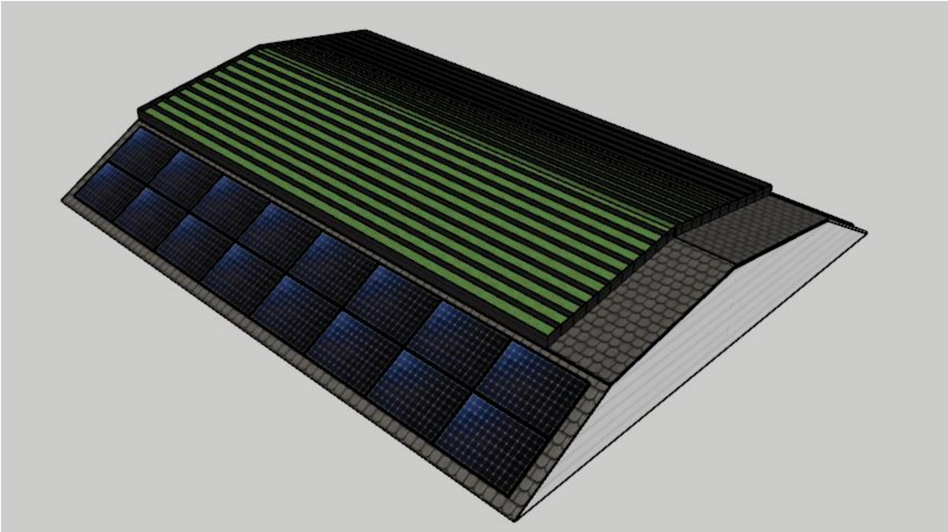
Affordable Sustainable Roof



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by
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Abstract

The goal of this project was to design and assess the value of an innovative roofing system that integrates a green roof with solar panels and a water collection system. Through research and testing, we were able to determine the thermal, drainage, weight, and solar properties of our roofing layers in order to conduct a life-cycle cost analysis for use on residential homes. A wood truss with a polygonal top chord was designed to support the roof structure.

1.0 Introduction

The Earth's average surface temperature has risen about 0.9 degrees Celsius since the Industrial Revolution. This temperature increase is believed to have been mainly driven by the release of carbon dioxide and other man-made emissions into the atmosphere [1]. On December 12th, 2015, delegations from 196 countries met in Paris and agreed to combat climate change and to intensify the actions and investments needed for a sustainable low-carbon future [2]. This meeting drafted what's known as The Paris Agreement. This document has many goals; its primary goal is to strengthen the global response to the threat of climate change. Specifically, the agreement states to limit the global temperature rise to between 1.5 to 2 degrees Celsius above pre-industrial levels [3]. To reach their goals, each country has to strictly monitor and reduce their emissions in the years to come.

While the Paris Agreement was a groundbreaking achievement for the world as a collective body, it has become more apparent over recent years that the shift towards sustainable energy systems must be led by some of the world's largest polluters, such as the United States [4]. According to the United States Environmental Protection Agency, electricity production is the second largest source of US greenhouse gas emissions. The US EPA also reports approximately 63% of all US electricity comes from the burning of fossil fuels, especially coal and natural gas. As illustrated by Figure 1, 28% of US emissions in 2017 came from electricity production. Another significant contributor to US emissions are the commercial and residential sectors which accounts for 12% of emissions [5].

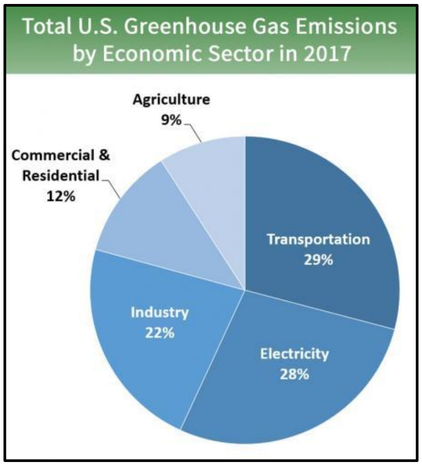


Figure 1: US Emissions 2017 [5]

While the transition to clean energy for certain sectors is an uphill battle, residential and commercial areas are the prime candidates for a sustainable switch. Two areas in particular, electricity production and residential heating, are sectors that could easily be improved on because there are options for clean, renewable energy. Solar energy for example has been increasingly accessible in the US, with the current solar energy production being 35 times greater than it was in 2008 [6]. Since the beginning of 2014 the average cost of solar photovoltaic panels has dropped nearly 50%, making them more accessible for residential homes [6]. Other systems, such as rain collection systems and grass roofing, can also be used to provide different benefits for a residence, such as cooling, heating, and filtrating. These systems are regularly used independently of one another, but the team considered the possibility of integrating some of these systems together.

The goal of this project is to design an affordable sustainable roof for residential homes that implements photovoltaic cells, grass roofing, and water collection in one unified system. The proposed roofing system aims to improve on a conventional roof by decreasing environmental impacts and reducing roofing costs by providing a longer life-cycle from installation to replacement than a conventional shingled roof.

2.0 Background

2.1 Green Roofing Versus Conventional Roofing

A green roof is defined as a vegetated landscape built up from a series of layers that are installed on a roof surface [7]. A major focus of this project is to incorporate a green roof co-dependently with other residential roofing systems. Compared to conventional style roofing systems, green roofs bring additional eco-friendly aspects such as energy, insulation, or filtration. Energy benefits of a green roof versus a conventional roof construction include better roof environment stability, better insulation, and potentially significant energy savings from a financial standpoint. The exact energy savings depend on the size of the house and the climate [8].

Conventional roofing systems typically have gutter systems to help funnel away excess stormwater and snowmelt from the structure, as to not weigh down and damage the roof itself; but gutters and retention ponds are not part of a standard roof installation and come at separate, expensive costs. Green roofing, however, can actually utilize the rainwater for numerous purposes. Natural filtration through the green roof can be a source of usable water to supply systems in a home with natural air conditioning, irrigation, and other applications. It also aids the region by preventing more stormwater from entering the sewer system and can help prevent overflow.

Green roofing can also help to insulate a house in the summer. Due to the high thermal mass of soil and light color of plants, a green roof can reflect more heat than a conventional asphalt roof and can also retain the heat that it receives [9]. Additionally, this can also be helpful during the winter in that heat is kept inside thanks to the soil. The plants shade the top of the building and release heat through evaporation, cooling the roof itself. In addition, since the roof uses plants instead of asphalt, the roof reduces air pollution in the immediate area. Having a green roof means that there is natural vegetation and nature on the structure, and with nature comes biodiversity. A well-kept green roof can reap benefits not only to the homeowner, but to wildlife in the area, such as bees and birds whose habitats may be otherwise impeded on by a highly populated human region or other factors.

While only on a small scale, green roofing can increase the quality of air in and around the building in question. The vegetation on the green roof is able to absorb air pollution and other harmful pollutants, and exchange them for clean, breathable air. Additionally, green roofing more than doubles the lifespan of a conventional roof, which includes both sheathing and shingles, and reduces maintenance costs and roof replacement [8]. The vegetation and soil help shield roofing materials from outside factors such as UV rays and weather. A conventional roof is eventually worn down by either weather or other natural factors and requires maintenance every 20-30 years, especially if the roof is shingled. The main maintenance aspect of a green roof is applying nutrients in the form of compost annually for the vegetation and soil. The irrigation system would need to be cleaned similar to a gutter system [8].

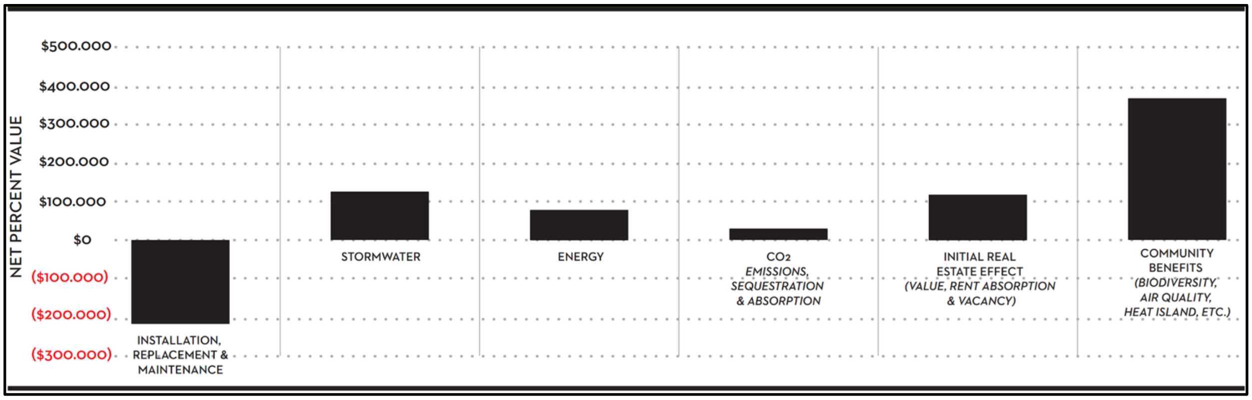


Figure 2: Net Present Value of Various Green Roof Benefits for Commercial Building [8]

As shown in Figure 2, the initial cost of the installation for a green roof and the perceived benefits outweigh the capital investment for some property owners [8], which usually takes about 5-10 years depending on how complex the roofing system is. For example, this study showed the money saved from stormwater, energy, CO_2 emissions, real estates and community benefits over the course of 6.5 years. After this time period, the roofing system had been paid off and a return investment of 193.8% had been achieved.

2.2 Conventional Roof Structure

When constructing any type of building, it is necessary to know exactly what the standards are, in order to avoid any malfunction or safety hazard to those inside. This is especially necessary for roofing, since miscalculations can result in collapse, leading to injury or death to the people in and around the structure.

A conventional roofing system, composed of asphalt shingles and a wooden frame, typically holds a dead load of around 15 lbsf [10]. The asphalt shingling on its own only weighs about 2 ½ to 4 lbsf, meaning that the remainder of the roofing system, specifically the wooden framing, is around 10-12 lbsf [11]. A conventional asphalt shingled-wooden frame roof supports a live load of about 30 lbsf based off the weights described previously [10].

2.2.1 Components and their Function

Figure 3: Conventional Roofing Layers

The typical layers of a conventional roof are mapped out above in Figure 3. The top layer is asphalt shingles which are 3/16" thick and are the most important layer for protection as well as the roofing aesthetic. The water barrier membrane is a very thin, 1/16" to 1/8" layer that makes the roof waterproof. The roof sheathing, made of 7/16" plywood, is how the shingles attach to the roof and act as another layer of support. The air barrier membrane is also very thin, 1/16" to 1/8" thick. The purpose of the air barrier membrane is to stop air from flowing into and out of the house. Lastly the plywood decking is the bottom most layer made of 7/16" plywood which attaches to the truss or rafters underneath [12].

2.2.2 Moisture Protection and Thermal Performance

As mentioned in Section 2.2.1, the main layer in the roof that deals with thermal performance, such as keeping heat from leaving or entering the house, is the insulation. Insulation is placed in the attic floor and, if the attic is finished, insulation is also placed between the rafters [13]. Shingles in terms of thermal performance can vary based on color and material, since lighter colors will reflect more light than darker colors, allowing for less heat to be absorbed through the roof [9]. With lighter colored shingles, the temperature of the plywood sheathing has been shown to be 10 to 15^{O}F lower than darker shingles; however, darker shingles are still the most used color for roofs [9]. Additionally, an asphalt roof reflects less light than a metal roof [9]. Ventilation and ridge vents are used to get rid of heat and moisture from inside the house that could possibly ruin other roofing layers, such as causing the truss, sheathing, or framing to develop mold [13]. To protect the roof from liquids from outside, waterproof layers and underlayment layers are used to block water from moving through the roof to inside the house [13].

2.2.3 Building Codes and Structural Design Criteria

Unfortunately, there haven't been many studies conducted on residential buildings that incorporate green roofing systems. Instead, different sources in terms of building codes and design criteria were utilized. One study, done by the EPA, sets design guidelines and a maintenance manual for green roofing, and while it is intended for arid climates in the southwest United States, the group was able to pull some critical information on roofing. One important point in the report was that shallow (extensive) 4-6" green roof systems, including modular, continuous, and loose laid systems are typically 15 - 55 lb/square foot [14]. For this, the team looked to the *Massachusetts State Building Codes* [15] and *AWC Wood Frame Construction Guidelines* [16]. Referring to the Massachusetts State Building Codes 780 CMR residential chapter 9, the group was able to gain an understanding of exactly what went into roofing assemblies and what kinds of constraints would be necessary in order to support a heavier load than typical asphalt shingle assemblies. Additionally, the MA Building Guidelines Section R905 provide information on the necessary plywood sheathing requirements that our group will need to consider and use while designing the roof. Similarly, Sections 2.5.3 and 2.5.4 in the AWC framing guidelines provided further requirements pertaining to roof trusses and roof sheathing, specifically that of wooden roof trusses, which is what we were looking to delve further into. Figure 4 below shows an example of roof trusses on a structure which represented what our house's structural roofing system would look like, but on a smaller, simpler scale [16] (Our design will look to incorporate mainly shallow gable end trusses only).

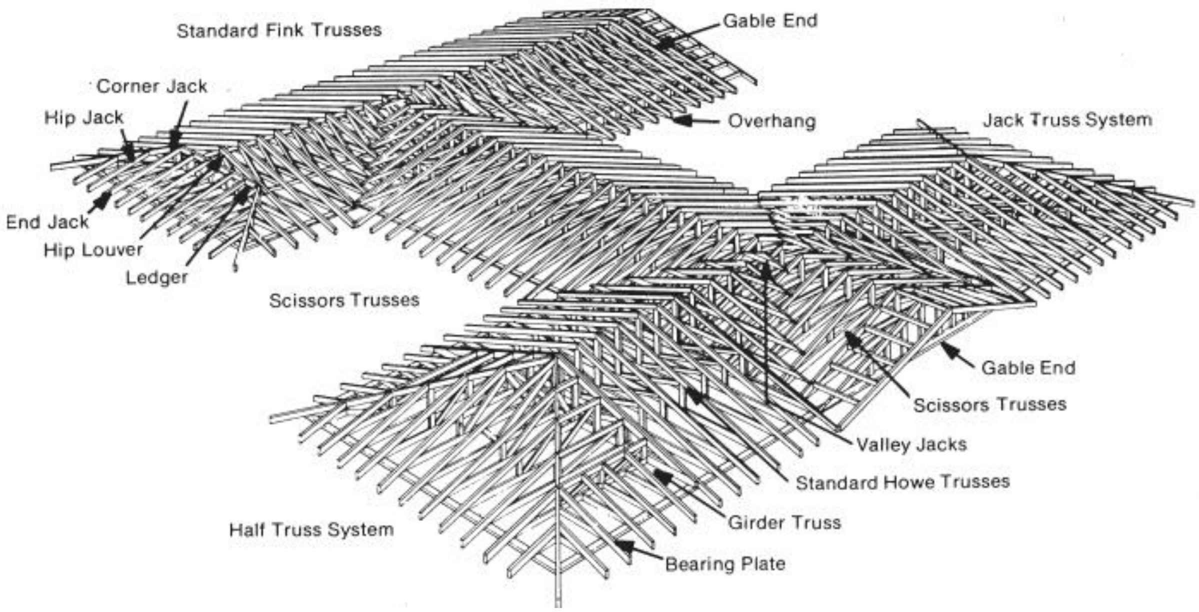


Figure 4: Wooden Truss Roofing System - Wood Frame Construction Manual Figure 2.18b Total Roof Truss System

2.3 Green Roof Structure

There are three main layers of a green roof: vegetation, growing medium, and drainage layers. The vegetation layer is the plants on the roof; a wide range of plants have been grown in the past, from grass to trees. The growing medium layer means the material the plants are grown in, composed of a mix of inorganic and organic components. The drainage layers encompass multiple layers to ensure maximum drainage of the system and waterproofing of the roof [7].

2.3.1 Vegetation

There are two types of green roofs, intensive and extensive. Our focus will be on extensive roofs which primarily function as storm-water collection systems and thermal insulation. These roofs have less soil and require less maintenance compared to intensive roofs [17]. The average extensive roof has between 2 to 6 inches of soil as shown in Figure 5 [7]. This substrate depth supports most low growing plants such as

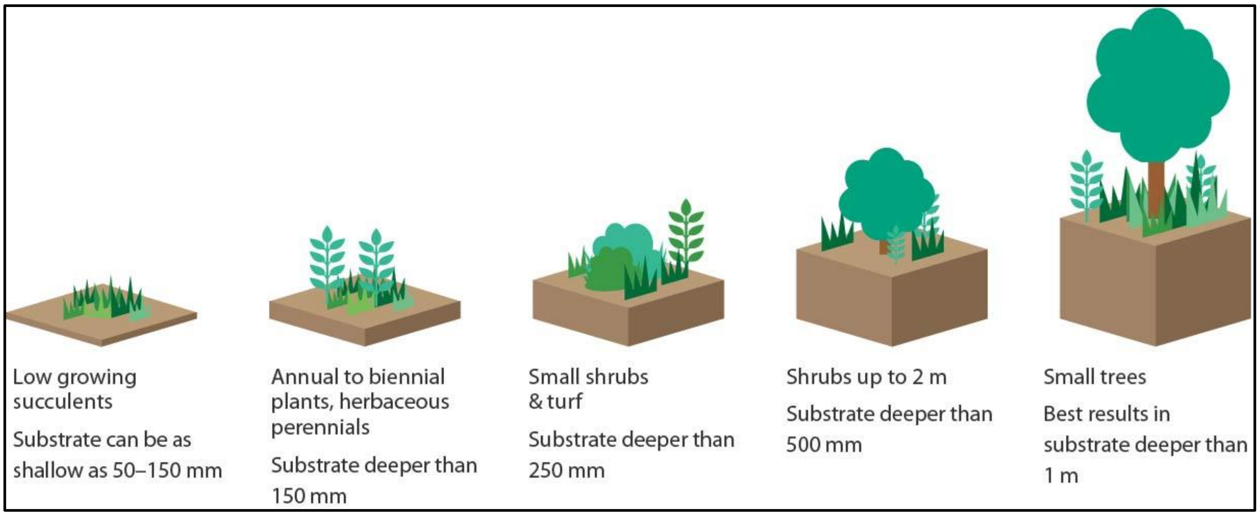


Figure 5 : Substrate Depths and Plant Types [7]

grasses and succulents [18]. The benefit of lower soil thickness is less superimposed weight.

One option for green roof vegetation is Fine Fescues which are lower maintenance cool season grasses that can grow in shade and withstand cold climates [19]. In the *Festuca* genus Hard Fescue is the most resilient, being able to survive extreme drought and shade while also not requiring mowing [20]. Succulents are also resistant to poor conditions and do not require constant care [21]. The Creeping Stonecrop (*Sedum acre*) can survive extreme cold, is drought resistant, and only grows up to 6 inches tall [22]. Jenny's stonecrop (*Sedum reflexum*) is another succulent species that is excellent for green roofs [23].

Plants can have a significant impact on a home's heating and cooling needs. Green roofs reduce the amount of heat that is absorbed by the roof over the course of the day while also increasing the amount of heat radiated away as shown in Figure 6. This study found a maximum temperature difference of 20 °C between a conventional roof and a green roof in the summer months in Singapore. Overall summer cumulative monthly heat flux values showed the building receiving net heat gain for the conventional roof while the green roof was shown to provide a cooling effect [24]. Another study found that the addition of a green roof to a building reduced its heat absorption in the summer months by an average of 75.3% and reduced the heat loss by an average of 8.2% in the winter months [25].

Type of roof surface	Total amount of heat gained over a day (kJ/m^2)	Total amount of heat lost (kJ/m^2)
Shrub	0	104.2
Turf	29.2	62.1
Tree	15.6	53.3
Bare soil	86.6	58
Hard surface	366.3	4.2

Figure 6: Vegetation Cooling Effects in Summer [25]

One study looking at the effects of different plant and substrate combinations on roof thermal performance found that significant differences in radiation absorbed only came from differences in plant types. The study also found that substrate types have more of an effect on heat flux transferred through the roof. This means that both the thermal storage capacity of substrates and the shade provided by plants play important roles in a roof's thermal performance. However, the shade provided by the plants ultimately determines how much energy can be absorbed by the soil. The study concluded that different combinations of plants and substrate could affect the thermal performance of the green roof by as much as 15%. The best combination of plants and substrate was Sedum album: a succulent and Avondale (Mainly quartz SiO_2 (sand); trace leucite; trace dolomite (Ca-Mg carbonite)) [26].

Another study observed the effect of substrate depth on the growth of different succulent species. The plants grown in deeper substrates from 5.0-7.5 cm (2-3 inches) had higher survival rates than those in 2.5 cm substrates. The substrate depth also affected the plant coverage. The results from the same study stated that on day 343 of the study, plants growing in 2.5, 5.0, and 7.5 cm of substrate had reached 47%, 74%, and 96% coverage, respectively [27]. Therefore, the deeper the substrate, the greater the survival rate of the vegetation. These differences are due to deeper substrate layers allowing more vertical space for roots to grow -- this generates better moisture retention and root protection from temperature fluctuations. This also means that less soil depth reduces plant growth rates and survivability due to the reduced root growth.

Another reason why succulents are good candidates, is that they do not absorb as much water as other types of vegetation. A study utilizing four different crop species measured the production of biomass and the effects on rainwater capture on a simulated green roof. The study included the species *Amaranthus tricolor L.* and *Portulaca oleracea L.* as succulents are the most widely used group of plants on green roofs because they are adapted to grow in xeric (dry) environments. The results of the study showed that amaranth reduced runoff volume compared with the unplanted control three times more (70%) than the succulent (22%). This is consistent with other research showing that grasses and forbs capture more stormwater than succulents [28]. In summary, since succulents absorb less water than other species, they are good candidates for systems that include a rainwater cistern.

2.3.2 Growing Medium

For a green roof's growth medium, a lightweight and long-term sustainable mixture is needed. The main components used in soil mixtures are minerals–such as sand, silt, and clay–as well as organic materials so that they can satisfy a certain application with the recommended ratio of the ingredients [29][30]. For green roofs the soil mix is designed to be lightweight to minimize the load on the roof especially if the green roof is extensive. Every ingredient for the soil has advantages and disadvantages. For example, sand provides a good anchor for plants but is heavy as well as not being able to hold nutrients. Clay has good moisture and nutrient retention but can clog drainage layers and fabrics [31]. Because of these advantages and disadvantages, it is important to create the right ratio of ingredients so they can complement one another in the soil mix. Table 1 below describes more of the advantages and disadvantages for different materials.

Table 1: Advantages and Disadvantages of Soil Material [31]

Material	Advantages	Disadvantages
Sand	–Provides sturdy anchorage for plants and facilitates wetting of the medium –Causes no pH effects if free of carbonates and other contaminants	–May create saturation problems or may not hold enough moisture depending on grade –Heavy –Negligible source of nutrients –Holds nutrients poorly
Clay	–Good moisture retention –High cation exchange capacity and nutrients retention	–Gradual loss from medium may clog drainage layers and fabrics
Lava (scoria)	–Lightweight and porous	–Low pH may require adjustment with dolomite
Pumice	–Lightweight and porous	–Expensive
Gravel	–Stable and provides strong support for plants –May enhance good drainage	–Heavy compared to other minerals –Poor water retention –Provides no nutrients
Perlite	–Porous and sterile –Stable, improves drainage, and does not disintegrate in a mix	–Coarser particles are crushable during transportation –Has no cation exchange capacity (CEC); contains no plant nutrients and holds water poorly –Contains small quantities of fluoride that may cause toxicity in some plants
Vermiculite	–Light weight and porous but its porosity is lower than that of perlite in mixes –Relatively high CEC and retains water better than perlite –Supplies magnesium and potassium	–Deteriorates over time –Absorbs anions poorly except PO_3^- –Generally holds water poorly

	–Immobilizes ammonium and phosphate	
Expanded shale, clay and slate (ESCS)	–Porous and lightweight and provide good moisture retention –Have high CEC hence good nutrient retention and supply –Do not break down or decay –Inert, sterile, and non-toxic therefore have no pathogen, weed and disease problems, and stable under environmental conditions	–Too light to provide good anchorage for plants when used alone –Tend to have alkaline pH and that may affect the availability of micronutrients (e.g. boron and iron)
Rockwool	–Lightweight, porous and regulates air and water supply	–Does not contain or hold nutrients
Crushed clay bricks, tiles or brick rubble	–Stable and strong material –Can hold some moisture	–Possible high pH problems due to presence of mortar and cement
Crushed concrete	–Low cost and readily available at demolition sites	–Alkaline and has little moisture holding capacity
Aerated concrete	– High capacity to absorb and hold water when mixed with organic matter	–May require periodic maintenance –Not applicable to all roof types
Subsoil	–Readily available at construction sites as a by-product	–Heavy and poor in plant nutrients
Styrofoam	–Does not break down or compress in use –Improves aeration and drainage	–Insignificant cation exchange capacity –Contains and holds no nutrients –Too light and exhibits electrostatic characteristics during mixing
Urea-formaldehyde resin foam	–Relatively high water-absorption capacity	–Light and degrades slowly over time –Acidic and largely devoid of nutrients

One example from the Heidelberg Company's A-1 Greenroof/Hydroponic Mix shows the use of blending Pumice, Coir, Peat Moss, Washed Sand and A-1 Lifelike 3/8" Compost. This mix has a high percentage of organic compost and a low percentage clay content which causes the soil to be good at filtering water but not hold moisture and nutrients as well [32]. Other examples are from the Rooflite company that have 2 different types of extensive green roof growing mediums. One is in a heavier weight class of about 80-90 lb/ft^3 than the other, which is about 60-70 lb/ft^3. Both use the organic compost as a main ingredient in it [33][34].

Other considerations for the soil are the properties that must be achieved like the pH value being between 6.0-8.0 so the plants can live and grow in the soil [35]. Not only does this requirement help plant growth but can improve runoff quality too. Rainwater has a pH value between 5 and 6 while the growth medium, with a higher pH value, can increase the pH of the runoff to a more neutral value of about 7 and 8. This helps lower the degree of acidification, which can help protect roofing materials.

Different materials in the soil can affect the properties and function of the soil meaning the function of the soil must be considered before deciding on a mixture. For example, adding about 10% more organic matter (by volume) will help increase plant growth; however, high concentration of nitrogen is found in runoff resulting from the compost in the growing medium. For instance, an extensive green roof that contains 15% compost in the soil has been shown to have a higher total nitrogen in its runoff than a conventional roof [36].

According to the experiment done on nutrients found in runoff, a green roof produced about 1.88-1.71 mg/l of nitrogen and a conventional roof produced 0.41-0.68 mg/l of nitrogen in its runoff. Other examples include phosphorus with a green roof producing 1.57-1.82 mg/l while a conventional roof produced 0.01-0.02 mg/l of phosphorus in the runoff. Additionally, it was found that soils that contain more heavy metals will produce runoff containing these metals [36]. Soils with high levels of organic matter have higher percentages of chemicals in the runoff. Succulents are a useful vegetation as they can tolerate nutrient poor soil, which generates less chemicals in the runoff. Nutrient pollution is one of the most challenging environmental problems in America, which is caused by excess nitrogen and phosphorus in the air and water. Excess nitrogen in water used for drinking can cause many health problems especially for infants that are vulnerable to the nitrogen-based compound, nitrates, in drinking water [37].

Organic materials provide the nutrients in a mixture but can break down in a short time, which results in a loss of depth. Minerals such as expanded aggregates, pumice, and volcanic rocks are lightweight aggregates and because of the pore spaces in them, they are capable of holding water for the plants. According to Green Roof Construction and Maintenance, the recommended ratio is 80% mineral and 20% organic material so that the soil mixture has a longevity of 3-5 years and stays lightweight. One way to help recharge the organic material requirement is to have plants that shed and will lay on the surface and then decompose into the soil [38]. For succulents, it is suggested to annually fertilize the soil.

In terms of thermal properties, soil thermal conductivity can vary based on the mixture and the particle sizes. In one experiment done by Sailor, different percentages of pumice, sand and compost were tested with the addition of four different moisture percentages to observe the effect it would have on the thermal properties of the soil [39]. Figure 7 shows the different soil types and their thermal conductivities at different moisture levels.

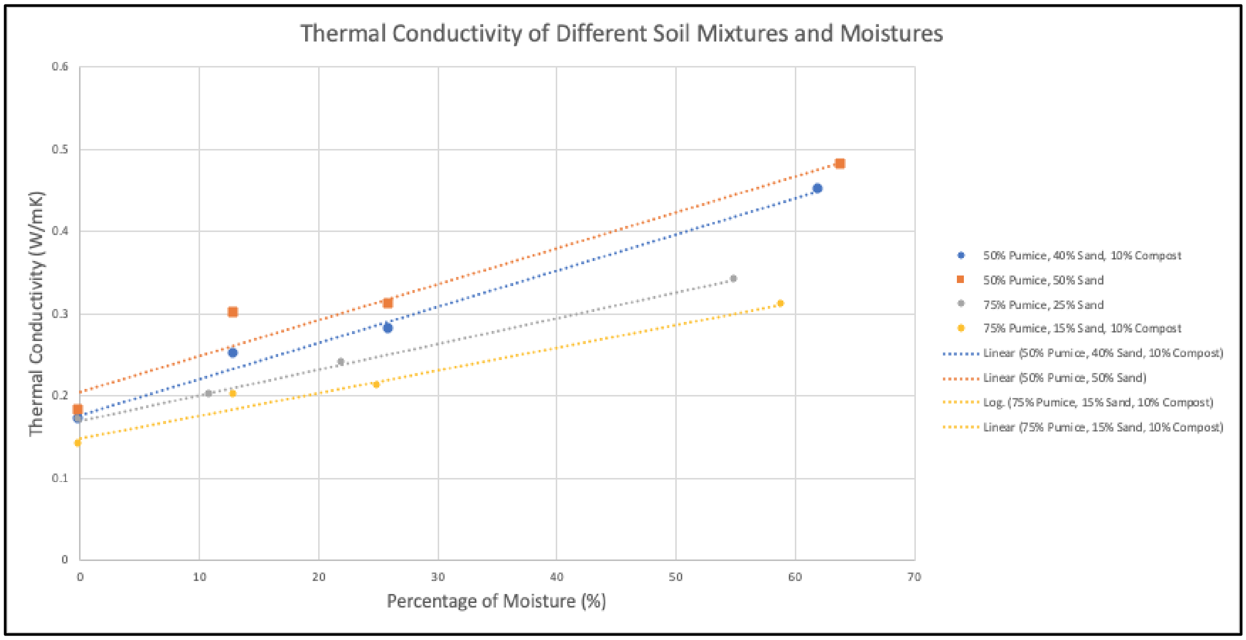


Figure 7: Thermal Conductivity at Different Soil Mixtures [39]

Based on the results found, a lower percentage of pumice and higher percentage of sand resulted in higher thermal conductivity. As the percentage of pumice increases with the percentage of sand decreasing, the results produced lower thermal conductivity values. The addition of compost also showed to decrease the thermal conductivity value. In terms of moisture, there is a positive correlation with the thermal conductivity, which means as the moisture increases the thermal conductivity increases. For insulation, it is desired to have a low thermal conductivity to get a high R-Value, which can be seen in the equation below, where L is the thickness of the soil, R is the R-Value, and k is the thermal conductivity.

$$R = \frac{L}{k}$$

Based on the experiment, to maximize the insulation of a green roof, the recommended mixture involves a high percentage of materials like pumice (70% – 80%) with some compost added in (5% – 15%) and a little sand (5% – 15%).

2.3.3 Additional Layers

The additional layers to a green roof are standard among most roofs. The other layers are shown below in Figure 8.

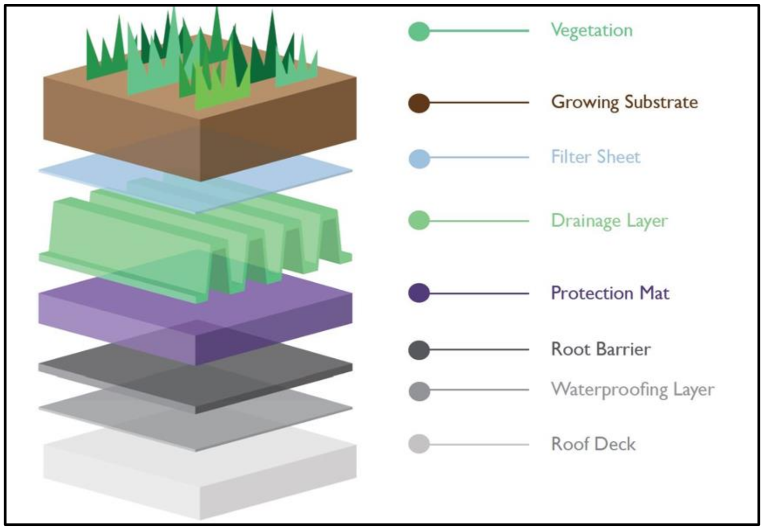


Figure 8: Green Roof Layers [40]

The filter sheet is a thin layer used to allow water to flow through but block most other substances. Some sheets allow the penetration of roots, others do not, depending on what type of vegetation is desired. Drainage layers can be made up simply of rocks, or more modern versions are made of plastics and typically in an egg carton shape which can store water for the vegetation on the roof. The protection layer is a protective mat which is water-permeable and made up of dense synthetic fibers, polyester and polypropylene. The root barrier is made up of polyethylene sheets which prevent the growth of roots from the vegetation layer. The waterproofing layer is the most complex layer and can vary from system to system. This layer must provide a strong but flexible barrier that allows expansion under physical or thermal movements of the building structure without compromising water tightness. There are two main types of waterproofing methods: liquid applied treatments and preformed waterproofing sheets. The sheets are for more conventional roofs while the liquid applied treatments are for roofs with more obstacles preventing the laying of the sheets. Lastly there is the roof deck which is the structural support of the actual roof underneath the newly added green roof [40].

2.3.4 Solar Panels

Across the United States, renewable energy is becoming a more and more prominent source of energy for homeowners, as originally steep prices start becoming more affordable for the common resident [41]. As seen in Figure 9 below, the price of solar panels (Solar PV) has been on the greatest decline compared to other renewable sources. This has made solar panels a realistic option for homeowners to replace getting electricity from the grid.

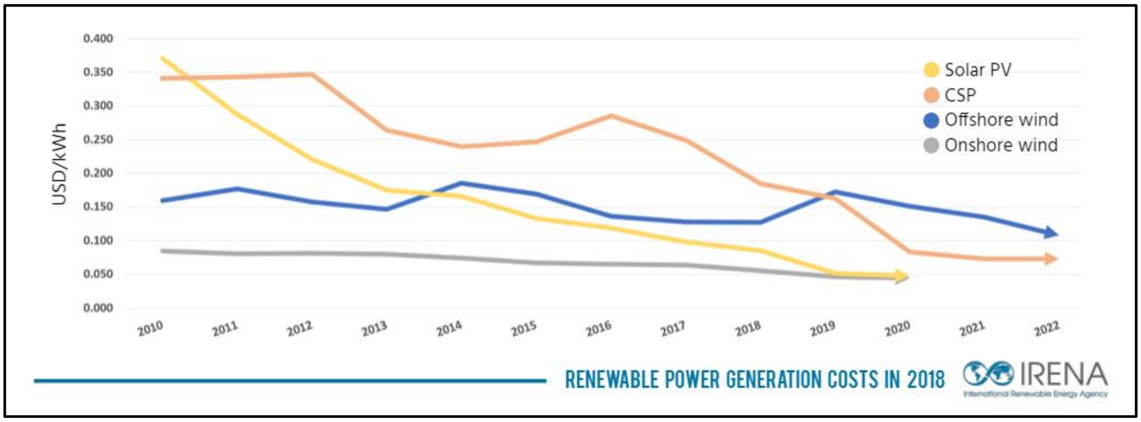


Figure 9: Cost of Renewable Energy Sources Over Time [41]

There are few studies that test the effects of photovoltaic panels on a green roof, but the few are favorable. One study examined three plots of area: one with just a green roof, one with just solar panels, and one with both [42]. Everything else in the experiment remained constant: Plot size, climate, drainage layers, and growing substance. The presence of photovoltaic panels on the grass roof resulted in higher heterogeneity, well mixed, in substrate moisture as well as increased growth of the plant specimens. The increase in substrate moisture was most likely a side effect from the shading from the solar panels. The study reports that the shaded area under the panels averaged 6 degrees Celsius cooler than the outside temperature. Something important to note is that of the twenty different plant specimens in this experiment, the paper noted the greatest growth was by the Sedum sediforme, a member of the succulent family. On the other hand, even though it was hypothesized in the study that the green roofs would produce more electricity than non-green roofs, the study found that the grass roof did not improve electricity production of the solar panels. Overall, the solar panels had a positive effect on the grass roof, in plant growth, cooling, and moisture, while the green roof had no effect on the solar panels [42].

The energy from the rooftop solar panels can be used directly to heat the collected water. The multifunctional solar panel water heater proposes that this system can not only supply hot water but can also lower the indoor temperature since the water is heated instead of the roof itself [43]. This system is beneficial for preventing photoelectric transformation efficiency of the solar panel from lowering and can simultaneously supply hot water for users and cool in summer. In addition, the solar panels can be used to power heating coils through the water collection system. These coils can heat up in the winter, melting any ice dams that may occur. Overall, the solar panels can improve the water collection system by heating the water, cooling the house, and melting any ice dams.

2.3.5 Water Collection

For water collection from a conventional roof, rain collects in gutters and channels the water into downspouts and then into some sort of storage vessel. Rainwater collection systems can be as simple as collecting rain in a rain barrel or as elaborate as harvesting rainwater into large cisterns to supply the entire household demand. Rainwater can be used primarily for grey water systems including toilet water, dishwashers, and washing machines. The water efficiency standards for these appliances have been increasing over the years, which has resulted in these appliances requiring less water per use, as seen in Figure 10 [44].

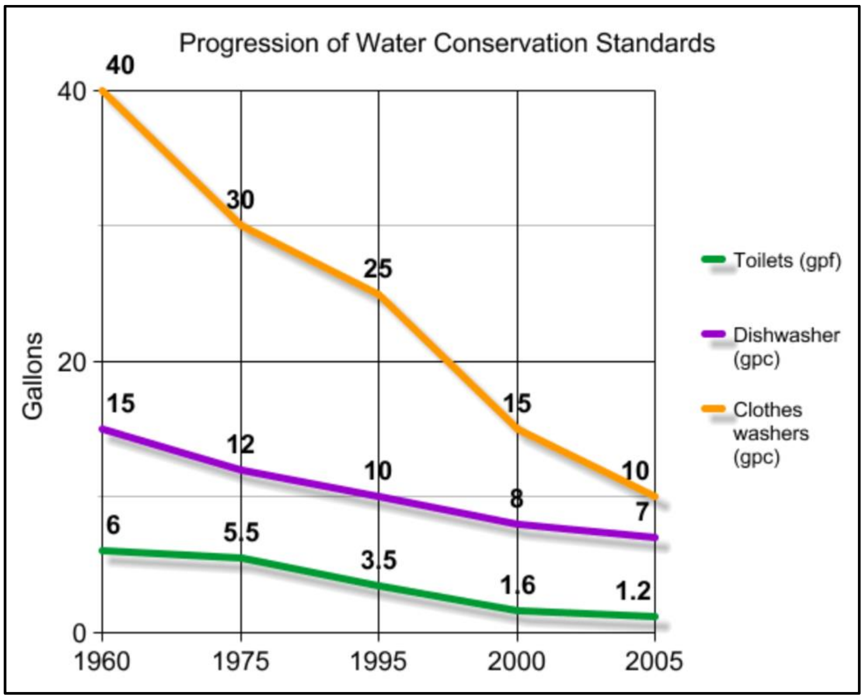


Figure 10: Water Conservation Standards [44]

The amount of rainfall that can be collected can be calculated with the equation:

1″ of rain x 1 sq. ft. = 0.623 gallons.

The average rainfall in Worcester, Massachusetts is 49.2 inches [45]. This means that in theory, for 1 square foot of roof 30.65 gallons of water could be collected in a year. This number assumes a maximum efficiency water collection system, while the estimated gutter efficiency is 62% [46].

Three types of water collection systems are rain barrels, dry systems, and wet systems. The rain barrel system involves installing a barrel under a gutter downspout to collect rainwater. This system is good for its easy implementation and not taking up much space; however, it can hold only about 50-100 gallons making it easy to overflow. A dry system is a variation of the rain barrel that is larger and has pipes that empty rainwater directly into the top of the tank. This system can store a large amount of water and has a low cost for implementation and maintenance since it is a simple system, but it requires the tank to be near the house. A wet system involves installing pipes underground to connect multiple downspouts to fill these pipes. As the underground pipes fill, water will rise in vertical pipes that will then spill into the tank. Also, this system can have the tank installed away from the house; however, a wet system is more expensive [44].

2.4 Revit Simulations

The end goal of this project was to analyze the effects of different components on our green roofing system, and specifically how these components affected energy efficiency and roof structure. To explore these effects further, we incorporated the use of a computer aided design program called Revit, which is used to create civil, structural, and architectural models of different structures. The program is unique as it also comes with built-in energy analysis features, allowing for the user to compare different designs to one another in terms of their energy efficiency. Once the roofing parameters were designed and checked by the use of building code and roofing standards, the design was incorporated into Revit, which was then followed by the final design of our proposed roofing structure. Once the model was fully defined according to our design, we ran energy tests to compare economical and environmental benefits and disadvantages of our green roof with those of a conventional roofing system. Additionally, Revit also accounted for individual aspects of the roof, and the group conducted a solar and thermal analysis to determine the effectiveness of each component, so that we gained a better understanding of how they functioned together.

3.0 Design

3.1 Design Objectives

From the extensive background research done on green roofs, solar panels, and rainwater runoff systems, the team identified design parameters that were essential for an efficient roof that could integrate all these systems together. One of the biggest gaps noticed was that green roofs have been primarily constructed for commercial use rather than residential. The team made that a priority for this project: affordability and a design such that it could be incorporated on the residential houses. With that in mind, the team identified the following factors that should be incorporated in the roof design.

- Efficiency from solar panels based on tilt and azimuth
- Water collection for grey water systems
- Structural design to support roof loads
- Insulation - keep heat in during the winter, keep heat out during the summer
- Affordable at a residential level - includes lifecycle and maintenance cost

However not all the factors can be optimized - there have to be compromises for overall goals to be reached. Table 2 below highlights the many benefits and disadvantages of the above parameters and how they affect one another.

Table 2: Design Objectives

	Solar Efficiency	Water Collection	Roof Structure	Insulation (Soil depth)	Affordability
Solar Efficiency		Solar panels would not affect water collection	More Solar panels would increase the weight of the roof	Solar panels results in a decrease in temperature on the shaded surface	Need enough solar generated electricity to offset energy bill
Water Collection	Water collection would not affect solar efficiency		Water collection drainage layer would add weight to the roof	Water collection drainage layer would add an extra layer of insulation	Water collection system would save money if the water can be reused
Roof Structure	Roof tilt needs to be at 30 degrees to maximize solar efficiency	Roof tilt would affect the flow of water in the drainage system		The Roof structure would not affect the soil, but air entrapment would improve overall insulation	Cost of roof structure contributes to overall cost
Insulation (Soil Depth)	Soil Depth would not affect solar efficiency	Thicker soil depth would result in less water getting through to the water collection system	More soil would result in more weight		Less soil would cost less up front, but more soil would be a better insulator

3.2 Preliminary Designs

3.2.1 Conventional Roof Construction

For this project we compared our green roof to a more standard design. Our conventional house has a typical 9 pitch roof. The roofing layers are what would commonly be found for residential homes. This includes installing insulation in the attic floor which would not have any effect on our roof. The layers starting from the bottom are plywood decking (7/16in. thick), air filtration barrier (1/8in.), plywood decking (7/16in.), water barrier (1/8in.), tar paper (1/16in.), and asphalt shingles (3/16in.). This setup served as our residential roof baseline.

Figure 11: Conventional Roofing Layers

3.2.2 Initial Green Roof Design

To achieve the design factors identified in section 3.1, an initial design for the green roof was modeled as seen in Figure 12. The roof was put at 10-degree pitch so that rainwater would be able to run off into a storage system, and any additional precipitation, such as snow, would slide off the roof due to gravity, as opposed to a flat roof in which snow and rain could accumulate and inflict structural damage. Then the solar panels were mounted at a 20-degree tilt on top of the green roof, so their overall tilt was 30-degrees, which is the tilt needed to maximize the efficiency of the panels in Massachusetts [47].

The entire roof was covered by the green roof to maximize rainwater collection that would be filtered by the green roof. This water would either be absorbed by the soil or pass through it to the drainage layer underneath and the gutters, ending up in a dry system tank. The dry system tank was chosen because it is inexpensive to install and can hold 50-100 gallons of rainwater to be used for greywater systems. Any precipitation on the solar panels would flow down them into the green roof to be collected as well. The growing medium was set to be 6 inches thick, since having the recommended maximum amount of thickness for an extensive green roof would provide the best thermal resistivity, which would help with the energy performance of the roof.

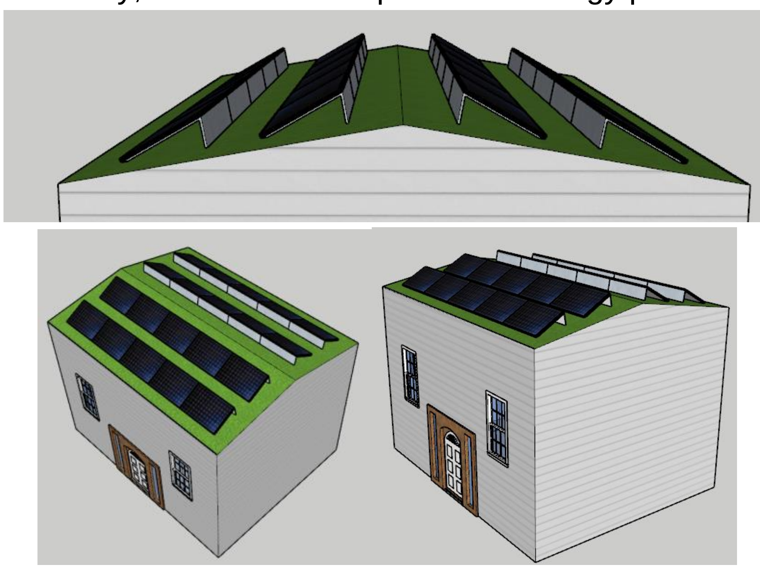


Figure 12: Initial Design

3.2.3 Evolution of Green Roof Design

Four different preliminary roof designs were considered that incorporated all the aspects of the initial design as seen in Figure 13-16.

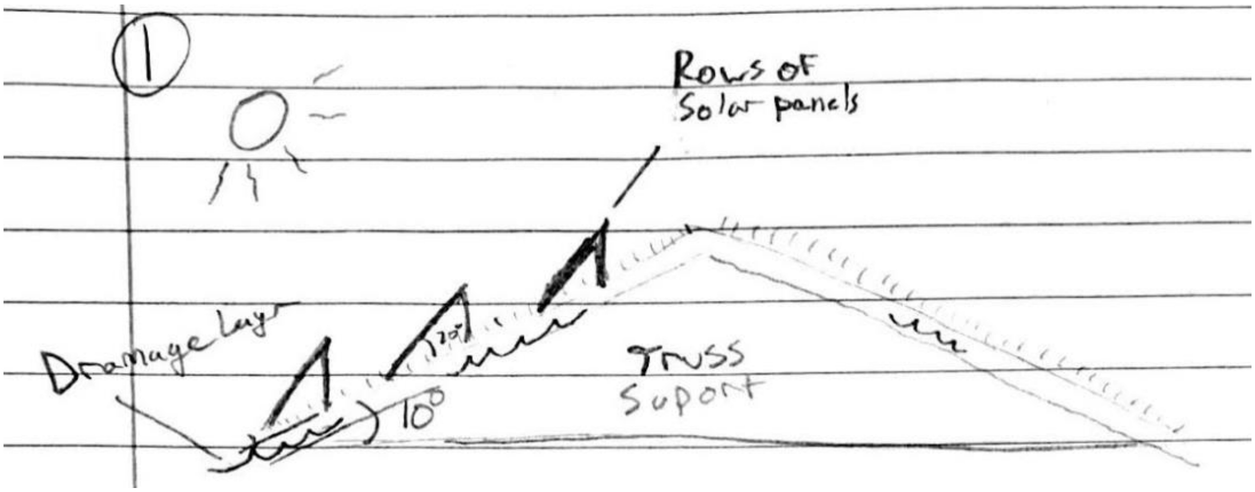


Figure 13: Roof Design 1

PROS: Green roof throughout the whole roof, maximizing water collection.
CONS: Difficult to mount solar panels to soil, mounting could affect drainage layer.

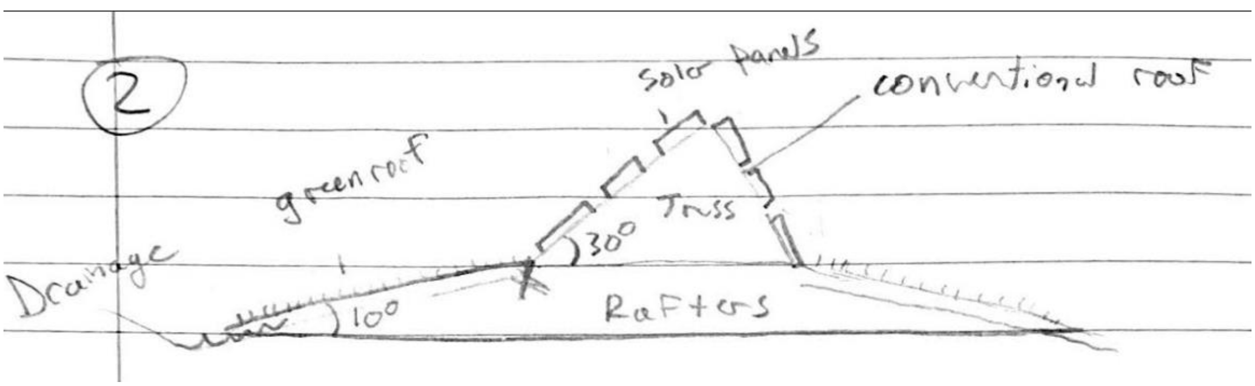


Figure 14: Roof Design 2

PROS: Solves the solar panel mounting issue, balances green and conventional roof.
CONS: Greatly reduces the amount of actual green roof, likely snow would accumulate at sections where the two roofs meet, would need two sets of structural support.

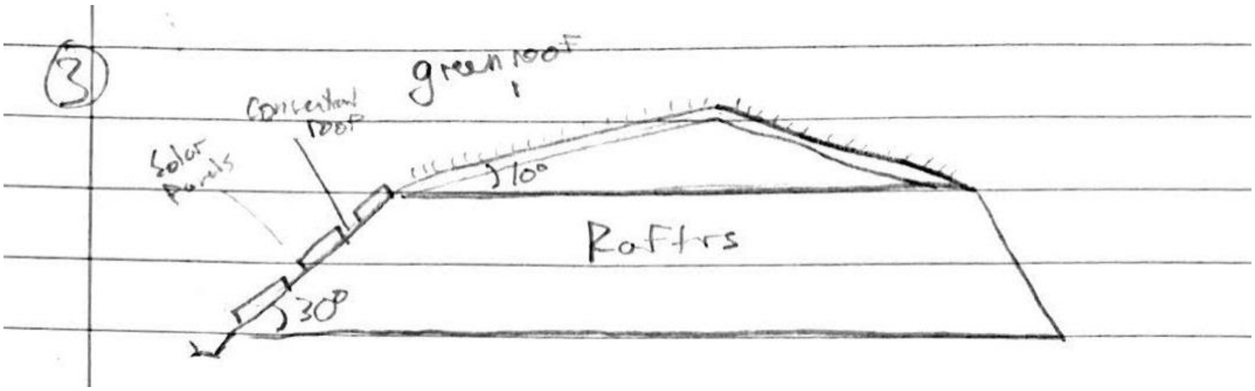


Figure 15: Roof Design 3

<u>PROS:</u> Easier to construct than roof design 2, fixes the snow load issue, could be built with a single roof support
<u>CONS:</u> Possible drainage issue, water runoff from solar panels may not be collected, would need two sets of structural supports.

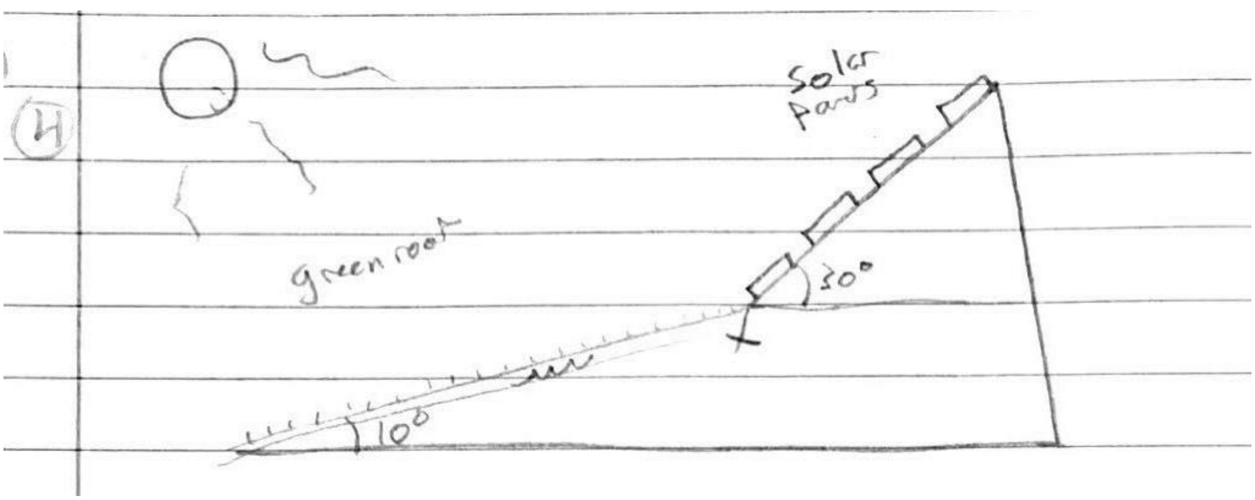


Figure 16: Roof Design 4

<u>PROS:</u> Maximizes both green roof and conventional roof
<u>CONS:</u> Snow load issue again, non-symmetric framing

Roof Design 3 was selected as the most feasible option for best integrating the solar panels, grass roof, and water collection systems. While there were concerns about collecting water runoff from the solar panels, the rainwater leaving the green roof drainage system could flow underneath the solar panels. When the solar panels are mounted to the roof, there will be an approximate 2-inch gap between the solar panels and the roof. This way, there would be no interference with the water to flow into the gutters. Roof Design 3 also avoided the issue with snow loading. The team was concerned about the roof collapsing due to snow pile-up on Roof Design Two and Four, where the upper roof section meets the lower roof section. Roof Design Three does not have a section of concern.

To support the structure of Design Three, the group designed a truss system to support the weight of a heavier roof. The truss was designed for two rows of solar panels fit on the 30-degree slope on each side, with the middle slope designed to hold the green roof. The truss is shown below in Figure 17.

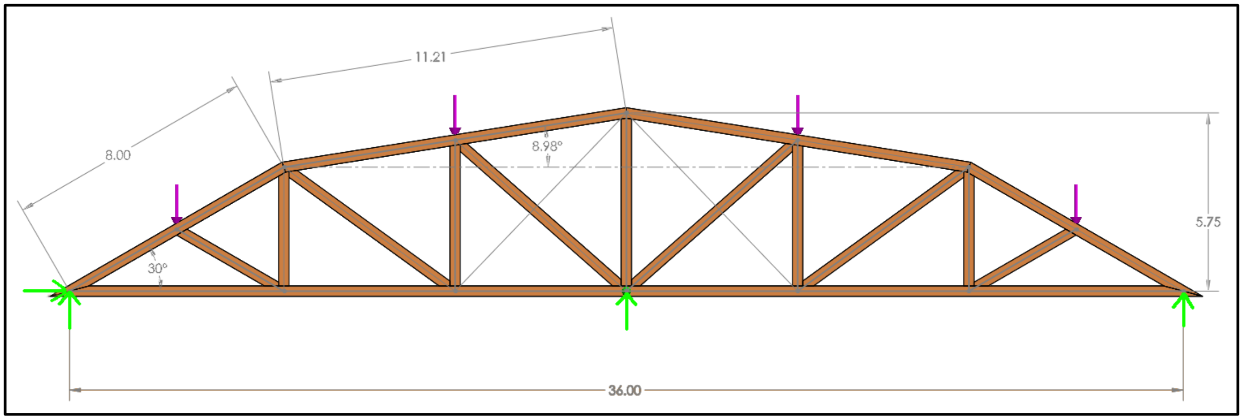


Figure 17: Proposed Truss Design

The truss has a total of 14 joints and 25 members. To check if the truss would be stable, the equation below was used:

$$2n \leq m + r$$

Where n is the number of joints, m is the number of members, and r is the number of reaction forces. The amount of reaction forces (green arrows) that would act on the truss would be 4 with three being exerted from the supporting two exterior walls on the edges of the truss. They both exert vertical reaction forces, with one side exerting an additional horizontal force for stability. The last reaction force comes from an interior wall at the midspan. The 4 forces applied from the green roof areas and solar panels are depicted by the purple arrows in Figure 17. The roof loads within the green roof areas and solar panels were modeled as a set of concentration forces.

Research had to be done on what material would be best suited for the truss, and the conclusion was that a wooden structure would suit a residential home best. While steel trusses are stronger and widely used, they are more suited for commercial structures such as storage warehouses and larger buildings, and since they are significantly heavier, there would be a risk of structural damage without redesigning supporting walls, which the team wanted to avoid at all costs. Steel trusses could not simply be placed on typical stud walls. For this reason, wood was the desired material to be used due to its durability and lighter weight, and upon further research in the US Lumber database, Southern Pine was decided on, since it was a stronger, abundant wood. Referring to American Wood Council [48] and National Design Specification standards, it was also decided that in the case of a residential roofing truss, 2x4 members would best suit the structure of the house and also provide for a stable truss.

Upon deciding on material, as well as completing weight calculations for each of the four split roof sections (two for solar panels, two for green roof), the final step was to apply the calculated loads onto the truss system and determine the members were below the allowable stress. Upon applying these loads, it was determined that the truss was sufficient to hold the roofing as long as they were spaced at between 16”-18” following the wood studs of the wall structure.

The trusses would then be covered by standard 7/16” plywood decking (which was confirmed along APA design specifications) followed by the proposed green roof layers, which from bottom to top include a water vapor barrier, protection barrier, gravel drainage layer, air barrier, growing medium, and vegetation. The team decided to replace the plastic drainage layer of the initial design with a gravel layer, which would allow for water to seep through more naturally while still keeping the growing medium and vegetation in place. In addition, gravel would remove the large air gaps that the plastic layer would create, creating more surface area to act as support for the above layers. However, this would also add more weight to the roof, as the concentrated gravel weighs about 4lb/ft^2 compared to the plastic drainage layer that weighs 1lb/ft^2, so as a result more trusses that are tightly spaced are required, which was previously expected.

In terms of a conventional roof, estimates for a typical asphalt roof range from $1.50 - $5.50 per square foot, depending on the slope, pitch, and size of the roof [49]. Prior to weight testing (see Section 3.5.2), the initial cost estimate for the proposed green roofing system was around $22 per square foot, with $10 of that stemming from the plastic drainage layer. However, pea gravel costs only 0.38$/sq ft which significantly reduced the estimated cost of the green roof to $13/sq ft.

3.3 Proposed Roof Design

With all parameters from above, a proposed roof was modeled in Figure 18. The 30-degree tilt section of the roof was covered with solar panels, while the green roof section was divided with 1-foot baffles to contain the soil. A 4-foot maintenance walkway was located on the side of the roof to allow the residents to reach the green roof as needed. The image below shows the roof without the soil mixture or vegetation.

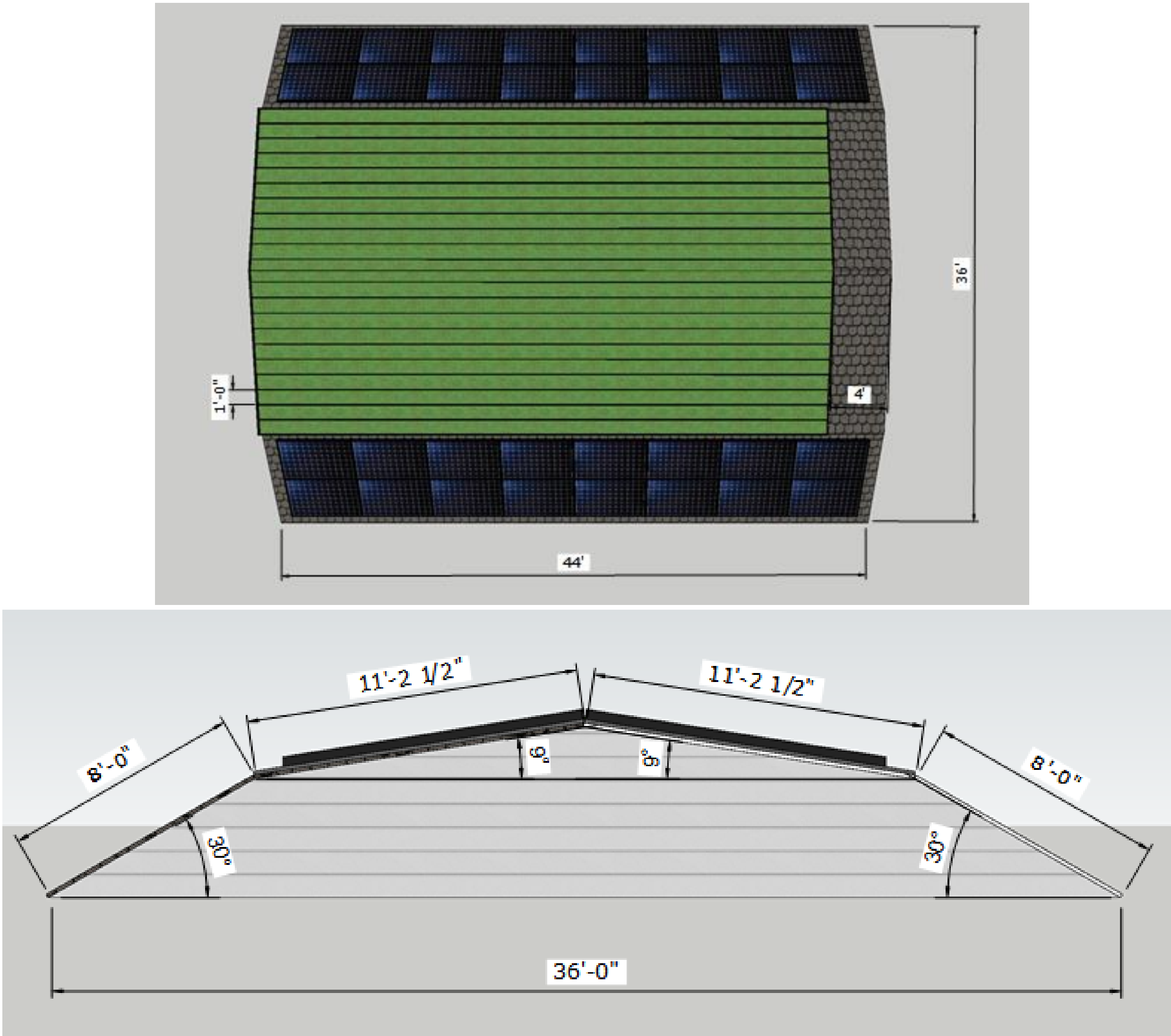


Figure 18: Proposed Roof Design

The baffles shown in the green roof section are 1-foot apart and are meant to keep the soil from blowing off the roof. There are slits at the bottom of the baffles to allow water to pass underneath them. The gutter system would then direct the water into a tank that the residential house could use for grey water systems. This way the water could flow from the green roof onto the conventional roof, underneath the solar panels, and into the proposed gray-water collection system. The Figure 19 below shows the slits.

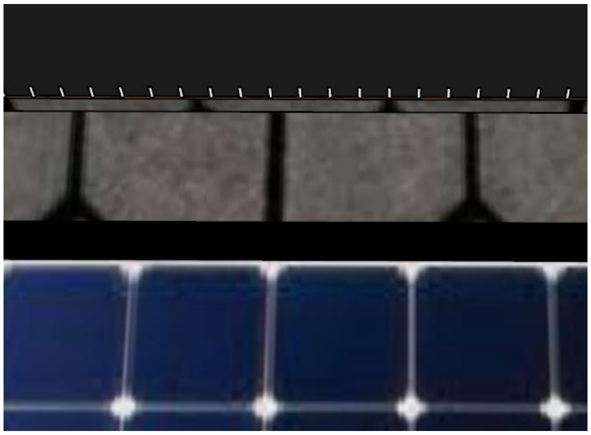


Figure 19: Drainage Slits on Green Roof Baffles

3.4 Experiments

To test the proposed design, the team constructed multiple experimental designs that involved investigating the compatibility of different vegetations and growing mediums, drainage of water through the growing medium, and the power output from a solar panel. Other aspects were considered, such as the weight of the overall system, the roof's supporting structure, and the local weather's effects on the system. The purpose of these experiments was to determine which combination of vegetation and soil mixture would work best for this green roof in terms of drainage, weight, survival of the vegetation and thermal insulation. Additionally, the experiments helped determine whether the truss would have to be redesigned to hold the weight that the resulting soil would have.

3.4.1 Experimental Design

To test our proposed system of vegetation roof, our team assembled 10 plywood boxes that replicated the exact layers that were planned for use on the green roofing system. Each test box was built and loaded with the layers as shown in Figure 22, assigned 1 of 3 soil mixtures, and then assigned 1 of 3 vegetation types. A 10th box with no vegetation was made for solely soil testing. The boxes were also labeled using an alpha-numeric numbering system to allow for easy identification. The two initials represent the genus and species of the plants and the number is the soil mixture. Figures (20-23) show details of each specific box and its soil mixture contents, as well as the framing of the box itself.

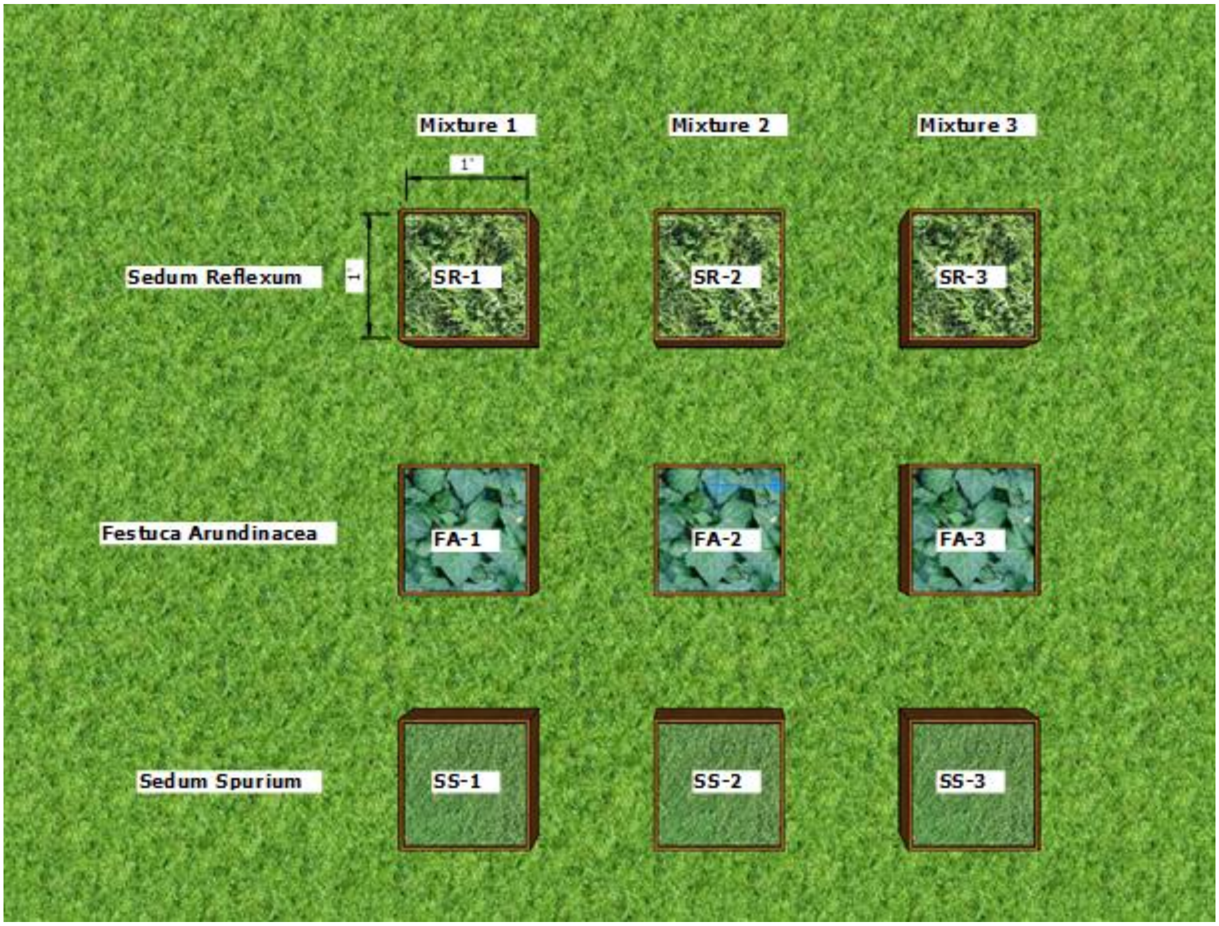


Figure 20: Experimentation Model

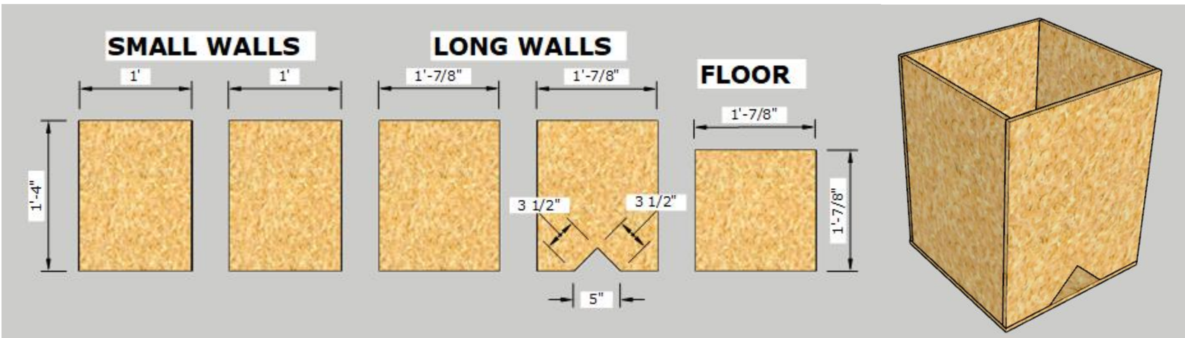


Figure 21: Dimensions of Planter Box Walls and Floors

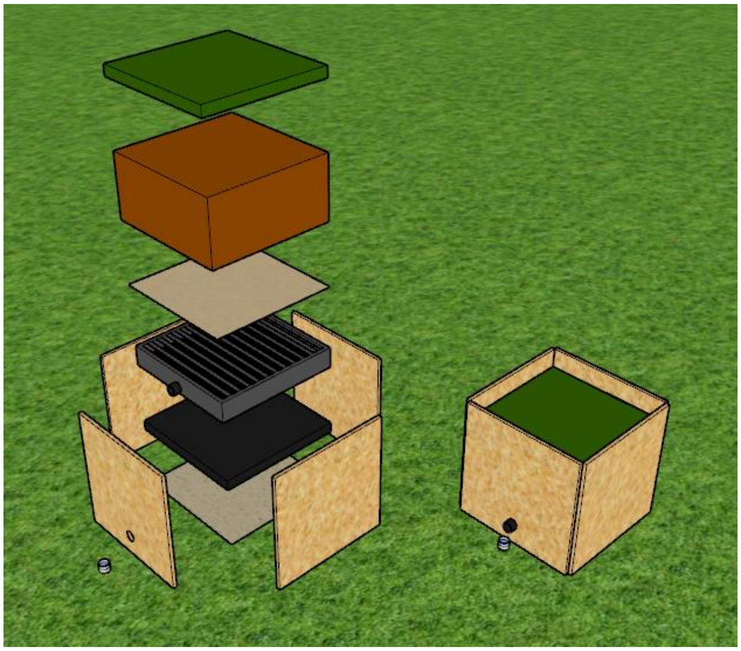


Figure 22: Exploded View of Assembled Planter Box

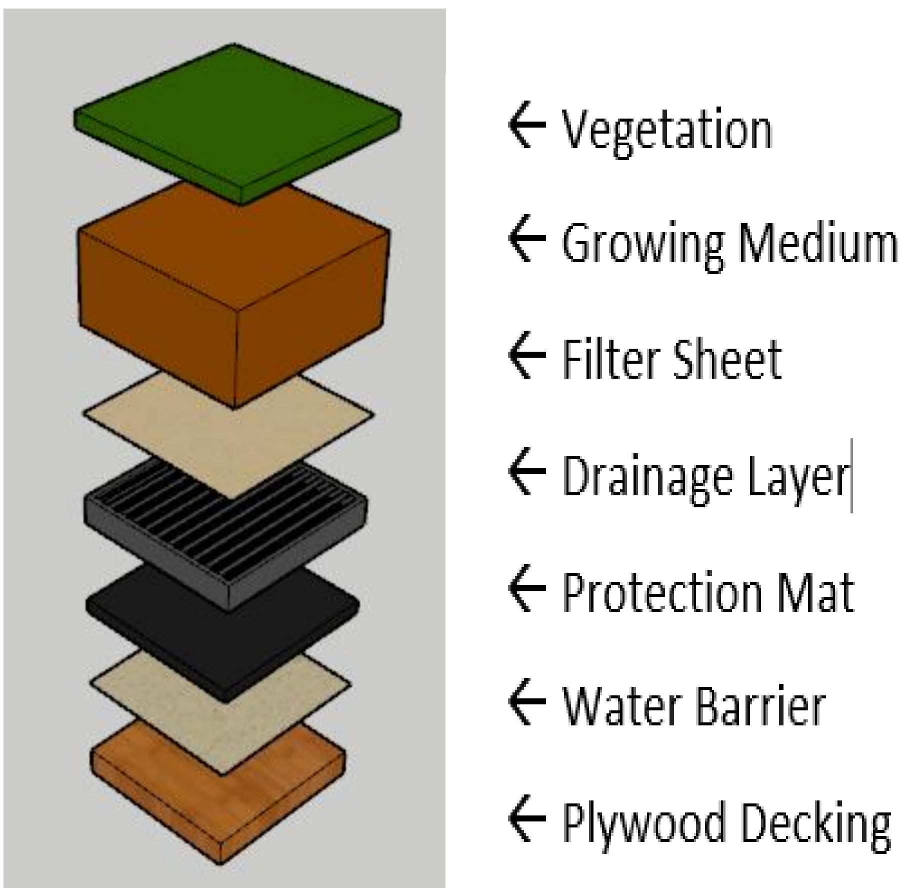


Figure 23: Green Roofing System Layers

Table 3: Detailed Layer Parameters

Layer	Cost	Weight	Thickness
Solar Panel Layer	$3/Watt	3lbsf	2”
Baffles	$0.50/sf	3lbsf	7/16”
Vegetation Layer	$5/sf	2lbsf	2”
Growing Medium Layer	$1.73/sf	4.375lbsf	3”
Filter Sheet Layer	$0.13/sf	~0lbsf	1/16”
Drainage Layer	$0.38/sf	4lbsf	1/2”
Protection Mat Layer (Rubber vinyl)	$1.23/sf	0.03lbsf	1/2”
Water Barrier	$0.25/sf	0.1lbsf	1/16”
Plywood Decking	$0.50/sf	1lbsf	7/16”
Total per square foot	$12.72/sf	17.505/sf	8”

3.4.2 Vegetation Decisions

One of the most important aspects of our green roofing system is the vegetation. Table 4 below shows the three of the vegetation types that were used for the experiments, based on different factors such as their height, cost, soil mixture, water needed

Table 4: Vegetation Details

Vegetation	John Creech Stonecrop Succulent *Sedum spurium* 	Blue Spruce Stonecrop Succulent *Sedum reflexum* 	Tall Fescue Grass *Festuca arundinacea* 
Water	minimal	minimal	1in per week
Cooling effects	4°C lower	4°C lower	12°C lower
Height	1-3in	3-5in	4-6in
Hardiness zones	3-8	3-8	4-9
Suggested Growing Medium	Sandy soil with other lightweight minerals such as perlite and pumice, and with the addition of peat moss or coconut coir (good drainage mix/mostly no organic compound)	Sandy soil with other lightweight minerals such as perlite and pumice, and with the addition of peat moss or coconut coir (good drainage mix/mostly no organic compound)	Soil with about 20% organic compound (needs to hold some moisture) and 80% minerals (clay, sand, pumice, vermiculite, etc.)
pH of soil	5.5-6 (slightly acidic)	5.5-6 (slightly acidic)	Neutral (around 7)

Succulents in the Sedum genus require minimal water. In the climate of the northeast their water needs would often be met with 1 rainfall event every two weeks. The John Creech Sedum is recommended for USDA hardiness zones 3 to 8. Worcester is located in zone 6a which is well in range for these plants [50].

One paper studying the cooling effects of different plant types found on warm days, the temperature below Sedum canopies was on average 4°C lower than the temperature of bare substrate [51]. Another study looked at the thermal behavior of sedum plants under Nordic winter conditions. The study simulated green roof conditions and used thermocouples to observe the roof layers. Thermal resistance of the green roof when all layers were frozen was 2.01 m^2 K W−1. The study found that the vegetation layer was a consistently better insulator than the substrate layer [52]. These cold conditions are comparable to Worcester winter conditions. Since sedum spurium have been shown to be efficient insulators, these plants would be ideal candidates for our proposed vegetation layer. The species were ultimately chosen based on availability as the vegetation was acquired at the end of the season.

3.4.3 Growing Medium Decisions

Since succulents require minimal water, the growing medium has to be good at draining, which means most of the ingredients need to be minerals with little to no organic matter in it. The suggested soil mixtures to achieve good drainage and still be lightweight are sandy soils mixed with volcanic rock, such as pumice, or other mixtures such as bark and gravel. Additionally, succulents thrive better in slightly acidic soil, which has a pH value of about 5.5-6. This is not ideal for our water collection system because the water becomes somewhat acidic and therefore harmful to both internal systems and people using the water itself. Therefore, the aim was to achieve a neutral pH value and run pH tests on our plants' outflow water.

For grass, which typically needs more water, the suggested soil mixture requires about 20% organic matter to hold water and supply nutrients to the grass. The rest of the soil must be a combination of lightweight minerals such as sand, pumice, perlite, and vermiculite to provide drainage, so the grass is not over-watered. This also supplies a method for water to drain to the water collection system under the soil layer. Also, grass prefers a soil with a pH value of about 7 (neutral).

Using Sailor's experiment of thermal properties of green roof soil mentioned in Section 2.3.2 above, the R-Value of the soils that were most similar to the mixtures for the team's roof design were calculated and graphed below.

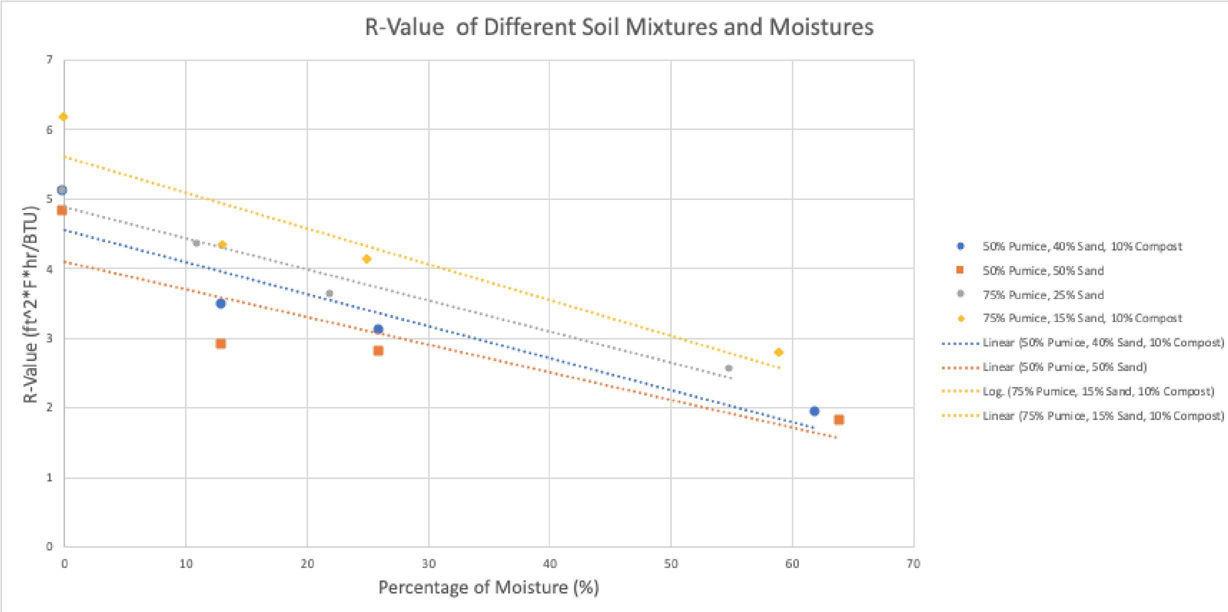


Figure 24: R-Value of Different Soil Mixtures

Because of the time and budget constraints, the team was not able to test all combinations or different materials but using the data of the different soil's R-Values and the effect of moisture, the team decided on three different mixtures. These mixtures were used for experiments to test their thermal properties and ability to drain water. Since Sailor's results showed that a high percentage of pumice increased the R-Value, the team decided to use a high percentage of volcanic aggregate. Perlite is a good substitute for pumice because it acts as a great insulator, is lightweight, and is a more affordable option as well. Sand acts as a good anchor and holds some moisture, but because of its high weight a low percentage was added in the mixture. To achieve a soilless mixture for succulents, in place of compost, coconut coir was used as it still can absorb enough water to supply the succulents while draining most of the water meaning it also permits good air travel to supply the roots with oxygen. To compare to coconut coir and Sailor's results, compost was used in one mixture with a higher percentage than Sailor used. These mixtures and their ingredients can be seen in the table below:

Table 5: Soil Mixtures Used for Testing

Soil Mixtures	Perlite	Sand	Coconut Coir	Compost
Mixture 1	80%	20%	0%	0%
Mixture 2	75%	15%	10%	0%
Mixture 3	75%	10%	0%	15%

As stated in the design goals, the five aspects that were measured for each mixture were insulation, water collection, weight, cost, and survivability/growth of vegetation. To measure insulation, the team measured the thermal conductivity using a thermal conductivity probe, as well as temperature readings with thermal couplings. Water collection was measured by pouring a set amount of water through the growing medium and measuring the percent of water that flowed out of the drainage layer and into a measuring water pitcher, as well as measuring the flow rate. Survivability and growth of the vegetation, shown in Appendix 1, in the mixtures was observed throughout the testing period and at the conclusion of the tests. The cost and weight of these mixtures can be seen in the table below.

Table 6: Cost & Weight of Soil Mixtures

Soil Types	**Cost**	**Weight**
Perlite	$8.5 cuft	2 lb/cuft
Sand	$0.5 cuft	100 lb/cuft
Coconut Coir	$15 cuft	42 lb/cuft
Compost	$5 cuft	40 lb/cuft
Mixture 1	1’ (Thickness) = $6.90/sf **6” (Thickness) = $3.45/sf**	1’ = 21.6 lbsf **6” = 10.8 lbsf**
Mixture 2	1’ = $7.95/sf **6” = $3.98/sf**	1’ = 20.7 lbsf **6” = 10.35 lbsf**
Mixture 3	1’ = $7.15/sf **6” = $3.58/sf**	1’ = 17.5 lbsf **6” = 8.75 lbsf**

3.5 Experimental Testing

3.5.1 Drainage Testing

The drainage tests were conducted using our control (box 10), which was constructed specifically for this test. For this test, the box was placed on a 10° incline intended to mimic the tilt of the green roof design, and 0.5 gallons of water were poured into each soil mixture at the same flow rate. For our experiments, the team poured half a gallon of water into the mixture over a time period of 30 seconds. This resulted in a flow of 0.0167 gallons per second. The volume of the outflow was then measured and recorded, and the water’s new pH value was compared to its original value.

Figure 25: Drainage Test Setup with Tester Box

Table 7: Drainage Testing

Week	Box	Flow Rate (Gallons/s)	Moisture Content	pH Level Input Water	pH Level Drainage Water	Water added (Oz.)	Water collected (Oz.)	% Water Return
12/9/2019	Mixture 1	0.0167	**Before**: 10% **After**: 40%	7	6.5	64	16	0.25
	Mixture 2	0.0167	**Before**: 10% **After**: 50%	7	6.5	64	8	0.125
	Mixture 3	0.0167	**Before**: 10% **After**: 90%	7	6.5	64	12	0.1875

The table above shows the data collected from the drainage testing of Box 10, and moisture content was measured both before and after testing. After the drainage water was collected, the moisture content of each mixture was measured with a hydrometer to assess generally how much moisture was in the growing medium. Mixture 3 had a higher moisture content because the compost absorbs water more as the other mixtures are combinations of minerals that don't really absorb water but rather hold it in air gaps between the minerals, which the hydrometer did not read too well. This means that mixture 1 and 2's moisture content could be higher than what is shown above. The water that flowed through the filter sheet in the box was drained into a large measuring cylinder so that the reclaimed water could be measured, and the percentage returned was calculated by dividing the amount of collected water by the initial volume, which was a constant of 64 oz (½ gal). Once all of the excess water was in the cylinder, pH strips were used to measure whether or not the water had become too acidic or basic. The standard pH levels of drinkable water are normally between 6.5-8.5, and the input water was measured to have a pH of 7 meaning the water collected from each mixture became slightly acidic, but still within normal range.

Using the horizontal surface area of both roofing types, and incorporating the 18.75% drainage of soil mixture three, we were able to calculate the amounts of rainfall collected by each roof. From Section 2.3.5, it was estimated that 49.2 inches of rainfall occurs in Worcester per year, and it is assumed a gutter system collects 62% of rainwater that follows through it [46]. From all the information above, about 14,927.61 gallons per year would be collected for the team’s roof design.

$$\textbf{\textit{Conventional Section}}:$$
$$49.2in/12in \times 609.84ft^2 \times 7.41gallons/ft^3 = 18{,}527.55\ gallons/yr$$

$$\textbf{\textit{Green Roof Section}}:$$
$$49.2in/12in \times 974.16ft^2 \times .1875 \times 7.41gallons/ft^3 = 5{,}549.24\ gallons/yr$$

$$\textbf{\textit{Total}}: 5{,}549.24 + 18{,}527.55 = 24{,}076.79 * 0.62 = 14{,}927.61\ gallons/yr$$

Compared to a conventional roof that would collect 29,836.57 gallons per year from the calculations below.

$$\textbf{\textit{Conventional Roof}}:$$
$$49.2in/12in \times 1584ft^2 \times 7.41gallons/ft^3 * 0.62 = 29{,}836.57\ gallons/yr$$

Even though the conventional roof collects more water, the green roof produces 9,149.18 gallons per year of runoff as the conventional roof produces 18,286.93 gallons per year of runoff based on 38% of rainwater not being collected by the gutters. This percentage could be lower based on rainwater not being collected in gutters by other causes such as evaporation. Overall, the green roof produces less runoff as well as collects a good amount of water, this making it the better choice environmentally.

3.5.2 Weight Testing

For our weight test, each box was placed on an electronic scale and its weight was recorded. All of the boxes were weighed both before and after drainage testing, which was done to determine how much water the soil mixtures were absorbing, as we also wanted to see how the weight would change when retaining rainwater and how that would affect the stress on the structural system. These results were used to determine how much a 1 square foot section of the roof would weigh when fully saturated. The box itself weighed 7 lbs, so 7 pounds was subtracted from each.

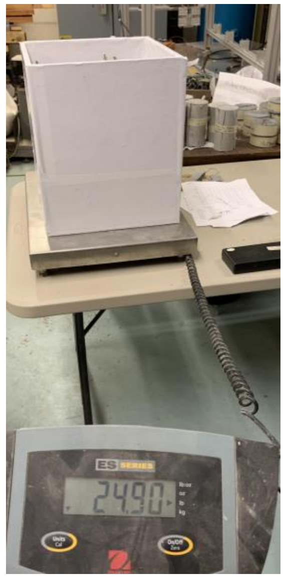


Figure 26: Scale Measuring Boxes

The weight of the 9 boxes are shown in the table below. The moisture levels were measured with a hydrometer. The average weight of the boxes was 29 lbs. By plant type, the average weight of boxes 1, 4, and 7 containing Sedum spurium was 20.4 ± 0.72 lb. The average weight of boxes 2, 5, and 8 containing Sedum reflexum was 25.9 ± 0.62 lb and the average for boxes 3, 6, and 9 containing Festuca arundinacea was 19.7 ± 1.49 lb. By soil mixture, the average weight of boxes 1, 2, and 3 containing mixture 1 was 20.4 ± 3.88 lb. The average weight of boxes 4, 5, and 6 containing mixture 2 was 25.9 ± 2.36 lb and the average for boxes 7, 8, and 9 containing mixture 3 was 19.7 ± 2.2 lb.

Table 8: Weight Measurements of Boxes

Box	**Weight (lbs)**	**Moisture Level (out of 10)**
SR-1	21.3	1
FA-1	28	5
SS-1	18.8	1
SR-2	20	2
FA-2	25.25	5
SS-2	20.55	2
SR-3	19.95	2
FA-3	24.55	5
SS-3	19.8	3
Average	22.02	

3.5.3 Survivability Journal

For the survivability test, a journal was compiled for a six-week testing period. The four categories were green percentage, ground cover percentage, average height and maximum height. Figures 27-30 below show the change over time for each category for each box. The legends contain the abbreviation for the genus and species for each vegetation type and the number of the associated soil mixture.

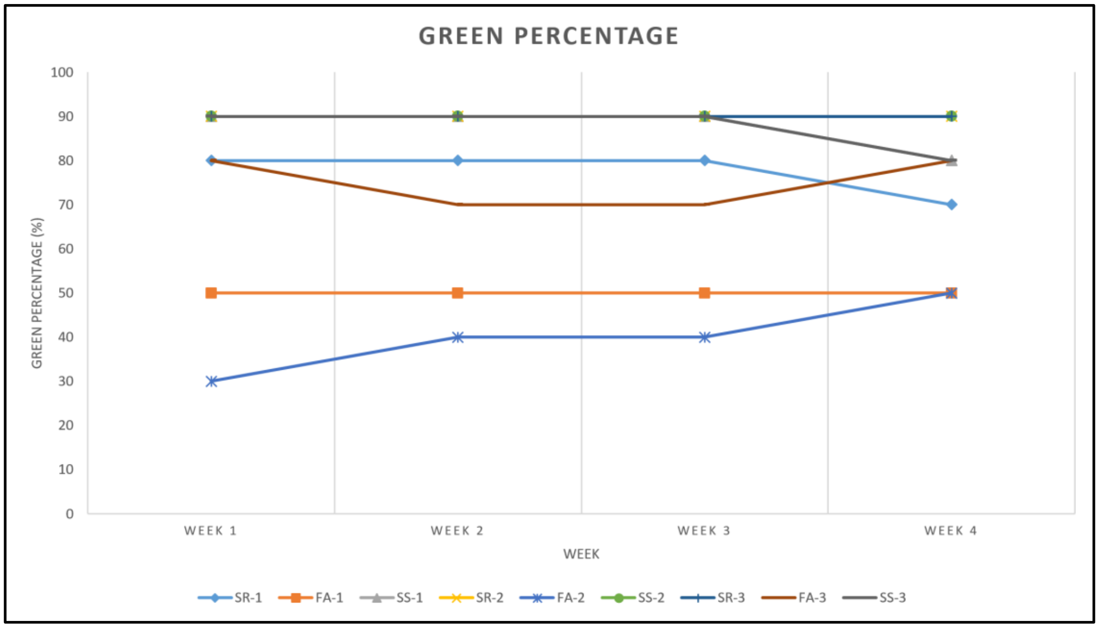


Figure 27: Graph of Green Percentage

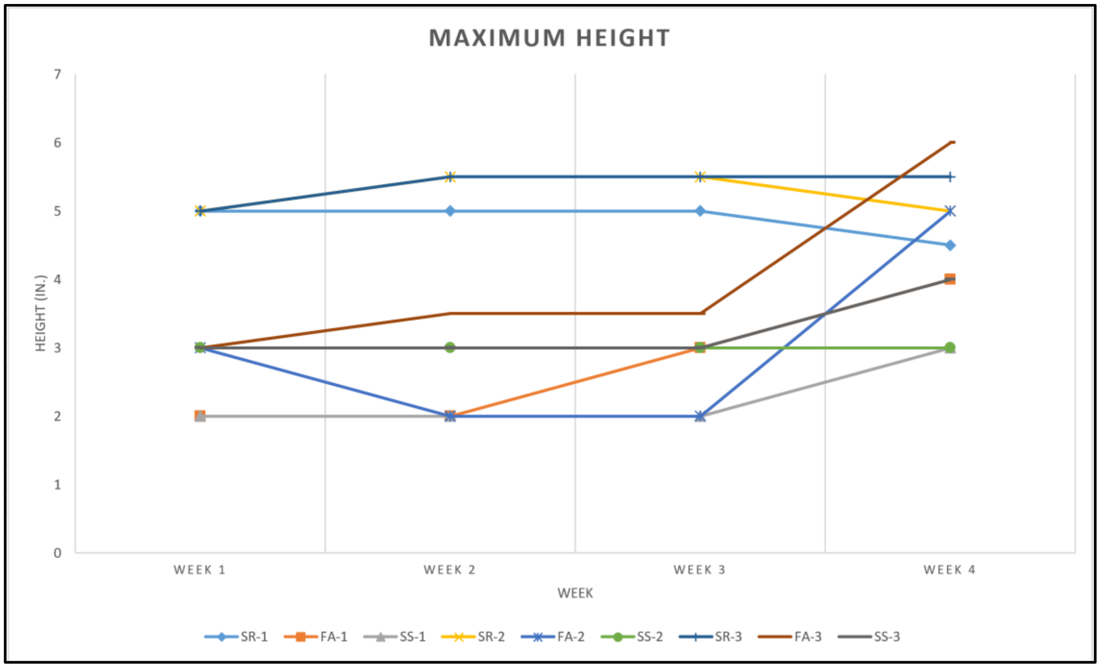


Figure 28: Graph of Plants' Maximum Height

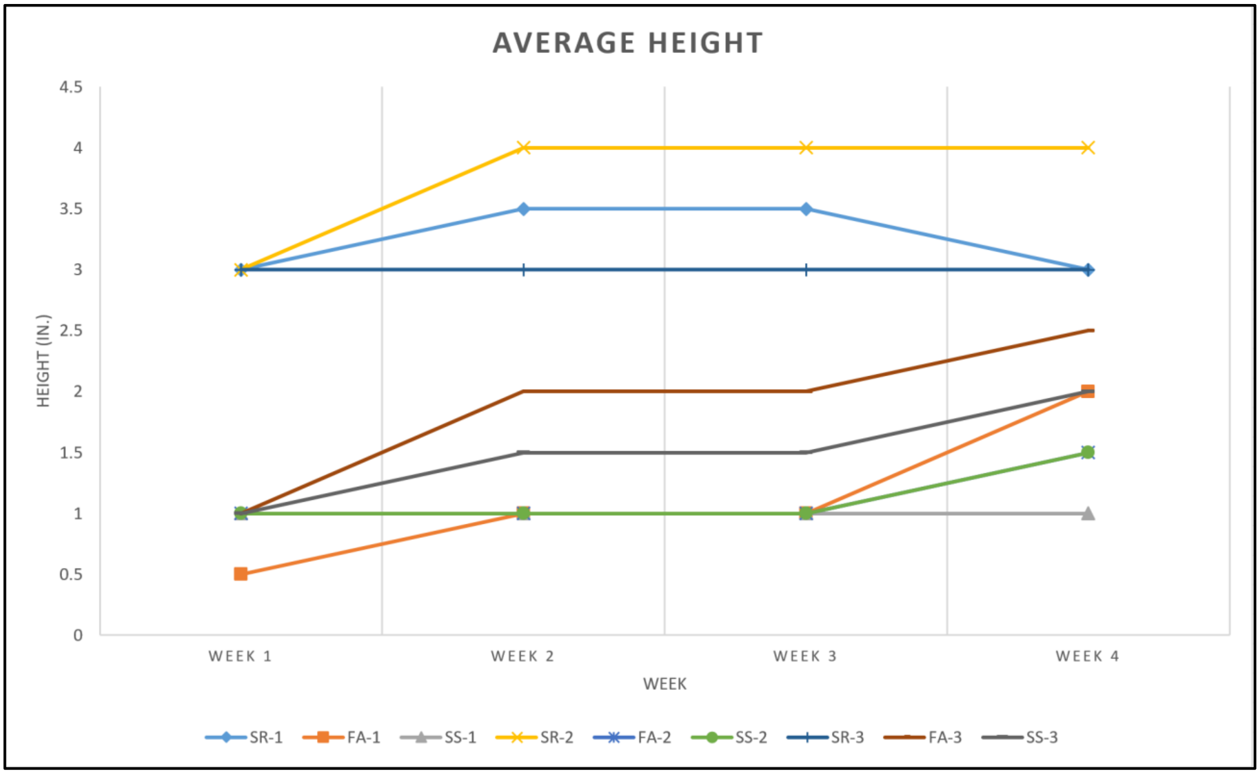


Figure 29: Graph of Plants' Average Height

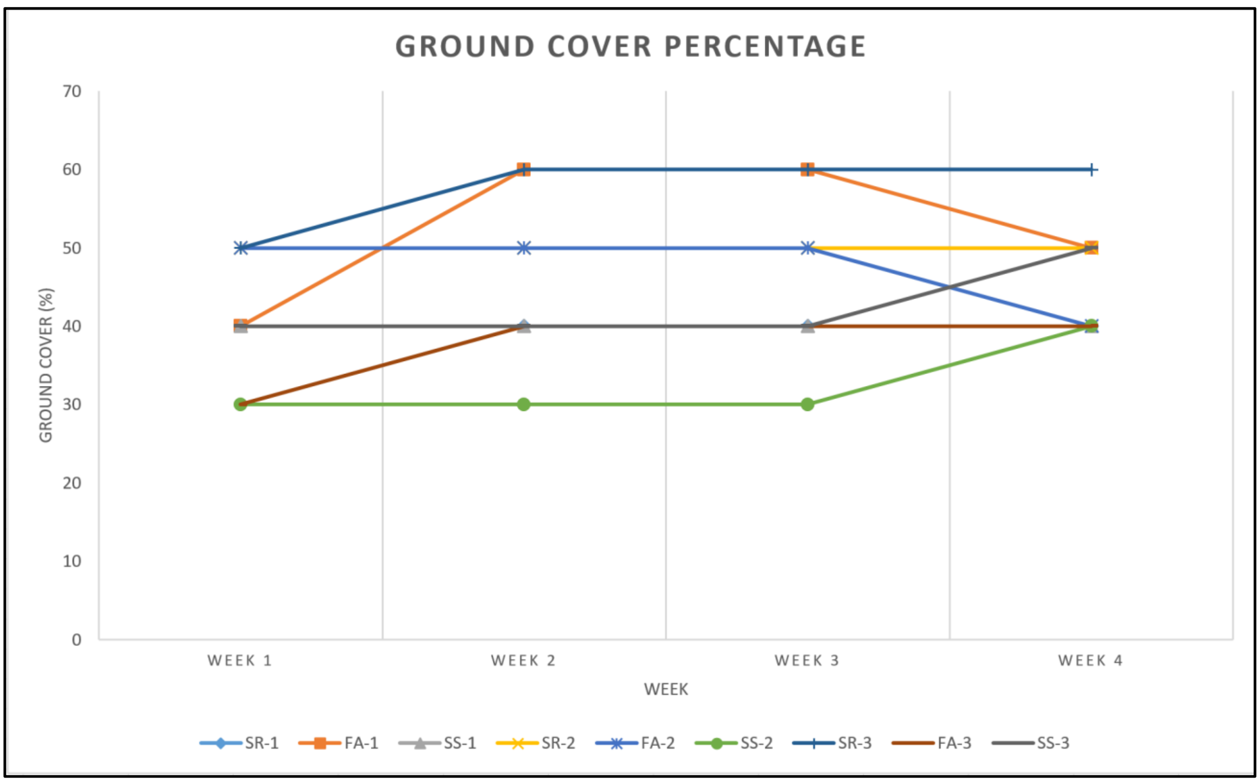


Figure 30: Graph of Plants Ground Covered

3.5.4 Solar Testing

The Solar Panel the team used in the experiment was the SunPower X22-360. This silicon photovoltaic cell produces a nominal power of 360W at an irradiance of 1000W/m^^{2} according to US Solar Works. This panel has dimensions of 5.11 ft by 3.43 ft, giving the panel a surface area of 17.5273 ft^2. 360W / 17.5273ft^^{2} results in 20.54 W per square foot. Similarly, the SunPower X22-360 weighs 41 pounds, meaning it weighs 2.34 lb per square foot of covered area. Different variables, such as the tilt of the roof, orientation of the house, and weight of the racking (which is typically 1-2 lbsf [53]) could also affect the panel's output numbers and the roofing structure itself. For our testing, the panel was mounted on a 30° tilt solar racking and placed on the WPI East Hall Parking Roof.

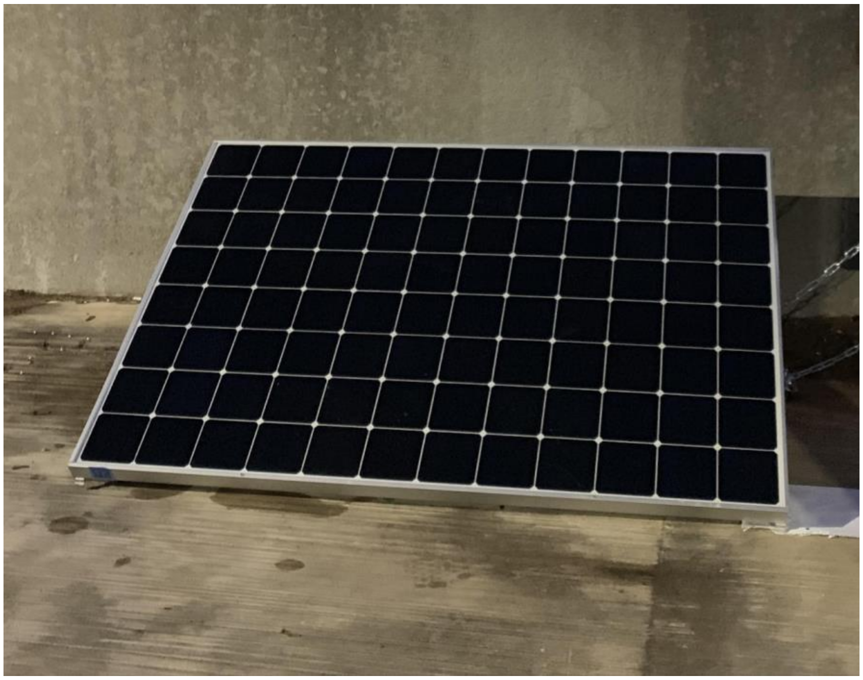


Figure 31: SunPower X22-360 Solar Panel

The solar panel was then tested from 7am-5pm every two hours over a three-week period. For each test, a digital multimeter was used to measure the voltage and the current from the solar panel. The voltage and current values were input into a google sheet that calculated the wattage at that hour.

$$Watts = Volts * Amperes$$

The weather for each day was also recorded along with the wattage so that the team could observe which conditions would affect the panel's output.

Figure 32: Mounted Solar Panel

Figure 33 below shows the results collected from the solar panel during the different times of the day and the watts recorded at those times for different types of weather.

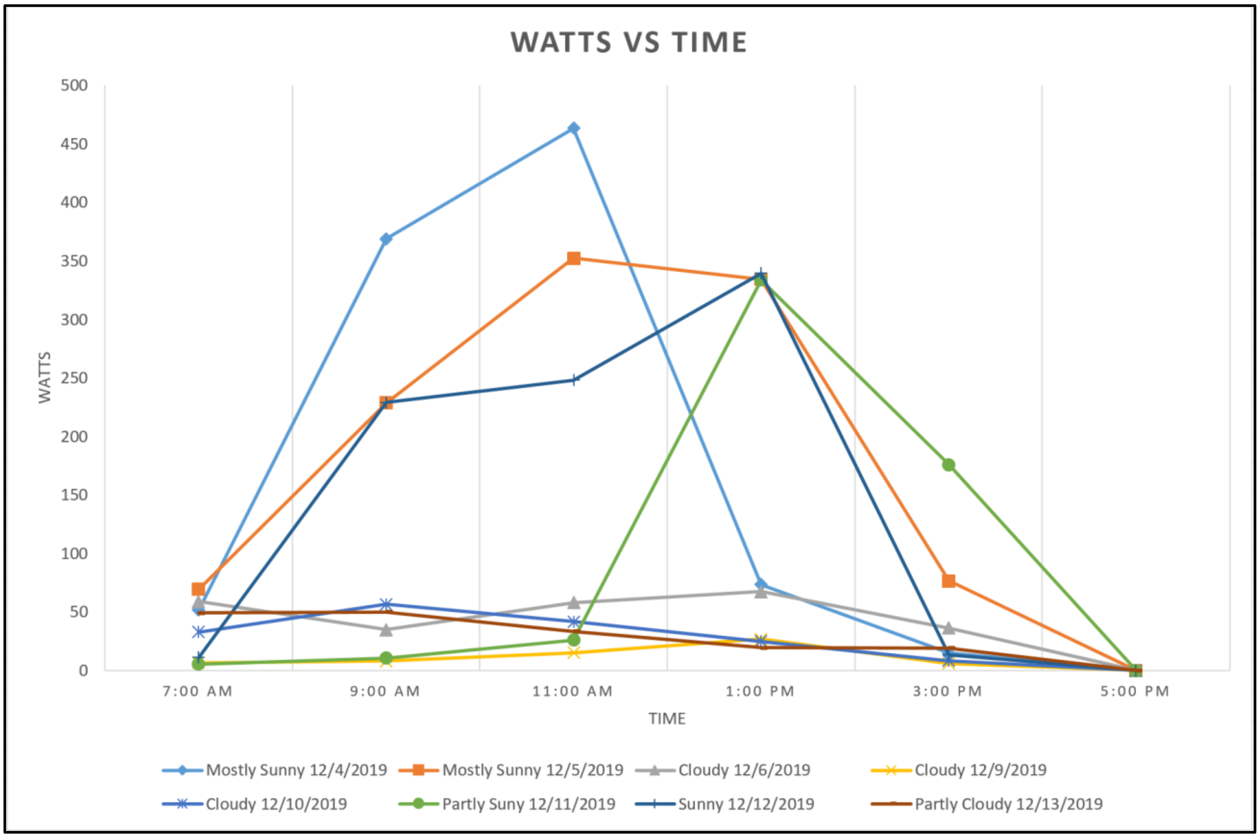


Figure 33: Graph of Solar Results (Time vs. Watts)

Below is the Global Horizontal Irradiance (GHI) for our solar panel testing times vs the wattage per square meter generated by the solar panel. GHI is the total irradiance received on a horizontal surface.

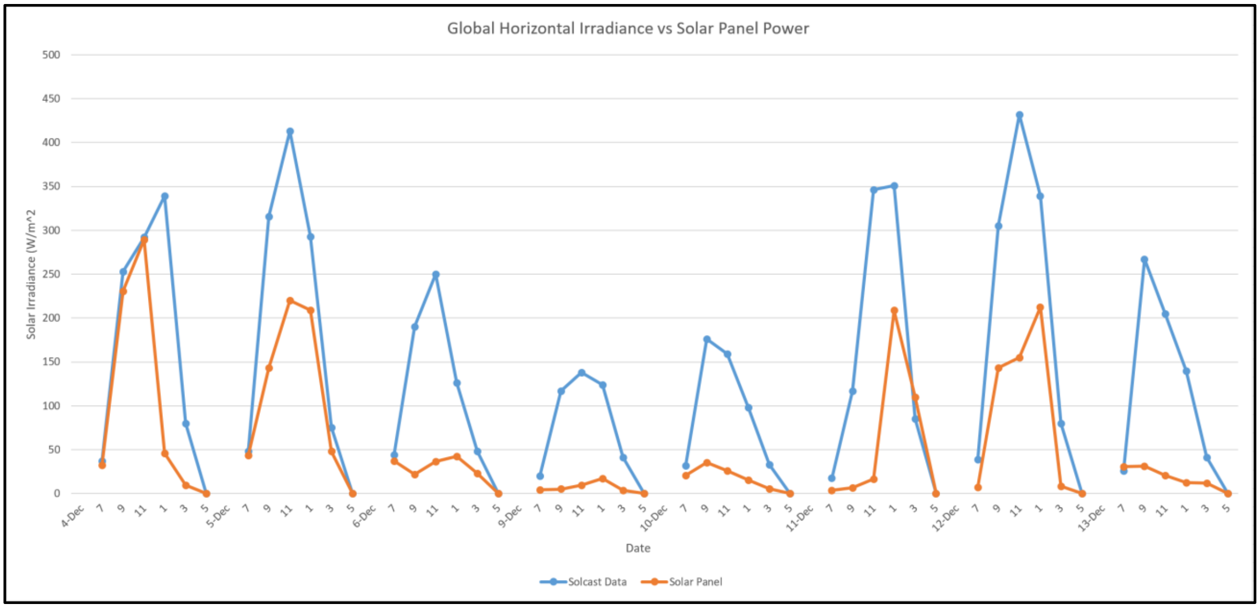


Figure 34: Global Horizontal Irradiance vs Solar Panel Power

3.6 Testing Result Analysis

At the conclusion of the experiments, the team was able to make decisions on layers and properties for the final roof. The following sections discuss what and how the decisions were made.

3.6.1 Solar Preliminary Design

Once the preliminary roof structure was decided upon, a solar test was simulated to determine the optimal roof pitch and directional orientation that would yield maximum solar efficiency. This solar test was run on with Aurora Solar software which incorporated the tilt and the azimuth. This house was simulated on the Worcester Polytechnic Institute football field since the estimations of this house have been in Worcester MA. Solar system efficiency is measured by total solar resource fraction (TSRF). The house was placed facing 8 different directions, the cardinal and intercardinal directions. Figure 35 below shows the results of the solar system efficiency. In order to optimize all the solar panels, the ideal house for this roof is east or west facing since it has the most uniform solar collection across the roof. However, the house can face any direction and the average TSRF is 80%. Therefore, this roof could be implemented on a house facing any direction. Figure 36 is an example of a shade report generated from Aurora Solar software showing the annual TSRF in the bottom right corner. Figure 37 is a 3D model generated from Aurora showing the panel locations.

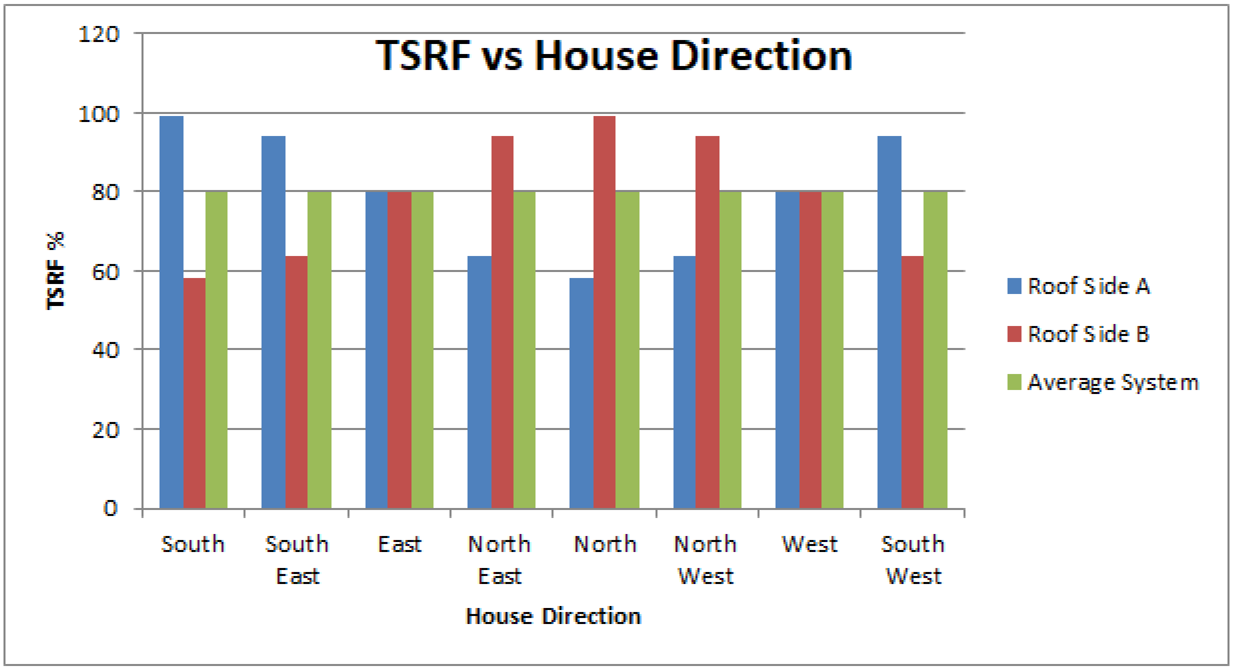
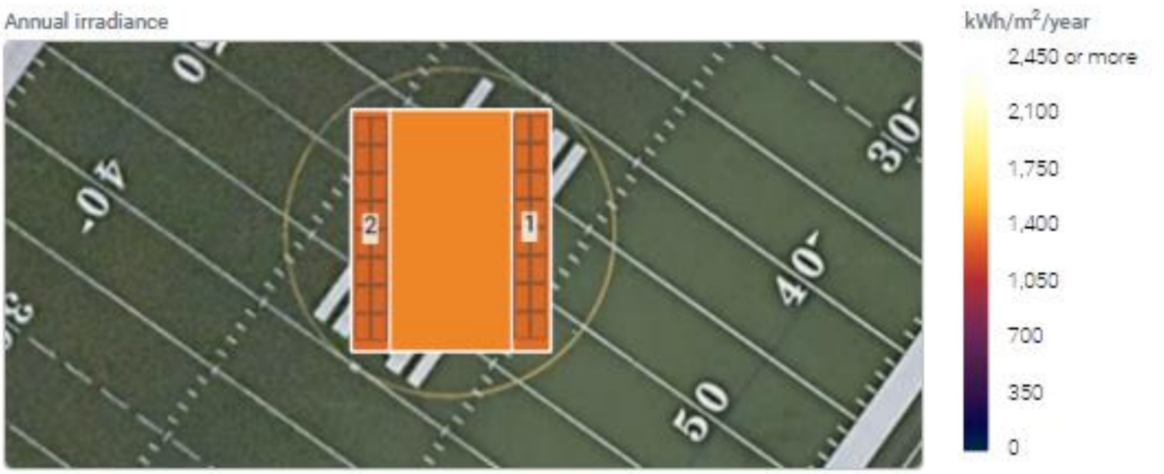


Figure 35: Solar Panel Efficiency vs House Direction



Summary

Array	Panel Count	Azimuth (deg.)	Pitch (deg.)	Annual TOF (%)	Annual Solar Access (%)	Annual TSRF (%)
1	16	90	30	81	100	81
2	16	270	30	80	99	79
Weighted average by panel count	-	-	-	-	99.4	80

Figure 36: Solar Annual Irradiance for Final Design

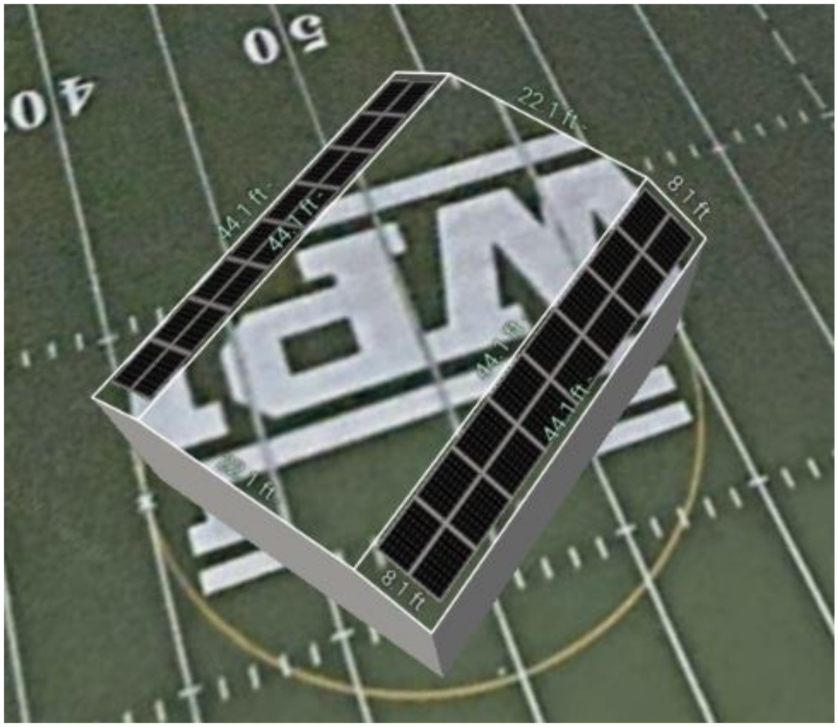


Figure 37: Solar Simulation Model

3.6.2 Vegetation and Growing Medium

Based on the results from the experiments, the team decided that the best vegetation and growing medium combination was the Blue Spruce Stonecrop Succulent grown in mixture 3 (75% Perlite, 10% Sand, 15% Compost) as shown in Tables 4 & 5. In the experiments this was box 7. In terms of survival, this mixture had the most consistent green leaf percentage, height, and ground cover percentage. Soil mixture 3 had the lightest weighing box on average and had the second best water return rate in the drainage test. With these three results considered, this combination was selected for the preliminary and final roof design.

The growing medium depth needs to be 6 inches or less in order to prevent too large of a strain on our roofing structure as well as avoiding unnecessary cost since the vegetation we chose doesn't require a large soil depth to survive. The optimal depth was determined through results from testing drainage, weight, and thermal properties. Having a growing medium of about 6 inches would have a better thermal resistivity; however, more rainwater would be absorbed into the soil and would result in a heavier load. Having a thickness below 6 inches could show an improvement in water collection and weight, but a reduction in thermal resistivity.

To make sure the growing medium and vegetation stays within its area on the roof, the tilt also has to be relatively low with surrounding baffles. The baffles act as a barrier to confine the soil in a certain area on the roof. The baffles also cover the other layers below it as well as leaving an opening for the drainage layer to allow water to flow towards the gutters to be collected in the tanks.

3.6.3 Runoff / Drainage Management

The intent of the drainage layer in our design was to allow for rainwater collection to be incorporated into our roofing system, although the group didn't get to go into further research regarding this system. For this reason, the topic of rainwater collection is further discussed below in Section 5.2.3. The drainage layer would consist of pea gravel that is 0.5 inch thick. Water moves easily through gravel and would come with the advantage of being a natural material compared to a plastic drainage layer. After the rainwater exited the drainage layer, it would flow through little slits in the exterior baffle and under the solar panels, in which there would be a space of about 2 inches between the panels and the roof, allowing runoff into the gutter. The gutter would then transport the collected rainwater into a dry system tank that could be used for grey-water systems.

3.6.4 Thermal Results

To measure estimated insulation values for our soil mixture, the group used a thermal conduction test configuration as shown below in Figure 38. Using a biodegradable cooler, 4 inches of the final growing mixture was placed inside the container. The final growing mixture was composed of 75% Perlite, 10% Sand, 15% Compost. A plastic bag with vaseline was then placed on top of the soil to make sure there was no air between the bag and soil. Ice water was dumped into the remaining area and since there was no air between the bag and soil, the temperature of the water was the surface temperature of the soil, 0° Celsius. The container was placed on a hot plate at 100° Celsius and the bottom of the container was covered in a layer of aluminum foil for protection. The sides of the container were insulated with layers of bubble wrap and tin foil to ensure 1-D conduction. 100k thermistors were used to measure the temperature of the soil at 1-inch intervals, and conduction equations were used to measure the thermal resistivity for the soil mixtures.

Figure 38: Thermal Testing Configuration

With the resistance values recorded during the thermal experiment, the temperature values were found using the data from the 100k thermistor output table, which can be seen in Figure 39 below.

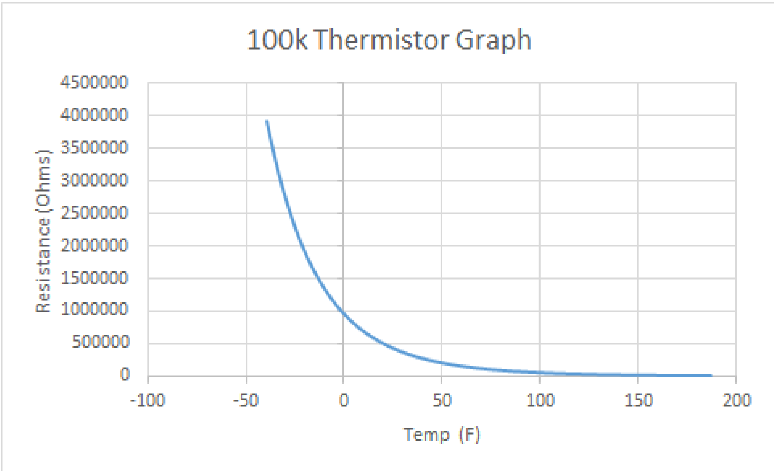


Figure 39: Thermistor Resistance vs Temperature

The data collected from the thermal test after converting the resistance values to temperature can be seen in the graph below by the depth of the thermistor in the soil (Figure 40). The data showed a linear change in temperature through the soil mixture. The R-squared value was 0.973, which means there were some sources of error during the experiment, but the correlation was still fairly linear, which is the result wanted after reaching steady-state conduction through the soil.

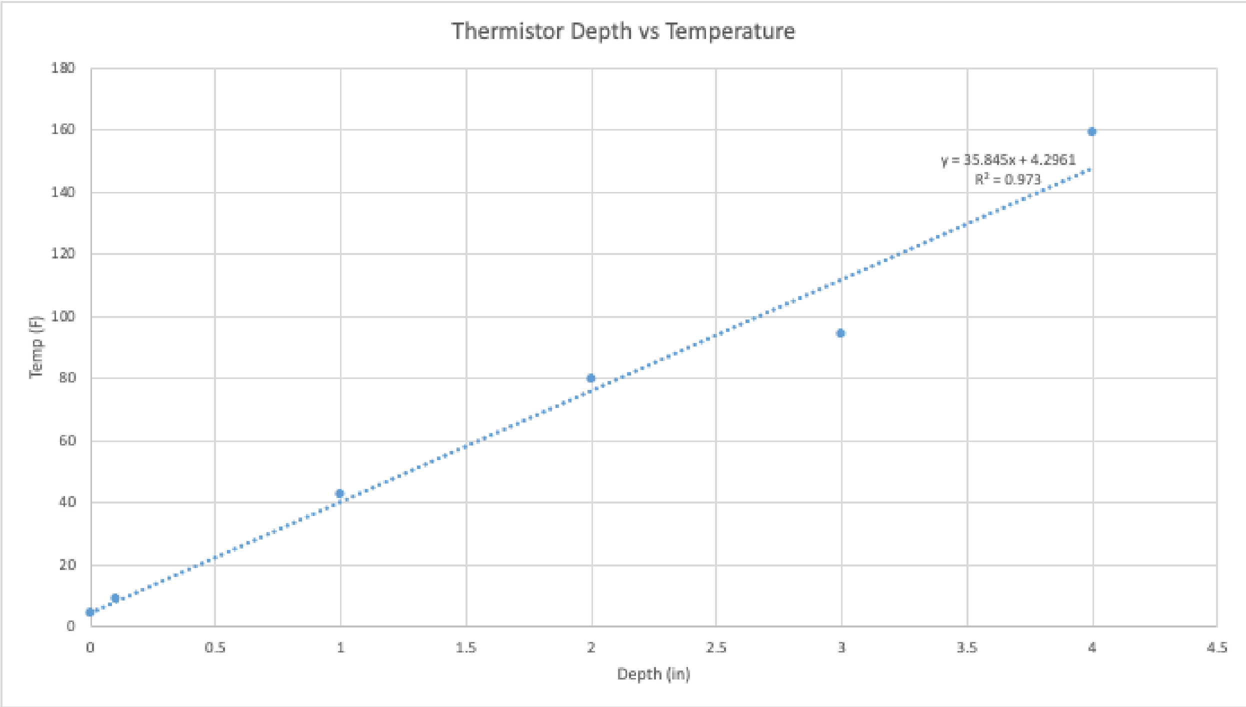


Figure 40: Thermistor Depth vs Temperature

After the temperatures were recorded and the box was at steady-state at 0°C, all the ice was removed and replaced with a known mass of ice that was then sealed with an insulated cover. After 35 minutes, the remaining ice's mass was measured. Then the heat energy was calculated with the equation:

$$Q = mh_{fg}$$

Where m is the difference in mass of the ice and h_{fg} is the latent heat of the ice melting at 32 degrees Fahrenheit. The starting mass of ice was about 1.125 lbs and the final mass was 0.75 lbs, so there was a difference of 0.375 lbs. The latent heat is 1070.9 Btu/lb. The energy calculated was:

$$Q = mh_{fg} = 0.375(1070.9) = 401.588\ Btu$$

The rate of heat flow was calculated by dividing the energy by the difference in time, which is then substituted in the equation:

$$\frac{Q_{total}}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

Where k is the thermal conductivity of the soil, A is the cross-sectional area of the soil, ΔT is the change of temperature through the soil, and Δx is the thickness of the soil. The thermal conductivity was then calculated:

$$\frac{Q_{total}}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

$$\frac{401.588\ BTu}{(35/60)\ hours} = k(\frac{8.5}{12} \times \frac{10.25}{12})ft^2(\frac{317.854 - 39.754\ F}{(4/12)ft})$$

$$k = 1.363\ \frac{Btu}{h \cdot ft \cdot F}$$

Compared to Sailor's results, mentioned in Section 2.3.2, the soil most closely related to the team's choice of soil was 75% pumice, 15% sand, and 10% compost. This mixture showed a thermal conductivity of about 0.32 W/mK as a maximum (70% moisture) and 0.15 W/mK as a low (0% moisture). These are 0.1850 Btu/h•ft•F and 0.0867 Btu/h•ft•F respectively. The team's thermal conductivity was much higher than Sailor's, which could account for some errors in testing or differences in mixture used compared to Sailor's mixture. When the experiment was conducted, the soil was moist, which in turn would increase conductivity. The mixture used by Sailor used pumice instead of perlite, which could have consisted of bigger particles of the rock since most green roofs use 3/8-inch pumice rocks, which would allow for the soil to hold less water as the perlite was closer to 1/8 inch. The team's soil also consisted of 5% more compost which absorbs more water, making the soil moisture higher. Sailor's experiment also used a thermal conductivity probe, which is more accurate and precise in measuring thermal conductivity. In addition, the team's experiment consisted of trying to control the temperatures at both ends so that steady-state could be achieved, which could have led to some human error in the experiment. The difference in thermal conductivities was analyzed through Revit to show if the thermal properties are an important factor in designing the roof. It was determined that this outputted no difference, conveying that the thermal properties of the soil would have no effect on the team's design. The importance of the soil would be towards vegetation growth since the vegetation reflects more sunlight causing the roof to be cooler in the summer months. Another importance of the growing medium would be how much water it absorbs so that there would be less stormwater runoff that goes back into water supplies with all the chemicals it collected on the way that would contaminate the water. These results helped confirm that the depth of the soil mixture doesn't result in reduced insulation properties, and therefore decreasing our soil mixture depth from 6" to 3" will not negatively affect our insulation values.

3.6.5 Truss Static Simulations

After searching CES EduPack Database [54], the team found the specific properties of Southern Pine and input them into our truss design in SolidWorks in order to determine the stresses of each member (See Appendix 3) and whether or not it could hold the roof, by looking at what members were in compression and tension.

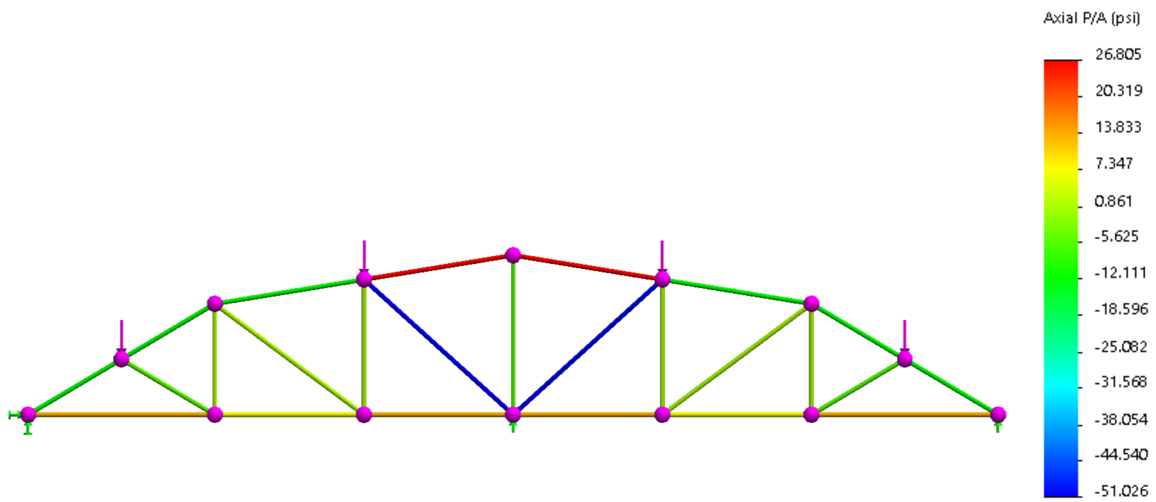


Figure 41: Initial Truss SolidWorks Analysis

As the simulation results above show, any members that have negative stress are experiencing compression (blue and green members) and positive stresses are members experiencing tension (red, yellow, and orange members). The compressive stresses were still at a high value, so to alleviate the compressive forces, two counter members were added.

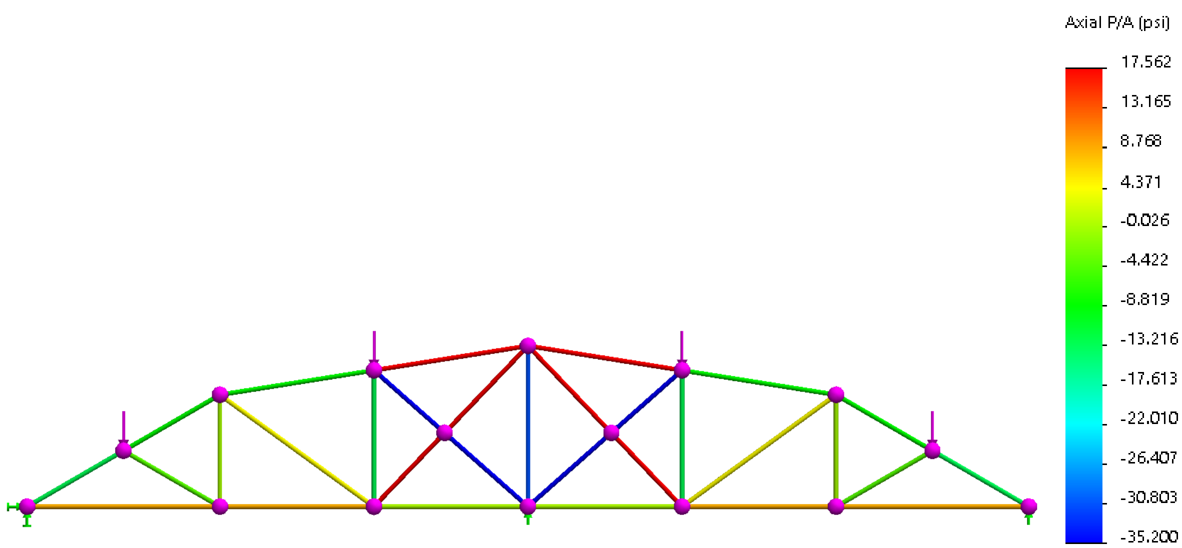


Figure 42: Final Truss SolidWorks Analysis

As the simulation results with the counters show, the stresses were decreased greatly (exact stresses in Appendix 3). The truss design was considered acceptable based on comparing the calculated stress levels, with a maximum compressive stress of 35.2 psi and a maximum tensile stress of 17.562 psi, to the design values for 2x4 Southern Pine No. 2. The bending, tension parallel to the grain, and compression parallel to the grain design values for Southern Pine are 1100, 675, and 1450 psi respectively [55]. It can be concluded that the truss made of Southern Pine No. 2 will have no problem supporting the roof as well as any additional loads, such as snow, since the calculated stresses are considerably below the design values.

3.6.6 Modeling

To determine whether or not our roofing system would yield positive environmental and economic benefits, it was necessary to design a model structure with both a conventional roof and our proposed green roof. Our test conventional roof (Figure 43) and proposed green roof design (Figure 44) are shown below.

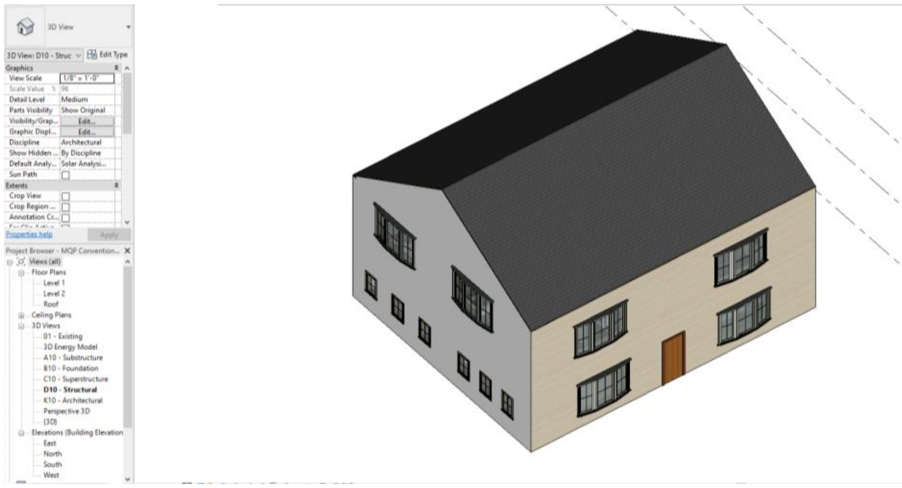


Figure 43: Conventional Roof Model

Figure 44: Green Roof Model

The housing dimensions used were 44' in length by 36' in width. The outer sections of our roof which have the solar panels mounted on them had a length of 8' with a pitch of 30 degrees. The inner sections of the roof had a length of 11' and a pitch of 9 degrees. The thermal conductivity value, 1.363 Btu/h•ft•F, that was calculated from the thermal test for the growing medium was used in a simulation and a second simulation was run with Sailor's values. This outputted no difference, conveying that the team's design is not sensitive to the thermal properties of the soil. The importance of the soil would be towards vegetation growth since the vegetation reflects more sunlight causing the roof to be cooler in the summer months. Another importance of the growing medium would be how much water it absorbs so that there would be less stormwater runoff that goes back into water supplies with all the chemicals it collected on the way that would contaminate the water.

Upon running the analysis for both roofing designs, the preliminary results showed that the energy cost per m^2 for a conventional roof was only 70 cents higher per year ($35.00) than that of the proposed green roof ($34.20), which is not that substantial. However, the solar panel aspect of the green roof was not accounted for in this analysis.

To accurately gauge the efficiency of the green roof compared to the conventional roof, a solar analysis was also run through Revit to determine how much solar energy would be collected using SunPower 360 solar panels. The green roof model is shown below in Figure 45 after the analysis was conducted.

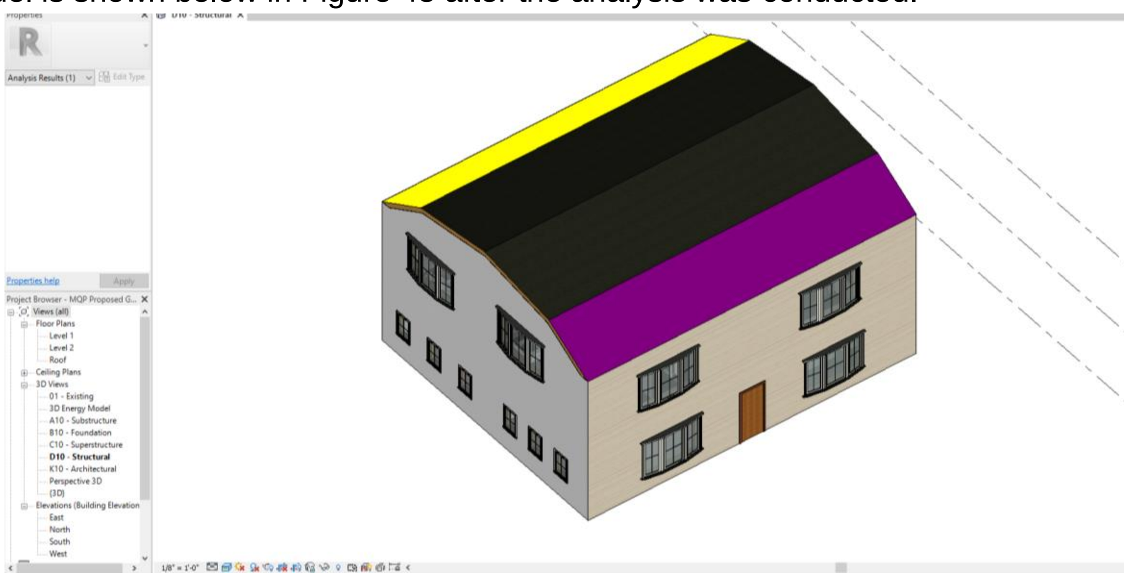


Figure 45: Green Roof Solar Analysis

In terms of the colors displayed on the roof, the dark midsections were taken out of consideration as there will be no solar panels mounted in that area. The house orientation had the front of the house (purple) facing east and the rear of the house (yellow) facing west. According to the analysis, the solar panels on both the east and west orientation would operate at 80% efficiency, reinforcing our previous findings in the Solar Preliminary Design section. The analysis also showed that each solar panel would yield just under 700 kWh annually, with 32 panels being expected to span the roof. To confirm this number, the team used the following equation for the SunPower 360:

$$\text{Wattage} * \text{Sunny Days/year} * \text{Efficiency} = \text{Watt Hours} / 1000 = \text{kWh}$$
$$360 * 2600 * .80 = 748.8 \text{ kWh/year}$$

4.0 Discussion

The team developed a sustainable residential roof design that implements photovoltaic cells, grass roofing, and water collection in one unified system. The final proposed roof layers as well as an image of the final roof are given in Table 9 and Figure 46.

Table 9: Final proposed Green Roof Layers

Solar panels	SunPower 360W panels mounted on conventional roof section
Vegetation	Sedum reflexum succulents
Growing medium	3 inches of 75% perlite, 15% compost, 10% sand
Filter Sheet	Thin sheet of unwoven polyethylene
Drainage layer	½ inch of pea gravel
Protection mat	½ inch of rubber membrane
Waterproofing barrier	Thin sheet of high-density polyethylene
Plywood decking	7/16-inch plywood

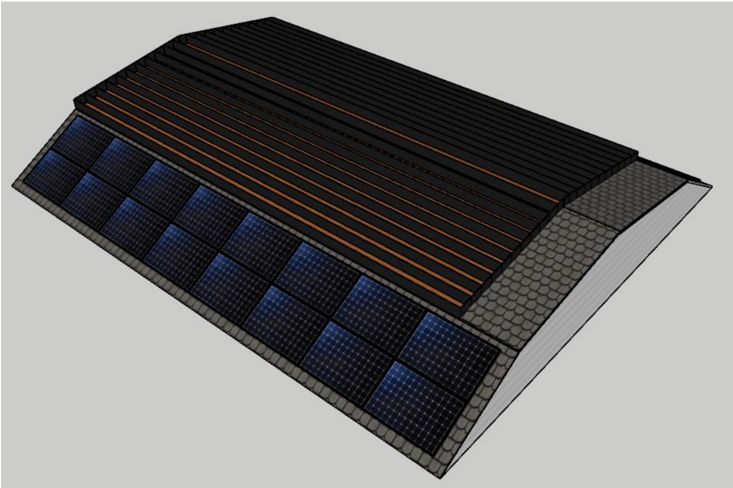


Figure 46: Final Green Roof Design

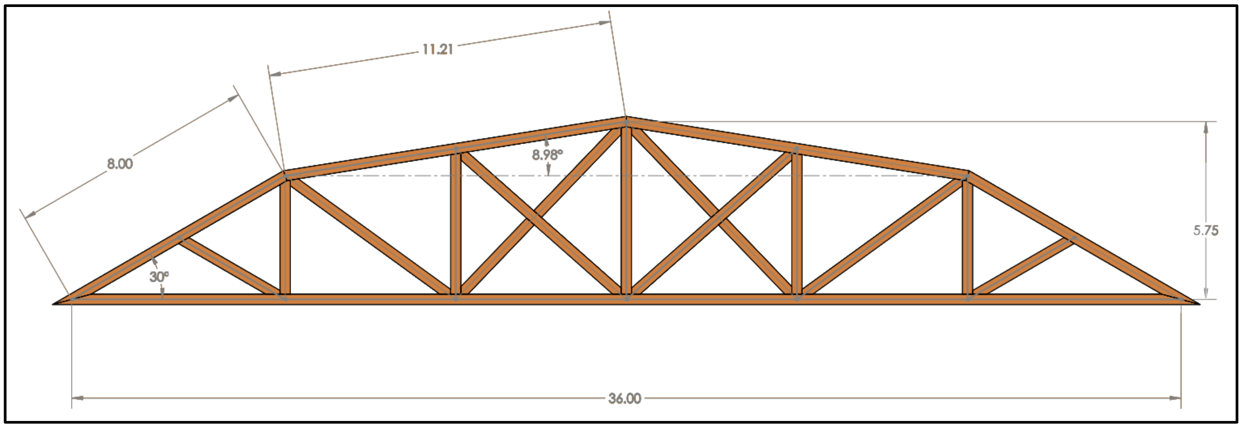


Figure 47: Final Truss Design

For the final design of our truss seen in Figure 47, it was decided that the 8-foot long, 30-degree sloped sides of the roof would be conventional roofing for the solar panels to be mounted on, and the slope would ensure maximum efficiency of the solar panels. The 11.21-foot long, 8.98-degree tilt section would be where the green roof layers would be placed. The truss would be made of 2x4 No. 2 Southern Pine lumber, in which the team had to input specific properties into SolidWorks in order to calculate which members are in compression and tension, as well as any deformation mentioned in Section 3.2.2. As shown by the stresses, the final iteration decreased the compressive stresses on certain members, allowing for members to be in tension that prevent buckling from occurring. In addition, there was little to no deformation thus it could be concluded that the truss is capable of holding the proposed roof. It was determined that trusses would be spaced at about 16", following the house's wall stud spacing. This would require about 15 trusses per every 10 feet, which is standard for lightweight construction. There is a 4-foot walkway located on one side of the roof; this allows for roof access for maintenance.

4.1 Cost and Maintenance

Table 10: Framing Estimates

Roofing	Framing	Cost ($/sf)	Square Footage	Total	Comments
Conventional	Rafters	6.41	1,900	**$12,179**	9 pitch slope (37°) roof input to program
Green	Trusses	4.23	1,900	**$8,037**	Polygonal truss with 2 pitches on top cord (9° & 30°)

In order to get accurate framing estimates, the group used the construction software RSMeans and input the results into Table 10. For the conventional roofing system, we used a rafter system since most conventional roofing incorporate the system to keep attic spaces open and accessible. According to the software, the cost per square foot came out to $6.41, which when multiplied by the square footage of our roof came out to total $12,179. On the other hand, our green roof utilized a specialized truss that would be incorporated into the roofing system, and these trusses were estimated to cost $4.23 per square foot. This would equal a cost of $8,037 when multiplied by the square footage of the roof.

Table 11: Layering Estimates

Roofing	Layering Percentages	Cost ($/sf)	Square Footage	Total	Comments
Conventional	Conventional (100%)	$4.00	1,900	**$7,600**	Conventional roofing average used for calculation input
Green	Conventional (40%) Proposed system (60%)	$4.00 $12.72	760 1,140	$3,040 $14,501 **Total: $17,541**	Design estimates used for calculation input

Since RSMeans didn't have the settings for calculating our green roofing layers, we used our cost estimations from our design for both roofing types in order to calculate the cost of layering. The conventional roofing layers were calculated using our 9 pitch, 44' x 36' structure, and the pricing came out to an average of $4.00 per square foot over the total area of the roof (1,900sq) to get a pricing of $7,600. We then calculated the cost of our green roofing structural system, which was a polygonal truss with 2 pitches on the top cord (9° and 30°), on our 2 story 44' x 36' structure, but this price had to be calculated in two different parts. The first was taking the 40% of the roofing that will be conventional layering and multiplying it by the cost per square foot of conventional roofing, coming to $3,040. The other 60% of the green roof was estimated using our calculated values in Table 3 (Section 3.4.1), getting a cost of $14,501. The two totals were then added for an overall layering cost of $17,541. The installation cost of solar panels was not included in Table 11, as the cost of installation for Massachusetts came about to be around $12,000 for both roofing systems. The installation of the panels wouldn't create any cost difference since the installation would cost the same for both types of roofing [56]. However, the difference between the conventional roofing and green roof design in terms of solar panel layering would be the output levels. The green roof was built so that the solar panels would specifically be at an optimal tilt to perform at maximum efficiency, while the conventional roof was not, and this is reflected in the energy savings column of Table 12.

Table 12: Cost Benefits Per Roofing Type

Roofing	Framing	Layering	Maintenance	**Total (20 years)**	Energy Savings per year
Conventional	$12,179	$7,600	$650 / 20 yrs	**$20,429**	$2,600/yr (Avg)
Green	$8,037	$17,541	$400 / 20 yrs	**$25,578**	$3,100.70/yr

After inputting the cost data from Tables 10 and 11, our next step was to calculate maintenance costs for both systems. Conventional roofing is usually $150 to $400 for minor repairs, $400 to $1000 for moderate repairs, and $1000 to $3000 for major repairs [57]. The average was about $650 to fix issues pertaining to the roof [57]. Most issues will fall under minor or moderate, however, it can depend on the region, such as due to the harsh weather conditions in New England, storm damage is more likely to occur causing the issue to possibly fall under moderate or major. Asphalt shingle roofs also have a lifespan of about 20 years, but weather conditions like snow decrease the lifespan [58]. In terms of the proposed green roof, costs will likely vary. The vegetation on the roof is very resilient and intended to endure most conditions. The succulents would likely only need occasional watering during the hot summer months and to be fertilized for required nutrients. Maintenance cost for the vegetation could increase based on harsh storms that could rip the succulents out of the soil or potential kill it. As for the soil, it would depend on whether or not there were conditions which resulted in soil mixture falling off the roof, in which case more would have to be purchased. The solar panels also require no maintenance unless they are either dislodged, damaged, or disconnected, which is unlikely. Overall, the average maintenance costs for the proposed system will average about $400 every 10 years based on the known low maintenance costs of solar panels and the assumption of resilient succulents, which is significantly less than that of a conventional roofing system [59].

Overall, the conventional roofing does end up pricing out about $5,000 less than the green roofing, mainly due to its lower layering cost. However, after accounting for the solar panels and the tilt at which they will be placed, a homeowner can expect to save around $3,100 a year (Assuming 32 solar panels) for the green roof design due to the advantageous tilt of the roof allowing for the solar panels to operate at maximum efficiency (See Sections 3.6.1 and 3.6.5 above). Additionally, the green roof saves an average of 70-cents in terms of energy efficiency per year as concluded via Revit simulations, and $100 per year on water from rainwater collection systems (See Section 3.5.1). Similarly, the cost of solar panels is decreasing with every year, making multi-paneled roofing much more cost efficient. Even though the green roof has a high initial cost, being $5,149 more expensive than the conventional roof, the green roof saves about $3,200.70 per year based on energy savings from the solar panels and water savings from rainwater collection. The payback to offset the initial cost difference would be about 1.61 years, a little over a year and half.

5.0 Conclusions and Recommendations

In summary, the proposed roof that integrated the three systems–solar panels, green roof, and rainwater collection–comes with many benefits, including a lower life-cycle cost compared to a conventional roof. The overall expenses of the green roofing system would be relatively higher than that of a conventional roofing system during installation, mostly due to the green layering that would cover a significant portion of the roof. However, the proposed green roof would have a payback period of about 17 years for the roofing cost in addition to other benefits from solar power and rainwater collection (See Table 12 above). In terms of sustainability, the proposed roof would be a great option considering it integrated three systems that are driven towards making a residential house environmentally friendly. The vegetation on the green roof would absorb rainwater, and any remaining water not absorbed would be collected and used for grey-water systems. The green roof can also help to deflect sunlight, reducing heat absorption and helping to keep the house cool during the summer months. For the winter month, there would not be any major changes compared to a conventional roof except the solar panels mounted on the sides of the roof would offset a majority of a residential households' electrical cost, which could help if the house uses electric heat. The average electricity cost for the area comes out to about 13-cents/kWh, or $2,500 annually [60] as the solar panels would save an average homeowner around $3,100 per year. The rain collection system was integrated based on calculations from section 3.5.1 allowing the roof to collect 14,927.61 gal/yr. With the cost of water in Worcester MA being around .50 cents per gallon that would save the homeowner a projected additional $100 a year [61].

Even though the proposed roof could be a viable choice for sustainability there are many areas that still need to be researched, such as roof construction and weather effects, before this design can become a complete and competitive option. The climate in Massachusetts includes many snowstorms that could pack a large amount of snow on top of the roof. If the snow packs enough it could kill the vegetation, which would increase the maintenance cost. In addition, there are the effects of wind, which could potentially blow individual plants and some soil off the roof. In conclusion, there are many aspects of the design that research must be continued before this proposed roof can be considered an option.

5.1 Benefits & Disadvantages of Conventional VS Green Roofs

For our conclusions and recommendations, the team wanted to lay out exactly what the benefits and disadvantages were for each category of both roofing types for the example house the team used.

Table 13: Conventional vs Green Roof Benefits and Disadvantages

Category	Benefits	Disadvantages
Construction	Conventional: N/A Green: Can be easily incorporated into construction of new house, structural part of system $4,000 less than conventional	Conventional: Cost of framing system is steeper than truss system at $12,179 Green: Layering is about $10,000 higher than conventional layering due to green roofing
Cost Analysis	Conventional: Roof costs $5,000 less overall than green roof Green: Payback period of between 15-17 years, low maintenance cost	Conventional: Less payback & environmental benefits than green roof Green: $5,000 more than conventional roof installation
Energy Analysis	Conventional: Can still support solar panels, has some payback Green: 70 cents per m^2 lower cost than conventional roof in energy cost per year based on Revit simulation modeled housing footprint, proposed solar coverage saves $3,000/year (Predicted 7 year payback depending on roof size, payback is quicker due to better roof tilt which optimizes solar output), can incorporate rain water filter system saving another $100 per year	Conventional: Rainwater collection system on conventional roof will have more runoff, solar panels may not operate at maximum efficiency Green: House orientation and roof size could affect solar production and consequently payback period

5.2 Future Research & Recommendations

There are many possibilities for future research to improve the green roof design. Due to the limited amount of time given for this project, the team recommends that certain aspects be further investigated, as stated below.

5.2.1 Soil and Vegetation

The team didn't have the time or resources to test every potential soil mixture for the roof so there may be a soil mixture to use that would better suit the vegetation, as well as provide better drainage. In terms of the vegetation itself, the team was constrained to only a few select types due to both budget and time of year. However, the team recommends the investigation of other succulent and plant types to see if there would be a more resilient type of vegetation that would also potentially aid in insulation and water absorption.

5.2.2 Wind and Additional Weather Factors

While the sunlight and weather patterns were analyzed for the duration of the solar panel testing, the team didn't get to test the effects of wind and other weather on the roof. Since the roof was not actually constructed, the effects of wind and snow could not be fully studied. The team would strongly recommend this be investigated further. The presence of wind over the roof and the uplift it could create has the potential to blow soil and vegetation off the roof, which would cause the homeowner to spend more money on maintenance and soil replacement. Similarly, snow could potentially pack on top of the vegetation causing it to die, resulting in more vegetation needing to be replanted.

5.2.3 Rainwater Collection

In terms of rainwater collection, the roofing design has a gravel layer to allow for rainwater to drain easily out of the green roof to the gutters to be collected. The team was unable to experiment on which material would drain the rainwater better. For future research, the team would recommend looking into the drainage effects using pea gravel versus a plastic layer. Additionally, different storage and filtration systems can be researched and how the rainwater is reused and whether a more expensive tank is worth the cost for the Massachusetts area.

5.2.4 Location

The project testing and simulations were based in Worcester, MA, and most of the data related to utilities costs and weather patterns were based on this location. To analyze the feasibility of the roof as a generalized construction practice, it is recommended that it be tested in other locations and that utility costs and weather patterns for those regions be factored into a new final price range. That would include the new climate the roof would be located in which would affect the energy needs.

5.2.5 Construction

For construction the team would recommend further research on truss systems as the team was not able to devote much focus to this subject. Finding a way to incorporate the design into a pre-existing structure without total reconstruction of an old roof would help make the project a lot more cost effective and attractive to the average homeowner. Additionally, we would strongly suggest looking into how much more of a cost there would be to incorporate this roofing system into a pre-existing structure, since the group focused primarily on roof installation during new construction of homes.

5.3 Reflection

In conclusion, the team completed the goal of designing an affordable sustainable roofing system. Throughout the project the team used the knowledge they acquired during their time at WPI and gained new skills to solve the problems that were presented in this project. This included stress analysis, heat transfer, and the use of engineering software such as SolidWorks and Revit. The construction of experimental boxes simulating a portion of the green roof and test cases was used to evaluate several iterations of the design and ensure that the system was on par with professional engineering standards. While there are still some areas of the design that will need to be addressed before this becomes a real-world solution, it is an important foundation for the future of sustainable roofing.

5.4 CEE Capstone & Design Statement

For this project, the main design problem was designing a roofing system capable of holding several key components: Soil, solar panels, vegetation, and non-conventional roofing layers. When the project first got underway, the two ideas were to have either a more complex rafter system that would allow for a home to still incorporate an attic space, or a truss system that would come at a higher cost but a better option strength wise. In order to figure out which would be more beneficial, it was important to first figure out exactly how the roof was going to be oriented. The reasoning behind this was that the team wanted the roof to help optimize the benefits of the solar panels, rainwater collection system, and vegetation, and therefore would have to figure out which support system would best conform to it. Additionally, the weight of the final design would also influence the supports used, as heavier roofing would call for more complex supports.

After some initial brainstorming, a roofing design was proposed in which there were two different sections. The outer part of the roof would be at a steep 30-degree angle in order to accommodate solar panels, while the inner part of the roof would be at a much shallower 9-degree tilt, which would hold the soil and vegetation portion of the roof. Based on this proposed design, it was decided that a truss system would be best suited for this type of structure for a few different engineering reasons. Firstly, a rafter system usually performs best for conventional roofing supports due to its uniform structure. However, the roof proposed is oriented as a gambrel design, and therefore not the typical gable design that rafters are typically used in. While a more complex rafter system was considered, trusses specifically configured to a gambrel design seemed much more suitable for the proposed design.

Once it was decided that a truss system would be used, the next step was to configure it to our proposed design. For project purposes, the model house used was 36’ wide, and was therefore the length of the trusses used. Since the solar panels needed to be oriented at a 30-degree angle for maximum optimization, and the green roof section needed to be flatter to retain the soil, the group designed a truss that satisfied all the constraints.

Truss Loads and Specifications

Once the truss was designed and decision making was done, the implementation portion began in which realistic constraints and codes needed to be abided by. The first step was looking at both Massachusetts and United States Roofing Guidelines [62], as well as ASTM guidelines [63] to figure out what could and could not be done for a roof and making sure that our truss was up to building code and regulations. By referring to these guidelines, the group ensured that the safety and health of the public was being held in the highest regard, and that there would be no hazards resulting from an overlook of building codes. After confirming our truss was approved for residential construction, it was then essential to calculate the different stresses acting on our proposed truss design and either confirm that it was stable or go back and make revisions. The static calculations for the forces of each truss member are shown below in Appendix 3 and deemed the structure to be stable. Following the calculations, the truss design was input into a computer-aided design program, SolidWorks, and the appropriate calculations were input. In addition, the truss was also fixed, and a load was applied along the bottom member to represent the force of the attic floor that would be exerted on the truss. It then became crucial to identify the total weights of the different sections of the roof so that uniformly distributed loads could be applied along the correlating members of the truss.

For the truss, one of the most essential pieces of the design and decision-making processes was to evaluate the engineering standards and realistic constraints. It was necessary to refer to Massachusetts State Building Code [15] as well as national building codes for roofing, in addition to wood standard guidelines in order to ensure that our structure was stable and efficient. Referring to these documents also helped the team to identify the following four realistic constraints.

Health and Safety

The health and safety of the public is first and foremost when considering civil engineering. According to ASCE [64] and NSPE [65] guidelines, the top fundamental canon of an engineer is to “hold paramount the safety, health, and welfare of the public”. To ensure that the public’s safety and well-being is upheld, it was important for our group to refer to all proper building specification sheets and guidelines, such as those of the Massachusetts State Building Code [15] guidelines and American Wood Council [48], when constructing the roof, especially in terms of the structure itself. Ensuring that our roof framing structure was stable was critically important, as the group needed to adhere to design specifications for residential buildings to avoid code violations that could endanger people living there. Once we calculated our roofing systems’ layers and weight, we were able to determine whether or not this was within roofing parameters in terms of public safety and decide which type of wood would be best suited for the roof and safest to support it.

Manufacturability

Manufacturability was addressed when looking over the American Wood Council guidelines [48], as the southern pine that was decided on for the truss was identified as an abundant source that could be quickly manufactured, and the trees themselves are easily regrown. Southern pine is also less expensive than other types of wood due to its abundance, and because of that we decided that using it for our truss system would be beneficial, as the trusses could be manufactured quickly and cost effectively.

Ethical

Another constraint that was present during our project was the ethics of civil engineering and verifying that the designs and projects are up to building standards also adheres to ASCE [64] and NSPE ethics guidelines [65]. These guidelines are essential to follow for civil engineers when conducting any type of project, as ethics are one of the most important aspects of an engineering project. These ethics state that the engineers must uphold public safety, stay within their expertise parameters, be truthful to all, and be dedicated to their work, so incorporating these into the project was essential.

Sustainability

Since lumber is a natural, renewable resource, it also serves to keep the roofing system more environmentally friendly than materials such as steel and metal, which requires mining finite resources and assembling them through a process that is far less environmentally friendly. While metal roofing is effective for things such as temperature control and shedding snow loads, the process in which to make them is more environmentally detrimental than that of assembling lumber into truss systems and roofing. Additionally, southern pine is a sustainable resource as long as the trees are replanted and taken care of accordingly, whereas metal and steel roofing costs finite materials only found in the Earth, which have to be extracted using environmentally harmful mining methods. Additionally, the integration of vegetation on the roof serves as a natural insulation as well as a home for different wildlife, while solar panels mounted on the roof provide a clean source of electricity for the homeowners.

5.4.1 Professional Licensure Statement

Licensure is the process of granting or regulating licenses to professionals in a certain field of work, in this case civil engineers. According to the NSPE, getting a license will allow for a civil engineer to become a registered Professional Engineer, which is a four-step process. The first step is to earn a four-year degree in civil engineering from an accredited engineering program, and then pass the Fundamentals of Engineering exam. The Fundamentals of Engineering exam, for reference, is a cumulative exam of all the fundamental engineering knowledge academically speaking. Once a passing grade is obtained on the exam, the individual must then complete at least four years of progressive engineering experience while serving under the guidance of a professional engineer, and then must finally pass the Principles and Practice of Engineering exam. Licenses are applicable for 2-year periods before they must be renewed, and they must be renewed in order for a professional engineer to continue their practice.

Licensing is a crucial part of a profession, especially in engineering because of its importance to a country's infrastructure. Licensure identifies an individual as someone who is viewed as a skilled worker in the eyes of their peers and the public. It also ensures that individuals who are not skilled enough yet will not be put in charge of jobs that could, if performed wrong, endanger the individual or public in general. In terms of the profession, licensure is important to keep a good reputation in the eyes of the public, as well as retaining the integrity of the field itself. Additionally, licensure is also a way to help ease the minds of the public, especially when it comes to engineering, and civil engineering in particular. As a member of the public, it'd be much better knowing that the bridges and tunnels and commercial buildings used on a daily basis were designed by licensed professionals whose work is respected amongst peers, rather than someone who may not be as qualified. For projects in civil engineering, making sure that the public has trust in the professionals is essential, since the public is directly affected by the engineers' quality of work. Therefore, making sure that licensed professionals with a good reputation and work ethic are overseeing these projects will help the most in the eyes of the common people.

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Appendix 1: Survivability Test Parameters

Green Percentage					Ground Cover Percentage				
Box	Week 1	Week 2	Week 3	Week 4	Box	Week 1	Week 2	Week 3	Week 4
SR-1	80	80	80	70	SR-1	40	40	40	40
FA-1	50	50	50	50	FA-1	40	60	60	50
SS-1	90	90	90	80	SS-1	40	40	40	40
SR-2	90	90	90	90	SR-2	50	50	50	50
FA-2	30	40	40	50	FA-2	50	50	50	40
SS-2	90	90	90	90	SS-2	30	30	30	40
SR-3	90	90	90	90	SR-3	50	60	60	60
FA-3	80	70	70	80	FA-3	30	40	40	40
SS-3	90	90	90	80	SS-3	40	40	40	50
Average Height					Max Height				
Box	Week 1	Week 2	Week 3	Week 4	Box	Week 1	Week 2	Week 3	Week 4
SR-1	3	3.5	3.5	3	SR-1	5	5	5	4.5
FA-1	0.5	1	1	2	FA-1	2	2	3	4
SS-1	1	1	1	1	SS-1	2	2	2	3
SR-2	3	4	4	4	SR-2	5	5.5	5.5	5
FA-2	1	1	1	1.5	FA-2	3	2	2	5
SS-2	1	1	1	1.5	SS-2	3	3	3	3
SR-3	3	3	3	3	SR-3	5	5.5	5.5	5.5
FA-3	1	2	2	2.5	FA-3	3	3.5	3.5	6
SS-3	1	1.5	1.5	2	SS-3	3	3	3	4

Green Percentage					Ground Cover Percentage				
Box	Week 1	Week 2	Week 3	Week 4	Box	Week 1	Week 2	Week 3	Week 4
Box 1: Mixture 1- *Sedum reflexum*	80	80	80	70	Box 1: Mixture 1- *Sedum reflexum*	40	40	40	40
Box 2: Mixture 1- *Festuca arundinacea*	50	50	50	50	Box 2: Mixture 1- *Festuca arundinacea*	40	60	60	50
Box 3: Mixture 1- *Sedum spurium*	90	90	90	80	Box 3: Mixture 1- *Sedum spurium*	40	40	40	40
Box 4: Mixture 2- *Sedum reflexum*	90	90	90	90	Box 4: Mixture 2- *Sedum reflexum*	50	50	50	50
Box 5: Mixture 2- *Festuca arundinacea*	30	40	40	50	Box 5: Mixture 2- *Festuca arundinacea*	50	50	50	40
Box 6: Mixture 2- *Sedum spurium*	90	90	90	90	Box 6: Mixture 2- *Sedum spurium*	30	30	30	40
Box 7: Mixture 3- *Sedum reflexum*	90	90	90	90	Box 7: Mixture 3- *Sedum reflexum*	50	60	60	60
Box 8: Mixture 3- *Festuca arundinacea*	80	70	70	80	Box 8: Mixture 3- *Festuca arundinacea*	30	40	40	40
Box 9: Mixture 3- *Sedum spurium*	90	90	90	80	Box 9: Mixture 3- *Sedum spurium*	40	40	40	50
Average Height					Max Height				
Box	Week 1	Week 2	Week 3	Week 4	Box	Week 1	Week 2	Week 3	Week 4
Box 1: Mixture 1- *Sedum reflexum*	3	3.5	3.5	3	Box 1: Mixture 1- *Sedum reflexum*	5	5	5	4.5
Box 2: Mixture 1- *Festuca arundinacea*	0.5	1	1	2	Box 2: Mixture 1- *Festuca arundinacea*	2	2	3	4
Box 3: Mixture 1- *Sedum spurium*	1	1	1	1	Box 3: Mixture 1- *Sedum spurium*	2	2	2	3
Box 4: Mixture 2- *Sedum reflexum*	3	4	4	4	Box 4: Mixture 2- *Sedum reflexum*	5	5.5	5.5	5
Box 5: Mixture 2- *Festuca arundinacea*	1	1	1	1.5	Box 5: Mixture 2- *Festuca arundinacea*	3	2	2	5
Box 6: Mixture 2-	1	1	1	1.5	Box 6: Mixture 2-	3	3	3	3

Sedum spurium					*Sedum spurium*				
Box 7: Mixture 3- *Sedum reflexum*	3	3	3	3	Box 7: Mixture 3- *Sedum reflexum*	5	5.5	5.5	5.5
Box 8: Mixture 3- *Festuca arundinacea*	1	2	2	2.5	Box 8: Mixture 3- *Festuca arundinacea*	3	3.5	3.5	6
Box 9: Mixture 3- *Sedum spurium*	1	1.5	1.5	2	Box 9: Mixture 3- *Sedum spurium*	3	3	3	4

Appendix 2: Solar & Multimeter Measurements

Mostly Sunny	Volts	Amps	Watts
Wednesday 12/4/19			
7:00 AM	61.7	0.84	51.828
9:00 AM	67.1	5.5	369.05
11:00 AM	72.4	6.4	463.36
1:00 PM	68.1	1.08	73.548
3:00 PM	64.8	0.23	14.904
5:00 PM	24.2	0	0
Mostly Sunny	Volts	Amps	Watts
Thursday 12/5/19			
7:00 AM	63.1	1.1	69.41
9:00 AM	71.1	3.22	228.942
11:00 AM	71.5	4.93	352.495
1:00 PM	70.7	4.73	334.411
3:00 PM	63.4	1.21	76.714
5:00 PM	27	0	0
Cloudy	Volts	Amps	Watts
Friday 12/6/19			
7:00 AM	62.8	0.94	59.032
9:00 AM	67.2	0.52	34.944
11:00 AM	67.6	0.86	58.136
1:00 PM	68.3	0.99	67.617
3:00 PM	65.3	0.56	36.568
5:00 PM	26	0	0

Cloudy	Volts	Amps	Watts
Monday 12/9/19			
7:00 AM	61.2	0.11	6.732
9:00 AM	63.1	0.13	8.203
11:00 AM	66.1	0.23	15.203
1:00 PM	64.5	0.42	27.09
3:00 PM	61	0.1	6.1
5:00 PM	24.7	0	0

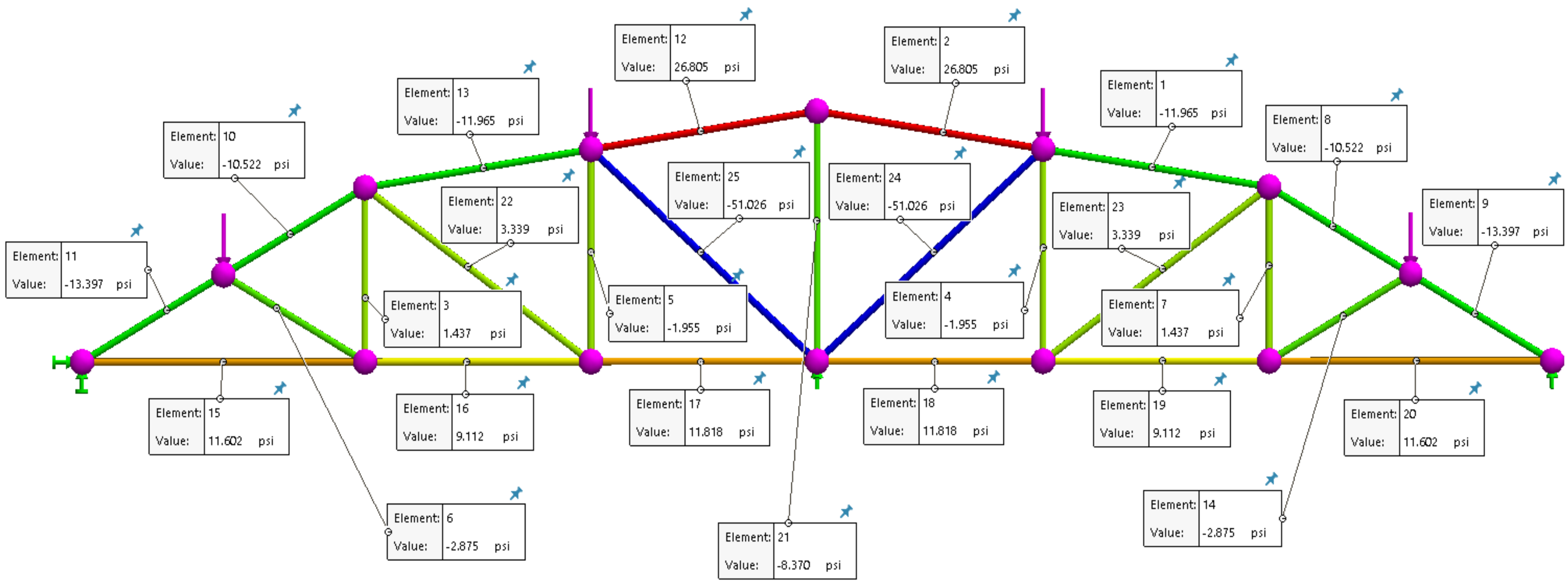
Cloudy	Volts	Amps	Watts
Tuesday 12/10/19			
7:00 AM	62.3	0.53	33.019
9:00 AM	65.1	0.87	56.637
11:00 AM	65.5	0.64	41.92
1:00 PM	64.1	0.39	24.999
3:00 PM	60.8	0.14	8.512
5:00 PM	12.9	0	0

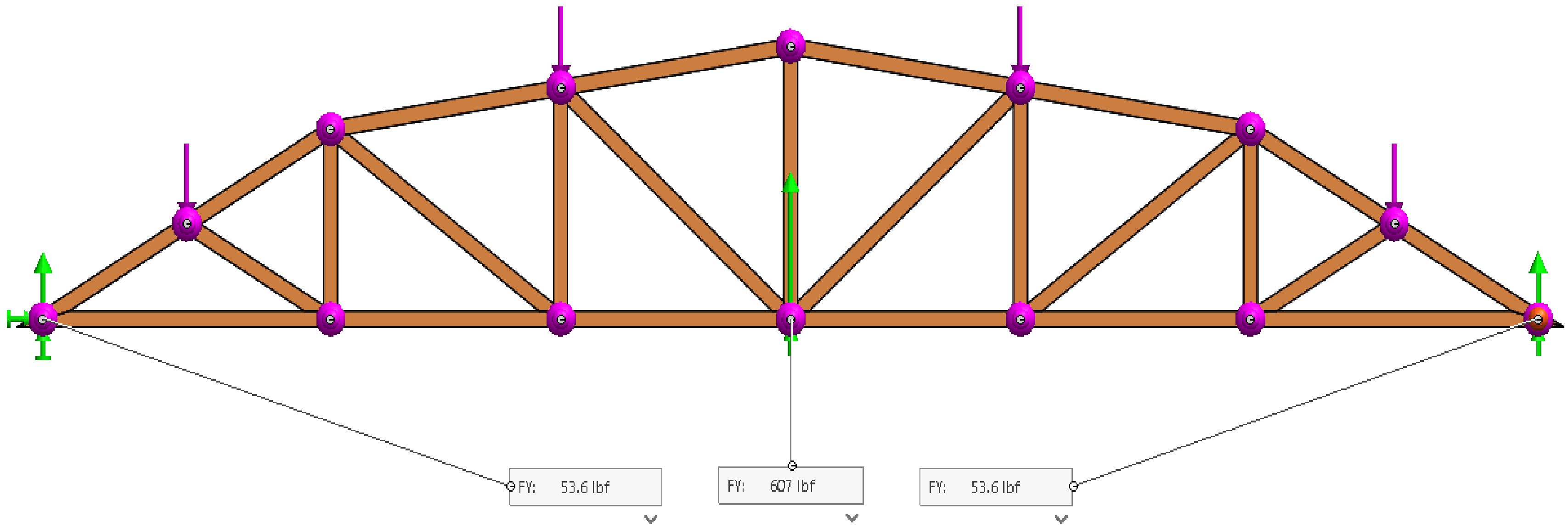
Partly Cloudy	Volts	Amps	Watts
Wednesday 12/11/19			
7:00 AM	62.4	0.09	5.616
9:00 AM	63.6	0.17	10.812
11:00 AM	68.9	0.38	26.182
1:00 PM	70.3	4.75	333.925
3:00 PM	71.2	2.47	175.864
5:00 PM	25.8	0	0

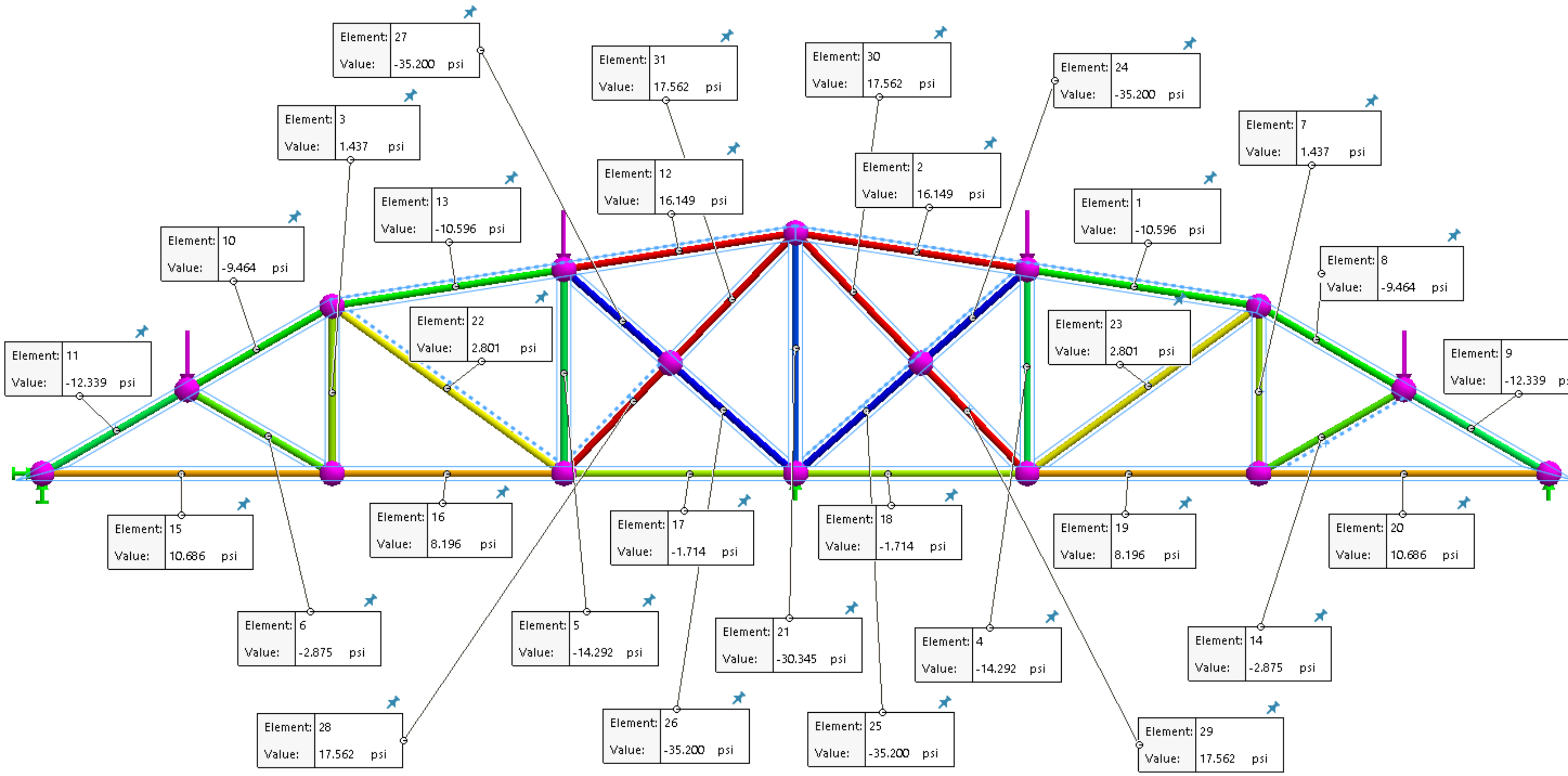
Sunny	Volts	Amps	Watts
Thursday 12/12/19			
7:00 AM	65.8	0.17	11.186
9:00 AM	71.6	3.2	229.12
11:00 AM	70.9	3.5	248.15

1:00 PM	72.1	4.71	339.591
3:00 PM	68.4	0.2	13.68
5:00 PM	24.2	0	0
Partly Cloudy	Volts	Amps	Watts
Friday12/13/19			
7:00 AM	61.5	0.8	49.2
9:00 AM	68.6	0.73	50.078
11:00 AM	66.8	0.5	33.4
1:00 PM	65.5	0.3	19.65
3:00 PM	63.9	0.3	19.17
5:00 PM	23.1	0	0

Appendix 3: Truss Member Stresses & Reaction Forces




FY: 53.6 lbf
FY: 607 lbf
FY: 53.6 lbf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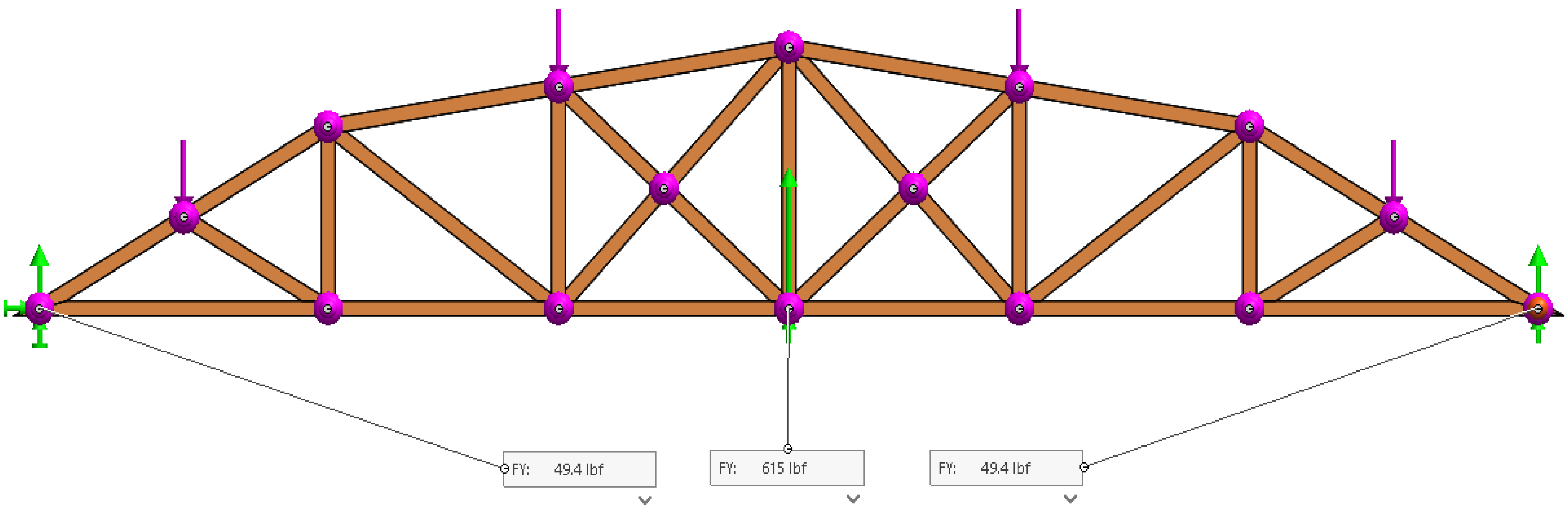
Element: 31 Value: 17.562 psi
Element: 30 Value: 17.562 psi
Element: 24 Value: -35.200 psi
Element: 3 Value: 1.437 psi
Element: 7 Value: 1.437 psi
Element: 12 Value: 16.149 psi
Element: 2 Value: 16.149 psi
Element: 13 Value: -10.596 psi
Element: 1 Value: -10.596 psi
Element: 10 Value: -9.464 psi
Element: 8 Value: -9.464 psi
Element: 22 Value: 2.801 psi
Element: 23 Value: 2.801 psi
Element: 11 Value: -12.339 psi
Element: 9 Value: -12.339 psi
Element: 15 Value: 10.686 psi
Element: 16 Value: 8.196 psi
Element: 17 Value: -1.714 psi
Element: 18 Value: -1.714 psi
Element: 19 Value: 8.196 psi
Element: 20 Value: 10.686 psi
Element: 6 Value: -2.875 psi
Element: 5 Value: -14.292 psi
Element: 21 Value: -30.345 psi
Element: 4 Value: -14.292 psi
Element: 14 Value: -2.875 psi
Element: 28 Value: 17.562 psi
Element: 26 Value: -35.200 psi
Element: 25 Value: -35.200 psi
Element: 29 Value: 17.562 psi


FY: 49.4 lbf
FY: 615 lbf
FY: 49.4 lbf