ABSTRACT

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Rising energy costs and a warming climate create the need for innovative, low-carbon technologies that help cool buildings. We constructed four small buildings and instrumented them to measure the cooling effect of a green façade on their south and west walls. The green façade significantly reduced the temperature of the building's ambient air, exterior surface, and interior air, and the heat flux through the vegetated wall. Using a mathematical model, we determined that the whole-building cooling load reduction (1.4 to 28.4%) depended on building construction, green façade placement, and especially whether the windows were covered. An emergy analysis of a south-facing green façade revealed that the total emergy consumed could be balanced by the electricity saved from reduced air conditioning if the cooling load was reduced by at least 14%. With thoughtful design and placement of a green façade it can sustainably and effectively help cool buildings.

# GREEN FAÇADE ENERGETICS

By

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# Dedication

I would like to dedicate this thesis to my grandmother, Donna Cooper, who taught me the value of hard work, to be curious about the world around me, and to always ask questions.

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# Chapter 1: Introduction

Between 1980 and 2001, the number of U.S. households with central air conditioning increased from 27 to 55 percent ("South Atlantic…" 2006). They consumed 183 billion kWh of electricity for air conditioning in 2001, comprising 16% of their total electricity consumption ("South Atlantic…" 2006). With rising energy costs and a warming climate, there is an increased need for innovative, low-carbon technologies that help cool buildings. Research done in the U.S. has shown increases in summertime urban air temperatures due to the urban heat island effect of between 0.5°C – 3.0°C. Much of this may be mitigated by the addition of living vegetation and high-albedo surfaces (Akbari et al. 2001). British meteorologist Luke Howard first observed and documented the urban heat island effect in *The Climate of London* (1818). In his original publication, he outlined the three main differences between the city and countryside: the city has a more complicated geometry of many vertical surfaces, buildings impede wind circulation, and the city lacks a store of moisture available for evaporation and hence energy dissipation (Howard 1818). Strategies to mitigate the urban heat island effect include reducing energy consumption of buildings, cars, and other heat dissipating entities within the city, changing the albedo of the urban surfaces, and incorporating vegetation into the built environment.

Research on the incorporation of vegetation into the urban environment has shown positive results not just in terms of urban heat island effect mitigation, but also in reducing air pollution, improving quality of life, and mitigating stormwater runoff. Researchers in Toronto (Currie and Bass 2008) used the Urban Forest Effects Model (UFORE; developed by the US Forest Service) to estimate air pollution retention in an urban area under various vegetative scenarios. They found that trees are very effective at removing airborne pollutants and that the installation of green roofs on all downtown buildings would significantly enhance that removal. Experimentally, Thoennessen (2002) in Germany found high rates of air pollution deposition and retention on Boston ivy-vegetated green façades, particularly in the first meter above street-level. Ulrich (1984) found that patients with a window view of a natural scene versus a brick wall healed faster, took fewer potent analgesics, and received fewer negative evaluative comments in nurse's notes. While researchers have found green roofs to reduce total stormwater runoff by approximately 50% (Dunnett and Kingsbury 2008), a small-scale experiment by Schumann (2007) as well as modeling work done by Roehr et al. (2008) showed potential reductions in stormwater runoff from green façade systems as well.

Growing vegetation on building walls has potential to positively affect the urban environment, primarily because in most instances, there are four walls to every roof. A green façade is a trellis system for supporting climbing plants most commonly on building walls or other man-made structures. In most instances, the plants are rooted in the ground or in planter boxes at ground level.

**Green Façade Research**

Köhler (2008) published an article that summarized the history of and current and ongoing research efforts on green façades in Germany. He stated that over 770 articles had been published on green façades. Most of the articles were published in the 1980s and 1990s, when many green façades were installed in Germany.

In North America, green walls are one of the fastest growing green building technologies being installed today. Green Roofs for Healthy Cities, a non-profit industry association representing North America was founded as a direct result of a research project entitled *Greenbacks from green roofs* by Peck et al. (1999). While the majority of the paper outlined the history, benefits, and barriers to a flourishing green roof industry in Canada, there was also discussion on green walls. There was little detail on the thermal benefits of green walls in the paper. This, in part, stems from the uncertainty of research data on the topic. The technology has a significantly longer modern history in Central Europe and the vast majority of published papers are not available in English.

Peck et al. (1999) were able to find and cite one resource that is particularly relevant. Gaudet (1985) published an article in *Harrowsmith* magazine entitled "Sunspots: landscaping for energy efficiency." It is from this source that Peck et al. (1999) drew the following data; "…every degree (F) of summer heat requires an additional 5-7% of cooling energy. Hence, a 10 F reduction in the outside air temperature achieved through the judicious arrangement of shade trees (green roofs and vertical gardens), can reduce energy consumption for air-conditioning by 50-70%."

Dunnett and Kingbury (2008) cited the Peck et al. (1999) article numerous times in their book about planting green roofs and living walls. This book has made its way into mainstream media and has perhaps become the most popular source for information on the technologies, certainly one of the few on green façades. The authors in this case again presented the data on potential energy saved by the technology (50-70%). Unfortunately, these data come from books that are out-of-print so it is hard to know if the numbers were actually found through peer-reviewed researched or research at all. Because of these types of references, more thorough and citable research needs to be made available to industry.

Hoyano (1988) published an article in English that summarizes research that had only been published in Japanese. The study consisted of measuring thermal parameters through the west ivy-covered wall of a residential home near Tokyo.

He first measured the solar transmittance through green façades covered in Japanese ivy (assumed to be *Parthenocissus tricuspidata*) at numerous sites around Tokyo and found the mean to be 2-7%. In other words, only 2-7% of the energy reaching the top of the plant canopy was transmitted to the underside of the canopy and subsequently reached the building exterior. He also found a strong inverse correlation between canopy thickness and transmittance and also between leaf area index (LAI) and transmittance. Plant canopy thickness ranged from 15-35 cm while LAI ranged from 2-4.5. The ivy-covered wall at the home where the rest of the study was conducted was considered to have an average plant canopy. Similar plant canopy growth was observed on dilapidated tobacco barns in Southern Maryland (Schumann 2007).

Using measured temperatures of the interior and exterior wall surfaces, Hoyano calculated heat flow on the interior and exterior surface of the wall. He found a maximum of 232 W $m^{-2}$ entering the bare wall and that the ivy covering reduced that by 75% down to around 58 $Wm^{-2}$. He also found that the ivy reduced the heat flux from the interior surface to the interior air to around zero and concluded that the ivy layer mostly eliminated the influence of solar radiation on the indoor environment.

Finally, he calculated what he called the equivalent shading coefficient. It was defined as the ratio of the incident solar radiation on the wall to the heat flux at the exterior surface. The ratio ranged between 6-16% when the weather was clear. He also states that a transmittance of 5% corresponded to an equivalent shading coefficient of

12% (Hoyano 1988). While this study was comprehensive, it dealt with only one building and one green façade in one part of the world. More intensive, experimental research in North America is needed to compare and hopefully confirm his results.

The following year, Holm (1989) published an article summarizing his work on green façades in South Africa. In the first part of the study, he looked at thermal properties of plant leaves. Using relatively simple calculations, he found that a single plant layer should transmit 12.8%, while two leaf layers would transmit around 5% of the incident solar energy. He also stated that the spectral and thermal properties of the five species he tested were no different beyond a canopy thickness of 20cm. Leaf transmittance and canopy characteristics are important in modeling heat transfer reduction and will be looked at more thoroughly in the following chapters.

Holm's main conclusion was that green façades are most effective when placed on the equator-facing wall of a low thermal mass building in a hot-arid climate. A passive building of this type in this climate would experience 4 K lower maximum indoor air temperatures during the day and 1 K higher minimum indoor air temperatures. One factor omitted from all modeling in his research was the effect of transpiration.

Di and Wang (1999) published an article entitled *Cooling effect of ivy on a wall*. In this study, they were able to show a 28% reduction in peak cooling load through the west-facing wall of a large brick building. They also found that the leaf layer insulated the building wall at night thereby increasing the nighttime temperature of that wall. And finally, they found the cooling effect to be much greater in July and August versus June, when the outdoor temperature was much higher. During June the green façade may have actually increased the building interior temperature. While this article was also quite comprehensive, there was still no experimental replication, and it took place in Beijing.

Stec, Van Paassen, and Maziarz published an article on green façades entitled *Modelling the double skin façade with plants* in 2005. A double skin façade is a glass layer placed outside the building exterior to add insulation and create a ventilated cavity that may contain shading devices to block solar insolation during the cooling season. The researchers compared the effect of the blinds, the shading device typically used, to live plants. They found the cavity air temperature to be lower in the cavity with plants than with blinds. They also concluded that the building's cooling load was reduced by nearly 20% and expected a similar reduction in energy consumption by the cooling system.

Laura Schumann (2007) published her thesis on 'Green Cloaks,' an innovative green roof retrofit technology that utilized a lightweight frame with vines growing on it suspended over the roof and walls of a building. She found that the green cloak reduced the peak indoor air temperature of a small-scale un-cooled building in July by 11.3 °C saving an estimated 73% in cooling energy costs. Further, for every one point increase in LAI the building's indoor temperature was reduced by 1 °C. Finally, she measured plant canopy characteristics on dilapidated barns in Southern Maryland, USA and found a mean LAI of 3.14 and canopy thickness of 70 cm.

Alexandri and Jones (2008) modeled the effect of green walls and roofs on the urban canyon. Using rudimentary equations, they calculated cooling load reductions due to both technologies and just green walls alone in cities across the globe. Their reductions, however, were simply calculated from reduced urban canyon air temperatures and cannot be directly compared to other papers on the topic. One interesting conclusion they made was that adding vegetation to cool an urban area was more effective the hotter and drier the climate was, though still effective in humid areas, which reinforced the modeling work done by Holm (1989). Cooling load reduction of the buildings within the canyon ranged from 35% to 68%.

In the article entitled *Energy simulation of vertical greenery systems*, Wong et al. (2009) explore the thermal effects of green façades on a hypothetical 10-story building in Singapore. They completed a number of simulations looking at the effect of the greenery on the interior mean radiant temperature (MRT), and then through the model, applied that to cooling load energy reduction. Under scenario one, the building was made entirely of opaque surfaces (i.e. no windows). After being entirely covered (i.e., roof + walls) in vegetation they observed a 74% reduction in energy use for cooling. For scenario two the building had windows on each level of the building while only the opaque surfaces were covered with vegetation. Under this scenario, the effect was much less pronounced at 10% reduction in cooling load. Under the final MRT scenario, all building façades had windows and were subsequently covered with 50% vegetation for one simulation and then 100% for the second. Here, the cooling load was reduced by 12% and 32%, respectively. The major limitations to this study were that they modeled only one building shape and did not incorporate any experimental data. Also, the modeling was performed for a building in a tropical climate.

Two recent papers have come from an engineering lab in Greece. Both address the cooling effect of climbing plants on both passive and climate-controlled buildings in the northern Mediterranean. In the first paper (Eumorfopoulou and Kontoleon 2009), they showed significant reductions in both exterior and interior building surface temperatures when they added a layer of Boston Ivy to the east wall of a passive building. On many days in July and August, they found the vegetation reduced exterior wall temperatures by around 6-8 °C and the interior wall surface temperature by about 1 °C. They also calculated daily mean heat flow into the building interior air. While the bare wall section allowed on average between 4 and 13 W $m^{-2}$ into the building interior air, the vegetated wall averaged -1 to -11 W $m^{-2}$. This means that the green façade converted the east wall in this experiment, on average, from a source of heat to a flow-path for heat dissipation. Results from this study are similar to Hoyano (1988) where he found the vegetation to eliminate the covered building wall as a heat source. Unfortunately, there was still no experimental replication in the study and it took place in a Mediterranean climate.

A second paper by Kontoleon and Eumorfopoulou (2010) was quite similar and probably came out of the same thesis. In this, they assembled a model to address the above variables on a simple climate-controlled building. The major findings were that the exterior surface temperature was reduced highest to lowest in the following order: west > east > south > north. For their windowless cubical building, they found that completely covering the west wall in vegetation reduced the cooling load by 20%, and for the other walls: 18%, 8%, and 5% for the east, south, and north walls, respectively. This study and the Wong et al. (2009) study were the only two I could find that discussed the effect of green façade vegetation on the cooling load of the whole building. Unfortunately, neither study was performed in North America and neither investigated residential buildings.

Wong et al. (2010) discussed an experimental approach to investigating the thermal benefits of what they call 'vertical greenery systems.' In this experiment, they placed 8 different types of green walls each in front of their own concrete wall in a park in

Singapore. The predominant results they showed were surface temperature reductions of the concrete wall behind each green wall. All but one of the green walls were living walls, with small compartments of soil at elevation and plants rooted into the wall's medium. The vine-based green façade cooled the concrete the least out of all 8 systems showing at most a 4.35°C reduction while the best living wall system reduced the concrete wall temperature by 11.58 °C. These results only reinforce what had been reported before, but although they are specific to that climate, the numbers match other studies reasonably well (Hoyano 1988, Di and Wang 1999, Eumorfopoulou and Kontoleon 2009).

Ip, Lam, and Miller (2010) performed an experiment to describe the *Shading performance of a deciduous climbing plant canopy*. They grew Virginia creeper (*Parthenocissus quinquefolia*) on small trellises in front of a building's southwest windows in South Britain and measured the incident and transmitted solar radiation extensively. The main goal of the paper was to define what they call the 'Bioshading Coefficient,' which was simply a ratio of the transmitted solar irradiance over the solar irradiance above the canopy. They found that a leaf area index of 5 resulted in a Bioshading Coefficient of 12%. Wong et al. (2010) used 10% transmittance in their model but this was not nearly as low as others (Hoyano 1988, Holm 1989) have found, especially for an LAI of 5.

Based on this comprehensive review of the literature on the thermal performance of green façades, no studies have been conducted in North America nor have any simulated a North American climate. Given the prospects of incorporating green façades into North American buildings and the lack of geographically-focused research, there is a strong need for research to be performed in the temperate climate of North America, using adapted plants in typical installations to understand the thermal effects of a green façade.

In addition, only two studies (Wong et al. 2009, Kontoleon and Eumorfopoulou 2010) considered the effects of vegetation on the energy budget of the whole building. In other studies (Hoyano 1988, Di and Wang 1999, Peck et al. 1999 (research summarized), Eumorfopoulou and Kontoleon 2009) researchers simply determined the reduction in heat flux through the wall covered with vegetation.

**Objectives**

1. Determine the cooling effect of a green façade on the building's ambient environment, exterior wall surface, interior air, and heat flux to the interior air.
2. Build a cooling load model to translate the heat flux reduction of one building wall due to a green façade to the whole-building cooling load.
3. Determine the environmental benefits and embodied energy consumption required to manufacture, install, maintain, and decommission a green façade over its lifetime.

**Plan of Study**

1. To determine the cooling effect of a green façade, we constructed four small-scale wood-framed buildings with multiple-species green façades and measured temperature and other environmental conditions extensively through the 2010 growing season.

2. To determine the effect of a green façade on the whole-building cooling load, we used an ASHRAE cooling load model under several scenarios. First we simulated our own experimental buildings using real data. Then we modeled whole-building cooling load reduction under several scenarios on two hypothetical residential buildings.
3. To determine the environmental benefits and embodied energy consumed in the lifetime of a green façade, we completed an emergy analysis of a green façade on a hypothetical residential home in College Park, MD, USA.

## Chapter 2: Cooling effects of a green façade

Living vegetation that covers building walls reduces solar radiant heating during the summer decreasing mechanical cooling demand, electricity consumption, and greenhouse gas emissions (Peck et al. 1999). Other significant benefits to adding vegetation include: slowing storm runoff (Tilley and Schumann 2008), creating urban wildlife habitat (Lundholm 2006), lowering environmental noise (Kohler 2008), improving air quality (Currie and Bass 2008), and mitigating the urban heat island effect (Bass 2001). Green façades predominantly affect the thermal environment of buildings by shading them. In addition to this, they act as an insulating layer for the building wall increasing its R-value by trapping a pocket of air between the vegetation and building wall, as a radiant barrier attenuating radiant heat loss at night, and as a physical obstacle impeding air flow across the building wall surface limiting convective heat exchange with the ambient environment. Much of the solar energy absorbed by the plant and its leaves can be lost through transpiration as latent energy. This solar energy dissipation pathway is very important to maintaining a comfortable ambient environment and is often missing or severely reduced in urban environments. The lack of this cooling mechanism and the enormous solar heat storage of man-made building materials ubiquitous in urban environments (such as concrete) are the primary causes of the urban heat island effect.

Several studies to date have documented the cooling effects of a green façade. A mature Boston Ivy canopy attached to the west-facing wall of a building near Tokyo reduced the exterior wall surface temperature by 18 °C and the daily heat flux into the building's interior to nearly zero, which eliminated the west wall as a heat source (Hoyano 1988). A thick canopy of English Ivy attached to the west wall of a large brick building in Beijing reduced the exterior surface temperature by 18 °C and the peak heat flux into the building's interior by 28% (Di and Wang 1999). In a experiment, Eumorfopoulou and Kontoleon (2009) determined that a thick layer of Boston Ivy cooled the exterior surface of a multi-story building on average by 5.7 °C and to a daily maximum of 8.3 °C. The un-vegetated wall allowed between 4 and 13 W $m^{-2}$ of heat into the building interior while the vegetated wall allowed between 1 and 11 W $m^{-2}$ to leave the building. Thus, adding a green façade changed the east wall of the building from a source of heat into a pathway for interior air heat dissipation to the exterior.

**Objectives**

The aims of this study were to experimentally measure the effect of a green façade on the 1) building interior air temperature, 2) building exterior surface temperature, 3) building ambient air temperature, and 4) heat flux into the building interior air. We constructed four small wooden buildings and placed green façades with commercially available trellises and a mix of plant species on two of them, the other two serving as control buildings, to measure the cooling effects of adding vegetation to a building's exterior wall.

**Methods**

<u>Experimental Building Construction</u>

Four buildings of dimensions 2.5 meters (8ft) long by 2.5 meters (8ft) wide by 3.5 meters (11ft) high were constructed and placed on a concrete pad at the University of Maryland Central Research and Education Center in Clarksville, MD (approx. 30km north of Washington, D.C.) on July 8th, 2009. The buildings consisted of a 4-sided square-hip 4/12-pitch roof with three-tab charcoal asphalt shingles (GAF Materials Corporation) and 5cm x 15cm (2x6 in.) wood rafters, a ceiling hung from 5cm x 10cm (2x4 in.) joists, 5cm x 10cm (2x4 in.) wood framed walls, and a 5cm x 15cm (2x6 in.) wood floor all at a 40cm (16 in.) center spacing. R-13 fiberglass insulation (CertainTeed Corporation), 9cm (3-1/2 in.) thick, was installed on the ceiling, walls and floor. The interior walls and ceiling were covered with 1.6 cm (5/8 in.) thick gypsum drywall. The buildings were wrapped in a vapor barrier material (Dupont Tyvek HomeWrap) and then sided with Georgia-Pacific T1-11 1.5cm (19/32 in.) thick pine wood siding. The buildings were spray painted blue-grey slate (Glidden Premium Latex Exterior Paint-Flat) in May 2010 for the growing season (Figure 1). The buildings had no windows and a single door was installed on the wall opposite the vegetation. The buildings were neither cooled nor heated during any part of the experiment. Thermal resistances (R-values) of each building surface are summarized in Table 1.

**Figure 1.** Vegetated experimental buildings with west-facing green façades mid-summer 2010.

**Table 1.** Because the instrumentation was fixed on one wall, each building was rotated 90° to switch the vegetated wall from south to west and back. The instrumented wall was built opposite the wall with the door.

| Building Surface | Composite R-Value, $m^2\,K\,W^{-1}$ ($ft^2\,°F\,h\,Btu^{-1}$) |
|---|---|
| Walls without door | 2.27 (12.9) |
| Wall with door | 1.72 (9.77) |
| Roof | 3.21 (18.2) |
| Floor | 2.45 (13.9) |

Green Façade Construction

Sixteen 1.25m wide by 2.5m tall (4 x 8 ft) green façades were constructed for the experiment. Twelve of the façades were constructed with a wood frame made from 5cm x 10cm (2x4 in.) boards and either a commercially available trellis system (Carl Stahl—DecorCable Innovations, LLC or Jakob-USA) or a trellis made from 3/4-inch manila rope designed and built in our lab. The other four green façades were rigid panels (**green**screen). Two of these green façades covered an entire wall of the experimental buildings. At all times, the non-vegetated control buildings had just the wood frame component of the green façade on their instrumented wall. We mounted the green façades to wood frames and potted them to reserve the flexibility of applying various treatments and types of green façades in the experiment. In real-world installations, the wood frames are not present, so we accounted for their effects by placing them on the non-vegetated control buildings as well.

The commercially available green façades were covered with a mix of nine climbing plant species adapted to the United States Mid-Atlantic region (Richter-110 grapevine (*Vitis berlandieri x V. rupestris)*; Paulson 1103 grapevine (*Vitis berlandieri x V. rupestris)*; Dogridge grapevine (*Vitis champini)*; Crossvine (*Bignonia capreolata)*; Coral Honeysuckle (*Lonicera sempervirens*); Carolina Jessamine (*Gelsemium sempervirens*); American Bittersweet (*Celastrus scandens*); American Wisteria (*Wisteria frutescens*); and Purple Passionflower (*Passiflora incarnata*). These plants were placed under their corresponding façade in early January 2010 and grown in the UM Research Greenhouse until they were moved to Clarksville in May 2010. One of each type of commercially available green façade served as a control and was not vegetated. Three Riparia Gloire (*Vitis riparia*) plants were placed under each manila rope green façade in March 2010 and grown in the greenhouse until being placed outside in May (Figure 2).

The plants for the nine-species mix were potted in 6-liter (1.5-gallon) plastic pots in a hand-mixed medium. The medium consisted of equal parts Leafgro compost (Maryland Environmental Service, Millersville, MD), Fafard topsoil (Conrad Fafard, Inc., Agawam, MA), and all-purpose sand. The Riparia Gloire plants for the manila rope façades were potted in the same medium but in 12-liter (3-gallon) plastic pots. See Figure 3 for a diagram of the green façade planting scheme. While in the greenhouse during the winter and spring, all plants were irrigated as needed to maintain a moist growing medium. Outside at Clarksville, during the experiment, the plants were irrigated every eight hours for 30 minutes starting at each day at 4am. The irrigation system consisted of a Vigoro Electronic AquaTimer (Melnor, Inc., Winchester, VA) and soaker hose (Teknor Apex Company, Pawtucket, RI) sections suspended over the pots at the base of each green façade. Under these conditions, each plant received nearly 3 liters (95 ounces) of water per day. Excess irrigation water was allowed to drain from the bottom of each pot.

**Figure 2.** The green façades growing in the UM Research Greenhouse in mid-March 2010. Supplemental lighting was provided during the early morning and late evening to effectively extend the day length to 16 hours and encourage faster growth.

| Wall Type | Carl Stahl | **green**screen | Jakob-USA | Manila Rope |
|---|---|---|---|---|
| Vegetation | Nine-species | Nine-species | Nine-species | Riparia Gloire |
| | Nine-species | Nine-species | Nine-species | Riparia Gloire |
| | Nine-species | Nine-species | Nine-species | Riparia Gloire |
| | None-Control | None-Control | None-Control | Riparia Gloire |

**Figure 3.** There were a total of sixteen green façades. Three, one of each commercial product, remained un-vegetated to serve as controls.

Thermal Instrumentation and Data Collection

A single wall of each building was outfitted with instrumentation to gather continuous measurement of temperatures, including those to calculate heat flux, and solar irradiance. A CS300 silicon pyranometer (Campbell Scientific, Inc., Logan, UT, 300-1000nm) measured solar irradiance on the instrumented wall. Interior temperature was measured with three evenly spaced, thermistors (#44006, Omega Engineering, Inc., Stamford, CT) mounted vertically on a column located in the center of each building. Each instrumented wall had three horizontal profiles of thermistors (Figure 4) arranged in a diagonal pattern across the wall (Figure 5). Exterior surface temperature referred to measurements from thermistors mounted directly to the exterior wall surfaces, which were painted to match the building exterior color. Building ambient air temperature sensors referred to measurements from shaded but open-air thermistors that were mounted approximately 10 cm from the building surface, or in the case of the buildings with a green façade, 10 cm above the plant layer surface. A CR1000 data logger (Campbell Scientific, Inc., Logan, UT) controlled the sensors and logged their data every 10 minutes during the experimental period. All sensors in each building were connected to an AM16/32B multiplexer (Campbell Scientific, Inc., Logan, UT) and each multiplexer was connected to the datalogger located in one of the experimental buildings. A 12-Volt RV/Marine deep-cycle battery (Interstate Batteries, Dallas, TX) powered the instrumentation and data-logging system.

Soil Moisture Measurements

Soil moisture data from a single *Vitis riparia* plant were logged every 10 minutes

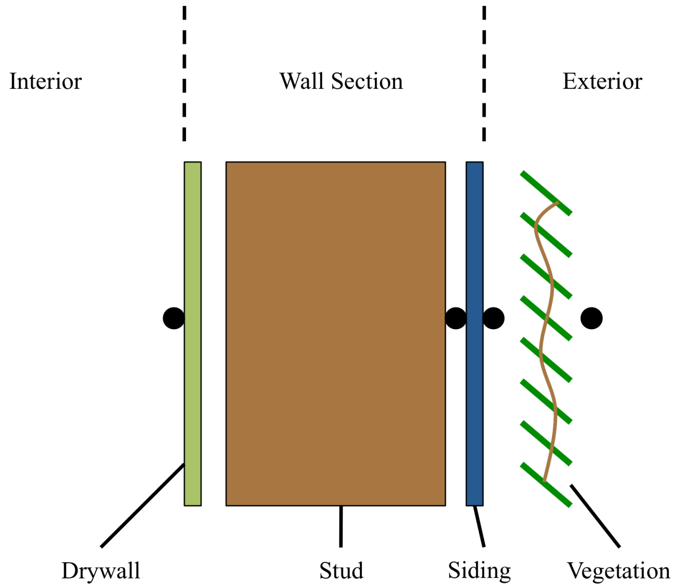



**Figure 4.** Cross-section diagram of the sensor layout. This profile of thermistors was installed in three locations across the surface of the wall to calculate a representative mean temperature for each of the measurements.

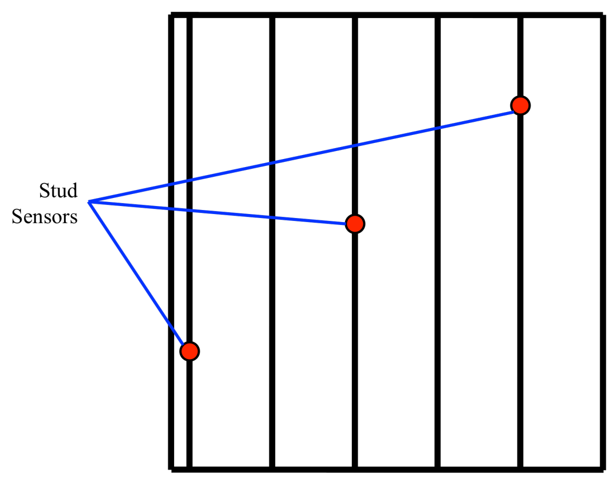



**Figure 5.** Approximate locations of each profile of thermistors as they were installed in the experimental buildings. The black lines represent a drawing of the wall framing including the studs, header, and footer.

during the experimental period using a CS616 Water Content Reflectometer (Campbell Scientific, Inc., Logan, UT) and were used to calculate evapotranspiration. We were limited to a single pot due to financial constraints and chose to measure a *Vitis riparia* plant because we assumed it would grow to represent a large portion of its green façade. Also, it remained in-place for the duration of the experiment giving us a constant measurement and way to compare data through the season. The instrument output data as percent water content. We multiplied the water content by the volume of the pot to get the mass of water and calculated ET using the following equation:

$$ET = \frac{m_w * H_w}{A}$$

where the mass of water, $m_w$ (kg), was multiplied by the enthalpy of vaporization of water, $H_w$ (kJ $kg^{-1}$), and divided by the area of the wall that the plant covered, $A$ ($m^2$). We used the change in water mass over the previous hour as the input for the current data point. The ET curves were interpolated to smooth over the irrigation events that occurred at 4:00am, 12:00pm, and 8:00pm each day.

<u>Plant Growth Measurements</u>

Growth measurements were taken on the green façades through the duration of the experiment. Leaf area index was measured at six evenly spaced points on each wall using a thin 12 mm (0.5 inch) PVC pipe. We counted the number of contacts the vegetation had with the pipe after being inserted perpendicularly into the plant canopy at each measurement point. The value recorded for each façade was taken as the mean of these six measurements. Percent plant cover was calculated digitally from a photograph of the shadow projected by each wall. We tilted each façade perpendicular to the sun to project a shadow of the leaf cover onto the ground (Figure 6). This photograph was then processed in Adobe Photoshop (Adobe Systems Inc., San Jose, CA) using the threshold function, which converted the image to black and white, and a pixel count calculated percent leaf cover.

**Figure 6.** Shadow projected by the green façade. The area within the wood frame was cropped and processed in Adobe Photoshop to estimate percent cover.

Experiment Duration

The experiment took place from May 25th to July 12th, 2010. The instrumented and vegetated wall faced south for the first half of the experiment and then the buildings were rotated on June 18th such that the vegetation and instrumented wall faced west. Every third day, a randomly chosen green façade was placed on a randomly chosen vegetated building. The other half of the instrumented building wall was covered by one manila green façade for the duration of the experiment. Each green façade type received four rotations of 3-days each (Figure 7).

| | | | | | | |
|---|---|---|---|---|---|---|
| **May** | | | | | | |
| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
| 23rd | 24th | 25th | 26th | 27th | 28th | 29th |
| | | greenscreen South | greenscreen South | greenscreen South | CarlStahl South | CarlStahl South |
| 30th | 31st | | | | | |
| CarlStahl South | Manila South | | | | | |
| | | | | | | |
| **June** | | | | | | |
| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
| | | 1st | 2nd | 3rd | 4th | 5th |
| | | Manila South | Manila South | Jakob South | Jakob South | Jakob South |
| 6th | 7th | 8th | 9th | 10th | 11th | 12th |
| greenscreen South | greenscreen South | greenscreen South | Manila South | Manila South | Manila South | Jakob South |
| 13th | 14th | 15th | 16th | 17th | 18th | 19th |
| Jakob South | Jakob South | CarlStahl South | CarlStahl South | CarlStahl South | Switch orientation | Jakob West |
| 20th | 21st | 22nd | 23rd | 24th | 25th | 26th |
| Jakob West | Jakob West | Manila West | Manila West | Manila West | CarlStahl West | CarlStahl West |
| 27th | 28th | 29th | 30th | | | |
| CarlStahl West | greenscreen West | greenscreen West | greenscreen West | | | |
| | | | | | | |
| **July** | | | | | | |
| Sunday | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday |
| | | | | 1st | 2nd | 3rd |
| | | | | CarlStahl West | CarlStahl West | CarlStahl West |
| 4th | 5th | 6th | 7th | 8th | 9th | 10th |
| greenscreen West | greenscreen West | greenscreen West | Manila West | Manila West | Manila West | Jakob West |
| 11th | 12th | 13th | 14th | 15th | 16th | 17th |
| Jakob West | Jakob West | | | | | |

**Figure 7.** Green façade rotation schedule. On June 18th, the buildings were rotated 90° clockwise such that for the second half of the experiment, the green façades and instrumented walls faced west.

Data Analysis

The effect of the green façade on the building's interior air temperature, exterior surface temperature, ambient air temperature, and heat gain on the interior air were all analyzed on a 24-hour basis. The effect of the green façade on these variables was based on the mean difference between the control buildings and the vegetated buildings.

We categorized each day during the experimental period as sunny or cloudy and as hot or cool, giving four possible classifications. The mean value of either the outdoor temperature or solar radiation for the day served as the threshold for whether the day was hot or cool and sunny or cloudy, respectively. We analyzed the effects of the green façade only when the weather was classified as either hot, sunny or cool, cloudy. Evapotranspiration data were analyzed only for hot, sunny days.

Interior air temperature difference was calculated as the mean of six interior temperature sensors, three from each control building subtracted from the six from the vegetated buildings. Likewise, the exterior surface temperature difference was calculated as the mean of the six exterior wall surface sensors from the control buildings subtracted from the six on the vegetated buildings. Heat flux to the interior air was calculated using the mean of the interior air temperature and the interior wall surface temperature of the instrumented wall using the following equation:

$$q = h * (T_s - T_i) + \varepsilon\sigma * (T_s^4 - T_i^4)$$

Where the heat flux (q) in W $m^{-2}$ was equal to the sum of the convective and radiative energy exchange between the interior wall surface ($T_s$) and interior air ($T_i$), both in Kelvin. The convective heat transfer coefficient ($h$) was 8.29 W $m^{-2}$ K (McQuiston and Parker 1994). We assumed an interior wall surface emissivity (ε) of 0.90 and sigma (σ) was the Stefan-Boltzmann constant approximately equal to $5.67x10^{-8}$ W $m^{-2}$ $K^{-4}$ (McQuiston and Parker 1994). Positive values indicated heat flux into the building.

We generated 95% confidence intervals for each curve using temperature reductions from each 10 minute interval from each day. For example, if there were 10 hot, sunny days, the reduction was the mean of those ten days, and the confidence interval was generated from the variation in the means from those same ten days.

**Results and Discussion**

Figure 8 shows the mean interior and exterior temperatures for hot, sunny days for the control buildings. The south exterior wall reached a maximum temperature of 43 °C around noon DST on hot, sunny days. The west exterior wall reached a maximum temperature of 56 °C around 5:00pm DST on hot, sunny days. The control buildings' interior temperatures were higher during the second part of the experiment when the green buildings' vegetation faced west. The interior temperature reached a maximum of 35 °C during the south-facing vegetation period and 38 °C during the west-facing vegetation period for hot, sunny days. The maximum interior temperature for the south-facing period occurred around 7:00pm DST and about an hour later for the west-facing period (Figure 8).

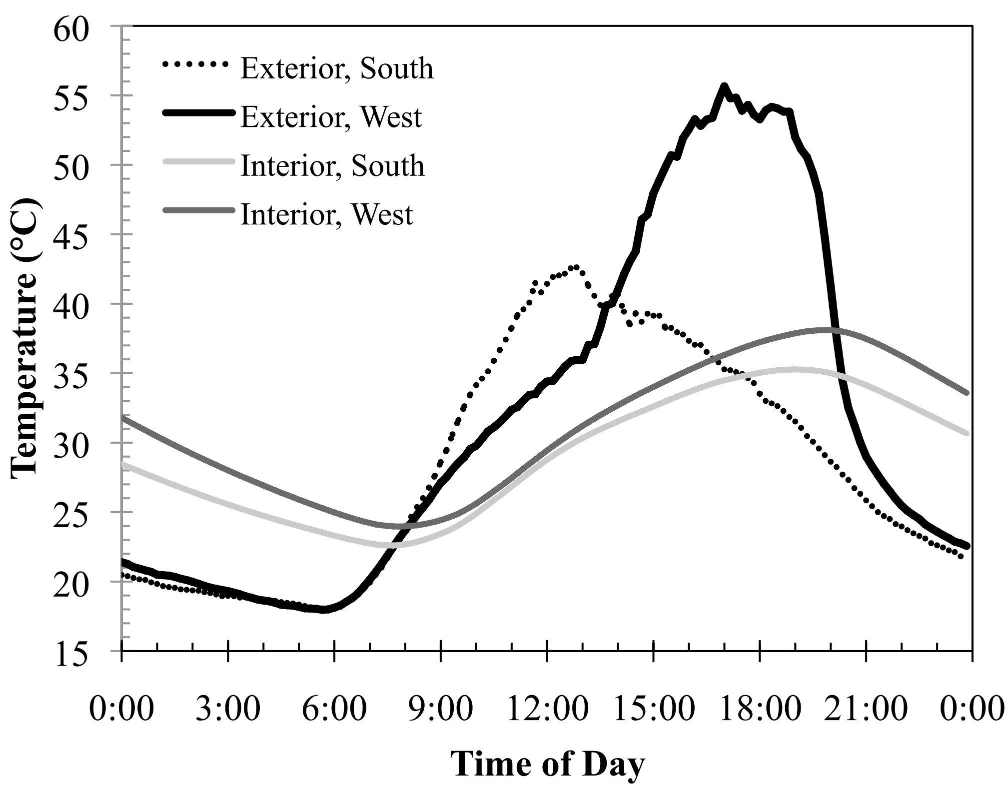



**Figure 8.** Mean interior air and exterior surface temperatures for the control buildings on hot, sunny days.

Interior Temperature

Figure 9 shows the 24-hr cooling effect that the green façade had on interior temperatures when the weather was either hot, sunny (Figure 9a) or cool, cloudy (Figure 9b) for south and west-facing walls. The south-facing green façade reduced the interior air temperature by at most an average of 1.04 °C at 3:30pm DST on hot, sunny days (Figure 9a). When they were on the west side, they cooled the interior air temperature by 1.75 °C at 8:10pm DST for hot, sunny days (Figure 9a). Due to the high variability and small sample size for west-facing, cool, cloudy days (n=3), the 95% CI included zero (Figure 9b), indicating that the experiment could not conclusively ascertain a cooling effect for west-facing green façades on cool, cloudy days.

Due to financial constraints, the experimental buildings were not mechanically cooled, nor were they designed and built to be passively cooled. Because of this, the analysis of the green façade's effect on interior temperature is limited. The range of indoor air temperatures experienced during the study far exceeded acceptable levels for human comfort even in a passively cooled building (17 to 37 °C (62 to 99 °F) with south-facing vegetation and 18 to 41 °C (65 to 106 °F) with west-facing vegetation).

Exterior Surface Temperature

On hot, sunny days, the green façade on the south and west sides cooled their respective exterior walls by a maximum of 6.42 and 11.30 °C (Figure 10a), respectively. The green façade cooled the south wall from dawn to dusk and was nearly symmetrical about 12:00pm DST. The west-facing green façade cooled the exterior surface beginning at dawn, continued into dusk, and was heavily skewed toward late afternoon (Figure 10a). The west-facing green façade was particularly effective after 1:00pm DST when it began to receive direct irradiance.

During cool, cloudy days the south green façades cooled their exterior walls by on average as much as 2.38 °C at 11:20am DST (Figure 10b). Vegetation on the west-facing wall cooled by as much as 6.17 °C at 4:30pm DST on cool, cloudy days but frequently had a confidence interval below zero which indicated a non-significant reduction (Figure 10b). Similar to detecting an effect of the west green façades on the interior temperature described above, there were only three cool, cloudy days during the west wall experimental period. A larger sample size would perhaps remedy the inability to detect the cooling effect of west-facing vegetation on cool, cloudy days. Furthermore, some of the variability may also come from the fact that the cutoff for what made a day cloudy versus sunny and cool versus hot was made at the average value. This means that two very similar days, one with slightly above average solar irradiance and air temperature versus another with slightly below average solar irradiance and air temperature could have been assigned opposite categories when in fact they were quite similar days.

The effect of the green façade on exterior surface temperature is perhaps the most straightforward to analyze. Adding vegetation can reduce the daily exterior surface temperature range of a wall from 10 to 60 °C to between 5 and 30 °C (Peck et al. 1999). This magnitude of reduction in temperature swing of the building surface can have profound effect on the longevity of building materials and exterior waterproofing. The other more immediate benefit of reducing the exterior surface temperature daily range is the reduction of heat flux through the building wall due to less of a temperature gradient between the interior and exterior surfaces. Unfortunately, the green façades in this study were relatively immature with a thin canopy that did not completely cover the experimental building walls. Because of this, the experimental buildings only experienced exterior surface temperature range reductions of from between 10 to 50 °C down to between 11 to 46 °C when south-facing vegetation was added and from between 11 to 64 °C down to between 12 to 53 °C when west-facing vegetation was added.

Building Ambient Air Temperature

On hot, sunny days, the green façade on the south and west sides cooled their respective ambient air temperatures by as much as 1.12 °C at 12:00pm DST and 2.97 °C at 7:50pm DST (Figure 11a), respectively. The south-facing green façade was most effective around 12:00pm DST but maintained a small but significant effect from mid-morning through sunset. The west-facing green façade was particularly effective after 1:00 DST, when it began to receive direct irradiance. While it is difficult to extrapolate these data to specifically quantify any effects the green façade vegetation have on the urban heat island effect, it is clear that the air surrounding the living vegetation is cooler than the air in front of the bare building surface.

During cool, cloudy days the variability in the data for both south and west green façades was very high and the confidence intervals frequently included zero, indicating that a significant effect could not be detected. The west-facing green façade, for several brief periods during the evening, did however cool the building ambient air by around 0.5 °C (Figure 11b).

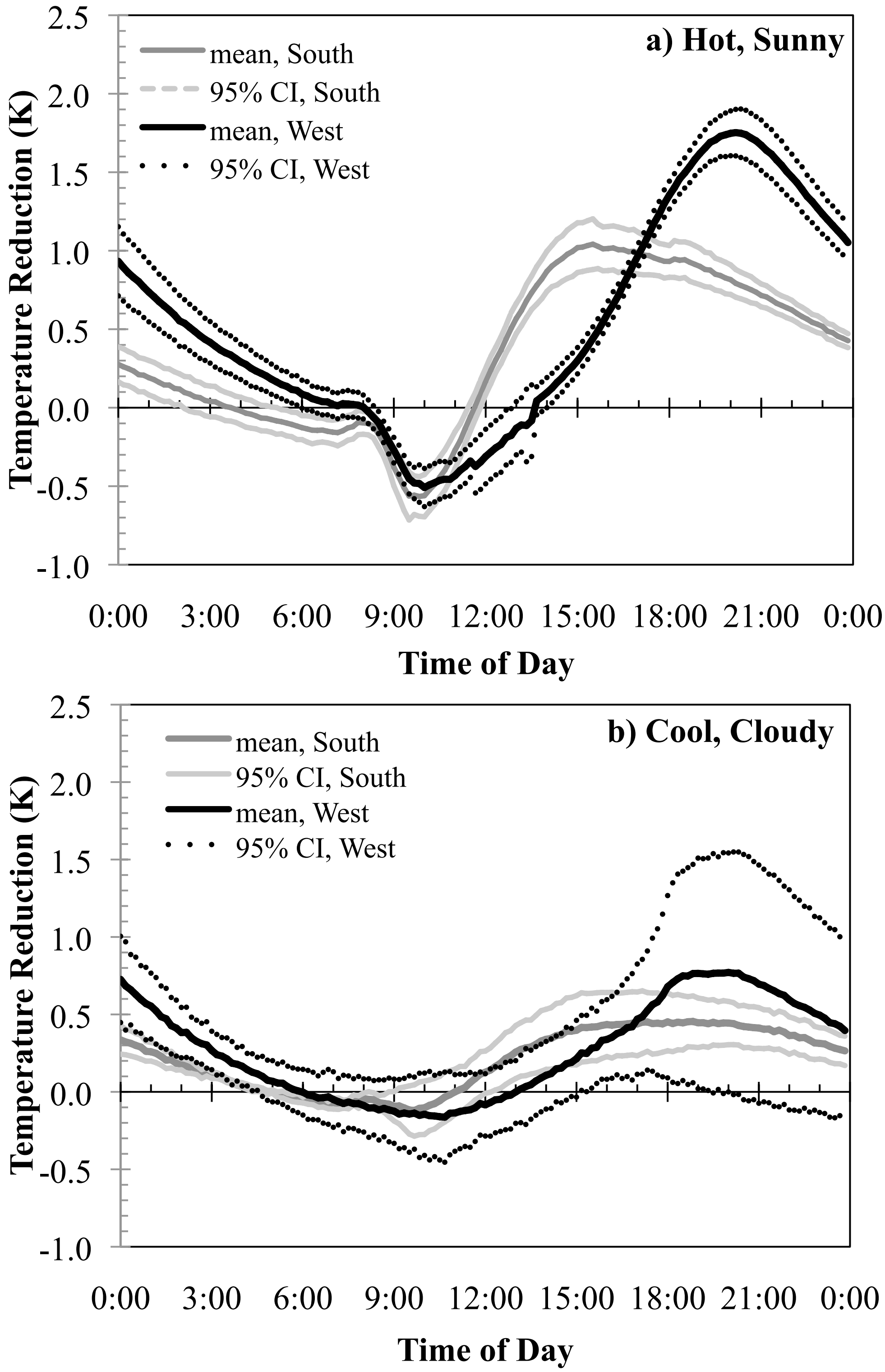



**Figure 9.** Reduction in building interior air temperature due to vegetation on the south or west building wall during either (a) hot, sunny or (b) cool, cloudy days.

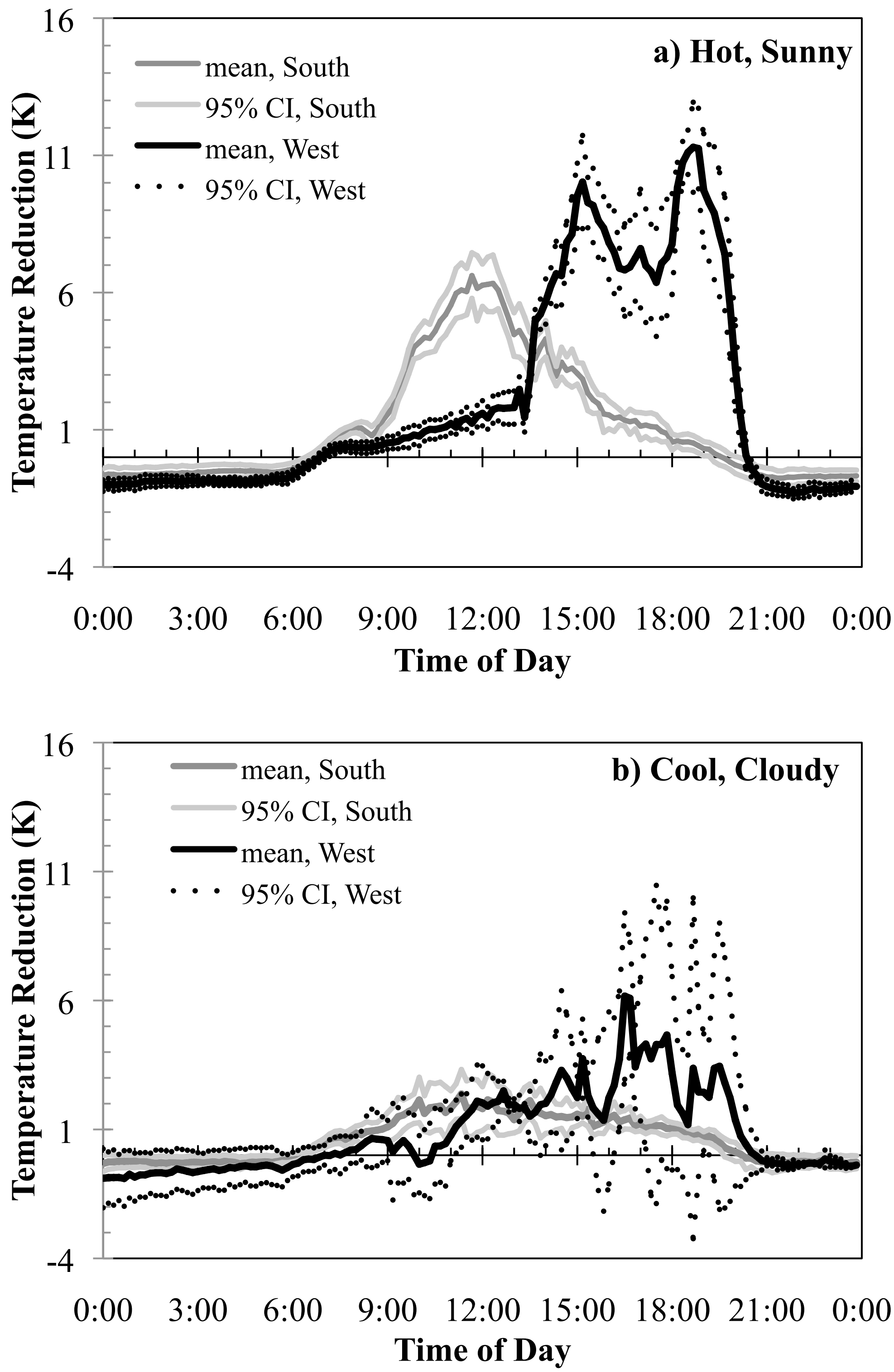



**Figure 10.** Reduction in the experimental building's exterior surface due to green façade vegetation during either (a) hot, sunny or (b) cool, cloudy days.

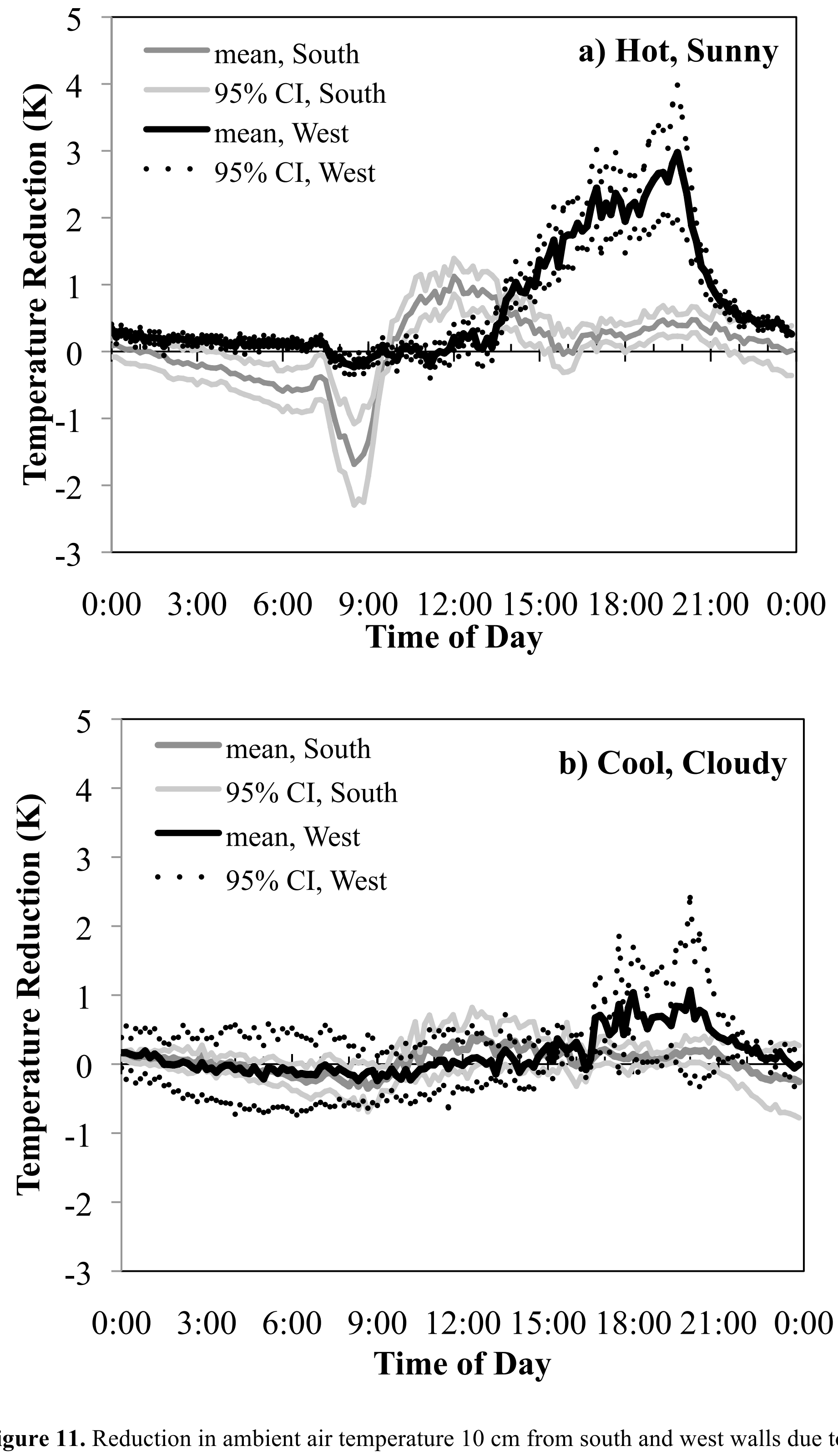



**Figure 11.** Reduction in ambient air temperature 10 cm from south and west walls due to a green façade for (a) hot, sunny and (b) for cool, cloudy days.

Heat Flux to Building Interior Air

Figure 11 shows heat flux reduction to the building interior due to south and west-facing green façades on hot, sunny days (Figure 12a) and cool, cloudy days (Figure 12b). The south-facing green façade reduced heat flux into the building on hot, sunny days by as much as 3.57 W $m^{-2}$ at 1:30pm DST from an original peak of 13.0 W $m^{-2}$. The mean heat flux reduction for hot, sunny days between 11:00am and 4:00pm DST was 33.7%. On cool, cloudy days it reduced mean peak heat flux into the building by 2.11 W $m^{-2}$ at 12:30pm DST.

The west-facing green façade reduced the mean peak heat flux into the building by 10.65 W $m^{-2}$ at 5:40pm DST from an original peak of 23.6 W $m^{-2}$ on hot, sunny days (Figure 12a) but for cool, cloudy days, variability in the data did not allow us to draw any conclusions (Figure 12b). On hot, sunny days, the mean heat flux between 2:30pm and 9:30pm was reduced by 47.5% through the west wall.

Evapotranspiration

Total daily ET from a single *Vitis riparia* plant and its potting mix on the south-facing green façade for hot, sunny days was estimated to be 47% of the total daily solar irradiation on those days (Figure 13a). Solar radiation was symmetrical about noon while ET was approximately symmetrical about 2:00pm and slightly skewed toward the afternoon. Total daily ET from a single *Vitis riparia* plant and its potting mix on the west-facing green façade for hot, sunny days was estimated to be 40% of the total daily solar irradiation on those days (Figure 13b). West-wall ET was approximately symmetrical about 2:00pm and was nearly equal to solar irradiance until the wall began receiving direct sunlight after 1:00pm. These values agree reasonably well with the value reported by Di and Wang (1999), 32%, which was a daily average value from a west-facing English Ivy canopy in Beijing, China in July.

A building wall can absorb almost all of incoming solar radiation, converting most of that radiation into stored heat. A typical plant canopy will absorb 75% (Gates 1980) of incoming radiation but instead of storing it, will release it in several forms. One dominant pathway to release that energy is through transpiration. Heat that the leaf absorbs is temporarily stored in water contained within the leaf. The water turns to vapor when its energy content reaches the heat of vaporization, at which point the water exits the leaf through the stomates. In effect, solar energy was blocked from entering the building by the leaf, and removed from the system as water vapor. Through this mechanism, plants cool themselves, the building they are covering, and the urban airshed. Adding water vapor to an urban environment that lacks vegetation and suffers from the heat island effect may be an effective way to cool it (Bass 2001).

Plant Growth

Near the end of the experimental period (July 13$^{th}$, 2010), after approximately six months of growth, the leaf area index for all green façades was the same, with a mean of 3.07 ($p<0.05$) (Figure 14a). In addition, the mean plant cover was 80% by July 15$^{th}$ (Figure 14b) with no significant differences between green façade types ($p<0.05$). This rapid first-year growth demonstrated the potential of a new green façade to quickly establish and cool its building. This may be particularly advantageous in new construction where newly planted shade trees may take many years to establish.

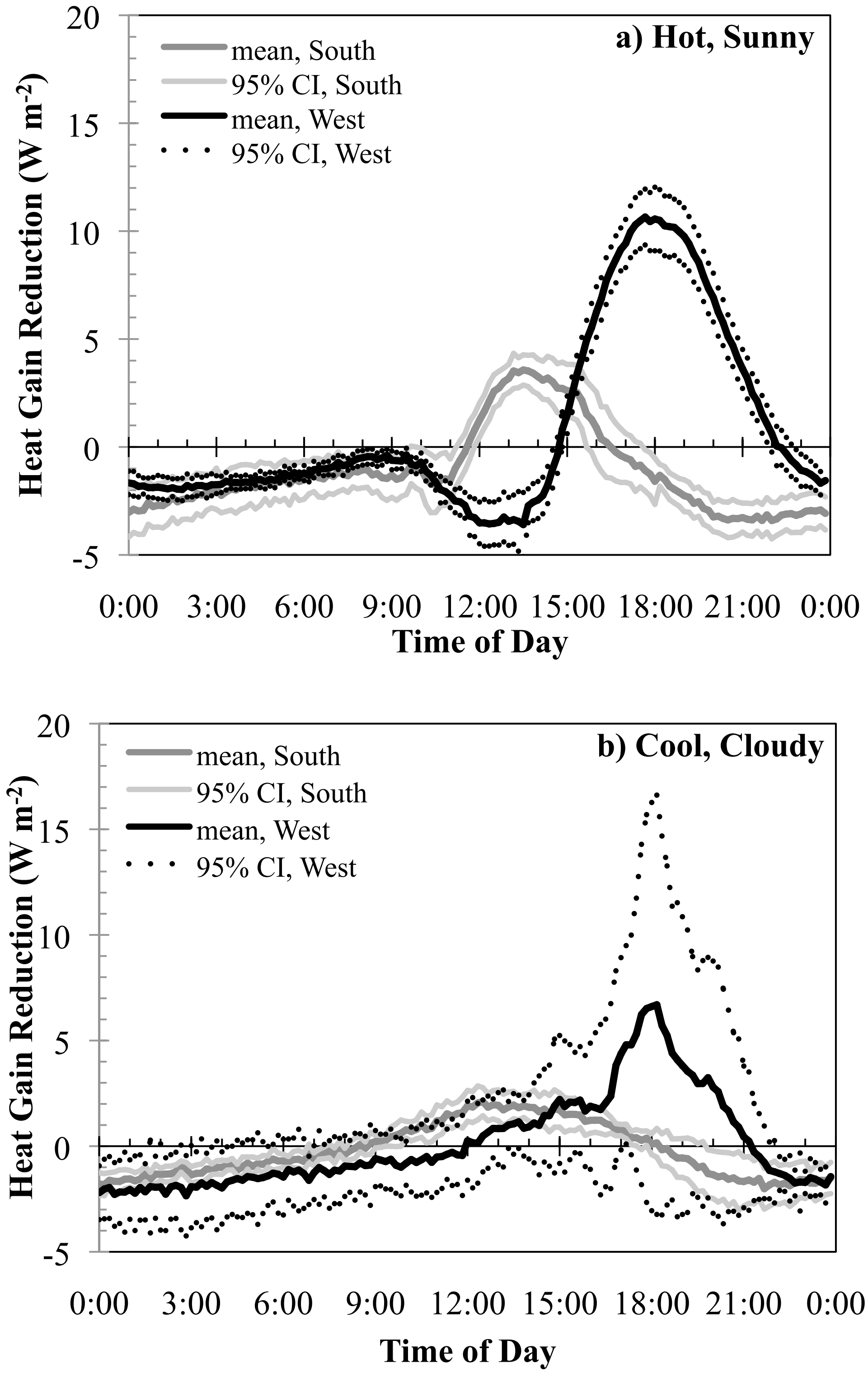



**Figure 12.** Reduction in heat flux into the building's interior air due to green façade vegetation during either (a) hot, sunny or (b) cool, cloudy days.

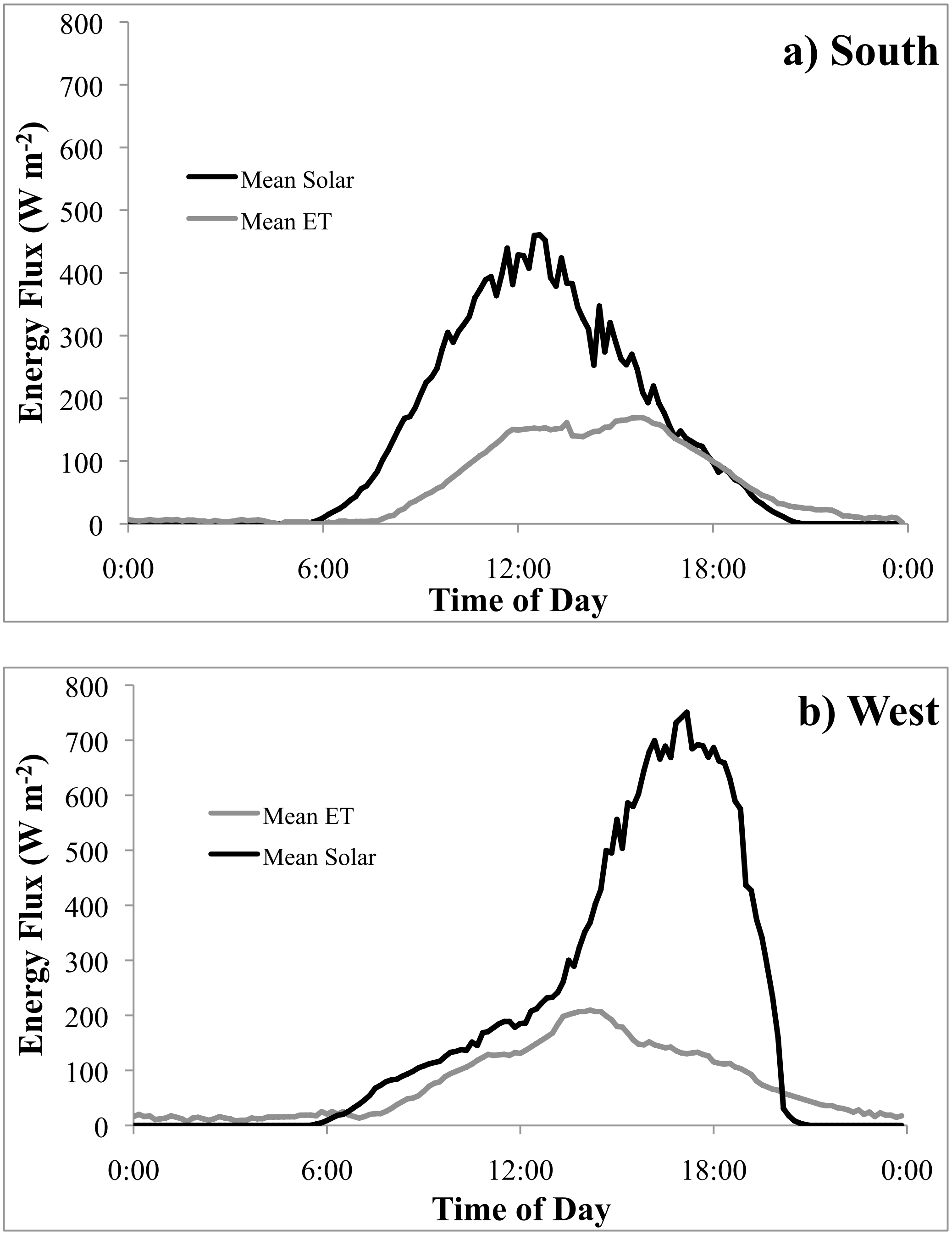
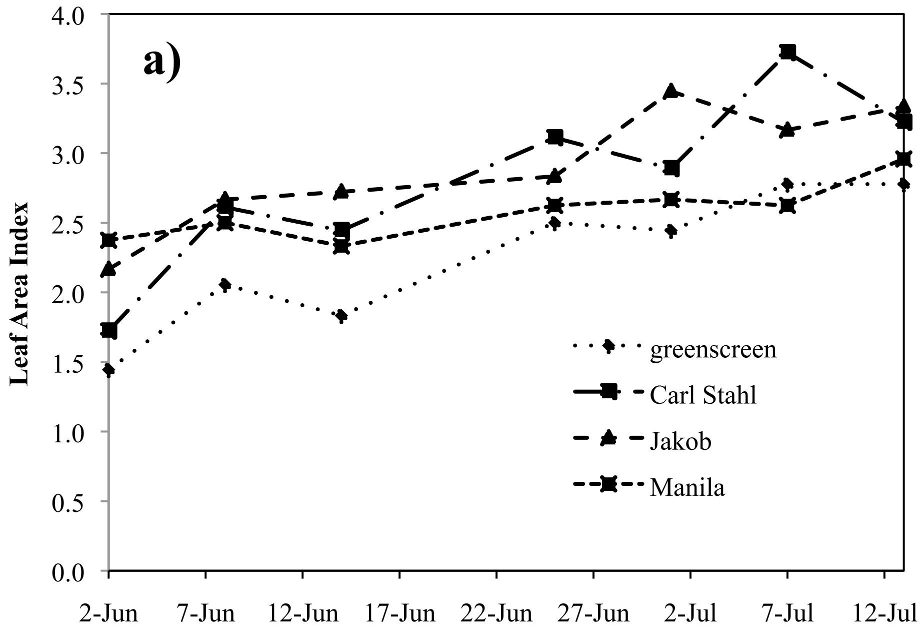



**Figure 13.** Observed solar irradiance and estimated evapotranspiration of the (a) south-facing vegetation for hot, sunny days and of the (b) west-facing vegetation for hot, sunny days.



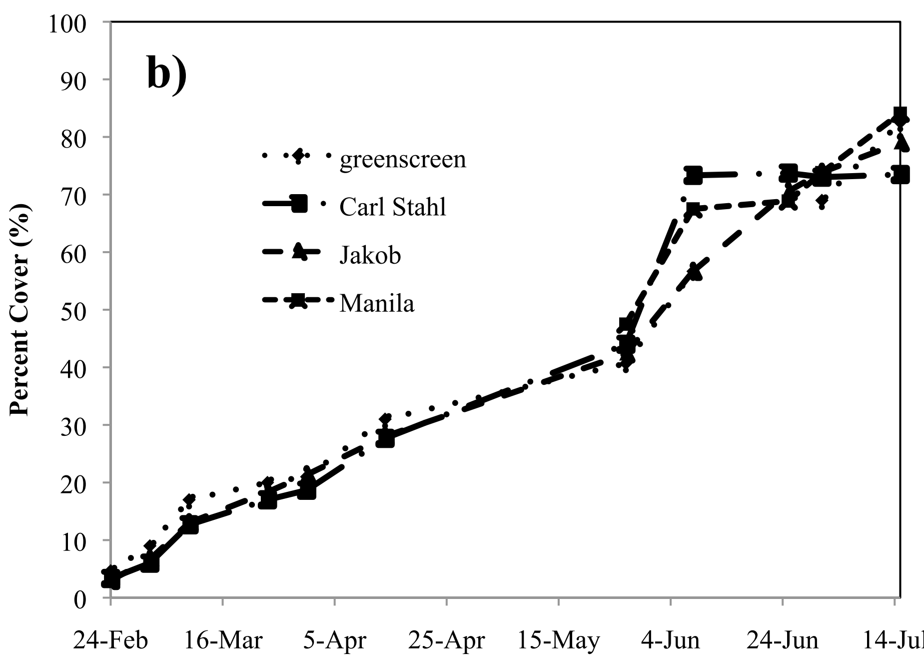




**Figure 14.** Plant growth measurements of experimental green façade vegetation. Leaf area index (a) represented the number of leaf layers per unit area of wall covered and percent cover (b) represented the amount of wall space covered with vegetation. Data were presented as means of each green façade type.

## Conclusions

The green façade significantly reduced the ambient air temperature, exterior surface temperature, heat flux through the wall, and interior air temperature of the 8 ft x 8 ft wooden experimental buildings on hot, sunny days in May, June, and July in Maryland, USA (Table 2).

**Table 2.** Summary of the peak cooling effects of the green façade during the early summer 2010 in Maryland, USA.

| | South | West |
|---|---|---|
| Ambient air, K | 1 | 3 |
| Exterior surface, K | 6 | 11 |
| Interior air, K | 1 | 2 |
| Heat flux, W $m^{-2}$ | 4 | 11 |
| Heat flux, % | 34 | 48 |

On cool, cloudy days, which had lower average ambient air temperatures and solar irradiance, the effects were less detectable due to high variability and a small sample size. In every comparison, the peak reduction was greater for west-facing vegetation than for the south. However, the study was conducted in late-May, June, and early-July, when the sun was at or near its maximum altitude. Later in the summer, when the air temperature is high but the solar altitude is lower, the effects of the green façade could be different. A longer experimental period is needed to answer this question.

Evapotranspiration accounted for 47% and 40% of the incoming solar energy on hot, sunny days for south and west-facing vegetation, respectively. This confirmed that evapotranspiration was a significant pathway for heat dissipation by the green facade. Further research needs to address the trade-off between water use and evaporative cooling, particularly in drier climates.

Finally, after approximately six months, the green façades had plant canopies with a mean leaf area index of three (i.e., LAI = 3) and percent leaf cover of 80%. There were no differences between commercial trellis products or species configurations. This rapid first-year growth demonstrated the potential of a new green façade to quickly establish and cool its building.

Though the results presented in this chapter apply specifically to our small, wooden experimental buildings in Maryland, they may be used to enhance our general understanding of green façade energetics. By green façades decreasing ambient air temperatures, as observed on our experimental buildings, they have the potential to mitigate the urban heat island effect.

Growing vegetation on the south or west wall of a building may significantly decrease the need for air conditioning during the cooling season. The green façade reduced both the interior air temperature of our experimental buildings and the heat flux from the interior wall surface to the interior air. These effects are further explored in the next chapter.

# Chapter 3: Modeled cooling load reduction using a green façade

The number of U.S. households with central air conditioning increased from 27 to 55 percent between 1980 and 2001 ("South Atlantic…" 2006). They consumed 183 billion kWh of electricity for air conditioning in 2001, which was 16% of their total electricity consumption ("South Atlantic…" 2006). With rising energy costs and a warming climate, the need for innovative, low-carbon technologies that help cool buildings is rising. Research done in the U.S. has shown increases in summertime urban air temperatures due to the urban heat island effect of between 0.5°C – 3.0°C and that much of this may be mitigated by the addition of living vegetation and high-albedo surfaces (Akbari et al. 2001).

One effective technology for cooling the urban environment is to add vegetation to building façades and roofs. While a growing number of researchers have evaluated the thermal benefits of green roofs (Palomo Del Barrio 1998, Wong et al. 2003, Kumar and Kaushik 2005, Hien et al. 2007, Takebayashi and Mariyama 2007, Fang et al. 2008), less has been written about green façades and most of it is in German and about German green façades (Köhler 2008). One relevant study by Di and Wang (1999) measured the cooling effect of a 10 cm thick ivy plant layer on a west-facing brick wall in Beijing. The researchers measured the thermal properties of the façade and compared those data to a section of wall where they removed the vegetation. The ivy layer reduced the maximum exterior wall temperature from approximately 52 °C (126 °F) to 36 °C (97 °F). They found that the green façade reduced the peak heat flux from the interior wall surface to the indoor air by 28% on a clear summer day. Akira Hoyano (1988) measured the heat flux through the vegetated west wall of a residence near Tokyo, Japan. The home had a 15 cm thick bare reinforced concrete wall that was completely covered with Japanese Ivy (*Parthenocissus tricuspidata*). He found that the vegetation reduced the heat flux at the indoor surface from a peak of approximately 58 W $m^{-2}$, to a fluctuating value just below zero. Therefore, he concluded that green façade vegetation could effectively eliminate the influence of solar radiation on the indoor thermal environment (Hoyano 1988).

While the researchers in both of these studies thoroughly quantified the effect of adding vegetation to a building façade on the heat flux to the interior environment, neither investigated this effect on the energy budget of the whole building. Wong et al. (2009) used a computer program to simulate the whole-building cooling load reduction due to a number of different vegetation scenarios on a 10-story office building. Under scenario one, the building was made entirely of opaque surfaces (i.e. no windows) and after being entirely covered in vegetation saw a 74% reduction in energy use for cooling. In scenario two they added windows to each level of the building and then covered the opaque surfaces only with greenery. Under this scenario, the effect was much less pronounced at just over a 10% reduction in cooling load. Under the final scenario, the building façades were entirely windows and subsequently covered with vegetation to 50% and 100%. Here, the cooling load was reduced by 12% and 32%, respectively.

Kontoleon and Eumorfopoulou (2010) simulated a small, cubic, windowless, climate-controlled building to which they added vegetation and simulated the cooling load reduction. They found that completely covering the west wall in vegetation reduced the cooling load by 20%, and for the other walls: 18%, 8%, and 5% for the east, south, and north walls, respectively. They also found a linear relationship for percent cover such that 50% plant cover on the west wall resulted in a 10% reduction in cooling load.

There is a need for replicated experimental research that considers the effects of green façade vegetation on the whole-building cooling load. And furthermore, acknowledging that every green façade installation and its effects on cooling the building is unique, Heating, Ventilation, and Air Conditioning (HVAC) Engineers need data on how to best integrate green façades into their design.

## Objectives

The objectives of this study were to 1) determine the reduction in peak heat flux through south and west walls covered with a green façade on replicated, wood-framed, experimental buildings, 2) estimate the reduction in whole-building cooling load of the experimental buildings by incorporating experimental data into a peak cooling load model, and 3) use the peak cooling load model to estimate the whole-building cooling load reduction of two simulated, full-scale residential buildings with vegetation covering either their south or west walls.

## Methods

### Experimental Buildings

#### Construction

Four buildings of dimensions 2.5 meters (8 ft) long by 2.5 meters (8 ft) wide by 3.5 meters (11 ft) high were constructed and placed on a concrete pad at the University of Maryland Central Research and Education Center in Clarksville, MD (approx. 30 km north of Washington, D.C.) on July 8$^{th}$, 2009. Each of the buildings consisted of a 4-sided square-hip 4/12-pitch roof with three-tab charcoal asphalt shingles (GAF Materials

Corporation, Wayne, NJ) and 5 cm x 15 cm (2x6 in.) wood rafters, a ceiling hung from 5 cm x 10 cm (2x4 in.) joists, 5 cm x 10 cm (2x4 in.) wood framed walls, and a 5 cm x 15 cm (2x6 in.) wood floor; all at a 40 cm (16 in.) center spacing. There were no windows and one door, which was centered on the wall opposite the instrumentation wall (described below). The floor joists rested upon three 10 cm x 10 cm (4 x 4 in.) treated posts laid flat on the ground, which served as the building's foundation. R-13 fiberglass insulation (CertainTeed Corporation, Valley Forge, PA), 9 cm (3-1/2 in.) thick, was installed on the ceiling, walls, and floor. The interior walls and ceiling were covered with 1.6 cm (5/8 in.) thick gypsum drywall (USG Corporation, Chicago, IL). The buildings were wrapped with vapor barrier (Dupont Tyvek HomeWrap, Wilmington, DE) and then covered with 1.5 cm (19/32 in.) thick pine T1-11 (Georgia-Pacific Building Products, Atlanta, GA). The buildings were first spray painted white (Glidden Premium Flat Latex Exterior, Akzo Nobel N.V., Amsterdam, Netherlands) in in July 2009 and then blue-grey slate (Glidden Premium Flat Latex Exterior, Akzo Nobel N.V., Amsterdam, Netherlands) in May 2010 before the second growing season began. This construction represented a total heat gain coefficient ($K_{tot}$) of 12.9 W/K (24.4 Btu/hr °F). Table 3 summarizes the thermal resistances (R-values) of each building surface.

**Table 3.** Because the instrumentation was fixed on one wall, each building was rotated 90° to switch the vegetated wall from south to west and back. The instrumented wall was built opposite the wall with the door.

| Building Surface | Composite R-Value, $m^2K/W$ ($ft^2{}^\circ F\ h/Btu$) |
|---|---|
| Walls without door | 2.27 (12.9) |
| Wall with door | 1.72 (9.77) |
| Roof | 3.21 (18.2) |
| Floor | 2.45 (13.9) |

Instrumentation

A single wall of each building was outfitted with instrumentation to gather continuous measurement of temperatures, including those to calculate heat flux, and solar irradiance. A CS300 silicon pyranometer (Campbell Scientific, Inc., Logan, UT, 300-1000nm) measured solar irradiance on the instrumented wall. Each instrumented wall had three horizontal profiles of thermistors (#44006, Omega Engineering, Inc., Stamford, CT) (Figure 15a) arranged in a diagonal pattern across the wall (Figure 15b). Interior temperature was measured with three evenly spaced thermistors mounted vertically on a column located in the center of each building. A CR1000 data logger (Campbell Scientific, Inc., Logan, UT) controlled the sensors and logged their data every 10 minutes when the system was powered. All sensors in each building were connected to an AM16/32B multiplexer (Campbell Scientific, Inc., Logan, UT) and each multiplexer was

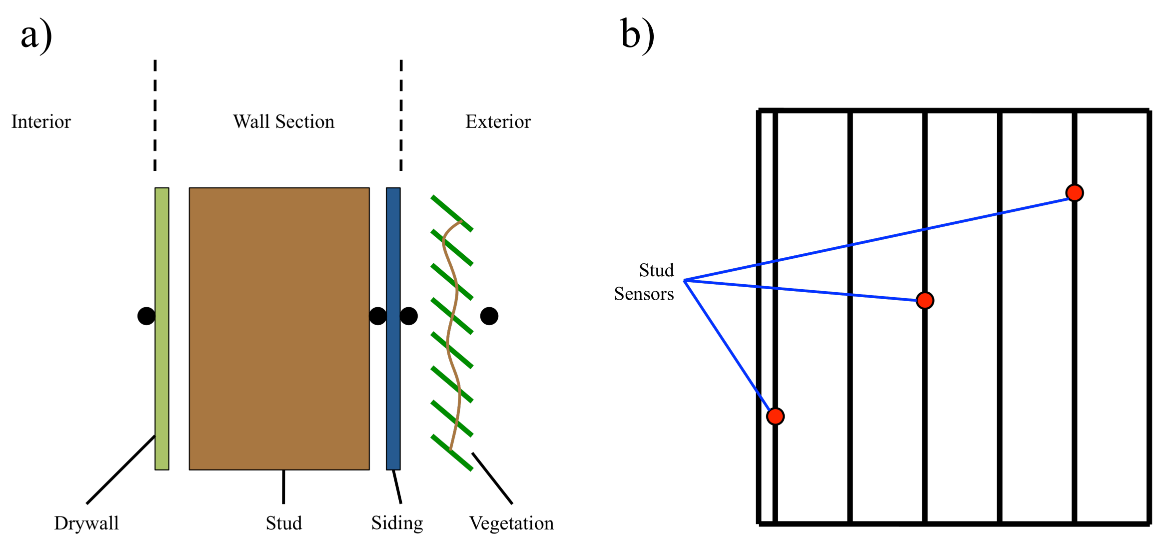



**Figure 15.** a) Cross-sectional diagram of profile of thermistors located across the instrumented wall from exterior (10 cm from vegetation surface) to the interior wall surface. b) Diagonal pattern of sensor profile locations evenly spaced across wall

connected to the datalogger, which was located in one of the experimental buildings. A 12-Volt RV/Marine deep-cycle battery (Interstate Batteries, Dallas, TX) powered the instrumentation and data-logging system.

Experimental Data Analysis

Heat flux through the instrumented wall was calculated by the following equation:

$$Q = h_{wi}(T_w - T_i) + \varepsilon\sigma(T_w^4 - T_i^4)$$

Where heat flux (Q) in W $m^{-2}$ was equal to the sum of the convective and radiative flux from the interior wall surface to the interior air. $T_w$ was the interior wall surface temperature and $T_i$ was interior air temperature, both were in units of Kelvin. The convective heat transfer coefficient ($h_{wi}$) was assumed to be 8.29 W $m^{-2}$ $K^{-1}$ (1.46 Btu $h^{-1}$ $ft^{-2}$ $°F^{-1}$) based on a vertical surface in still air (McQuiston and Parker 1994, pg. 157). Interior wall surface emissivity (ε) was assumed to be 0.90 and sigma ( $\sigma$ ) was the Stefan-Boltzmann constant, approximately equal to $5.673 \times 10^{-8}$ W $m^{-2}$ $K^{-4}$ (McQuiston and Parker 1994). Positive values indicated heat flux into the building.

Two days with similar climatic conditions were chosen to compare the effects of a south and west green façade on our experimental buildings. The climatic characteristics of these days are summarized in Table 4.

ASHRAE Cooling Load Modeling

Calculation Methods

We used the "radiant time series" method as described in Chapter 29 of the *2001 ASHRAE Fundamentals Handbook* (ASHRAE 2001) to generate hourly peak cooling loads for each opaque building surface. The method began by calculating the hourly

**Table 4.** Climatic characteristics for the days chosen for the study. July 4th was slightly warmer and drier than June 12th. Temperature data were as measured by our thermistors, solar data were calculated using solar geometry.

| | June 12, 2010 | July 4, 2010 |
|---|---|---|
| Mean Temperature, °C (°F) | 27 (80) | 26 (79) |
| Max Temperature, °C (°F) | 33 (92) | 37 (98) |
| Min Temperature, °C (°F) | 19 (67) | 15 (59) |
| Mean Humidity, % | 70 | 51 |
| Max Humidity, % | 90 | 84 |
| Min Humidity, % | 49 | 18 |
| Mean Insolation on horiz. surface, W $m^{-2}$ | 616 | 610 |
| Max Insolation on horiz. surface, W $m^{-2}$ | 1000 | 998 |

solar loading, including direct and diffuse irradiance, on each building surface, which was used to calculate a "Sol-air" temperature of that building surface. The Sol-air temperature was defined as:

> "…the temperature of the outdoor air that in the absence of all radiation changes gives the same rate of heat entry into the surface as would the combination of incident solar radiation, radiant energy exchange with the sky and other outdoor surroundings, and convective heat exchange with the outdoor air" (ASHRAE 2001).

The next step was to calculate the heat input, which was the conduction through the wall surface based on the temperature gradient between the Sol-air temperature and the indoor air temperature. The conduction time series (CTS) method redistributed this heat input temporally based on physical properties of the specific building materials, i.e. the material stored heat and released it with a time delay. Next, the energy was divided into radiant and convective components based on source of heat gain (Table 5). These values did not vary based on differences in construction materials.

For opaque surfaces like walls, convective heat (Table 5) contributed to the cooling load instantaneously, while radiant heat (Table 4) was transformed by a radiant time series (RTS) distribution also based on wall construction characteristics. The convective and transformed radiant heat gains were then added to derive the total cooling load for each hour for the wall surface.

**Table 5.** Convective and radiant percentages of total sensible heat gain (ASHRAE 2001).

| Heat Gain Source | Radiant heat, % | Convective heat, % |
|---|---|---|
| Transmitted Solar | 100 | 0 |
| Absorbed Solar (by fenestration) | 63 | 37 |
| Conduction, exterior walls | 63 | 37 |
| Conduction, exterior roofs | 84 | 16 |

For transparent surfaces, like windows, transmission of solar radiation into the building interior often accounts for a large proportion of the total cooling load. For these surfaces, the previously calculated hourly direct solar load was multiplied by the window area of the corresponding building façade and then transformed by a representative solar RTS where 100% of the gain was radiant. Prior to being processed by the RTS, the heat gain was reduced by a solar heat gain coefficient (SHGC), which was defined as the fraction of incident irradiance that entered through the glazing and became heat gain (ASHRAE 2001). Also prior to multiplying by the RTS, any shading devices, both exterior and interior, were accounted for accordingly. The next step was to multiply the ground and sky diffuse solar irradiance by the window area and corresponding SHGC to get the diffuse solar heat gain. After these values were added to the conductive heat gain, which was equal to the window area multiplied by the inverse R-value of the window and the temperature difference between the inside and outside air, they were split where 37% of the gain is convective and 63% is radiant. The radiant heat gain was then transformed by the corresponding RTS and finally added to the direct solar cooling load to get the total window cooling load for that façade.

Heat gain due to household appliances, occupancy by people, and air infiltration can also be added. Household appliances were assumed to add 469 W (1600 Btu/hr). An adult male occupant added 161 W (550 Btu/hr), an adult female added 132 W (450 Btu/hr), and each child was assigned a heat gain of 121 W (413 Btu/hr) (ASHRAE 2001). Heat gain due to air infiltration was calculated for each hour using the temperature difference between the indoor and outdoor air, a tabulated value for the air exchange rate based on tightness of building construction, and the necessary unit conversion factors (Bobenhausen 1994).

### Annual Energy Savings Calculations

Use of the degree-day method for energy analysis remains simple and accurate even today in an age of complex computer modeling (ASHRAE 2001). The degree-day concept accurately describes the severity of a given climate. Cooling degree-days are standard tabulated values generally available for major cities across the world. We used the book value for Washington, D.C., which was 1430 °F days (Bobenhausen 1994). A cooling degree-day (CDD) is “the difference between a particular base temperature and the mean outdoor temperature, in degrees Fahrenheit, on that day" (Bobenhausen 1994). The typically used base temperature is 65 °F, which refers to the lowest outdoor temperature at which mechanical cooling is required to maintain indoor comfort. When estimating the quantity of electricity consumed by the air conditioning equipment during the cooling season, the cooling degree-day value must be converted to cooling load-hours (CLH) using the formula (Bobenhausen 1994):

$$CLH = \frac{CDD_{65} * 24}{(T_{std} - 65)}$$

where $T_{std}$ is the outside summer design temperature in °F. Once the CLH is calculated, the electricity consumption is calculated using the following formula (Bobenhausen 1994):

$$kWh_{c-yr} = \frac{CLH * q_c}{1000 * SEER}$$

where the electricity consumption is in kilowatt hours, the CLH is in hours, the design cooling load ($q_c$) is in Btu hour$^{-1}$, and the Seasonal Energy Efficiency Ratio (SEER) is in Btu hour$^{-1}$ W$^{-1}$. The SEER ratio is a measure of cooling efficiency per input Watt over the entire cooling season. We used a SEER ratio of 10, which was appropriate for an older average home ("Central Air Conditioners" 2010). The design cooling load ($q_c$) was the hourly peak cooling load that we estimated as explained above. As is common practice, we used the outside summer design temperature for Washington D.C. at the 2.5% design condition (91 °F), which meant our system was capable of cooling 97.5% of summer hours (Bobenhausen 1994). This practice is used to avoid excessive over sizing of equipment, which would lead to an overall decrease in system efficiency

(Bobenhausen 1994). Finally, cost savings were calculated for each hypothetical full-scale building scenario. The cost of electricity used in the calculations was \$0.1502 $kWh^{-1}$, the average retail price for the residential market in Maryland as of July 2010 ("Average retail price…" 2010).

## Modeling the Green Façade

The green façade vegetation serves primarily as an external shading device for the building wall. External shading devices are accounted for in ASHRAE modeling by tracking the shadow throughout the day and reducing the direct irradiance on any surface behind it to zero. However, the solar irradiance penetrating a vegetative canopy will never be zero and may vary considerably. One study in Britain found a shading coefficient (i.e., ratio of solar irradiance below a canopy to above it, SC) of 12% through a thick canopy of Virginia creeper with a leaf area index (LAI) of 5 (Ip et al. 2010). Hoyano (1988) measured the solar transmittance (SC) under a large number of green façades in Tokyo and found it to range from 2-7%. Schumann (2007) found the transmittance through a thick canopy (LAI 3.17) of Virginia creeper using a hyperspectral radiometer to be 9.3% (Schumann 2007). For the purposes of this study, we used 12% in our modeling and considered the effect of using 2%. To model the reduction in solar irradiance by the green façade, we reduced both the direct and diffuse solar irradiances before the Sol-air calculation for the affected surface. This is not the same as the traditional definition of the shading coefficient. ASHRAE (2001, pg. 30.38) defines the shading coefficient as "the ratio of the solar heat gain coefficient of a glazing system at a particular angle of incidence and incident solar spectrum to that for standard reference glazing at the same angle of incidence and spectral distribution." Because our model was in spreadsheet form and we had access to each component, we were able to account explicitly for the transmitted irradiance.

Simulation of the Experimental Building

Simulation of the experimental buildings used the observed indoor and outdoor temperatures from July 4th, 2010, and assumed Wall Number 6 (Wood siding, sheathing, R-11 batt insulation, gyp board) for the wall CTS, and Roof Number 4 (Asphalt shingles, wood sheathing, R-19 batt insulation, gyp board) for the roof CTS. The representative non-solar RTS used was under the conditions of the interior zone, light construction, and no carpet. The representative solar RTS used was under the conditions of light construction, no carpet, and 10% glass (ASHRAE 2001, Chapter 29). All building surfaces had an area of 4.83 $m^2$ (52 $ft^2$). The experimental building simulation contained cooling loads for the roof, walls, floor, and infiltration. The geographic coordinates used were 39° North, 77° West, which was the approximate location of Washington, D.C., USA. All simulations were performed using June solar geometry. See Figure 16a for a sketch of the experimental building.

Simulation of the Full-Scale Buildings

The first simulation of a full-scale building was of a 2-story building that had a square floor-plan 10.7 m (35 ft) on each side and a flat roof 6.1 m (20 ft) off the ground for a total floor area of 228 $m^2$ (2450 $ft^2$) (Fig. 16b). The walls consisted of 5x15 cm (2x6 in) wood studs filled with R-19 fiberglass insulation, and covered with wood siding with gypsum on the interior walls. Each wall had 10% window area, and the door was located on the north wall. The windows were double paned operable vinyl windows with an R-value of 0.53 $m^2$ K $W^{-1}$ (3.0 $ft^2$ °F hr $Btu^{-1}$). The total heat gain coefficient for the building was 189 W/K (359 Btu/hr °F). Observed data from July 4th were used for the outdoor temperature, but the interior temperature was held constant at 23.9 °C (75 °F) to simulate an air-conditioned interior. This simulation had four trials; two with vegetation on the south wall and the other two with just the west wall covered. One simulation for each orientation had the vegetation covering just the opaque wall surfaces, while a second had both the wall and windows covered.

The second full-scale building simulation was for a rectangular building 10.7 m (35 ft) wide by 6.1 m (20 ft) long by 9.1 m (30 ft) high for a total floor area of 195 $m^2$ (2100 $ft^2$) (Figure 16c). Construction was the same as in the first full-scale simulation except windows were placed only on the two smaller walls. Interior temperature was also held constant at 23.9 °C (75 °F) for this simulation. The simulation was performed in two sets, once with the small surface area of the building facing west and once with it facing south. Vegetation was placed on either the south or west wall for both building orientations. In the two cases where the vegetation was placed on the wall with windows, an extra simulation was done covering both walls and windows. These configurations yielded a total of six scenarios for the rectangular building.

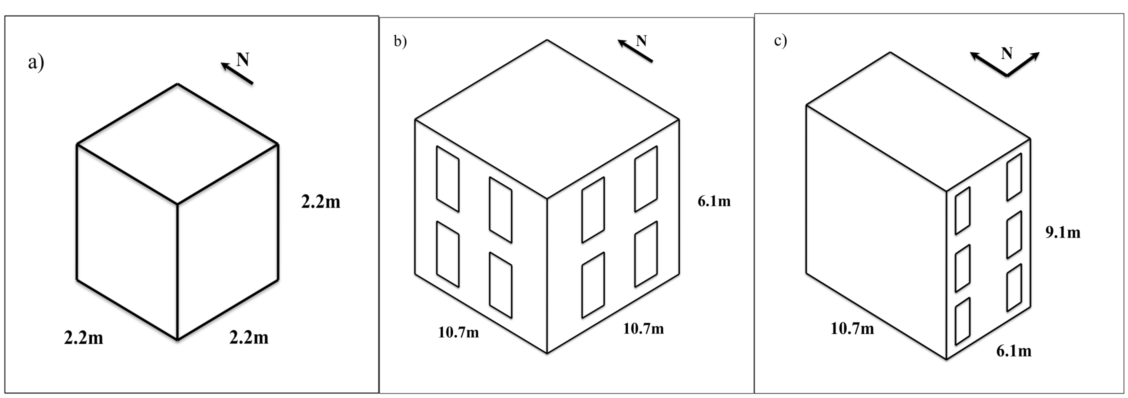



**Figure 16.** Modeled building sketches of a) the experimental building, b) the square building, and c) the rectangular building. Note: in (c) the north arrow points in two directions, one depicts the Rectangle-EW orientation simulation and the other the Rectangle-NS simulation.

**Results and Discussion**

Experimental Buildings

Validation that the ASHRAE cooling load model could reproduce the heat flux of the experimental buildings when there was no green façade was satisfactory, but not perfect (Figure 17). The modeled cooling load for the south wall fit reasonably well, especially from midnight to 2:00 pm. The largest error for the south wall occurred during the afternoon and into the evening (Figure 17). However, the modeled cooling load for the west wall was overestimated during the morning and early afternoon, and grossly underestimated during the late afternoon and evening. One reason for the differences may have been that the ASHRAE cooling load model was meant for climate-controlled buildings, which the experimental buildings in this study were not. Since the inside temperatures of the experimental buildings rose to 27.4 °C (81.4 °F) before 12:00 pm, when the west wall started to receive direct irradiance, heat flux was likely directed from the indoor air to the west-facing interior wall. This reversal of the temperature gradient would not occur in a climate-controlled building.

The cooling load contributed by each building surface of the experimental building without a green façade is shown in Figure 18. The east-facing wall included the door in this simulation and was responsible for nearly the entire building's cooling load from sunrise until mid-morning. Although the total daily cooling load for the east-facing wall was the highest of any surface (120 W $m^{-2}$), the hourly peak cooling load for the entire building occurred at 3:00 pm when the other building surfaces each contributed to an overall higher hourly peak (62.5 W $m^{-2}$).

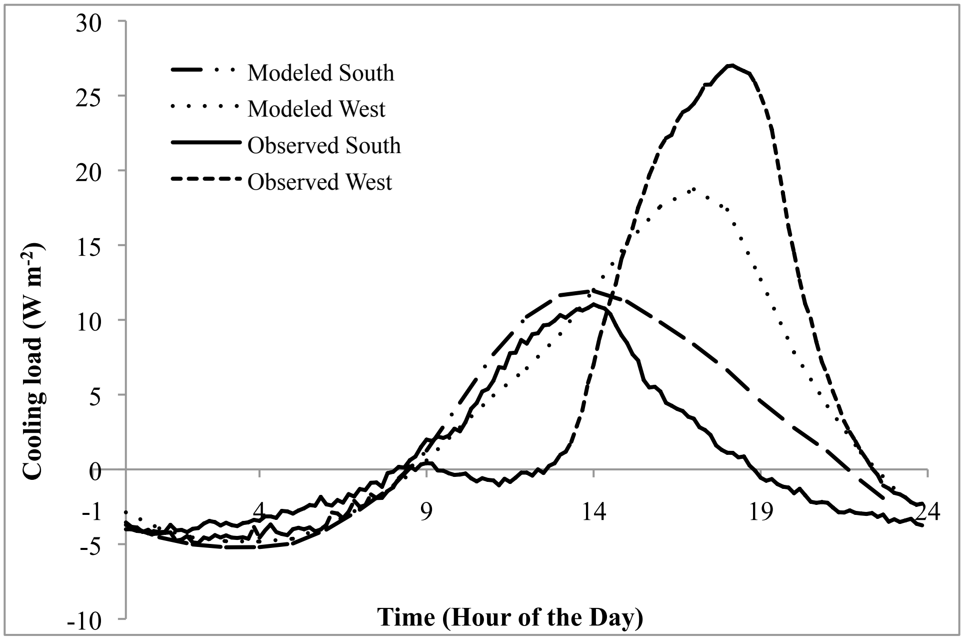



**Figure 17.** Comparison of mean observed and modeled cooling load for south and west-facing walls on the experimental buildings.

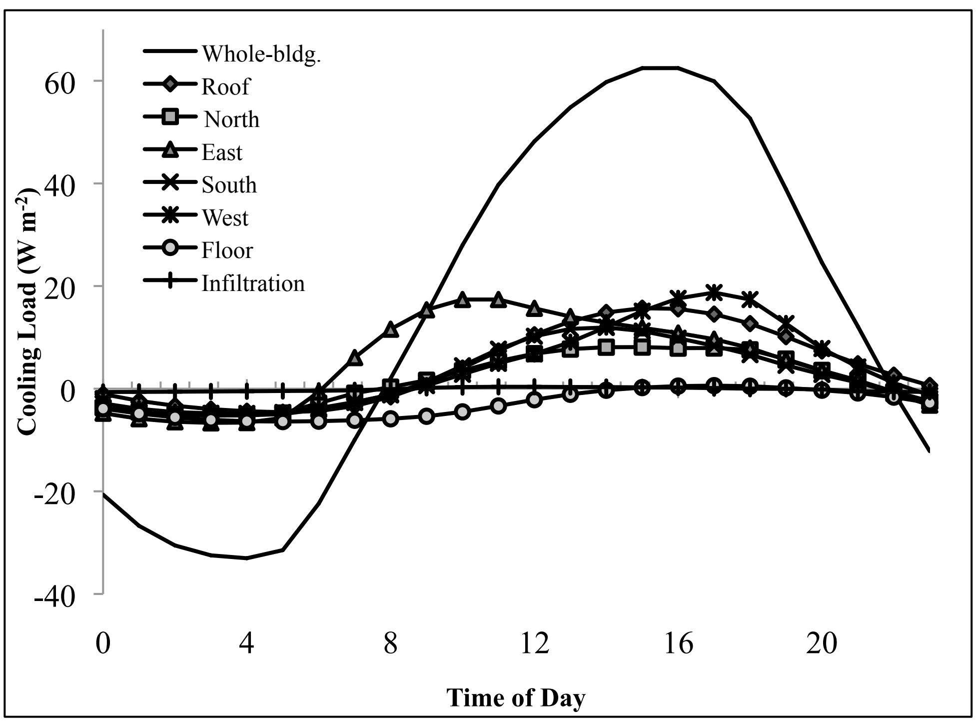
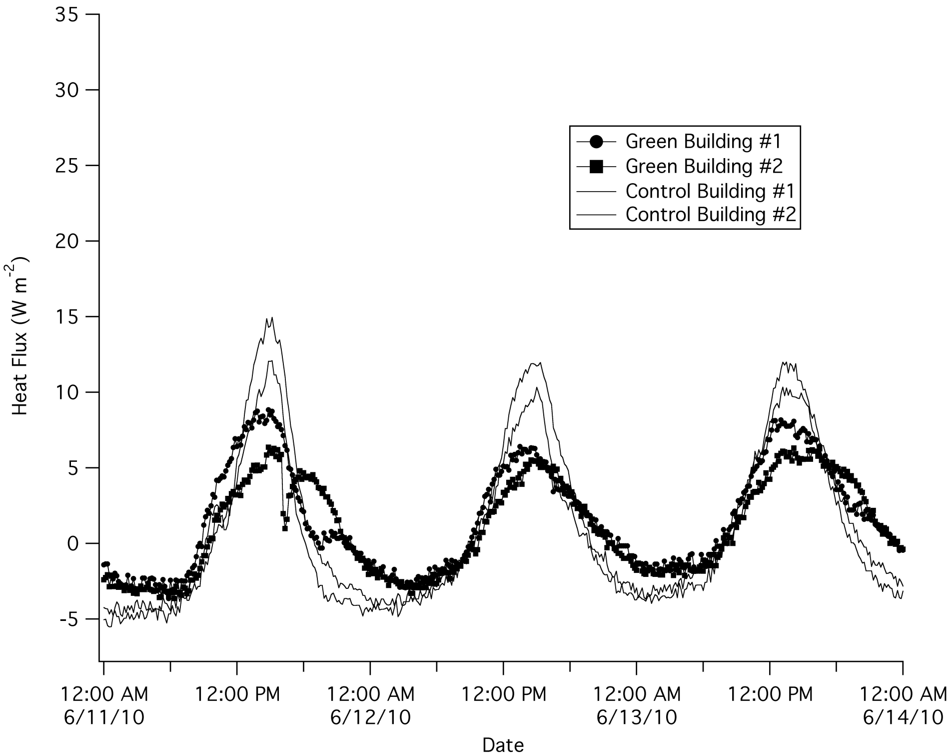



**Figure 18.** ASHRAE cooling load model output for the experimental building without a green façade in June.

The green façade reduced the peak heat flux of the south wall on June 12th by 48% at 3:00 pm DST ($p<0.05$) (Figure 19a) from an original value of 10.9 W $m^{-2}$ (3.46 Btu $hr^{-1}$ $ft^{-2}$). When considering the impact of the south wall's heat flux reduction on the cooling load of the entire experimental building, the ASHRAE model estimated that the peak hourly cooling load would be reduced by 3.4% at 4:00 pm DST from an original value of 308 W (1052 Btu $h^{-1}$). The impact of the south wall reduction was diluted because it was only 17.6% of the total peak cooling load for the whole building.

In order for the ASHRAE model to estimate a similar whole-building peak cooling load, the shading coefficient needed to be set equal to 0.45. This was the SC that yielded a peak cooling load reduction most similar to the experimental measurements. The SC was high because the plant canopy was immature; the mean LAI of the south wall vegetation was 3.4 and the cover was only 55%. With a plant cover of 55%, almost half of the building wall was receiving direct irradiance. Within the first few years of installation, properly designed and maintained green façades should grow a thick, full canopy that entirely covers their wall. Under these conditions, one can expect a shading coefficient in the range of 2 to 12% (Hoyano 1988, Schumann 2007, Ip et al. 2010).

The green façade reduced the peak cooling load of the west wall on July 4th by 52% at 5pm DST ($p<0.05$) (Figure 19b) from an original value of 27 W $m^{-2}$ (8.57 Btu $hr^{-1}$ $ft^{-2}$). When considering the impact of the west wall's heat flux reduction on the cooling load of the experimental building in the ASHRAE model, the peak hourly cooling load was reduced by 4.8% for the entire building at 2:00pm DST from an original value of 308 W (1052 Btu $h^{-1}$). A shading coefficient of 0.49 achieved a similar cooling load reduction in this case. On July 4th, the mean LAI of the west wall vegetation was 2.7 and a)




b)

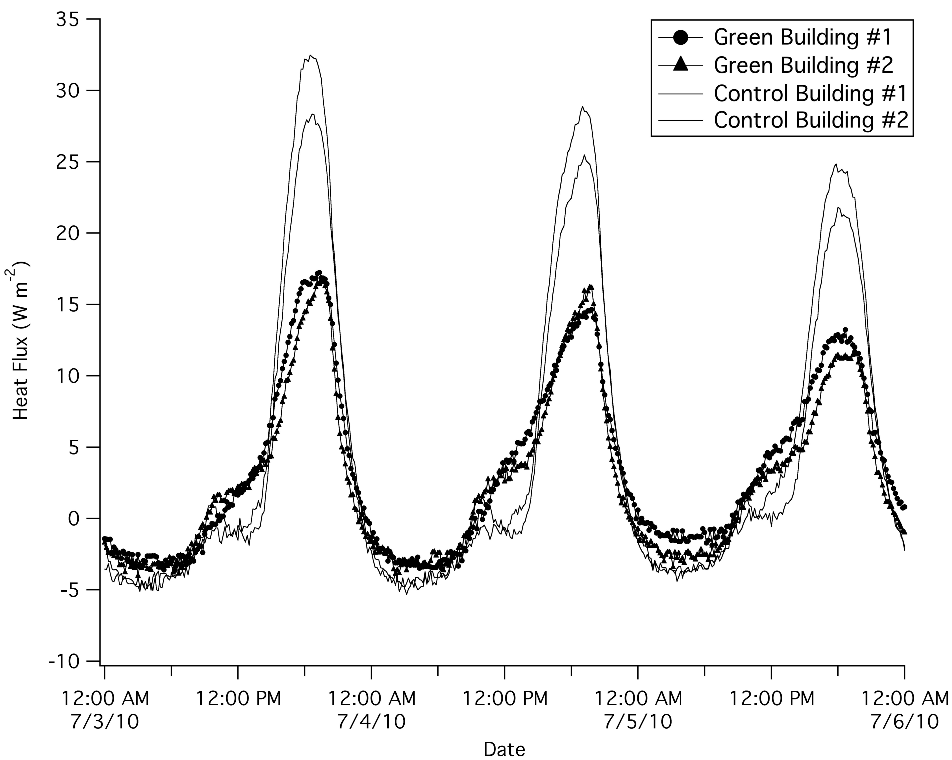



**Figure 19.** Observed heat flux through a) the south wall for three days including June 12$^{th}$ and b) the west wall for three days including July 4$^{th}$ on experimental buildings. Dotted lines denote buildings with green façades; solid lines denote buildings without a green façade.

the cover was about 67%. The green façade canopy at that time was slightly thinner but covered the wall more. Although the west wall vegetation reduced the cooling load by approximately the same percentage as the south wall, the amount of reduction was nearly double that of the south. Because of this, placing the green façade on the west wall was more effective in reducing the peak cooling load of the experimental buildings in June.

The whole-building cooling load results (3.4 and 4.8% for south and west, respectively) were considerably less than the 7.6% and 20.08% reduction for the south and west-facing building walls found in the Kontoleon and Eumorfopoulou (2010) study, in which they modeled a geometrically-similar, windowless building. However, when we increased our SC to 12%, an SC closer to what they were probably using, on the experimental buildings in the cooling load model, the cooling load reductions increased to 10.2 and 17.3% with the addition of south and west-facing vegetation, respectively. These results agreed reasonably well with the previous study (Kontoleon and Eumorfopoulou 2010).

Simulation of the Square Building

The peak cooling load for the square building was 10,975 W (37,449 Btu $hr^{-1}$) for a total annual A/C energy cost of $742 (Table 6). Covering the south wall with vegetation reduced the peak cooling load by 1.4% at 6:00 pm DST with a SC of 12% resulting in $10 saved in annual A/C energy costs. When the west wall of the square building was covered with vegetation instead of the south, the peak cooling load was reduced by 2.8% and $20 was saved. Finally, when the green façade installation included covering the windows as well as the opaque wall surfaces, the hourly peak cooling loads were decreased by 7.8% and 26.4% for the south and west walls, resulting in $58 and $196 in annual A/C costs saved, respectively (Table 6).

Peak cooling load of opaque walls in the square building accounted for only 11% of the total load, while 56% was from the windows (Figure 20). With this type of load distribution it was clear that shading the windows had a much larger effect on the whole building's peak cooling load.

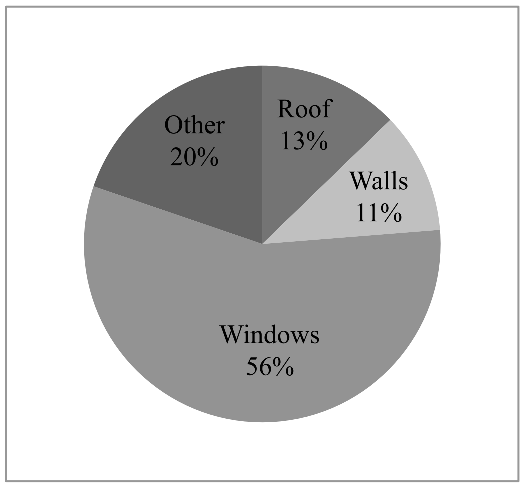



**Figure 20.** Sources for the cooling load of the square building. "Other" included outside air infiltration, occupants, and the floor.

The square building simulated in our study (10.7 m wide x 10.7 m long x 6.1 m tall, 10% window area) was somewhat similar to one simulated in the Wong et al. (2009) study though they covered all four of the walls with vegetation. In the Wong et al. (2009) scenario 2B, they found that adding vegetation to all the opaque surfaces reduced the whole-building cooling load by 10.35%.

Simulation of the Rectangular Building

The hourly peak cooling load for the rectangular building when its long axis was oriented east-west was 8330 W (28,423 Btu $hr^{-1}$) for a total annual A/C energy cost of $564 (Table 6). Covering the south wall with vegetation reduced the peak cooling load by 2.4% at 6:00 pm DST with a SC of 12% resulting in $14 saved in annual A/C energy costs. When the west wall of the same building was covered with vegetation instead of the south, the hourly peak cooling load was reduced by 3.4% and saved $19. Finally, when the green façade installation included covering the windows as well as the opaque wall surfaces, the hourly peak cooling load was decreased by 28.4% for the west resulting in $160 in annual A/C costs saved (Table 6). There were no windows on the south wall in this scenario.

The hourly peak cooling load for the rectangular building, when its long axis was oriented north-south, was 6866 W (23,430 Btu $hr^{-1}$) for a total annual A/C energy cost of $464 (Table 6). Covering the south wall with vegetation reduced the peak cooling load by 1.5% at 6:00 pm DST with a SC of 12% resulting in $7 saved in annual A/C energy costs. When the west wall of the same building was covered with vegetation instead of the south, the hourly peak cooling load was reduced by 7.9% and saved $37. Finally, when the green façade installation included covering the windows as well as the opaque wall surface, the hourly peak cooling load was decreased 8.9% for the south resulting in $41 in annual A/C costs saved (Table 6). There were no windows on the west wall in this scenario so no simulation was conducted.

For the north-south oriented rectangular house, opaque walls accounted for 28% of the peak cooling load while windows accounted for 27%. This scenario was somewhat unique in that it had no east or west-facing windows, which meant the window cooling load was low. Because of this, covering the opaque west wall surface had a significant effect and in fact, the largest effect of all scenarios where windows were not covered (7.9% whole-building cooling load reduction, Table 6).

**Table 6.** Summary of ASHRAE cooling load model simulations.

| Building type (see Fig. 2) | Orientation of Vegetation | Original peak cooling load, W (Btu $hr^{-1}$) | Whole building cooling load reduction, (%) | Annual A/C energy consumed, ($USD) | Annual A/C energy saved, ($USD) | Windows covered? |
|---|---|---|---|---|---|---|
| Experimental | South | 308 (1,052) | 3.4 | N/A | N/A | N/A |
| | West | | 4.8 | N/A | N/A | N/A |
| Square | South | 10,975 (37,449) | 1.4 | $742 | $10 | No |
| | West | | 2.8 | | $20 | No |
| | South | | 7.8 | | $58 | Yes |
| | West | | 26.4 | | $196 | Yes |
| Rectangle-EW | South | 8,330 (28,423) | 2.4 | $564 | $14 | No |
| | West | | 3.4 | | $19 | No |
| | West | | 28.4 | | $160 | Yes |
| Rectangle-NS | South | 6,866 (23,430) | 1.5 | $464 | $7 | No |
| | West | | 7.9 | | $37 | No |
| | South | | 8.9 | | $41 | Yes |

Decreasing the shading coefficient from 12%, which was used in the square and rectangular building simulations, to 2%, improved the cooling load reduction for example, in the square building simulation with south-facing vegetation, to 1.5% from 1.4%. Similar reductions were found in each scenario and because of this minor difference and to simplify presentation of the results, we reported data from the model using only the 12% SC.

**Conclusions**

The green facade reduced the peak heat flux through the south and west facing walls on the experimental buildings by 48% and 52%, respectively on two hot and sunny days in June and July in Maryland, USA. The ASHRAE (2001) cooling load model showed that this large reduction in heat flux through one building wall amounted to a small fraction of the total building cooling load (3.4% and 4.8% for south and west walls, respectively) because the wall was only one of five solar-exposed heating surfaces. The un-vegetated north and east walls and the roof continued to receive significant amounts of solar energy.

Peak cooling load models of two simulated wood-framed residential buildings in Maryland were then generated in an effort to apply our experimental data to full-scale buildings that had windows and were climate-controlled. We showed using the model that the green façade was significantly more effective when it shaded the building's windows—particularly those facing west (1.4%-7.9% for opaque walls versus a 7.8 – 28.4% reduction for walls with windows covered).

Modeling scenarios were restricted to June for simplicity and because this time period corresponded to the experimental period. Future modeling should assess the effects of green façade vegetation during other months of the year, in particular, in August and September when outdoor air temperatures are still high but the solar geometry is different. In late summer, when the solar altitude is lower and the south wall receives more solar irradiance than the west wall, south-facing vegetation may reduce the building's peak cooling load more than the west. Further, even though solar loading may be at its maximum in June, many buildings' cooling loads peak in late summer when the lower solar angle allows more sunlight to enter through windows.

There are many factors to consider that can affect cooling load reduction by a green façade including but certainly not limited to: building and vegetation orientation, building construction, window placement and total area, climate, presence and condition of surrounding tree canopy, green façade plant canopy development, and plant species. We acknowledge the vast amount of variability in the effect each individual installation may have on cooling load and have presented here a few examples to demonstrate one way of how users can account for the effect of the green façade in their own specific model in order to properly design their HVAC equipment accordingly. The results of this research should be used as guidelines for what to consider when installing a green façade. It is our hope that the methods discussed here for how to integrate the effect of a green façade into a cooling load model will be used in future models for real-world installations.

# Chapter 4: Emergy evaluation of a green façade

(At the time of thesis submission, this manuscript was *In Review* for Emergy Synthesis 6, the conference proceedings for the $6^{th}$ Biennial Emergy Systems meeting.)


**Abstract**

Increased environmental awareness and demand for green space in urban areas are driving the need to find ecological solutions to environmental problems. Green façades are a promising eco-technology that can help moderate temperature, create habitat, attenuate noise pollution, and mitigate stormwater runoff in urban areas. A green façade is a type of green wall system in which climbing plants or cascading groundcovers are trained to cover specially designed supporting structures (i.e. a trellis). The aim of this study was to evaluate the emergy invested in a 50 $m^2$ green façade. The model system consisted of a stainless steel trellis mounted to the south façade of an existing building with its plants rooted in the ground. The solar emergy required to manufacture, install, maintain, and decommission the green façade was 9.8 E12 sej/$m^2$/yr, with nearly 55% embodied in human services, 14% in non-renewable materials, and 31% in renewable materials. Depending on how much A/C electricity could be saved, the benefit of the green façade ranged from 0 to 5 times the total solar emergy cost. If 10% of A/C electricity was saved, the green façade had an emergy return on emergy invested for its non-renewable materials of five. However, inclusion of the emergy invested as human services in this ratio reduced it to 1.0, indicating that the ecological benefit was highly sensitive to the financial cost of the façade. These results suggested that the emergy

benefit of a green façade was highly sensitive to its effect on building cooling load and total lifetime costs.

**Introduction**

Man-made structures that dominate the urban environment can increase urban afternoon ambient air temperatures by as much as 8°C (Peck et al. 1999), a phenomenon known as the urban heat island effect. Urban heat island effect mitigation strategies strive to create a more natural environment by increasing transpiration, decreasing heat storage and altering surface albedo. Incorporation of vegetation is a simple way to achieve this. Much of the research done in the US has shown that significant increases in urban temperatures over the last 100 years are caused by the absence of urban vegetation and abundance of low-albedo urban surfaces (Akbari et al. 2001).

While planting trees is probably the most common way to introduce vegetation into urban areas, planting climbing plants can significantly add to the potential area of green space in our cities. Green façades have long inhabited our urban areas, dating back to the Hanging Gardens of Babylon and the middle ages of Europe, lining Mediterranean villas and castle walls and gardens. Green façades gained their modern momentum in Central Europe in the 1980s and 1990s when Berlin offered incentives to install them. The vast majority of those systems used the self-clinging climber Boston Ivy (*Parthenocissus tricuspidata*) (Köhler 2008). However, due to the desire for better growth control and protection of newly constructed buildings, the installation of trellises and use of non-clinging climbers accounts for the majority of installations today (Dunnett and Kingsbury 2008).

While the exact energy saved by a green façade is not well known, up to 70% was found in the literature. Peck et al. (1999) suggested that a 10°F reduction in air temperature outside a building achieved by well-placed shade trees can reduce A/C energy consumption by 50-70%. A study in Britain showed a 25% reduction in annual energy costs through deciduous shade trees and wind chill reduction (Peck et al. 1999). And finally, as a point of comparison, a study in Canada found a 25% reduction in summer cooling needs with an extensive green roof (Dunnett and Kingsbury 2008, pg. 73). This wide range of estimates and comparisons of the green façade to shade trees and green roofs reflects the lack of research data on the technology. Preliminary modeling results from our work suggest that the green façade may only reduce the peak cooling load by 10-15% when the south or west wall including the windows are covered (Price and Tilley, unpublished data). Actual reductions will vary considerably due to geographic location, proportion of façade covering, window placement, existing building construction and use, and many other factors.

**Objectives**

Our objectives were to: (1) determine the amount of renewable and non-renewable emergy required to manufacture, install, maintain, and decommission a green façade in a temperate climate; (2) estimate the amount of embodied energy saved by a green façade due to lowered air conditioning (A/C) electricity consumption; (3) estimate the embodied energy value of the ecological production of the green façade; and (4) estimate the emergy benefit-cost ratio of the green façade.

**Methods**

System Description

The green façade evaluated in this study completely covered the 50 $m^2$ (10m long x 5m high) south wall of a two-story residential building. The façade was assumed to have a 25-year lifetime, which represents the industry average. The trellis consisted of 4 mm diameter stainless steel cable (grade 316) bolted to the building wall on 15 cm long stainless steel spacer bars. The cables were mounted in a grid pattern with 40 cm vertical spacing and 30cm horizontal spacing, as recommended by Dunnett and Kingsbury (2008, pg. 206). The vines were planted in the ground and irrigated with tap water as needed to make up for rainfall deficiency, fertilized, and sprayed with fungicide during plant establishment for the first three years. The area used in the rainfall and tap water calculations was the planting bed dimension, 10 m long by 1 m wide. This was the area assumed to contain the majority of the root structure. It was assumed that a contractor installed the system and the homeowner provided the maintenance labor.

Inventory of emergy inputs

An emergy evaluation was completed that accounted for all components needed to manufacture, install, maintain, and decommission the green façade. Renewable inputs evaluated were sun, rainfall, transpiration, and recycled stainless steel. Non-renewable inputs were plants, tap water, fertilizers, fungicide, stainless steel, product services, and human labor. Product services was the total cost of the system without the cost of labor and the stainless steel material. The remaining costs were assumed to account for the emergy of designing and manufacturing the system. Benefits consisted of A/C electricity saved due to reduced heat gain on the interior air and the amount of ecological production. All calculations were made using the 15.83 E09 sej/y global baseline.

Grade 316 stainless steel was used for the cable trellis, as is the case for installations where corrosion due to sea spray and/or urban air pollution may be an issue. We derived a transformity for the stainless steel by incorporating the emergy of other metals into an existing steel transformity. The alloy composition was simplified to the following metals: 67% Iron, 17% Chromium, 12% Nickel, 2% Manganese, 2% Molybdenum (AK Steel 2009). We assumed steel was made entirely of iron, which was a simplification. We then set up a proportion equation relating the stainless steel metal composition to the steel composition and the steel transformity to the transformity of stainless steel (see Table 9).

Since stainless steel can be recycled, we used data given by Buranakarn (1998) to estimate the proportion of its embodied energy that could be reused. This required proportioning the emergy among the metals, which could be reused, and the electricity and fuel, which could not be reused because they were dissipated during primary manufacturing. It was assumed that the metal of a used trellis was 100% recyclable, because very little of it was oxidized during its 25-year lifetime (Table 10).

### Estimate of emergy of benefits

The main benefit of the green façade considered in this analysis was the electricity saved from reduced use of air conditioning (A/C). The emergy of ecological production was assumed to be the same as transpiration, which was calculated using leaf area from estimates by Dragoni et al. (2006). Transpiration is a good proxy for ecological production because it is directly related to gas exchange.

Data Analysis

The total solar emergy required to manufacture, install, maintain, and decommission the green façade was the sum of all the renewable and non-renewable inputs to the system. The total benefits of the system were the sum of the A/C electricity saved and ecological production. The benefit-cost ratio was the total annualized benefit divided by the total solar emergy consumed, amortized over the life of the system. We chose to report the results in Table 7 with 10% A/C electricity saved. Benefit-cost ratios were calculated over the entire range of expected percent A/C electricity saved both with consideration for human services and when they were ignored. Human services in this case encompass product services embodied in the cost of the green façade and both installation and maintenance labor.

**Results**

A green façade requires that non-renewable resources be consumed in mining, manufacturing, installation, and maintenance so the vegetation can control the microclimate of the building envelope (Figure 21). The vegetation reflects unneeded near-infrared solar radiation, and absorbs a large fraction of the ultraviolet, visible, and near-infrared radiation into latent heat via transpiration. The vegetation accumulates biomass to provide ancillary ecological benefits such as songbird habitat, but through transpiration requires the consumption of water as a renewable resource for its operation. By reducing the solar load on a building's interior air, the green façade reduces the need for A/C use and thus lowers electricity consumption (Figure 21).

The total annual solar emergy required to manufacture, install, maintain, and decommission the green façade for the 25-year expected lifetime was 9772 E9 sej/$m^2$/yr

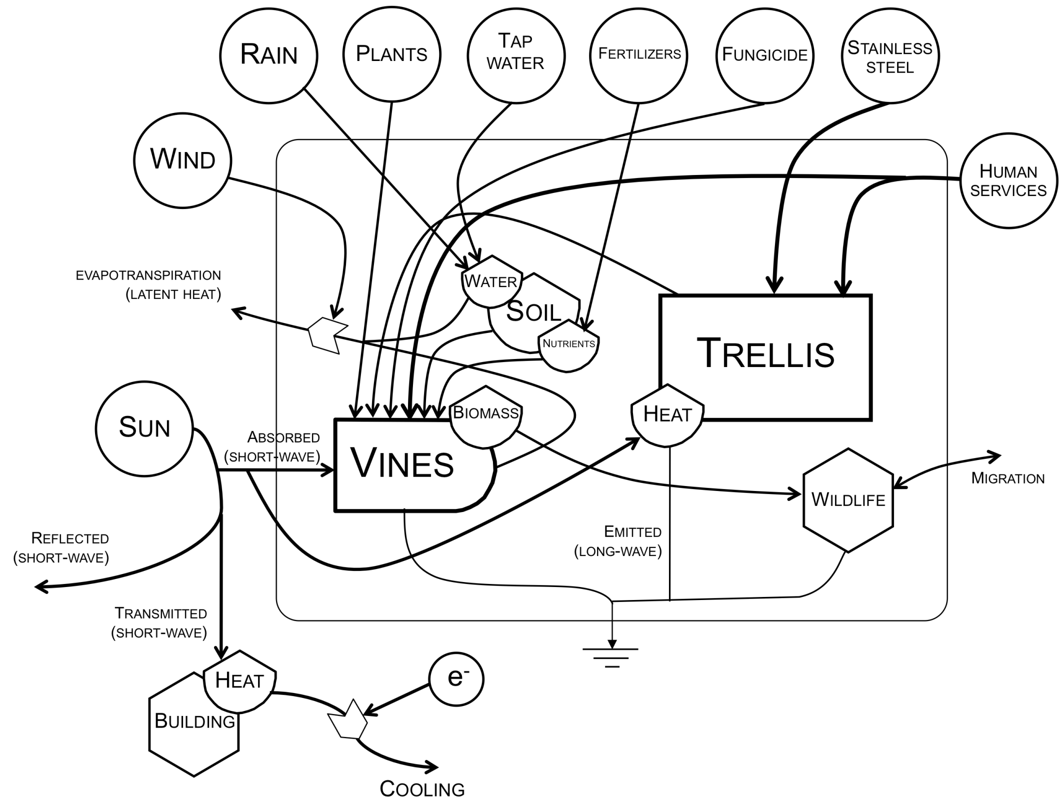



**Figure 21.** Systems diagram for the green façade.

(Table 7). Assuming that the stainless steel was recycled, 31% of the total emergy was from renewable resources. Just over half (55%) of the total emergy was embodied in human services (items #12, #13, and #14 in Table 7). Approximately 13% of the total emergy was embodied in the stainless steel and not recyclable (#11 in Table 7). Transpiration was the second largest renewable input after recycled stainless steel, but only accounted for 1.2% of the total (item #3 in Table 7). All other inputs combined, including plants, tap water, fertilizers, and fungicide accounted for less than 1% of the total (items #4-10 in Table 7). With 10% of A/C electricity saved, the benefit was 6831 E9 sej/m$^2$/y (item #15 in Table 7). The ecological production benefit accounted for 1.2%

of the total solar emergy (item #16 in Table 7). Ignoring all the solar emergy of human services, the total solar emergy dissipated over the 25-yr life of the green façade was 4357 E9 sej/$m^2$/y (Table 7).

The benefits of the green façade matched the emergy costs (9772 E9 sej/$m^2$/y) at 14.4% A/C electricity saved. Over the range of A/C electricity savings we evaluated, the emergy benefit-cost ratio was as great as 4.8:1 and as small as 0.012:1 (Figure 22). If the human services are ignored, then the benefit-cost ratio could be as great as 10.8:1, or at the conservative estimate of 10% of A/C electricity saved, it would be 1.57:1 (Figure 22). Comparing non-renewable inputs to benefits, at 10% of A/C electricity saved the green façade nearly breaks even (0.99, Table 8). If human services are ignored, the ratio of non-renewable inputs to benefits increases to 4.97 (Table 8).

**Discussion**

Other environmental benefits provided by the green façade (i.e., in addition to saving A/C electricity and ecological production) were not evaluated here because they were considered outside the scope of this study. Therefore, the emergy benefits and benefit-cost ratios calculated here should be considered minimum values. Other benefits including: habitat creation, air and noise pollution attenuation, building envelope weatherization, stormwater flow attenuation, psychological well-being, urban food production, and winter insulation should be evaluated in future research.

We chose to assess this eco-technology based on its emergy benefit-cost ratio, to determine how much A/C electricity a green façade would need to save to recoup the emergy dissipated for its manufacture, installation, maintenance, and decommissioning.

**Table 7.** Emergy required to manufacture, install, maintain, and decommission a 50 $m^2$ green façade during its expected 25-year lifetime. Benefits percentage is shown for Total Emergy with services.

| Number | Item | Unit | Value (unit/yr/ $m^2$) | Solar Transformity (sej/unit) | Solar Emergy (sej/$m^2$/yr) E09 | % Total |
|---|---|---|---|---|---|---|
| Renewable | | | | | | |
| 1 | Sun | J | 3.68E+09 | 1.00E+00[d] | 4 | |
| 2 | Rain | J | 1.05E+06 | 3.06E+04[d] | 32 | |
| 3 | Transpiration | J | 4.46E+06 | 2.59E+04[d] | 116 | 1.2% |
| 4 | Stainless Steel (69% recycled) | g | 6.27E+01 | 4.61E+10[%] | 2890 | 29.6% |
| | Renewable Subtotal | | | | 3005 | |
| Non-renewable | | | | | | |
| 5 | Plants | J | 3.08E+05 | 1.90E+04[d] | 6 | 0.1% |
| 6 | Tap Water | J | 7.83E+04 | 3.14E+05[f] | 25 | 0.3% |
| 7 | Potash | g | 1.12E+00 | 1.74E+09[d] | 2 | 0.0% |
| 8 | Phosphorus | g | 1.58E-01 | 2.20E+10[d] | 3 | 0.0% |
| 9 | Nitrogen | g | 2.14E-01 | 2.41E+10[d] | 5 | 0.1% |
| 10 | Fungicide | g | 5.10E-01 | 2.49E+10[a] | 13 | 0.1% |
| 11 | Stainless Steel | g | 2.82E+01 | 4.61E+10[%] | 1298 | 13.3% |
| 12 | Product Services | $ | 4.00E+00 | 8.30E+11[c] | 3324 | 34.0% |
| 13 | Maintenance Labor | ind.*year$^2$ | 9.13E-06 | 1.55E+17[g] | 1415 | 14.5% |
| 14 | Installation Labor | ind*year | 2.92E-06 | 2.31E+17[g] | 676 | 6.9% |
| | Non-renewable (subtotal w/ services) | | | | 6766 | |
| | Non-renewable (subtotal w/o services) | | | | 1352 | |
| | **Total Emergy (w/ services)** | | | | **9772** | 100.0% |
| | **Total Emergy (w/o services)** | | | | **4357** | |
| 15 | A/C Electricity Saved[#] | J | 2.50E+07 | 2.69E+05[d] | 6715 | 68.7% |
| 16 | Ecological Production | based on transpiration | | | 116 | 1.2% |
| | Total Benefits | | | | **6831** | 69.9% |

[a]Brown and Arding 1991; [b]Buranakarn 1998; [c]Cohen et al. 2006; [d]Odum 1996; [e]Tilley 2006; [f]Buenfil 2001; [g]Campbell and Lu 2009.

[#]Assumed 10% of A/C electricity saved.
[%]Calculated in this paper.

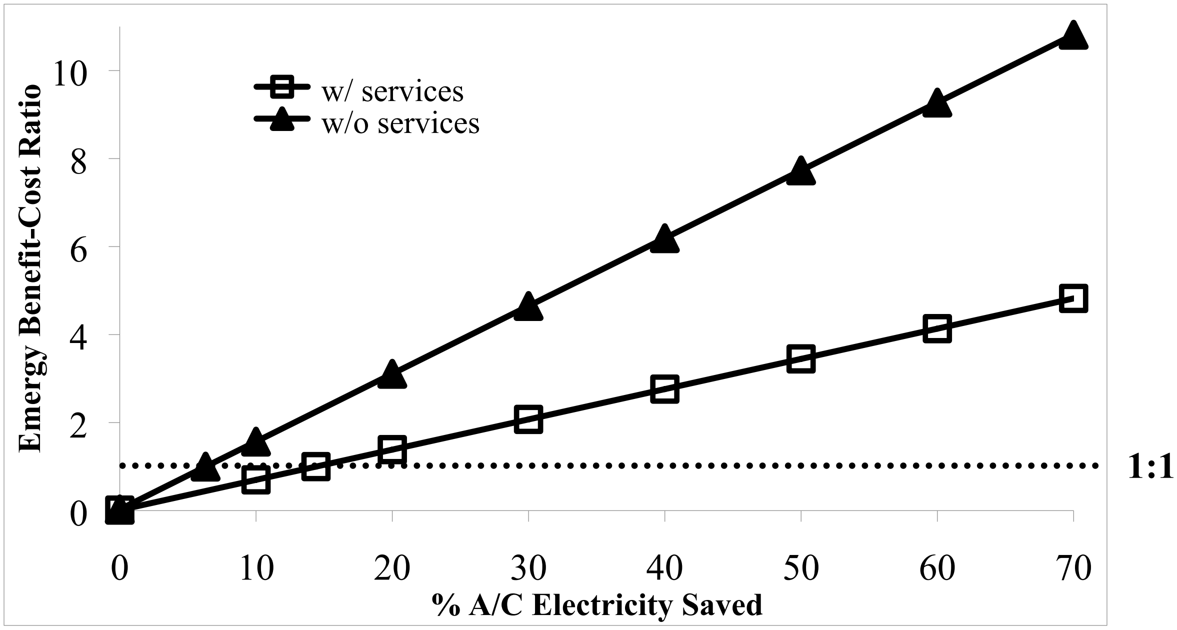



**Figure 22.** A/C electricity saved due to a green façade is not well known but has been estimated to be up to 70%. Not considering human services yields more than twice the benefit-cost ratio than if they are considered.

The emergy breakeven point for the recycled green façade is at the low end of the range with 14.4% of A/C electricity saved. If the A/C electricity saved were to reach the high end of the range (70%), the green façade benefits would outweigh the costs by nearly five times (Figure 22). Ignoring human services, the emergy breakeven point occurred when 6.3% of A/C electricity was saved by the green façade.

**Table 8.** Summary of emergy table.

| Item | Solar Emergy (sej/m$^2$/yr) E09 |
|---|---|
| Renewable Used | 3005 |
| Non-renewable Used w/ Services | 6766 |
| Non-renewable Used w/o Services | 1352 |
| Services Used | 5414 |
| Benefit, A/C electricity saved | 6715 |
| A/C saved per non-renewable (w/ Services) | 1.0 |
| A/C saved per non-renewable (w/o Services) | 5.0 |

This more than half reduction in the amount of A/C electricity saved necessary to reach the emergy breakeven point demonstrated the magnitude of the human services investigated in our study. Efforts to increase the sustainability of the green façade should be aimed at reducing costs and time spent maintaining it.

Rustagi et al. (2008) recently calculated a benefit-cost ratio of 0.116 for an extensive green roof with 20% of electricity saved. Our green façade benefit-cost ratio (1.39 at 20% of A/C electricity saved) was twelve times higher than this. Such a low benefit-cost ratio for the green roof reflected the high emergy materials that were used to construct it—they found the highly engineered drainage and growing media to account for over 90% of the total emergy consumption.

Climate is one of the primary factors affecting the amount of A/C electricity saved by a green façade due to factors such as solar geometry, cloudiness, and ambient air temperature. For example, a home in the high latitudes with a south-facing green façade could experience increased energy bills. These locations may have very few or no cooling days and the shading provided by the green façade may reduce solar energy inputs enough to require heat where it was not needed before. However, residents in the low latitudes, like in the southern US, could conceivably save the estimated maximum of 70% of A/C electricity under optimal conditions. The greatest benefit would most likely come from shading a very poorly insulated west wall that contains many windows and represents a large portion of the total cooling load for the home.

The solar orientation of the green façade will also have a large effect on the amount of A/C electricity saved. The addition of vegetation to the west and/or east wall or even the roof, as with the Green Cloak (Schumann and Tilley 2008), could further decrease A/C electricity consumption. Green façades may be particularly effective against west wall heat gain where direct afternoon sun exposure is exacerbated by high afternoon air temperatures.

A third factor that will affect A/C electricity saved by a green façade is the proportion of glazing to opaque surface a building has and how much the green façade shades that glazing. While there is a lack of experimental research on this factor, on-going research suggests that 10% A/C electricity saved can be achieved, but only when a significant portion of a building's heat gain was due to glazing and that glazing is subsequently shaded by the green façade (Price and Tilley, unpublished data).

A new transformity was derived for stainless steel based on its elemental concentrations of iron, chromium, nickel, manganese, and molybdenum. The transformity increased over six times to 4.61E10 sej/g with the addition of these rare metals (Table 9). Stainless steel compared to steel is extremely resistant to corrosion. In fact, within its 25-year lifetime the trellis considered in this study only lost 0.0000516% of its mass (Table 10). The mass lost was considered negligible and thus ignored in the recycling calculation. It was also calculated that 69% of the total energy was embodied in the stainless steel material itself and was able to be returned through material recycling (Table 11).

**Conclusions**

The emergy analysis of a south-facing green façade revealed that the total emergy consumed could be balanced by the electricity saved from reduced air conditioning if the cooling load was reduced by at least 14%. Thus, a green façade can recover the emergy consumed during its manufacturing, installation, maintenance, and decommissioning simply from saving electricity. Other benefits, such as habitat creation, noise mitigation, and reduction in the urban heat island effect were not part of the analysis, but would help to further balance the emergy consumption. Future emergy analyses should consider these benefits. In addition, the 14% cooling load reduction was specific to our green façade design and assumptions. For any specific application the breakeven point would depend on many factors including building size and shape, green façade size and orientation, and plant canopy thickness and cover.

With 98% of the energy embodied in the human services and stainless steel trellis, we encourage the use of alternative materials such as wood, natural fibers, or other low-emergy materials where possible. However, it should be noted that these materials may not last as long as stainless steel or other metals. Today's green façades can be made more eco-friendly by maximizing the emergy in benefits. To do this, learn as much about the building and site as much as possible. If unable to perform a cooling load calculation, note visually the parts of the building that receive direct sunlight and concentrate on shading those areas, particularly the windows.

**Calculations**

**TABLE 9. STAINLESS STEEL TRANSFORMITY CALCULATION**

Assumed Electric Arc Furnace (EAF) process able to make stainless steel similarly to regular steel with different alloy composition. Set up proportion equation to scale up the Steel, EAF process transformity with higher transformity metal elements. Alloy composition was simplified to the following metals: 67% Iron, 17% Chromium, 12% Nickel, 2% Manganese, 2% Molybdenum (AK Steel 2009).

Steel, EAF process transformity 4.19E09 sej/g from Buranakarn (1998, pg. 142)

4.19E09*1.68 = 7.04E09 sej/g corrected by a factor of 1.68 (Odum 2000)

Iron (Fe) transformity 1.20E10 sej/g from Cohen et al. (2006, pg. 16.6)

Chromium (Cr) transformity 1.50E11 sej/g “”

Nickel (Ni) transformity 2.0E11 sej/g “”

Manganese (Mn) transformity 3.50E11 sej/g “”

Molybdenum (Mb) transformity 7.0E11 sej/g “”

[ (Fe trans.)(Fe proportion) + (Cr trans.)(Cr prop.) + (Ni trans.)(Ni prop.) + (Mn trans.)(Mn prop.) + (Mb trans.)(Mb prop.) ] * (steel trans.) / (iron trans.) = (stainless steel transformity)

[ (1.20E10*0.67 + 1.50E11*0.17 + 2.0E11*0.12 + 3.50E11*0.02 + 7.0E11*0.02) ]*(7.04E09) / (1.20E10) = **4.61E10 sej/g**

**TABLE 10. STAINLESS STEEL LIFETIME CORROSION CALCULATION**

Mass loss from the stainless steel trellis over its lifetime was explored. This value was then used in the material recycling calculation (see Table 11). The average corrosion rate for grade 316 stainless steel is 0.1 mg/m$^2$/year (Herting et al. 2005). Surface area = 2 * π * r * L. Wetted area ratio (WA) for 7x7 (7 braided strands with each strand having 7 wires) stranded wire rope = 7:1 (Pisaturo 2009).

Exposed area of horizontal cables: (2)(π)(0.002 m)(10 m)(10 cables)(7 WA) = 8.796 m$^2$

Exposed area of vertical cables: (2)(π)(0.002 m)(5 m)(30 cables)(7 WA) = 13.195 m$^2$

Exposed area of posts: (2)(π)(0.015 m)(0.15 m)(40 posts) = 0.565 m$^2$

Exposed area of clamps: (2)(π)(0.02 m)(0.02 m)(300 clamps) = 0.754 m$^2$

Exposed area of bolts: (2)(π)(0.005 m)(0.1 m)(40 bolts) = 0.126 m$^2$

Total exposed surface area = 8.796 + 13.195 + 0.565 + 0.754 + 0.126 = 23.44 m$^2$

Lifetime corrosion = (23.44 m$^2$)(0.1 mg/m$^2$/year)(25 yr) / (1000 mg/g) = 0.0586 g

Percent mass loss = 0.0586 / 113636 = **5.16E-05 %**

**TABLE 11. STAINLESS STEEL RECYCLING CALCULATION**

Calculated recyclable portion of stainless steel using the emergy evaluation of Conventional Steel Product, EAF process for the entire U.S. from Buranakarn (1998, pg. 52). Assumed no material loss in trellis' 25-year lifetime (see Table 10).

| Item | Emergy (sej) 1.0E20 |
|---|---|
| Pig iron | 1283.00 |
| Natural gas | 152.38 |
| Other fuels | 18.51 |

| | |
|---|---|
| Electricity | 319.45 |
| Transport (Railroad) | 3.80 |
| Transport (Truck) | 72.34 |
| Labor | 18.98 |
| Annual Yield (Y) | 1867.60 |

% Recyclable is proportion of Pig Iron to Total Emergy Yield =1283 E20 sej / 1868 E20 sej = **69%**

**Footnotes to Table 7 Calculations**

The following calculations were made for a 50 $m^2$ stainless steel cable trellis green façade in the US state of Maryland with an expected lifetime of 25 years. The final unit for all calculations was per unit area per year.

1 Sun: Average annual solar radiation for "South Facing Vertical Flat Plate" located in Maryland, 3.50 kWhr/$m^2$/day (Solar Radiation… 2009). Average plant canopy absorption 80% (Campbell and Norman 1998).

Equation: (average insolation)(plant canopy absorption)

(3500 Whr/$m^2$/day)(60 sec/min)(60 min/hr)(365 day)(80% absorption) = **3.68 E09 J**

2 Rain: Average annual precipitation for Baltimore-Washington International (BWI) Airport (1871-2008), 42 inches (Baltimore Average… 2009). Used 3.06

E04 sej/J for the transformity which was 18,199 sej/J corrected by a factor of 1.68 (Odum et al. 2000).

Equation: (rainfall)(affected area)(Gibbs free energy)/(façade area)

(42 in)(0.0254 m/in)(10 $m^2$)(4.94 J/g)(1000 g/L)(1000 L/$m^3$)/(50$m^2$) = **1.05 E06 J**

3 Transpiration: Average total daily transpiration per unit leaf area 1.65 liters for grapevines in New York state (Dragoni et al. 2006). Leaf area for green façade estimated to be 3 (Schumann and Tilley 2008). We used a six-month growing season.

Equation: (LAI)(transpiration rate)(Gibbs free energy)(growing season length)

(3 leaf area)(1.65 L/day/$m^2$ leaf area)(4.94 J/g)(182.5 day/yr)(1000 g/L) = **4.46 E06 J**

4 Stainless Steel: 69% of value placed here as renewable due to recycling (see Table 11). The remaining 31% was added to the Non-renewable inputs (see footnote #11 in Table 7). Density of stainless steel 7.99 g/$cm^3$ (AK Steel 2009). Mass of stainless steel estimated by volume.

Equation: Volume cylinder = $\pi r^2 h$.

Volume of horiz. cables: ($\pi$)(0.002 m)$^2$(10 m)(10 cables) = 0.0012566 $m^3$

Volume of vertical cables: ($\pi$)(0.002 m)$^2$(5 m)(30 cables) = 0.001885 $m^3$

Volume of posts: ($\pi$)(0.015 m)$^2$(0.15 m)(40 posts) = 0.004241 $m^3$

Volume of clamps: ($\pi$)(0.02 m)$^2$(0.02 m)(300 clamps) = 0.006524 $m^3$

Volume of bolts: ($\pi$)(0.005 m)$^2$(0.1 m)(40 bolts) = 0.000314 $m^3$

Total mass = ($0.01422\ m^3$)($7990\ kg/m^3$)(1000 g/kg) = 1.14 E05 g

(1.14 E05 g)/(25 yr)/($50m^2$)(69%) = **6.27 E01 g**

5 Plants: Approximated emergy of plants using emergy in organic matter of potting mix from Leonard and Rangarajan (2007). Planted one plant per foot of wall length (Dunnett and Kingsbury 2008).

Equation: (mass organic matter)(energy in organic matter)

(1 plant/foot)(30 feet)(1 gal soil/plant)($3785\ cm^3$/gal)($0.3\ g/cm^3$)(0.5 g organic matter /g mix)(5.4 kcal/g organic matter)(4186 J/kcal)/(25 yr)/($50\ m^2$) = **3.08 E05 J**

6 Tap Water: Tap water used for three years after planting to establish root system. Estimated watering need, 1 inch/week during growing season.

Equation: (water depth)(Gibbs free energy)(ground area watered)/(25 yr)/($50\ m^2$)

(1 in/week)(26 weeks)(0.0254 m/in)(4.94 J/g)(1000 g/L)($1000\ L/m^3$)($10\ m^2$)/(25 yr)/(50 m2) = **2.60 E04 J**

7, 8, 9 Fertilizers: Spectrum Analytic (2009) recommends an average annual application of 100lbs K/acre, 50lbs P/acre, and 75lbs N/acre for grapes. The fertilizer is only needed for the first three years to establish complete façade coverage. We used a façade area of $50\ m^2$ instead of ground area to better estimate leaf area since the green façade is vertical. DAP = Di-ammonium phosphate fertilizer.

Equation: (application rate)(molar mass)(years applied)/(façade lifetime)

Potash: (1 acre / 4047 $m^2$)(100 lbs $K_2O$/acre/yr)(454 g/lb)(78 g/mol K/94 g/mol $K_2O$)(3 yr)/(25 yr) = **1.12 g K**

Phosphorus: (1 acre / 4047 $m^2$)(50 lbs P/acre/yr)(454 g/lb)(31 g/mol P/132 g/mol DAP)(3 yr)/(25 yr) = **0.158 g P**

Nitrogen: (1 acre / 4047 $m^2$)(75 lbs N/acre/yr)(454 g/lb)(28 g/mol N/132 g/mol DAP)(3 yr)/(25 yr) = **0.214 g N**

10 Fungicide: DeMarsay (2009) from the Maryland Cooperative Extension recommends roughly four ounces of fungicide per acre every ten days through the growing season. Transformity from Brandt-Williams (2001), 1.48 E10 sej/J corrected by 1.68 (Odum et al. 2000) to 2.49 E10 sej/J.

(1 acre/4047 $m^2$)(4 oz/acre/app.)(182.5 days/year)(1 app./10 days)(28.3 g/oz) = **0.510 g**

11 Stainless Steel: 31% of the value calculated in footnote #4 of Table 7.

(1.14 E05 g)/(25 yr)/(50$m^2$)(31%) = **2.82 E01 g**

12 Services: Total system cost estimated at $12-20 per square foot (Greenscreen 2009). Used low end of range because the system installed was very simple. A representative from Jakob-USA (pers. comm.), a cable trellis green façade company, confirmed the pricing estimate. The cost of system was divided into three parts: installation, product, and raw material. We assumed services needed to account for product costs only and that they were already embodied in both the

raw material and labor costs. We used the current AK Steel Stainless Steel Price List (2009) to estimate the commercial rate for stainless steel and used the prevailing wage rate for one general carpenter and one common laborer in Prince George's County, Maryland for installation labor rate ("Labor..." 2009).

Total system cost: (12 $\$/ft^2$)(10.76 $ft^2/m^2$)(50 $m^2$) = \$6456

Installation cost: (32 hr)(33.58 \$/hr + 21.35 \$/hr)/2 = \$879

Raw material cost: (1.14E05 g)(1 lb/454 g)(\$2.28 /lb) = \$571

Product cost: (\$6456 total) – (\$879 labor) – (\$571 stainless steel) = \$5006

(\$5006)/(25 yr)/(50 $m^2$) = **\$4.00**

13, 14 Labor: Maintenance and installation labor were estimated based on experience. Labor emergy calculated using EMERGY/individual method from Odum (1996) and restated in Campbell and Lu (2009). The façade was installed by a local contractor and his or her general laborer. Maintenance labor by the homeowner included pruning, applying fertilizer and fungicide, and watering.

Equation: (individuals)(time worked)(façade area)

Maintenance: (1 individual)(4 hr)(1/8760 hours/year)/(50 $m^2$) = **9.13 E-06 ind*yr$^2$**

Installation: (2 individuals)(2 days)(8 hours/day)(1/8760 hours/year)/(25 yr)/(50 $m^2$) = **2.92 E-06 ind*yr**

15 A/C Electricity Saved: South Atlantic (USA) average A/C electricity consumption 3467 kWh/year (EIA 2009). Used 10% of A/C electricity saved.

Equation: (annual A/C electricity consumption)(% electricity saved)/(façade area)

(3467 kWh/year)(10%)(3.6E6 J/kWh)/(50 $m^2$) = **2.5 E07 J**

16 Ecological Production: Estimated by transpiration to be **4.46 E06 J** (see footnote 3).

# Chapter 5: Conclusions

Growing vegetation on building walls has many benefits including reducing daily temperature extremes of the building's exterior surfaces and reducing the need for air conditioning in the summer. Few researchers have focused on how green façades reduce the whole-building cooling load and no studies originate from North America. The objectives of the research were to experimentally reinforce existing research on the cooling effects of green façades in North America, to model the effect of a green façade on hypothetical residential buildings' cooling loads, and to account for the sustainability of a green façade in an emergy analysis.

Based on data gathered from our experimental building, we concluded that adding vegetation to the south or west-facing wall effectively reduced the building's interior air temperature, exterior surface temperature, exterior ambient temperature, and heat flux through the wall on hot, sunny days (Chapter 2). Each of these values agreed reasonably well with those found in the literature. Every comparison between the south and west-facing wall favored the west wall. This was most likely because our measurements were made around June when the solar loading on the west wall was much higher than on the south due to a high sun angle. Later in the summer, when the air temperature is still high but the solar altitude is much lower, the differences due to orientation in the cooling effect of the green façade vegetation may be more equal.

In Chapter 3 we took experimental data from the building measurements (detailed in Chapter 2) and applied them to an ASHRAE cooling load model to translate the cooling effect of one wall covered with vegetation to the energy budget of the whole building. As modeled, our green façades had a minor effect (3.4 and 4.8% for south and west, respectively) on the peak cooling load of our experimental buildings in June. In order to further apply the knowledge gained by this model, I then changed the building characteristics and created new models for two hypothetical residential buildings. These models were more realistic in that they accounted for heat gains due to people, appliances, and through windows. The results from these models varied greatly depending on orientation and whether or not the building's windows were covered. Overall, if windows made up a large part of the whole-building cooling load, then covering the building's opaque wall surfaces had little effect (1.4 – 3.4% reduction in whole-building peak cooling load). However, when we covered the windows with vegetation, which is very rare in real-world installations, the peak cooling load was reduced by a much larger amount (7.8 – 28.4%).

In Chapter 4 we determined the amount of renewable and non-renewable embodied energy required to manufacture, install, maintain, and decommission a 50 $m^2$ green façade in a temperate climate on a hypothetical residential home. The model system consisted of a stainless steel trellis mounted to the south façade of an existing building with its plants rooted in the ground. The solar emergy required to manufacture, install, maintain, and decommission the green façade was 9.8 E12 sej/$m^2$/yr, with nearly 55% embodied in human services, 14% in non-renewable materials, and 31% in renewable materials. Depending on how much A/C electricity could be saved, the benefit of the green façade ranged from 0 to 5 times the total solar emergy cost. If 10% of A/C electricity was saved, the green façade had an emergy return on emergy invested for its non-renewable materials of five. However, inclusion of the emergy invested as human services in this ratio reduced it to 1.0. These results suggested that the emergy benefit of a green façade was highly sensitive to its effect on building cooling load and total lifetime costs.

Installing a green façade on the south or west-facing wall of a building in North America has many benefits including cooling the building's interior and exterior environment. The whole-building cooling load reduction benefit may vary greatly depending on the green façade's placement on the building, geographic location, building construction, and plant canopy development. Taking into consideration that few new green façades cover the building's windows, the whole-building cooling load benefit is significantly less than previously thought.

It is our hope that the research presented in this thesis contributed valuable new information to fellow green façade researchers, designers, installers, and proponents. It was our intention to provide replicated experimental data for a North American climate and to present models that realistically estimate the whole-building cooling load benefit. Considering this new information, we challenge designers to find new and innovative ways to cover the building's windows while allowing daylight penetration at the right time and in the right place.

**Future Work**

A lot of time was spent on the project designing and constructing the buildings and instrumentation to be flexible so that Dr. Tilley and future students could expand upon the project. I would like to suggest the following list of topics for future research using these buildings.

- Add thermistors to every wall surface, at least on the interior walls, to allow calculation of the heat flux into the building through every surface. These data can be used to validate a model that completely accounts for the heat content and flow in the building. We were only able to assume that the north wall and floor, for instance, were letting a significant amount of heat out of the building during all hours of the day.

- Combine the green façade concept with Dr. Tilley's green cloak idea that was discussed in Laura Schumann's 2007 thesis. There are many ways to incorporate vegetation onto the experimental buildings, and doing so with the addition of adding thermistors to every surface could allow for a powerful analysis of heat flux and the abilities of the green cloak to perhaps eliminate the need for air conditioning.
- Adding small room-scale air conditioner units to each building and directly recording energy consumption with a power meter on each building would be the best way to estimate reduction in energy use due to green façade vegetation. This would be particularly useful for calculating an annual or whole-season budget and would help eliminate many of the uncertainties in the ASHRAE cooling load model. One major limitation of the ASHRAE cooling load model is that it estimates annual energy consumption from the peak cooling load and the cooling degree-day method making a number of large assumptions along the way.
- The folks at Green Roofs for Healthy Cities would like to see data on how the green façade vegetation affects building materials other than those in a wood-framed house. While brick and concrete are very easy to integrate into the ASHRAE cooling load model, further funding is needed to actual construct and test these materials at the experimental building site.

- It would be very useful to estimate the thermal resistance (R-value) of the green façade vegetation. The R-value concept is easily understood and could go a long way towards communicating the effects of vegetation on a building's thermal environment to non-technical audiences.
- Repeating all data analyses for August or September would help further compare the cooling effects of the vegetation between building orientations. As stated before, the solar geometry later in the summer is very different while air temperatures are still high making a south-facing green façade a potentially more favorable design choice.

# References


Alexandri, E. and P. Jones 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment* 43: 480-493.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) 2001. 2001 ASHRAE Handbook: Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Akbari, H., M. Pomerantz, and H. Taha 2001. Cool surfaces and shade trees to reduce energy use and improve air quality in urban areas. *Solar Energy* 70(3): 295–310.

AK Steel. 2009. Product Data Sheet: 316/316L Stainless Steel. Last Accessed: December 31, 2009. < <http://www.aksteel.com/>.

AK Steel. 2009. Stainless Steel Price List. Last Accessed: January 1, 2010. <http://www.aksteel.com/>.

"Average Retail Price of Electricity to Ultimate Customers by End-Use Sector, by State" 2010. Energy Information Administration (EIA), United States. Last Accessed: October 21, 2010. <http://www.eia.doe.gov/electricity/epm/table5_6_a.html>.

Balcomb, J.D. (editor) 1992. Passive Solar Buildings, The MIT Press, Cambridge, Massachusetts.

Baltimore Average Monthly Precipitation (since 1871). 2009. Maryland State Climatologist Office. Accessed December 30, 2009. <http://metosrv2.umd.edu/~climate/Weather/marylandnormals.htm>.

Bass, B. 2001. Reducing the urban heat island and its associated problems: Examining the role of green roof infrastructure. *The Green Roof Infrastructure Monitor* 3(1): 10-12.

Bobenhausen, W. 1994. Simplified design of HVAC systems. John Wiley & Sons, Inc. New York, NY.

Brown, M.T. and J. Arding. 1991. Transformities Working Paper. Center for Wetlands, University of Florida, Gainesville.

Buranakarn, V. 1998. Evaluation of recycling of building materials using the emergy analysis method. Ph.D. dissertation. University of Florida. 258.

Campbell, D.E. and H. Lu. 2009. The Emergy to Money Ratio of the United States from 1900 to 2007. Emergy Synthesis 5:Theory and Applications of the Emergy

Methodology. Center for Environmental Policy, University of Florida, Gainesville.

Campbell, G.S. and J.M. Norman. 1998. An introduction to environmental biophysics. Springer-Verlag, New York.

"Central Air Conditioners" 2010. Energy Efficiency and Renewable Energy: Energy Savers. U.S. Department of Energy. Last accessed October 18th, 2010. <http://www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12440>

Cohen, M.J., S. Sweeney, and M.T. Brown. 2006. Computing the unit emergy value of crustal elements. Emergy Synthesis 4: Theory and Applications of the Emergy Methodology. Gainesville, Florida. 16.1-16.12.

Currie, B.A. and B. Bass. 2008. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. *Urban Ecosystems* 11(4): 409-422

DeMarsay, A. 2009. Guidelines for developing an effective fungicide spray program for wine grapes in Maryland. Maryland Cooperative Extension. 12pp.

Di, H.F. and D.N. Wang 1999. Cooling effect of ivy on a wall. *Experimental Heat Transfer* 12: 235-245.

Dragoni, D., A.N. Lakso, R.M. Piccioni, and J.M. Tarara. 2006. Transpiration of grapevines in the humid northeastern United States. *American Journal of Enology and Viticulture* 57(4): 460-467.

Dunnett, N. and N. Kingsbury 2008. Planting green roofs and living walls. Timber Press. Portland, OR.

Energy Information Administration (EIA), United States. 2009. "South Atlantic Household Electricity Report." Last Accessed: December 28, 2009. <http://www.eia.doe.gov/emeu/reps/enduse/er01_so-atl.html>.

Eumorfopoulou, E.A. and K.J. Kontoleon 2009. Experimental approach to the contribution of plant-covered walls to the thermal behaviour of building envelopes. *Building and Environment* 44: 1024-1038.

Fang, C. 2008. Evaluating the thermal reduction effect of plant layers on rooftops. *Energy and Buildings* 40: 1048-1052.

Gates, D.M. 1980. Biophysical Ecology. Dover Publications, Inc. Mineola, New York.

Green Roofs for Healthy Cities (GRHC). 2008. Introduction to green walls: technology, benefits and design. Last Accessed: September 2008. <http://www.greenroofs.net/ >.

Greenscreen. 2009. Resources and downloads: Frequently asked questions. Last Accessed: December 2009. <http://www.greenscreen.com/home.html>.

Herting, G., I.O. Wallinder, and C. Leygraf 2005. A comparison of release rates of Cr, Ni, and Fe from stainless steel alloys and the pure metals exposed to simulated rain events. *Journal of The Electrochemical Society* B23-B29.

Hien, W.N., T.P. Yok, and C. Yu 2007. Study of thermal performance of extensive rooftop greenery systems in the tropical climate. *Building and Environment* 42: 25-54.

Holm, D. 1989. Thermal improvement by means of leaf cover on external walls—A simulation model. *Energy and Buildings* 14: 19-30.

Hoyano, A. 1988. Climatological uses of plants for solar control and the effects on the thermal environment of a building. *Energy and Buildings* 11: 181-199.

Ip, K., M. Lam, and A. Miller 2010. Shading performance of a vertical deciduous climbing plant canopy. *Building and Environment* 45: 81-88.

Kontoleon, K.J. and E.A. Eumorfopoulou 2010. The effect of the orientation and proportion of a plant-covered wall layer on the thermal performance of a building zone. *Building and Environment* 45: 1287:1303.

Köhler, M. 2008. Green Facades—a view back and some visions. *Urban Ecosystems* 11(4): 423-436.

Kumar, R. and S.C. Kaushik 2005. Performance evaluation of green roof and shading for thermal protection of buildings. *Building and Environment* 40: 1505-1511.

Labor, Licensing, and Regulation, Maryland Dept. of. 2009. Prevailing wage informational rates. <http://www.dllr.state.md.us/PrevWage/PWRequestRates.aspx>.

Leonard, B. and A. Rangarajan. 2007. Organic Transplant Media and Tomato Performance. Cornell University. 6.

Lundholm, J.T. 2006. Green roofs and facades: A habitat template approach. *Urban Habitats* 4(1): 87-101.

McQuiston, F.C. and J.D. Parker 1994. Heating, Ventiliation, and Air Conditioning: Analysis and Design. John Wiley & Sons, Inc. New York, NY.

National Climatic Data Center (NCDC). 1998. Climatic Wind Data for the United States. US National Oceanic and Atmospheric Administration. <http://www.ncdc.noaa.gov/oa/mpp/wind1996.pdf>.

Odum, H.T. 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley and Sons. New York.

Odum, H.T., M.T. Brown, and S.L. Brandt-Williams. 2000. Folio #1: Introduction and global budget. Handbook of Emergy Evaluation: A compendium of data for emergy computation issued in a series of folios. Center for Environmental Policy, University of Florida, Gainesville.

Palomo Del Barrio, E. 1998. Analysis of the green roofs cooling potential in buildings. *Energy and Buildings* 27: 179-193.

Peck, S.P., C. Callaghan, M.E. Kuhn, and B. Bass. 1999. Greenbacks from greenroofs: forging a new industry in Canada. Canada Mortgage and Housing Corp. Toronto, Canada.

Pisaturo, C. 2009. Works of Carl Pisaturo: Materials notes: Epoxy. Last Accessed January 1, 2010. <http://www.carlpisaturo.com/_MaNo_EPOX.html>.

Roehr, D., J. Laurenz, and Y. Kong. 2008. "GREEN ENVELOPES: Contribution of green roofs, green façades and green streets to reducing stormwater runoff, CO2 emissions and energy demand in cities." *2008 International Low Impact Development Conference.* ASCE. Seattle, WA.

Rustagi, N., D.R. Tilley, and J. Schramski. 2009. Total energy requirements of a living extensive green roof. Manuscript submitted to: Emergy Synthesis 5. University of Florida, Center for Environmental Policy, Gainesville.

Schumann, L. 2007. Ecologically Inspired Design of Green Roof Retrofit. M.S. Thesis, Biological Resources Engineering, University of Maryland, College Park. 269 pp. <http://hdl.handle.net/1903/7399>.

Schumann, L.M. and D.R. Tilley. 2008. Green vine canopies for restoring ecological benefits to all urban surfaces. 8th Annual meeting of the American Ecological Engineering Society, June 11-13, Blacksburg, VA. (presentation)

Solar Radiation Resource Maps, United States. 2009. National Renewable Energy Laboratory. Last accessed: December 28th, 2009. <http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/atlas/Table.html>.

Spectrum Analytic Inc. 2009. A Guide to Fertlizing Grapes. <http://www.spectrumanalytic.com/>.

"South Atlantic Household Electricity Report." 2006. Energy Information Administration (EIA), United States. Last Accessed: October 21, 2010. <http://www.eia.doe.gov/emeu/reps/enduse/er01_so-atl.html>.

Takebayashi, H. and M. Moriyama 2007. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Building and Environment* 42: 2971-2979.

Thoennessen, M. 2002. Elementdynamik in fassadenbegrünendem Wilden Wein. *Kölner Geograph. Arbeiten Heft* 78: 1–110.

Tilley, D.R. 2006. National metabolism and communications technology development in the United States, 1790-2000. *Environment and History* 192(3-4): 327-361.

Tilley, D.R., L.M. Schumann 2008. Vine Inspiration: living canopy covers over roofs help mitigate urban stormwater problems. *Living Architecture Monitor* 10(2): 21-23.

Ulrich, R.S. 1984. View through a window may influence recovery from surgery. *Science, New Series* 224(4647): 420-421.

Wong, N.H., Y. Chen, C.L. Ong, and A. Sia 2003. Investigation of thermal benefits of rooftop garden in the tropical environment. *Building and Environment* 38: 261-270.

Wong, N.H., A.Y.K. Tan, Y. Chen, K. Sekar, P.Y. Tan, D. Chan, K. Chiang, and N.C. Wong 2010. Thermal evaluation of vertical greenery systems for building walls. *Building and Environment* 45: 663-672.