Edible Wallscapes

Green Facades for Shade and Food in The Southeastern United States

Carnegie Mellon University MSSD Synthesis Report

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Edible Wallscapes

Green Facades for Shade and Food in the Southeastern United States

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ABSTRACT

Increased impervious surfaces in growing cities have affected our modern landscape contributing to rising temperatures (the heat island effect) and leading to an overall lack of natural and biotic matter within many urban environments. The use of vertical greenery systems on building facades is an effective strategy that not only reduces cooling loads but also provides a dynamic vegetated space that interacts with its surroundings. Through constructing and analyzing façade systems that use edible plants as their greenery, this research thesis aims to examine not only the thermal performance of such systems but also the greater social impact they may have in terms of agriculture, education and community engagement. An experimental test bed of three different green façade systems is tested over the month of July at a small community building in Savannah, Georgia. Environmental data, projected produce yield and any increase in social activities linked to the façade systems is recorded in order to quantify the effects that the implementation of an edible façade system has on its surroundings, both immediate and peripheral. This project intends to illustrate a more holistic view of the benefits associated with greening a building envelope to reveal new ways in which we can interact with the buildings that we occupy.

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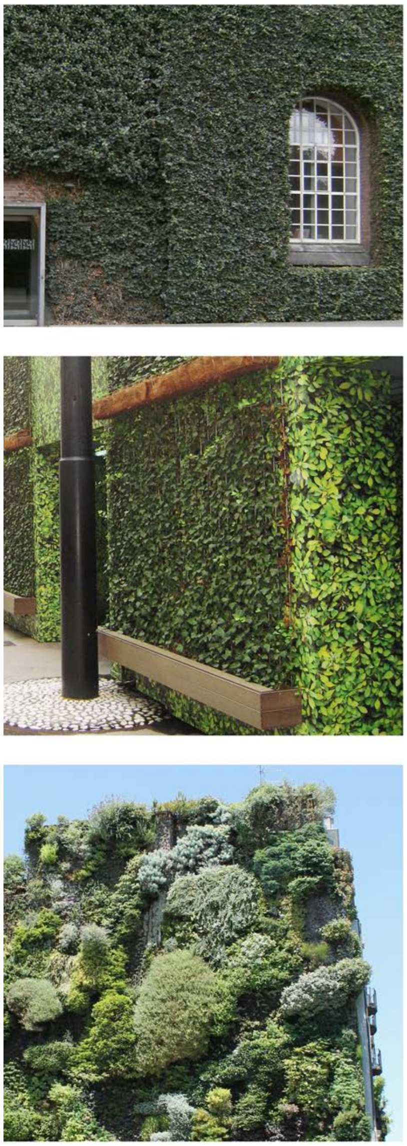


Figure 1. Green Façade Systems (Manso, 2015)

Green Façade systems have become increasingly popular in modern architecture and design. However, research on the full extent of their performance and benefits is still limited. While Green Façade systems are one of the most promising ways to reduce cooling loads and provide energy savings in existing buildings, their effects transcend their thermal benefits. By introducing more greenery, especially edible plants, to the built environment, a building façade can transform from an inert, passive object to an active space for interaction and collaboration providing opportunities for social engagement, community involvement and education. This research aims to contribute to the existing body of work relating to the thermal performance of vertical greening systems and add to it by studying the specific benefits of utilizing edible plants, for which there is little to no existing published research.

An experimental investigation into the thermal benefits derived from the shading capacity of the façade systems as well as the potential for agricultural and social benefits will be evaluated in this research through the construction of three different green façade systems at a small community building in Savannah, GA. Temperature data will be recorded at each facade system and compared to a bare, control surface to evaluate the thermal performance of each facade system. Edible plants will be implemented on each system and although the testing period is not long enough to cycle through a whole growing system and produce any notable yield, projections of the potential yield will be calculated.

This research provides a unique opportunity to not only quantify the benefits of the tested systems but also to create a toolkit for those interested in implementing their own edible green façades. By presenting strategies that accomplish both reduced indoor temperatures and community engagement and to prove the hypothesis that: **The implementation of green wall systems in warm humid climates will reduce cooling loads while serving as a food source and a place-maker for the surrounding community.**

1.1 Classification of Green Façade Systems

The recent interest in the implementation of vertical greenery systems call for a clear and comprehensive classification according to the characteristics and construction techniques of various system types. The most common terminology used to describe all plant-linked systems that enable the greening of a vertical surface, whether located indoors or outdoors is "Vertical Greenery System" (Safikhani, 2014; Wong, 2010; Ottelé, 2011) or "Green Wall Systems" (Manso and Castro-Gomes, 2015; Feng 2014). To further subdivide this category, authors generally refer to two main types of systems: Green Façade Systems and Living Walls. In this classification, "Green Façade Systems" refer to ground-based systems that utilize climbing plants to cover a vertical surface while "Living Walls" describe a construction of container systems that each contain their own growing medium and support a wider array of plant use. There is an evident distinction between the construction and characteristics of these "green façade" and "living wall" systems; however, the existing terminology ignores the fact that living walls can also be utilized as a façade system for buildings. Therefore, to promote a clearer categorization of these systems, an alternative classification has been created (Figure 3).

This classification also refers to all plant linked vertical systems as "Vertical Greenery Systems" but specifies that "green façade systems" are vertical greenery systems which are located outdoors, adjacent to a building envelope. This category can then be subdivided into ground based systems and container based systems to denote a clearer reference to system type characteristics.

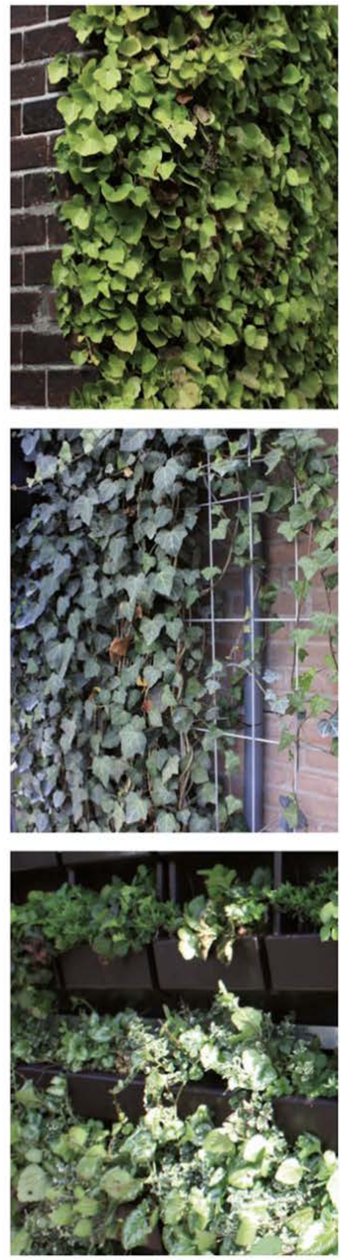


Figure 2. Ground Based Façade Systems (Perini, 2011)

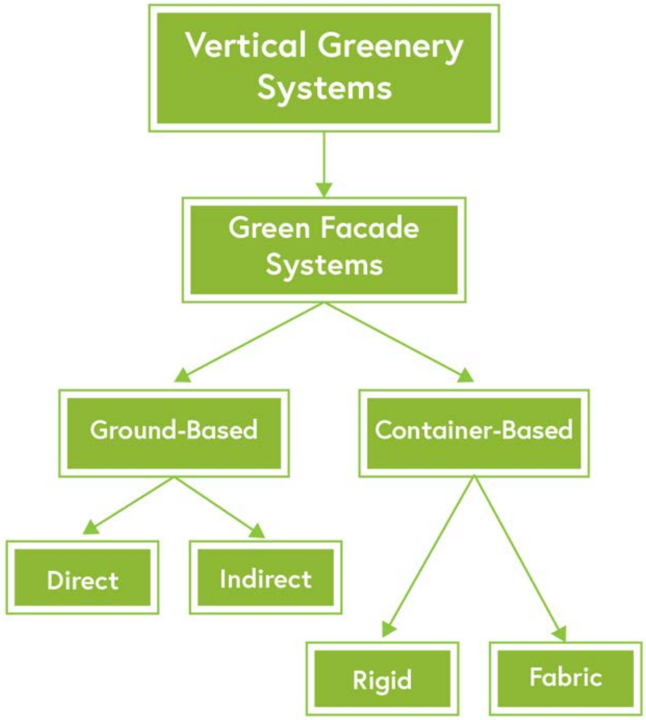


Figure 3. Classification of Vertical Greenery Systems Utilized in this Research

1.2 Choosing Between Ground vs. Container Based Systems

A thorough investigation into the system characteristics and requirements of the green facades system outlined in this research will be provided in the following chapters; however, there are several key considerations to take into account when choosing between container-based and ground based-systems.

Table 1. System Characteristics of Green Façade Systems

System	Type		Opacity	Maintenance	Weight	Price	Additional Comments
Container Based	Potted Systems (Rigid)		Poor	Must maintain plant size	10-12 lbs/SF (LiveWall System)	$45-65 / SF	Allows greater plant diversity
	Felt Systems (Fabric)		Poor	Must maintain plant size	1.5 lbs/SF (Dry) 5 lbs/SF (Panted + Wet)	$30/ SF (Flora felt system)	Allows greater plant diversity, Easily moved and relocated
Ground Based	Indirect: Trellis System		Good	Easy to maintain	0.75 lb/ SF (Without Plants)	$6/SF	Lightweight and cost effective
	Indirect: Trellis System Overhang		Great	Easy to maintain once plant growth is trained	0.6 lb/ SF (Without Plants)	$6/SF	Does not impede view
	Indirect: Tension Wire Systems		Good	Easy to Maintain once growth is established	0.90 lbs/FT (Ottelé, 2011)	$25/SF (Includes Installation cost)	Lightweight and aesthetically interesting
	Direct		Fair	Easy Maintenance	Plant Weight	Plant Cost	Highly dependent on facade type and structural integrity

Table 1 Outlines the average costs and characteristics of various green façade systems, in addition to this information a few key points to understand are:

- Ground Based Systems must utilize climbing plants to attain coverage of a building facade.
- Container Based Systems allow for more uniform coverage at greater heights
- Ground Based Systems are lighter weight than Container Based Systems
- Ground Based Systems are generally easier to maintain than Container Based Systems
- A wider variety of plants can be utilized in Container Based Systems

2. Guidebook to Ground-Based Systems

Ground-based green façades can be categorized into two main types: direct and indirect systems. Although both systems consist of climber plants that can be rooted directly into the ground or in planter beds, a direct system grows directly onto the wall, relying on the capacity of climbing plants to attach themselves to the vertical surface while an indirect system includes a vertical support structure upon which the climbing plants can grow. Indirect systems function as "double skin façades" (Manso and Castro-Gomes, 2015) by creating an air gap between the green façade system and the exterior building wall. They also increase the system resistance to environmental forces by anchoring and holding the vegetation weight. The most common support structures used for indirect green facades include wooden and metal trellises or tension wire cables made of galvanized or stainless steel (Manso and Castro-Gomes, 2015). The shape of the support structure can be varied to support different rates of plant growth.

Figure 4. (Left) Direct system in Savannah, GA. (Right) Indirect System (http://www.clairepotterdesign.com/)

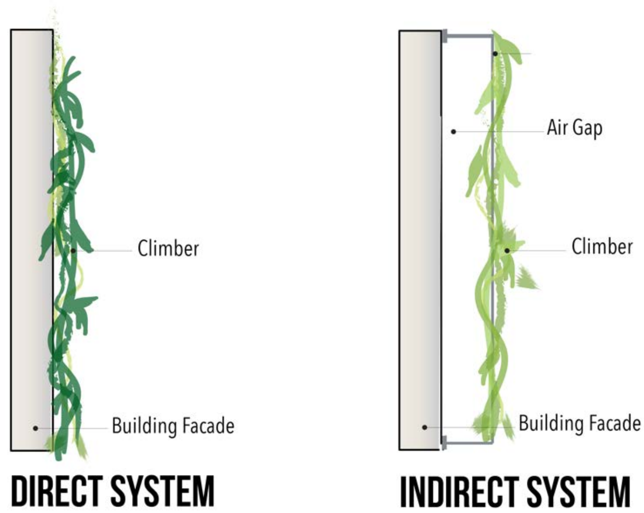


Figure 5. Diagram of Ground Based Green Façade System Configuration and Components

Figure 5 illustrates the general system characteristics of the two main categories of ground-based green facades. While both systems rely on climbing plants to create foliage cover across a building surface; a direct system consists of only self-adhesive climbers that can support themselves directly onto the façade. An indirect system allows for more variation of climber plant use. Based on the configuration and shape of the support structure, various types of climbing plants can be used to reach the desired foliage coverage.

2.1 Overview of Climbing Plants

The type of climbing plant utilized on a façade or façade system will influence system choice and performance of a green façade. Before reviewing the design characteristics for the various indirect system types available on the market, it is important to first understand the different types of climbing plants and their mechanisms for attachment to façades and façade systems.

Climbing plants are subdivided into two categories: **Self-Adhesive Climbers** and **Climbers that Require a Support Structure**. Self-Adhesive plants cling to a building surface through climbing mechanisms built directly into their plant structure, such as invasive roots that can bury into porous surfaces or glands that act as suction cups that cling to building façades. The non-self-adhesive climbers require some type of support structure to promote vertical plant growth along a building surface. These plants cannot attach themselves directly to a surface but rather grow in a way that allows themselves to wrap around or climb up an external structure. (Jakob, AG, 2003) The main species of climbing plants and their mechanisms for façade attachment and vertical growth are illustrated in the following table and figures.

Table 2. Overview of Climbing Plants

Self-Adhesive	Root Climbers
	Adhesive Sucker Climbers
Support Structure Needed	Vining Plants
	Tendril Climbers
	Scrambling Plants

Self-Adhesive Climbers

Figure 6. Root Climber

Root Climbers

Root climbing plants are self-adhesive and attach themselves directly to a façade by growing their roots into its surface. They do not require any trellis to support their growth; however, they are notorious for causing damage to building facades.

Examples: Ivy, Trumpet Vine

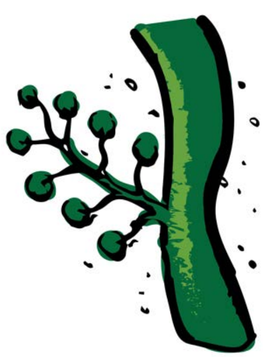


Figure 7. Adhesive Sucker Climber

Adhesive Sucker Climbers

Adhesive sucker climbers attach themselves directly to surfaces with short lateral shoots tipped with glandular pads. They also do not require any support structure for growth and while they do not cause as much harm to the structural integrity of the attached surface, some damage can occur when attempting to remove the plant.

Example: Boston Ivy

Climbers That Require Support Structures for Vertical Growth

Figure 8. Vining Climber

Vining Climbers

Vining climbers wind around their support structure as a result of the circular growth motion of their stem tips. They form a strong structure and are well-suited for high wind locations. Only a single vertical support structure is needed.

Examples: Wisteria, Honeysuckle, Hops, Morning Glory

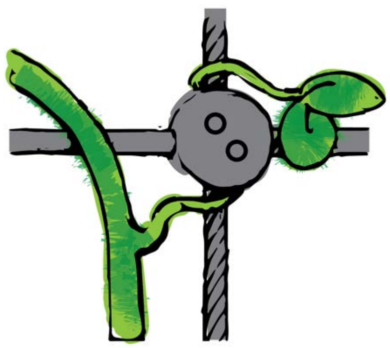


Figure 9. Tendril Climber

Tendril Climbers

Tendril Climbers have specialized stems or leaves with a threadlike shape (tendrils) that the plants use to coil around their support structure. Unlike vines, they impart less load on to the support structure.

Examples: Clematis, Passionfruit, Grape Vines

Figure 10. Scrambling Climber

Scrambling Climbers

Scrambling plants work their way up by using epidermal outgrowth such as thorns or bristles.

Examples: Bougainvillea, Climbing Roses, Winter Flowering Jasmine

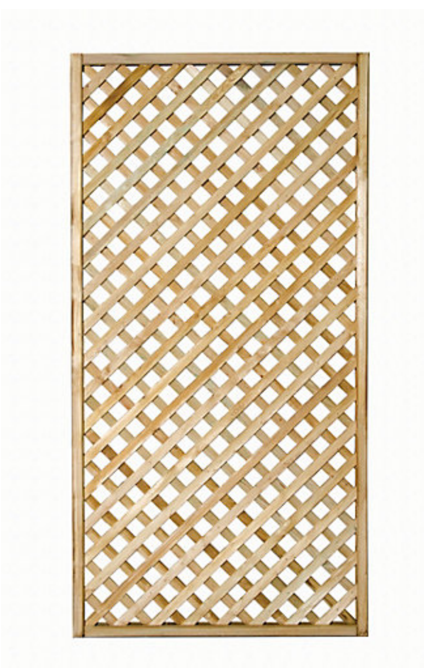
2.2 Indirect Green Facade System Types

Based on the available literature review for green façade systems as well as market research for products that are currently available to buy, for the purpose of this research, indirect systems have been subdivided into three main categories: **Trellis and Lattice Systems, Overhang Systems and Tension Wire Systems.**

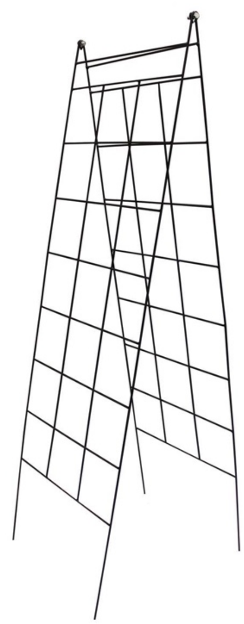
Trellis and Lattice Systems

Trellis systems are commonly used support structures for climbing plants in southeastern gardens. These systems consist of a free-standing or anchored structure made from an open framework, or lattice assembly, of interwoven pieces of wood, metal or vinyl. There are several varieties of trellis systems that suit the growing requirements of different plants including Flat Trellises, A-Frame Trellises and Teepee Trellises.

A.



B.



C.

Figure 11. A) Wooden Flat Trellis (wickes.co.uk) B) metal A-Frame Trellis (farmandfleet.com) C) wooden Teepee Trellis (outdoorfurnitureplus.com)

Flat Trellises are the most commonly recognized trellis system. They can either be freestanding or anchored to walls or posts. These systems are generally easy to move around and are used to define a space and provide a sense of privacy. Examples of flat trellises include wood lattice panels, metal trellises, plastic mesh trellises. (LaLiberte, 2017) Similar to flat trellises, A-frame trellises are made by constructing two frames either from wood or metal and covering each frame with lattice or mesh material that will support the plant material. These frames lean against each other, creating an A-shape and providing two separate surfaces for growth. A-Frame trellises are self- supporting and ideal for small gardens where space is limited. (LaLiberte, 2017) Teepee trellises are similar to an A-Frame Trellis in that they are self-supporting and provide several surfaces for growth. They also add a strong aesthetic quality to a garden. System costs for trellis constructions vary by brand and material used. Table 3 presents a range of costs for each of these systems.

Table 3. Range of Trellis System Costs for Currently Available Products

Trellis System	Material	Cost/SF ($)
Flat Trellis	Vinyl	4
	Metal	7 - 10
	Wood	3 - 6
A- frame trellis	Metal	2 - 4
	Wood	4 - 12
Tee-Pee Trellis	Metal	2 - 25
	Wood	10 -15

Overhang Systems

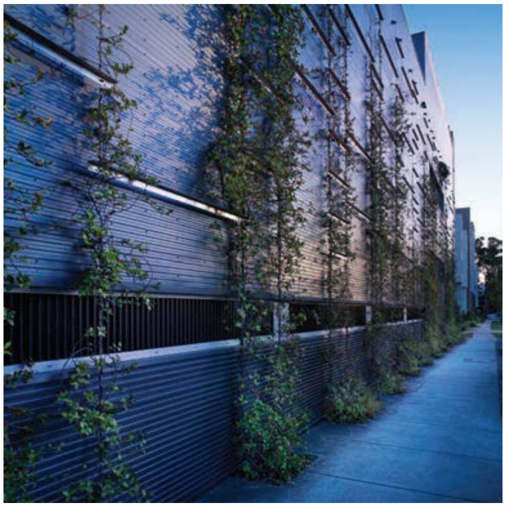
Another commonly used support structure is an overhang, or pergola system. This system differs from a trellis systems since the support structure on which the plant grows is predominately located overhead. These archway structures can be self-supporting or connected directly to the building. Table 1 shows the average prices of wooden overhang systems currently for sale. Prices are presented in terms of cost per square footages of growing area for the overhang system

Figure 12. (Left) Self-supporting pergola (samsclub.com) (Right) Wall Pergola (homeclick.com)

Table 4. Average Prices of Currently Available Wooden Overhang Systems

Type	**Material**	**Cost/SF ($)**
Self-Supporting	Wood	8.20
Overhang	Wood	11.30

Tension Cable Systems

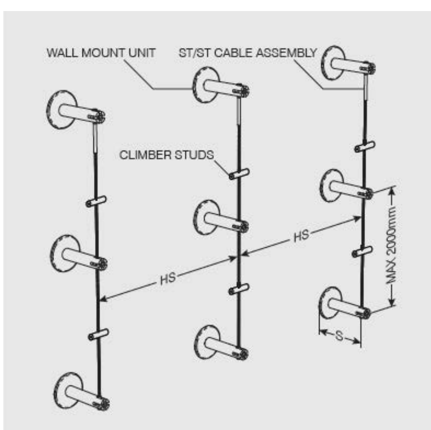


Recent innovations in cable technology have allowed for new advances in construction of tension cable systems that can be arranged in various patterns to support the growing patterns and rates of different climbing plants. Of the tension cable systems currently on the market, the most commonly utilized patterns include: vertical, horizontal, grid and diagonal grid. Each of these patterns has its own unique benefits and support specific climbing plant species as outlined below.

Figure 13. Ronstan Cable Trellis system (Ronstan Cable Trellis System Catalogue: https://www.caddetails.com/CompanyContent/847/docs/847Trellis.pdf)

Vertical Cable Systems

Vertical cable systems are ideal for vining plants and tendril climbers. They consist of galvanized steel cables that are held off the wall using mounting brackets so that plants can easily weave around the cables providing optimal growth conditions. Wall mounts should have backing plates to spread the load across the façade and additional climber studs can be implemented to give plants an extra foothold.



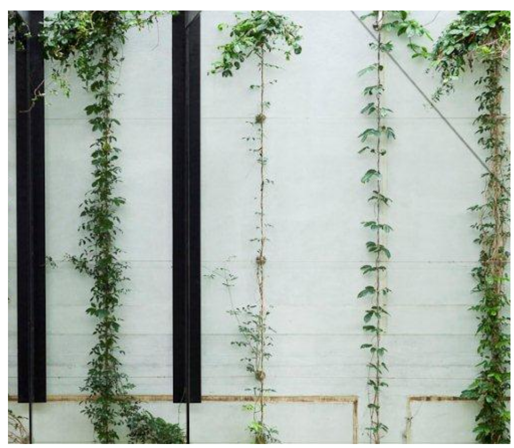


Figure 14. Ronstan Vertical Cable System (Ronstan Cable Trellis System Catalogue: https://www.caddetails.com/CompanyContent/847/docs/847Trellis.pdf)

Horizontal Cable Systems

Horizontal cable systems have the ideal layout for promoting broad plant growth of scrambling plants. The system is constructed similarly to a vertical system just rotated ninety degrees to be horizontal.

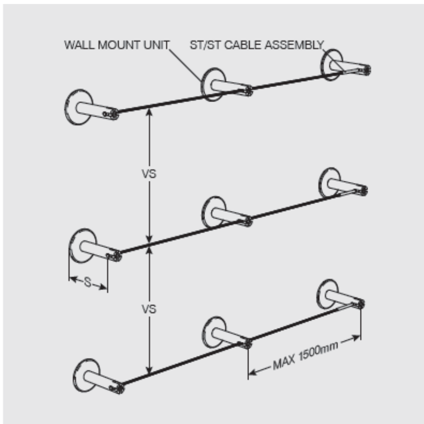


Figure 15. Ronstan Horizontal Cable System (Ronstan Cable Trellis System Catalogue: https://www.caddetails.com/CompanyContent/847/docs/847Trellis.pdf)

Grid Cable Systems

A Grid patterned cable system allows plants to grow both vertically and horizontally promoting more expansive plant growth and wall covering. A grid system uses steel cables to form a tensioned rectangular grid with steel wall mounts placed at the borders to offset the cable grid from the wall. The locations at which cables cross over each other are outfitted with cross clamps to help secure the structure.


Figure 16. Jakob Grid Cable System
Source: http://www.homedepot.com/p/Jakob-96-in-Wire-Rope-Plant-Trellis-System

Diagonal Grid Cable Systems

Much like the normal grid cable systems, a diagonal grid pattern is optimal for achieving wall coverage since plants are directed to spread naturally both horizontally and vertically. The benefit of the diagonal system is that less training is pruning of the plants is needed and an interesting aesthetic effect is also achieved.

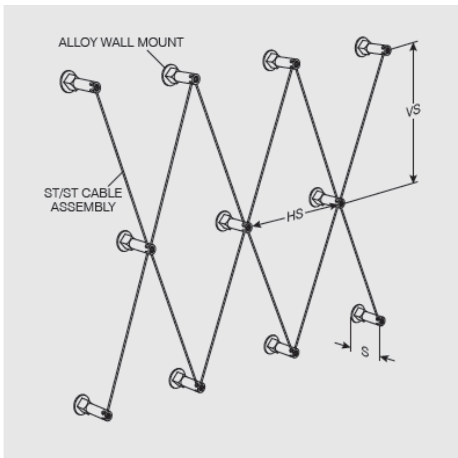


Figure 17. Ronstan Diagonal Grid Cable System (Ronstan Cable Trellis System Catalogue: https://www.caddetails.com/CompanyContent/847/docs/847Trellis.pdf)

Currently, there are five (5) main manufactures of tension cable systems. Table 5 illustrates these manufactures and the system types they provide.

Table 5. Overview of Tension Wire System Manufacturers

Manufacturer	Website	System Types
Jakob	https://www.jakob-usa.com/green-walls/	- Vertical - Grid - Horizontal
Ronstan	http://www.ronstantensilearch.com/vertical-garden/	- Vertical - Horizontal - Grid + Diagonal Grid - Mesh
S3i	https://www.s3i.co.uk/greenwalltrellis.php	- Vertical - Horizontal - Grid
Feeney	http://www.feeneyinc.com/Garden/Somerset-II-Trellis	- Grid
Seco South	https://www.secosouth.com/products/stainless-steel-cable-trellis-system-2000-60/	- Grid

2.3 Planting choice

Ground based systems are limited to the use of climbing plants for façade vegetation. Climbing Plants can have either evergreen or deciduous foliage. Evergreen plants maintain their leaves all year and deciduous plants lose their leaves during the fall, which allows for strong visual change throughout the year. Direct systems generally utilize ivy as the plant material and two main species are most commonly grown: Boston and English ivy. English Ivy is an evergreen ivy, but has roots that can grow into the façade material (wood, masonry stone or concrete) and can cause damage to the surface, so it is recommended that this type be avoided. Boston ivy, a deciduous species, uses suckers to attach to surfaces, mitigating any damages from root growth. If utilizing a direct system, it is recommended to only use adhesive sucker climbers such as Boston Ivy. For indirect systems, a selection of native (To the Southeastern United States), non-invasive species is shown in Figure 18. These are divided into the more common flowering or inedible selection of climbing plant species and edible climbing plants. (Wallace, 2013). Based on the species of plant used some will require training to climb and wrap themselves around the trellis. This can be accomplished by passing the growing shoots through the trellis and/or tying them to the framework. (Wallace, 2013)

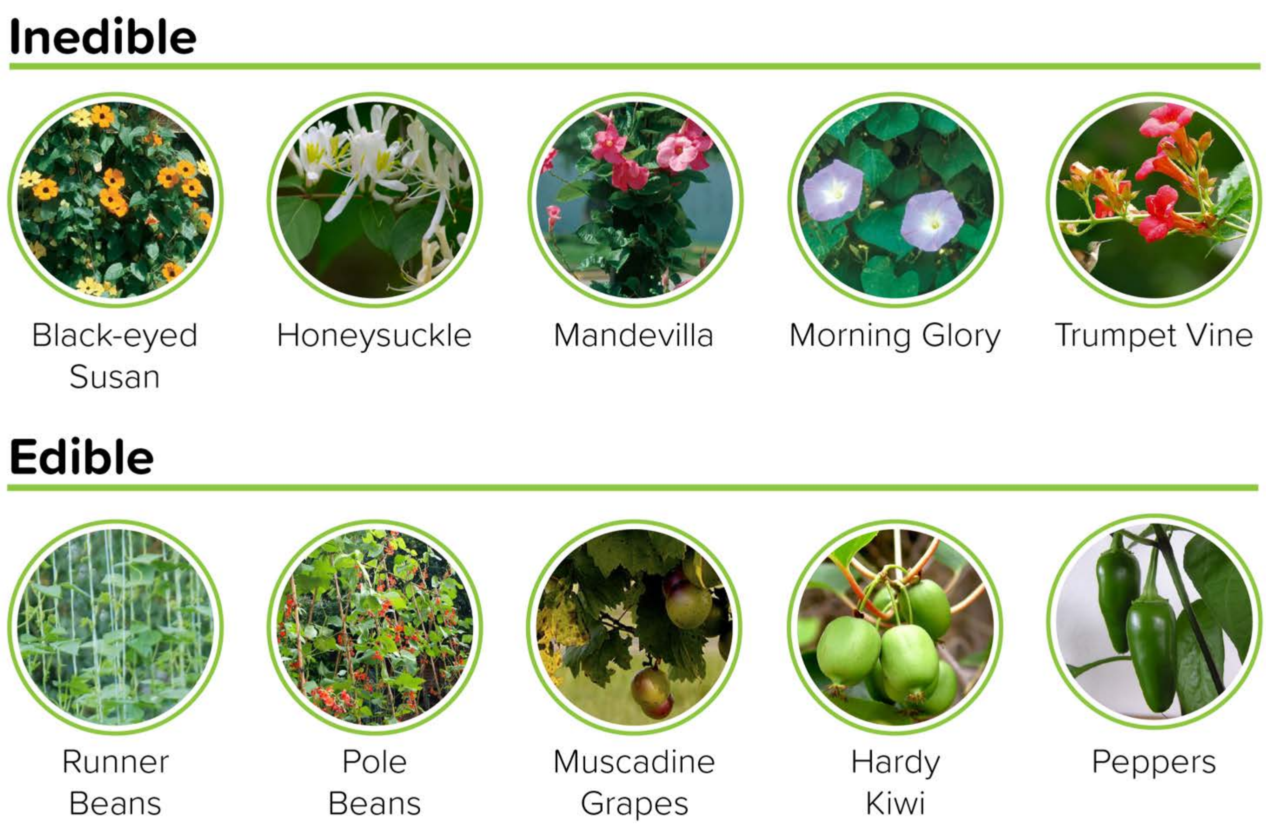


Figure 18. Climbing Plants Well-Suited for the Southeast

3.Guidebook to Container-Based Systems

Container based green façade systems, sometimes referred to as Living Wall Systems (Ottelé, 2011), are a more recent area of development in vegetated wall cladding. They allow for rapid cover of large surfaces and result in more uniform coverage at greater heights than direct or indirect ground-based systems. (Manso and Castro-Gomes, 2015) The nature of container based systems allow for a wider variety of plant use since the growing medium is located within each container and plant selection is not limited to only climbing and vining species. Two main types of container based systems are on the market currently: rigid and fabric based systems. Rigid systems come in the form of planter trays, pots or tiles that are generally modular and attachable to each other while fabric systems, usually made from felt, are a series of continuous fabric bags of various sizes that contain the growing media.

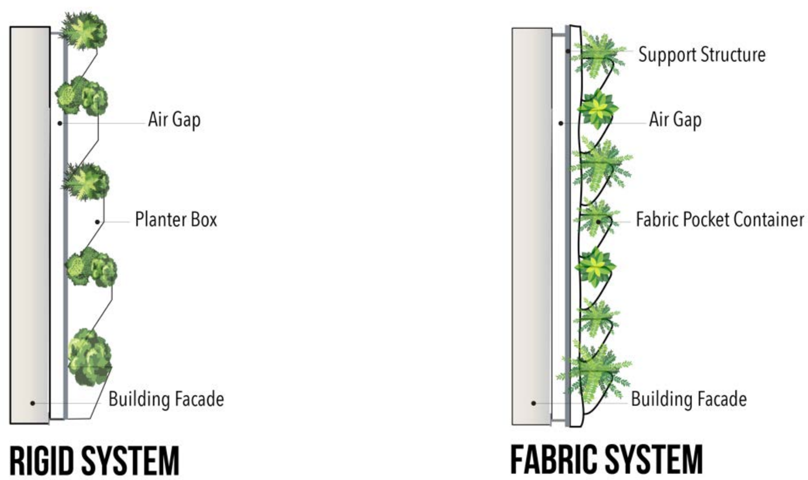
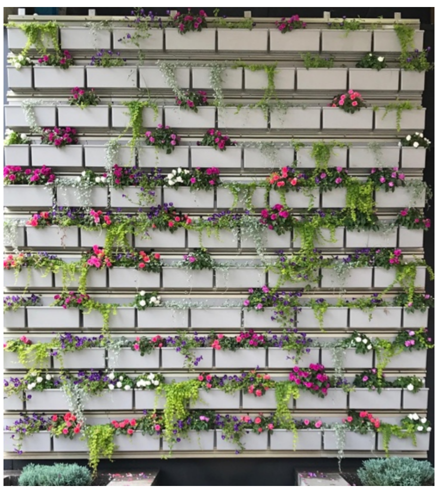


Figure 19. Diagram of Container-Based Green Façade System Configuration and Components

Most container based systems are installed using a support frame that is usually fixed to a wall, forming an air gap between the green façade system and the exterior wall. Since they do not utilize the terrestrial soil like ground based system, container based systems require a growing media to be located within each container, whether rigid or fabric-based. Most container based systems utilize a mixture of light substrate with a porous material (mineral granules, coconut fibers or recycled fabric, etc.) in order to obtain a light-weight water retention capacity (Manso and Castro-Gomes, 2015). Due to the diversity and density of plant life, container based green facade systems typically require more intensive maintenance than ground based systems.

3.1 Rigid Container-Based Systems

Rigid container systems are composed of panels, planters or modular tiles that are attached to a structural wall or frame. These containers can be made of plastic, polystyrene, clay, metal, and concrete, and support a great diversity and density of plant species (Green Roofs for Healthy Cities, 2008). Each container is filled its own soil or growing medium and water requirements are usually met through an irrigation system supplied at various heights along the wall.



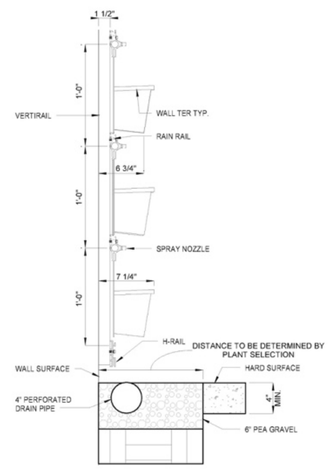


Figure 20. Rigid Container System in Pittsburgh, PA (Left) Construction Detail for LiveWall Container System (Right)
Source: https://livewall.com/technical/green-wall-design/detail-drawings/

Figure 20 illustrates how the containers within the rigid system are connected together to form one monolithic surface. Compared to ground-based systems, the volume of growing medium available for the plant material is significantly smaller than the terrestrial ground; therefore, the containers tend to dry out much more quickly and require more frequent watering (Manso and Castro-Gomes, 2015) In order to reduce the amount of maintenance required to water these green-facades, container systems are usually outfitted with some type of irrigation system or drip lines placed above each row of containers to help maintain the moisture and nutrients required for plant growth. (https://livewall.com/technical/green-wall-design/)

Modular Rigid Container Systems

A subset of rigid container systems is **Modular Rigid Container Systems**. Similar to modules used for green roof applications (Green Roofs for Healthy Cities, 2008) these consist of square tiles which contain the growing media to support the vegetation. These modules are supported onto a façade by metal brackets that are configured to allow installation along various levels of the brackets. One major benefit of modular systems is their ability to be pre-vegetated to provide an instantaneous green effect upon installation.

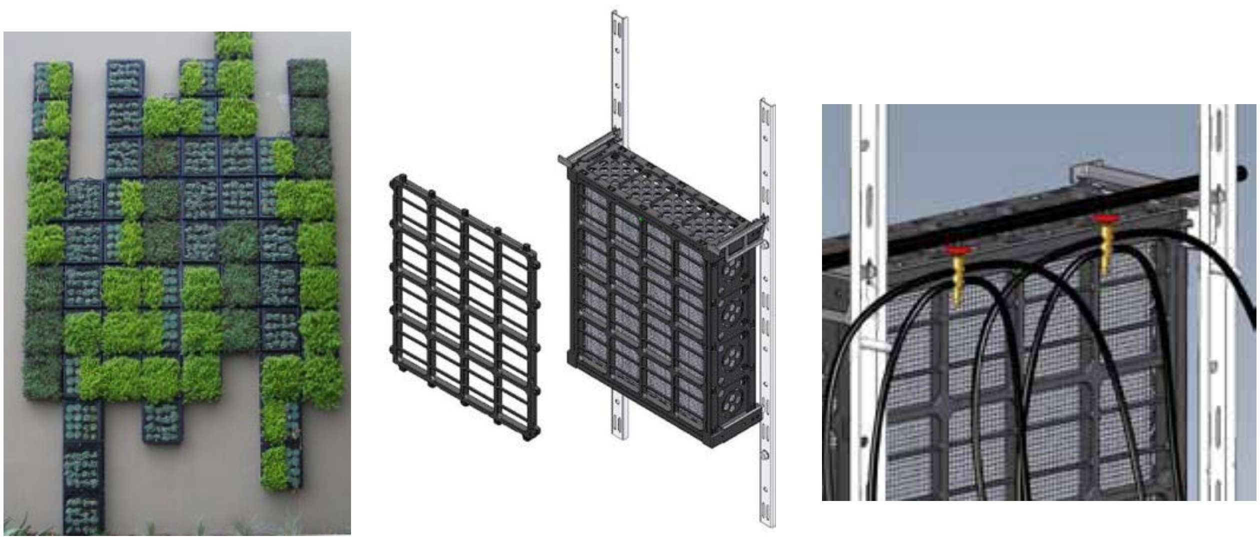


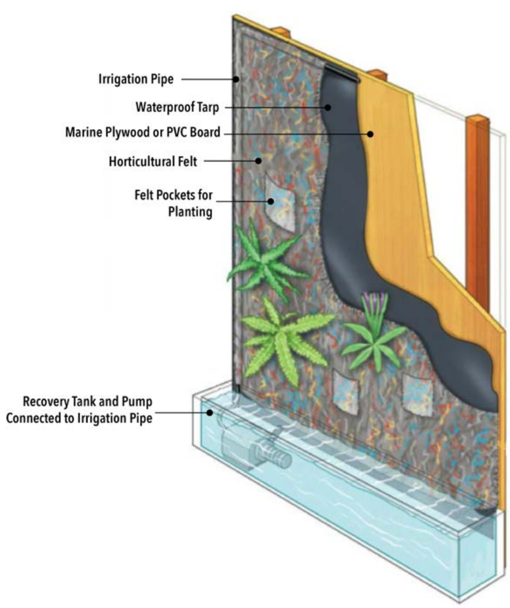
Figure 21. Elmich VGM Green Wall System
Source: http://www.elmich.com.au/wp-content/uploads/2014/11/Elmich-VGM-Green-Wall.pdf

The VGM modular system shown in Figure 21 above has cut-away side openings that enable all-around planting allowing for instantaneous and dense vegetation upon installation. Each VGM is secured by steel brackets anchored to steel pilasters that require minimal wall penetrations. An automated drip irrigation is inserted directly into the planting medium to lower maintenance requirements and deliver nutrients to each module. (Elmich VGM Green Wall Catalogue)

3.2 Fabric Container-Based Systems

Figure 22. Mur Végétal by Patrick Blanc (https://www.murvegetalpatrickblanc.com/patrick-blanc/dates-clefs)

Fabric based container systems are a unique form of green wall pioneered by Patrick Blanc (Green Roofs for Healthy Cities, 2008). One of the first designs for this type of configuration was his “Mur Vegetal”



The “Mur Végétal” is composed of two layers of synthetic fabric with pockets that physically support plants and growing media. The fabric walls are supported by a frame and backed by a waterproof membrane against the building wall because of its high moisture content. Water is distributed through an irrigation system that cycles water from the top of the system down. (Groult, 2008)

Figure 23. Mur Végétal System Configuration Diagram (Groult, 2008)

The Florafelt container system is a more recent fabric-based system currently on the market (Florafelt.com). The system consists of pleated felt stapled onto a lightweight plastic board. The system can be watered from the top, either manually or with an irrigation system, water can then wick down to each plant. The nature of the felt will allow the plant roots to grow into the fabric allowing for larger growth than a rigid container of the same size would allow. The felt is breathable and light allowing the growing medium to breather and mitigating mold and mildew issues.

Figure 24. Florafelt Container System (www.florafelt.com)

The fabric-based container systems discussed in this chapter are beneficial due to their flexibility and ability to cover non-uniform surfaces. They are also more light weight than their rigid counterparts and can be easily transported or relocated.

3.3 Planting Choice

Container based systems allow for a wide variety of plant use since each container is filled with its own growing medium. Considerations for light exposure and watering requirements must be taken into account, as well as growth limitations based on the container size of the system. The flexibility of container based systems increase the functional potential of green facade systems and creates opportunities for urban agriculture, particularly in cities where land for growth and cultivation is lacking.

This new concept of container based green facades that integrate vegetables and herbs in green facades is of particular interest to this research therefore, a table of commonly grown vegetables in the Southeast that could be easily integrated into container based systems are outlined in Table 6 below. A harvesting schedule is also presented in Figure 25 to aid in determining when to sow and harvest your chosen plants.

Table 6. Commonly Grown Vegetables in the Southeast by Season (Wallace, 2013)

Spring Cool	**Warm**	**Fall Cool**
Asian Greens	Celery	Asian Greens
Beets	Corn	Brussel Sprouts
Onions	Cucumber	Onions
Carrots	Artichokes	Carrots
Fava Beans	Lettuce	Fava Beans
Kale, Cabbage, Broccoli	Spinach	Kale, Cabbage, Broccoli
Leeks	Nightshades	Leeks
Lettuce	Okra	Lettuce
Peas	Parsnips	Peas
Potatoes	Peanuts	Radishes
Radishes	Potatoes	Shallots
Southern Greens	Runner Beans	Southern Greens
Spinach	Snap Peas	Spinach
Swiss Chard	Southern Peas	Swiss Chard
	Sunflowers	
	Sweet Potatoes	

Planting + Harvesting Dates for Savannah, GA

First Frost: 11/25
Last Frost: 3/1

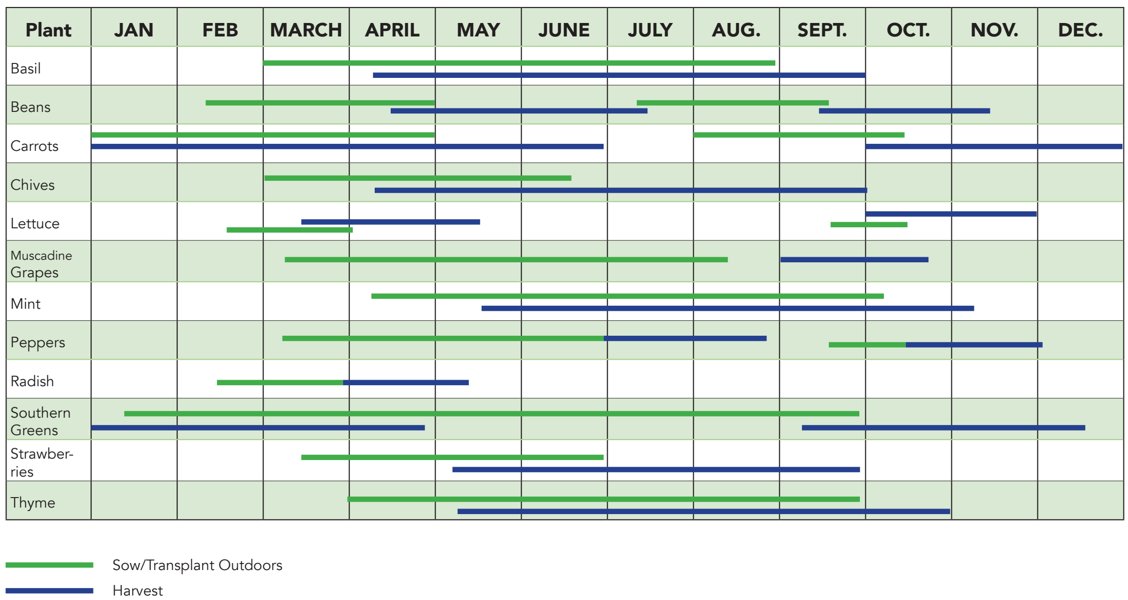


Figure 25. Sowing and Harvesting Schedule for the Southeast (Wallace, 2013)

3.4 Container Sizing

One limitation to container based systems is the sizing limitation that these systems pose to plant growth; therefore, container based green façade systems require attention to container size versus selected plant species. Based on the growing requirements of commonly used edible plants in Southeastern garden a sizing analysis was performed to develop a rule set of plant selection for various container sizes. (Figure 26)

Table 7. Container Sizing Requirements for Selected Herbs and Vegetables

Plant	Soil Depth (in)	Seed Depth (in)	Seed Spacing (in)	Thinning Spacing (in)	Grow Time
Basil	6 - 8	1/2	8 - 10	As needed	40 days
Carrots	8 - 10	1/4	3 seeds/ inch	1 - 2	65-75 days
Chives	3 - 4	1/2	6 - 8	As needed	30 - 60 days
Lettuce (Looseleaf)	6-10	1/4	4 - 6	As needed	50 days
Okra	8 - 10	3/4	6 - 8	As needed	80 days
Peppers	4 - 8	1/2	6 - 8	As needed	50 days
Radishes	4 - 5	1/2	3/4 - 1	As needed	30 - 60 days
Southern Greens	10 - 12	1/4 - 1/2	2	12 - 18	60 - 75 days
Spinach	8 - 10	1/2	4 - 6	As needed	50 - 60 days
Thyme	6 - 8	1/2	6 - 8	As needed	40 - 50 days

Pocket Size	*Suitable Plants*
4" x 6" 	Basil, Chives and Radish
4" x 10" 	Basil, Chives, Lettuce and Radish
6" x 6" 	Basil, Chives, Lettuce, Peppers, Radish and Thyme
6" x 10" 	Basil, Carrots, Chives, Lettuce, Peppers, Radish and Thyme
8" x 10" 	Basil, Carrots, Chives, Lettuce, Peppers, Radish, Spinach and Thyme
10" x 10" 	Basil, Carrots, Chives, Lettuce, Peppers, Radish, Spinach and Thyme
12" x 10" 	Basil, Carrots, Chives, Lettuce, Peppers, Radish, Spinach, Southern Greens and Thyme

Figure 26. Containers Sizing Matrix for Selected Herbs and Vegetables

4. The Benefits of Green Façade Systems

Figure 27. People Interacting with a Green Façade
Source: (http://cubtab.com/ua/212590143/garden-plot/212590/)

The integration of vegetation on a building facade provides opportunities for improvements in building performance through environmental, ecological and social benefits. These particular benefits have been the focus of various studies and research since seventies (Perini, 2011; Otellé, 2011) when the ideas of Eco-design and Permaculture (Bill Mollison and David Holmgren) began to take root. Design which revolves around nature and the environment has continued to gain popularity and research proliferating into the field of new technologies that green the built environment. Beyond the aesthetic value that vegetation adds to a space, green facade systems offer numerous benefits that can have positive impacts on both the building occupants and the surrounding environment. Research into the existing applications for greening the building environment has focused on both green roofs and walls with much emphasis placed on the thermal benefits and energy savings associated with these strategies; however, this research recognizes that the benefits, though difficult to quantify, go far beyond this. The addition of more greenery to a building facade not only produces a thermal benefit through the mitigation of urban heat island effect, and increase in outdoor and indoor comfort through its shading properties, but also adds social and ecological value to a space through increasing biodiversity and providing opportunities for agricultural use and community involvement and education.

4.1 Thermal Benefits of Green Façade Systems

Green facade systems use three fundamental mechanisms to act as passive conditioning systems: (Perez, 2015)

1. Shadow produced by the vegetation
2. Thermal insulation provided by the vegetation and substrate
3. Evaporative cooling that occurs by evapotranspiration from the plants and the substrate

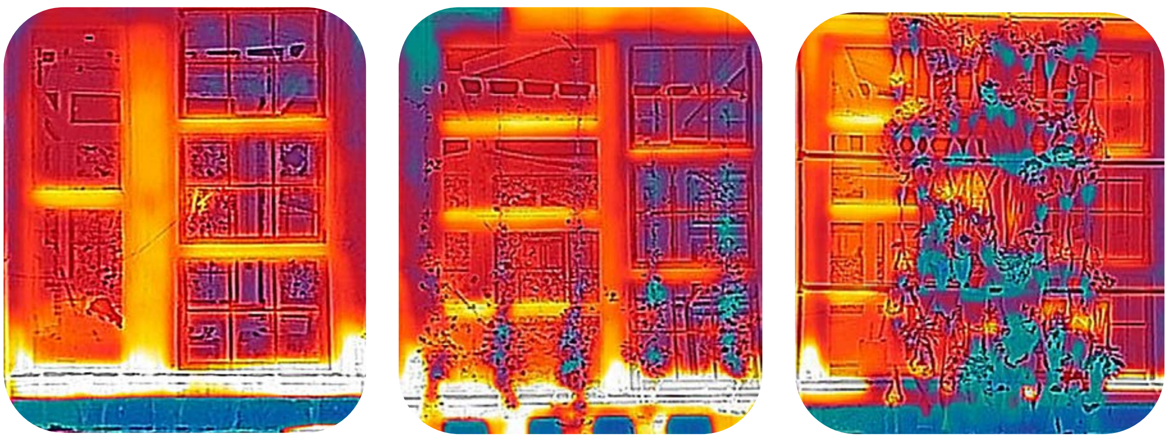


Figure 28. Cooling Capacity of Vegetation Demonstrated by Thermal Imaging of a Façade Surface without Vegetation (Left) and with Vegetation (Middle and Right)

By constructing green façades, solar radiation normally absorbed by a bare wall will be absorbed for the growth of plants and their biological functions (photosynthesis, transpiration, evaporation and respiration). Approximately 5-30% of the remaining solar radiation will then pass through the leaves and onto the building surface where it will then affect the internal climate of building. (Perini, 2011) Especially in dense and paved urban areas, the impact of evapotranspiration and shading of plants can significantly reduce the amount of heat that would be re-radiated by façades and other hard surfaces. Every decrease in the internal air temperature will reduce the cooling load and subsequent electricity use for that building. (Perini, 2011) Research into this area has been covered in many field experiments and studies. A field experiment by Safikhani et al in Malaysia found an average decrease in indoor air temperature of 3°C and 4°C of Container Based and Ground Based Indirect Facade systems respectively when compared to a bare, control wall.

Figure 29. Experimental Green Façade System Configuration. Indirect System (Left) Felt, Container Based System (Right) (Safikhani et al, 2014)

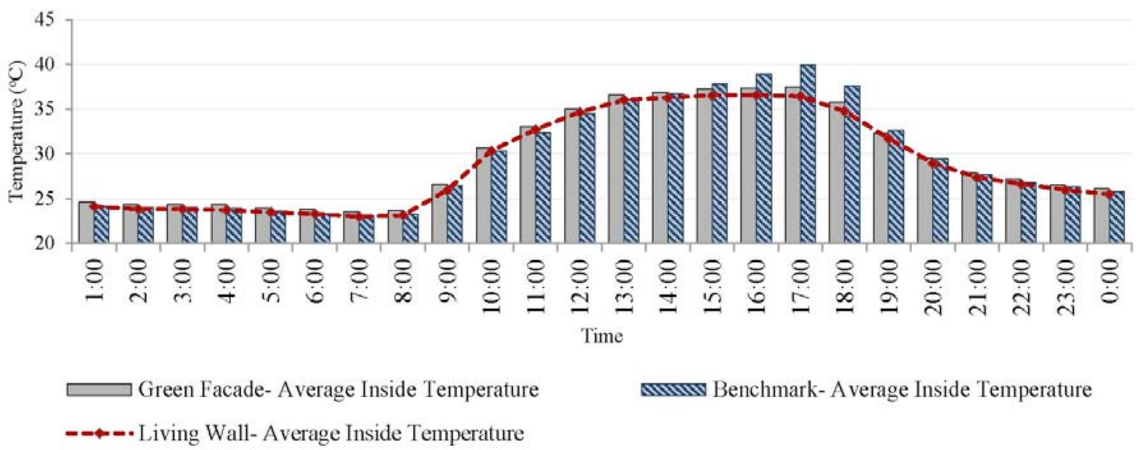


Figure 30. Average Indoor Temperature Comparison of Test Boxes Behind Container Based System (Living Wall), Indirect System (Green Façade) and the Benchmark Control Wall. (Safikhani et al, 2014)

In a recent study by Wong et al., 8 different green façade systems were analyzed on a wall in Hortpark in Singapore. Surface temperature reductions were found in all of the greened walls in comparison to the bare control wall – with a maximum reduction in surface temperature found to be 10.03°C for a container-based system. This demonstrates that a greened façade absorbs less heat than a non-greened façade. The differences in the thermal performance of the various green façade systems can be attributed to several factors including substrate type, insulation from the system structure, substrate moisture content as well as the shade and insulation from greenery coverage. (Wong, 2010)

Figure 31. Eight Facade Systems Analyzed in HortPark, Singapore (Wong, 2011)

Investigations beyond simple temperature reduction measurements and in to the energy savings associated with the thermal performance of green façade systems have also been performed. Many energy savings extrapolations have been simulation studies (Alexandri and Jones, Otellé et al); however, Perez et al conducted a field experiment in Spain which resulted in measured energy use data. In this experiment, an indirect, ground-based green façade system on a small conditioned building, referred to as a "cubicle" was studied. Surface temperatures and energy use of a conditioning system to reach a set point of 24°C were compared to a reference cubicle of the same square footage and orientation. Perez et al found reductions in surface temperature from 15-16.4°C depending on the wall orientation and an overall reduction in energy use of 34% compared to the reference building over a week in August. (Perez, 2017)

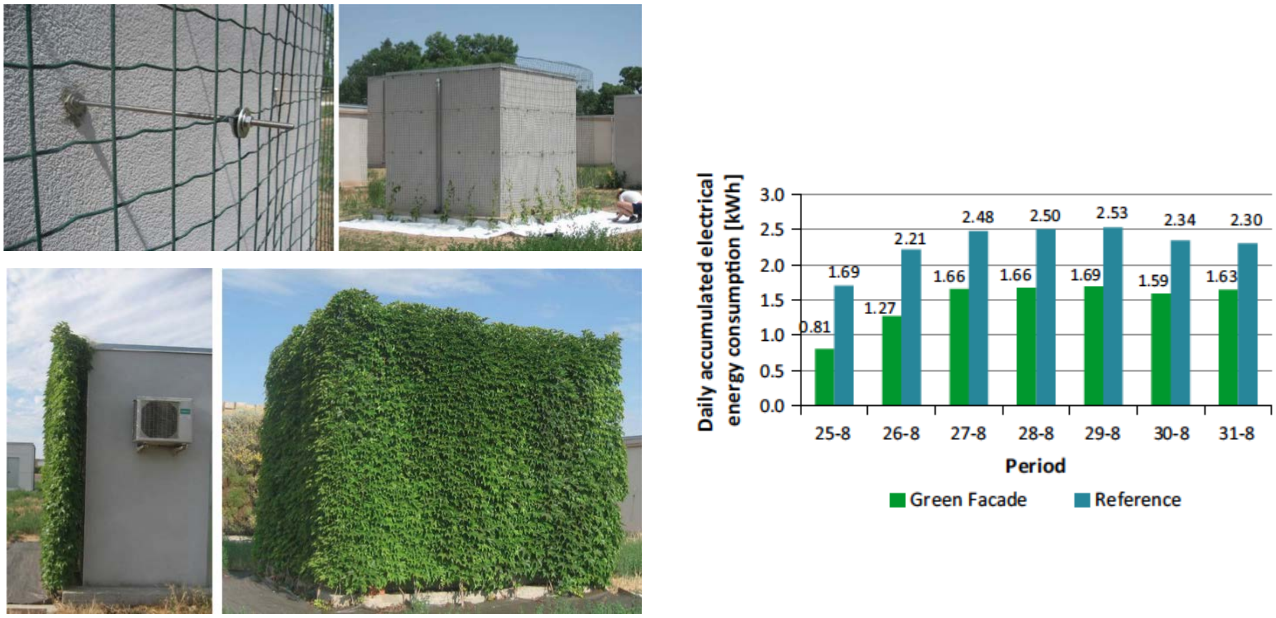


Figure 32. Perez Experiment Set-up and Energy Consumption Results (Perez et al, 2017)

These studies reveal great opportunities for the use of vertical greenery systems to reduce energy consumption and increase thermal comfort of the built environment. These experiments also reveal that the effectiveness of the green facade systems can vary greatly based on system construction, foliage coverage and climate. A summary of the literature focused on the thermal performance of green façade systems is outlined in Table 8.

Table 8. Temperature Reduction and Energy Savings from Green Façade Systems: Literature Review Summary

System Type	Orientation	Energy Savings (Cooling)	Temp. Decrease (Indoors)	Temp. Decrease (Surface)	Location	Article
Container-Based: Rigid		43%	4.5°C		Mediterranean	Otellé et al (2011)
Container-Based: Fabric		43%	4.5°C			
Ground-Based: Indirect		43%	4°C			
Container-Based: Fabric	West		3°C		Malaysia	Safikhani, T. et al. (2014)
Ground-Based: Indirect	West	--	4°C			
Ground-Based: Direct	East + West	68%			Brazil	Alexandria, E. & Jones, P. (2008)
Ground-Based: Direct	East + West	66%			Hong Kong	
Ground-Based: Direct	East + West	52%			Montreal	
Ground-Based: Direct	East + West	43%			Athens	
Ground-Based: Direct	East + West	37%			Beijing	
Ground-Based: Direct	East + West	37%			Riyadh	
Ground-Based: Direct	East + West	35%			Mumbai	
Container-Based				10.03°C	Singapore	Wong, N. (2010)
Ground-Based: Indirect				3.33°C		
Container-Based: Fabric				6.58°C		
Ground Based: Direct	North-West			1.2°C	Netherlands	Perini, K. (2011)
Ground Based: Indirect	North-East			2.7°C		
Container-Based	West			5°C		
Container-Based		7.30%			Kelowna, Canada	Feng, H. and Hewage, K. (2014)
Ground Based: Direct			11°C	13°C	Tokyo	Hoyano, A. (1988)
Ground Based: Indirect	East	34%		15°C	Puigverd de Lleida, Spain	Perez, G. et al (2017)
Ground Based: Indirect	South	34%		16°C		
Ground Based: Indirect	West	34%		16.4°C		

4.2 Social and Ecological Benefits of Green Façade Systems

Introducing more greenery to the built environment has additional benefits than the thermal impacts reviewed in the previous section. Beyond the aesthetic value added to a space, more vegetation, in the form of green façades, increases access to nature to those which come in contact with the system. More access to nature has been shown to positively influence the health and well-being of a person, providing psychological and health benefits, including a reduction in stress (Grinde and Patil, 2009) Increased green space also adds habitat for wildlife increasing the biodiversity of the site for a healthier ecological environment; furthermore, landscaped areas act as place-makers, designating spaces for social interactions and collaboration to take place.

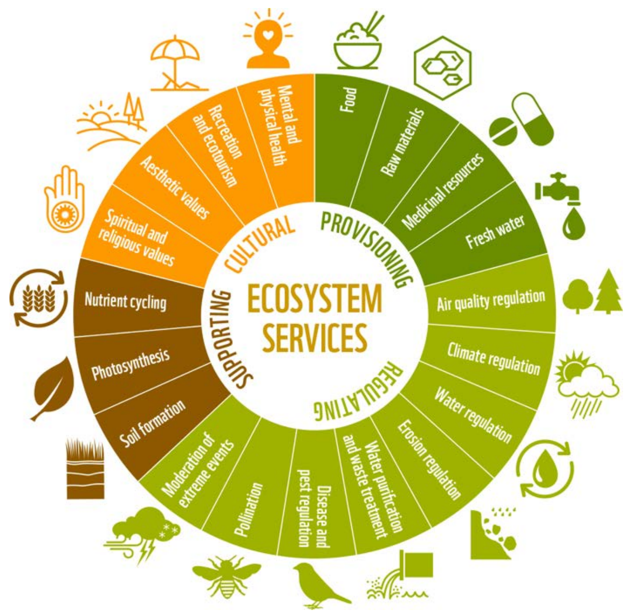


Figure 33. Benefits of Biodiversity Source:
Source: http://www.wwf.eu/what_we_do/biodiversity/

These ecological and social benefits are well known and agreed upon; however, one particular area of impact has not been researched as heavily – the agricultural potential of vertical greenery systems. With the underlying factors of rapid population growth and urbanization, the opportunity to utilize green façade systems as a food source is increasingly promising. In addition to urbanization, the decrease in healthy agricultural land with also threaten the ability to meet a rising demand for food. At present, some 11 percent (1.5 billion ha) of the globe's land surface (13.4 billion ha) is used in crop production (FAO 2015), but intensive forms of agriculture have been shown to cause severe environmental damage eventually limiting access to productive land. (Specht, K. 2009) Urban food production could provide new opportunities for building-integrated forms of food production taking some pressure off our agricultural land.

Figure 34. Biber Architects Milano Expo
Source: http://inhabitat.com/biber-architects

Currently, three main types of building integrated farming have been implemented and studied: rooftop gardens or farms, rooftop greenhouses, and indoor farms (Specht, K. 2009). Little research and few case studies have been realized in the area of edible green walls and green façades; however, their potential for agricultural applications is huge. Although there exist many concept studies for edible green facade systems, large scale real life applications of the strategy are few. One example is the Vertical Farm designed by Biber Architects for the 2015 USA Pavilion for Expo Milano. This installation featured variety of harvestable crops in a vertical array along the pavilion facade. Although this installation was not a proposal for a serious urban farm, it gives a depiction of the opportunities for scale and beauty of the application of edible facades.

Innovations in vertical gardening technology has also resulted in a rise in popularity for smaller-scale applications for edible vertical farming. Due to their ability to provide access to fresh produce while taking up less square footage than a traditional garden, vertical gardens and specifically container based systems are being used in restaurants and homes to grow fresh herbs and vegetables. Pizzeria Mozza in Los Angeles, California, for example has installed a 72- square foot green wall growing spinach, Chinese celery, parsley, pansies, rosemary and varieties of sage, geranium, mints and lettuce.

Figure 35. Edible Green Façade at Pizzeria Mozza in L.A.
Source:http://tournesolsiteworks.com/wordpress/index.php/tag/pizzeria-mozza/

Research into the impacts of using edible plants on green facade systems is new and little published data currently exists. Some potential drawbacks for utilizing edible plants is the increased maintenance associate with them. Plants will need to be harvested and possibly replanted after each growing season. Overall, the impacts of utilizing edible plants on a green façade system is overwhelmingly positive, presenting multiple functions and producing a range of goods and opportunities that would have positive impacts on the urban setting. There would be environmental benefits resulting from the saving and recycling of resources and reduced food miles. Social advantages from improving community food security, and education opportunities by linking consumers to food production.

5. E. 34 Greenhouse Field Test: Savannah, GA

Figure 36. Southwest Perspective of the E. 34 Greenhouse in Savannah, GA

In order to quantify the benefits associated with green façade systems, an experimental case study was implemented at a small community building in Savannah, Georgia. The E. 34 Street Greenhouse is an educational "greenhouse" built from all reclaimed materials. The majority of the façade is comprised of single-pane windows with large sliding doors (fashioned from the single pane windows) that allow the space to open up and be used for indoor/outdoor workshops. It was the goal of the initial design to be used as an agricultural and green job training center for high school students; however, the space is currently unoccupied. In order to help bring the original intent to fruition, three different green façade systems with the potential to grow edible plants was implemented along the southern wall of the greenhouse and the effects of its installation recorded for the month of July.

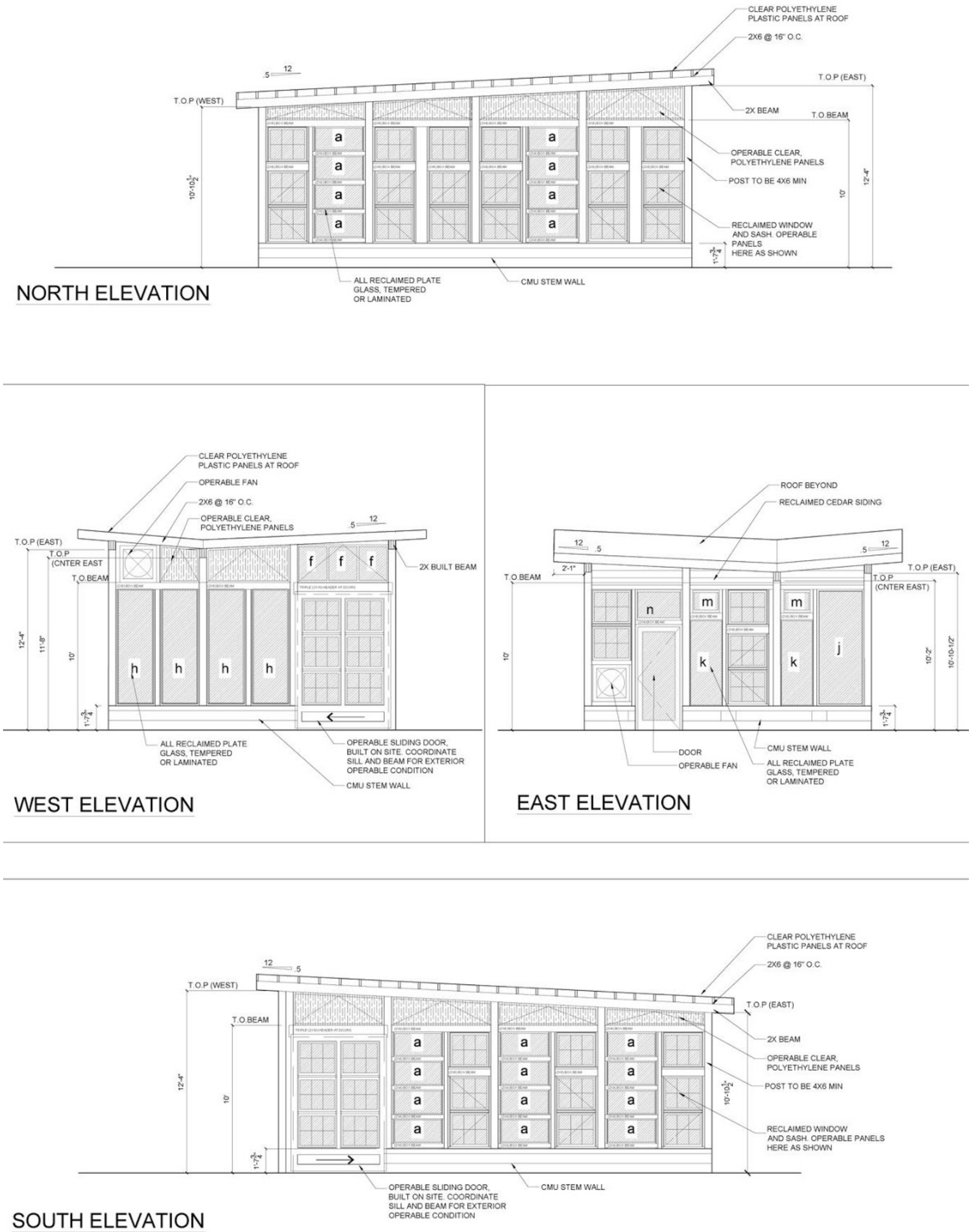


Figure 37. Architectural Drawings of the E. 34 Greenhouse c/o Emergent Structures

5.1 Climate Conditions and Architectural Constraints

Savannah, GA is located in Climate Zone 2A on the International Energy Conservation Code (IECC) map (Figure 22). It is a warm and humid climate with average highs above 90 °F in the summer. In the winter temperatures rarely reach below 20 °F. Figure 38 Savannah is a cooling-dominated climate with 1,840 Heating degree days (HDD) and 2,636 Cooling Degree Days (CDD). (Bizee.com)

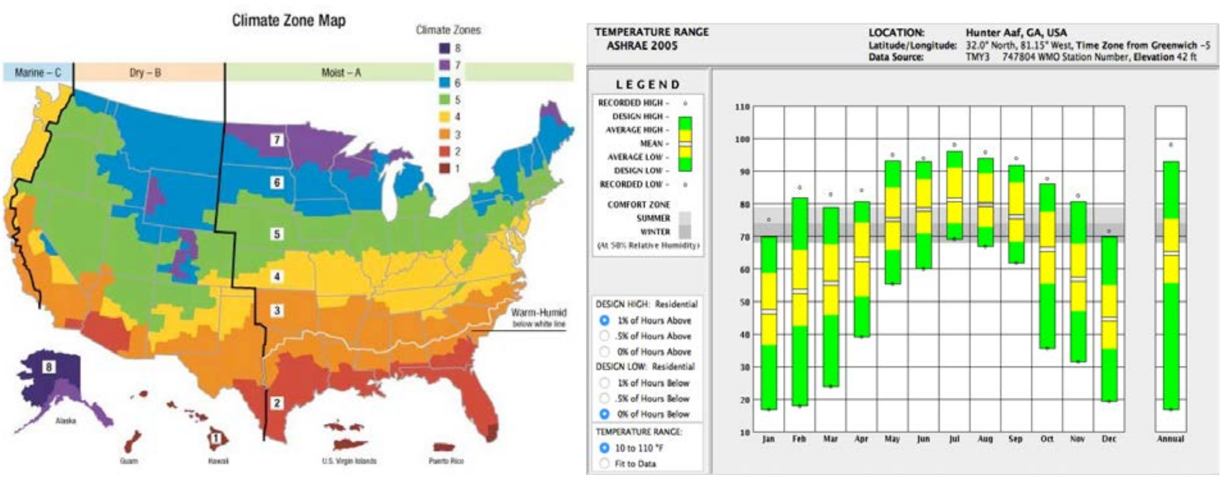
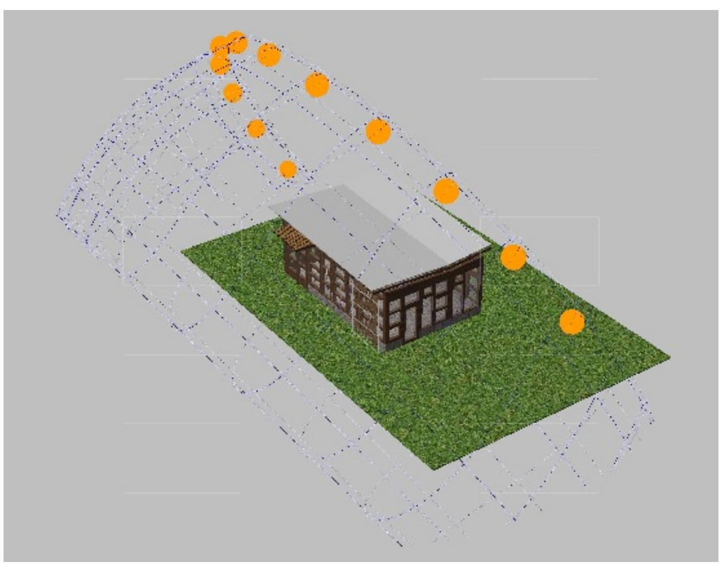


Figure 38. Climate Map of the United States (IECC, 2009) (Left) Climate Consultant Average Monthly Temperature Range for Savannah, GA (Right)



The sun path diagram shown in Figure 39 shows the sun angle condition during the testing period for the field test. During the month of July, the sun angle is high, at around 80°. This particular figure shows the path at the sun from 8AM to 8PM and the view is set at the southeast corner of the greenhouse.

Figure 39. Sun Path Diagram Using Diva-for-Rhino of the E. 34 Greenhouse

Solar Analysis

In order to determine the existing radiation conditions at E. 34 Greenhouse a solar analysis using Diva-for-Rhino (Solemma, LLC), daylighting and energy modeling plug-in for Rhino, was performed. This analysis examined the seasonal radiation intensity for all façade orientations as well as the interior floor of the greenhouse in order to help determine which façade orientation would be the optimal focus for the case study in terms of both system and plant selection as well as opportunities for improvements in thermal performance.

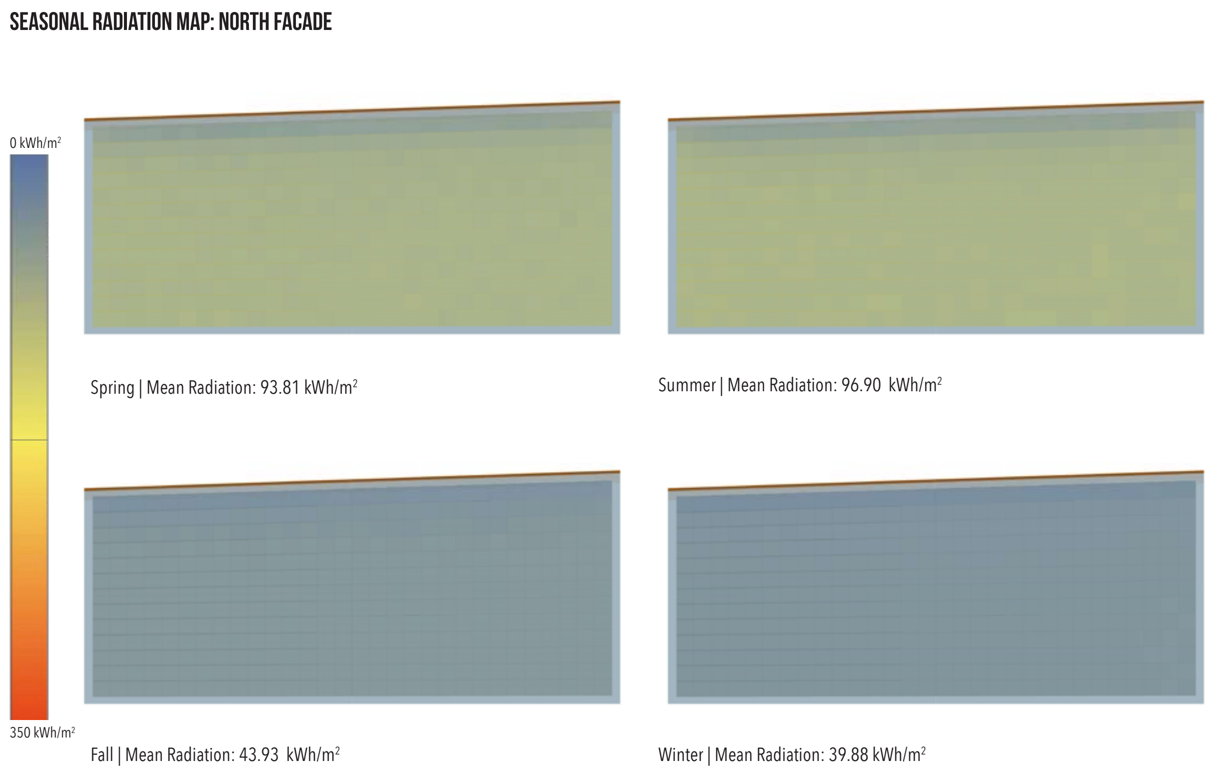


Figure 40. Seasonal Radiation Map of the North Façade of the E. 34 Greenhouse (Diva-for-Rhino)

SEASONAL RADIATION MAP: SOUTH FACADE

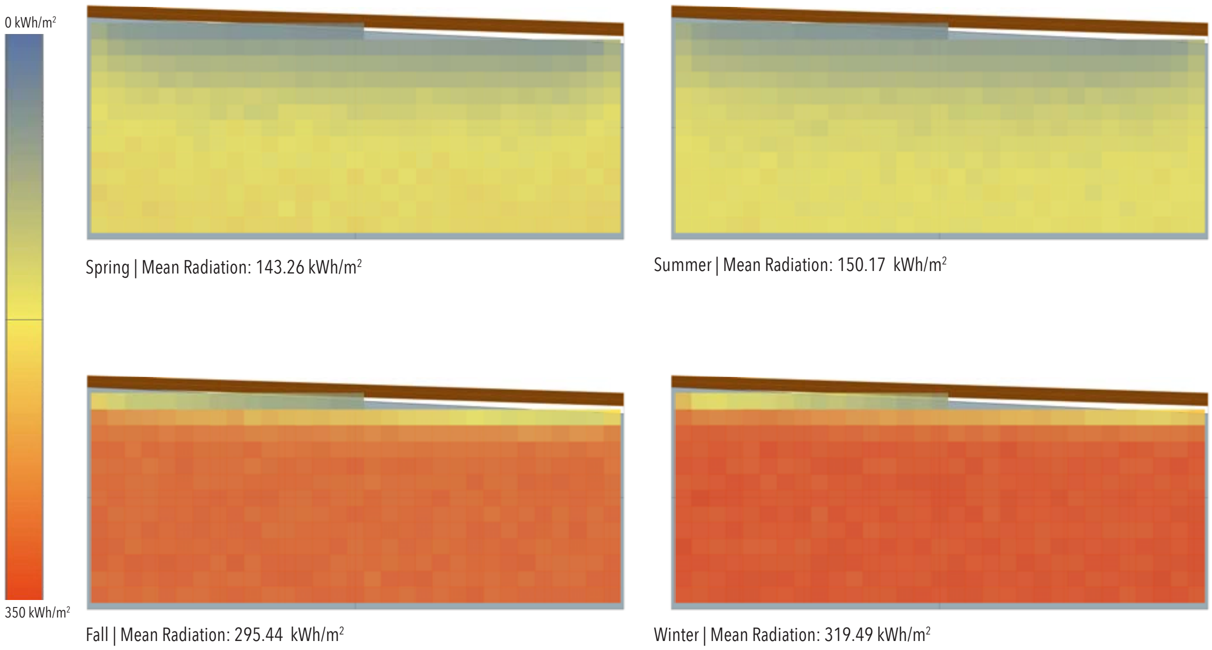


Figure 41. Seasonal Radiation Map of the South Façade of the E. 34 Greenhouse (Diva-for-Rhino)

SEASONAL RADIATION MAP: EAST FACADE

Figure 42. Seasonal Radiation Map of the East Façade of the E. 34 Greenhouse (Diva-for-Rhino)

Figure 43. Seasonal Radiation Map of the West Façade of the E. 34 Greenhouse (Diva-for-Rhino)

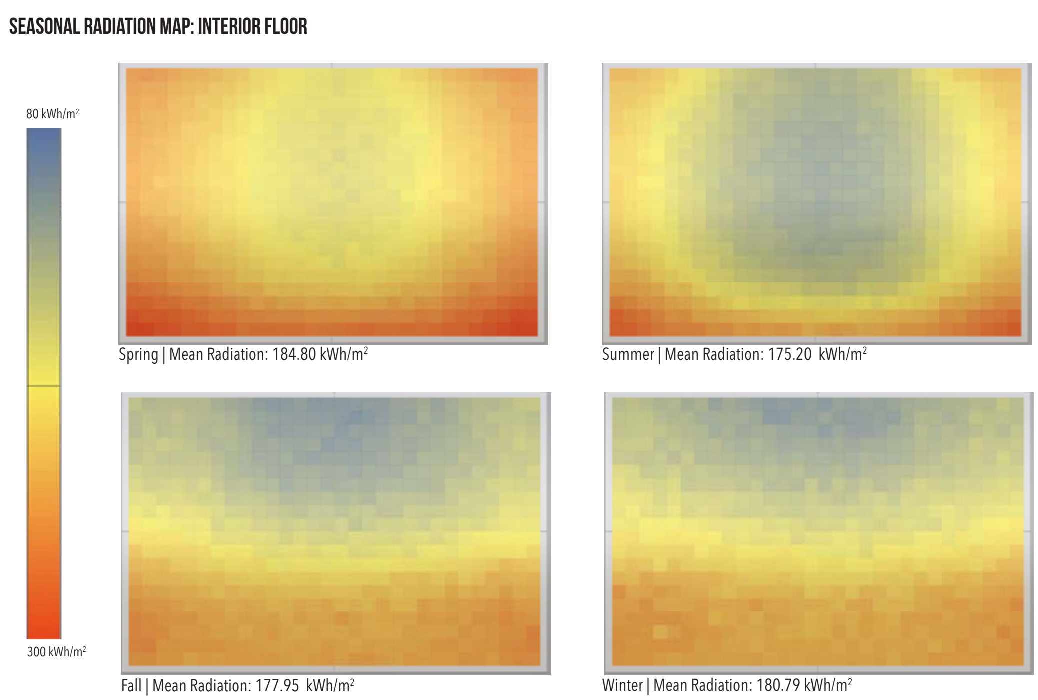


Figure 44. Seasonal Radiation Map of the Interior Ground of the E. 34 Greenhouse (Diva-for-Rhino)

Table 9. Seasonal Radiation Analysis of E. 34 Greenhouse Results

Orientation	Radiation Intensity by Season (kWh/m^2)			
	Spring	Summer	Fall	Winter
North	93.81	96.90	43.93	39.88
South	143.26	150.17	295.44	319.49
East	238.00	225.91	161.55	162.38
West	238.96	228.89	160.16	159.74

The DIVA analysis revealed a fairly uniform distribution of solar radiation across all façade orientations with the East and West facades receiving the most intense radiation during the Spring and Summer months and the South being exposed to the most radiation during the Fall and Winter months. The East and West facades present the most opportunity for improvement in thermal performance of the greenhouse since they receive the most intense radiation during the hotter months of spring and summer; however, the East façade abuts the property line of the adjacent property, leaving no space for façade construction and the West façade includes an operable sliding door that takes up a third of its surface area. Also, in terms of plant selection, the intense temperatures (above 90°F) jeopardize the viability of planting and propagating edible plants along the West Façade since it is subject to such intense solar radiation. Therefore; the southern façade was chosen for its capacity to grow vegetation, over the east and west facades in the hot summer months as well as its greater surface area that allows the implementation of several different façade systems.

Figure 45. Southern Façade of the E. 34 Greenhouse

Once the façade orientation was chosen, a Bennett sun angle analysis was performed to determine the existing sun cut off angles at the greenhouse as well as to determine a target cut off angle that could be achieved using a horizontal overhang trellis system. The existing 2-foot overhang gives a cut off angle of 79° which does little to block the intense radiation that the greenhouse is exposed to year-round.

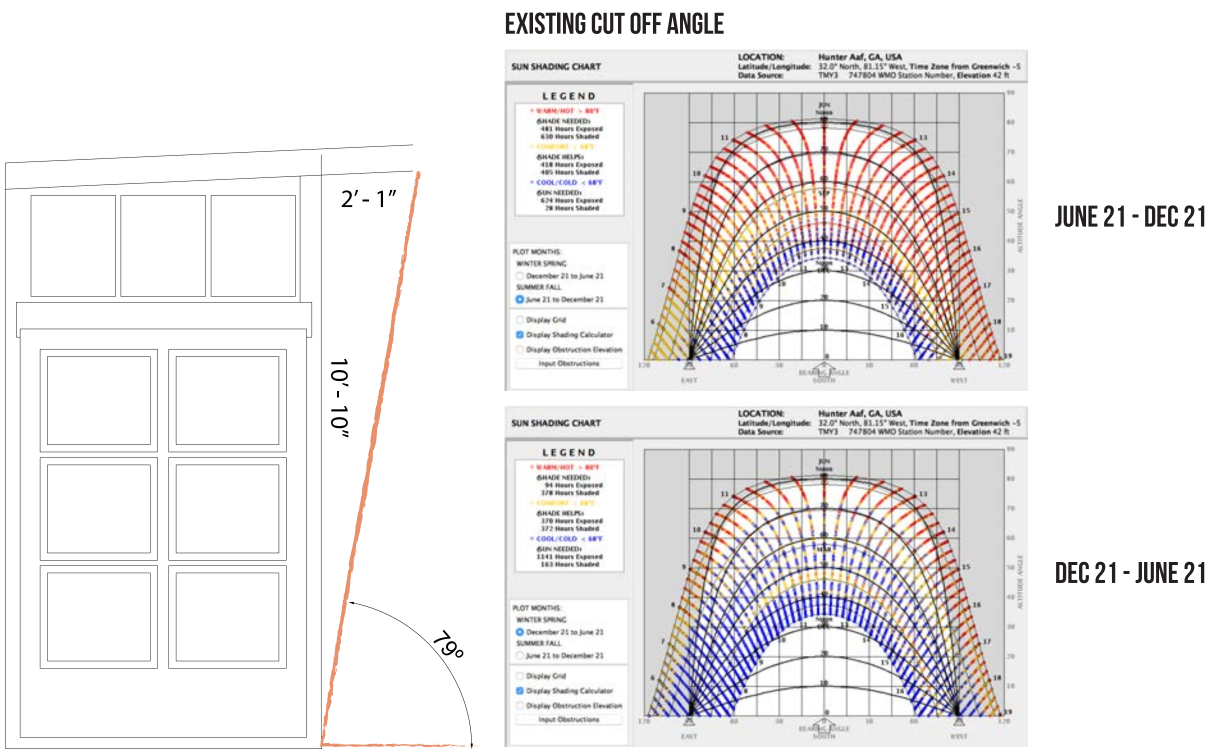


Figure 46. Exiting Cut-off Angle for the Southern Façade of the E. 34 Greenhouse

Based off of the Bennett Sun Angle Chart for Savannah, Georgia (from June 21 - December 21) a cut-off angle of 45° would eliminate the intense radiation on the southern façade during the hot summer months. To achieve this angle an overhang of 10' - 10" (equal to the height of the building) is needed.

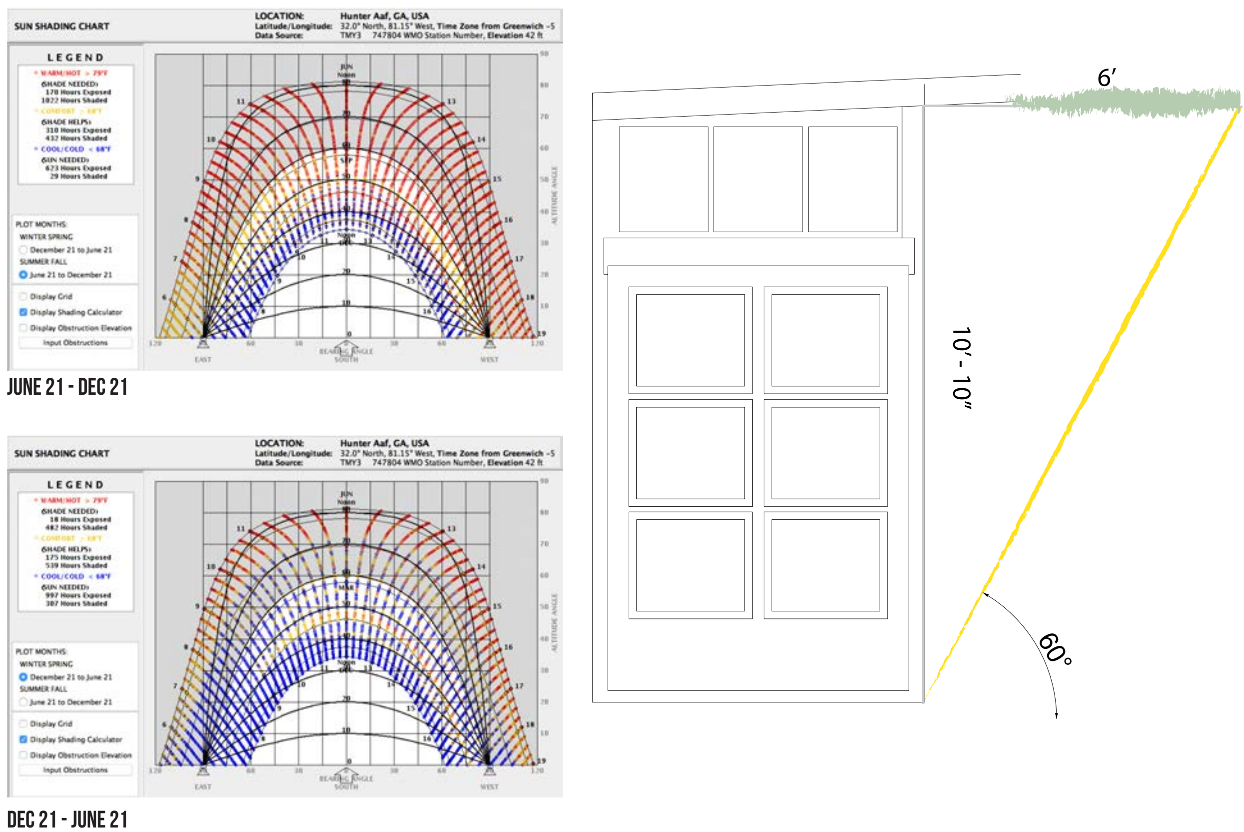


Figure 47. Proposed Cut-off Angle for the Southern Façade of the E. 34 Greenhouse

Based off of the Bennet Sun Angle Chart for Savannah, Georgia (from December 21 - June 21) a cut-off angle of 60° would eliminate the intense radiation on the southern facade. To achieve this angle an overhang of 6 feet is needed. This length is more feasible for construction and is therefore set as the target for the horizontal overhang.

Architectural Constraints

In addition to the solar analysis results, there were several architectural constraints and considerations that influenced the selection of façade systems for the case study.

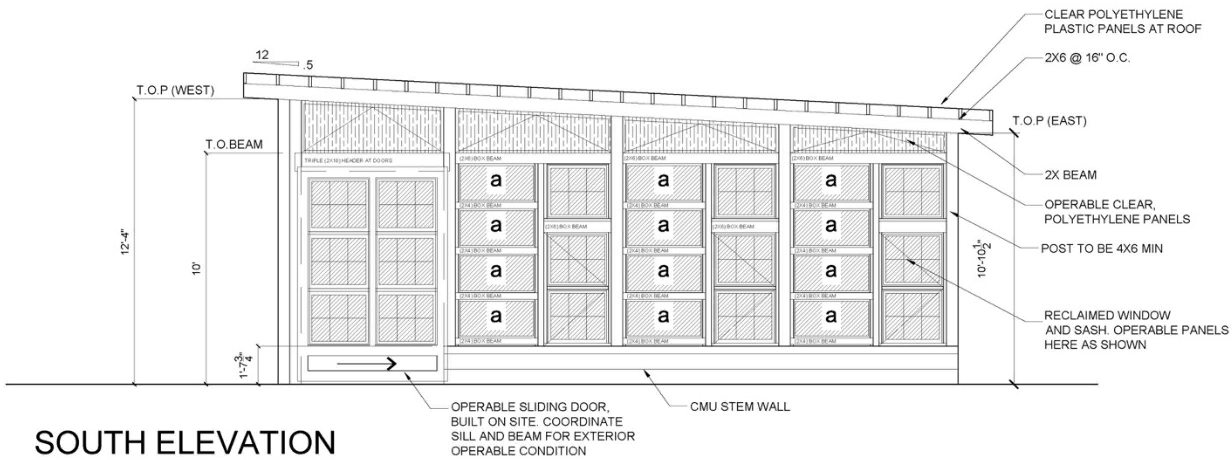


Figure 48. Detailed Construction Drawing of the Southern Facade of the E. 34 Greenhouse c/o Emergent Structures

Since the greenhouse is made almost entirely of reclaimed windows, intermediate anchor points for a vertical facade system are non-existent. The systems can only be anchored at the top from the wooden beams or through the rafters. The bottom anchor point also presents a problem since the base of the greenhouse is a CMU stem wall for which more invasive anchoring methods will be needed. Also, an important quality of the greenhouse is its transparency, so it was important to choose systems that maintain the ability to have a view to the outdoors if you are inside the space. Finally, the large sliding door will need to remain operable so the system located at the bay in which the door slides over will need to be constructed so that its implementation does not impede the movement of the door.

5.2 Chosen Façade Systems and Plant Selection

The three chosen systems for implementation at the E. 3 Greenhouse include: an overhang trellis system, a tension-based cable system and a felt, container-based system.

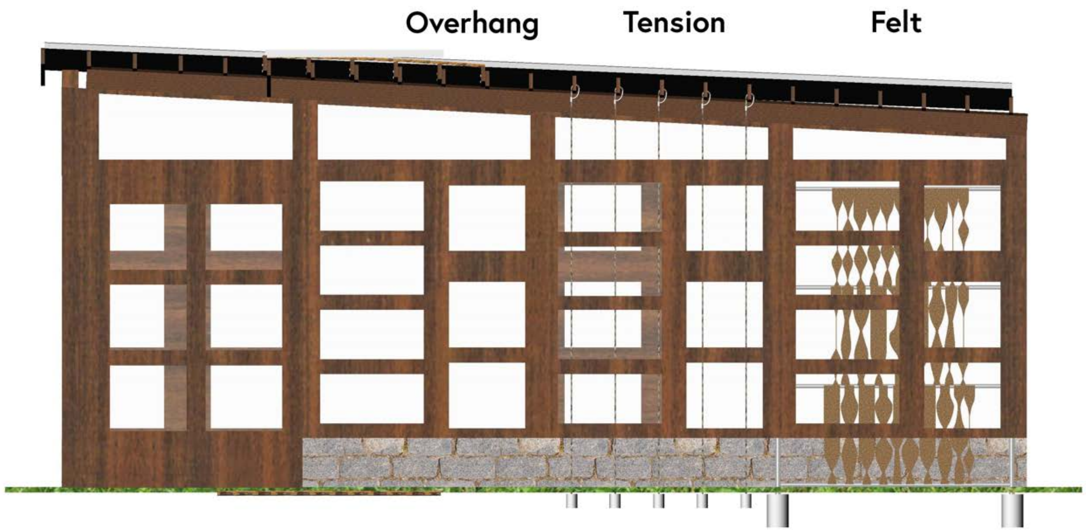


Figure 49. Rendered Drawing of South Elevation with Green Façade System Support Structure

Trellis Overhang

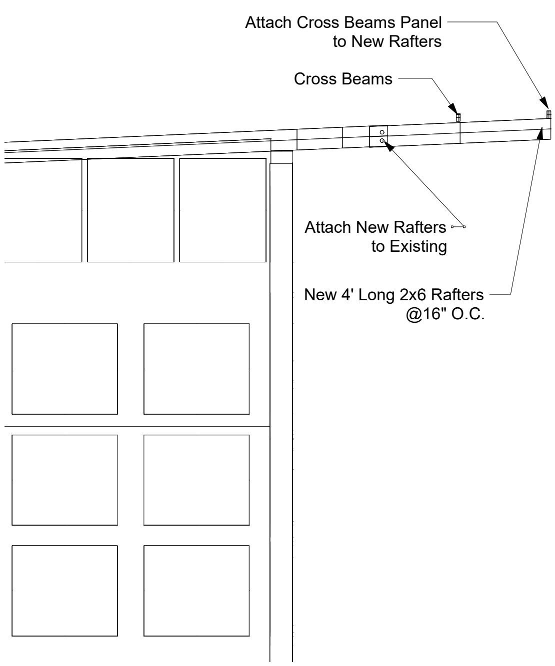


Figure 50. Construction Drawings for Overhang System

To construct the overhang system the rafters were extended to increase the overhang length from the original 2-foot length to a total of 6 feet to reach the required cut off angle. Five (5) 4-foot long 2x6 pine rafters were scabbed onto the existing rafters using stainless steel bolts. Two (2) 5-foot long cross beams made of 1x2 pine were then placed across the rafters to create a space for vegetation to grow through. For this system, Muscadine Grapes will be the plant ultimately utilized on this overhang system due to its capacity to reach the heights of the overhang elevation; however, due to the short nature of the experiment, ivy was used to simulate the leafing density of grape leaves. Pots of Boston ivy were placed on the roof of the greenhouse and the foliage laced throughout the rafters and cross beams.

Table 10. Overhang System Components

Component	Quantity
4' Long 2x6 Rafters	6
Bolts/Screws	12
1x2 Cross Beams	2 @ 5 FT Length

Figure 51. Overhang System Installation Process

Tension Wire System

The tension based system will be constructed using galvanized metal wire threaded through ¼" holes drilled into the existing rafters. The wire is looped through the rafters then clamped together with metal bolts and secured to the ground in a concrete form to create a taught, tensioned wire. Edible climbing plants such as Malabar Spinach, Hardy Kiwi, Beans and Peas have been planted at the base of the various wire cables; however, for testing purposes, pots of jasmine were used to simulate the foliage that will eventually be attributed to the edible plants.

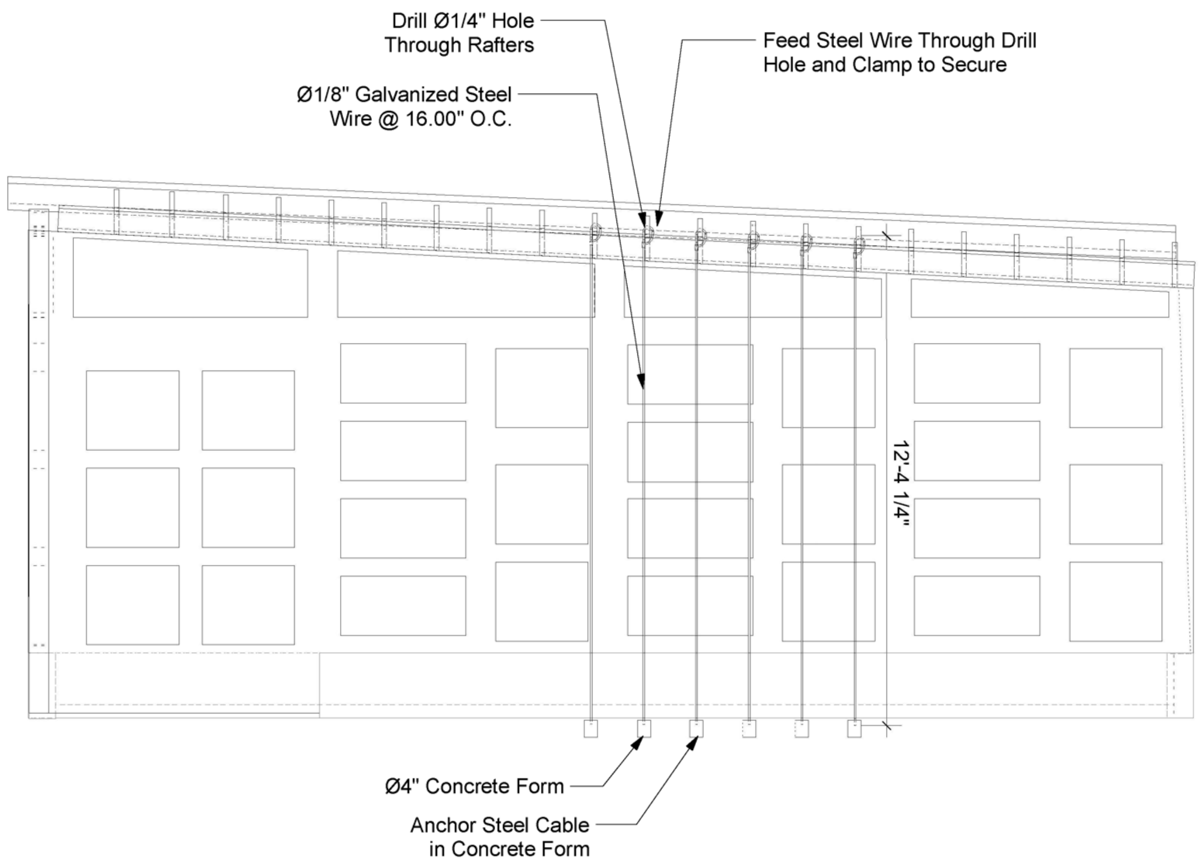


Figure 52. Construction Drawing for Tension Wire System

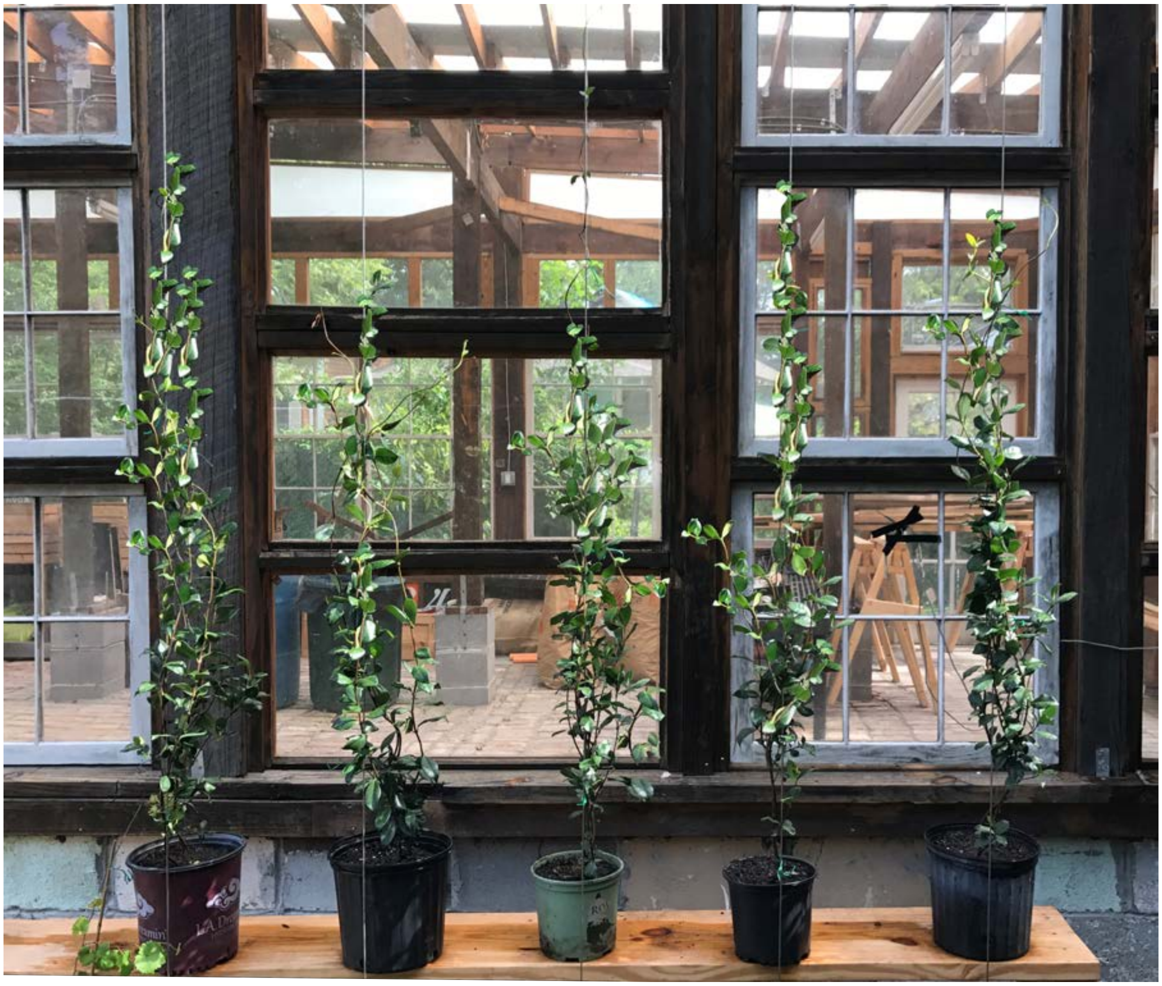


Figure 53. Picture of Installed Tension Wire System with Jasmine Foliage

In order to reach a higher vertical coverage, the jasmine pots were placed on a wooden bench right up to the height of the CMU knee wall. Since the bench is in front of an already opaque surface, it will have no notable effect on the experimental readings which focus on the glazing surface.

Table 11. Tension Wire System Components

Component	Quantity	Cost/item
1/8″ Steel Wire (13′)	5	$6.50
Cable Clamp Set	5	$2.00
Concrete Form	5	$1.50
Concrete Mix	1	$6.50

Felt Container System

The felt container system is unique compared to the other two systems used in this case study because its design differs from those currently on the market. While the other two systems are similar to current examples of indirect green façade systems, this specific fabric container-based design differs from other felt or fabric-based systems since it is not one monolithic, opaque structure, but contains openings through which a view can still be maintained. The felt based system was constructed from felt panels that have been laser cut and sewn to form a variation of pocket container sizes and shapes. The system was then attached to an aluminum frame made from ½" threaded pipe that has intermediate removable cross bars that allow the system to be modular, providing the flexibility to move the felt containers to different locations around the frame based on the need of the user. A more thorough discussion of the specific design process is given in the following section; however, a brief over view of the system configuration is given below.

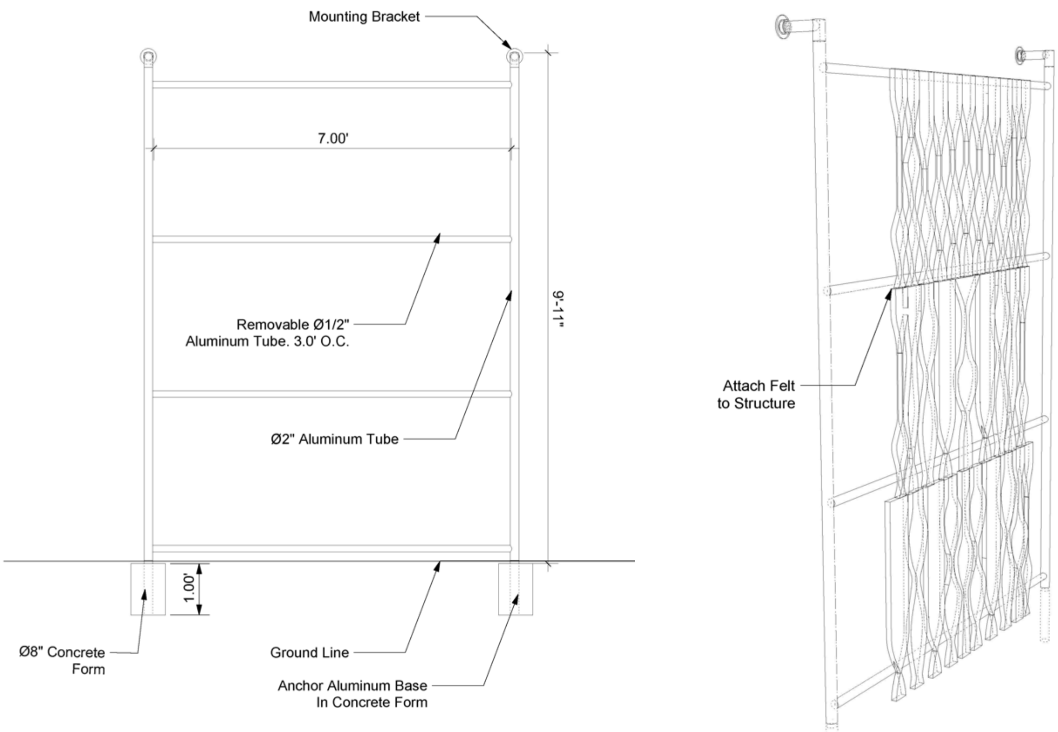


Figure 54. Construction Drawing for Felt System Support Structure and Installation

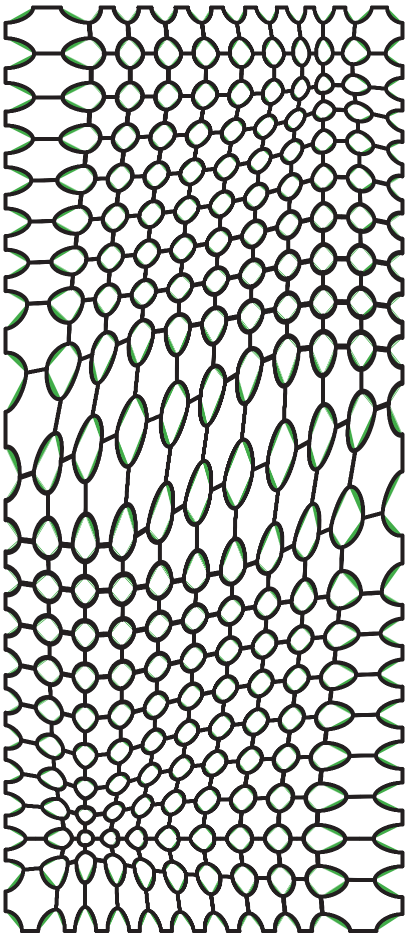
Table 12. Felt System Components

Component	Cost/Item	Quantity
Support Structure		
Mounting Brackets	$9.00	2
Ø1/2" Aluminium Pole (11')	$14	2
Ø1/2" Aluminum Pole (6")	$2	2
Ø1/2" Aluminum Pole (7')	$10	4
Concrete Form	$8.50	1
Concrete Mix	$6.50	1
Container System		
Felt	$130	8 Yards
Geotextile Fabric	$10	1

Figure 55. Pictures of Felt System Installation

5.3 Design Process for Felt System

Initial Prototype



The design process for the felt system utilized in this thesis began as a project for the Ecologics course, a design seminar conducted by professor Cupkova in the Spring Semester of 2017 at Carnegie Mellon University. The course explores performative architectural systems and how specific environmental data and relationships can inform the morphological form of an object. Using digital fabrication techniques, students are tasked with creating an object that shows a response to some sort of environmental feedback, whether in a direct or abstract way. The exploration into this specific research project began by imagining a fabric based green façade structure informed by the radiation pattern of the surface in front of which it would be placed. The idea was to have a non-monolithic, porous structure that could block intense radiation but still allow light into the interior of a space. Researching current container façade felt structures that are on the market revealed that they are completely opaque assemblies that, if placed in front of a window, would block the entire view outside. In order to avoid this characteristic, the intention of this design was to create a felt-based constructed from specific patterns that created both opaque areas of felt pocket planters and open spaces through which light could enter and a view could be maintained.

Figure 56. Initial Sketch of Facade Structure with Variable Openings Based on Radiation Exposure

Therefore, the multi-variable design parameters for this felt facade structure include:

- Block intense solar radiation
- Maintain visual access (view out)
- Create Pocket containers sized to grow edible plants

Investigation into this design strategy began by designing three different wall prototypes within Rhino (McNeel, 2016) that were assembled from patterns that could be laser cut and sewn to form pockets that would act as a container system for planted material. These initial façade structure prototypes were porous to varying degrees and uniform in their pattern configuration as seen in Figure 57.

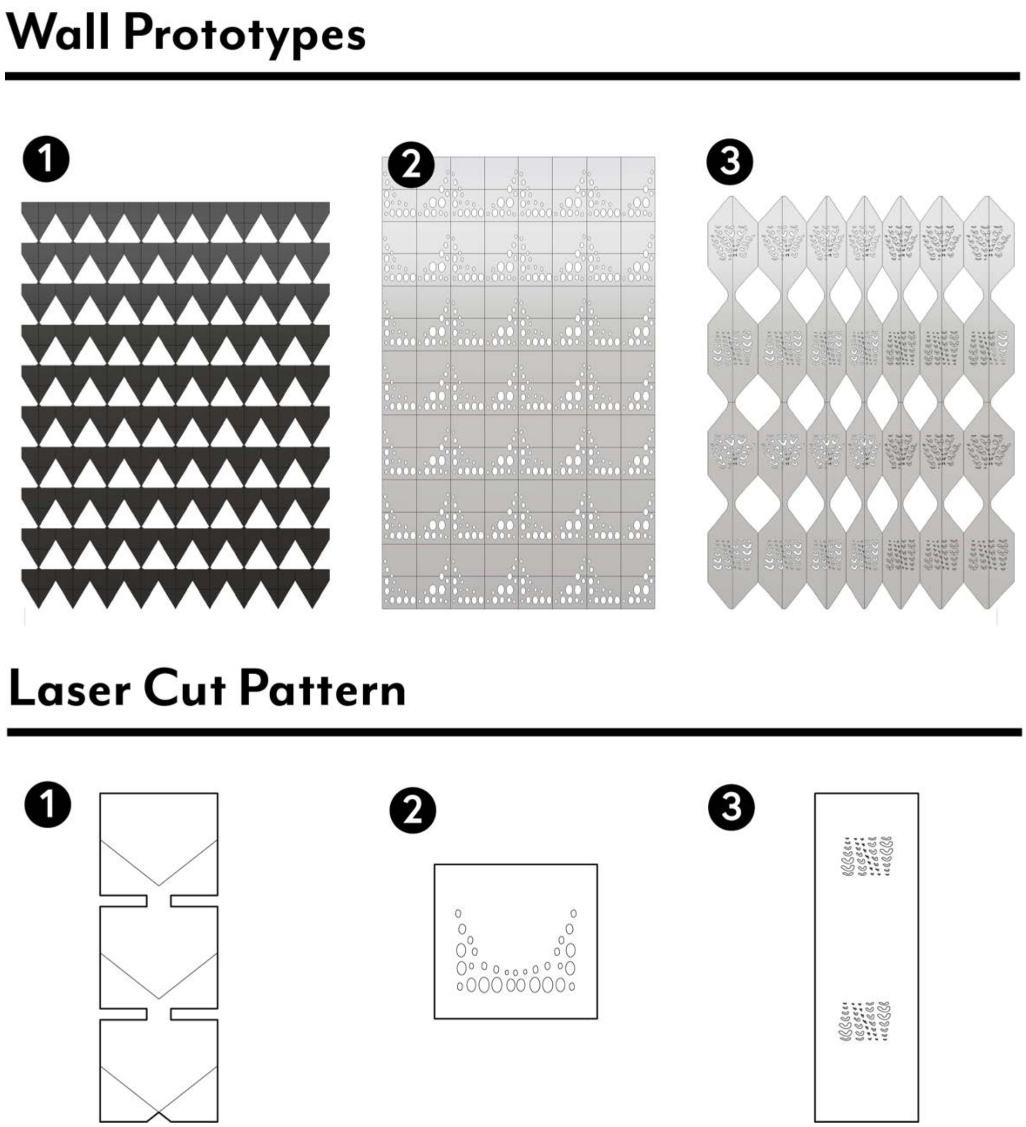


Figure 57. Initial Wall Prototypes and Their Associated Laser Cut Patterns

Once the prototypes were assembled their performance was simulated using DIVA-for-Rhino. The parameters on which their performance was evaluated included their ability to block intense radiation where needed but still allow light into the interior space, especially during fall and winter months.

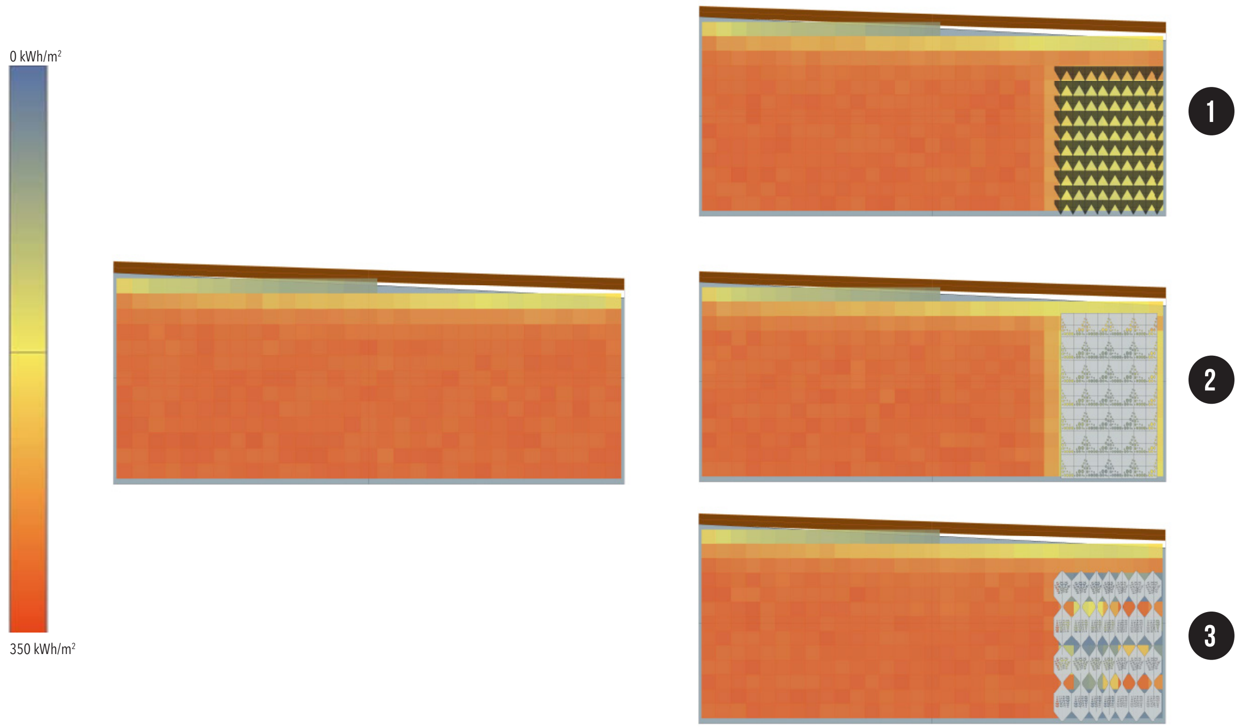
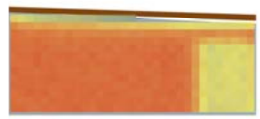
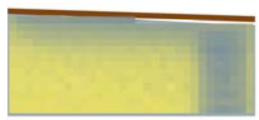
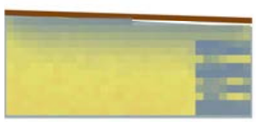
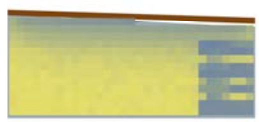
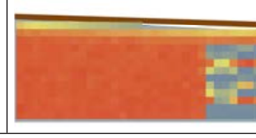


Figure 58. Radiation Analysis of Set Up for Each Wall Prototype

Using the south façade of the E. 34 Greenhouse as the baseline, a seasonal radiation analysis was then conducted for each wall prototype.

Table 13. Seasonal Analysis of the Southern Facade of the E. 34 Greenhouse with Each Wall Prototype

	SPRING	SUMMER	FALL	WINTER
BASELINE				
WALL 1				
WALL 2				
WALL 3				

The analysis on the south façade shows that wall 2 blocks the most solar radiation and wall 1 the least. Due to its multi-directional diagrid pattern, Wall 3 was the most successful at both blocking radiation but allowing radiation through the façade in the fall and winter months.

Table 14. Seasonal Analysis of the Interior Floor of the E. 34 Greenhouse with Each Wall Prototype

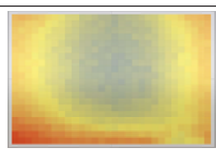
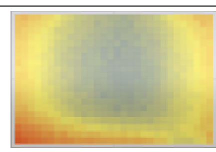
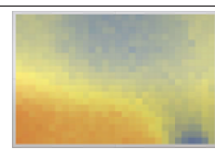
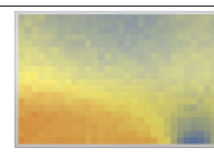
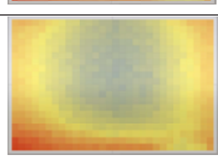
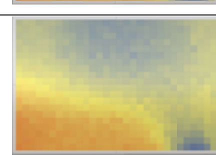
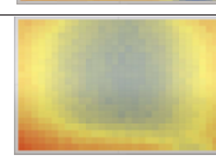
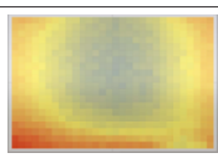
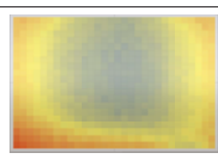
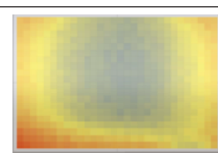
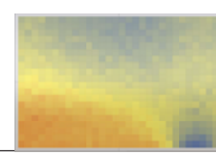
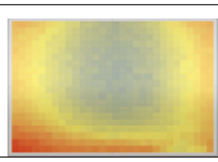
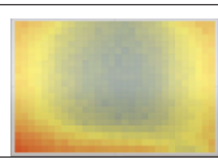
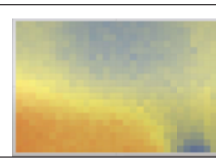
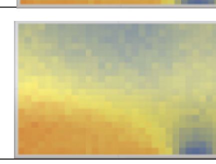
	SPRING	SUMMER	FALL	WINTER
BASELINE				
WALL 1				
WALL 2				
WALL 3				

Table 15. Seasonal Radiation Analysis Results for Each Wall Prototype

Simulation		Radiation Intensity (kWh/m²)				
		Spring	Summer	Fall	Winter	Total
Baseline	South Wall	143.26	150.17	295.44	319.49	908.36
	Interior	184.8	175.2	177.95	180.79	718.74
Wall 1	South Wall	134.55	128.99	268.66	292.47	824.67
	(+/-) Baseline	-8.71	-21.18	-26.78	-27.02	-83.69
	Interior	180.33	170.49	166.94	168.93	686.69
	(+/-) Baseline	-4.47	-4.71	-11.01	-11.86	-32.05
Wall 2	South Wall	131.32	125.67	254.64	275.19	786.82
	(+/-) Baseline	-11.94	-24.5	-40.8	-44.3	-121.54
	Interior	179.02	169.55	163.21	164.62	676.4
	(+/-) Baseline	-5.78	-5.65	-14.74	-16.17	-42.34
Wall 3	South Wall	130.55	124.85	255.5	276.42	787.32
	(+/-) Baseline	-12.71	-25.32	-39.94	-43.07	-121.04
	Interior	178.92	169.81	164.44	166.22	679.39
	(+/-) Baseline	-5.88	-5.39	-13.51	-14.57	-39.35

Examining the radiation intensity associated with each façade system revealed that Wall 3 performed best according to the evaluation parameters of blocking radiation (especially in the summer months) but allowing light into the space during the colder months.

Using the desired multi-directional pattern found in wall prototype 3, the pattern was improved upon by introducing even more variation into the form. Eventually, three different pocket configurations were utilized to construct the final prototype. Fabrication for these pockets was simple, 1/8” felt was laser cut into the patterns shown in Figure 59 and folded in half and sewn to form the pocket containers.

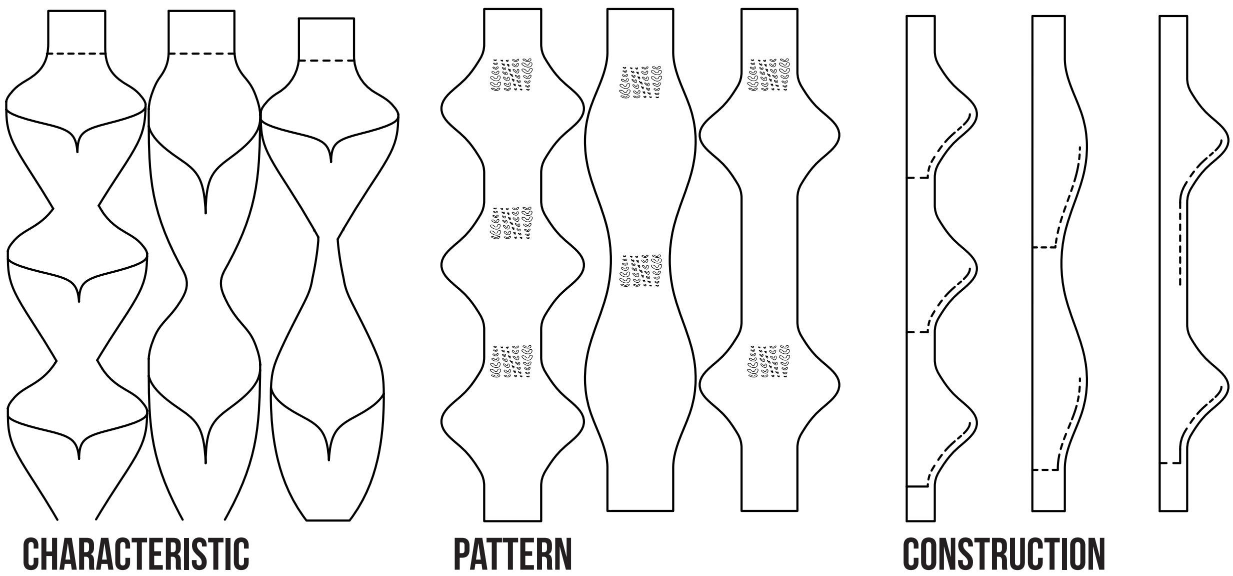


Figure 59. Felt Pocket Characteristic, Pattern and Construction

The possibility for variation utilizing only these three patterns was great. A series of nine possible configurations were designed, each being tailored to specific benefits including blocking radiation, maintaining views to the outdoors and promoting plant growth. These nine patterns are presented in the following figures.

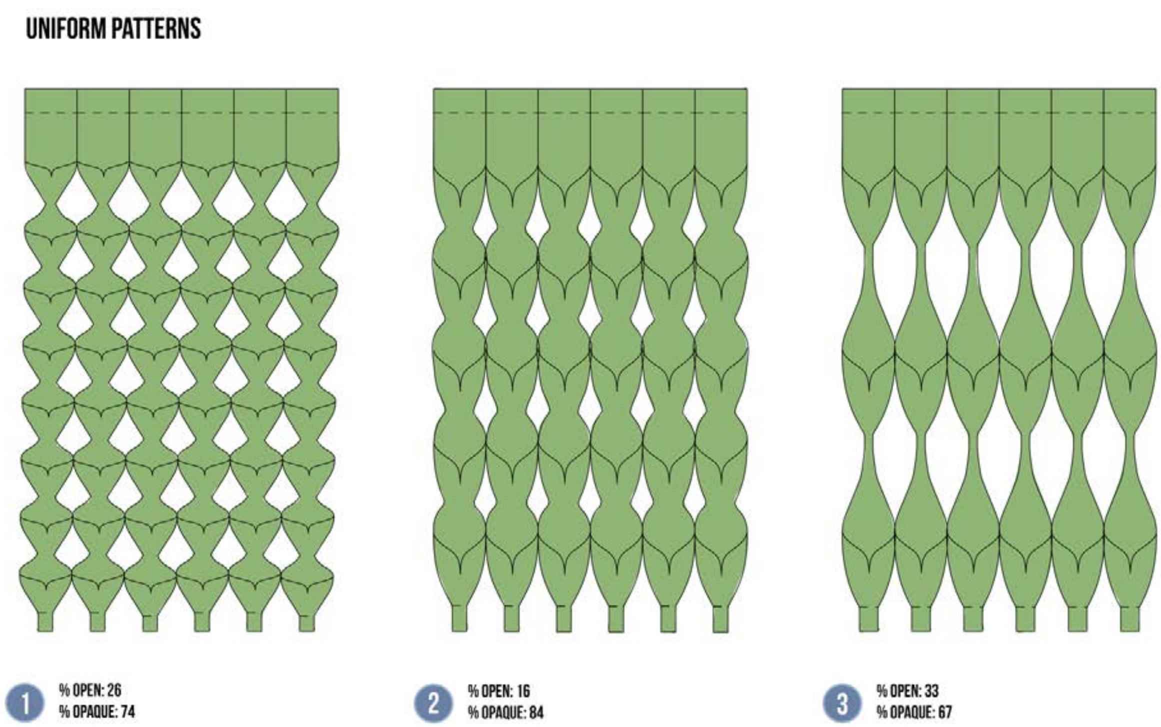
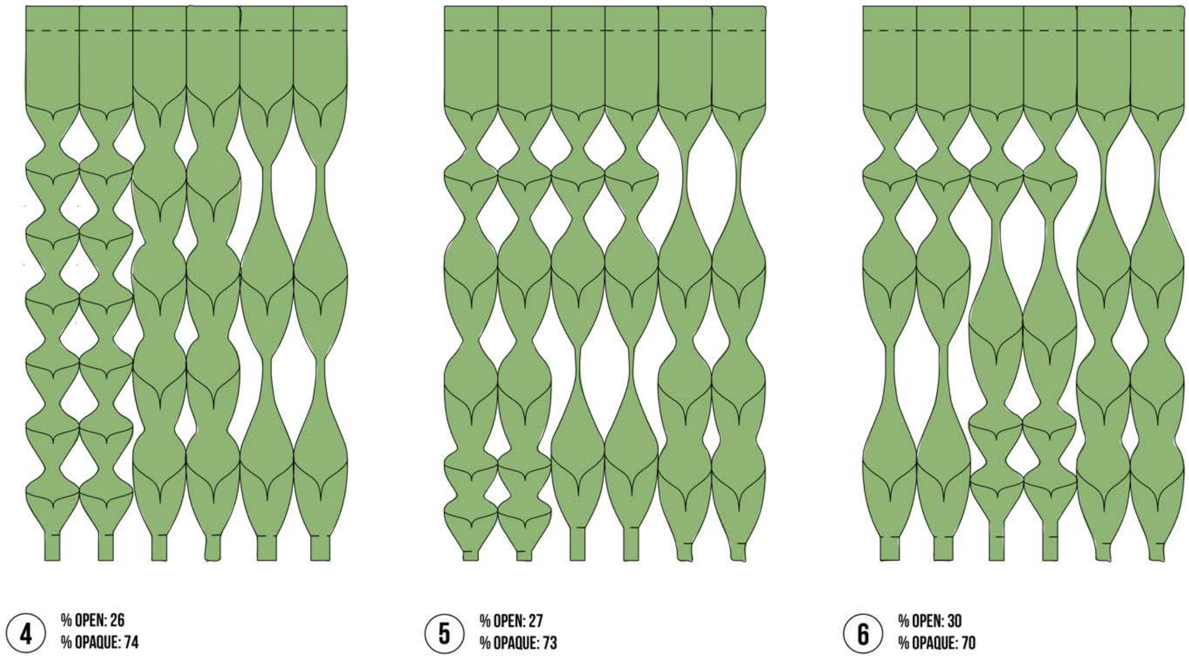


Figure 60. Uniform Patterning of Felt Façade System

VARIATIONAL PATTERNS



VARIATIONAL PATTERNS

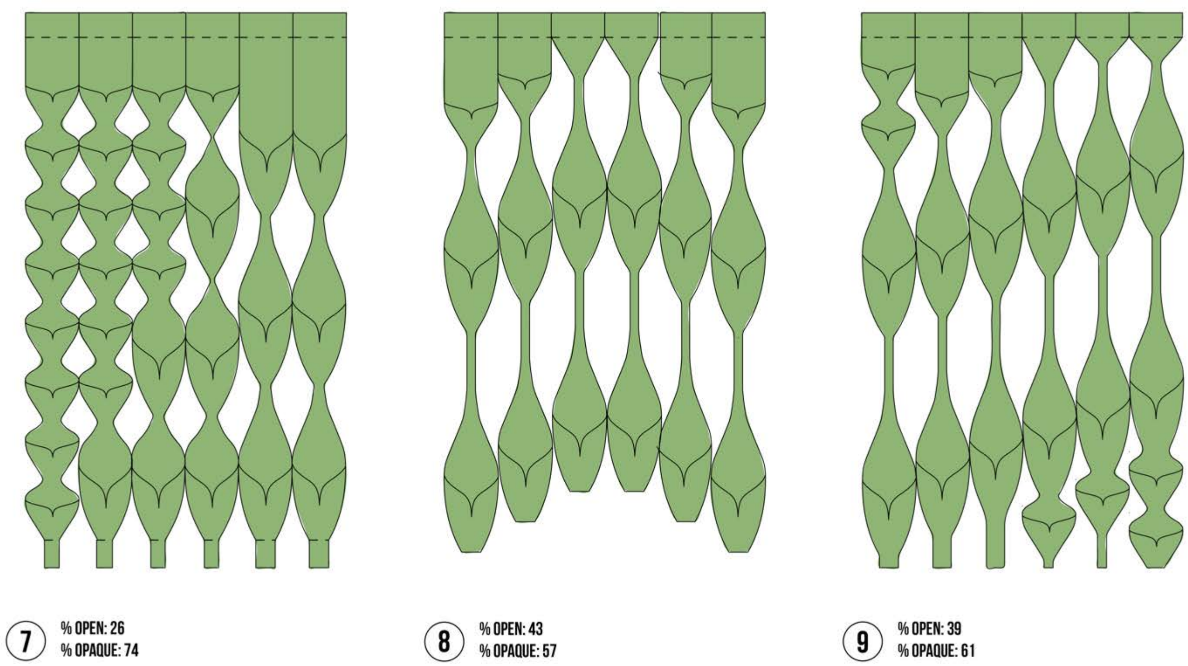


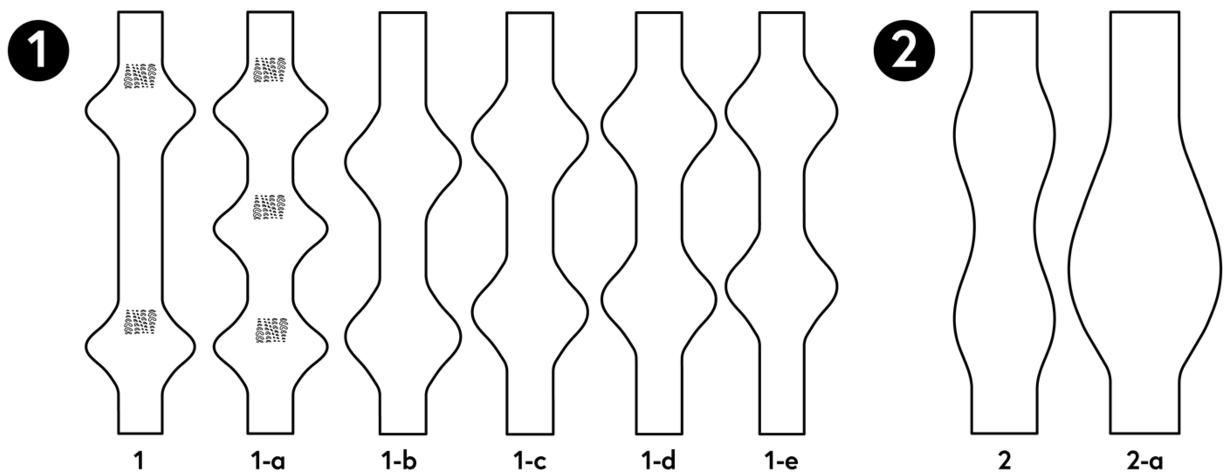
Figure 61. Variational Patterning of Felt Façade System

Analyzing these possible configurations demonstrate the versatility in this specific design. For example, configurations 4-7 would be best suited to block intense radiation since there is a tighter clustered of pockets, while configuration 8 is much more porous and would successfully maintain views to the outdoors. Ultimately, Configuration 9 was chosen to be fabricated and installed as the final prototype as seen in Figure 62.

Figure 62. Fabrication and Installation Process for the Initial Prototype (Spring 2017)

Full Scale Installation for Field Test

Taking the design formulated in the spring semester to a full-scale installation for the greenhouse required a few additions and modifications to the original pocket patterning. The three original patterns would still be utilized in the full-scale design; however, these are somewhat small pockets that could only support herb and small plant growth. In order to promote more variation in plant use large pockets would need to be implemented. Patterns 2-a and 3 through 3-c were added to provide pockets with a larger volume. A specific sizing configuration was created (Figure 64) to determine which plants could be implemented into each pocket according to the sizing matrix shown in Figure 26.



Style	Pattern	Number
1	1	5
	1-a	2
	1-b	2
	1-c	2
	1-d	2
	1-e	1
2	2	2
	2-a	2
3	3	4
	3-a	5
	3-b	2
	3-c	1
Total		30

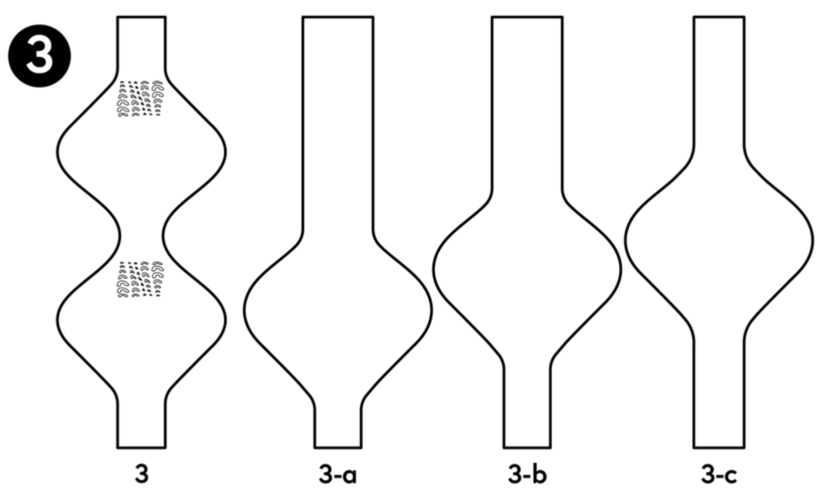


Figure 63. Modifications of Felt Patterning for Full-scale Installation

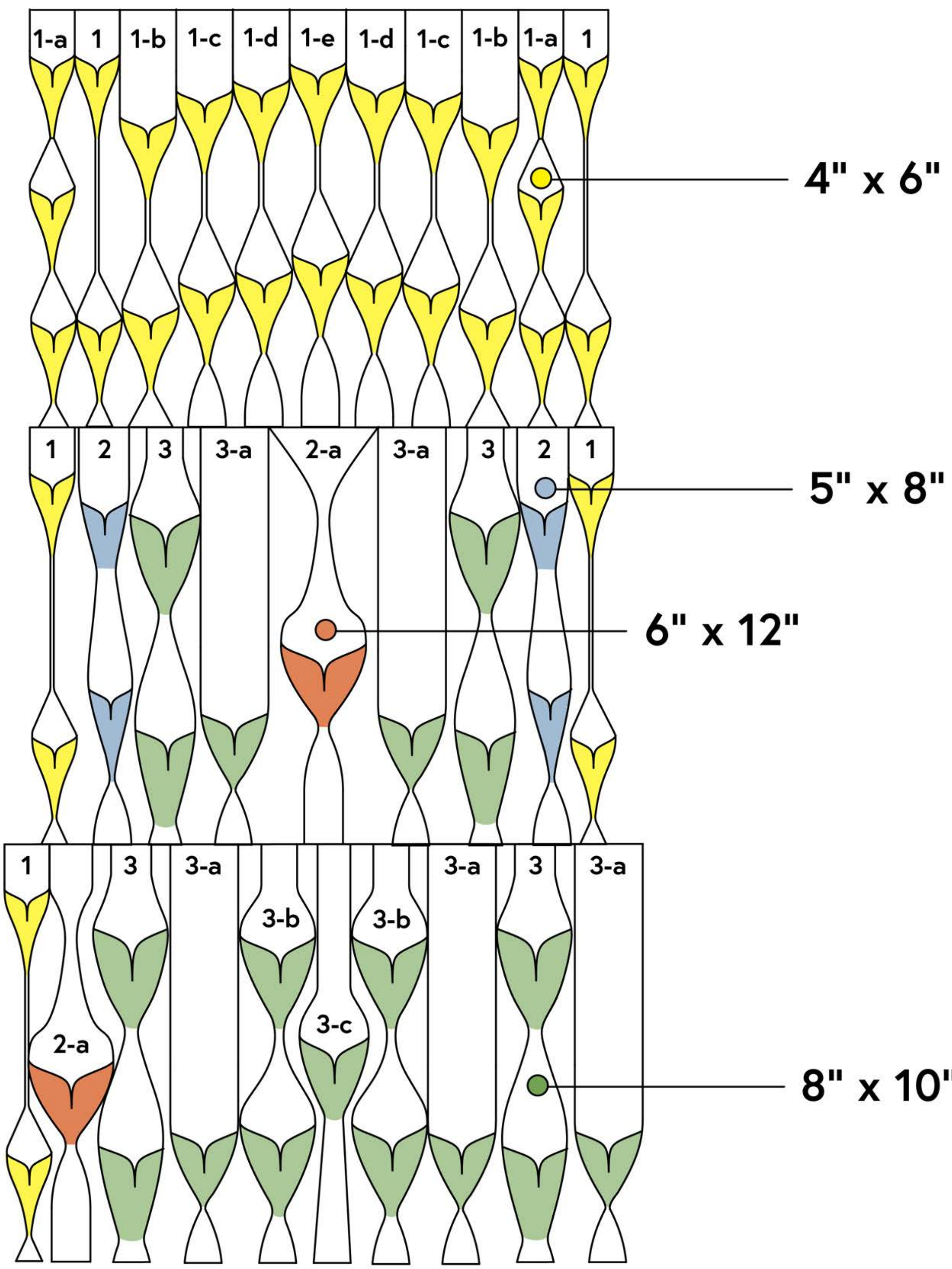


Figure 64. Container Sizing for Full-scale Felt System Installation

Figure 65. Full Scale Installation of Felt System

5.4 Completed Façade System Installation

Figure 66. Final Green Facade System Installation at E. 34 Greenhouse

Figure 66 above shows the final green façade installation for the E. 34 Greenhouse. These are the conditions under which the experiment was conducted. The foliage coverage pictured here maintained fairly consistent over the testing period for the field test experiment.

Overhang System Effect on Total System

10 AM – 11 AM **11AM – 1 PM** **1-3PM**

Figure 67. Effect of Overhang System on Different Facade Bays Throughout the Day

It should be noted before discussing the experimental methods and results for the field test that the overhang system affects various testing bays throughout the day. As seen in Figure 67 above, the trellis is shading the control bay from 10AM-11AM, the overhang bay from 11AM-1PM, The Tension System from 1PM-3PM and the Felt System from 3PM-5PM. This condition has influence on the thermal results presented in subsequent sections of this report.

5.5 Experiment Methods and Materials

Different parameters to evaluate the shading performance of the chosen green facade systems were measured throughout the month of July. The monitored parameters include: indoor and outdoor illuminance levels (lx), with a Leaton Digital Luxmeter, Indoor and Outdoor Air temperatures at the façade surface (°F) with three (3) HOBO U-12-006 Temperature/Relative Humidity/4 External Channel Data Loggers and nine (9) TMC6-HE Temperature Sensors, the surface temperature of the southern facade (°F), with a FLIR ONE Thermal Imaging Camera Attachment and infrared thermometer for iOS, and finally weather conditions were tracked using a local weather station. Four Bays of the Greenhouse were tested. A control bay (**Control**), outfitted with no green façade system, the bay directly under the overhang system (**Overhang**), the bay directly behind the tension wire system (**Tension**), and the bay directly behind the felt system (**Felt**).

Figure 68. Reading Locations for Field Test Data Recording

Testing Period

In order to gather an accurate depiction of the performance of the installed green façade systems at the E. 34 Greenhouse, continuous temperature logging at the façade surface began several days prior to any installation of the façade systems. From **June 28th to July 3rd** measurements were taken at each façade bay to determine how these areas performed without the influence of the façade systems. Full installation of the entire façade system was completed around July 12th and thereafter subsequent data measurement could be taken to determine the effect of the system installation. Three (3) separate "testing days" were chosen on which hourly measurements of illuminance and thermal images were taken. These three days were **July 18th, July 21st** and **July 22nd**. After comparing the outdoor temperatures of these days with those from the June 28th to July 3rd period of pre-installation, **July 1st** was chosen to be a "control day" on which to compare the post-installation results due to the similarity in outdoor temperature with the "testing days". Throughout the discussion of experimental methods and results, data will be presented in reference to these four particular sample days.

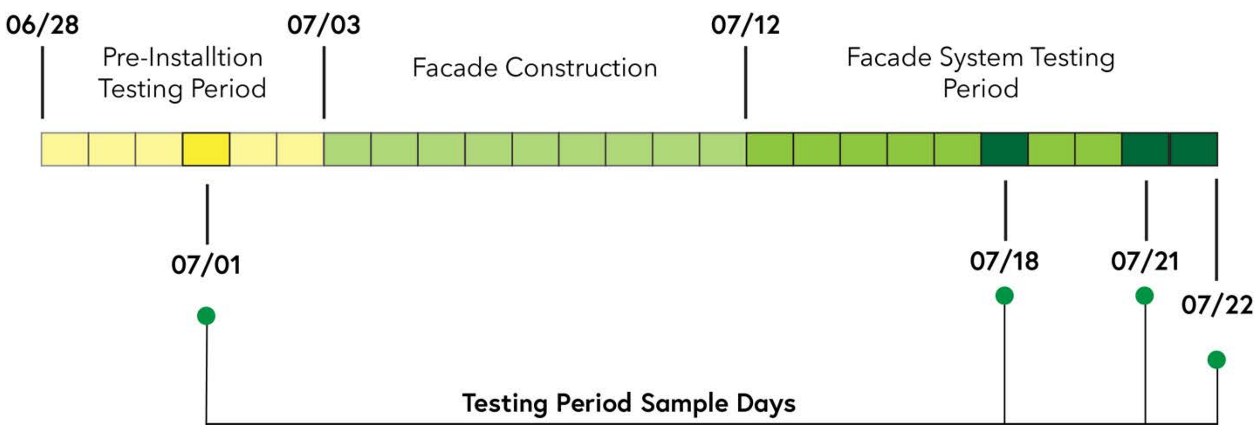


Figure 69. Timeline for E. 34 Greenhouse Field Test

Continuous Temperature Logging

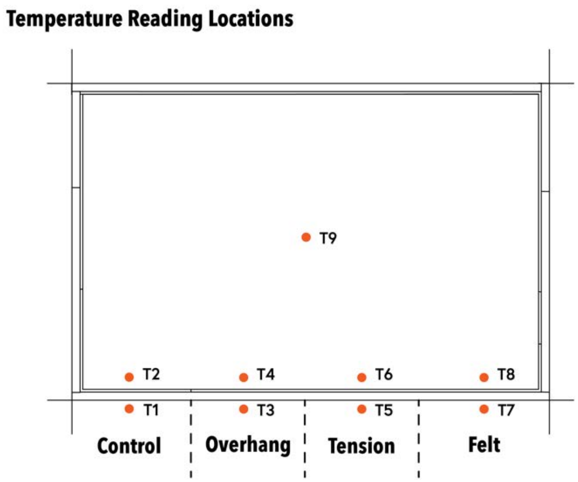


Figure 70. Continuous Temperature Loggings Locations

Continuous Temperature logging was conducted throughout the course of the testing period at both the interior and exterior surface of each testing bay at one-minute intervals. T1, T3, T5 and T7 represent the exterior air temperature recorded at the surface while T2, T4, T6 and T8 represent the interior air temperature recorded at the façade surface. T9 represents the ambient air temperature in the center of the greenhouse. T1 and T2 correspond to the Control Bay, T3 and T4 with the Overhang Bay, T5 and T6 with the Tension Bay and T7and T8 with the Felt Bay. The temperature sensors were located in the center of each bay as pictured in Figure 71.

Figure 71. Temperature Sensor Locations

Hourly Thermal Imaging

Hourly thermal images were taken from 8AM to 8PM at three (3) separate locations for each testing bay for a total of twelve pictures per hour. This was conducted for the three testing days, post-installation of the façade systems (July 18th, 21st and 22nd). Thermal images were taken at the exterior of each bay to illustrate the effect of the associate façade system. Interior images were taken to show the effect of each façade system on the indoor space. And finally, interior ground images were taken to show the amount of solar radiation let into the interior through each façade system.

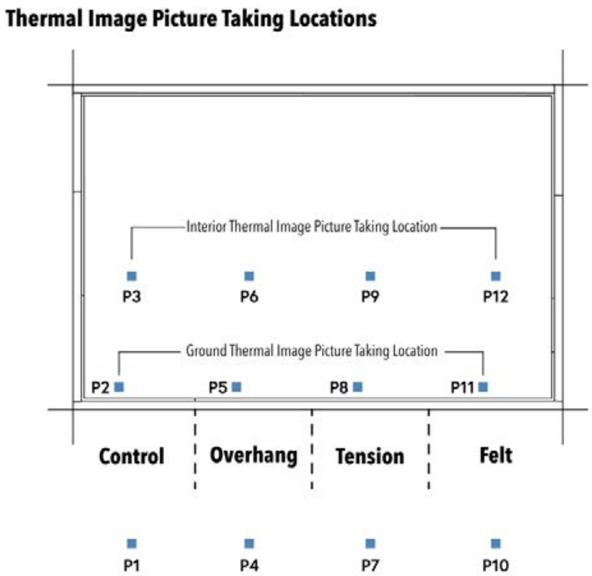


Figure 72. Picture Taking Locations for Hourly Thermal Imaging

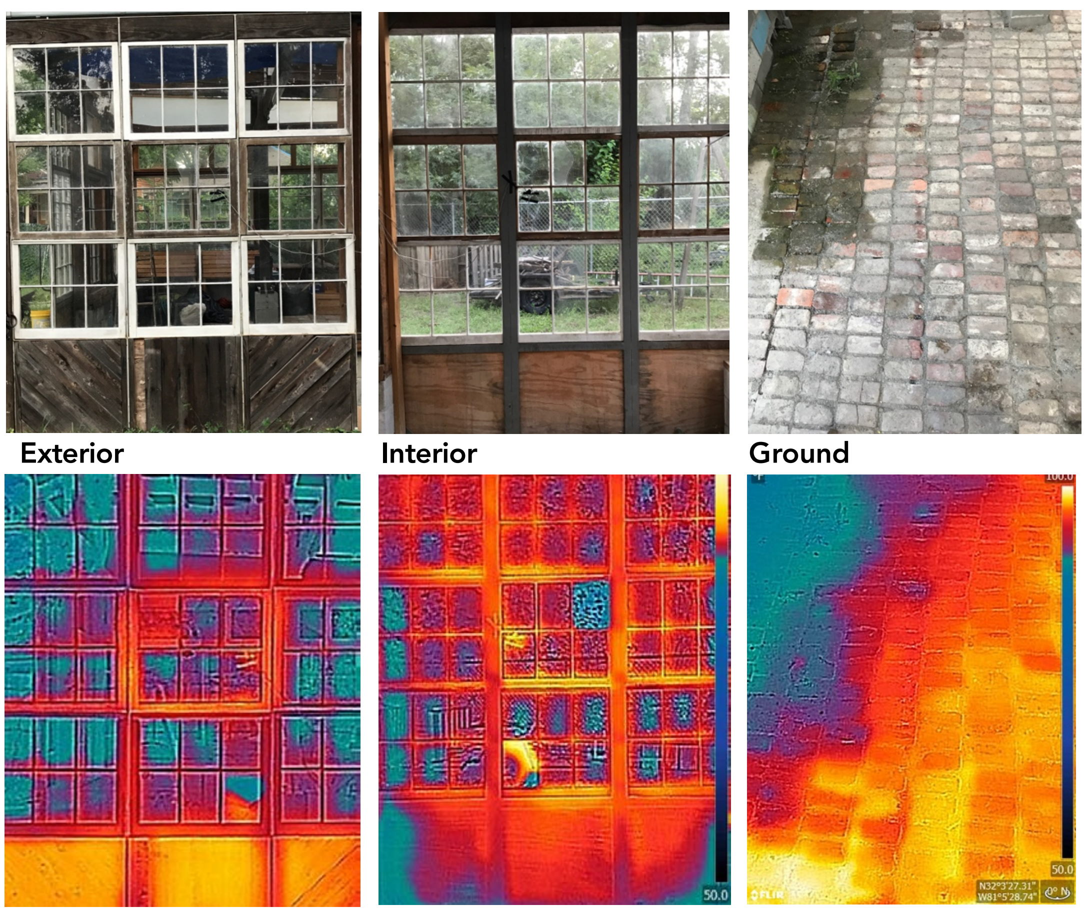


Figure 73. Examples of Thermal Imaging Data Recording at the E. 34 Greenhouse

Hourly Illuminance Level Readings

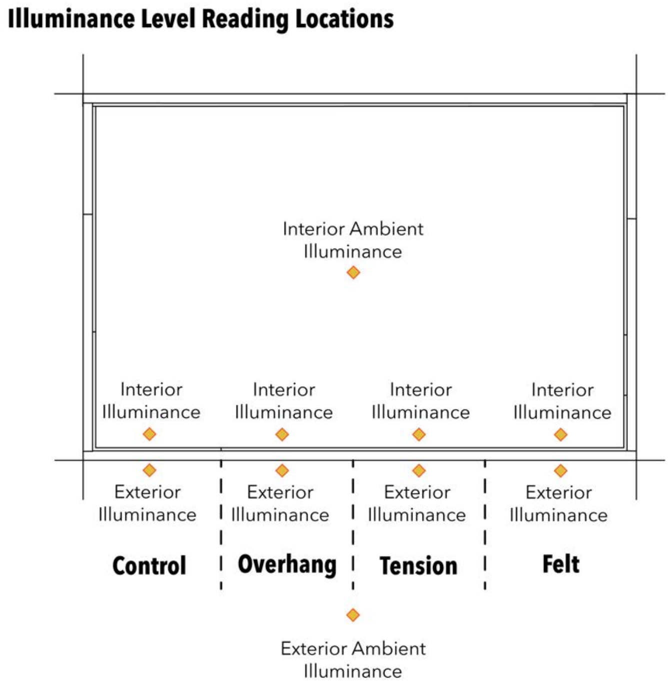


Figure 74. Illuminance Level Reading Locations

Illuminance level readings were taken in order to determine the shading capacity associated with each façade system. As seen in Figure 68, exterior illuminance levels were taken at the area located between the green façade system and the actual building façade. These levels were then compared to the exterior ambient illuminance levels to determine the shading factor for each system. Interior illuminance levels were taken at the interior façade surface at the center of each testing bay.

Social and Agricultural Measurements

Since the ultimate goal of this research is to demonstrate the social and agricultural benefits as well as the thermal benefits of green façade systems, social and agricultural data was recorded as well. Due to the short period of testing no significant growth or produce yield could be obtained from the edible plants on site; therefore, a projection of yield potential was calculated. Social impacts were determined by keeping record of the community activities and involvement that occurred due to the Greenhouse project.

6. Results

The following section presents the results from the green façade field test at the E. 34 Greenhouse in Savannah, GA. The thermal data section will present results from the continuous thermal logging, hourly thermal imaging and hourly illuminance level readings. The Social Section will present the projected potential for produce yield as well as the social impact the project had on the surrounding community.

6.1 Thermal Data

As mentioned in the previous section, four sample days from the testing period were utilized to depict the performance of each façade system. Figure 75 shows the average hourly outdoor temperature for each of these testing days. July 1st, which occurred before installation of the façade systems, was chosen as the control day to which the subsequent post-installation days would be compared since the outdoor temperature most nearly matched those of July 21st and July 22nd. July 18th has a significantly lower hourly temperature since it was a cloudy day, whereas the other sample days were mostly sunny.

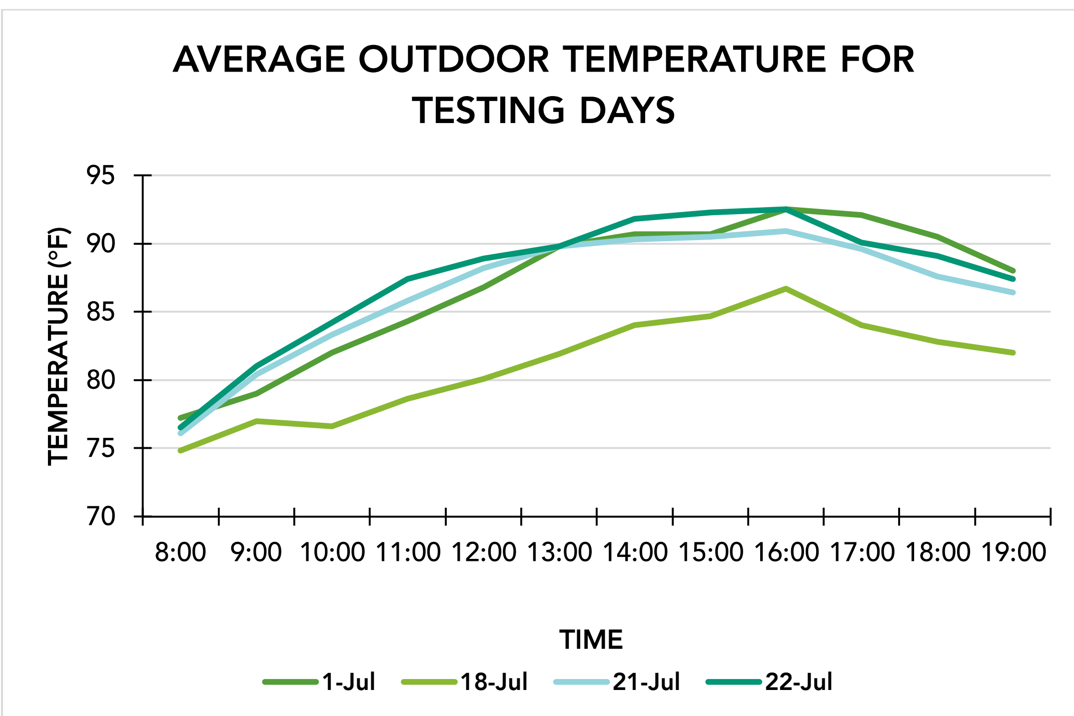
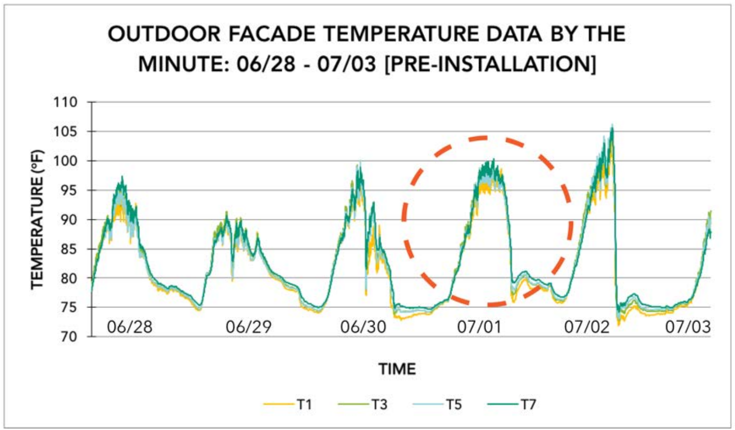


Figure 75. Average Outdoor Temperature for Testing Days

Pre-Installation Results



The continuous temperature logging results from the four-and-a-half-day testing period prior to any green façade installation (from June 28th to July 3rd) are given in the graphs to the left. The outdoor façade temperature at each bay is rather consistent between the four different bays; however, the indoor façade temperature results show that **T2** was consistently lower than the other three bays. Since the control bay is located at the corner of the greenhouse and is the part of the façade that also functions as a sliding door, this area of the greenhouse is subject to the most ventilation and is therefore benefiting from the air convection flowing through the spaces where the sliding doors meet. This is an important condition that will need to be accounted for in the subsequent results for the post installation testing days.

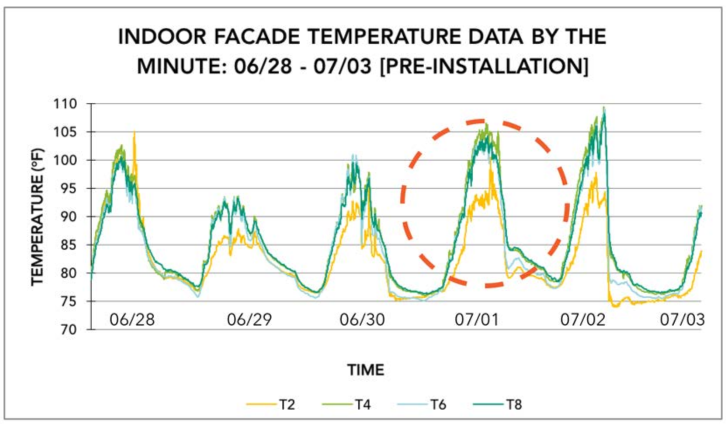


Figure 76. Pre-Installation Temperature Data by Minute

July 1st | Control Day

In order to take a closer look at the behavior of each façade bay prior to any installation of a green façade system, the data for July 1st, the control day, is presented here. The dashed lines represent indoor air temperatures while the solid lines refer to outdoor air temperatures.

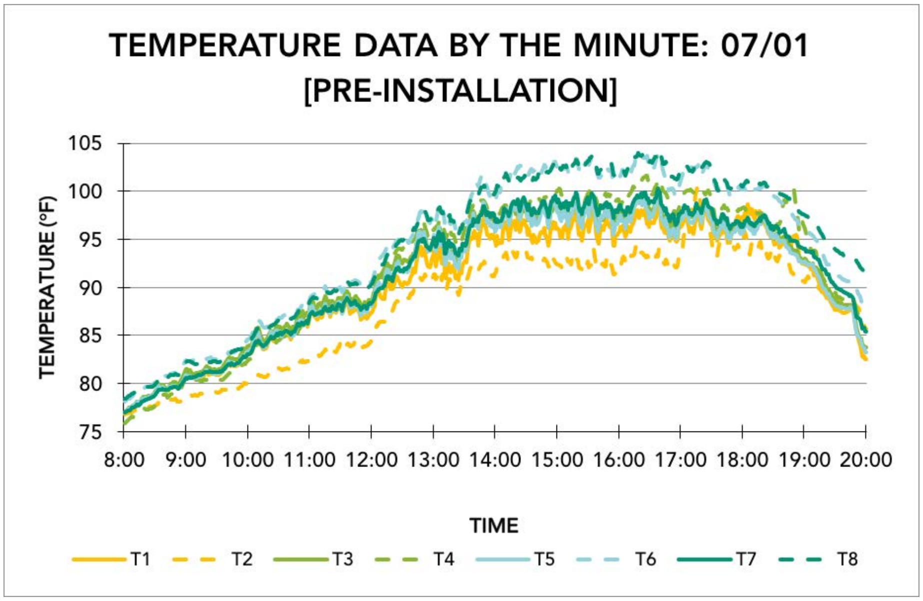
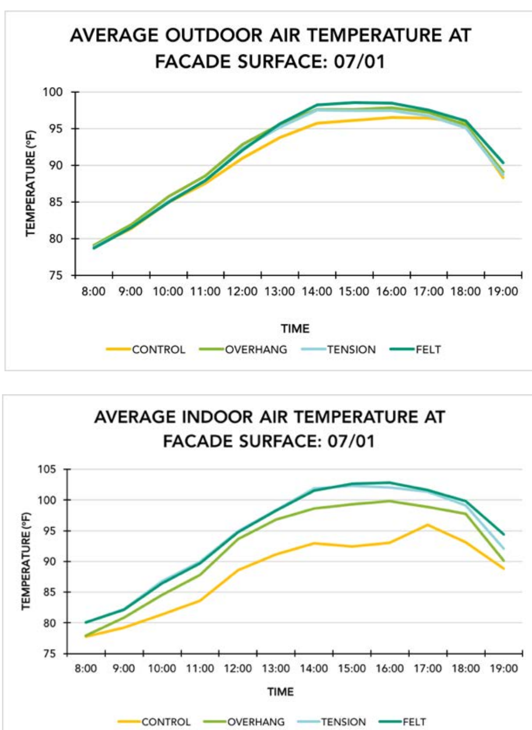


Figure 77. July 1st Temperature Data by the Minute



The continuous temperature logging data for the July 1st control day brings attention to the phenomenon seen in the pre-installation recordings for the greenhouse. While the outdoor façade temperatures remain fairly consistent at each bay, there is a discrepancy in the indoor temperatures in that the control bay is experiencing significantly cooler conditions than the other three bays. By Isolating this specific day, the average temperature differences of each bay from the control can be calculated and used to normalize the readings in the post-installation testing period. The hourly average temperature differences of each bay from the control bay are given in the following tables.

Figure 78. Average Air Temperature at Façade Surface: July 1st

Table 16. Average Outdoor Air Temperature Difference at Façade Surface from Control Bay (July 1st)

	Outdoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	+0.24	+0.05	-0.10
9:00	---	+0.56	+0.11	+0.10
10:00	---	+0.77	+0.19	+0.04
11:00	---	+1.02	+0.35	+0.42
12:00	---	+1.92	+1.38	+1.13
13:00	---	+1.80	+1.47	+1.92
14:00	---	+1.89	+1.78	+2.45
15:00	---	+1.51	+1.30	+2.43
16:00	---	+1.36	+0.91	+1.97
17:00	---	+0.80	+0.29	+1.11
18:00	---	-0.21	-0.58	+0.32
19:00	---	+0.76	+0.37	+2.08
AVG.	---	**+1.03**	**+0.63**	**+1.16**

Table 17. Average Indoor Air Temperature Difference at Façade Surface from Control Bay (July 1st)

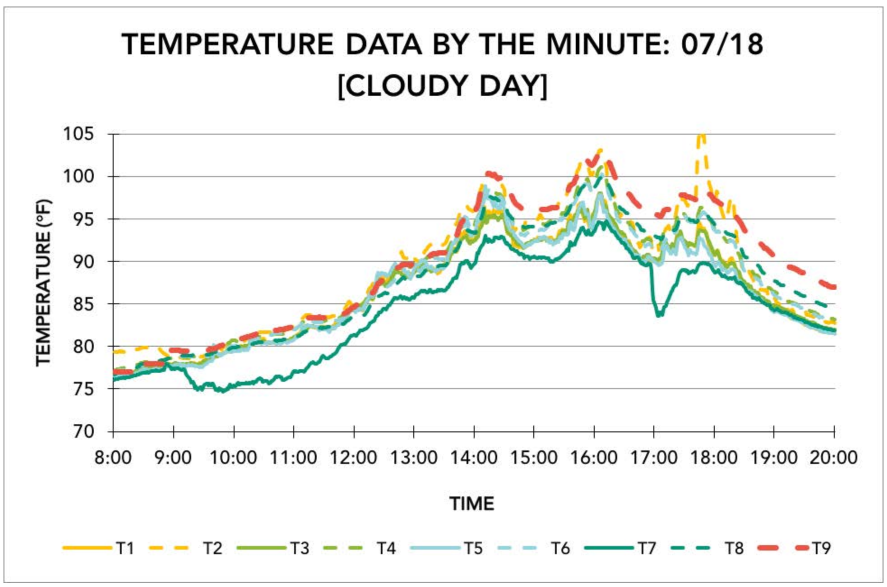
	Indoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	+0.20	+2.39	+2.34
9:00	---	+1.63	+2.96	+2.87
10:00	---	+3.23	+5.41	+5.07
11:00	---	+4.23	+6.33	+6.11
12:00	---	+5.14	+6.39	+6.22
13:00	---	+5.66	+7.20	+7.10
14:00	---	+5.61	+8.91	+8.57
15:00	---	+6.87	+9.93	+10.24
16:00	---	+6.78	+9.06	+9.82
17:00	---	+2.86	+5.35	+5.63
18:00	---	+4.61	+6.00	+6.70
19:00	---	+1.32	+3.24	+5.55
AVG.	---	**+4.01**	**+6.10**	**+6.35**

These average values of temperature differences at each bay façade will be used throughout the subsequent results for the post-installation testing days, factoring it in to the temperature differences found after the green facades were put in place to give a more accurate depiction of the performance of each system.

Post-Installation Results

The following section presents the thermal data recording results for the three testing days conducted after the installation of the green façade systems. One cloudy day and two sunny days are presented here to give a holistic picture of how the façade react under different climactic conditions. In addition to the data recorded and synthesized from the continuous temperature logging (as seen in the pre-installation results) data from the thermal imaging and illuminance level readings will also be discussed.

July 18th



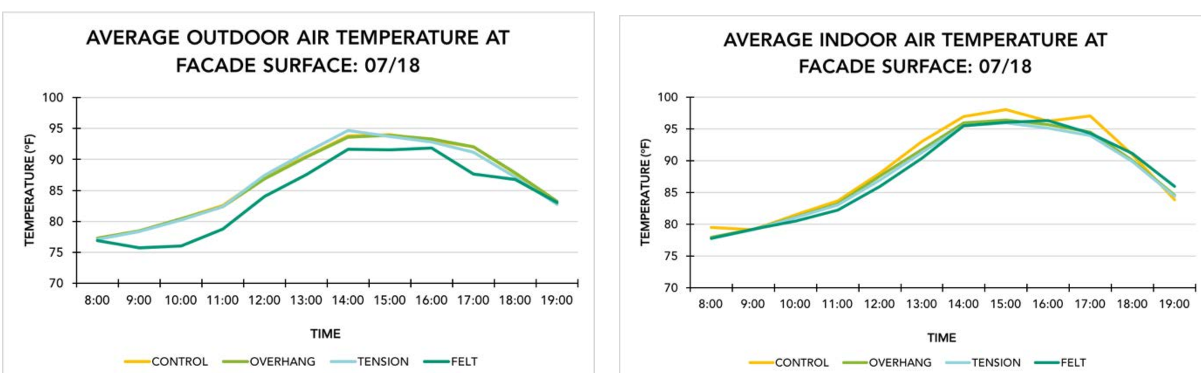


Figure 79. Continuous Temperature Logging Results (July 18th)

The installation of the green façade systems has an obvious effect when compared to the control day of July 1st. Figure 79 shows that the outdoor temperature of the felt system is noticeably lower than the other three systems while the indoor temperatures have evened out with the installation of the façade vegetation rather than the control bay experiencing significantly cooler conditions.

Table 18. Average Outdoor Air Temperature Difference at Façade Surface from Control Bay (July 18th)

[07/18]	Outdoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	+0.05	-0.18	-0.40
9:00	---	+0.01	-0.15	-2.72
10:00	---	0.00	-0.19	-4.44
11:00	---	-0.13	-0.13	-3.79
12:00	---	-0.40	+0.20	-3.27
13:00	---	-0.18	+0.60	-3.00
14:00	---	-0.15	+0.93	-2.14
15:00	---	-0.12	-0.27	-2.43
16:00	---	+0.21	-0.24	-1.22
17:00	---	+0.03	-0.85	-4.44
18:00	---	+0.13	-0.50	-0.92
19:00	---	+0.47	-0.05	+0.25
AVG.	---	-0.01	-0.07	-2.38
PRE-INSTALL		+1.03	+0.63	+1.16
OVERALL		**-1.04**	**-0.70**	**-3.54**

Table 19. Average Indoor Air Temperature Difference at Façade Surface from Control Bay (July 18th)

[07/18]	Indoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	-1.50	-1.74	-1.68
9:00	---	+0.09	-0.03	+0.02
10:00	---	-0.35	-0.50	-1.03
11:00	---	-0.47	-0.62	-1.48
12:00	---	-0.47	-1.14	-2.05
13:00	---	-1.26	-1.73	-2.61
14:00	---	-0.98	-1.43	-1.45
15:00	---	-1.59	-2.11	-2.01
16:00	---	-0.48	-1.05	+0.14
17:00	---	-2.52	-3.07	-2.68
18:00	---	-0.92	-1.14	+0.15
19:00	---	+0.73	+0.56	+2.08
AVG.	---	-0.81	-1.17	-1.05
PRE-INSTALL		+4.01	+6.10	+6.35
OVERALL		**-4.82**	**-7.27**	**-7.40**

The addition of the green façade systems to the southern wall of the greenhouse has an evident effect on the surface temperature of each façade bay. While the felt system has the greatest effect in reducing the surface temperature of the outdoor façade both the felt and tension systems have succeeded in helping to reduce the interior surface temperature from the original conditions.

HOURLY THERMAL IMAGES

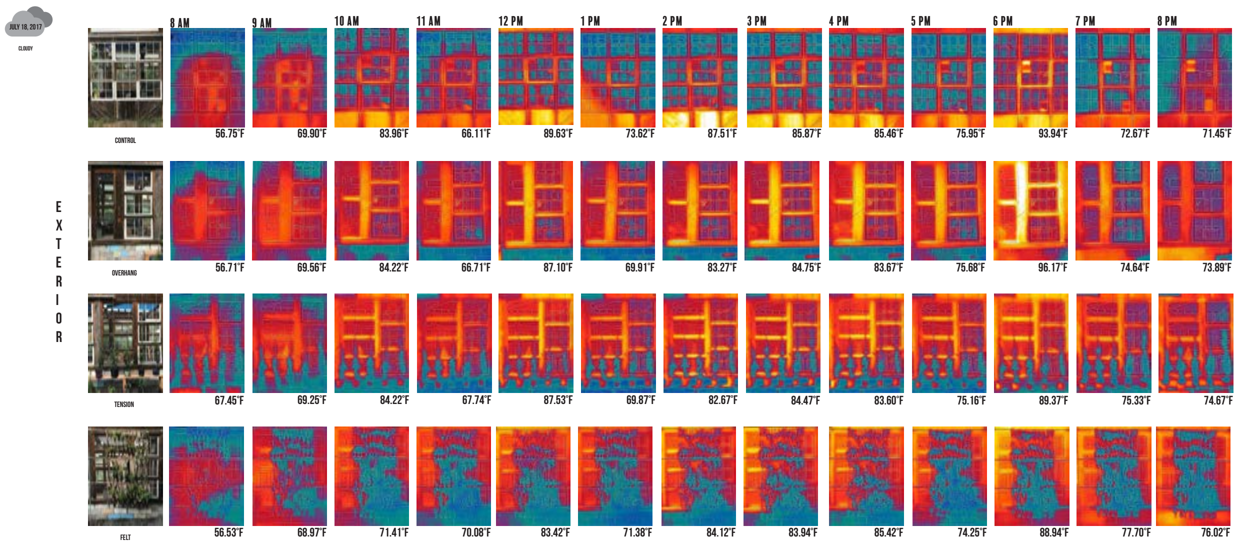


Figure 80. Hourly Exterior Thermal Images of Testing Bays (July 18th)

Figure 80 above illustrates the exterior hourly thermal images of each testing bay. The blue areas of the images represent the cooler surfaces in the image while the yellow and white areas are the hottest. The average surface temperature for each image has been calculated and the value place in the bottom right hand corner of each picture; however, the benefit of the thermal imaging is that it illustrates the relationship between the different materials at a surface. As you can see in the images for the felt and tension system, the plant material and growing medium significantly aid in reducing the surface temperature of the façade.

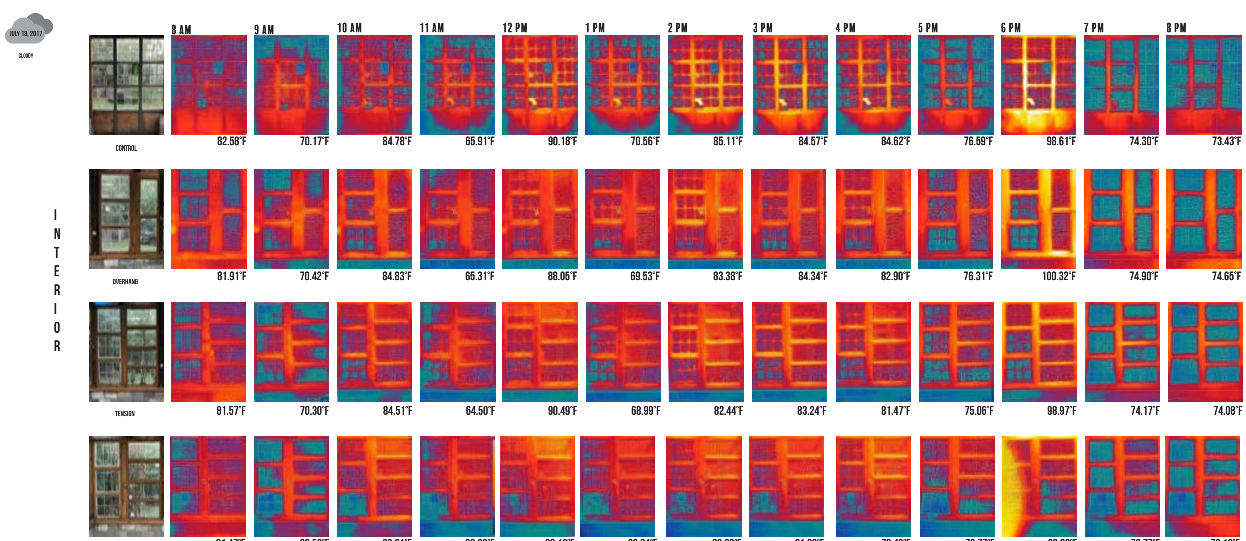


Figure 81. Hourly Interior Thermal Images of Testing Bays (July 18th)

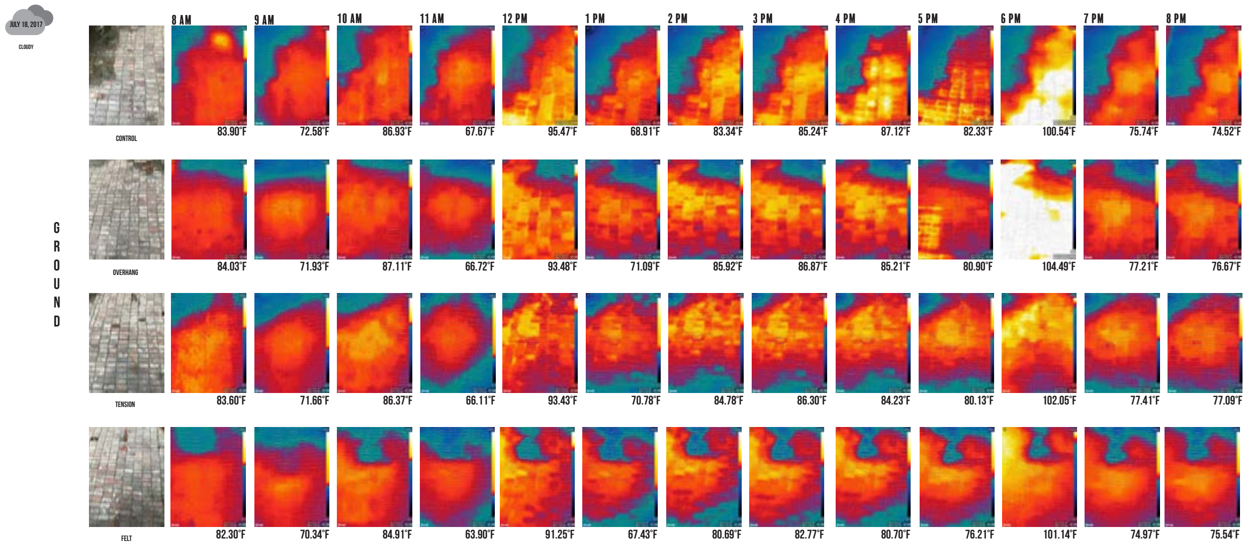


Figure 82. Hourly Interior Ground Thermal Images of Testing Bays (July 18th)

The thermal images of the interior ground floor give a good depiction of the amount of light each façade system allows into the greenhouse. As seen in Figure 82 above, the control and overhang systems allow the most solar radiation into the greenhouse, especially around 5 PM, while the tension system and felt systems block more of the light.

Illuminance Levels

Illuminance levels were taken every hour from 8AM to 8PM at both the exterior and interior of each façade. The illuminance readings are presented in the following tables, while the shading factor for each façade (the ratio of the illuminance level of the façade to the ambient illuminance level) is presented in the following graphs. It is important to remember when discussing the illuminance levels, the condition discussed in section 5.4 of the effect of the overhang trellis on different systems during the day. Since July 18th was a cloudy day the trellis did not have a significant impact on the illuminance levels; however, during the sunny testing days this effect is more pronounced and temporary decreases in the shading factors occur at the time in which the trellis is shading each testing bay.

Table 20. Hourly Outdoor Illuminance Levels (July 18th)

Outdoor Illuminance Levels (7/18)					
Time	Ambient	Control	Overhang	Tension	Felt
8:00	5330	4160	3140	2190	613
9:00	6760	4300	3240	2300	774
10:00	9875	6214	4622	3400	798
11:00	13410	8350	6230	4500	894
12:00	42500	26100	18000	11340	2190
13:00	33900	19500	16000	10500	2020
14:00	31500	18900	14700	9490	1890
15:00	39000	19600	15000	9990	2170
16:00	32100	18400	13340	8070	1940
17:00	28055	14615	10243	6760	1502
18:00	12010	6830	5130	3450	845
19:00	3460	1960	1500	791	286
20:00	311	152	119.5	73.8	28.2

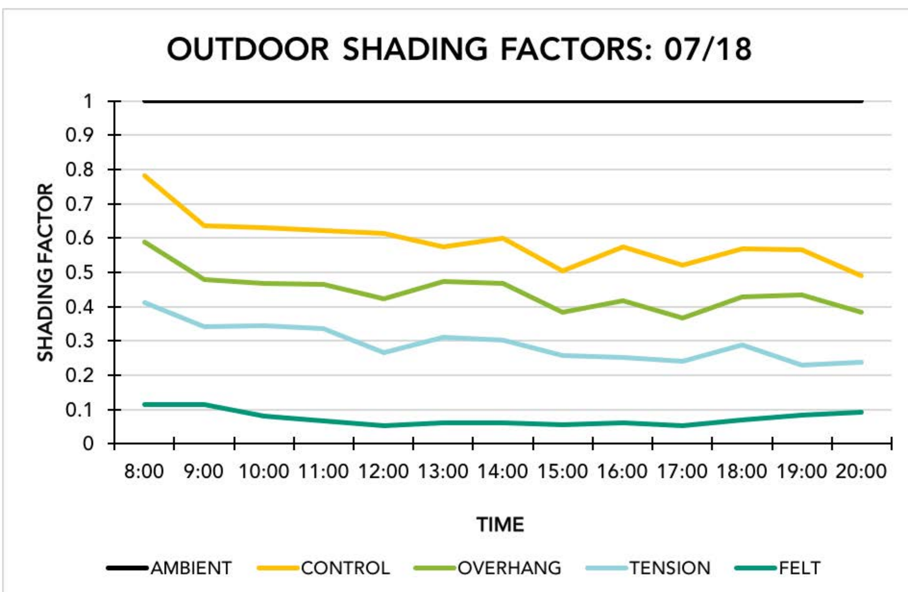


Figure 83. Hourly Outdoor Shading Factors (July 18th)

Table 21. Hourly Indoor Illuminance Levels (July 18th)

Indoor Illuminance Levels (7/18)					
Time	Ambient	Control	Overhang	Tension	Felt
8:00	1540	2120	1630	1610	1470
9:00	1500	2350	1620	1560	1410
10:00	2110	2700	1695	1798	1421
11:00	2780	3150	1770	2060	1450
12:00	6290	10750	6100	4090	2220
13:00	7800	11290	6860	5230	3320
14:00	7450	10580	5290	3810	2430
15:00	7920	10650	5860	4270	2790
16:00	7130	10160	3950	4100	2380
17:00	5320	8513	3301	3015	2083
18:00	2610	3720	1469	1138	933
19:00	791	888	504	467	333
20:00	70.3	72.1	38.1	40.9	24.5

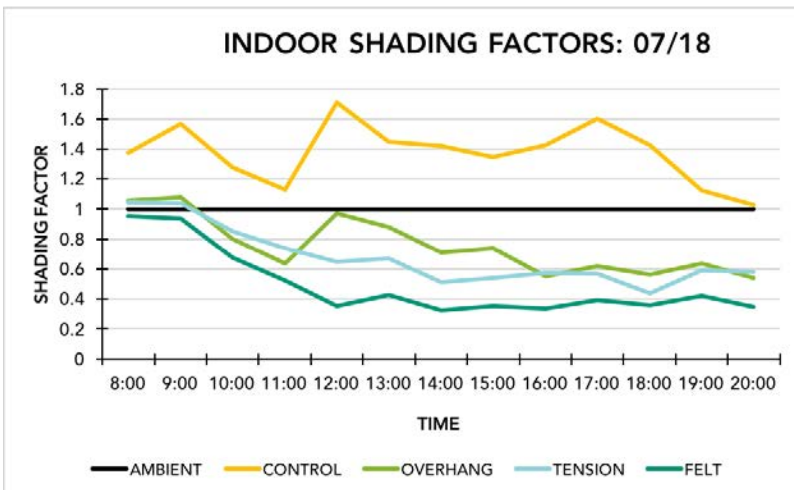


Figure 84. Hourly Indoor Shading Factors (July 18th)

The illuminance level results from July 18th demonstrate that the felt system provides the most shade out of all the green façade systems in place at the greenhouse and this shading effect is more pronounced outdoors than indoors.

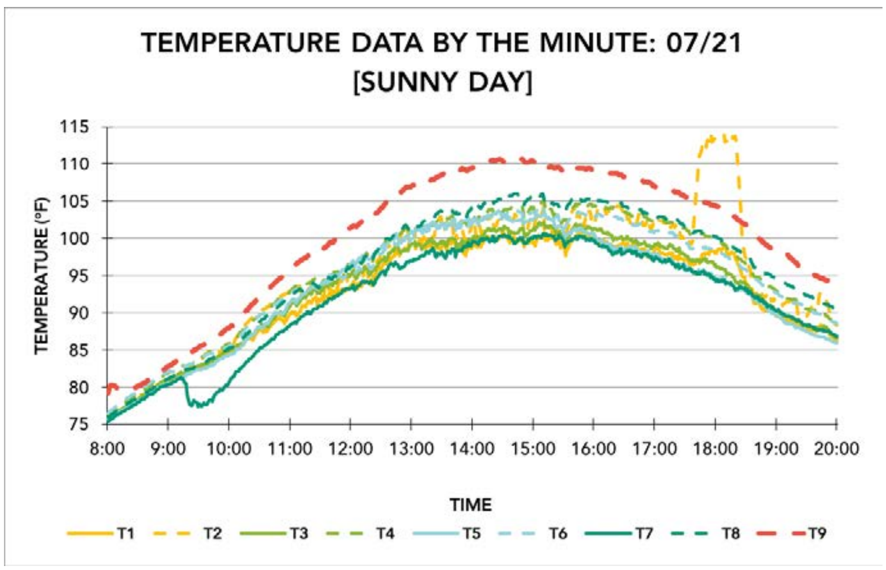
Table 22. Average Outdoor Shading Factors (July 18th)

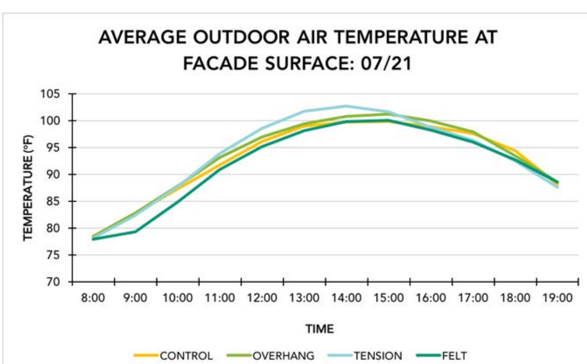
Average Outdoor Shading Factor (07/18)				
Ambient	Control	Overhang	Tension	Felt
1.00	**0.60**	**0.45**	**0.30**	**0.07**

Table 23. Average Indoor Shading Factors (July 18th)

Average Indoor Shading Factor (07/18)				
Ambient	Control	Overhang	Tension	Felt
1.00	**1.40**	**0.77**	**0.68**	**0.50**

July 21st





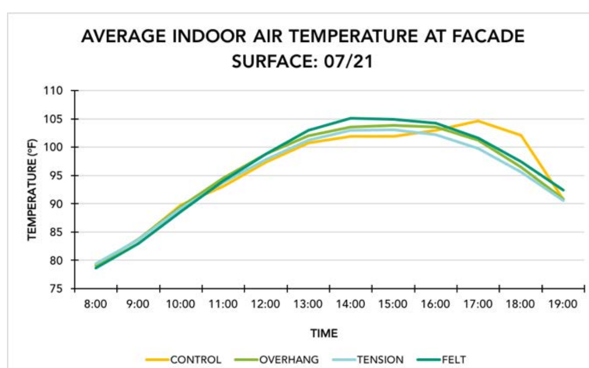


Figure 85. Continuous Temperature Logging Results (July 21st)

The temperature results from July 21st help demonstrate the performance difference in the green façade systems on a sunny day (July 21st) versus a cloudy one (July 18th). The more intense exposure to radiation seems to even out the outdoor surface temperature more than seen in the cloudy day testing result. The felt system still produces the greatest cooling effect on the outdoor façade surface while the tension has the greatest effect on the indoor surface. These results are demonstrated in the following tables.

Table 24. Average Outdoor Air Temperature Difference at Façade Surface from Control Bay (July 21st)

[07/21]	Outdoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	0.00	-0.34	-0.52
9:00	---	+0.12	-0.36	-3.45
10:00	---	+0.50	+0.46	-2.45
11:00	---	+1.41	+2.15	-0.80
12:00	---	+0.80	+2.49	-0.98
13:00	---	+0.40	+2.75	-0.90
14:00	---	+1.08	+2.96	+0.10
15:00	---	+1.37	+1.80	+0.18
16:00	---	+1.04	-0.20	-0.71
17:00	---	+0.27	-1.33	-1.56
18:00	---	-0.89	-1.83	-1.64
19:00	---	+0.39	-0.55	+0.34
AVG.	---	0.54	0.67	-1.03
PRE-INSTALL		+1.03	+0.63	+1.16
OVERALL		**-0.49**	**0.04**	**-2.19**

Table 25. Average Indoor Air Temperature Difference at Façade Surface from Control Bay (July 21st)

[07/21]	Indoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	-0.08	0.20	-0.61
9:00	---	+0.07	0.00	-0.67
10:00	---	-0.27	-0.51	-1.14
11:00	---	+1.44	+0.64	+0.95
12:00	---	+1.41	+0.40	+1.44
13:00	---	+1.31	+0.56	+2.28
14:00	---	+1.69	+1.06	+3.21
15:00	---	+1.96	+1.15	+3.01
16:00	---	+0.54	-0.78	+1.21
17:00	---	-3.34	-4.87	-2.96
18:00	---	-5.65	-6.48	-4.63
19:00	---	+0.03	-0.18	+1.67
AVG.	---	-0.07	-0.73	0.31
PRE-INSTALL		+4.01	+6.10	+6.35
OVERALL		**-4.08**	**-6.83**	**-6.04**

Hourly Thermal Images

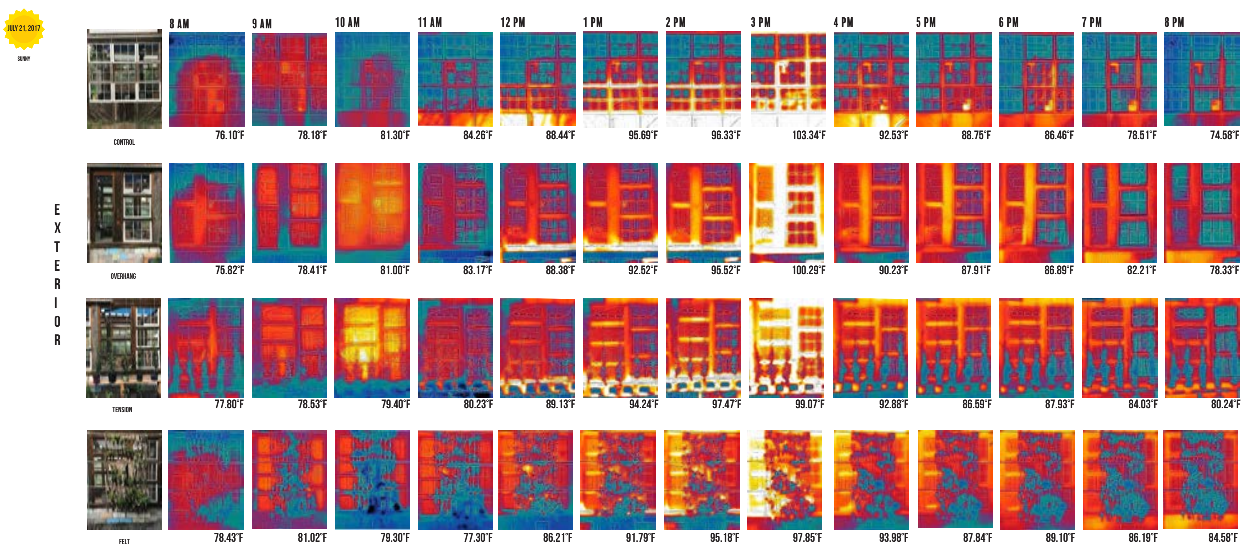


Figure 86. Hourly Exterior Thermal Images of Testing Bays (July 21st)

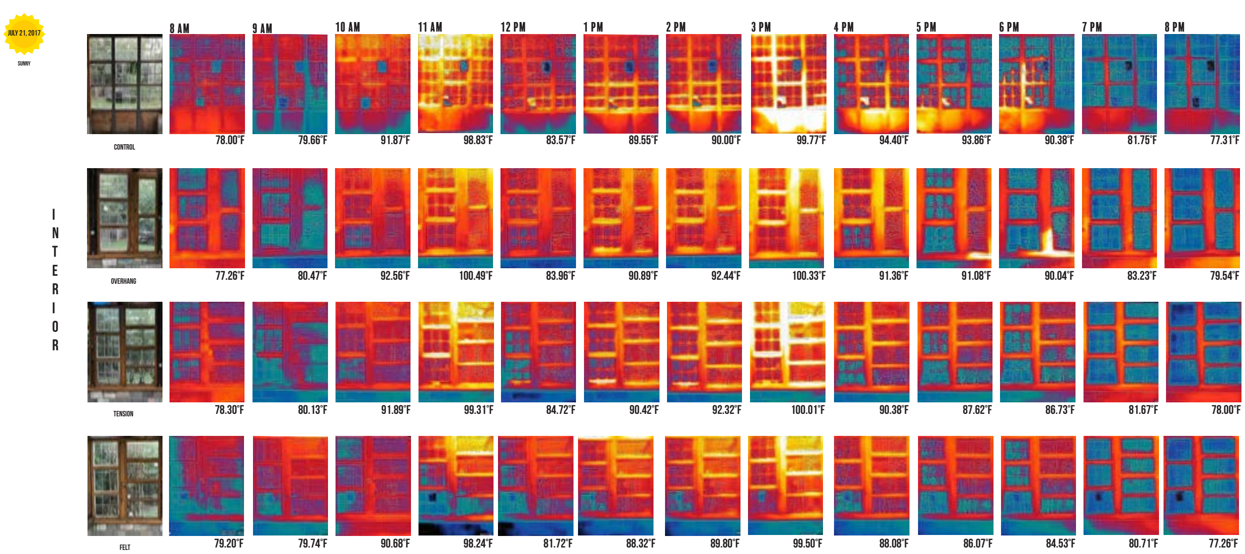


Figure 87. Hourly Interior Thermal Images of Testing Bays (July 21st)

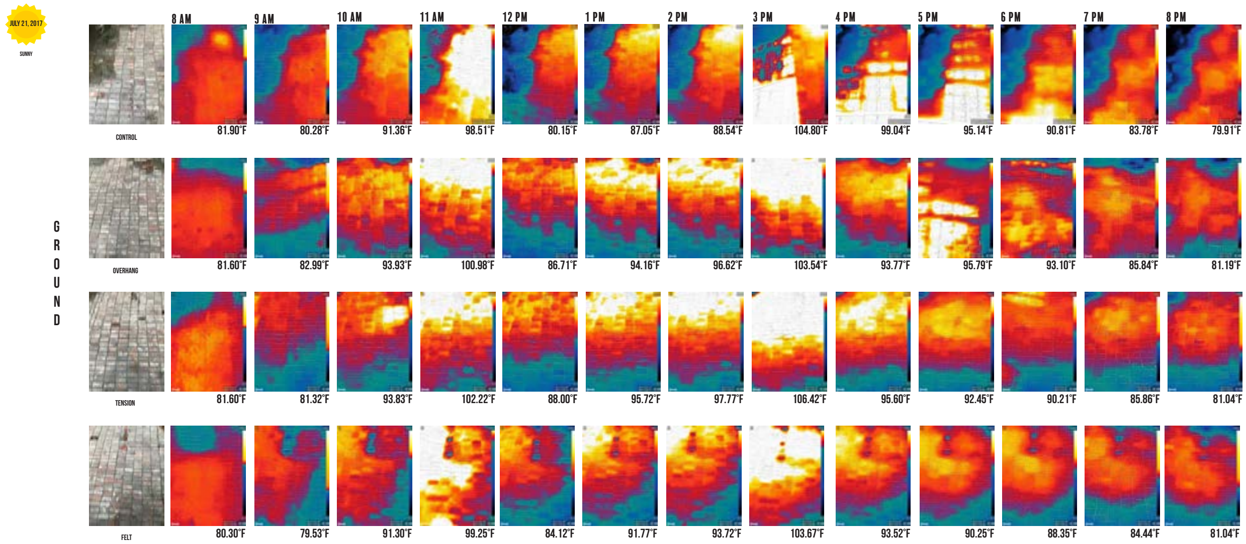


Figure 88. Hourly Interior Ground Thermal Images of Testing Bays (July 21st)

The thermal images for the July 21st testing day show a much higher exposure to solar radiation than the previous cloudy testing day. The exterior thermal images demonstrate the capacity of the foliage to cool down the surface temperature, even on a hot sunny day (especially around 3 PM) while the interior ground images reveal the greater exposure to radiation that the interior space is subject to on sunnier days.

Illuminance Levels

Table 26. Hourly Outdoor Illuminance Levels (July 21st)

Outdoor Illuminance Levels (7/21)					
Time	Ambient	Control	Overhang	Tension	Felt
8:00	6215	2970	2510	1530	583
9:00	15800	7673	2980	1830	785
10:00	20600	5440	3710	3100	1027
11:00	78100	13200	62900	37100	4200
12:00	78800	70400	33490	40200	4860
13:00	81600	69200	30300	35000	5360
14:00	82050	78050	65400	16495	5575
15:00	82500	76900	70500	12990	5790
16:00	72000	62700	49210	25830	3370
17:00	56900	49100	32480	24180	1241
18:00	6350	4630	3280	2640	1010
19:00	3710	1850	1377	1036	372
20:00	1363	774	668	495	123

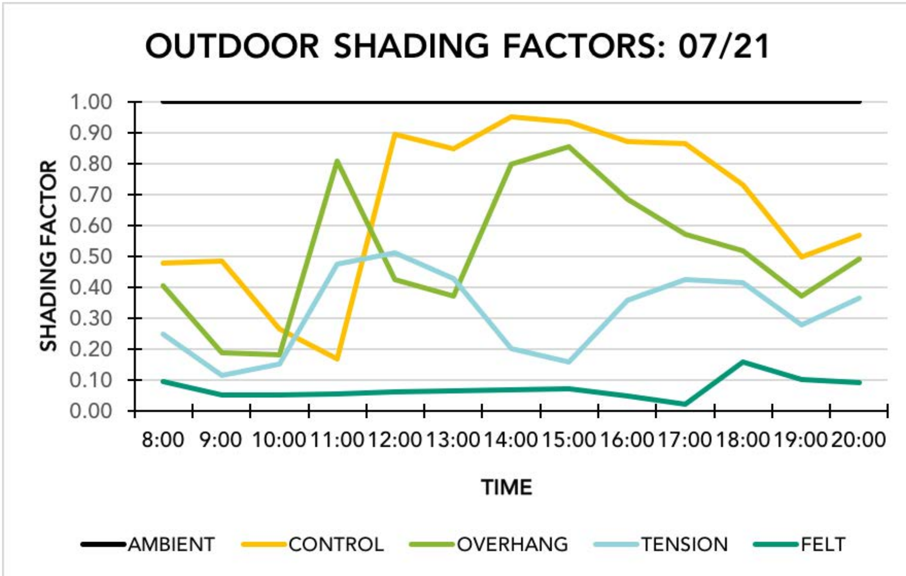


Figure 89. Hourly Outdoor Shading Factors (July 21st)

The shading factors associated with each façade system is not as linear for the sunny day as for the cloudy day. This can be attributed to the effect of the overhang trellis shading different parts of the façade throughout the day. As mentioned in section 5.4, the trellis is shading the Control system from 10-11, the Overhang from 11-1PM, The Tension System from 1-3PM and the Felt System from 3-5PM. You can see dips in the shading factors at each of these times for the associated façade system. The trend from the July 18th results remains, still. The felt system has the greatest shading capacity followed by the tension system.

Table 27. Hourly Indoor Illuminance Levels (July 21st)

Indoor Illuminance Levels (7/21)					
Time	Ambient	Control	Overhang	Tension	Felt
8:00	4100	1622	1501	1125	614
9:00	4300	1822	1840	1366	891
10:00	6960	2490	2170	1649	1050
11:00	10900	3330	3980	3510	1870
12:00	14800	4480	4680	4020	3010
13:00	14900	5340	5210	5170	4880
14:00	13095	5510	4955	4620	4080
15:00	11290	5680	4700	4070	3280
16:00	7640	4270	3900	3360	2580
17:00	5270	3210	2420	1931	1231
18:00	3050	3150	2060	1700	1180
19:00	991	1381	812	767	463
20:00	412	433	285	195	138

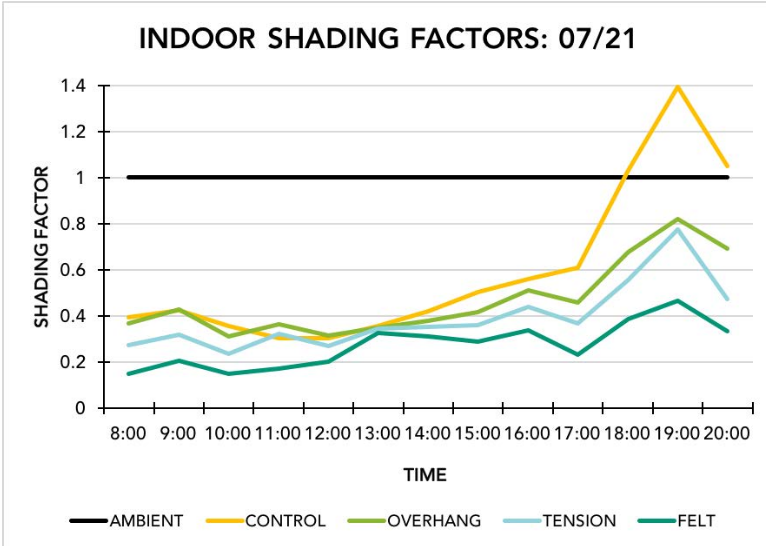


Figure 90. Hourly Indoor Shading Factors (July 21st)

The average shading factors calculated for each façade system are given in the tables below:

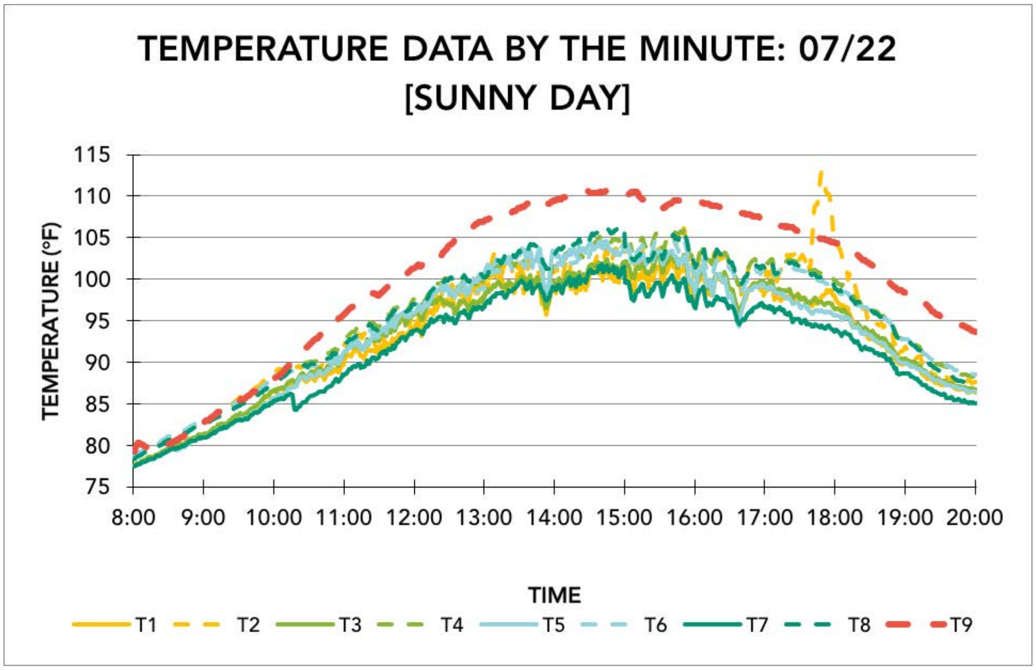
Table 28. Average Outdoor Shading Factors (July 21st)

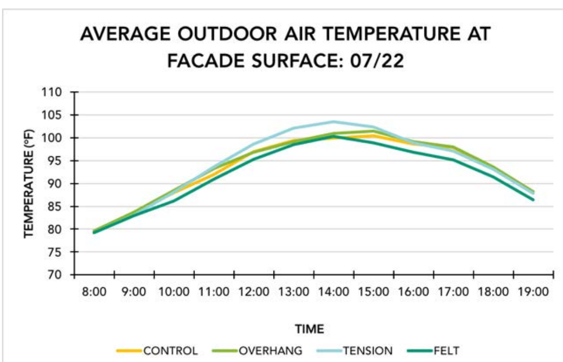
Average Outdoor Shading Factor (07/21)				
Ambient	Control	Overhang	Tension	Felt
1.00	**0.67**	**0.52**	**0.31**	**0.07**

Table 29. Average Indoor Shading Factors (July 21st)

Average Indoor Shading Factor (07/21)				
Ambient	Control	Overhang	Tension	Felt
1.00	**0.59**	**0.47**	**0.39**	**0.27**

July 22nd





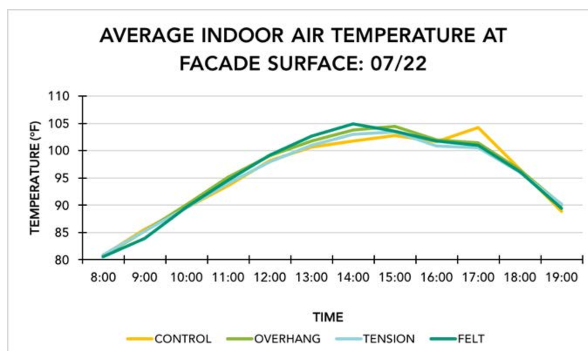


Figure 91. Continuous Temperature Logging Results (July 22nd)

The temperature results from July 22nd resemble those from the 21st. As seen in both of these days the felt system creates the lowest outdoor façade temperature, though not as pronounced as seen on the July 18th day and the indoor temperatures are evened out more so than seen in the original, pre-installation results. The following tables depict these results.

Table 30. Average Outdoor Air Temperature Difference at Façade Surface from Control Bay (July 22nd)

[07/22]	Outdoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	+0.14	-0.23	-0.15
9:00	---	+0.18	-0.44	-0.56
10:00	---	+0.57	+0.19	-1.76
11:00	---	+1.30	+1.69	-0.98
12:00	---	-0.07	+1.67	-1.66
13:00	---	-0.25	+2.67	-0.90
14:00	---	+0.99	+3.53	+0.40
15:00	---	+1.12	+1.95	-1.52
16:00	---	+0.56	+0.19	-1.84
17:00	---	+0.12	-0.74	-2.66
18:00	---	+0.23	-0.26	-1.89
19:00	---	+0.39	+0.12	-1.30
AVG.	---	+0.44	+0.86	-1.24
PRE-INSTALL		+1.03	+0.63	+1.16
OVERALL		**-0.59**	**+0.23**	**-2.40**

Table 31. Average Indoor Air Temperature Difference at Façade Surface from Control Bay (July 22nd)

[07/22]	Indoor Average Temperature Difference (°F)			
Time	CONTROL	OVERHANG	TENSION	FELT
8:00	---	-0.12	+0.18	-0.23
9:00	---	-0.29	-0.26	-1.68
10:00	---	+0.58	+0.00	+0.15
11:00	---	+1.57	+0.43	+1.05
12:00	---	+0.96	-0.23	+1.08
13:00	---	+1.13	+0.39	+1.98
14:00	---	+1.98	+1.18	+3.17
15:00	---	+1.70	+0.70	+0.81
16:00	---	+0.29	-0.79	+0.11
17:00	---	-2.75	-3.66	-3.25
18:00	---	-0.08	-0.47	-0.42
19:00	---	+1.19	+1.34	+0.56
AVG.	---	+0.51	-0.10	+0.28
PRE-INSTALL		+4.01	+6.10	+6.35
OVERALL		**-3.50**	**-6.20**	**-6.07**

Hourly Thermal Images

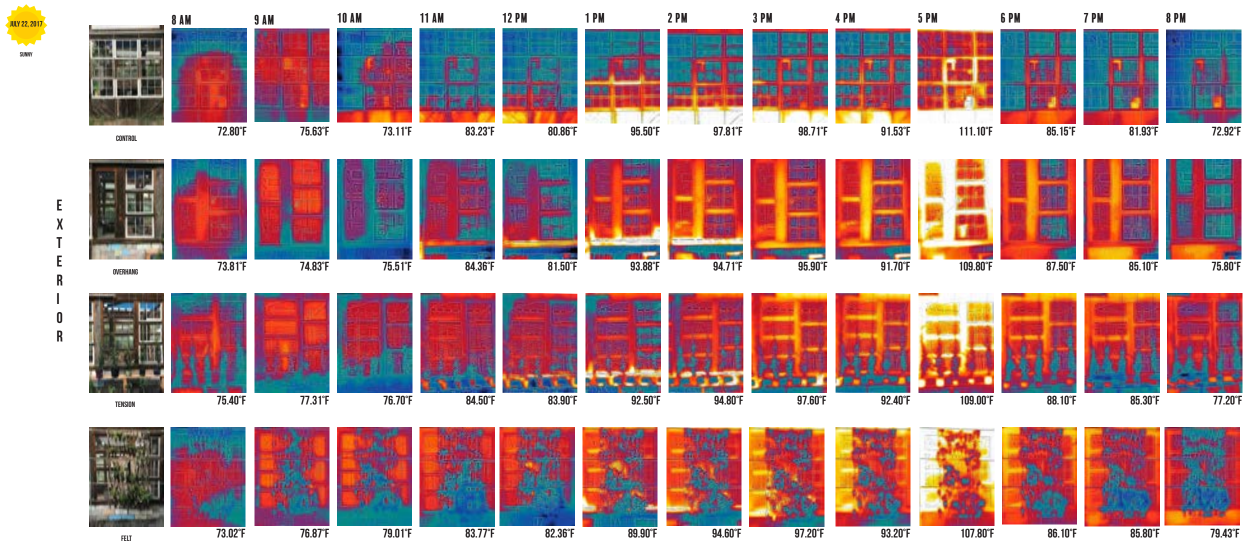


Figure 92. Hourly Exterior Thermal Images of Testing Bays (July 22nd)

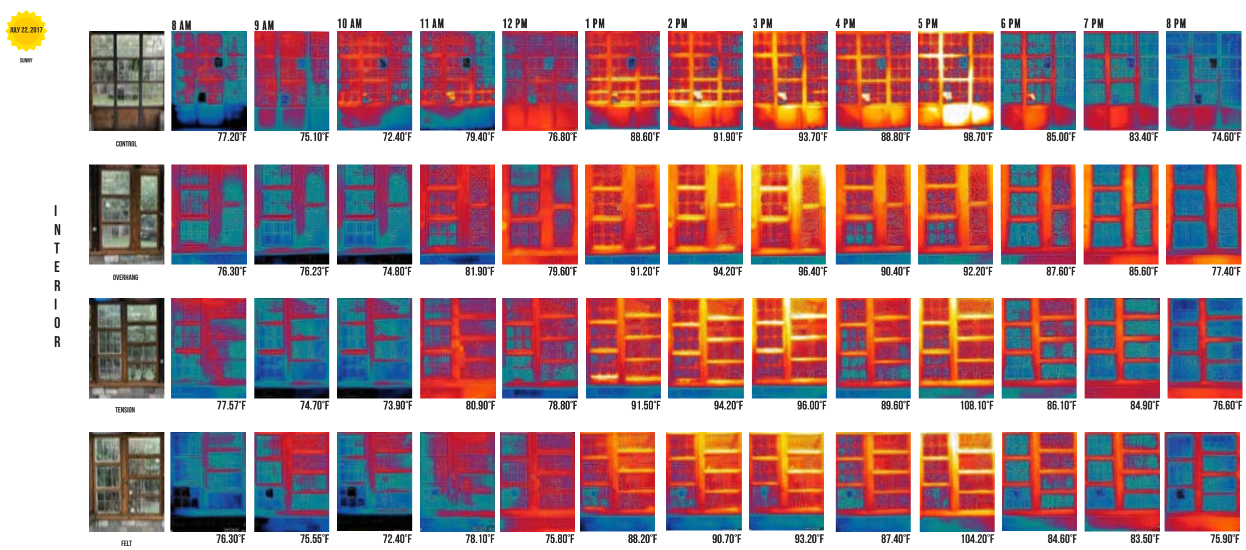


Figure 93. Hourly Interior Thermal Images of Testing Bays (July 22nd)

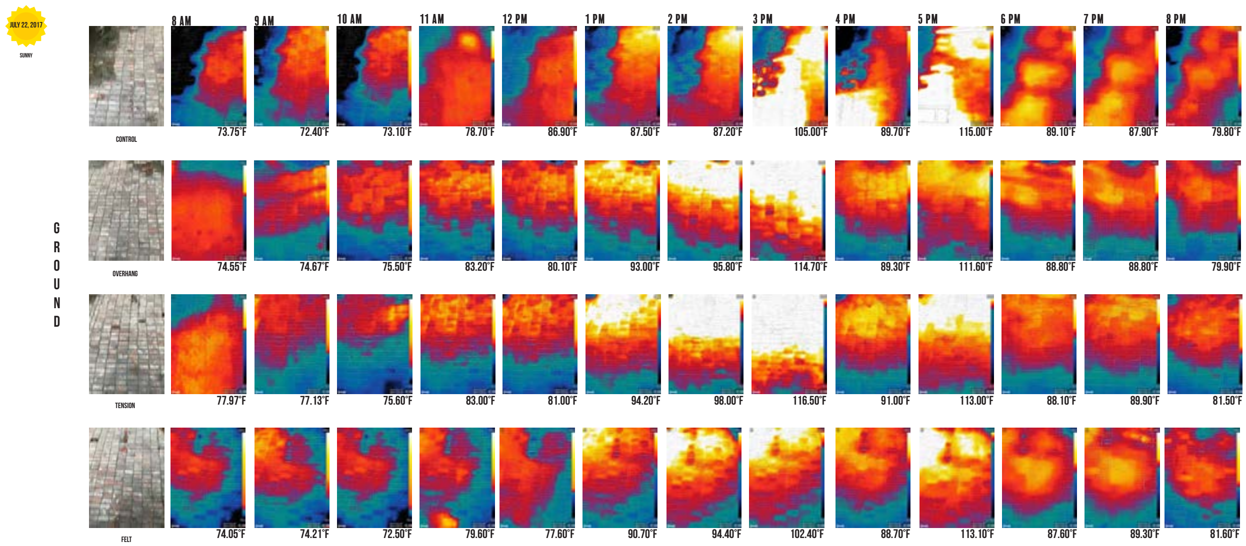


Figure 94. Hourly Interior Ground Thermal Images of Testing Bays (July 22nd)

The thermal images for the July 22nd are similar to those of the previous day with the tension system receiving a bit more radiation exposure to the interior ground than previous days. The exterior thermal images have consistently demonstrated the capacity of the foliage and growing medium (especially on the felt system) to cool down the surface temperature.

Illuminance Levels

Table 32. Hourly Outdoor Illuminance Levels (July 22nd)

Outdoor Illuminance Levels (7/22)					
Time	Ambient	Control	Overhang	Tension	Felt
8:00	5330	4160	3140	2190	613
9:00	45300	4600	3350	2055	1030
10:00	71900	5760	5290	4420	1670
11:00	80600	46000	68000	32080	3550
12:00	81300	68000	38500	27000	6190
13:00	84300	77400	36800	25700	6650
14:00	80600	74600	62070	12050	5590
15:00	82000	76700	59020	8380	6950
16:00	66950	63250	46860	10470	5205
17:00	51900	49800	34700	8560	3460
18:00	22700	2810	3590	2630	1320
19:00	4660	1590	1350	1281	786
20:00	1180	470	402	352	159

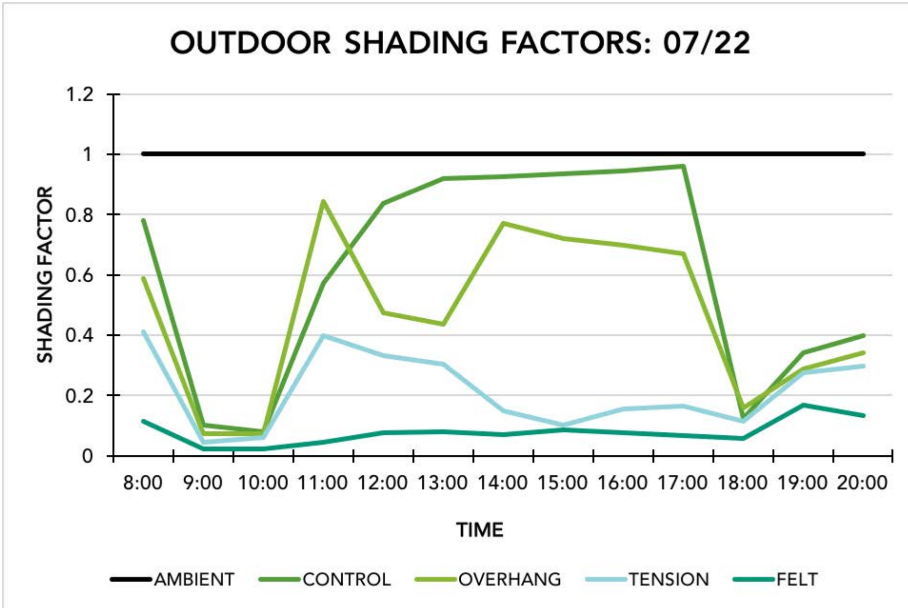


Figure 95. Hourly Outdoor Shading Factors (July 22nd)

The shading factors associated with each façade system follows the same trend as seen in the previous testing day with the effect from the overhang trellis still occurring at the specific times associated with each façade. The trend from the all the previous testing days remains with the felt system demonstrating the greatest shading capacity followed by the tension system.

Table 33. Hourly Indoor Illuminance Levels (July 22nd)

Indoor Illuminance Levels (7/22)					
Time	Ambient	Control	Overhang	Tension	Felt
8:00	3500	1730	1304	1413	716
9:00	5100	1985	1798	1836	1024
10:00	7950	2330	2420	2050	1320
11:00	11470	3730	3780	3600	2530
12:00	11470	4120	4000	3780	3080
13:00	17400	6110	5170	4380	3630
14:00	14390	5350	5320	4440	3400
15:00	8750	4890	4860	4350	3180
16:00	7205	4335	3970	3670	2455
17:00	5660	3780	3080	2990	1730
18:00	2590	1631	1453	1372	846
19:00	1233	899	891	813	573
20:00	290	282	218	172	73

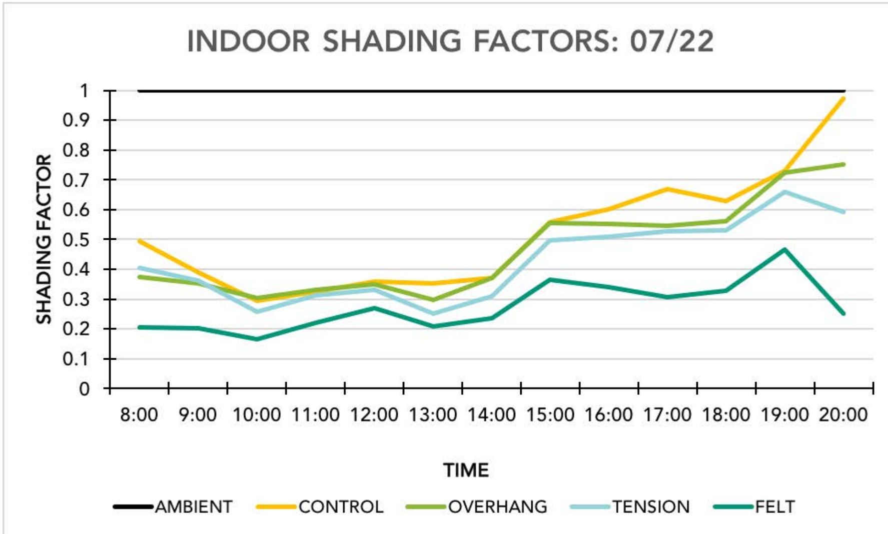


Figure 96. Hourly Indoor Shading Factors (July 22nd)

The average shading factors calculated for each façade system are given in the tables below:

Table 34. Average Outdoor Shading Factors (July 22nd)

Average Outdoor Shading Factor (07/22)				
Ambient	Control	Overhang	Tension	Felt
1.00	**0.63**	**0.48**	**0.21**	**0.07**

Table 35. Average Indoor Shading Factors (July 22nd)

Average Indoor Shading Factor (07/22)				
Ambient	Control	Overhang	Tension	Felt
1.00	**0.52**	**0.47**	**0.43**	**0.27**

Overall Results

Taking the results from the three post-installation testing days the following average results have been compiled to summarize the thermal performance of the various green façade systems.

Average Decrease in Façade Temperature

Table 36. Overall Average Decrease in Outdoor Temperature at the Façade Surface

AVERAGE DECREASE IN OUTDOOR TEMPERATURE (°F)				
	CONTROL	OVERHANG	TENSION	FELT
JULY18	---	-1.04	-0.7	-3.54
JULY 21	---	-0.49	0.04	-2.19
JULY 22	---	-0.59	0.23	-2.4
AVERAGE	---	**-0.71**	**-0.14**	**-2.71**

Table 37. Overall Average Decrease in Indoor Temperature at the Façade Surface

AVERAGE DECREASE IN INDOOR TEMPERATURE (°F)				
	CONTROL	OVERHANG	TENSION	FELT
JULY18	---	-4.82	-7.27	-7.4
JULY 21	---	-4.08	-6.83	-6.04
JULY 22	---	-3.5	-6.2	-6.07
AVERAGE	---	**-4.13**	**-6.77**	**-6.50**

While the implementation of each green façade system is effective in reducing façade surface temperatures, these average results indicate the felt system is the most successful in decreasing temperatures both indoors and out. The tension system is also effective at decreasing the surface temperature indoors but does not have as significant of an effect on the outdoor façade surface temperature.

Average Shading Factors

Table 38. Overall Average Outdoor Shading Factors

AVERAGE OUTDOOR SHADING FACTOR				
	CONTROL	OVERHANG	TENSION	FELT
JULY18	0.60	0.45	0.30	0.07
JULY 21	0.67	0.51	0.31	0.07
JULY 22	0.63	0.48	0.21	0.07
AVERAGE	**0.63**	**0.48**	**0.27**	**0.07**

Table 39. Overall Average Indoor Shading Factors

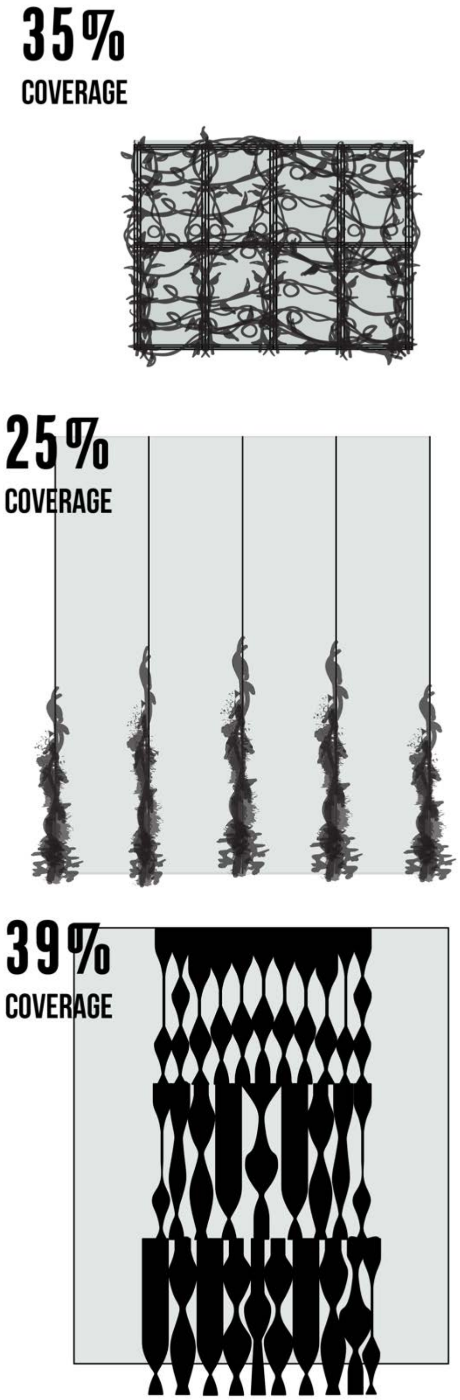
AVERAGE INDOOR SHADING FACTOR				
	CONTROL	OVERHANG	TENSION	FELT
JULY18	1.40	0.77	0.68	0.50
JULY 21	0.59	0.47	0.39	0.27
JULY 22	0.75	0.53	0.36	0.18
AVERAGE	**0.92**	**0.59**	**0.48**	**0.32**

Overall, the felt system has the greatest shading capacity, explaining its ability to also lower the surface temperatures the most out of the utilized façade systems. The tension system also exhibits significant shading capacity with the overhang system contributing the least shade overall.

Confounding Factors

Certain confounding factors exist in that the Greenhouse is not a completely sealed building and the overhang trellis affected different testing bays throughout the day.

Potential Increase of Benefits with Increased Foliage Coverage



Overhang System

At current coverage
Decrease in Surface Temperature
Outdoor: -0.71°F
Indoor: -4.13°F

At full coverage
Decrease in Surface Temperature
Outdoor: -2.03°F
Indoor: -11.8°F

Tension System

At current coverage
Decrease in Surface Temperature
Outdoor: -0.14°F
Indoor: -6.77°F

At full coverage
Decrease in Surface Temperature
Outdoor: -2.71°F
Indoor: -27.07°F

Felt System

At current coverage
Decrease in Surface Temperature
Outdoor: -2.71°F
Indoor: -6.50°F

At full coverage
Decrease in Surface Temperature
Outdoor: -6.95°F
Indoor: -16.17°F

In order to demonstrate each system's potential capacity for thermal benefits, the average decrease in temperature has been extrapolated to show the possibility for even further decreases in temperature if full foliage coverage was achieved in each system. This extrapolation reveals that the system tested in this research that is capable of the most reduction of indoor surface temperature is the tension system at approximately -27°F followed by the felt system at nearly -16°F. The felt system has the greatest capacity for outdoor surface temperature reduction at nearly -7°F with the tension and overhang systems each having approximately a 3°F and 2°F reduction capacity respectively. It is important to note that reaching full coverage with the felt system would be achieved more easily since the majority of coverage is due to the felt material not solely plant growth.

Figure 97. Potential Increase of Thermal Benefits with Increased Foliage Coverage

6.2 Agricultural Potential of Green Façade Systems

Since no significant yield could be obtained from any of the green façade systems due to having such a short period of testing; literature information and a vegetable yield calculator (http://www.ufseeds.com/Crop-Calculators.html) were used to predict the potential yield of each green façade system based on its specific configuration and growing area.

Overhang and Tension Systems

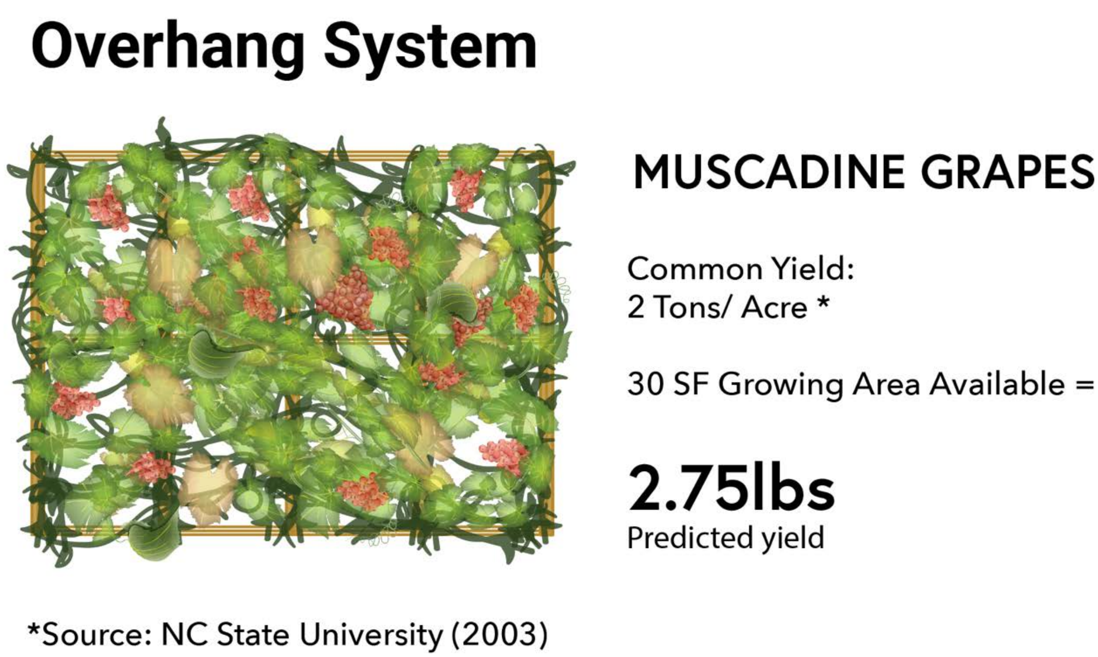


Figure 98. Potential Muscadine Grape Yield of Overhang System

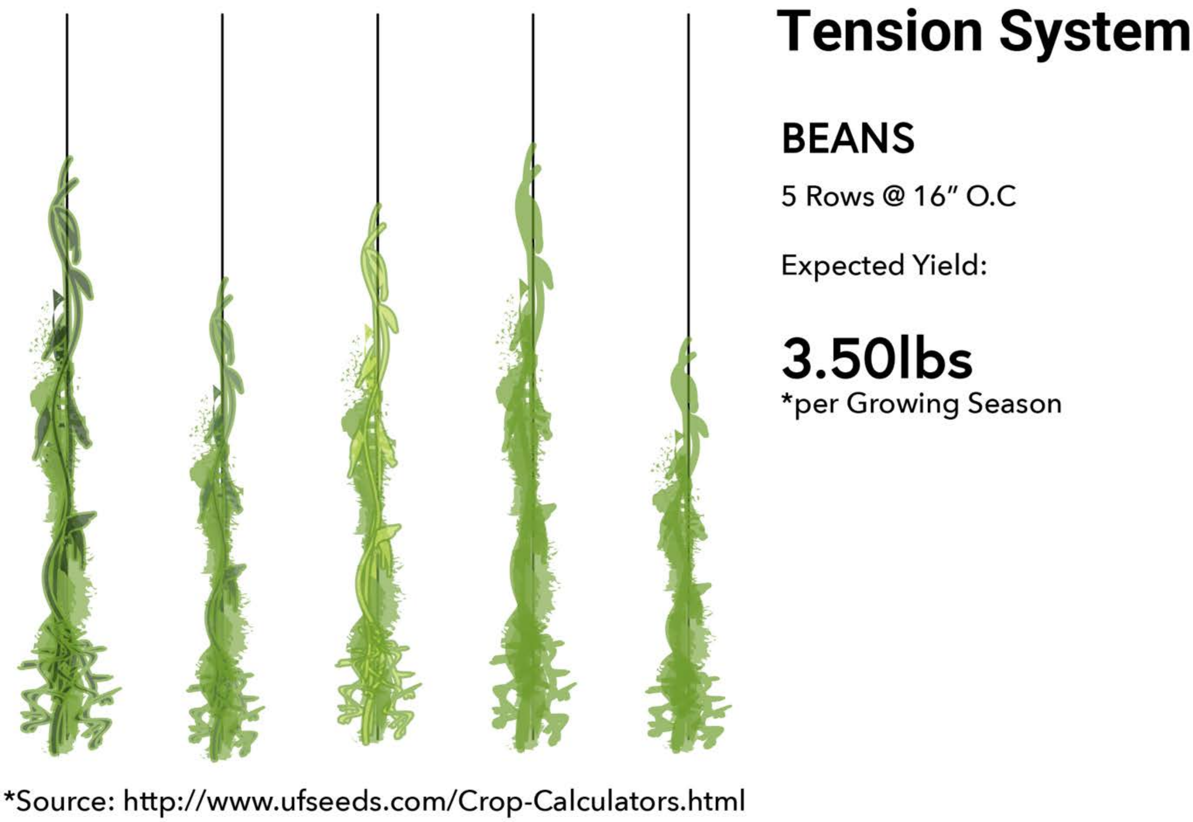


Figure 99. Potential Bean Yield of Tension System

Felt System

Since the felt system design provides more opportunity for variety of plant types several configurations of possible produce yield are presented here based on the growing season. The container size outlined in Figure 64 in Section 5.3 have been input into the vegetable yield calculator for each desired plant and the predicted yield calculated. In total the felt system utilized in this research has a total of 54 containers, or pockets, and contains just over 7 FT^3 of growing medium.

Late Spring / Early Summer

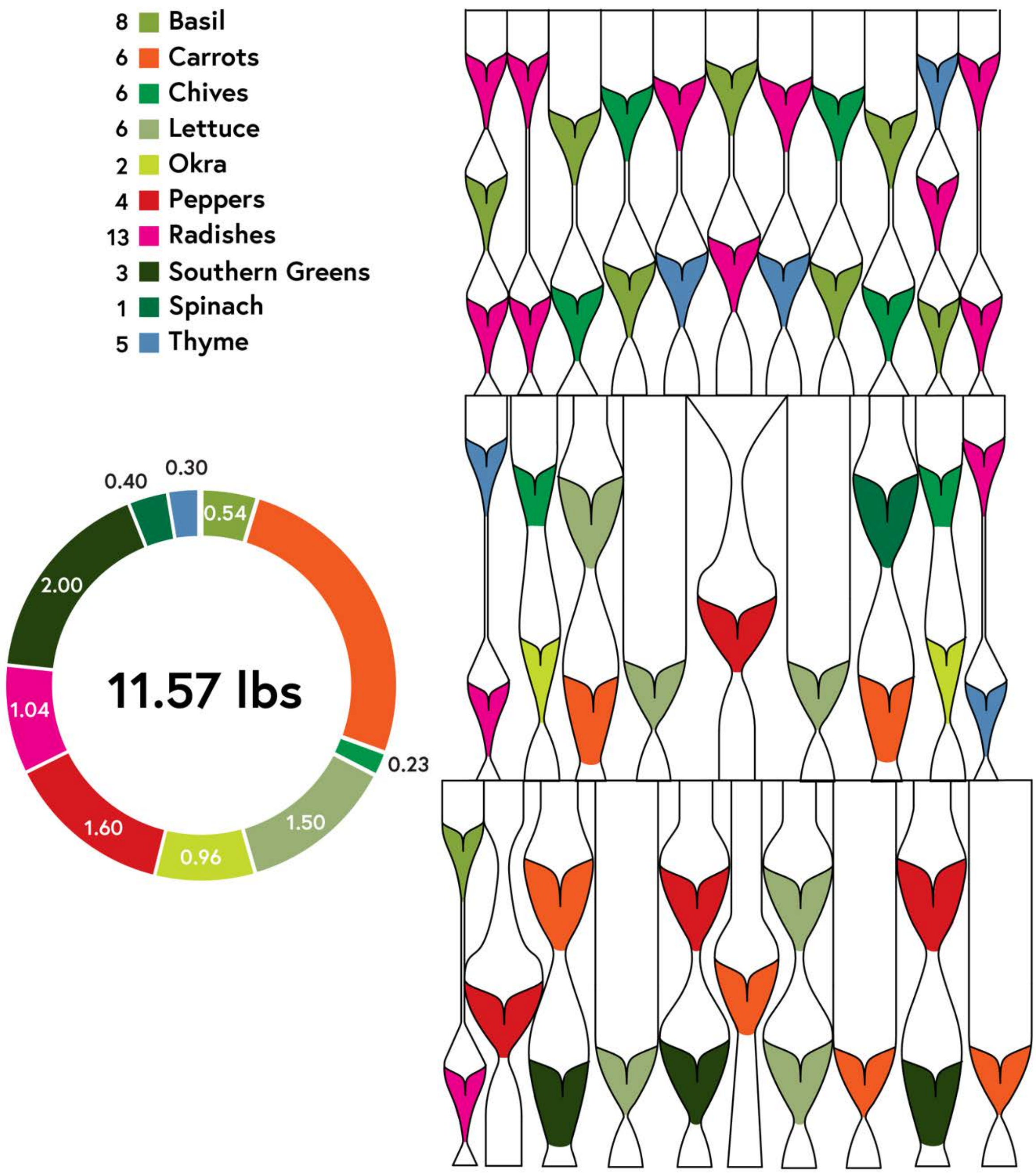


Figure 100. Potential Produce Yield for the Late Spring/Early Summer Growing Season

Full Summer

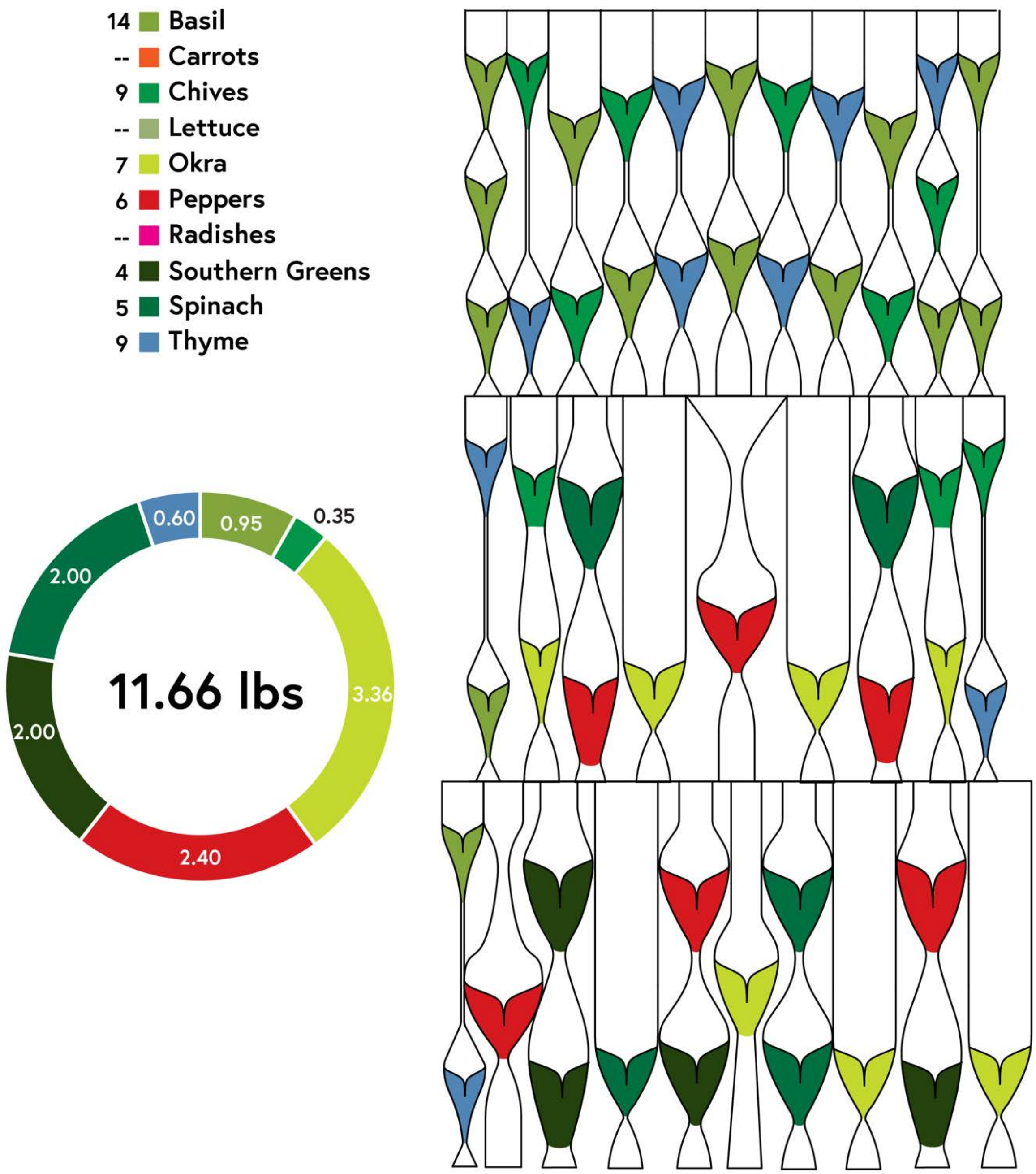


Figure 101. Potential Produce Yield for Selected Herbs and Vegetable for the Full Summer Growing Season

Late Summer / Early Fall

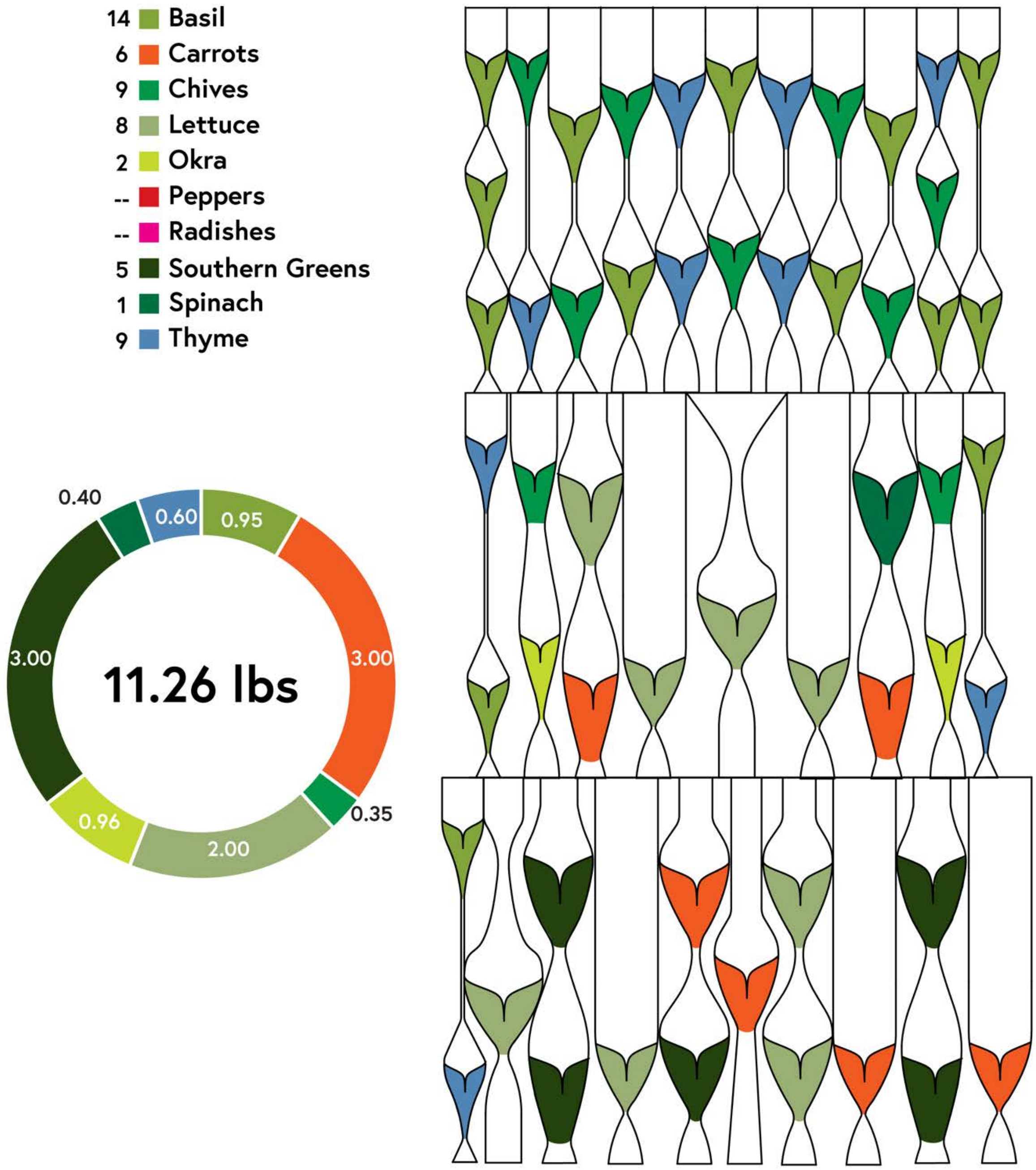


Figure 102. Potential Produce Yield for the Late Summer/Early Fall Growing Season

A summary for the potential yields from the felt season per crop and growing season are given in Table 40.

Table 40. Overview of Potential Produce Yield for the Felt System by Growing Season

	Late Spring Yield (lbs)	Summer Yield (lbs)	Fall Yield (lbs)
Basil	0.54	0.95	0.95
Carrots	3	0	3
Chives	0.23	0.35	0.35
Lettuce	1.5	0	2
Okra	0.96	3.36	0.96
Peppers	1.6	2.4	0
Radishes	1.04	0	0
Southern Greens	2	2	3
Spinach	0.4	2	0.4
Thyme	0.3	0.6	0.6
Total	**11.57**	**11.66**	**11.26**

6.3 Social Impacts

This research project at the E. 34 Greenhouse proved to be a far-reaching venture in the Savannah Community.
Figure 103 shows how various parties were connected throughout the various stages of the project.

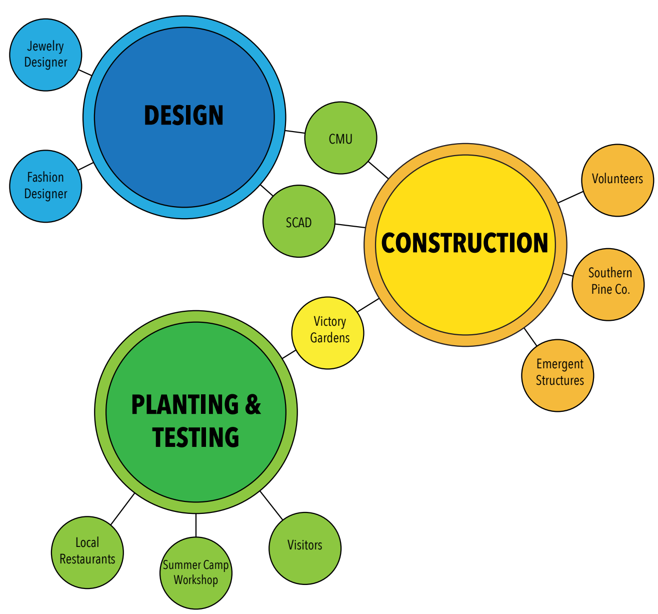


Figure 103. Social Impacts of the E. 34 Greenhouse Field Test

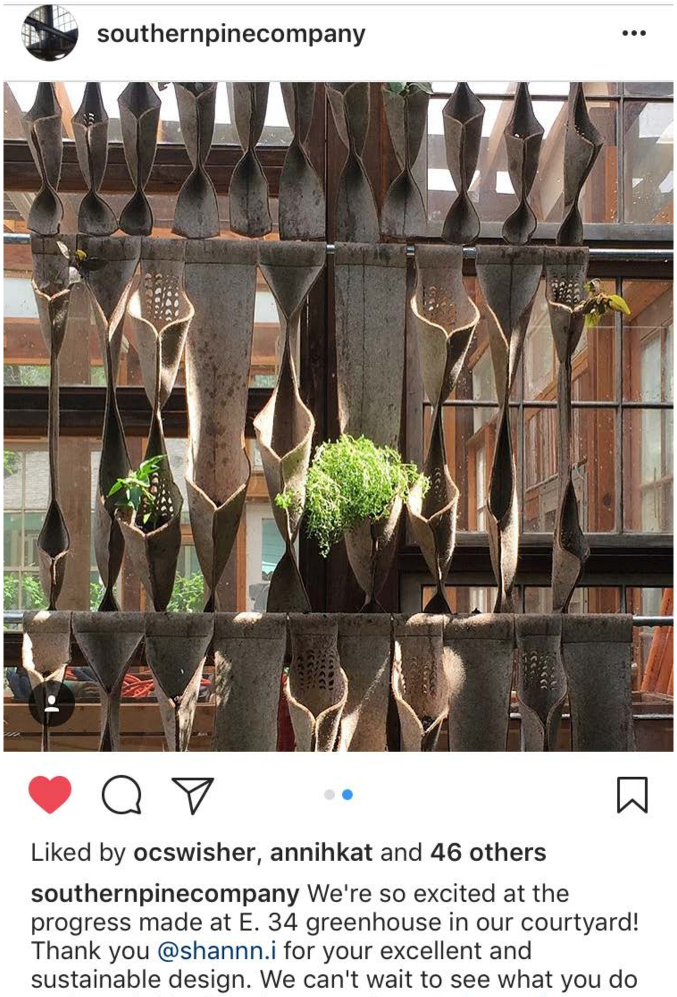


Figure 104. Instagram post from Southern Pine Company Highlighting the Green Façade Installation and Field Test

Throughout the design process several designers collaborated on the configuration and installation of the façade systems. Facilities at both Carnegie Mellon University (CMU) as well as Savannah College of Art and Design (SCAD) were used to fabricate the felt system. The Construction portion of the project was aided by Emergent Structures, a non-profit based in Savannah who currently owns the E. 34 Greenhouse and Southern Pine Company, a reclaimed lumber facility whose courtyard houses the Greenhouse. Friends and family volunteered to help in the installation of the façade systems, helping to clear and grub the site and construct the façade systems. Once the structure was in place, Victory Gardens, a local plant nursery, aided in the plant selection for the façade systems giving advice on successful species in the Southeast and providing several of the plants for installation. Once the system was in place, visitors in and around the area would stop by the Greenhouse to learn about the project. The greenhouse is located next to a local coffee shop which helped bring foot traffic into the area. Many of the patrons would see the installation and walk over to get more information. A local bar, The Alley Cat Lounge, also provides their old citrus rinds to put in the compost pile at the greenhouse, demonstrating the ability of this project to get people involved from many areas in the community.

Figure 105. Planting Felt Pockets at the Camp Wildflower Workshop

Camp Wildflower Workshop

One of the most exciting social impacts the greenhouse had on the Savannah community was in the form of a summer camp workshop I ran in late June. Camp Wildflower is an all-girl week-long summer camp that focuses on the arts and outdoors. I ran an hour-long workshop with the girls in which I presented the work I was doing at the greenhouse and then worked with the girls to create their own felt plant pockets to take home. Being able to share the work of this project with young girls and to see their interest and creativity in applying it to their own creations was a very fulfilling experience.

Figure 106. Assorted Felt Pocket Designs Made by Wildflower Campers

Each of the girls had their own unique way of approaching the design and construction of their plant pocket. They were each given a square piece of craft felt and kid scissors. We spent some time with the fabric coming up with ways to construct a pocket out of the fabric then when each girl had a design determined they cut their pattern and hot glued the seams to create a sealed pocket.

Figure 107. Wildflowers with their Planted Felt Pockets

Overall the E. 34 Greenhouse field test proved to be a project that intrigued many people throughout the community, peaking interest and those that encountered it. This highlights the ability of projects similar to this, and green façade installation in general, to provide education and interaction just by simply being in place.

Conclusion

This research project has demonstrated the benefits associated with green façade systems. Beyond the literature on the subject that currently exists, the field test at the E. 34 Greenhouse successfully demonstrated that the installation of Green Façade systems can have thermal benefits in reducing surface temperatures, agricultural benefits with the application of edible plants and societal impacts in facilitating community engagement and education. While the results from the thermal section demonstrate that all of the green façade systems utilized in the field test have a capacity to reduce surface temperature during hot summer days, the felt system has demonstrated the most capacity agricultural benefits, community engagement and education. Its design peaks people's interest and allows for more versatile plant selection. It does; however, require more maintenance and more frequent watering than the other two systems. Ultimately, the selection of green façade system is a personal preference and must take into account the many factors discussed in this research; however, it is the recommendation of this research that a felt based container based system, similar to the one utilized at E. 34 Greenhouse, provides the most holistic benefits.

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