higher education campuses continue looking more towards sustainability, they could consider the following points. When looking to become more efficient, a campus could focus on reducing total energy usage. Wall, roof, floor, and window insulation along with lighting replacements and window shadings reduced the WPI case study’s energy consumption by 75% and can do the same for buildings across various climates and building types. Campuses could focus on reducing energy before they work on producing their own. If this is considered, then they will have a lower threshold to reach when installing solar panels or implementing other green energy strategies.

In examining net-zero energy, this case study did not achieve net-zero energy. However, there was a 75% reduction in energy usage. A future study could examine implementation of different net-zero energy strategies such as improvements of HVAC systems, wind power, geothermal energy usage, and even future strategy innovations. With further research, the remaining 25% of energy within this case study could be decreased and the WPI Quad could achieve net-zero energy usage.

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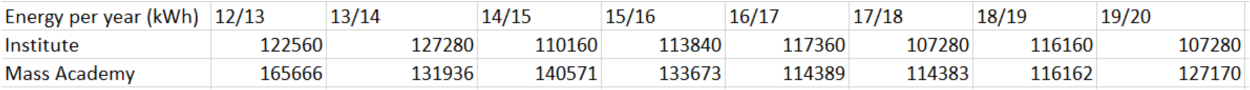
Appendices

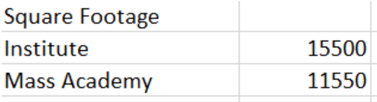
Appendix A

This section reviews information about how the WPI data was extrapolated to solve for the case study buildings.

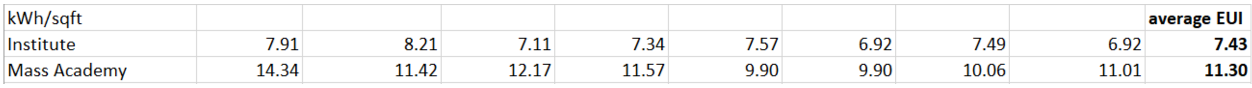
Both Daniels and Riley were modeled off Institute Hall's energy; another residence hall that had multiple years' worth of data. The Bartlett Center energy was extrapolated from the Mass Academy data. Both buildings have similar daytime occupancies. When extrapolating the data, the EUI of both Institute Hall and Mass Academy was solved for and then applied to the respective building in the case study to determine the building's total energy usage.



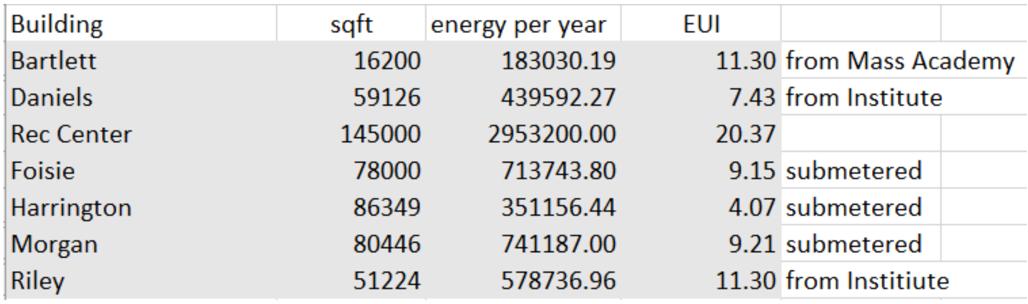
Energy per year (kWh)	12/13	13/14	14/15	15/16	16/17	17/18	18/19	19/20
Institute	122560	127280	110160	113840	117360	107280	116160	107280
Mass Academy	165666	131936	140571	133673	114389	114383	116162	127170



Square Footage	
Institute	15500
Mass Academy	11550



kWh/sqft									average EUI
Institute	7.91	8.21	7.11	7.34	7.57	6.92	7.49	6.92	**7.43**
Mass Academy	14.34	11.42	12.17	11.57	9.90	9.90	10.06	11.01	**11.30**



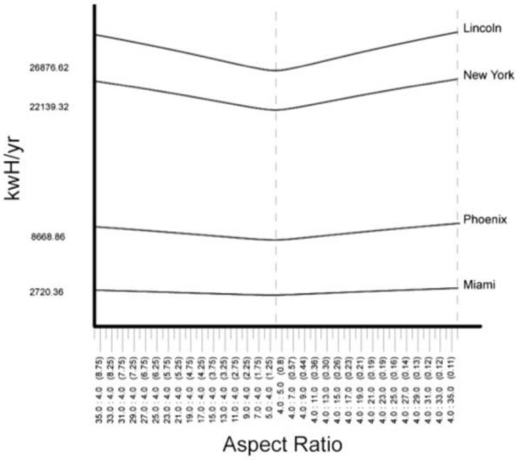
Building	sqft	energy per year	EUI	
Bartlett	16200	183030.19	11.30	from Mass Academy
Daniels	59126	439592.27	7.43	from Institute
Rec Center	145000	2953200.00	20.37	
Foisie	78000	713743.80	9.15	submetered
Harrington	86349	351156.44	4.07	submetered
Morgan	80446	741187.00	9.21	submetered
Riley	51224	578736.96	11.30	from Instiitute

Appendix B

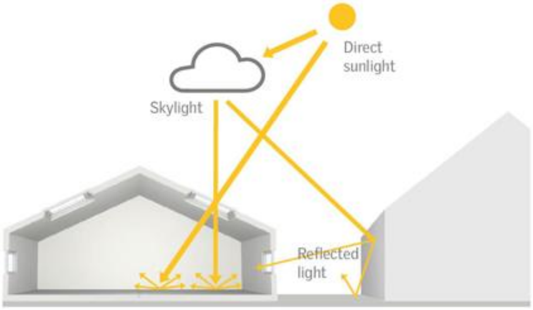
This section reviews information about various net-zero strategies.

<u>Passive Solar Energy</u>

1. Passive Solar: Building Geometry and Orientation
    a. In a study of energy performance based solely on the geometry of buildings in New York, Lincoln, Phoenix, and Miami, the aspect ratio of buildings found that the optimum aspect ratio is 0.5. Shown in figure.



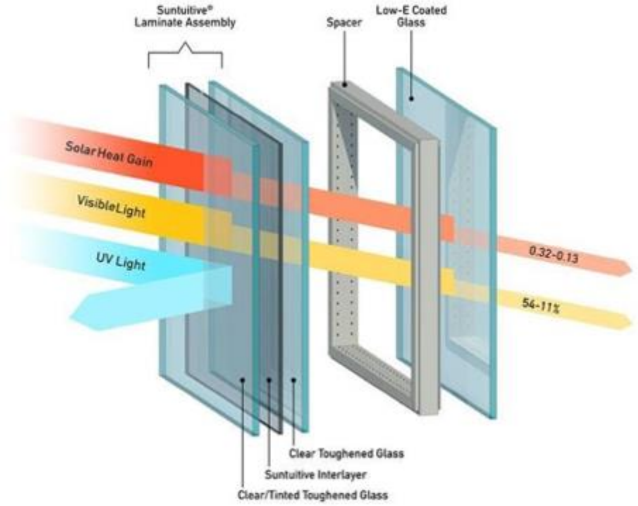
    b. Best practice has the building aligned to the north, in order to have multiple south facing walls and windows for maximum sun exposure.
    c. Sloping the roof towards the south and including a pitch that maximizes roof sun exposure will allow for an opportunity to have optimum area for photovoltaics on the roof and increase their solar potential (Hemsath & Alagheband Bandhosseini, 2015).
2. Passive Solar: Natural and Day Lighting
    a. Lighting a space with the sun rather than turning on LEDs is a direct way to decrease the energy consumption of the space (Velux, n.d.).



3. Passive Solar: Glazing Design

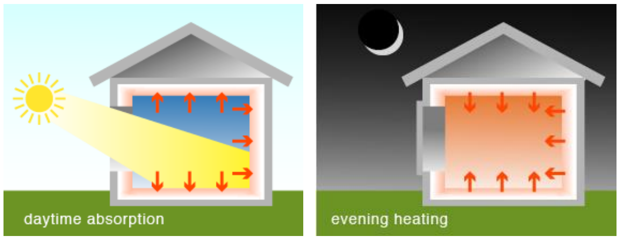
a. Allows for not only more daylight into spaces, but also increased insulation

b. There are a multitude of new and innovative glazing types that buildings can take advantage of. The example seen in the figure displays a triple glazed system that not only considers optimizing solar heat gain and visible light, but protects those inside the space from harmful UV light (GlassWorks, n.d.).



4. Passive Solar: High Mass Slab

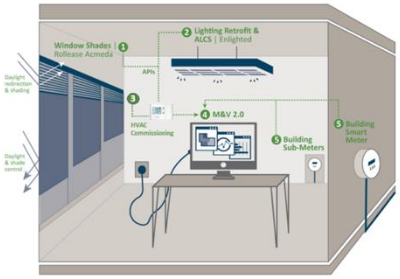
a. Decrease the heating load of a building by storing the energy from the sun during the day and radiating the heat throughout the building at night.



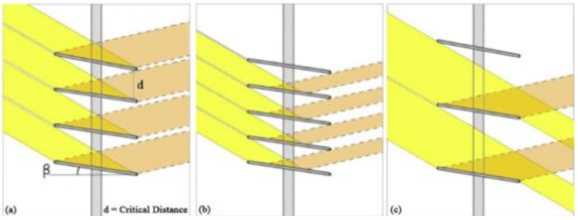
b. This phenomenon can be seen in the figure for a high mass floor, wall, and ceiling system (GreenSpec, n.d.).

Hybrid Solar Energy:

1. Hybrid Solar: Adaptive and Automated Shading

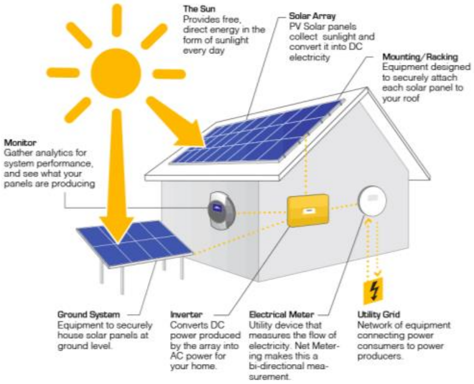


  a. incorporates a variety of features to sense how much sun exposure is in a room, and either manually or automatically change the shading in order to optimize solar potential (Chen et al., 2015).

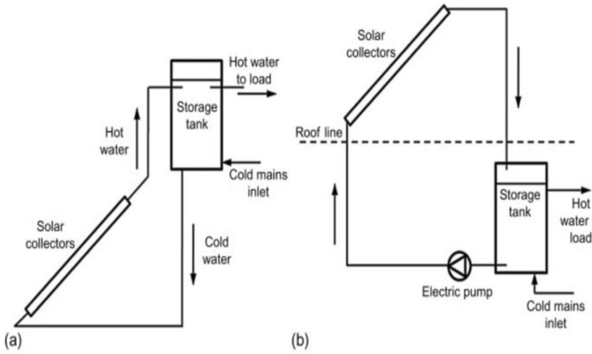


Active Solar Energy:

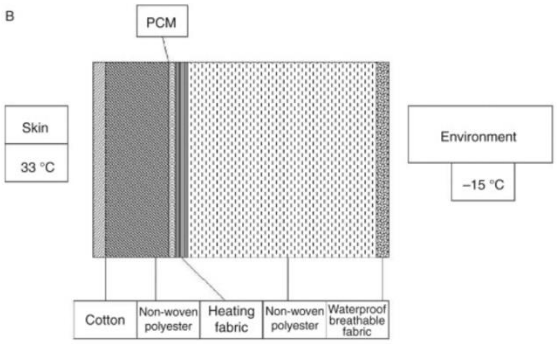
1. Active Solar: Photovoltaic Panels
    a. The most notable and popular net-zero strategy at the moment is the use of photovoltaic panels (PVs).
    b. installing them on roofs and walls, creating a source of energy for the loads inside of the building (Semprius, n.d.).



2. Active Solar: Solar Thermal Storage
    a. Solar Thermal Storage (STS) is the collection and storing of energy collected by a photovoltaic for a later use (Pitz-Paal, 2020).



3. Active Solar: Phase Changing
    a. "Phase change materials (PCMs) are substances which absorb or release large amounts of so-called 'latent' heat when they go through a change in their physical state, i.e. from solid to liquid and vice versa," (Tung Chai Ling, 2020).

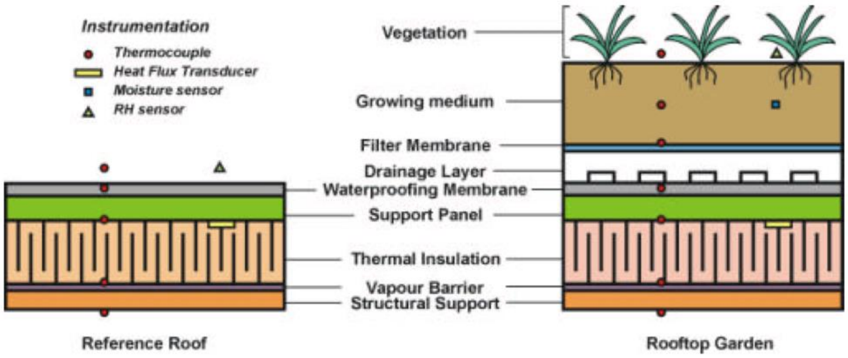


4. Active Solar: Solar Air Collector
    a. "The solar air heaters works by drawing in fresh outside air and circulating through a maze of black aluminum that has a special selective coating that absorbs much more heat than it emits. This heated air is then blown it into the dwelling via a solar powered fan." (*Solar Air Heating Using Solar Air Collectors*, n.d.)

<u>Passive Flora and Fauna</u>

1. Passive F&F: Local Plants
    - Local plants and trees can be used to shade air-conditioner units resulting in as much as a 10 percent increase in efficiency, shade windows that receive direct sunlight, shade east and west-facing walls and roofs, and shade heat sinks like patios and driveways. Local plants and trees can be used to shade air-conditioner units resulting in as much as a 10 percent increase in efficiency, shade windows that receive direct sunlight, shade east and west-facing walls and roofs, and shade heat sinks like patios and driveways (Landscape for Life, n.d.).
2. Passive F&F: Green Space
    - During summer months, people use energy in order to make their environments more comfortable and cooler. In urban locations, this amount of energy use is exceptionally higher due to the heat island effect. Increasing green space in these environments can help reduce the average temperature of the area, leading to a reduction in the amount of energy needed to cool a building (Zhang et al., 2014).
3. Passive F&F: Roof Gardens

- "Rooftop gardens offer many benefits to an urban area. They can reduce energy demand on space conditioning, and hence GHG emissions, through direct shading of the roof, evapotranspiration and improved insulation values. If widely adopted, rooftop gardens could reduce the urban heat island, which would decrease smog episodes, problems associated with heat stress and further lower energy consumption. They could also help to improve storm water management if sufficiently implemented in an urban area," (Liu, 2002).



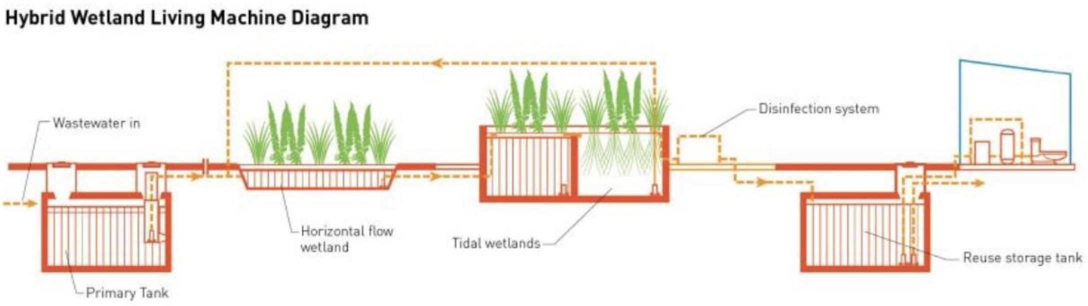
4. Passive F&F: Community Gardens
    - Introducing a community garden into an area decreases "food miles" (the travel required to obtain food) which decreases GHG emissions, keeps out chemicals from pesticides and weed killers, protects the pollinators and local animals of the area, improves air quality, and increases the knowledge of the community (Hummel, 2019).

Hybrid Flora and Fauna

1. Hybrid F&F: Green Walls
    a. Green walls have the potential to reduce energy costs by 23 percent, reduce air temperatures by as much as 10 degrees Celsius, reduce noise pollution in a

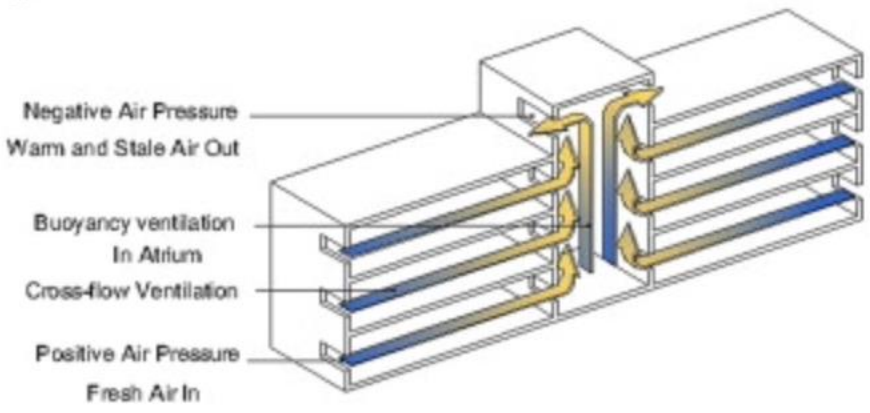
building, and improve indoor air quality (American Society of Landscape Architects, 2021).

2. Hybrid F&F: Living Machine
    a. Living machines provide a combination of increased green space as well as a decrease in the water consumption load of a building. Living machines reuse graywater and blackwater and can save upwards of 750,000 gallons of water a year as well as 500,000 gallons of irrigation (O’Connell, 2011).

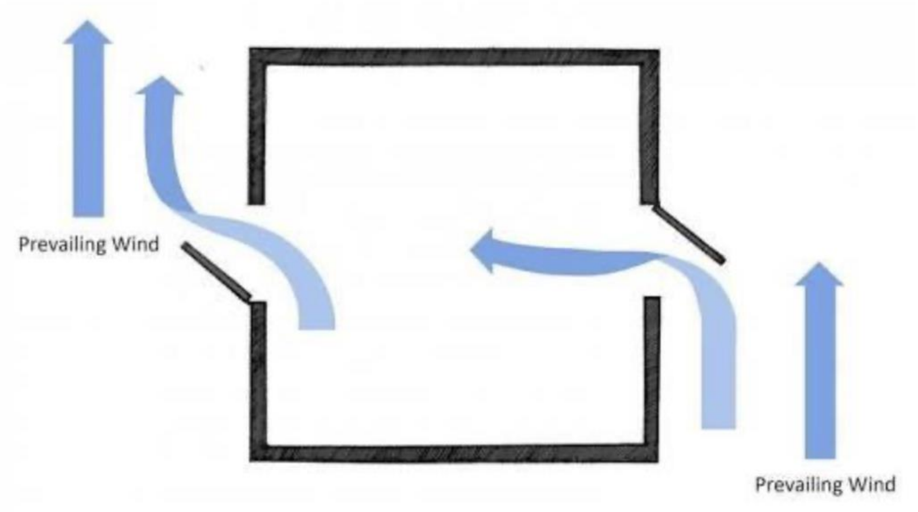

Hybrid Wetland Living Machine Diagram

Passive Wind

1. Passive Wind: Atrium Stack Ventilation
    a. Atrium space in buildings provide a unique opportunity for natural ventilation in a building. Stack ventilation can save as much as 60 percent of the buildings total energy use (Moosavi et al., 2014).



2. Passive Wind: Cross Ventilation
    a. Cross ventilation in a building can help moderate internal temperatures, reduce the accumulation of moisture, odors, and other gasses, create air movement which improves occupant comfort, and decrease the energy use by mechanical ventilation (*Cross Ventilation*, 2020).

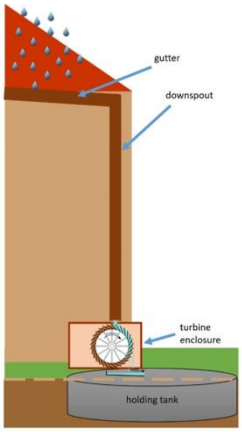


3. Passive Wind: Open Floor Plans
    a. An open floor plan in a building allows for more natural light to freely illuminate a space, especially in common areas where a buildings largest windows are typically located. As well, lighting fixtures are able to illuminate more space than a smaller area. Additionally, heating and cooling loads of the building can decrease. Since the floor plan is larger, air is able to flow more freely like light is. This results in less required energy on HVAC and a decrease in utility costs (Bold Construction, 2020).

<u>Active Wind</u>

1. Active Wind: Wind Turbines
    - The larger residential wind turbines require 1 acre or more of space to implement and a high initial cost, but provide a tremendous amount of energy for a home as long as the wind load of the area is high enough (Office of Energy Efficiency & Renewable Energy, n.d.).
2. Active Wind: Micro Turbines
    - Micro turbines placed on buildings produce energy dependent on how much wind the location receives. “Assuming a 5 kW wind turbine on a coastal location generates annually 10 MWh, if that same installation had run – theoretically – 24 hours a day and 365 days a year at full load, it would have generated 43.8 MWh,” (Renewable Energy World, 2008).
3. Active Wind: Night Flushing
    - “Night ventilation, or night flushing, is a passive cooling technique that utilizes the outdoor diurnal temperature swing and the building’s thermal mass to pre-cool a building through increased outdoor airflow at night, allowing radiant cooling to take place during the day when the building is occupied” (Landsman, 2017).
    - “Night flushing reduces annual end-use cooling energy and peak cooling load of mechanical air conditioning systems by 55% and 15%, respectively.” (Hoang et al., 2017)

Hybrid Water



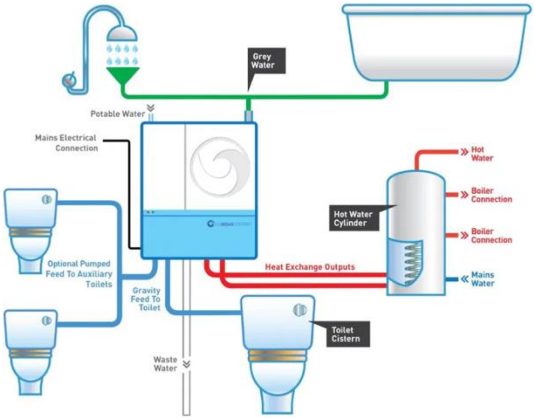
1. Hybrid Water: Roof Runoff Hydroelectric
    a. Using the runoff from the roof of a building, water can be forced down a downspout and into a turbine in order to both produce energy and reuse the collected water (Detora et al., 2019).

A close-up of permeable concrete.

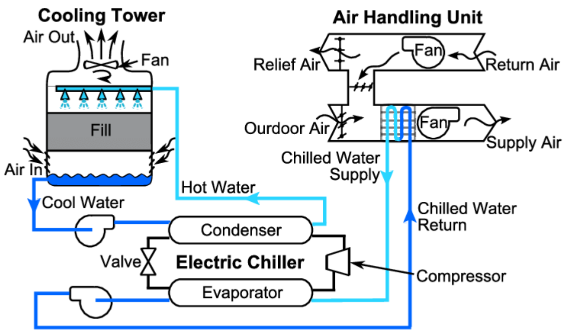
2. Hybrid Water: Permeable Surfaces
    a. Through introducing permeable surfaces in the place of typical concrete alternatives, runoff is able to enter the ground through the permeable membrane and the nonuse of concrete decreases the production of concrete resulting is less GHG emissions (Priebe, 2009).

Active Water

1. Active Water: Grey Water Reuse
    a. The reuse of grey water provides multiple benefits such as, "reusing graywater to flush toilets can reduce home indoor water use by 24 percent, on average. Using treated graywater to meet water demand for toilet flushing and laundry has the potential to reduce demand by nearly 36 percent" (Sharvelle, 2016).



2. Active Water: Water Cooled Air Delivery



    a. “HVAC shows the schematic of typical chilled-water ventilation and air-conditioning system for commercial buildings with three main components: air handling unit, chiller and cooling tower. The power consumption of such system is mainly from the chiller compressor and the cooling tower fan. Due to significant variations in ambient, load and equipment conditions, developing proper control strategy is critical for efficient operation of chilled-water systems.” (Li et al., 2012)

3. Active Water: Composting Toilets

    a. Introducing a composting toilet system will dramatically reduce domestic water consumption as they require no water for flushing. As well, they decrease the amount of wastewater to be disposed of onsite (US EPA, 1999).

4. Active Water: Chilled Beams

    a. Chilled beams, “Significantly improve the energy-efficiency of the hospital HVAC system, reduce energy use and maintenance costs by upgrading or designing around a chilled beam system for cooling and heating. Energy reduction can be primarily derived from reduced reheat and fan energy required to operate the system. In addition to the energy- and cost-saving benefits of a chilled beam system, there are significant space savings with chilled beams with a space reduction of 50% or more in duct area and supply and return chases and a 30 to

40% air handling unit footprint reduction, potentially increasing the usable floor space in a building” (Sustainability Roadmap for Hospitals, n.d.).

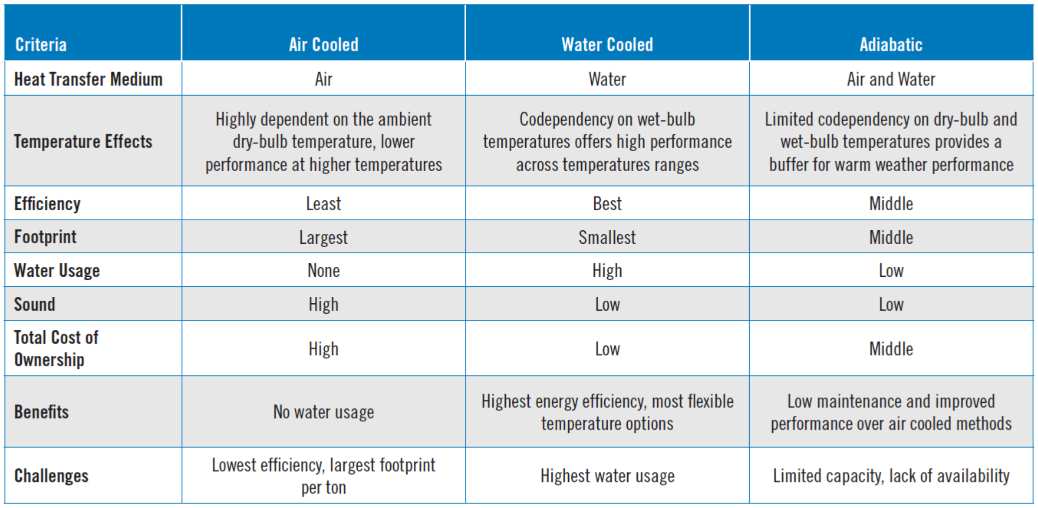
Active Mechanical and Electrical Load Reduction

1. Dedicated Plug Loads
    - Most plug loads in buildings (examples being TVs, computers, coffee pots, etc.) remain on most of the day or even all of the time. This creates a target for automation to decrease their energy use. By introducing dedicated plug loads and automation, the amount of energy used can be decreased from 15 to 50 percent (Dilouie, 2020).
2. Dimmable/Auto Lights

Strategy	**Definition**	**Examples**	**Average Savings**
Occupancy	Lighting status changes automatically based on presence of people	Occupancy sensors, timeclocks, energy management system	24%
Personal Tuning	Occupant control of light levels	Dimmers, wireless switches, workstation-specific control, preset scene control	31%
Daylight Harvesting	Lighting status changes automatically based on daylight levels	Photosensors	28%
Institutional Tuning	Light levels tuned to space needs by application, ballast tuning (reduction of ballast factor), task tuning, lumen maintenance, group controls	Dimmable ballasts, and dimmers and switches used to control group lighting	36%
Multiple Strategies	Any combination of the above		38%

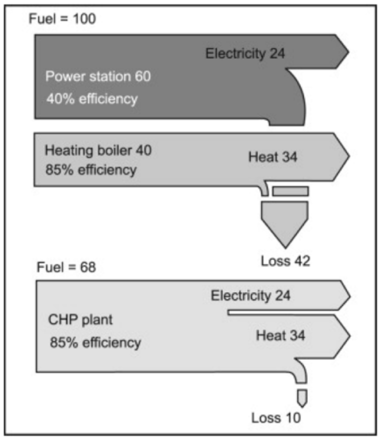
(Dilouie, 2013)

3. Wheel Heat Recovery
    - "In some climates, as much as half the cooling load for outdoor make-up air may be latent. If it's 15% or more, an investment in enthalpy wheels is probably well worth it for a new or upgraded HVAC system… The wheel eases the load on the cooling coil by as much as 80% and can shrink cooling and heating systems by 40% or so" (Sullivan, 2010).
4. Sewage Heat Recovery
    - Sewage heat recovery incorporates the potential energy that could be produced by the sewage of a building. In a study done in 2019, "Two options were evaluated: heating and cooling using a conventional system (connected to the local grid), and heat recovery from wastewater using heat exchangers and coupled heat pumps. The analysis of the scenarios suggested that the solution based on heat recovery from wastewater was more feasible, showing a 59% decrease in energy consumption compared to the conventional solution (respectively, 259,151 kWh and 620,475 kWh per year)" (Cecconet et al., 2020).
5. Heat Rejection System
    - "There are many factors that can influence the selection of a cooling system. Typically, the size of the system, the required design conditions, the operating sound level, along with the aforementioned efficiency, and price of the system all play a major role during the decision-making process." (Baltimore Air Coil, 2015) (source)
    - This table compares three heat rejection systems against these criteria:



Criteria	Air Cooled	Water Cooled	Adiabatic
Heat Transfer Medium	Air	Water	Air and Water
Temperature Effects	Highly dependent on the ambient dry-bulb temperature, lower performance at higher temperatures	Codependency on wet-bulb temperatures offers high performance across temperatures ranges	Limited codependency on dry-bulb and wet-bulb temperatures provides a buffer for warm weather performance
Efficiency	Least	Best	Middle
Footprint	Largest	Smallest	Middle
Water Usage	None	High	Low
Sound	High	Low	Low
Total Cost of Ownership	High	Low	Middle
Benefits	No water usage	Highest energy efficiency, most flexible temperature options	Low maintenance and improved performance over air cooled methods
Challenges	Lowest efficiency, largest footprint per ton	Highest water usage	Limited capacity, lack of availability

6. Co-generator
    - “Along with the saving of fossil fuels, cogeneration also allows to reduce the emission of greenhouse gases (particularly CO2 emission). The production of electricity being on-site, the burden on the utility network is reduced and the transmission line losses eliminated.” (Turbines, 2014)



7. Reduced Friction Losses
    - “Friction losses refer to the difference in pressure needed to overcome the pressure drop during flow through pipes…A reduction in friction loss from 1 bar to 0.5 bar will result in the energy loss being reduced by 50%, thereby saving 2 kWh every hour. This is why it is possible to achieve significant savings, especially in (near) continuous operations (365 days per year, 24 hours per day = 8760 hours per year!)” (Vogelesang, 2008).
8. High Efficiency Appliances

  - "On average, home appliances – including clothes washers, dryers, dishwashers, refrigerators, freezers, air purifiers and humidifiers – will account for 20 percent of your home's total electric bill. ENERGY STAR appliances, are certified by the U.S. Department of Energy, can reduce that share. The average home appliance lasts for 10 to 20 years, and an ENERGY STAR-certified appliance will use anywhere from 10 to 50 percent less energy each year than a non-energy efficient equivalent" (EnergySage, n.d.-a).

Active Geothermal:

1. Campus-wide Heat Pump
    a. "A geothermal heat pump is the greenest, most efficient, and most cost effective heating & cooling system available. That's because it uses the free renewable solar energy stored in your backyard rather than burning fossil fuels…Geothermal systems can save you up to 70% on your heating, cooling, and hot water costs" (Water Furnace, n.d.)

Appendix C

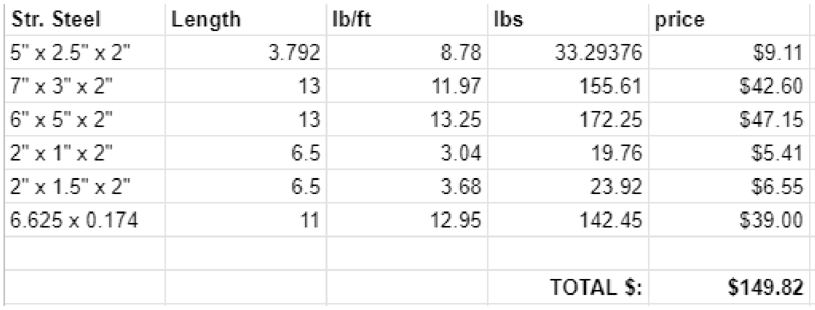
This section explores the logic behind the financial analysis of the solar canopy. This analysis is based on the raw material cost of a single canopy. They do not factor in the labor required to assemble the canopy.

Footing

To price the footing, the volume necessary for the 9’x9’x2.5’ footing is 202.5 ft^3. This volume would take 388 80lbs. bags of concrete to make. These 80lbs. bags cost $4 each, resulting in $1,352 for the base cost of the footing (Remodeling Calculator, n.d.).

Structural Steel

To determine the price of the structural steel, the length of each member was determined from the RISA-3D model. The weight per foot of each member was found using American Society for Testing and Materials (ASTM) 1085 tables for Hollow Structural Section (HSS) members. The weight of each member was found by multiplying the length by the pounds per foot. Using the market price of steel in dollars per pound, the price of each member was calculated (Focus Economics, n.d.). By summing these values, the total value of $150 was found. These calculations can be found in the table below.



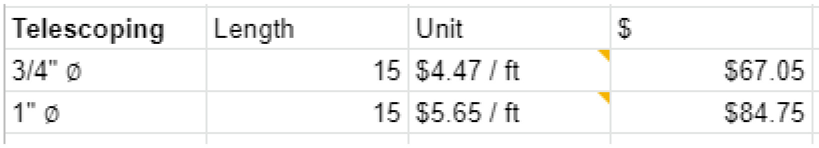
Str. Steel	Length	lb/ft	lbs	price
5" x 2.5" x 2"	3.792	8.78	33.29376	$9.11
7" x 3" x 2"	13	11.97	155.61	$42.60
6" x 5" x 2"	13	13.25	172.25	$47.15
2" x 1" x 2"	6.5	3.04	19.76	$5.41
2" x 1.5" x 2"	6.5	3.68	23.92	$6.55
6.625 x 0.174	11	12.95	142.45	$39.00
			TOTAL $:	**$149.82**

Solar Panels

Solar Panels are sold by wattage of the system. When looking into the price of four individual solar panels, some calculations were necessary. According to the energy analysis of the modular canopy, the panel produces 1,863 kWh per year. Converting this number to kW and multiplying by the cost in dollars per watt for the state of Massachusetts, the four panels on the solar canopy can be estimated at $608 (EnergySage, n.d.-b).

<u>Telescoping Members</u>

Using a similar strategy as the Structural Steel members, the length of the telescoping members was calculated. The unit cost per foot of each member was found and the total price was calculated based on the thickness of each member. The table below outlines each member.



Telescoping	Length	Unit	$
3/4" ø	15	$4.47 / ft	$67.05
1" ø	15	$5.65 / ft	$84.75