Food Producing Façades Key to A Sustainable Future

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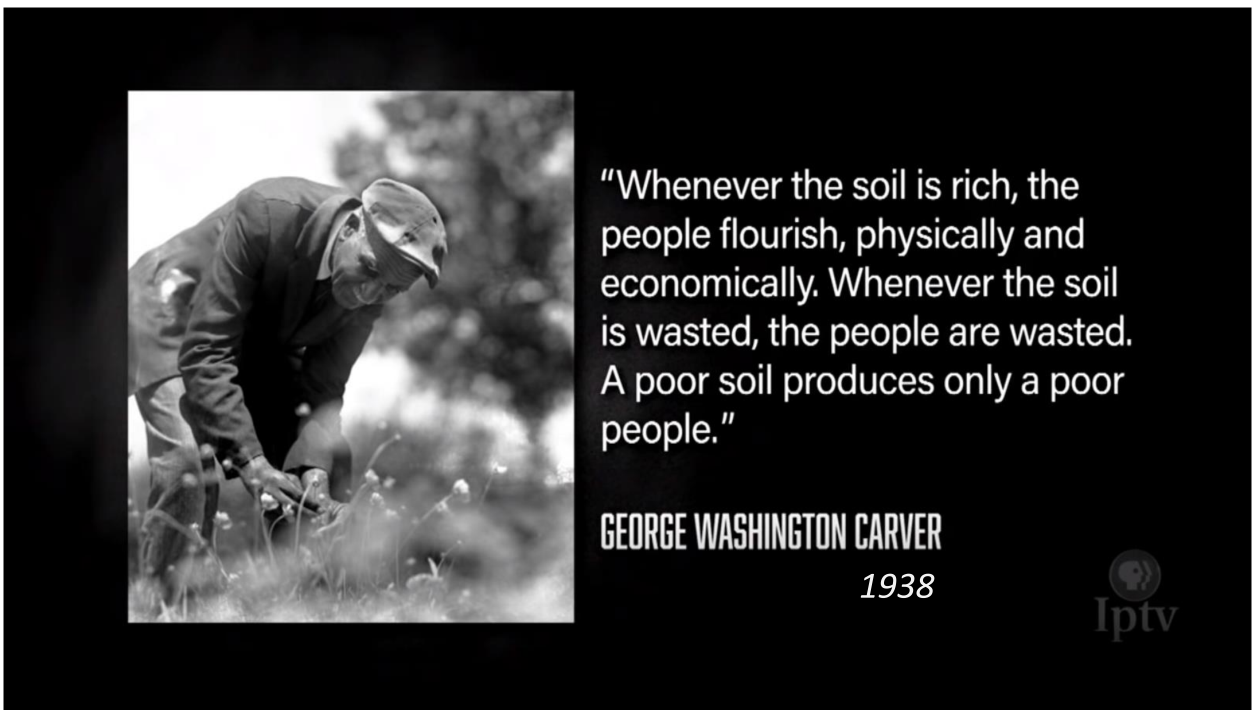
Acknowledgements

"Population must increase rapidly--more rapidly than in former times--and ere long the most valuable of all arts, will be the art of deriving a comfortable subsistence from the smallest area of soil."

Abraham Lincoln, 1859

Excerpt from An Address by Abraham Lincoln Before the Wisconsin State Agricultural Society in Milwaukee, Wisconsin, September 30, 1859



Excerpt from George Washington Carver: An Uncommon Life, Iowa Public Television, Youtube, May 8, 2018, https://www.youtube.com/watch?v=_3CVmluYFtI

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Abstract

The built environment uses significant and increasing amounts of energy, more than 1000 times the energy density per unit area of the natural environment, contributing to Urban Heat Island effect. Simultaneously, population growth and urban development have outpaced food production globally. In response, there has been a growing trend to further develop the ancient tradition of incorporating plants into the built environment via green roofs, green façades, urban agriculture and other green infrastructure. Research is limited, however, into the application of growing food producing plants on a living façade to improve total building performance. This dissertation investigates the role of integrating food producing plants into a living façade to positively impact four outcomes: food production, thermal performance, air quality and rain water management, in a temperate climate.

The design, construction, operation and end-of-life disassembly and recycling of a food producing living façade on the south and west of the Robert L. Preger Intelligent Workplace at Carnegie Mellon University successfully demonstrates the critical value of living façades for this climate. A maximum average production of 2.64 kilograms of produce per square meter of façade panel can be generated annually (0.54 lbs./ft^2) which could effectively meet 9% of summer nutritional demands for building occupants. The façade temperatures can be reduced between 10^oF-36.95^oF (5.56^oC-20.53^oC) with approximately 20% reductions in cooling energy, and positive impact on reducing urban heat island. A living façade can effectively remove pollutants from the natural ventilation air stream, measured at a maximum of 5.6% reduction in $PM_{2.5}$ for the living façade compared to the control. An average of 14.26 liters of rainwater per square meter of façade per day (0.35 gal/ft^2/day) can effectively redirect all the rainfall on the roof from storm drains into primary irrigation. In addition, field observations revealed enhanced access to nature for building occupants, wildlife habitat and biodiversity.

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Glossary of Terms

***Adiabatic* -** Relating to or denoting a process or condition in which heat does not enter or leave the system concerned.

***Albedo* -** The proportion of the incident light or radiation that is reflected by a surface.

***Anthropocene* -** The current geological age, viewed as the period during which human activity has been the dominant influence on climate and the environment.

***Ascending Energy* -** An inverse energy cascade, a transfer of energy from the small scale to the large scale, oftentimes using waste energy from one process to fuel the needs of another. Cascading energy flows, energy flowing as waste after initial use from one process, release energy, whereas ascending energy flows, harnessing waste energy flows from one process to drive ascending energy needs required for another use, consume energy.

***Bioclimatic* -** Relating to the interrelation of climate and the activities and distribution of living organisms.

***Biophilia* -** The term coined by the Harvard naturalist Dr. Edward O. Wilson to describe what he saw as humanity's "innate tendency to focus on life and lifelike processes," (Wilson, 1984); to be drawn toward nature, to feel an affinity for it, a love, a craving or a hypothetical human tendency to interact or be closely associated with other forms of life in nature: a desire or tendency to commune with nature.

***Bioregenerative* –** Plants, animals, and especially microorganisms regenerate, recycle, and control life's necessities (Odum, 1993).

***BioWall* –** A vegetated wall that naturally filters air and removes several harmful pollutants.

***Cascading Energy* -** In continuum mechanics, an energy cascade involves the transfer of energy from large scales of motion to the small scales (called a direct energy cascade) or a transfer of energy from the small scales to the large scales (called an inverse energy cascade). This transfer of energy between different scales requires that the dynamics of the system is nonlinear. Strictly speaking, a cascade requires the energy transfer to be local in scale (only between fluctuations of nearly the same size), evoking a cascading waterfall from pool to pool without long-range transfers across the scale domain.

***Cooling Load* -** The amount of heat energy that would need to be removed from a space (cooling) to maintain the temperature in an acceptable range.

***Cultural Services* –** The non-material benefits people obtain from ecosystems including aesthetic inspiration, cultural identity, sense of home, and spiritual experience related to the natural environment.

***Ecosystem Services* -** The benefits that people obtain from ecosystems including provisioning services such as food and water, regulating services such as flood and disease control, supporting services such as nutrient cycling that maintain the condition of life on Earth, and cultural services such as spiritual, recreational and cultural benefits.

Green Façade **-** A green facade is created by growing climbing plants up and across the facade of a building, either from plants grown in garden beds at its base, or by container planting installed at different levels across the building.

Green Infrastructure **-** A network providing the "ingredients" for solving urban and climatic challenges by building with nature

Green Wall **-** A green wall is comprised of plants grown in supported vertical systems that are generally attached to an internal or external wall, although in some cases can be freestanding. Like many green roofs, green walls incorporate vegetation, growing medium, irrigation and drainage into a single system. Green walls differ from green facades in that they incorporate multiple "containerized" plantings to create the vegetation cover rather than being reliant on fewer numbers of plants that climb and spread to provide cover. They are also known as "living walls", "bio-walls" or "vertical gardens".

Heat Gain **-** Heat gain is the term given to a temperature rise within a space due to heat from the sun (solar radiation), heat from surfaces (long wave infrared radiation), heat originating from other sources within the space (such as heating appliances, ovens, people, mechanical systems, lights and computers) and so on. It is the heat that is gained from such sources that changes the prevailing temperature within the space.

Holocene **-** The current geological epoch. It began approximately 11,650 calendar years before present, after the last glacial period. The Holocene corresponds with rapid proliferation, growth and impacts of the human species worldwide, including all of its written history, technological revolutions, development of major civilizations, and overall significant transition towards urban living in the present.

Living Façade **-** A vertical surface incorporating vegetation into its structure or face to facilitate various aesthetic, environmental, social or economic functions and benefits.

Living Wall **-** A wall covered with plants that are growing in containers or on special material attached to the wall, often used when there is not much space to grow things on the ground:

- *A living wall can be a place to experiment, just like in a garden.*
- *Water is fed from the top of a living wall, emulating the natural world.*

Particulate Matter ***$PM_{2.5}$*** **-** Airborne particulate matter (PM) is not a single pollutant, but rather is a mixture of many chemical species. It is a complex mixture of solids and aerosols composed of small droplets of liquid, dry solid fragments, and solid cores with liquid coatings. Particles vary widely in size, shape and chemical composition, and may contain inorganic ions, metallic compounds, elemental carbon, organic compounds, and compounds from the earth's crust. Fine particulate matter is defined as particles that are 2.5 microns or less in diameter ($PM_{2.5}$).

Particulate Matter Primary **-** Particles that are directly released into the atmosphere by wind, combustion processes, or human activities.

Particulate Matter Secondary **-** Particles that form in the atmosphere from other gaseous pollutants, particularly sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds

Provisioning Services **-** The tangible products that people obtain from ecosystems. These include food, water, raw materials, energy and genetic resources.

***Regulating Services* -** Ecosystem processes that maintain environmental conditions favorable to life. The most important of these are the cycling of substances and ensuring of the reproduction of organisms. Some regulating services are less vital, but still beneficial to humans such as the abatement of noise and pollution by trees and plants in cities.

***Sol-Air Temperature* -** The temperature that, under conditions of no direct solar radiation and no air motion, would cause the same heat transfer into a house as that caused by the interplay of all existing atmospheric conditions.

***Supporting Services* –** Those ecosystem services that are necessary for the production or the maintenance of all other ecosystem services

***Vertical Greenery System (VGS)* -** Structures that allow vegetation to spread over a building facade or interior wall.

Chapter 1. Living Systems Integration: Nature, Agriculture and Architecture

1.1 Overview

Ninety-Seven years ago, architect Le Corbusier declared that "a house was a machine for living in" (Etchells & Corbusier, 1968). This metaphor captured the essence of the industrial age, where innovations in technology and engineering were revolutionizing society. At the same time a new understanding of nature was also evolving. New terms such as Ecology (Ernst Haeckel, 2019) and Ecosystem (Ecosystem, 2019) were proposed to describe the relationship between organisms and the surrounding living (biotic) and non-living (abiotic) environment. Frank Lloyd Wright developed what he called Organic Architecture, defined as working with the nature of the site, the nature of materials and the nature of the client to develop suitable spaces for living, working and worshipping (Organic Architecture, 2020)

After World War II, the first analysis of the environmental forces that shape American architecture was published (Fitch, 1972). Victor and Aladar Olgyay began writing a series of books in the 1950's and 60's exploring the idea of a climate-based approach to designing human environments based on the human comfort zone, the ideal human environment in terms of temperature and humidity. There was a growing realization that we too, as human beings, are organisms within a living and non-living environment. The Olgyays advocated for a bio-climatic approach to design, where climate was the basis for the development of architectural form, massing and orientation. Only after the building was designed with consideration of the local climate, using energy conservation and passive renewable energy strategies, would fossil fuel powered active mechanical systems be employed for heating and cooling during peak seasons.

The Center for Building Performance and Diagnostics (CBPD) was established in the School of Architecture at Carnegie Mellon University (CMU), creating one of the first programs in the United States asserting that Building Systems Integration and Indoor Environmental Quality in design are the means for measuring, assessing and enhancing Total Building Performance, while forging innovative solutions for the built environment.

The performance of the building, in terms of providing suitable thermal, visual, spatial, acoustic and air quality, became the primary metrics for determining total building performance. The ability for the indoor environment to provide for the basic environmental needs for the occupants, to maintain health and productivity, while improving energy efficiency and environmental effectiveness, is the measure of a high-performance building.

In a TED talk in 2009, the late Ray Anderson, reviewed his process for moving his company from the take-make-waste linear process of manufacturing with its unintended waste and pollution production, to a cyclical process run solely on renewable energy and creating no waste to make his products (Anderson R. C., 1998).

In his talk, Anderson used Paul and Anne Ehrlich's Environmental Impact Equation to explain the strategy for moving his company to what he called the "new industrial revolution". To transform the Erhlich's original equation, I=PxAxT, where I is impact, P is population, A is affluence and T is technology, to this new conceptualization requires moving technology from the numerator, where it multiplies environmental impact, to the denominator where it reduces environmental impact. This requires transforming current manufacturing and production processes from:

- Extractive to renewable
- Linear to cyclical
- Fossil Fuel to renewable
- Wasteful to waste-free
- Abusive to benign
- Labor productivity to Resource Productivity (Anderson R. , 2009)

This shows how this trend toward the new industrial revolution requires an ecosystems approach to transform our technologies from a magnifier to a mitigator of environmental impact. The CBPD and others, contributed to the development of high-performance guidelines for systems integration and building performance. The *10 Strategies for Living, Bio-Climatic Façades for Human Health and Performance* established by the CBPD are designed to help architects make the transition to practicing this new approach to building design, construction, operation and decommissioning (Center for Building Performance and Diagnostics Carnegie Mellon University, 2010). The ten strategies are:

1. Access to nature
2. Daylighting
3. Natural Ventilation
4. Heat Loss / Heat Gain Control
5. Solar Heat and Glare Control
6. Load Balancing Heat & Power Generation
7. Passive and Active Solar
8. Water Management
9. Enclosure Life
10. Systems Integration

This author would argue that one additional goal should be added – food production. Today it can be stated that a building is not a machine for living in, but an organism within an urban ecosystem, through which energy flows and nutrients cycle. McDonough and Braungart have called this concept *Celebrating our Human Footprint A Building like a Tree, A City like a Forest* (Braungart, 2012). This energy flow and nutrient cycling generated by the construction and operation of the building is the building's metabolism, "the set of life-sustaining chemical reactions in organisms" (Metabolism, 2019). Metabolism has three main functions:

1. The conversion of food/fuel to energy to run cellular processes
2. The conversion of food/fuel to building blocks, proteins, lipids, nucleic acids and some carbohydrates
3. The elimination of nitrogenous wastes

The metabolism of a building is similar; it runs the building and business processes, fuels the building and business output of office work and manufacturing, and provides for the elimination of wastes. These metabolic reactions can be put into two categories:

1. Catabolic, or the breaking down of compounds
2. Anabolic, or the building up of compounds

Catabolic reactions usually release energy and anabolic reactions usually consume energy. The designer can work to harness the catabolic and anabolic reactions in the building processes to recapture, recycle and reuse this energy thereby improving energy efficiency and environmental effectiveness.

In the book *Ecology and Our Endangered Life Support Systems*, Eugene Odum (1993) wrote that the built environment used more than one thousand times the energy per unit area of a climax ecosystem. In defining human life support systems, Odum (1993) introduced the proposition that there are only three landscapes on Earth:

1. The Fabricated Landscape or Built Environment
2. The Cultivated Landscape or Agricultural Environment
3. The Natural Landscape or Natural Environment

He further went on to state that it was the agricultural environment and the natural environment that, when added together, provided our Life Support Systems. He based this on the fact that the Earth is *"bioregenerative meaning that plants, animals and especially microorganisms regulate, recycle and control life's necessities"* (Odum, 1993, p. 6). In his analysis the built environment was described as a parasite on these other two environments. Biologist and urban planner Patrick Bel Geddes, a century earlier, noted that the industrial city destroyed the green countryside like so much "mould upon the jam-pot" (Lyle, 1994, p. 13).

This growing body of work has begun to transform the prevailing industrial paradigm to a realization that nature provides ecosystem services that create value and are the source for our economy and our very life needs. These ecosystem services are defined as:

- Provisioning services, food, fresh water, fuel, fiber and other goods
- Regulating services, climate, water, disease regulation and pollination
- Supporting services, soil formation and nutrient cycling
- Cultural services, educational, aesthetic, cultural heritage, recreation and tourism (Millennium Ecosystem Assessment, 2005)

In an interview in 1992, Landscape Architect and Professor John. T. Lyle summarized this concept.

> *"…what we have to do is to learn how to make all those processes happen within the human environment; which means restoring the landscape to the city. … We have to put the landscape to work again. We have to redesign the landscape so that it processes our water, processes our waste, converts our energy and does all these things as much as possible in the urban environment itself. The city of the 21st century will be a collection of communities. And I see the working landscape as being a kind of network of landscape that flows through that collection of communities and helps to define them."* (AIA, 1992).

As each building is recognized as an organism capable of providing ecosystem services to the community, the community itself is transformed into a functioning urban ecosystem, providing ecosystem services. The building, in effect, becomes a tree and the community becomes a forest. Each building can begin to transform the liability it poses to the community through importing fossil fuel energy and materials and exporting waste, into a community asset by harnessing energy flows and nutrient cycles, using the waste released from one process to provide the energy required for another. The bi-products of such a process would be increased local food production, reduced façade surface temperature, improved air quality in terms of reduced small particulate levels, and reduced storm water runoff.

The Center for Building Performance and Diagnostics (CBPD) in the School of Architecture (SoArch) at Carnegie Mellon University (CMU) began to research these concepts and integrate them into the architecture curriculum emphasizing systems integration by design and developing the Total Building Performance Matrix. Human Performance Criteria indicating overall indoor environmental quality are Thermal, Spatial, Visual, Acoustic, and Air qualities as well as Building integrity.

Culinary performance, or the sensory quality of taste, including gustation and gastro-intestinal processes, are proposed to be included in the matrix due to the huge environmental and resource implications of food production, food waste and human waste. The resources used by these processes provide a significant opportunity for harnessing waste heat, water, energy and nutrient flows to improve efficiencies and performance across all the systems of the building, including the site, structure, enclosure, interior, mechanical, energy and water systems. Strategizing how specific building systems will provide specific human performance criteria, allows for integration between systems to harness the building metabolism.

Bringing a productive working landscape into the city, right up onto the building façade itself, to provide provisioning, regulating, supporting, and cultural ecosystem services directly to the built environment, is possible and can significantly reduce the ecological footprint of individual buildings and the larger neighborhood. Through this process, the building façade is transformed from a static, barren, brutal, desert-like environment of temperature extremes, to a dynamic, lush, productive environment of relative temperature stability. Reducing the extreme temperature difference between inside and outside is key to reducing heat gain/heat loss and therefore energy use. The main focus of this study is measuring, recording and verifying the performance of a food producing living façade installed on the façade of the Intelligent Workplace at CMU to reduce peak façade surface temperature in summer, improve air quality by reducing small particulates ($PM_{2.5}$), and collect, store and utilize rain water for irrigation.

This dissertation presents the design, fabrication, installation, operation and performance of this concept of a food producing living façade. This growing body of literature and research is crucial because these issues and the focus on incorporating living systems into the built environment are only going to continue to increase over time.

Chapter 2. The Key Challenges Addressed by Food Producing Facades

One response to the trends introduced in chapter one has been the creation of green infrastructure within urban environments, utilizing living systems and the ecosystems services they provide, to moderate, remediate or even eliminate negative environmental impacts due to development. The idea of bringing plants and aspects of nature into the city is as old as the hanging gardens of Babylon. It is only in the late twentieth and early twenty-first centuries that this concept has matured into a strategy for incorporating plants and living systems into a performance-based approach to the design and function of the built environment. This includes the introduction of urban agriculture not only on land within the city, but also on top of and integrated with green roofs and green facades on local commercial and residential buildings. This new approach of bringing productive natural and agricultural environments directly into the city, integrated within the building envelope itself, provides a new opportunity to increase food producing landscapes on previously unproductive urban surfaces.

In the class Building Performance Modelling, in the Fall of 2008 at CMU, Professor Khee Poh Lam made a presentation titled, *Environmental Aspects of Building Design*, where he discussed the relationship between the first and second laws of thermodynamics and living systems. The first law, or the law of conservation of energy, states that energy is neither created nor destroyed, but transforms from one form to another, and that the total amount of energy is always conserved. The second law, or law of entropy, states that nature works to minimize potentials, thus maximizing entropy, where entropy is defined as the amount of heat per unit of temperature available for doing useful work.   According to this view, the second law is known as the law of disorder. A new understanding, based on an expanded view of thermodynamics developed over the last two decades, proposes that the spontaneous production of order from disorder is the expected consequence of these basic laws.

> *"Rather than being infinitely improbable 'debt payers' struggling against the laws of physics in a 'dead' world collapsing to equilibrium and disorder, living things and their active, end directed striving or intentional dynamics can now be seen as productions of an active order producing world following directly from natural law."* (Lam, 2008, p. 7)

Living systems, as open systems which need external energy sources to be created and maintained, provide the best pathway for the energy available within the immediate environment, from sun, wind, rain and soil, to most quickly minimize potentials, thus maximizing entropy.   In that same class Professor Lam made another presentation called *Urban Heat Island*, which was a complete overview of the multi-year, multi-phase project to study Urban Heat Island effect and potential solutions in Singapore and Hong Kong. This research project looked at the use of living systems on building roofs to reduce entropy by providing a pathway for the energy reflected and rejected by the buildings and built environment of Singapore, which would otherwise achieve equilibrium by increasing the urban temperature.

An analysis of the thermal performance benefits of various roofing surfaces including a hard surface, and surfaces covered with soil, turf, shrub and tree layers respectively was reviewed (Figures 2.1 – 1.38). The analysis showed that while all vegetative layers performed better than a bare hard roof surface, the shrub layer brought all external heat gain to zero (from a high of 366.3 KJ/m^2) while increasing heat loss to 104.2 KJ/m^2 (from a low of 4.2 KJ/m^2) (Lam, 2008). The implications of this study indicated that living façades could provide a similar benefit in terms of reducing unwanted heat gain during peak power demands in the summer, while simultaneously producing food if those shrub plants were herbs and vegetables.

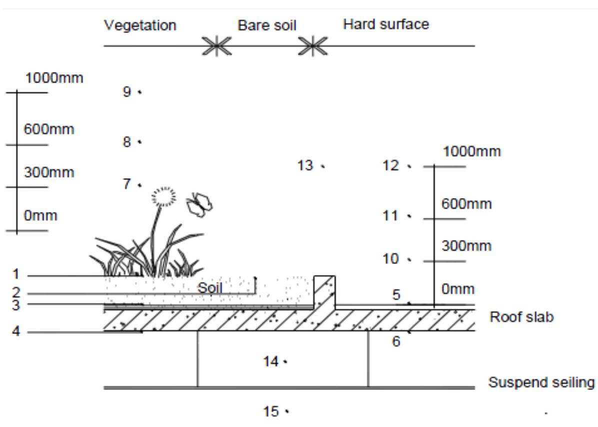


Figure 2.1 Experimental set up, including sensor locations (1-15), and 3 principal roof variations, hard surface, bare soil, and vegetation in 3 plant layers: turf, shrub and tree (Lam, 2008, p. 27).

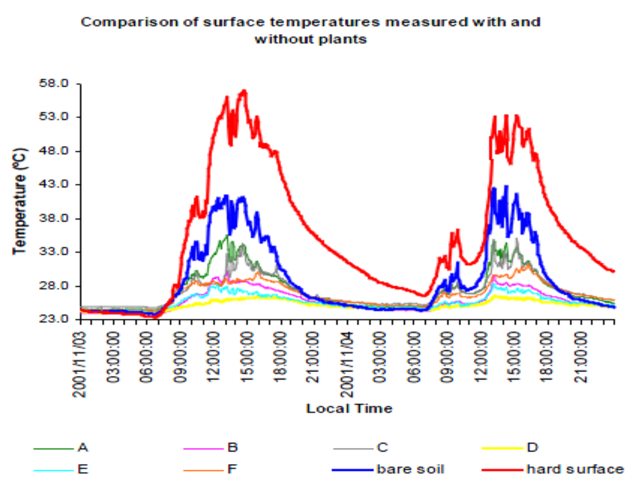


Figure 2.2 Direct temperature measurements showing a nearly 70° F difference (Lam, 2008, p. 31)

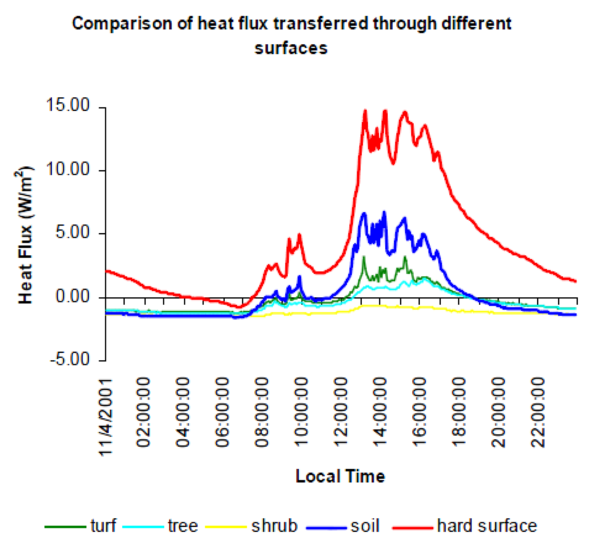


Figure 2.3 Heat Flux through the roof envelope. Note that the shrub layer has a net negative heat flux (Lam, 2008, p. 31).

Roof type	***Total Heat Gain/m^2 over a day***	***Total Heat Loss/m^2 over a day***
Bare hard surface	366.3KJ/m^2	4.2KJ/m^2
Bare soil	86.6KJ/m^2	58.0KJ/m^2
Turf	29.2KJ/m^2	62.1KJ/m^2
Tree	15.6KJ/m^2	53.3KJ/m^2
Shrub	0KJ/m^2	104.2KJ/m^2

Figure 2.4 The semi-intensive shrub layer is the best performing roof surface (Lam, 2008, p. 32).

The purpose of this dissertation is to demonstrate the concept of bioregenerative design to verify the idea that living facades can become food producing gardens, with similar thermal performance benefits as shown in the Singapore study. The goal is to reduce the surface temperature of the building façade during the heat of the day in summer, by growing fresh produce in lieu of burning fossil fuels. This is literally replacing fossil fuel energy with solar energy and photosynthesis via living systems, that produce order spontaneously in the form of fresh fruit and vegetables.

To achieve the ambitious goals of net zero energy use and carbon neutral or even carbon reducing operations in urban buildings will require demonstrating and perfecting the use of living systems to provide ecosystem services for the provision of energy and resources needed within the built environment as the global population continues to soar. The intention of this research project was to design, fabricate, install, operate and eventually decommission and disassemble a low-tech, low-cost, low-energy, user-friendly, food producing living façade (FPLF), thereby demonstrating the feasibility of this method on the CMU campus in the Oakland section of the City of Pittsburgh.

The performance of this FPLF was measured, recorded and verified to generate baseline data with which to compare and contrast against existing and ongoing research in this area. Potential benefits, impacts and implications of installing FPLFs on a larger scale in Pittsburgh, the region and other temperate climate zones in the United States and around the world will also be discussed. To better understand why this FPLF research project was initiated, the key challenges addressed by the research installation are discussed below.

2.1 Food Production

The successful adaptations of buildings to every climate zone around the globe, using increasing complex technical and mechanical systems, has pushed human population to record levels at an increasing pace, as shown in Figure 2.5. This has exacerbated both the total environmental impact and the shortage of energy and food systems globally needed to support this trend.

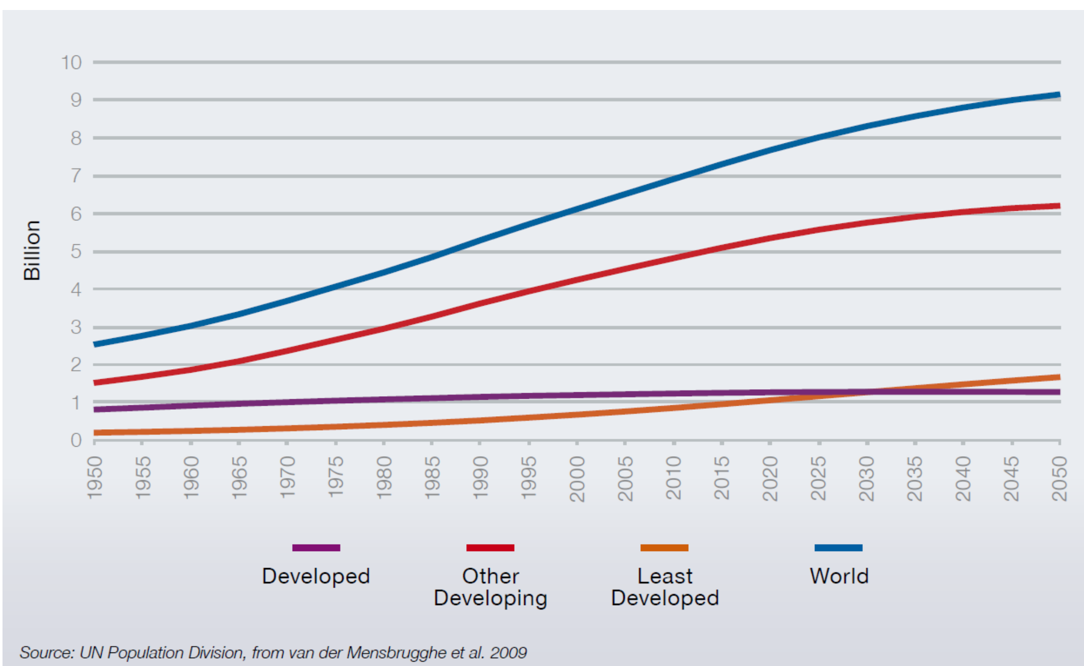


Figure 2.5 Population growth 1950 projected through 2050, (Food and Agriculture Organization of the United Nations, 2009, p. 1).

As the value of ecosystem services provided by living systems of plants and soils within the urban environment is rediscovered, there is a growing realization that the architecture of the city itself provides underutilized opportunities to support urban agriculture. The systems and technologies used to restore the working landscape to the city to provide ecosystem services, such as green roofs, green facades, rain gardens, permeable pavement, bioswales, and other green infrastructure, are increasingly recognized as environments that can support food producing plants.

The World Health Organization (WHO) and the United Nations Food and Agriculture Organization (FAO) have been working to understand the scope and consequences of malnutrition and set standards for global nutrition needs. Information on the WHO website outlines the parameters of this issue.

> *"Fruit and vegetables are important components of a healthy diet, and their sufficient daily consumption could help prevent major diseases, such as cardiovascular diseases and certain cancers. Approximately 16.0 million (1.0%) disability adjusted life years (DALYs, a measure of the potential life lost due to premature mortality and the years of productive life lost due to disability) and 1.7 million (2.8%) of deaths worldwide are attributable to low fruit and vegetable consumption. Moreover, insufficient intake of fruit and vegetables is estimated to cause around 14% of gastrointestinal cancer deaths, about 11% of ischemic heart disease deaths and about 9% of stroke deaths globally.*
>
> *A recently published WHO/FAO report recommends a minimum of 400g of fruit and vegetables per day (excluding potatoes and other starchy tubers) for the prevention of chronic diseases such as heart disease, cancer, diabetes and obesity, as well as for the prevention and alleviation of several micronutrient deficiencies, especially in less developed countries."* (World Health Organization, 2004, p. 7).

Food security is the metric used to determine the availability to food and an individual's access to it, if it is available. In some cases, the food is available, but the individual has no means to travel to access it. In many cases there is no locally available fresh food, with 11% of all U.S. households identified as food insecure (USDA, 2018). In the City of Pittsburgh, *"at least 20,000 low-income residents live a mile or more from a grocery store, and 85,000 live more than a half-mile from one."* (McCart, 2019). These areas of food insecurity are called "food deserts". One person interviewed stated that sometimes hard choices have to be made between paying utility bills or spending the money necessary to access fresh fruit and vegetables. *"It's a choice to pay the utilities or buy food to feed you and your children"* (Sundaram, 2018). Food producing living facades, installed on homes and apartment buildings in these low-income communities, could reduce the utility bills while simultaneously providing fresh produce right on the building itself. In Pennsylvania, 9-12% of households were food insecure in 2018 (Coleman-Jensen, Rabbit, Gregory, & Singh, 2018).

The response to these issues has been a growing trend for green and sustainable buildings that are also resilient, regenerative and incorporate living systems into their design using green roofs, green walls and green facades as part of the thermal envelope. This approach to green building has generated a significant amount of research on the energy performance benefit of green roofs and walls, and a lot of popular interest in and development of urban agriculture systems. This trend is an important reaction to the fact that there are now more people living in urban areas than in rural areas. The graph in Figure

2.6 shows that urban population exceeded rural population for the first time in 2008 (United Nations, 2004, p. 9)

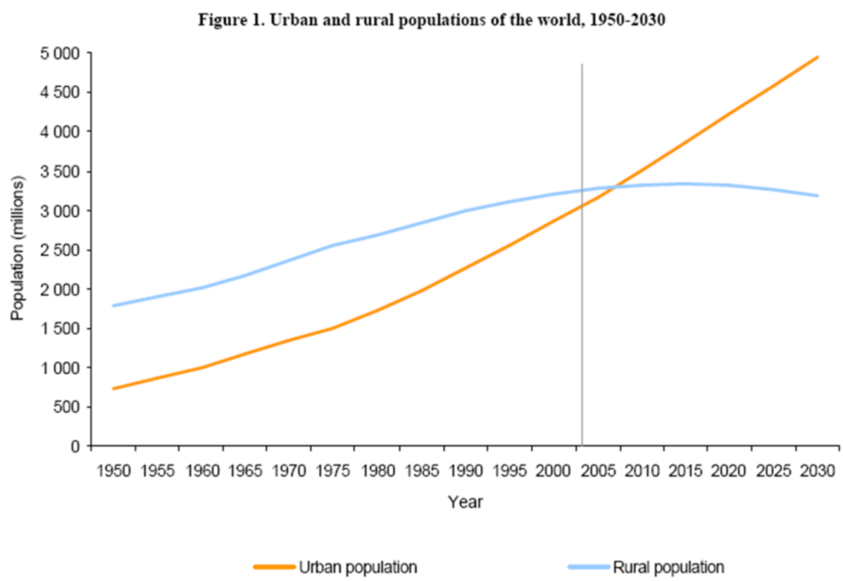


Figure 2.6 Urban and Rural populations of the world, 1950 to 2030 (United Nations, 2004, p. 9)

There continues to be a significant lag between population growth and food production. At the same time there is a significant amount of food waste discarded in the United States annually. That food waste can be composted to generate new fabricated soil to create FPLFs, potentially establishing billions of square feet of new agricultural production. While total arable land has been slowly increasing globally since 1961, it has been decreasing in developed countries as shown in Figure 2.7.

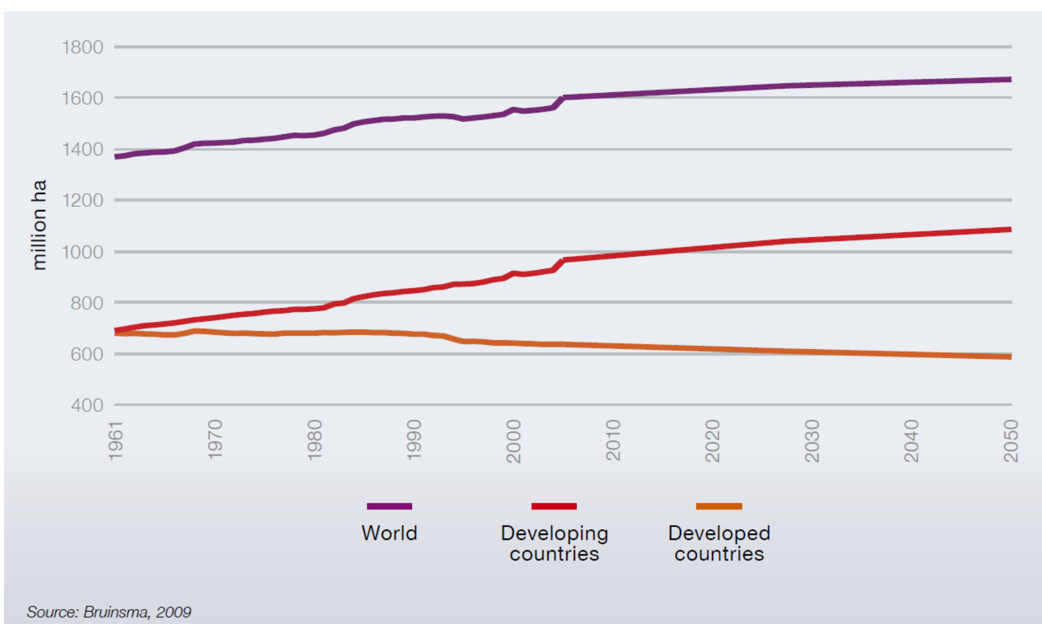


Figure 2.7 Arable land in millions of hectares, 1961 projected through 2050, (Food and Agriculture Organization of the United Nations, 2009, p. 3)

This increase of new arable "land" directly on the façades of buildings would have the dual benefit of intercepting incoming solar heat gain, reducing temperature differential at the façade, thereby potentially reducing the cooling load on the building and the heat island effect within the community, while producing calories of herbs, vegetables and additional biomass as a by-product. During the time of this research study, only two other research studies were published on the viability and potential building performance benefit of food producing living façade vertical garden systems.

The research study presented here posits this primary question: Can a living façade successfully grow food producing plants? Such a food producing living façade would provide many benefits to the building, its occupants, the larger built environment and its citizens.

The Building Performance benefits of a food producing living façade would include the following:

- Produces food (vegetables and herbs)
- Improves building operational efficiency
  - Reduces façade surface temperature during heat of the day in summer
  - Utilizes stored rainwater for irrigation and evaporative cooling
  - Utilizes food waste to create compost for fabricated soil mix
  - Utilizes façade micro-climate and waste heat to extend growing season
- Improves building environmental effectiveness
  - Increases oxygen
  - Decreases small particulates (PM 2.5)
  - Decreases carbon dioxide

Community performance benefits of a FPLF would include the following:

- Increases green infrastructure
- Increases evapo-transpiration community wide reducing urban heat island effect
- Provides ecosystem services
  - Improves groundwater recharge by reducing runoff rates
  - Reduces frequency of flooding
  - Improves air quality
  - Increases access to nature
  - Increases local food production
  - Closes cycles
    - Food to food waste to compost to food again
    - Cradle to cradle modular design for disassembly using biological components that can be composted and technological components that can be reused or recycled

To create such a food producing living façade requires an understanding of the necessities of life for humans. These have been well summarized in a paper by architect Henry McLean. He described these necessities as a reflection of the traditional natural elements identified in antiquity: Earth, Air, Fire and Water. *"…Each day we need to find shelter and a hearth for fire (50°- 90°F), breathe the air (on average 33 lb./day), eat some food (5.5 lb./day) and drink some water (3.3 lb./day)"* (Maclean, 1993, p. 2). Once again here it is shown that the development of agriculture and architecture were major factors in providing for these fundamental necessities of life, which played a major role in the worldwide success and expansion of our species as shown in Figure 2.8.

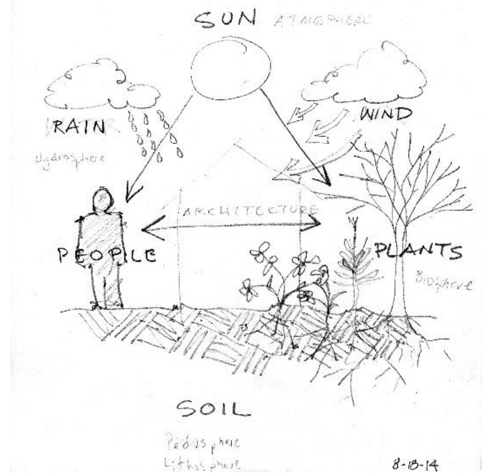
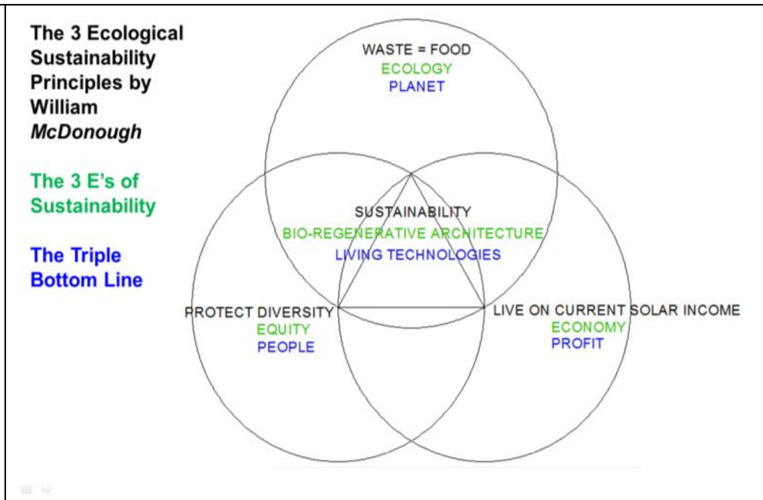
	

Figure 2.8 Plants integrate sun, rain, wind, soil (Leininger)	Figure 2.9 McDonough's Sustainability Principles, the 3 E's of Sustainability and the Triple Bottom Line

This concept of working with nature and living systems using ecological principles and ecosystem services as the underlying framework for achieving sustainability using systems integration in the design of buildings and communities has been evolving for decades, Figure 2.9. The paper *Global Relevance of Total Building Performance* states that "…systems integration concepts will help to enable the elimination of 'waste streams' avoiding obsolescence, as well as managing industrial and agricultural nutrient streams. …all material flows can be considered within life cycles for 'cradle to cradle' use. …this paper argues for the development and demonstration of such practices…" (Hartkopf & Loftness, Global Relevance of Total Building Performance, 1999, p. 377).

The paper *Case Studies of High Performance Building* explains that this ecosystems approach to green design is intended, "*…to create building enclosures that would engage organisms, such as plants, bees, birds, etc. to enable climate/weather responsive daylighting, natural ventilation, passive and active heating and cooling."* (Hartkopf, Yang, & Aziz, 2009, p. 4). A paper called *Roots to Our Ecology and Built Future*, in the Harvard University Graduate School of Design publication *Instigations Engaging Architecture Landscape and the City*, encourages the *"uneasy embrace of two giants, nature and the built world"* as well as a *"return to fundamentals – the spatial patterns and flows of water, soil, energy, air, plants, microbes and animals.* (Forman, Mostafavi, & Christensen, 2012, p. 125). More recently, a series of articles exploring concepts and trends for cities of the future called *Ideas for a Brighter Future* were published in a Special Issue of National Geographic Magazine, April 2019. The urban planning and architecture firm Skidmore Owings & Merrill (SOM) was asked how it would design a city of the future. Their plan follows the concept of an ecosystems approach to urban planning. "*The plan allows Ecology to guide development. Water sources are protected and systems are designed to capture, treat and reuse it. Energy is renewable…All waste* *becomes a resource. Food is grown locally and sustainably."* (National Geographic, 2019, p. 21). Vertical urban farming integrated with building façade design and morphology is also highlighted in their schematic designs, Figures 2.10 and 2.11.

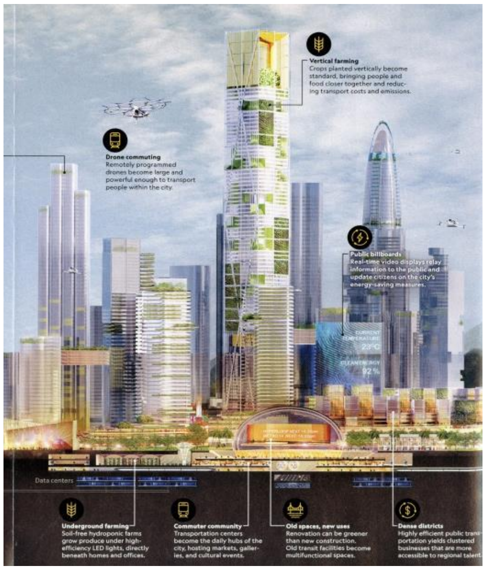


Figure 2.10 ***Ideas for a Brighter Future*** (National Geographic, 2019, p. 21)

Figure 2.11 ***Ideas for a Brighter Future,*** (National Geographic Magazine, 2019, p.21)

This new approach of partnering with living systems to provide services within the built environment is also being codified in federal policy in grant funded research programs such as the *Sustainable Bioenergy* grant program of the United States Department of Agriculture. This program describes what it calls a "New Biology" referencing recent technological and scientific advances in biological research looking to address a wide range of some of our most pressing societal problems. Four general areas identified that provide the biggest societal challenges are food, environment, energy and health. The four specific challenges that were identified are:

> *"1. Generate food plants to adapt and grow sustainably in changing environments - Food*
> *2. Understand and sustain ecosystem function and biodiversity in the face of rapid change - Environment*
> *3. Expand sustainable alternatives to fossil fuels - Energy*
> *4. Understand individual health."* (USDA-NIFA, 2010, p. 2).

In response to all this conceptual development the question must be asked, how can architecture be designed using plants, animals and microorganisms? The emerging trend to accomplish this is the use of green roofs and green facades, living surfaces attached directly to or adjacent to the thermal envelope of urban buildings.

Clearly one way to pursue this new approach to urban design is to combine agriculture and architecture creating food producing landscapes directly on the building. While food production on green roofs in the urban environment has been pioneered and researched extensively, food producing living facades are just now beginning to be researched in terms of measured, recorded and verified food production.

Increasing food production, and the amount of new land area needed to produce it, is of course the main reason for covering buildings with FPLF's. Scientists are beginning to call the era in which we live the Anthropocene epoch, superseding the Holocene, due to the fact that humans are now ploughing, logging or mining more than fifty percent of the Earth's land area. Increasing population, increasing demand for food, increasing use of resources and fossil fuels has led to the consumption of these resources at levels that are simply not sustainable in the long run. The Ecological Footprint, or share of those resource consumed by the average lifestyle of each country, is beyond what our planet can supply, if everyone attains a typical western industrial lifestyle as currently defined.

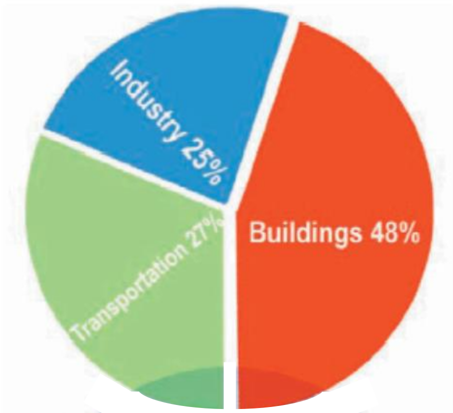
Bringing this landscape directly into the community and onto the buildings needed for everyday life and work, solves multiple issues simultaneously. The total area of building façades in cities is oftentimes much larger than the total roof area. Covering these facades with food producing landscapes would increase growing area significantly right within the community where the fresh produce would be consumed.

Food producing living façades located in lower income communities, defined as food deserts because there is no local grocery store within a mile or less, that also struggle with paying monthly utility bills and staying cool in the summer, would reduce building façade temperatures, reducing the need for electricity for mechanical air conditioning, while producing fresh produce for local consumption. Fresh local organic produce would improve diet and health, while also reducing mortality associated with heat waves and urban heat island effect. These issues are disproportionately experienced by low income and minority communities, and indicates how this kind of an environmental technology addresses social equity, economic and ecological issues, described in Figure 2.9, simultaneously.

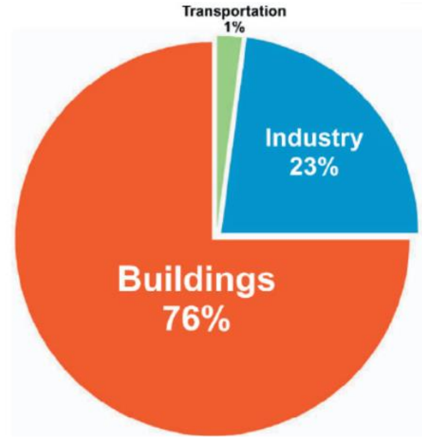
An extensive review of the literature on living walls, green facades, green walls, vertical greenery systems, biowalls and other vertical landscape systems has yielded very few studies on food production on a vertical building façade, to achieve more efficient and effective environmental performance. The original contribution of this proposed research study is to measure, record and verify food production on a living façade, using the advanced building systems integration framework, considering the design implications of the sense of taste and the gastrointestinal process, as contributing to the environmental qualities of the built environment. This food producing living façade research project addresses all four key challenges identified in the New Biology framework discussed above.

2.2 Building Façade Temperature Reduction

Commercial buildings in the United States are significant consumers of energy and are responsible for a significantly negative impact on the natural environment. Buildings in the United States are the leading consumer of electricity (76%), and a major consumer of all energy produced (48%) as shown in Figure 2.12 (Mazria & AIA, 2006). Sixty-one point three percent (61.3%) of the energy used to generate electricity is lost as waste heat in the generation process. An additional two point four percent (2.4%) of the net electricity generation is lost in transmission and distribution. These losses, totaling 63.7% of net generation, are highlighted in red on the energy diagram from the United States Energy Information Agency showing the generation, transmission, distribution and losses from 2018, Figure 2.13 (EIA, 2019).

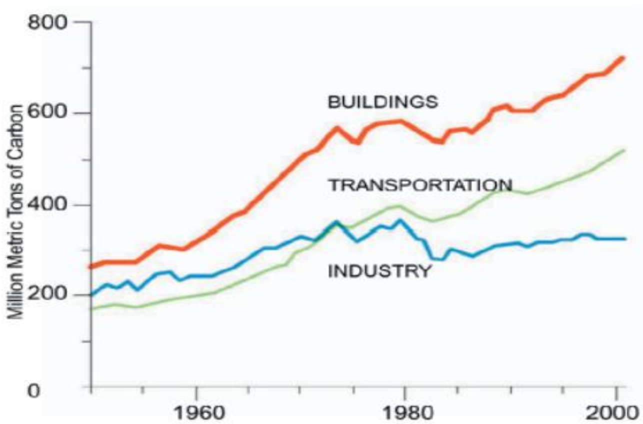


U.S. Energy Use by Sector



U.S. Electricity Use by Sector

Buildings Account For Half Of All Greenhouse Gas Emissions



U.S. CO_2 Emissions by Sector

Figure 2.12 Charts showing energy use, electricity use and CO2 production attributed to buildings in the U.S., 1950-2000 (Mazria & AIA, 2006, p. 1).

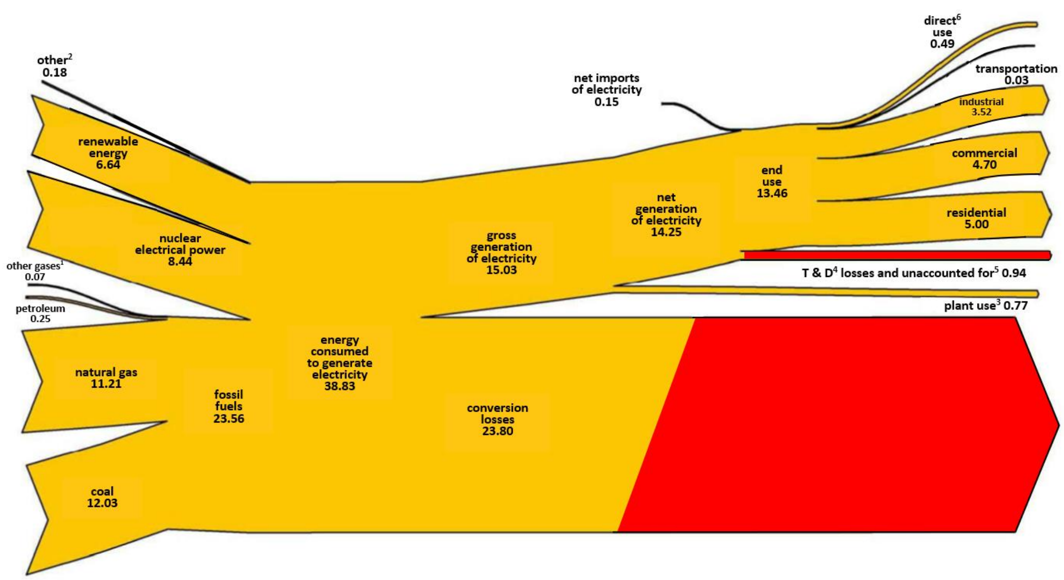


Figure 2.13 U.S. Electricity Flow 2018 Energy Information Agency, with Generation, Transmission and Distribution Losses (in red) and Use by Sector, as modified by the author following Hartkopf (EIA, 2019).

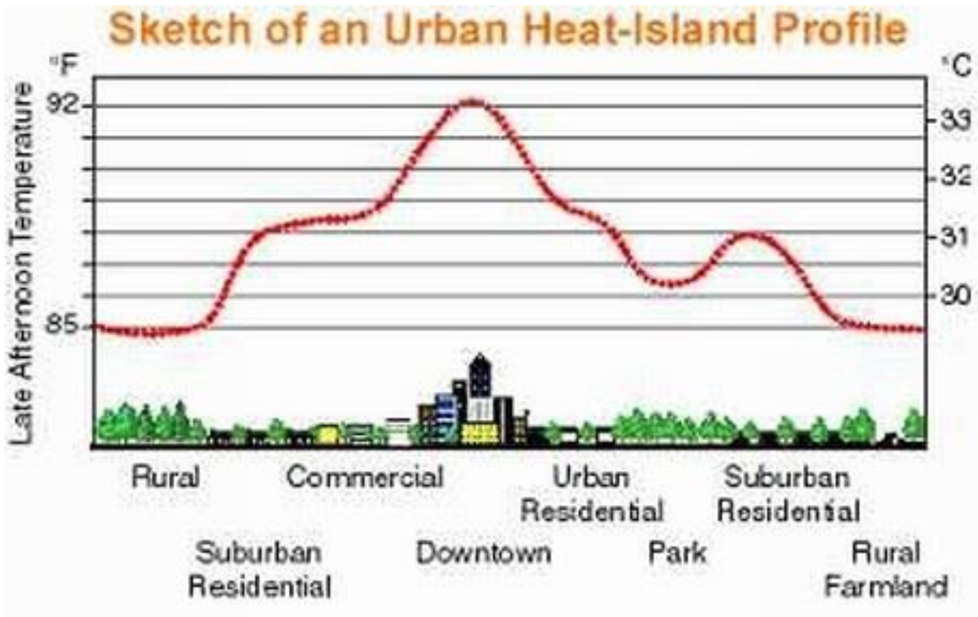


Figure 2.14 Urban Heat Island Diagram (Onder & Dursun, 2011, p. 38).

The inefficiency of the buildings themselves becomes one of the leading causes of urban heat island effect (Figure 2.14) and other environmental impacts that are detrimental to local, regional, national and international ecosystems (Lam, 2008) (Greenscreen, 2015). The chart in Figure 2.15 shows the summer load, peak day end-use for energy demand in Gigawatts.

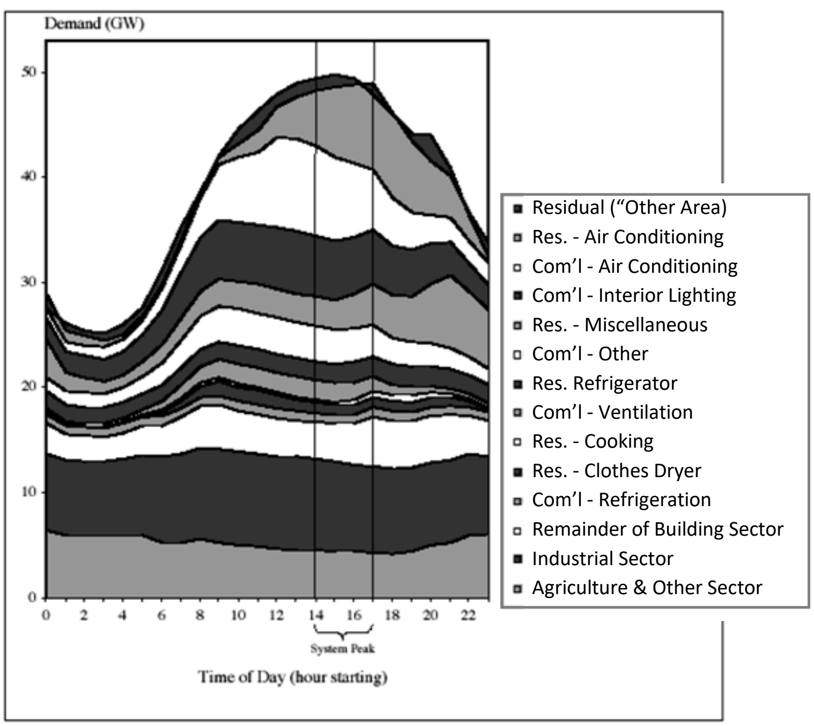


Figure 2.15 California 1999 Summer Peak-Day End-Use Load (GW): 10 Largest coincident building-sector end-uses and non-building sectors (Brown & Koomey, 2002, p. 16).

The three largest contributors to late afternoon system peak demand are Residential Air Conditioning, Commercial Air Conditioning and Commercial Interior Lighting. The increased demand for air-conditioning during the hottest part of the day during summer, results in dumping more heat into that environment exacerbating the problem. This pattern drives up average temperatures in dense urban areas contributing to a self-reinforcing cycle of increasing energy use and a worsening urban heat island effect.

Peak energy demand occurs during the summer, which is the growing season. The implementation of living systems on the roof and façade, along with daylighting strategies as part of an advanced building systems integration retrofit solution, would eliminate a significant portion of this peak power demand spike. Such a solution would not only increase energy efficiency, reduce urban heat island effect and provide ecosystem services such as food production, storm water management and air quality improvement, but also help limit mortality from the largest weather-related killer, which is heat wave accompanied by blackouts or brownouts, where the electricity that usually provides for air conditioning is knocked out or severely intermittent in supply.

Using living systems as design elements for bioclimatic façade design systems integration for improving total building and built environment performance requires engaging and utilizing natural energy flows and nutrient cycles. Intercepting incoming solar radiation with a food producing living façade irrigated with stored rainwater simultaneously reduces the façade temperature and increases the insulating value while also producing calories of food in the form of vegetables and herbs. The living façade is the mechanism for capturing, converting, storing and utilizing incoming solar energy, while providing direct ecosystem services, improving total building performance, and, when aggregated amongst multiple buildings on a campus or in a neighborhood, improving the performance of the larger urban environment.

In his book “Regenerative Design for Sustainable Development” Professor Lyle explains how solar energy, upon reaching the surface of the Earth, undergoes one of four natural conversions which play essential roles in supporting life on earth. The four potential conversions are:

1) photosynthesis,
2) absorption and convection,
3) reflection and
4) evaporation.

He shows in a table how these conversions drive specific global systems; the energy form they take and the utility they provide to human activities. Photosynthesis relates to the global food web by turning solar energy into biomass, a form of potential energy stored within the structure of the cells of the plants. This biomass, in its great variety and diversity, provides essential utility for human activities, including food, fiber, fuel and waste treatment.

Details of the global system, energy form and utility of the other conversions are shown in the Table 2.1 below.

Table 2.1 The Four Potential Solar Energy Conversions, (Lyle, 1994).

Source	Conversion Process	Global Systems	Energy Form	Utility
Solar Radiation	Photosynthesis	Food Web	Biomass	Food Fiber Fuel Waste treatment
	Absorption and Convection	Thermal balance Climatic Patterns	Heat Mechanical energy	Space heating Electrical power Water heating Process heating
	Reflection Evaporation	Reradiation Water cycle	Visible Light Mechanical energy	Daylight Electrical power

In Lyle's table, evaporation is given the energy form "mechanical energy" whose utility is defined as "electrical power". In the years since this table was published, researcher Professor Marco Schmidt has been working on understanding the energy phase change that occurs when water evaporates and condenses, and the corresponding effect this has on temperature. This effect is referred to as evaporative cooling and relies on latent heat, or the temperature effect of the phase change of water in the atmosphere. The diagrams below, Figures 2.16-2.18, show the global radiation balance in three conditions: natural environment, an asphalt roof, and a green roof.

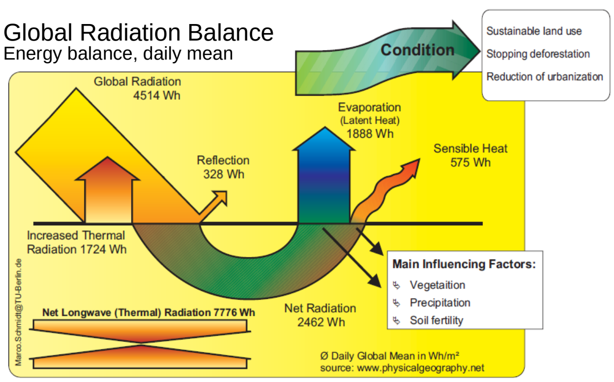


Figure 2.16 Global daily radiation balance as annual mean (Schmidt, Reichmann, & Steffan, 2007, p. 1) www.physicalgeography.net

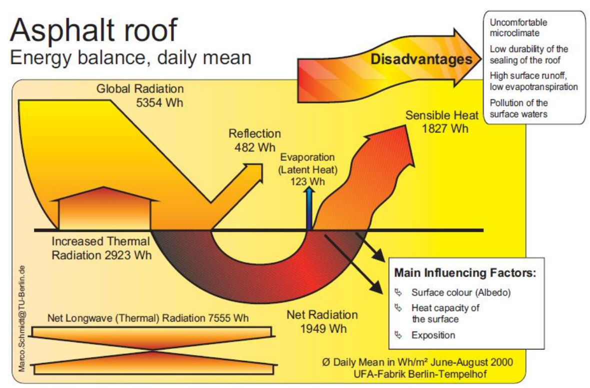


Figure 2.17 Radiation balance of a black asphalt roof as an example for urban radiation changes (Schmidt, 2005, p. 5)

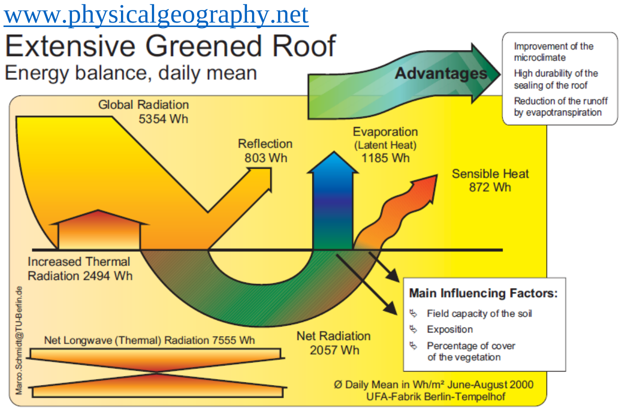


Figure 2.18 Extensive green roofs transfer 58% of net radiation into evapotranspiration during summer, UFA Fabrik in Berlin, Germany (Schmidt, 2005, p. 5)

Figure 2.19 Façade greening system (priority 2) (Schmidt M. , 2009, p. 9)

Professor Schmidt's work emphasizes the critical role of evapotranspiration in plants for providing cooling in the built environment, reducing urban heat island effect. Schmidt explains the benefit of the green roof effect based on measured results, and goes on to explain that green facades and roofs are effective alternatives for mitigating urban heat island effect.

> *"A cheap and reliable measure to create more comfortable air temperatures inside and outside of buildings is to green façades and roofs, thereby "consuming" this energy by evapotranspiration. According to measurements taken at the UFA Fabrik in Berlin, a greened vegetated roof covered with 8 cm of soil transfer 58% of net incident radiation into evapotranspiration during the summer months… (Figure 2.17 above). … With regards to the urban heat island effect and the issues of global warming, sustainable architecture and landscaping need to consider the natural water cycle, including evaporation, condensation and precipitation."* (Schmidt M. , 2009, p. 4).

The green façade shown in Figure 2.19 is a research project looking at evapotranspiration effects from the green façade and a greened courtyard at the Adlershof Physik building in Berlin. The chart below, figure 2.20, shows the amount of evapotranspiration in millimeters per day and the total cooling effect in kilowatt hours per square meter per day for that project (280 kWh per day for one of the courtyards). The graph shows the variation in the amount of evapotranspiration and the corresponding cooling effect based on location, orientation, exposure and elevation above the ground level.

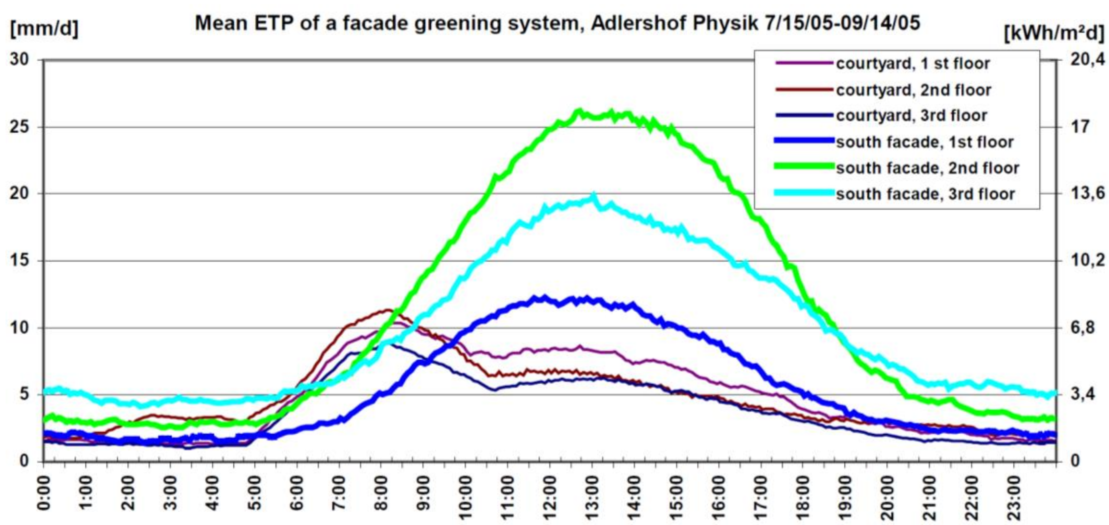


Figure 2.20 Mean evapotranspiration of the façade greening system in mm/day and correspondent cooling rates. The mature Wisteria sinensis increased up to 420 liters per day for 56 planter boxes. This represents a cooling value of 280 kWh per day for one of the courtyards. The courtyard has a size of 717 m2, the greened façade a surface of 862 m2. (Schmidt M. , 2009, p. 12)

Table 2.2 below prioritizes a list of sustainable measures that urban areas can implement to reduce urban heat island effect and global warming (Schmidt M. , 2009, p. 5). The measures are prioritized one through eight and are assigned a numerical value, also shown graphically with plus symbols equaling one point and circles equaling one third of a point. Green roofs and green facades are listed as the second priority after unpaved green open space, such as parks, planted courtyards and tree lined boulevards or parkways. The sustainable measures listed in this table are all examples of green infrastructure. Green storm water infrastructure is an emerging field and is beginning to recognize not just green roofs but also green facades as important tools to increase urban evapotranspiration, reduce storm water runoff and combined sewer overflows (CSO's), while decreasing urban temperatures by providing an evaporative cooling effect.

Table 2.2 Priority list of sustainable measures for urban areas regarding the mitigation of the urban heat island effect and Global Warming (Schmidt M. , 2009, p. 5).

Priority	value		Measure
1.	+ + +	3.0	unpaved greened areas (parks, greened courtyards, street trees)
2.	+ + O	2.3	green building developments (green roofs, green facades)
3.	+ +	2.0	artificial urban lakes and open waters
4.	+ OO	1.7	rainwater harvesting (for cooling and irrigation)
5.	+ O	1.3	trough infiltration combined with large vegetated structures, grass pavers
6.	+	1.0	rainwater harvesting for toilet flushing and further utilisation
7.	OO	0.7	trough infiltration systems through natural soil, semi-permeable surfaces
8.	O	0.3	trench infiltration directly into the underground

2.3 Urban Air Quality

The City of Pittsburgh consistently ranks among the top ten cities in the United states for worst air quality, as defined by the presence of small particulates (Lynn, 2020). In the U.S. 45% of the population live in counties with unhealthy levels of particulate or ozone pollution (Hahn, 2020). Air pollution kills an estimated 7 million people worldwide annually, with 4.2 million being from ambient (outdoor) air pollution (World Health Organization, 2021).

As the literature shows, plants on green walls, green facades, living walls, and biowalls have the ability to filter air and clean the air volume of Volatile Organic Compounds (VOC's) and fine particulates. Pittsburgh in particular has problems with air quality primarily due to $PM_{2.5}$ small particles. The lack of landscape in urban environments is correlated with a 4% increase in fine (PM_{10}) and ultra-fine ($PM_{2.5}$) dust particles (Kohler M. , 2008).

Key challenges for air quality research include uncontrolled variables, such as wind speed and direction, and uncontrollable activities, such as impacts from university lawn maintenance equipment, mechanical equipment, food service vehicles and vendors, or other campus related activated and functions. The food producing living façade and control façade test beds at the IW were both equally exposed to these real world influences.

2.4 Rainwater Management

Sustainable storm water management and wetland restoration projects are also the focus of Dreiseitl Atelier, a design studio that works on projects addressing these issues worldwide. Their work illustrates how current storm water management infrastructure produces measured results that are almost exactly the opposite of a natural environment (see Figures 2.21 and 2.22). Whereas the natural environment processes storm water with eighty percent going to evaporation, nineteen percent going to infiltration and only one percent resulting in runoff, the built environment processes only twenty-five percent as evaporation (a fifty-five percent reduction), five percent as infiltration (a fourteen percent reduction) and seventy percent as runoff (a seventy percent increase).

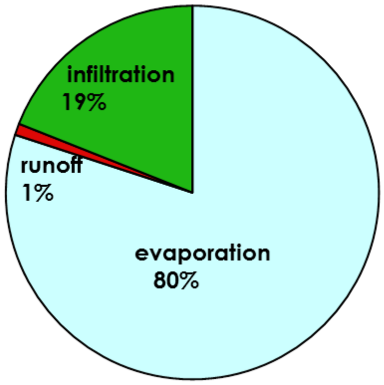


Figure 2.21 Water in the Natural Environment (Dreiseitl, 2005, p. 13).

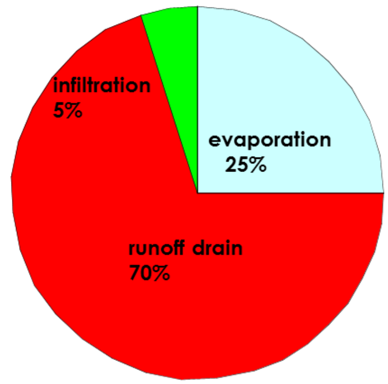


Figure 2.22 Water in the Built Environment: Chicago (Dreiseitl, 2005, p. 15).

This industrial approach to shedding water that falls within the built environment as fast as possible leads to increased flooding and increased drought as the subsurface recharge process is shortchanged. This approach also ignores the energy and biomass producing benefits of the hydrological cycle so well explained by the work of Lyle (1999), Schmidt (2009) and Dreiseitl (2005). Capturing and harnessing this work potential of water within the built environment through a food producing living façade vertical garden system increases the surface area for evapotranspiration and slows the rate of runoff and potential flooding, increasing infiltration rates and groundwater recharge. Functioning landscapes can return to the city using natural energy and rainwater to provide cooling via evapotranspiration using any type of plants, however, using food producing plants to achieve these benefits results in the by-product of fresh local produce.

This Vertical Garden produces fresh produce right on the building façade, while decreasing storm water runoff by capturing rainwater and storing it for irrigation. Calculating rainfall each month in Pittsburgh, along with daily irrigation requirements per unit area of façade, and the total area of the roof of the IW, would yield the total amount of irrigation needed to grow vertical gardens on the entire façade of the IW. This total demand for irrigation could meet or exceed the total rainfall generated during the entire growing season, virtually eliminating storm water runoff from the IW roof. Scaled up to all the buildings on campus or in a neighborhood or community, combined with smart storm water management and green infrastructure on the ground, such as bioswales, percolation impoundments and permeable paving, could reduce storm water runoff and Combined Sewer Overflows (CSO's) in Pittsburgh significantly.

The energy component of water, running through and fueling the photosynthesis process and driving evapotranspiration in the plants, is a significant benefit of this system. It provides evaporative cooling while the plants provide thermal shading of the façade during the peak of air conditioning season, reducing peak power demands and urban heat island effects. In so doing, the food producing living façade provides the double benefit of intercepting incoming solar radiation and transforming it into food calories, while simultaneously shading and cooling the building façade itself, saving a portion of the fossil fuel energy needed to maintain comfort levels in the indoor environment. This process of pulling the landscape right up onto and over the thermal envelope of the building allows several critical problems for the City of Pittsburgh to be addressed simultaneously: the need for low-cost, local fresh produce, especially in the food desert areas of the city; reduction of urban heat island effect; reduction of small particulates; and reduction of Combined Sewer Overflows (CSO's).

2.5 Research Hypotheses

This research study consisted of a proof of concept applied research project to demonstrate bioclimatic design principles and bioregenerative architectural solutions. The food producing living façade research installations were designed, fabricated, installed, and operated to measure, record and verify the performance of this system in four key areas:

1. Food production
2. Façade surface temperature reduction
3. Potential benefit to air quality via small particulate ($PM_{2.5}$) reduction
4. Rainwater capture, storage and use for irrigation

This research study is significant for several reasons. First, there are only two research studies found that have been completed and published to date that measure, record and verify food production on a living façade. This is the first research to document food production on a living façade over multiple growing seasons on an occupied building.

In addition, this research adds the sense of taste, the gustatory sense, to the Systems Integration Matrix for Total Building Performance. Food consumption performance is added to the other performance measures based on the human senses: Thermal performance (the sense of touch), Visual performance (the sense of sight), Acoustic Performance (the sense of hearing), Air Quality Performance (the sense of smell), and Spatial performance (the Kinetic or Haptic sense; the sense of motion).

In every building, every day, people are eating, drinking and using the restroom; all aspects of the gustatory sense involving the gastro-intestinal processes. Food preparation, consumption and elimination, consumes, transforms and wastes vast amounts of resources, including water, energy, materials and the food itself. This food producing living façade demonstration research project worked with natural energy flows and nutrient cycles, utilizing compost from food and yard waste inputs, and minimal organic fertilizers, with no fossil fuel inputs, to reduce the façade surface temperature of the building, while producing fruit, vegetables and herbs as the primary byproduct.

The system was irrigated with collected rainwater run through a solar powered pump drip irrigation system supplemented by hand watering. Air quality was monitored in terms of small particulate levels ($PM_{2.5}$) to document any reduction due to the living façade. Façade surface temperature was measured at several locations, on the white opaque aluminum façade surface and on the glazing, as well as on the corresponding interior surfaces at the living and control façades. This research project was designed to address the following issues:

1. Buildings use significant and increasing amounts of fossil-fuel based energy;
2. Buildings and the built environment contribute to urban heat island effect;
3. There is a continuous and growing lag between human population and food production;
4. There is an historic and growing use of plants in the built environment to provide ecosystem services, recently including the development of green roof and green wall technologies;
5. The growing use of plants in the built environment supports the urban agriculture industry;
6. Tons of food waste is discarded annually that could be composted to generate new soils;
7. More than 50% of the Earth's surface is being tilled, logged or mined with a shortage of new fertile land for increased agricultural production;
8. Very little research has been conducted as of the date of this study on the viability of food production as part of a living façade;
9. The sense of taste (the gustatory sense) has not been included in the Total Building Performance Matrix based on the other four senses (touch, smell, sight, sound) that was pioneered at the Center for Building Performance and Diagnostics (CBPD) at Carnegie Mellon University (CMU);

Therefore, this research project established food producing living façade research installations on specific segments of the South and West Facades of the Robert L. Preger Intelligent Workplace atop Margaret Morrison Carnegie Hall to demonstrate that such a living façade can grow fresh produce successfully through several growing seasons to test that:

1. Living facades will increase urban food production, producing measurable amounts of fresh vegetables, fruit and herbs;
2. Food producing living facades will decrease façade surface temperatures during the heat of the day in summer;
3. Food producing living facades will increase air quality by reducing $PM_{2.5}$ particulates at the building façade;
4. Food producing living facades will decrease Storm water runoff through the collection and redeployment of rainwater for irrigation.

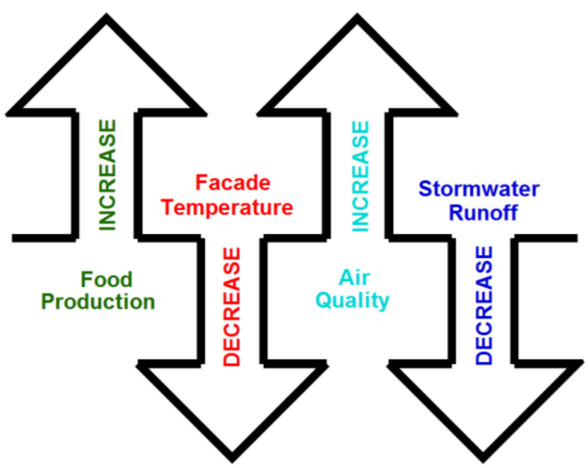


Figure 2.23 Leininger Research Hypothesis Diagram.

2.6 Delimitations

The design, fabrication, installation, operation, maintenance, decommissioning and disassembly of a food producing living façade for improved total building performance at the IW on the Pittsburgh campus of CMU was a demonstration of biophilic design, using bioclimatic façade design guidelines, to illustrate the ecological principles and ecosystem services provided by living systems to the built environment. It was a custom designed, modular system, using off the shelf components intended to be composted or reused / recycled at the end of the life cycle of the system, illustrating the Cradle to Cradle product design philosophy.

Measuring, recording and verifying the data collected, as outlined above, was intended to answer the primary question of whether or not a living façade can successfully support food producing plants. It was also to document and verify the already established benefits of providing façade surface temperature reduction, improved air quality in terms of reduced levels of $PM_{2.5}$ and use of stored rainwater for irrigation. Testing these assertions on the façade of an occupied, mixed-use academic building is another unique and original aspect of this research project, which allowed for a more realistic and practical testing of these ideas. This research study allowed for an unprecedented investigation into using systems integration to create a living façade application which documented the replacement of fossil fuel energy with living systems (biology) to attain desired indoor environmental quality and total building performance outcomes, as specific in the hypotheses.

Using a soil-based hybrid panel and trellis system for this food producing living façade prototype, along with zero fossil fuel energy inputs for operation, minimal organic fertilizers, and irrigation with rainwater as much as possible due to weather limitation, was intended to create a zero-energy system to operate, but which produces calories of food for the building occupants. This research project was not intended to maximize production of fresh produce, compare the production of one façade orientation to another, or compare total production of fresh produce annually to weather conditions or climate variations. Heat gain implications were limited to measurement of façade surface temperature at the opaque and glazed portions of the living and control façade areas, both exterior and interior. Air quality implications were limited to the levels of small particulates ($PM_{2.5}$) at the living and control façade areas, both exterior and interior. Storm water management implications were limited to rainwater storage and use daily for irrigation of the living façade research installations. The potential impacts and additional implications of these four discreet areas of measured performance are valid topics for additional research, but were beyond the scope of this proof of concept, field applied research study.

Efforts to maximize plant growth and the amount of fresh produce per unit area should be undertaken by future studies, due to the fact that measurable amounts of nutritional food were produced even though maximizing production was not the focus of this study. Additional efforts to understand the effect of the food producing living façade on direct solar heat gain, convective heat gain, shading, evapotranspiration and total cooling load reduction are also important areas of future research, but were beyond the scope if this study. The benefits of living façade installations on the oxygen and carbon dioxide ratios and levels at the building façade, as well as the benefit of improving air quality by reducing levels of other toxins such as volatile organic compounds, should be studied as well. Additional performance advantages of living facades as green infrastructure improving storm water management, lessening runoff and floods as well as improving groundwater recharge and limiting the severity of drought are all worthy of future research investigations. All of these related issues, and any other not specifically mentioned as the focus of the research hypotheses of this study, are beyond its scope and intention. Discussion of some of these potential implications are included in chapters six and seven which cover the analysis of the results and recommendations for future work.

The west façade research areas are outfitted with previously installed automated solar shading louvers at the façade balcony. The operation and deployment of the open and closed position of these louvers was not a controlled aspect of this study. Changes in the position of these lovers, and the related effect to incoming solar radiation was the same for both the living and control façade research areas. The operation of the heating, ventilating and air-conditioning systems within the IW were likewise not controlled for in this project, and are assumed to have been operating in an identical fashion in both the living façade and control façade isolated office areas. Throughout the research study period of six growing seasons, the living and control façade research areas on the west façade experienced identical influences from these uncontrolled variables.

Documentation of the harvest of fresh produce, and the minimum amount of daily irrigation required for plant health, was designed as a longitudinal study over multiple growing seasons to show variation and fluctuation of total annual production. Measurement of the façade surface temperature and $PM_{2.5}$ levels was designed as a cross sectional study with specific shorter time periods of data collection, consisting of specific days, weeks or months to sample performance data in those areas. This approach generated four specific data sets with sample sizes ranging from a few thousand to more than two hundred thousand individual samples. The details of this approach are explained fully in chapter five covering methodology and chapter six covering results.

Chapter 3. Green Façade Taxonomy – Systems and Performance

The initial literature review helped to define the scope of the problems, challenges and opportunities for the application of green façade for food producing outcomes. Table 3.1 lists all the possible system components along the left side column and all the potential performance benefits across the top row. This was created as a systems overview to identify where there were gaps in the existing research.

The full dark circles represent areas where there has been numerous papers and studies. The half circles represent areas where only one or a few studies have been published. Areas with full clear circles indicate areas where no research has been identified. This kind of a conceptual framework needs constant updating to stay current.

Table 3.1 Master Matrix for tracking precedents, products, research and new contributions

Physical Metrics	Performance Metrics																													
	Thermal Qualities						Air Qualities				Water Qualities				Visual Qualities				Acoustic Qualities				Material Qualities				Spatial Qualities			
Green Wall Type	SHADE	CLR	HLR	E-T	UHI	E	AQ	O_2	CS	BF	SW	GW	BW		DL	SHADE	GLARE	Color	STC	White Noise	Hab.		FFP	BP	SNC	PR/M	size	Ergo.		
Carrier System (panels)	●	○	◑	◑	◑	○	◑	◑	◑	◑	◑	○	○		◑	◑	○	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Support System (container & trellis)	◑	●	◑	◑	◑	○	◑	◑	◑	◑	◑	○	○		◑	◑	○	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Growing Media (soil type and mix)																														
Soil Mix	◑	◑	◑	◑	◑	○	○	○	○	○	◑	◑	○		◑	◑	○	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Depth	◑	◑	◑	◑	◑	○	○	○	○	○	◑	◑	○		◑	◑	○	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Soil less / Felt	◑	◑	◑	◑	◑	○	○	○	○	○	◑	◑	○		◑	◑	○	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Plant Types																														
Deciduous	●	●	●	●	●	●	◑	◑	◑	◑	◑	◑	○		◑	◑	◑	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Evergreen	◑	◑	◑	◑	◑	○	◑	◑	◑	◑	◑	◑	○		◑	◑	◑	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Agricultural	○	○	○	○	○	○	○	○	○	○	◐	○	○		○	○	○	○	○	○	○		○	○	○	○	○	○		
Ornamental	●	●	●	●	●	●	◑	◑	◑	◑	◑	◑	○		◑	◑	◑	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Irrigation / Filtration																														
Stormwater	○	○	○	○	○	○	○	○	○	○	●	◑	○		◑	◑	◑	◑	◑	◑	◑		◑	◑	◑	◑	◑	◑		
Greywater	○	○	○	○	○	○	○	○	○	○	◑	◑	○		○	○	○	○	○	○	○		○	◑	◑	○	○	○		
Blackwater	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○		○	○	○	○	○	○		
Structural Systems																														
Low rise	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○		◑	◑	◑	◑	◑	◑		
High rise	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○		○	○	○	○	○	○		
Access / Maintenance																														
Low rise	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑		◑	◑	◑	◑	○	○	○		◑	◑	◑	◑	◑	◑		
High rise	○	○	○	○	○	○	○	○	○	○	○	○	○		○	○	○	○	○	○	○		○	○	○	○	○	○		
Openings / View																														
Transparency	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	○	○	○		○	○	○	○	○	○	○		○	○	○	○	◑	◑		
Seasonality	◑	◑	◑	◑	◑	◑	◑	◑	◑	◑	○	○	○		○	○	○	○	○	○	○		○	○	○	○	◑	◑		
Innovative / Technologies																														
PhotoVoltaics	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Hydroponics	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Wastewater Treatment	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

CLR - Cooling Load Reduction
HLR – Heating Load Reduction
E-T – Evapo-Transpiration
UHI – Urban heat Island
E – Energy Production

AQ – Air Quality
O_2 – Oxygen
CS – Carbon Sequestration
BF – Bio-Filtration

SW – Stormwater
GW – Greywater
BW – Blackwater

DL – Daylight

STC – Sound Transmission
Hab. – Habitat

FFP – Food & Flower Production
BP – Biophilia
SNC – Soil Nutrient Cycle
PR/M – Public Relations/Marketing

Ergo. - Ergonomics

3.1 Green Façade Types

In the influential book *Vertical Greenery for the Tropics,* in the chapter *Typologies of Vertical Greenery* (Wong N. H., 2009) Vertical Greenery Systems (VSG's) were defined in two general categories, as shown in Figure 3.1:

1. Carrier Systems were defined as a panel system that can support a broader range of plant types; also referred to as Living Walls.

2. Support systems were defined as trellis or structure systems to guide plants up a vertical surface; also referred to as Green Facades. These systems usually have container plants with vines growing upward coupled with a ground cover in the container holding the roots and growing media.

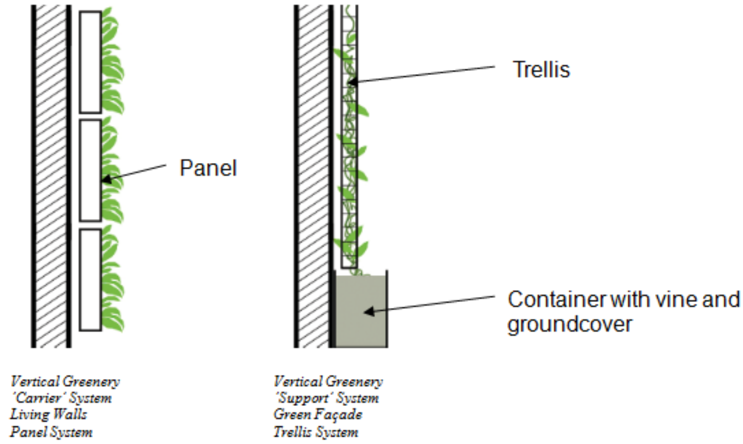


Figure 3.1 Living Wall and Green Façade Systems definitions (Wong N. H., 2009, p. 28).

In a definitive paper produced at the Queensland University of Technology Centre for Subtropical Design, *Living Walls – A Way to Green the Built Environment* (Loh, 2008), three basic green wall systems are defined, as shown in Figure 3.2:

1. Panel Systems (like the Carrier System described above).
2. Felt Systems, with pockets hung from a backing support.
3. Container and/or Trellis Systems, with a ground container for ground cover that also supports the growth of the vine.

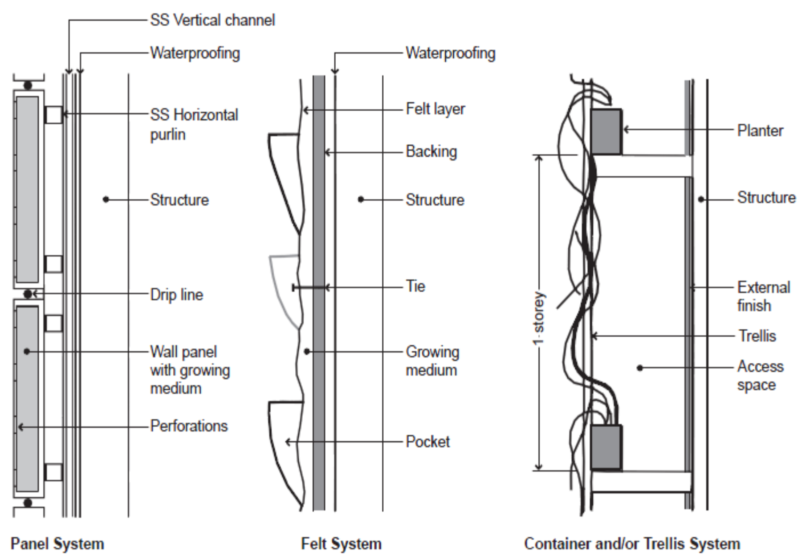
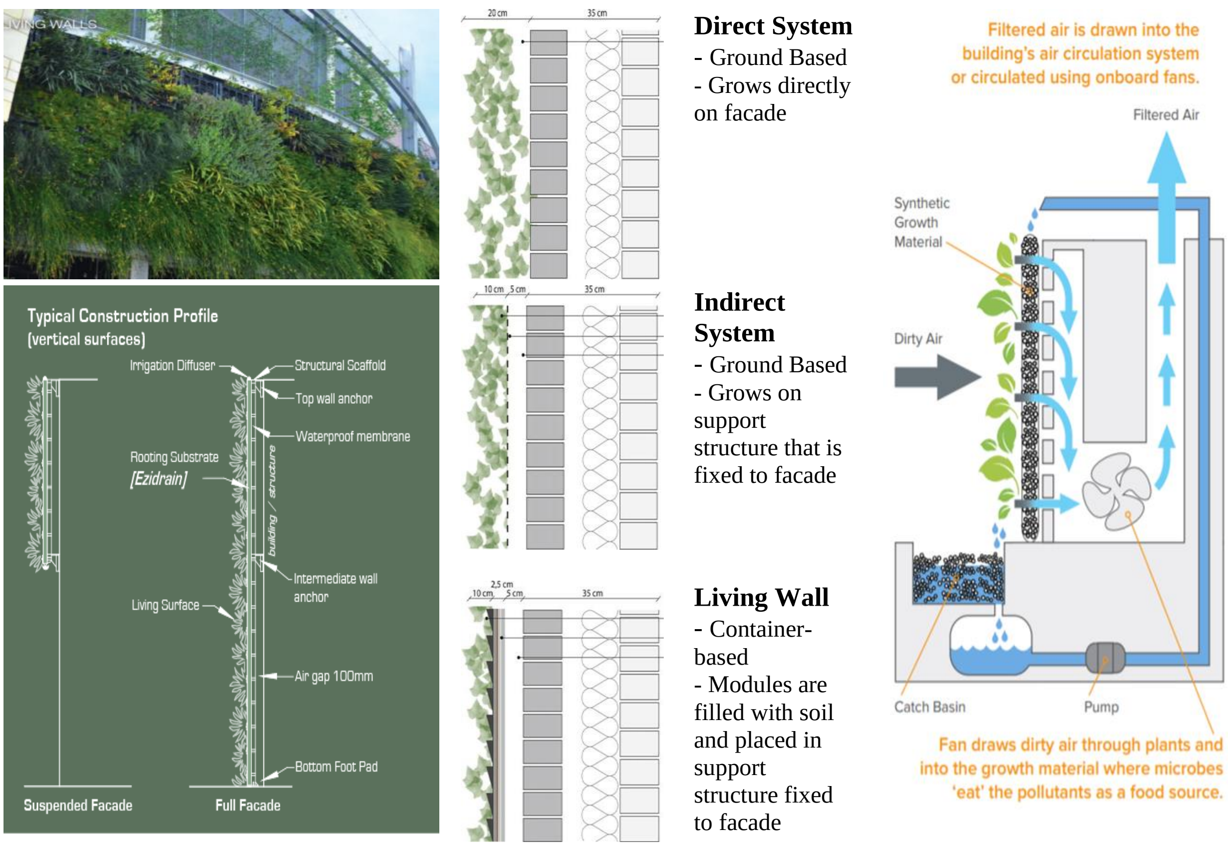


Figure 3.2 The three generic green wall systems (Loh, 2008, p. 2).

Figure 3.3 shows sections through living wall, indirect & direct vegetated façade and biowall systems. The indirect system is similar to a trellis system, whereas in the direct system the vines grow directly on the façade enclosure surface. The Nedlaw Living System is an indoor biowall system used for air filtering. The green wall types shown and reviewed above are meant to be a representative sample of the current state of systems development. The important point to understand is the general range of green wall, green façade, living wall and biowall systems and their applications.

The green façade / living wall system created for this research project was a hybrid panel and trellis system that had a fabricated soil based growing media. The system was a combination of the carrier and support systems illustrated in Figure 3.1 and the panel and trellis system images in Figure 3.2. The specific details of the particular system applied at the IW were modified and customized from the possible variations detailed in the images shown here, but the visual and performance outcomes are very similar.

Felt based panel systems installed on the exterior as green façades or on the interior to function as living biowalls also enhance system performance and provide indoor environmental quality benefits that are tangible and measurable. The subtle variations in the designs and materials that constitute these verticals garden living systems allow for this new concept to be adapted and applied to a variety of building types, forms, uses, geographic locations and climate zones.



Interconnections between Systems Vertical Cable Tension Systems Nedlaw Living Systems

Figure 3.3 Hunt Memorial Library Proposed Systems and Technologies: Hybrid Green Walls (Ottele, Perini, Fraaij, Haas, & Raiten, 2011, p. 214) (Nedlaw Living Walls, 2018, p. 2).

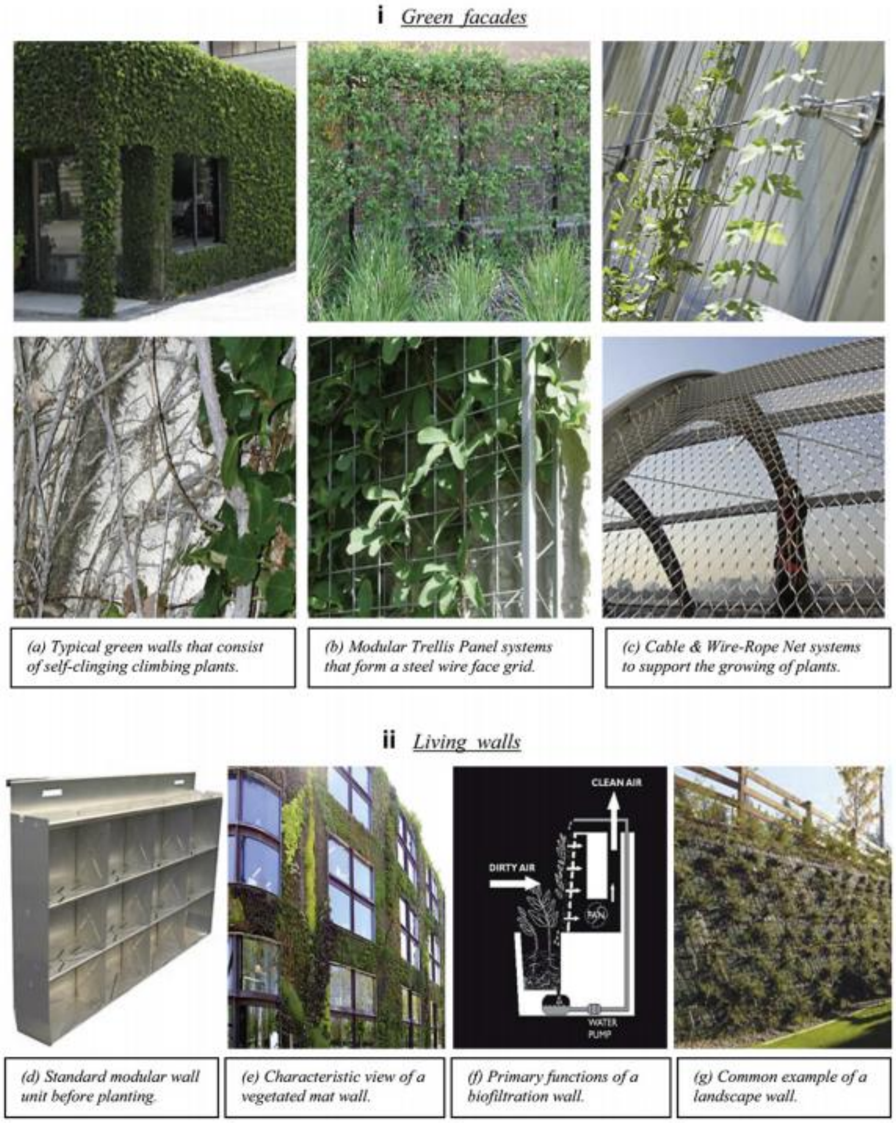


Figure 3.4 Green Façade and Living Wall descriptions, (Kontoleon & Eumorfopoulou, 2010, p. 1289).

3.2 Growing Media, Containerization and Structure

The literature provides only limited information about structure and configuration options for living façade and green wall installations in terms of research studies. There are a growing number of commercial manufacturers of green wall systems and components where most of the information about possible configurations can be found. These systems tend to break down into the following categories.

1. Panels can either be soil filled modules, with a minimum of 10 cm to 20 cm (4 in. to 8 in.) of soil or growing media, or they can be some kind of engineered membrane or panel, such as the felt panels used by botanist and researcher Patrick Blanc for green facades. Similar felt panel systems are also used for indoor biowall systems. These membrane and panel systems are oftentimes required to use a hydroponic system to deliver fertilizer in liquid form as the growing

media is sterile and has no nutritive benefit, unlike soil and fabricated soil systems which are part of the nutrient cycle.

2. Bags, pouches or other similar felt fabric container systems located strategically in vertical configurations for improved access or operation. These systems can likewise use either pockets of soil or other lightweight growing media, or soil-less systems that require feeding hydroponically.
3. Tension cable and wire trellis systems are a third way to structure green walls called living facades. There are a number of manufacturers of these systems, including Greenscreen, Ronstan, and the Japanese Parabienta system by Shinzu. These systems are used almost exclusively with vining plants.

The challenges with these systems, as with all architectural designs, revolve around cost, performance and aesthetics.

3.3 Vegetation

A living façade or green wall can be planted with virtually any type of evergreen, deciduous, ornamental or horticultural plant. The literature shows many different plant species being utilized from limited produce and sedum to ferns and the evergreen shrub Cherry Laurel. The work of Patrick Blanc shows that a myriad of dramatic plantings can be utilized to stunning effect in a well-designed, operated and maintained green wall or living facade system (Blanc, 2008).

This can also be one of the challenges of green walls and living facades, however. As the installation of the green façade panel system at the PNC tower in Pittsburgh showed, systems that are too difficult to access and maintain or that do not provide some performance benefit, will probably not be successful over the long term. The system at the PNC Tower was removed after just a few years in service (Belko, 2016). Another drawback is the fact that green walls are not green all year in areas where there are four seasons, such as Pittsburgh. This requires selecting plant species that have multifaceted aesthetics for when the growing season is over. This can include plants that go into autumn with an explosion of color and then provide interesting winter foliage or stem branching colors. Oftentimes succulents can be used which are tolerant to harsh conditions and can overwinter well with limited plant mortality. The wide variety of Sedum plants are a good option in this regard. Sedums turn beautiful shades of color in the fall and over the winter, but are low, dense and hardy enough to endure winter conditions. The food producing living façade at the IW used sedum as a ground cover effect on the surface of the mesh enclosure of the planting boxes and they were the most vigorous and successful plants, and always the first plants to come back in the spring. In a system like the IW installation where almost exclusively annual plants are used, the sedum is a perennial that endures and proliferates for years.

The literature discussed in Chapter 4 indicates that very little research has been done on horticultural plants or agricultural production as part of a vegetated façade vertical garden system. A Penn State study utilized mostly shallow rooted greens, such as collards and spinach, with some additional variety such as Cherry Tomatoes and various herbs (Nagle, Echols, & Tamminga, 2017). A Swedish study looked at several varieties of berries and herbs (Martensson, Wuolo, Fransson, & Emilsson, 2014). A proposed

Malaysian study indicated the value of using several varieties of vining bean plants (Amir, Yeok, Abdullah, & Rahman, 2011).

3.4 Irrigation

Like with plant selection there is an almost endless variety of irrigation methods for a food producing living façade. Water is essential, of course, and without it the plants will dry out within days. Unlike conventional gardens, rain does not fully irrigate a vertical garden system very well. This can have some benefits, such as the difficulty in flooding these plants. However, the opposite is also true; without regular irrigation the plants will die off rapidly.

3.5 Longevity/Durability

The life cycle of any system is an important consideration. All things wear out and eventually need removed or replaced. Designing this as a module system provides the opportunity to grow fresh healthy produce in additional modules at another location, a production facility, to provide an "evergreen lease" service benefit to the client or building owner. In this approach any modules that become diseased, or die could be "swapped out" to keep the green wall green.

The biggest challenges with considerations of system longevity and durability relate to the scale of the system, whether it is to be a permanent or temporary installation, and, of course, cost, performance and aesthetics. The recommended approach for dealing with longevity and durability is to design the food producing or any living façade with the Cradle to Cradle approach. Utilizing specific biological and technological components that can be disassembled at the end of their functional life is the best approach for a system that produces minimal construction and demolition waste. Design for Disassembly is a method promoted by the U.S. EPA and is a future trend in product design and fabrication (U S Environmental Protection Agency, n.d.).

Systems should either be designed with a large enough budget to purchase state of the art manufactured systems that will come with built in quality and material guarantees, or should be designed using relatively lower cost, custom manufactured materials and systems that can be designed for disassembly. High end manufactured living façade systems have the potential to be leased as a product of service to the client, so that it remains owned by the manufacturer. This would allow for the increased cost of a more durable system to be spread over the full life cycle of the product with one owner, the manufacturer. At the end of its life cycle, it can then be dismantled and separated into its core components for composting, recycling or reuse.

Chapter 4. Background Literature – Food Producing Living Facades

Two of the most pressing issues regarding the sustainability of society in the twenty-first century include the race between population growth and food production. Directly related to these issues are a host of trends that have been maturing over the last several decades including quantification of the costs of environmental impacts and the value of ecosystem services to the built environment. Calculating the Ecological Footprint of a modern lifestyle in heavily developed societies has helped to fuel the discussion of and research into alternative strategies of design.

The intention is to lessen, neutralize and even reverse the negative environmental impact created by the design, fabrication, installation, operation, maintenance, decommissioning, disposal, recycling or reuse of the built environment. In an extensive literature review completed for the qualifying exam and game plan requirements, covering the range of focus for the emerging research on vegetated building envelope systems, it became clear that there was only a small amount of green wall research being undertaken at that time. Table 4.1 below shows the extent and categories that research covered in 2012 as compiled for the qualifying exam. There is a growing body of work in this field, including a great deal of popular press and multimedia articles about green walls and vertical farming, but even now very little research has been published that documents food production on a vegetated façade. That is the primary focus of this research study.

Table 4.1 Table of key green roof and green wall research, Leininger, 2012.

Vegetated Envelope System	Materials and Plant Research				Policy Initiatives		Socio Bio-physical Benefits				Economic Benefits			
Green Roofs 136+47	Materials (growing media)	Plants	Other components	Standards and Guidelines	Policy Position	Program summary	Developers and Owners	Building Occupants	Neighbors	Community	Building Scale	City Scale	Regional Scale	Mixed Scale
General	2	6	2	5	23+3	34+3	0	12	2	4	2	2	1	3
Intensive	0	0	0	0	-	-	0	0	0	0	0	0	0	0
Semi-Intensive	0	0	0	0	-	-	0	0	0	0	0	0	0	0
Extensive	9	21	0	9	-	-	0	0	0	0	24	0	1	7
Mixed	0	1	1	0	-	-	0	0	0	0	4	0	0	2
Green Walls 52														
General	3	8	2	2	5	1	0	9	2	4	2	2	0	3
Green Façade – Support Systems	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Living Walls – Carrier Systems	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Indoor BioWall	0	2	2	0	0	0	0	3	0	0	2	0	0	0

Part of that literature review in 2012 identified a study of green wall research needs based on current activity and knowledge, shown in Figure 4.1 (Stav, 2008). This study looking at an overview of topics covered in green roof and green wall research showed that no studies focused on activity or knowledge about green walls had been covered or identified in four key areas:

1. Food Production
2. Stormwater Management
3. Urban Heat Island
4. Cost-Benefit Analysis

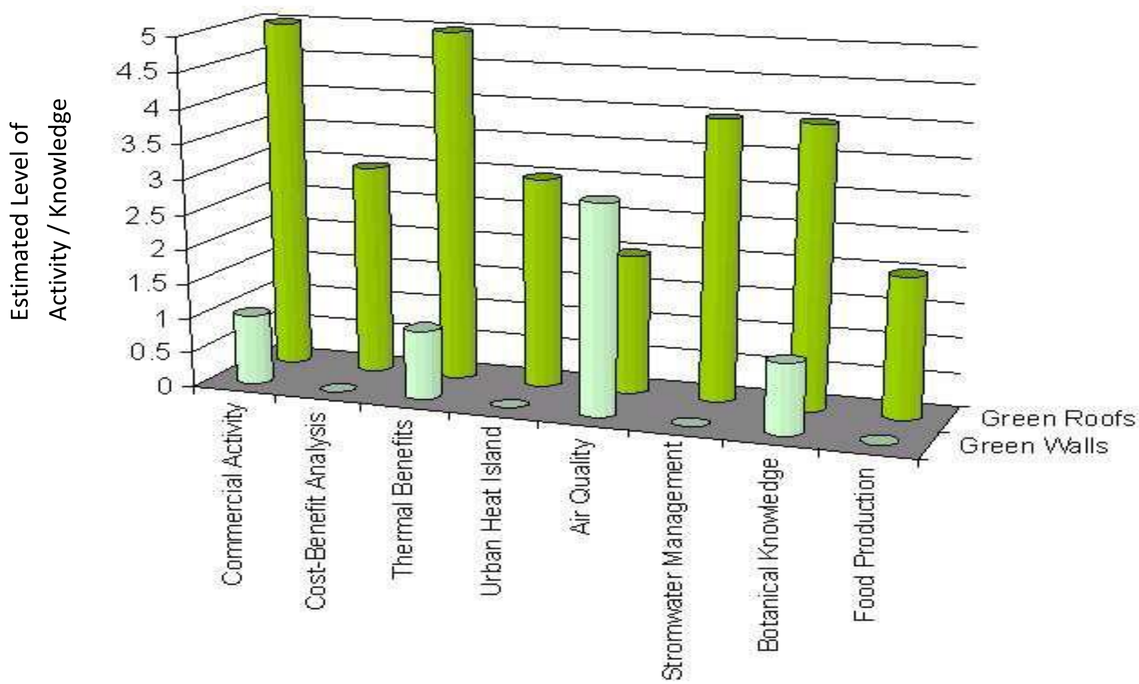


Figure 4.1 Identification of Research needs based on current activity and knowledge (Stav, 2008, p. 20)

As of 2012, no study could be found that covered the topic of food production as part of a green façade vertical garden system. Thus, food producing living facades became the main focus of this study. The diagram in Table 4.2, shows the range of potential impacts the food producing living façade will have.

Table 4.2 Broad Research Impact Categories

System	Impacts			
	Biospheric	**Energetic**	**Atmospheric**	**Hydrospheric**
Green Façade **Type:** Hybrid -Panel & Trellis **Growing Media:** Fabricated Soil **Vegetation**: Fruit, Herbs, Vegetables & Flowers	Photosynthesis Biomass Compost ↓ Food Waste Reduction On-site Processing Low Energy Inputs	Solar Radiation Reflected Direct Conversion to Heat Evaporation/Precipitation Wind Photosynthesis ↓ Biomass Façade Surface Temperature Reduction Heat Gain Reduction	Wind/Air CO2 O2 Biofiltration ↓ Natural Ventilation Small Particulate ($PM_{2.5}$) Reduction Improved Air Quality	Evaporation / Precipitation / Rainwater Irrigation ↓ Runoff Reduction Biomass

To organize the technical green façade performance research identified as important to the development of this dissertation, authors have been reviewed based on the four performance categories of food, temperature - cooling, air and water, with an identification of the climate region where these studies were conducted. As Table 4.3 below makes clear, a majority of the research on green walls and living facades has been focused on the temperate climate region, which is the dominant climate type in the United States and in Europe.

The table also clearly shows that the major area of focus for all these studies has been the thermal benefit, in particular the cooling effect of these systems. The next biggest focus has been air quality ramifications, followed by water quality issues. It is important to emphasize that very few published research studies have been found documenting food production on a green façade living wall system, the primary focus of this research study. This table provides an overview of the relevant literature on green façade/living wall performance in the four core areas identified in this research project.

Table 4.3 Table of major green wall research authors and areas of focus

Author	Food	Temperature - Cooling	Air	Water	Climate		
					Temperate	Subtropical	Tropical
Akbari		✓	✓			✓	
Amir	✓						✓
Bass		✓			✓		
Cameron		✓			✓		
Connelly (BCIT)				✓	✓		
Davis		✓					✓
Eumorfopoulou		✓				✓	
Köhler		✓	✓		✓		
Kontoleon		✓			✓		
Kew				✓	✓		
Martensson	✓				✓		
Nagle	✓				✓		
Othman		✓					✓
Petit			✓			✓	
Perini		✓	✓		✓		
Schmidt		✓		✓	✓		
Stec		✓					
Susorova		✓			✓		
Tilley		✓			✓		
Wang				✓	✓		
Wong		✓					✓
Leininger	✓	✓	✓	✓	✓		

This research study collected data in all four categories, in the temperate climate region of western Pennsylvania in the eastern United States. This research was conducted over six growing seasons from 2013 through 2018, harvesting fresh produce every season and documenting the fluctuation in produce amounts by façade, variety, month and year. The two food production studies in the literature that contain measured production results were conducted over a single growing season.

4.1 Food Production

Research that focused on vegetated façades as a source of fresh produce has been limited to date. In 2008 Manfred Köhler published a paper to review green wall and façade technology research activities, with a focus on Germany. Köhler noted the use of vines, even grape and other food producing varieties, on buildings in the Mediterranean cultures going back for thousands of years. He discussed how this practice had spread to the castles and villages of central Europe by five hundred years ago and included fruit espaliers of different fruit tree varieties up against garden walls and building facades. He broke down his analysis of hundreds of papers and articles into three broad categories including botanical research, gardening and technical aspects of the landscaping on houses, and ecological functions. While he briefly discusses the historical use of edible plants on green facades and living walls, he does not include or discuss any recent research in this area.

In the summer of 2015, researchers at Pennsylvania State University, Nagle, Echols and Tamminga, conducted a pilot study investigating food production on a living wall (2017) . The research façade was anchored to a concrete wall outside the school of architecture lab basement level facing southeast (Figure 4.3). The system consisted of corrugated plastic wall mounted boxes containing ten cells measuring 7.6 cm x 12.7 cm x 15.2 cm (3 in x 5 in x 6 in), arranged as five cells side by side (Figure 4.2).

Crop selection was made to replicate a small home garden with a preference for shallow rooted crops that could be continuously harvested throughout the growing season. Various salad greens, herbs, radishes, peas and cherry tomatoes were planted. The metrics measuring productivity of the living façade vertical garden system included harvest rates for all crops, light levels (irradiance), irrigation frequency and soil moisture levels. The growing media consisted of fifty percent local topsoil and fifty percent local compost.

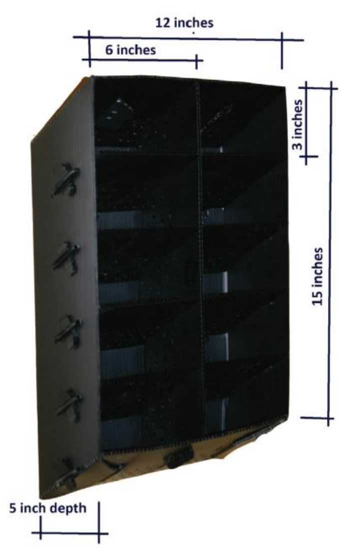


Figure 4.2 Planting Box (2017, p. 27)

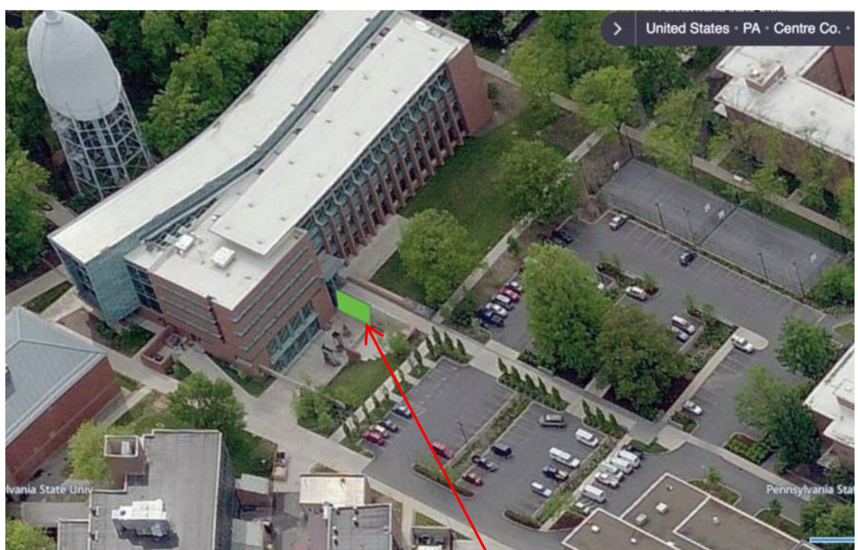


Figure 4.3 Living Façade Pilot Study location (shown in light green), State College, PA (Nagle, Echols, & Tamminga, 2017, p. 26)

Irrigation water was delivered twice a day, once in the morning and once in the afternoon, from two, 200-liter (52.84 gallon) rainwater collection barrels. It was fertilized with a 10-10-10 (N-P-K) granular fertilizer, 100 grams per barrel each month. While soil moisture was measured, water usage per unit of area per day was not. Collected rainfall was insufficient to supply all the irrigation requirements regularly. The plant types and arrangement are shown in Figures 4.4 – 4.6 below.

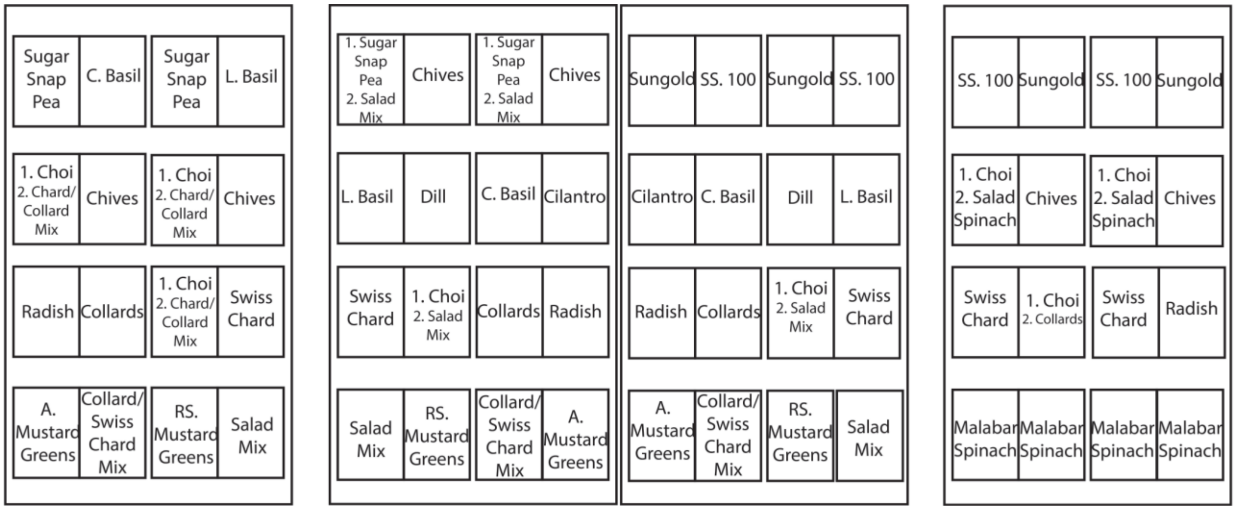


Figure 4.4 Plant selection and planting cell arrangement (Nagle, Echols, & Tamminga, 2017, p. 29)

Harvests were completed once or twice a week using a twelve-foot ladder to reach the upper box cells. Harvest data was compiled monthly per crop and then totaled at the end of the growing season. The range of plant production ran from a low of 1.5 kg/m^2 (0.31 lbs/ft^2) for the herbs Dill and Chives, to a high of 12.7 kg/m^2 (2.6 lbs/ft^2) for Collards. The Pilot Study average production was 6.73 kg/m^2 (1.38 lbs./ft^2).

Figure 4.5 Side View (Nagle, Echols, & Tamminga, 2017, p. 24)

Figure 4.6 Front View (Nagle, Echols, & Tamminga, 2017, p. 30)

To judge comparative productivity, the researchers found that The Rutgers Agricultural Experiment Station estimates that the average production rate for small scale, mixed production conventional agriculture is 2.44 kg/m^2 (0.5 lbs/ft^2). Average production was almost 3 times greater for the living façade as for conventional agricultural production, with some specific crops producing at rates twenty-five times greater than average conventional agricultural production. The means of measuring dietary value was by using the World Health Organization standard of at least 400g of fruit and vegetables per day for a healthy diet (World Health Organization, 2004). The living façade produced 523g daily, enough for one adult per day during the growing season.

In addition to measuring the horticultural productivity of the living wall system, the Penn State researchers also developed estimated dollar value of the produce to assign a quantified economic benefit to this provisioning ecosystem service. Using data from the USDA Agricultural Marketing Service for Specialty Crops, commodity price values were obtained in dollars per kilogram and applied to the total kilograms produced for each crop variety. The total yield for all crops of 55.8 Kg, would have an estimated commodity dollar value of $526.69. This quantification of the economic value of provisioning ecosystem services helps to build the case for food producing facades.

The survival and vitality of perennial plants when grown in a living wall system in a humid, continental Scandinavian climate region was the focus of a research study conducted in an old industrial area of Malmö, Sweden. Researchers Martensson, Fransson and Emilsson (2014) from the Department of Landscape Architecture, Planning and Management at Swedish University of Agricultural Sciences noted that few studies had been carried out on the suitability of different plant species for living wall system applications, especially in the Scandinavian climate.

In the Spring of 2013, sixteen rockwool panels (Vertigreen™, by Zinco GmbH) each measuring 70 cm x 50 cm x 7 cm (27.56 in x 19.69 in x 2.76 in) were installed in two columns totaling 1.4 m^2 and one column totaling 2.8 m^2, with the bottom of the column at 0.5 m (1.64 ft) above the ground and the top at 3.5 m (11.48 ft) above the ground. Seven species of edible perennials and seven species of evergreen perennials were randomly planted, including one species that is both edible and evergreen. The edible species were a variety of herbs and berries. Control plants were planted in wooden soil boxes measuring 0.8 m x 1.2 m x 0.4 meters (2.62 ft x 3.94 ft x 1.31 ft) which were lined with a landscape membrane to hold the soil. The control plants were used to do a visual comparative analysis of plant health, vitality and aesthetic appearance to gauge how well a rockwool living wall could support healthy plant life. No analysis of plant productivity was undertaken.

Plant visual quality was assessed in July, August, September and the following April, to gauge how the plants performed compared to the control plants throughout the growing season and then after overwintering. Scores were based on the proportion of dead or wilted leaves. The visual and pedagogical value of the study was the main focus of this research, instead of horticultural production. The rockwool living wall plants were irrigated with an essentially unlimited water supply initially, but between late June and early August irrigation was reduced to simulate drought conditions, to test the limits of survivability and visual signs of stress in the plants. The control boxes received no additional irrigation after the first two months. In these conditions some plants did better in the control boxes and some did better in the rockwool vertical garden living wall system.

This research study established that edible and evergreen plants can survive and overwinter successfully as part of a living wall system in a highly variable cold, humid continental climate. The edible species that not only survived but did well and showed promise for future research looking into the horticultural production value of such plants as part of urban living walls and green façade vertical gardens included *Allium schoenoprasum* (Chives), *Calamintha nepeta* (Lesser Calamint), and *Fragaria vesca* (Wild Strawberry). The value of growing edible plants in this climate was noted as a beneficial provisioning ecosystem service to enhance urban quality of life, while reducing the environmental impacts of current industrial food production and distribution and improving biodiversity.

A team of Malaysian researchers in 2011 published a paper espousing the use of legumes grown on biofacades as a way to both increase food biomass production within Malaysia (Amir, Yeok, Abdullah, & Rahman, 2011). The concept, terminology, benefits and needed for developing food producing plants on building facades is reviewed in this paper. The term biofacade is attributed to Sunakorn, Pakarnseree and Davivongs (2006) and defined as "a combination between natural environment and built environment forming a biological building skin". The other terms for these systems include "the vertical garden (Blanc, 2008), green facades (Kohler M. , 2008), bioshader (Ip, Lam, & Miller, 2010), living wall (Dunnett & Kingsbury, 2008), green wall (Irwin, 2010) and Vertical Greenery System (VGS) (Wong, et al., 2010).

As Malaysia needs to import crops to meet the total amount of produce necessary for a healthy diet for the population, the researchers selected four varieties of legumes as suitable for a full-scale future research application. The selected varieties, *Pisum sativum* (Sweet pea), *Vigna unguiculata sesquipedalis* (Long bean), *Psophocarpus tetrogonobulus* (Winged bean) and *Phaseolus vulgaris* (Kidney bean), were all looked at for their food, medicinal, and livestock feed value, and, in the case of sweet pea being used for the production of bio-plastics, commercial industrial value. In looking at the range of potential ecosystem services beyond food and medicinal production, such as carbon sequestration, indoor building temperature reduction and the mitigation of urban heat island effect as described in the literature, the researchers argue that full scale installation of biofacade systems can generate economic value, that once quantified, can be used to justify the investment in these systems within regular market value calculations.

While these three published studies are the only ones found to date that focus on food producing living facades, there has been a marked increase in popular articles and commercial systems focused on the promotion of growing fresh produce in vertical garden systems within the urban environment. These articles and products emphasize the potential for these systems to be productive, effective and beneficial, but there is a shortage in results providing measured, recorded and verified performance of these systems.

4.2 Façade Temperature Reduction

The benefits of vegetation in the built environment, in terms of reducing urban heat island effect and air temperatures, thereby improving micro-climate at the building scale, have been studied with simulations, computer modeling and measured effects. In a paper looking at how cool surfaces and shade trees reduce urban air temperatures while improving air quality in Los Angeles, Akbari, Pomneranz and Taha, of Lawrence Berkeley Laboratories, found that *"urban trees and high albedo surfaces can offset or reverse urban heat island effect. Mitigation of urban heat islands can potentially* *reduce national energy use in air conditioning by 20% and save over $10B per year in energy use and improvement in urban air quality. The albedo of the city may be increased at minimal cost if high-albedo surfaces are chosen to replace darker materials during routine maintenance of roofs and roads."* (2001, p. 295).

A research simulation on the potential energy savings, in winter, of green wall applications located immediately adjacent to building facades, in a study area in downtown Toronto by Bass, has shown a tremendous additional insulating effect (Figure 4.7). The effect of the green wall on the façade was modeled using UFORE the Urban Forest Effects model developed by the USDA. Green walls reduce wind speed at the façade during winter, reducing convective losses, and had a much larger benefit than the other landscape applications (Bass, 2007).

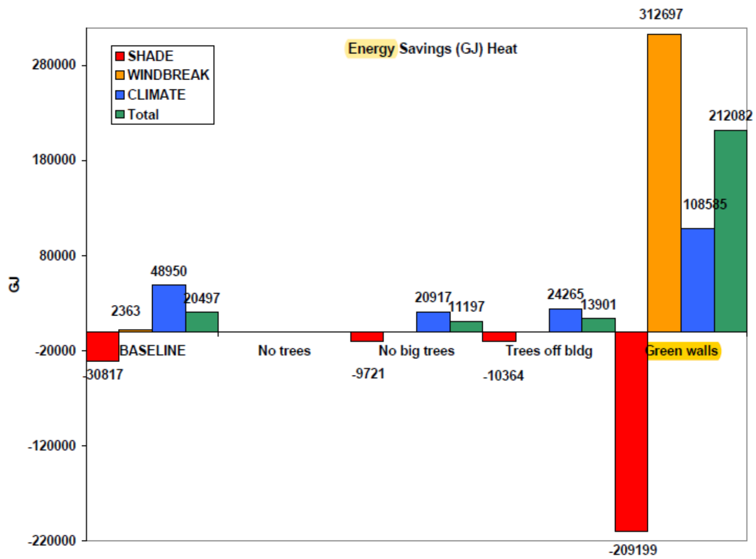


Figure 4.7 Reductions in energy required for heating in Midtown Toronto under five different scenarios of urban forestry and green walls (Bass, 2007, p. 20)

Several scenarios were modeled and the green wall scenario, with Juniper hedges planted within close proximity to the façade, showed a marked effect at reducing energy consumption by reducing wind speed at the façade and by adding insulating effect. This effect was pronounced and was more important for saving energy due to reducing windspeed, 312,697 GJ, than the loss of heat gain due to shading, -209,199, for a net energy savings of 103,498 GJ.

In 2008 a Vertical Greenery Systems research project was undertaken by a partnership between National University of Singapore, the National Parks Board and the Building Construction Authority (BCA) led by N.H. Wong, focused on performance variables, including surface temperature performance of eight different VGS systems mounted to reinforced concreate wall structures, with a bare concrete wall as the control wall (Wong N. H., 2008). Sensors placed at the bare wall surface for the control and behind the plants on the eight different VGS systems were compared for wall surface temperature reduction. Seven different panels systems and one container with trellis system were installed. The configuration of the freestanding concrete control wall and eight VGS systems walls are shown installed side by side in an outdoor green space in Figure 4.8.

Figure 4.8 Concrete control wall at the far left with eight VGS research systems installed on side-by-side freestanding concrete wall structures (Wong N. H., 2008, p. 27).

Surface temperature fluctuations on the face of the control and on the face of the concrete walls behind the vegetation measured on June 21, 2008, are shown in boxplots in Figure 4.9. The concrete control wall clearly records the highest temperatures with the largest diurnal temperature swing, 28.5 to 38.5°C (83.3 to 101.3°F) with a median temperature of 32.5°C (90.5°F). System 2 (the trellis system) with minimal vine coverage as shown in the photo in figure 4.8 (third from the left) records the next highest temperature and range, while System 6 has a lower minimum and maximum temperature but similar range. Systems 1, 4 and 8 have the lowest minimum and maximum temperatures and smallest overall temperature ranges, with System 4 ranging from 27 to 28°C (80.6 to 82.4°F), with a median of 27.5°C (81.5°F); a full 5°C (9°F) below the control.

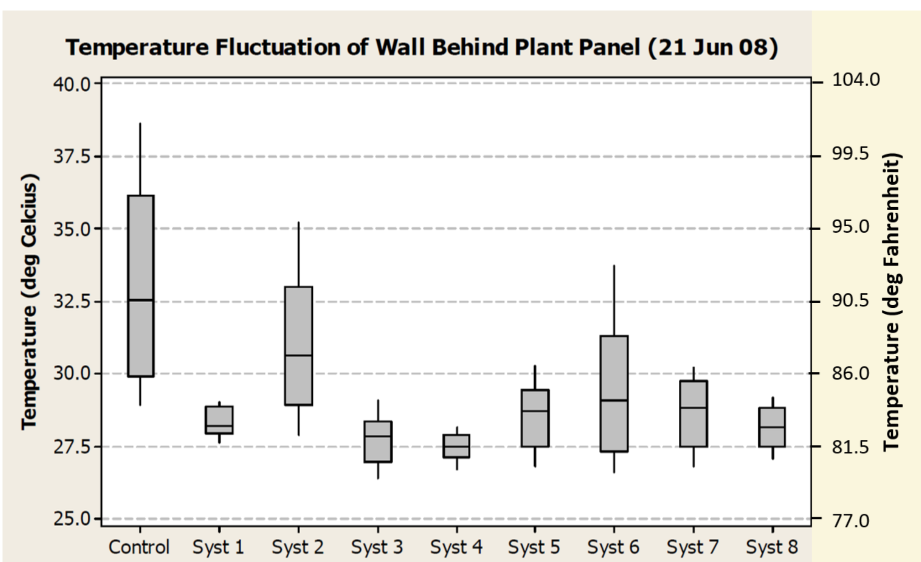


Figure 4.9 Boxplot diagrams of the control and eight VGS installations, June 21, 2008 (Wong N. H., 2008, p. 36). Temperature axis in degrees Fahrenheit along the right side of the boxplot diagram was added by the author.

Additional simulation analysis of VGS installations on opaque and glazed portions of a building façade, calculating heat gain using the Envelope Thermal Transfer Value (ETTV) method, reductions of 13.4% for the partial (floor level to one meter above floor level) opaque façade area, and 24.7% to 47.4% for the full (floor to ceiling) glazed façade area, were achieved (Wong N. H., 2008). This simulation analysis was applied to several variations of a hypothetical 10 story office building in Singapore. Cost reduction of energy consumption ranged from a high of 74.29% for 100% green façade on a 100% opaque façade enclosure, to 10.35% when the opaque wall is fully covered by green façade but has 25% window openings uncovered by plants.

A study in Northern Greece, where there is a temperate Mediterranean climate, was conducted in 2005 and 2006 by Eumorfopoulou and Kontoleon comparing green façade and bare façade finishes on two identical floor levels, the 2nd and 3rd floors, in a five-story reinforced concrete building with insulated brick masonry infill finished with light colored plaster inside and out (2009). The east facing façade was chosen due to its exposure to intense morning sun during the summer cooling period. This heavy mass building had punched window openings representing about 15% of the floor area. The opaque wall areas were covered with *Parthenocissus tricuspidata* (Boston Ivy), and the glazed areas were left uncovered.

Measured data showed maximum temperature peaks on both the exterior and interior façades were considerably lower for the ivy covered facade compared with the bare control façade. On a sunny day this temperature difference could be as high as 10-15^{o}C, while on cloudy days it could reach a more modest 2^{o}C. During overnight hours, however, the green façade would stay 1-2^{o}C warmer than the bare control façade. Exterior surface temperature differentials ranged from 1.9-8.3^{o}C, with an average of 5.7^{o}C. The benefits of the ivy covered façade also translated indoors where interior surface temperature differentials ranged from 0.4-1.6^{o}C, with an average of 0.9^{o}C.

This same typical Greek building and plant configuration was used in a simple building energy model simulation study (Kontoleon & Eumorfopoulou, 2010) by the same authors to look at orientation and the proportion of a plant covered wall layer in term of thermal performance benefit. This study concluded that cooling load reductions could be achieved of 18% on the east façade, 8% on the south façade, 18% on the west façade and 5% on the north façade. The building model was 10m x 10m (32.8ft x 32.8ft) square. The smaller cooling load reduction on the south façade is probably due to the high sun angle at noon, whereas the east and west façade receive straight, low angle direct gain in the early to mid-morning and late afternoon to evening hours respectively. While the modeling assumptions, building type and climate make these results difficult to generalize, they show the potential value to adding green façade systems to different building orientations, even facing away from direct solar gain.

In his 2008 paper Köhler describes the thermal performance benefits of green facades in a category he calls "surface shelter/thermal insulation energy savings" (Kohler M. , 2008, p. 428). He describes differences due to the green façade versus no green façade of up to 3^{o}C warmer in winter as insulation on cold nights, and up to 3^{o}C cooler in summer due to shade effect, citing his own research with Bartfelder in 1987 and 2005. He also describes up to a 25% heat loss from a north facing façade, depending on the insulation of the building, citing Minke and Witter from 1983.

In research on the cooling effects of plants in a green façade system undertaken between 2005 and 2009 at the Adlershof Institute in Berlin, Professor Schmidt found a cooling effect due to evapotranspiration of 157 kWh/m^2 per day on average in his study of the courtyard and south facing green wall installations in Berlin. This translates to an equivalency of 44 tons of cooling over a 24-hour period, or 1.8 tons of cooling per hour on average. This is enough of a cooling result to significantly reduce air conditioning loads. Schmidt also found, however, that contamination of rainwater, by roofing materials for instance, had a negative effect on the growth and vitality of the façade plants requiring additional filtering and remediation steps to be taken before the rainwater could be used for irrigation. (Schmidt M. , 2009).

Researchers Tilley, Price, Matt and Marrow, at the Ecosystem Engineering Design Lab at the University of Maryland, College Park, MD, between 2009-2012, conducted green façade experimental and modeling research looking into exterior and interior building façade temperature reduction, evapotranspiration water and energy patterns and total energy balance calculations on four small research structures measuring 8 ft x 8 ft x 11 ft tall, two structures with green facades and two without green facades as controls. The research configurations on the test structures are shown in Figures 4.10 and 4.11 (2012).

Figure 4.10 Experimental buildings in Clarkesville, MD with west facing green facades in mid-summer 2010 (Tilley, Price, Matt, & Marrow, 2012, p. 20).

Figure 4.11 The experimental buildings were covered with green facades on the west, south and east facing facades from late summer 2010 to September 2011 (Tilley, Price, Matt, & Marrow, 2012, p. 28).

These experimental buildings were constructed using typical residential wood framed construction methods. Calculated R-values in ft^2 ^{o}F h Btu^{-1} of 12.9 (walls), 18.2 (roof), 13.9 (floor) and 9.8 (wall with door) were achieved. The research and control structures were laid out in a well spaced arrangement, with the temperature sensors strategically located to capture temperature at specific layers from the exterior to the interior. The green facades are planter and trellis systems with wood framed soil planters the same width as each façade, and the wood framed metal trellis the same height as the façade.

Exterior wall temperature measurements of the south building wall comparing the green façade (called the green wall on the graph) and the control façade (called the bare wall on the graph) show that the green façade is cooler every day during the daylight hours. The bare wall had temperatures that reached a high of 50°C (122°F), while maximum highs for the green wall never exceeded 39°C (102°F), a difference of 11°C (20°F). This temperature difference between the green wall and the bare wall, referred to as the cooling effect, is shown at the bottom of the graph using the secondary scale shown on the right axis. The maximum temperature difference was recorded on July 14, 2011, when the green wall was shown to be 14°C (25°F) cooler than the bare wall control.

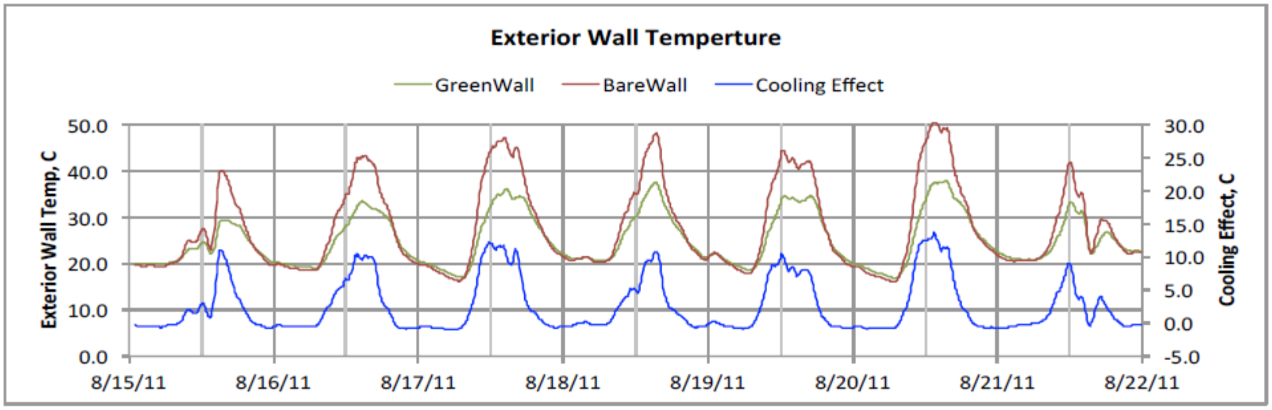


Figure 4.12 Exterior temperature of south building wall comparing the green wall to the bare wall, with the cooling effect graphed with a second axis at the left of the graph, August 2011 (Tilley, Price, Matt, & Marrow, 2012, p. 62).

Temperature comparisons were averaged for each month of data collection from May through September 2011 during the hottest part of the day from 12pm (noon) to 6pm. The average temperature difference, or cooling effect, was calculated and the results for each of the four test structures were tested statistically with the p-values listed in Table 4.4. The hottest months of the year, the months of June, July and August yielded results that are statistically significant, whereas the months of May and September yielded results that are not statistically significant.

Table 4.4 Exterior temperature of the south building wall comparing the green wall to the bare wall, with the cooling effect, and p-value for all four test structures (n=4), for each month of the growing season in 2011 (Tilley, Price, Matt, & Marrow, 2012, p. 63)

Month	Week	Time	Green wall Temp, C	Bare wall Temp, C	Reduction in Temp, C	p-value
May	13th to 20th	12p-6p	22.8	25.3	2.5	0.09
June	8th to 14th	12p-6p	32.6	39.6	7.0	0.01
July	11th to 17th	12p-6p	31.6	38.9	7.3	0.04
August	15th to 21st	12p-6p	31.9	38.9	7.0	0.04
September	4th to 10th	12p-6p	25.4	28.6	3.3	0.06

Additional areas of research within this study investigating heat flux to the interior, solar radiation and air temperatures, leaf area index, evapo-transpiration and latent energy effects, and total energy balance, are important contributions that can be useful in building on the baseline data generated in the FPLF research conducted at CMU to better understand total cooling load reduction.

Cameron, Taylor and Emmet (2014) came to similar conclusions in their paper on cooling effects of green walls and green facades. These researchers found that air adjacent to a green wall was 3°C cooler than the air adjacent to a blank wall, as shown in Figure 4.13 below. This effect was the result of evergreen shrubs growing on the green façade, and the study determined that the amount of cooling was influenced by plant physiology and leaf area. Two other plants studied in the same paper had 6.3^{o}C and 7.0^{o}C reductions respectively. Plant type, including leaf area and physiology, does influence the results.

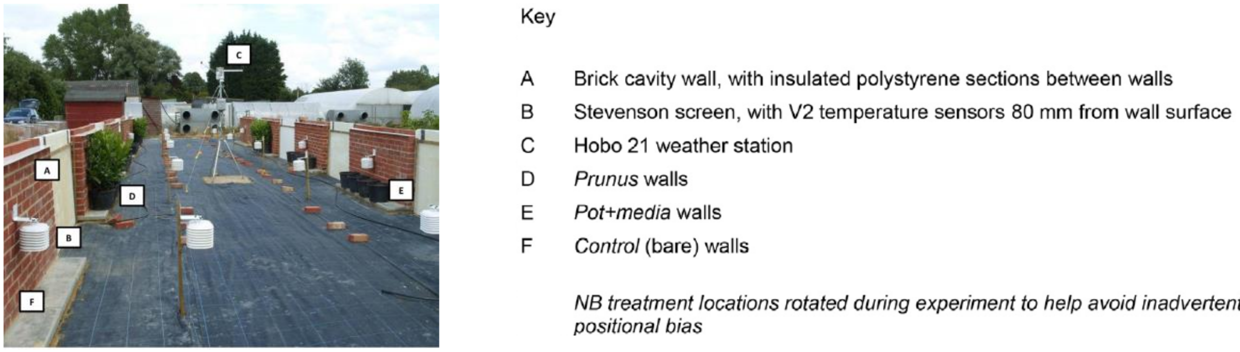


Figure 4.13 Cooling Effects of Green Walls and Green Facades (Cameron, Taylor, & Emmett, 2014, p. 200)

Research in the Netherlands found similar cooling effects. Simulation, modelling and validation done by Stec, Paassen and Maziarz, (2005) at the Technical University of Delft, working on models of double skin facades using plants as the outer skin, found a decrease in air conditioning of nearly 20%, similar to the research done at Lawrence Berkeley in Los Angeles. They found that the temperature of the plants never exceeded 35^{o} C (95^{o} F) but the blinds on the façade without plants could exceed 55^{o} C (131^{o} F), a difference of 20^{o} C (36^{o} F).

In a study in Chicago, looking at ivy growing on building facades in all four orientations on a university building, Susorova, Azimi and Stephens, (2014) from the Illinois Institute of Technology and the University of Chicago, found similar results in terms of temperature effects. They documented a 0.7^{o} C (1.2^{o} F) reduction of temperature across all façade orientations, with a 12.6^{o} C maximum (22.6^{0} F). In addition, heat flux though the opaque walls was reduced by 10%, and wind speed at the façade was reduced as much as 43%.

A 2016 research study conducted at the Architecture Faculty Building at the Pontifical Catholic University of Ecuador in Quito, Ecuador, by Davis, Ramirez and Perez, investigated the use of a building integrated green façade vertical garden as an active air-conditioning unit. This area of Ecuador has a temperate oceanic climate. The research installation consisted of 15 planting modules each 0.45m x 0.45m x 0.1m (1.48ft x 1.48ft x .33ft), arranged 3 wide and 5 high for a total size of 1.5m wide x 2.8m high (4.92ft x 9.19ft) or 4.2m^{2} (45.21ft^{2}). The system was installed as a reverse conceptualization of the traditional trombe wall. Where the trombe wall uses glass to enclose a shallow space usually along the south façade to trap solar radiation to heat up the air to warm the space inside, the green façade vertical garden air conditioner uses the plant panels to shield the sun, running air down the space between the panels and the façade to cool the air and the façade with evaporative cooling, to then bring that cooled air in through the façade at low vents cut into the glazed façade panels. These same vents were installed at an adjacent glazed façade area without the green façade panels for a control, Figures 4.14-4.17.

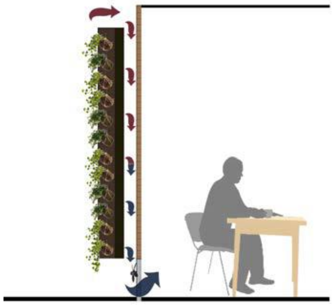


Figure 4.14 Green façade vertical garden diagram (Davis, Ramirez, & Perez, 2016, p. 1251)

Figure 4.15 Vertical garden installed (Davis, Ramirez, & Perez, 2016, p. 1253)

Figure 4.16 Vents behind the VG (Davis, Ramirez, & Perez, 2016, p. 1253)

Figure 4.17 Vents at the control facade (Davis, Ramirez, & Perez, 2016, p. 1253)

The soil mixture for this system consisted of potting soil, cocoa shell chips and sphagnum moss to increase its moisture holding capacity. There was no contact between the plant leaves and the air flow behind the plant panels, therefore the plants were assumed to have no influence on the cooling effect. Variations in the ambient air temperature and humidity levels in some of the experimental data led researchers to question some of the results, although the overall performance did reduce the incoming air temperature due to the green façade panels compared to the control. Results deemed to be the most accurate indicated a cooling effect of just over 2ºC (3.6ºF).

In a 2016 publication, researchers Othman and Sahidin, members of the Centre for Environment – Behaviour Studies, Faculty of Architecture, Planning and Surveying at the University of Technology MARA, in Shah Alam, Malaysia, evaluated green façade thermal performance as a passive approach to achieving sustainable design objectives. In a real world, field research study, two existing commercial buildings in the central business district of Jakarta, Indonesia, in a tropical climate, were studied to compare the existing mature green facade system on one, the PT. Indonesia Greenwall Building, with the typical commercial building without a green façade, the CMIB building next door (Figure 4.18).

Figure 4.18 The CMIB building on the left, and the PT, Indonesia Greenwall building on the right, are located side by side in the Central Jakarta Business District (Othman & Sahadin, 2016, p. 851).

The exterior and interior temperatures were measured and then the percent reduction was calculated and graphed for comparison, as shown in Figures 4.19-4.21.

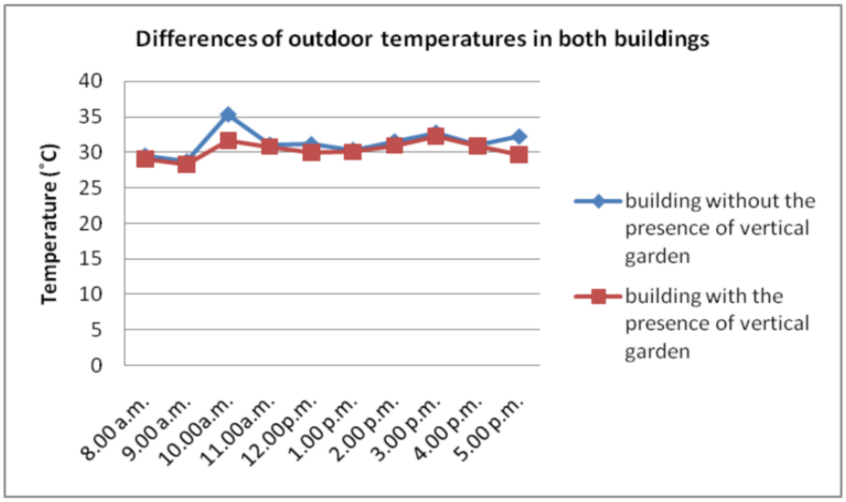


Figure 4.19 Differences in outdoor temperature in both buildings (Othman & Sahadin, 2016, p. 853).

The outdoor temperature measurements show clear indication of the benefit of the green façade when the temperature spikes at 10 am and at 5 pm. The rest of the time the temperatures are fairly close together with the green façade showing only a slight benefit. The graph is even more difficult to read then it could be because the axis range runs from 0°C to 40°C. The graph of the indoor temperatures, Figure 4.20, has an axis that runs from 25°C to 34°C, so the differences are more pronounced.

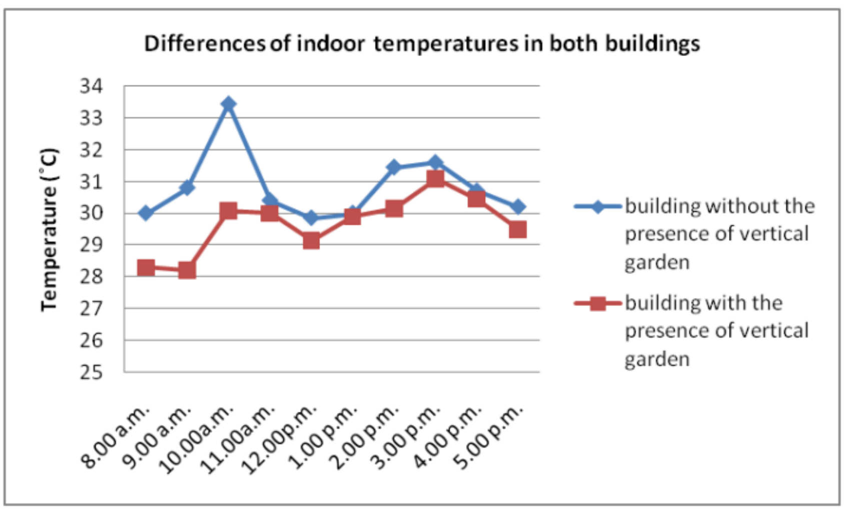


Figure 4.20 Differences in indoor temperature in both buildings (Othman & Sahadin, 2016, p. 853).

In this graph of indoor temperature comparison between the green façade building and the control building, the indoor temperature differences are much clearer. While the indoor temperature for the PT. Greenwall Building is still above the thermal comfort zone, it is less than the control building without the green façade by as much as 3.5°C.

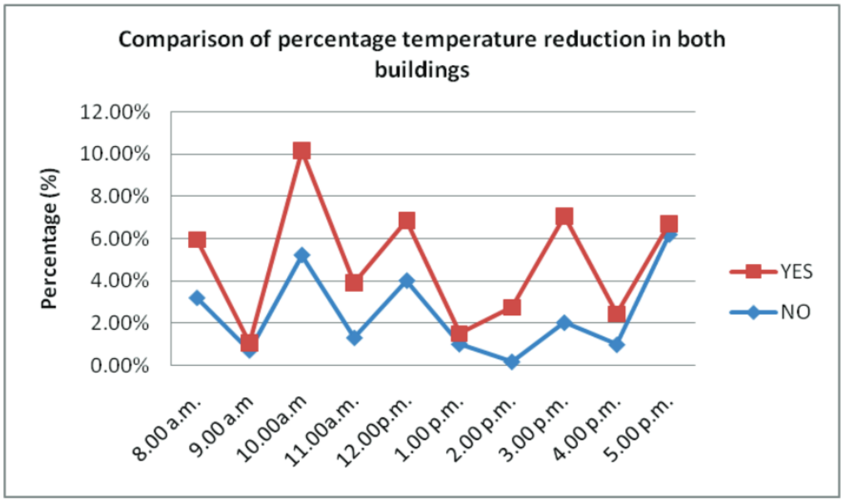


Figure 4.21 Comparison of temperature reduction in both buildings (Othman & Sahadin, 2016, p. 853)

The red line in Figure 4.21 is labeled yes to indicate that a green façade is installed on that building, whereas the blue line is labeled no, for no green façade. The green façade achieved temperature reduction percentages of between 0.99-10%, while the non-green façade building shows a temperature reduction. The largest temperature reductions recorded occurred at the hottest times of the day, in full sun, which accounts for the spikes at different times of the day sampled. When the temperature spiked, the green façade temperature reduction could be twice that of the control building façade.

The potential energy and cooling load reductions generated by reduced surface temperatures documented in other research studies were the focus of a research project on an existing building with a green façade in Genoa, Italy, which has a temperate Mediterranean climate. Researchers Perini, Bazzocchi, Croci, Magliocco and Cattaneo investigated the thermal performance of a vertical greenery system located on the south façade of the National Institute of Social Insurance (NIPS) building, site of the first green façade project in Italy in the 1980's (Figures 4.23 and 4.24).

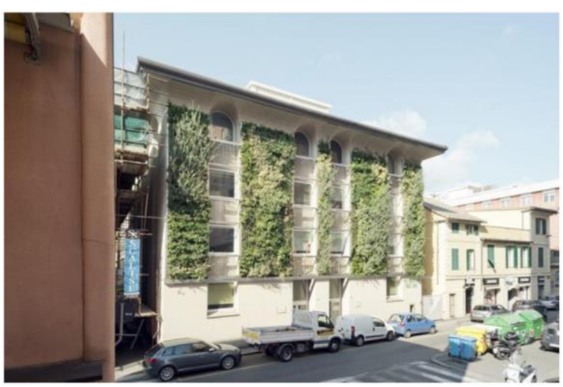


Figure 4.22 NIPS Building, Genoa (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017, p. 37)

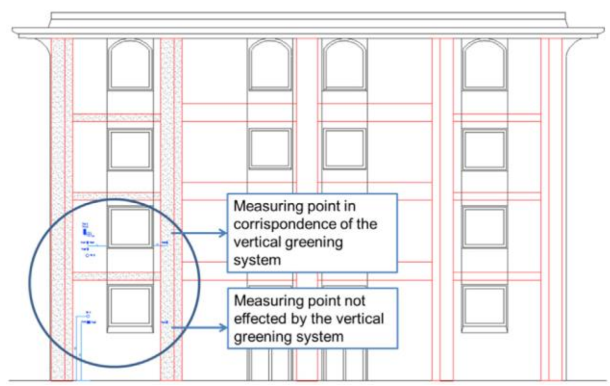


Figure 4.23 Monitoring locations (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017, p. 39)

The system instrumentation and monitoring systems for this research project were very well considered and installed to insure detailed data collection for accurate calculations of climate influence and system performance relative to potential energy use and cooling load reduction. The instrumentation installation and layout are clearly shown in Figures 4.24 and 4.25.

Figure 4.24 Green Façade instrumentation photo (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017, p. 38)

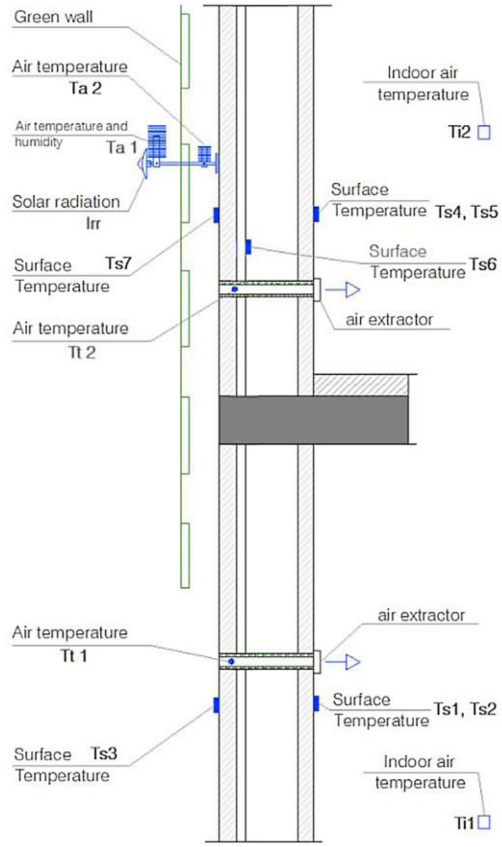


Figure 4.25 Green Façade section diagram (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017, p. 38)

The precise detailed installation of this instrumentation yielded the detailed measurements that allowed for accurate calculations to determine energy and cooling load reductions. The purpose of this study was to determine the implications of façade surface temperature reduction due to the installation of vertical greening systems in a temperate Mediterranean environment relative to energy reduction due to decreased demand for air conditioning to meet human comfort requirements. Tables 4.5 And 4.6 show the significant reductions in surface temperature and the corresponding theoretical percentage reduction in demand for cooling.

Table 4.5 Monthly average temperature, calculated during office hours (from 8 AM to 6 PM), of air extracted from the two ducts, in correspondence of the vertical greening system (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017, p. 41).

Month	Air extracted from outside	Air extracted behind vertical greening system	Number of hours that air, extracted from outside, temperature exceeds 26 °C	Number of hours in which air, extracted behind vertical greening system, temperature exceeds 26 °C
	[°C]	[°C]		
June	26.5	21.3	171	0
July	29.8	24.6	287	25
August	27.3	22.7	196	8
September	23.0	19.2	54	0

The hourly comparison of the amount of time that the air extracted from outside exceeds 26°C (78.8°F), the top temperature level of the thermal comfort zone, compared between the bare control façade and the vertical greenery system, indicates the clear benefit of the installation of façade greening in a Mediterranean climate. Savings range from 54-262 hours per month during the summer. The calculations based on these reductions in hours exceeding the upper comfort zone temperature limits are translated into percentage energy demand reduction related to theoretical cooling demand.

Table 4.6 Monthly energy saving, calculated during office hours (from 8 AM to 6 PM), deriving from the introduction of cool air extracted from the duct behind, in correspondence of the vertical greening system (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017, p. 41)

Month	ΔQve Energy saving per person	ΔQve Energy saving for the 27 users (9 persons per floor) of the area covered by INPS green façade	theoretical total energy demand for cooling	Percentage energy demand reduction related to the theoretical energy demand for cooling
	[kWh]	[kWh]	[kWh]	[%]
June	14.1	379.9	943	40.3
July	14.9	403.4	2219	18.2
August	13.3	360.2	2112	17.1
September	10.9	293.5	1035	28.4
Total	62.0	1674.8	6309	26.5

Savings ranging from 17.1-40.3% show the huge potential for community wide greening efforts to establish green façade infrastructure and vertical greening systems on as many building facades and vertical surfaces as possible. Practical limits and application challenges still need to be addressed, but the potential benefit for replacing fossil fuel energy consumption with living systems integration and performance are too significant to ignore.

4.3 Air Quality Improvement

The effects of green walls on air quality generally, and particulates specifically, is not as well studied as thermal effects, but some interesting findings have been documented. In his comparison of the benefits and costs of green facades, Köhler describes air quality issues in two sections. The first he calls "dust/particulate reduction", where he states that 4% of annual dust-fall could be trapped on plant leaves, if as many building facades as possible in an inner-city neighborhood covered with green facades and living walls, citing his own research from 1993. In the second section, called "heavy metal reduction" he states that dust gets trapped on and inside plant leaves, and that certain species, such as Boston and English ivy are well adapted to polluted air quality of dense urban environments, again citing his 1993 research (2008).

In their paper on how cool surfaces and shade trees improve air quality while reducing energy use in urban areas, Akbari, Pomeranz and Taha discuss the air quality benefit of trees (2001). The biggest benefit is related to reducing urban heat island effect, reducing the need for air conditioning and therefore electricity, which has the pronounced effect of limiting smog. Smog is made up of nitrogen oxides, sulfur oxides, smoke, ozone and other particulates mainly due to emissions from coal combustion, vehicles, industry, forest fires and photochemical reactions to these emissions - what the National Ambient Air Quality Standards (NAAQS) calls secondary source particulate pollution. Urban trees will reduce, via dry-deposition, levels of NO_x, O_3 and PM_{10}, however, Akbari cites work done by

Rosenfeld et. al, 1998, that 11 million trees in Los Angeles will only reduce PM_{10} by 0.1%. Increasing the surface area of vegetation, via green roofs, walls, and facades on as many buildings and urban structures as possible, would increase the surface area of living systems of plants significantly, potentially increasing particulate reduction (Akbari, Pomerantz, & Taha, 2001).

In a paper published in 2015, Wang, et. al. studied the accumulation of particulates on leaf surfaces during leaf expansion in Beijing. Three tree species were chosen for the variation in their leaf texture from smooth to coarse; *Ulmus pumila* (Siberian Elm), *Salix babylonica* (Weeping Willow), *Ginkgo biloba* (Maidenhair Tree). These three species were chosen because they have different epiticular wax ultrastructures, which is the structure of a natural wax coating on the leaves of plants, which are referred to as thin films, platelets and tubules. The type of wax structure and the amount of rainfall in an area determine the effectiveness of these structures to remove particulates (Figure 4.26). Rainfall improves removal via wet deposition compared to dry deposition. It was determined that the capacity of the Elm to remove particulates, especially $PM_{2.5}$ was the best due to its thin wax film, while the Gingko, with its dense wax tubes which decreased the interface area for the particulates to settle, was the worst. While green facades rarely are planted with tree species, this study shows how the variation in leaf texture and surface characteristics, and the use of daily irrigation increasing the opportunity for wet deposition, can become effective mechanisms for reducing $PM_{2.5}$ in urban environments.

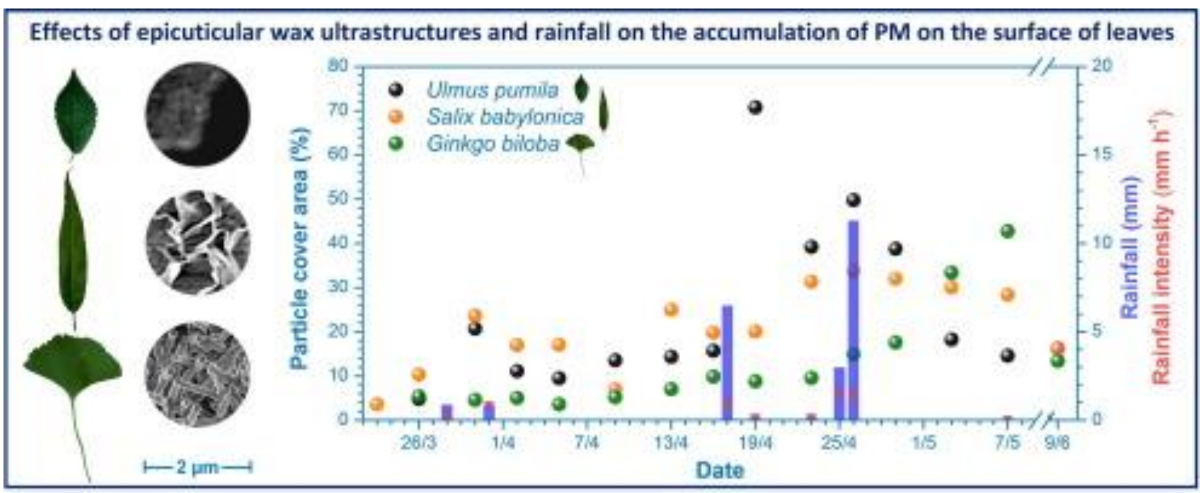


Figure 4.26 Effects of the leaf surface characteristics of *Ulmus pumila* (Siberian Elm), *Salix babylonica* (Weeping Willow), *Ginkgo biloba* (Maidenhair Tree) and rainfall on the accumulation of particulate matter on leaf surfaces (Wang, Gong, Liao, & Wang, 2015, p. 430)

In Genoa, Italy, researchers Perini, Ottele, Giulini, Magliocco and Roccotiello investigated the performance of four different evergreen plant species in terms of the ability to reduce fine and ultra-fine dust particles (PM_{10} and $PM_{2.5}$) when planted in a vertical greening system (2017). This paper used similar methods and reached similar conclusions as Wang, et.al. in Beijing. The four evergreen plants investigated, *Trachelospermum jasminoides* (Star jasmine), *Hedera helix* (Common ivy), *Cistus 'Jessamy Beauty'* (Rockrose), Phlomis fruticose (Jerusalem sage), were planted in a vertical greenery system on south façade of the National Institute of Social Insurance (NIPS) building, site of the first green façade project in Italy in the 1980's (Figures 4.27 and 4.28).

Figure 4.27 NIPS Building green façade (Perini, Ottele, Giulini, Magliocco, & Roccotiello, 2017, p. 270)

Figure 4.28 NIPS site, Genoa (Perini, Ottele, Giulini, Magliocco, & Roccotiello, 2017, p. 270)

The four plant species were planted in the green façade in March 2015. The first leaf samples were taken 3 months after planting (July) and the second samples were taken 6 months after planting (October). Two leaves were selected from each plant to be scanned with an Environmental Scanning Electron Microscope (ESEM), with care taken to ensure the same conditions were met in terms of height, pollution exposure and weather. The two sample periods were chosen on days where there had been no rain for the previous 15 days.

Analysis of the deposition and leaf characteristics indicated that the plants with waxy leaves (*T. jasminoides*) collected the highest amount of atmospheric particulates, whereas plants with hairy leaves (*P. frucitosa*) were less effective. The authors were careful to point out that these results refuted other published research and therefore needed further investigation. In addition, the leaves collected during the two different sampling periods showed similar effectiveness at particulate collection, indicating that the effectiveness at particulate removal, depending on the inherent plant characteristics, is similar throughout the growing season, and that particulates between 2.5 and 10 µm cannot be washed away from either waxy or hairy leaves.

As with the Beijing study, this study confirms that the capacity of vertical greenery systems to reduce atmospheric particulate concentrations depends on the specific characteristics of plant species. Creating a green wall that is a polyculture of various plant species may be the best way to insure multiple performance benefits for the built environment.

Petit, Irga, Abdo and Torpy, (2017) from the University of Sydney, in a paper looking at how well green walls filter fine particulate matter, found that green walls using different plant species had different single-pass removal efficiencies, with fern species showing the highest removal efficiencies for all fine particulate sizes (Figure 4.29).

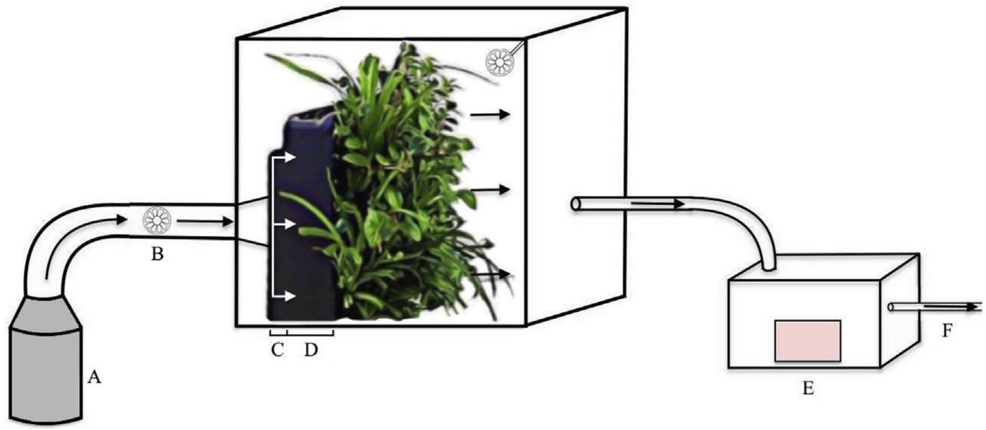


Figure 4.29 Single pass flow-through chamber. A ¼ combustion chamber; B ¼ axial impeller; C ¼ plenum within green wall module; D ¼ green wall packing medium; E ¼ laser nephelometer; F ¼ vacuum exhaust. (Petit, Irga, Abdo, & Torpy, 2017, p. 302)

Measured recordings of $PM_{0.3\text{-}0.5}$ had a removal efficiency of 45.78%, and $PM_{5\text{-}10}$ had a removal efficiency of 92.46%, as shown in Figure 4.10 below.

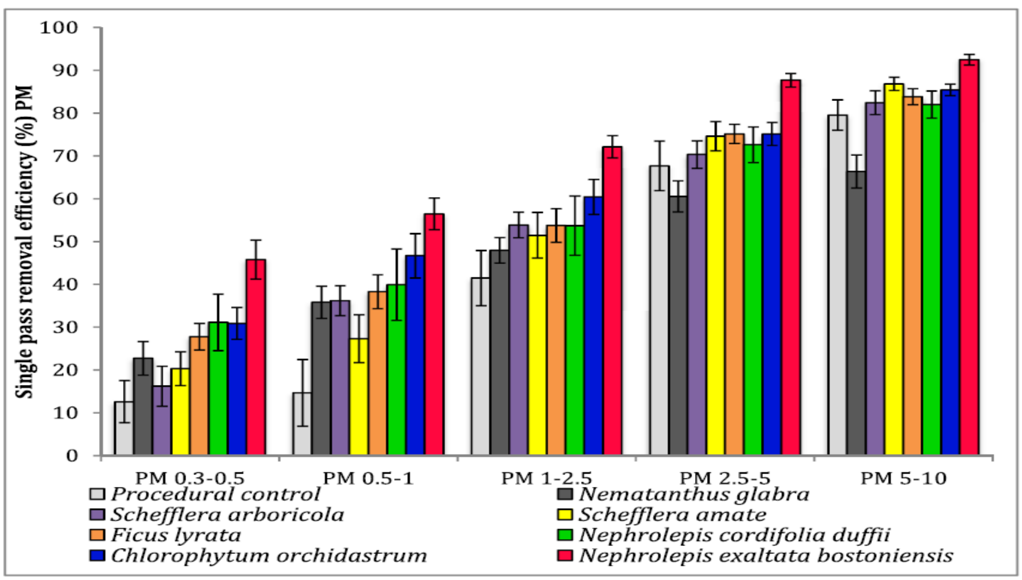


Figure 4.30 Average single pass removal efficiency (%) of different treatments used in this experiment across independently sized PM fractions. Error bars represent standard error of the mean (n ¼ 15). (Petit, Irga, Abdo, & Torpy, 2017, p. 303)

These are impressive results even for the finest of small particulates. The system tested in this experiment is a biowall filtration system that could be integrated at the façade in a through wall system, or as an indoor biowall connected to the ventilation system. The plants tested in this system include *Schefflera arboricola Dwarf* (Umbrella Tree), *Schefflera amate* (Umbrella Tree), *Ficus Lyrata* (Fiddle Leaf Tree), *Chlorophytum orchidastrum* (Fire Flash), *Nematanthus glabra* (Goldfish Plant), *Nephrolepis cordifolia duffii* (Lemon Button Fern), and N*ephrolepis exaltata bostoniensis* (Sword Fern). While these plants are not edible or fruit producing, they indicate the levels of particulate reduction that can be attained when living systems using plants are integrated with the building façade and/or mechanical ventilation systems.

4.4 Storm water Irrigation and Runoff Reduction

Research looking at water quality and effects are similar to the work and results obtained by Schmidt. Not only does water have a pronounced temperature effect, but it also is essential to the health of the plants in a living façade system.

In 2009, researchers Connelly, Compton-Smith, Rousseau and Huston, at the British Columbia Institute of Technology (BCIT) School of Construction and the Environment, Centre for Architectural Ecology, in Vancouver, initiated a study investigating the rainwater interception capacity of green facades. Vancouver, in western Canada, has a maritime temperate climate, with moderate temperatures throughout the year, with dry summers and high rainfall in the fall and winter. Seven separate green façades, measuring 1 meter (3.28 ft) wide and 3.7 meters (12.14 ft) high, consisting of soil-filled containers on the ground and three different commercial trellis and cable systems, were installed on the east, south and west walls of a research tailer. Each of the three commercial systems was planted with a different vining plant, *Polygonum auberti* (Siverlace vine), *Clematis armandii* (Evergreen clematis) or *Celastrus orbiculatis* (Oriental bittersweet).

The location of several of these green façade panels are shown on the green roof research center research trailer in Figure 4.31, with close up photos of panel 4 in Figure 4.32 showing the growing phases of Celastrus orbiculatus in eight different seasons from December 2009 to January 2012. June through September of the second growing season is when the vines were the most vigorous with the thickest leaf cover.

Figure 4.31 Installed wall-mounted trellis research panels (Connelly, Compton-Smith, Rousseau, & Huston, 2012, p. 26).

Figure 4.32 Panel 4 *Celastrus orbiculatus* (Oriental Bittersweet), shown over 8 different months from December 2009 to January 2012 (Connelly, Compton-Smith, Rousseau, & Huston, 2012, p. 31).

While the focus of this research study was documenting the ability of these green façade panels to intercept rainfall, shielding the building façade and reducing façade runoff, the soil containers were provided with automatic irrigation systems to keep the plants irrigated during the summer dry months. The total amount of irrigation provided was recorded and can be calculated per unit area of soil containers creating the same metric as developed for the food producing living façade installations at CMU.

Irrigation began in June 2010 at 30 minutes twice daily, for 3.9 liters/panel/day (1.03 gal). June to August 2010 irrigation was increased to 45 minutes twice a day for 5.9 L/panel/day (1.56 gal). August to October 2010, and May to November 2011 irrigation was modified again to 120 minutes, once a day for 7.7 L/panel/day (2.03 gal). Each soil container was 2 meters (6.56ft) long and 0.664 meters (2.18ft) high, for a surface area of $1.38m^2$ ($14.3ft^2$). This would translate into an irrigation per unit area progression from 2.83 L/m^2 ($0.07gal/ft^2$), to 4.28 L/m^2 ($0.11gal/ft^2$), to $5.58L/m^2$ ($0.14gal/ft^2$). This irrigation rate is a little less than half of the irrigation rate used for the FPLF installations at CMU.

In a paper published in 2014, Pennsylvania State University researchers Kew, Pennypacker and Echols discussed a storm water management project that tested the ability of green facades to effectively handle first flush rain runoff, reducing runoff volumes similar to green roofs. The green façade system and location were the same as the green façade food production research discussed earlier in this Chapter in Section 4.1. The test bed configurations included four panel systems facing the southeast and four panel systems facing southwest for two distinct comparative locations. The southeast facing greenwall system is shown in Figure 4.33.

Figure 4.33 Four southeast facing greenwall panel systems (Kew, Pennypacker, & Echols, 2014, p. 88)

Four plant species were utilized including sedum angelina, sedum ternatum, sempervivum tectorum, and ajuga reptans. Rainwater was collected in a 300-gallon cistern and was used to simulate average rainfall based on 1010 mm (39.76 inches) annually and 84.1mm (3.31 inches) monthly. The water was measured entering and leaving the greenwall panels, delivered by a gutter-based drip irrigation system with 5-gallon buckets capturing the runoff (Figure 4.34).

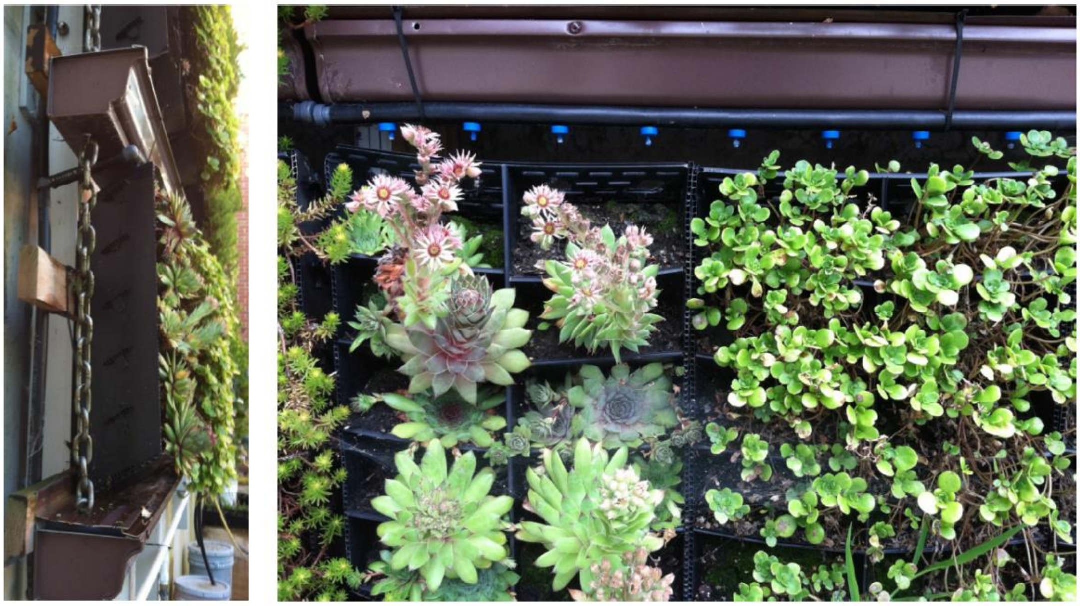


Figure 4.34 Drip irrigation simulating rainfall, and runoff collection system (notice the 5-gallon buckets in the lower left photo (Kew, Pennypacker, & Echols, 2014, p. 90)

This straightforward elegant research test bed yielded simple, easy to measure and understand results as shown in the Table 4.7.

Table 4.7 Typical seven day water sampling and averages in gallons (Kew, Pennypacker, & Echols, 2014, p. 92)

Gallons Southeast Green Wall System #1							Gallons Northwest Green Wall System #			
water in		**water out**	**capture**	**% capture**		**water in**		**water out**	**capture**	**% capture**
5.30		2.24	3.06	58%		5.30		2.63	2.67	50%
4.27		1.69	2.58	60%		4.27		2.58	1.69	40%
2.13		0.74	1.39	65%		2.13		1.11	1.02	48%
2.13		0.94	1.19	56%		2.13		0.95	1.18	55%
3.20		0.40	2.80	88%		3.20		1.26	1.94	61%
3.20		0.32	2.88	90%		3.20		1.19	2.01	63%
5.33		2.00	3.33	62%		5.33		2.66	2.67	50%
3.65		**1.19**	**2.46**	**68%**		**3.65**		**1.77**	**1.88**	**52%**

Rainwater runoff reductions of 40-90%, with average rates between 52-68% show how effective green facades can be as green infrastructure systems for the management of storm water flows, reducing flooding and potentially reducing droughts as well with increased groundwater recharge due to slower runoff rates. The south east façade, with greater solar exposure, has higher percentages of runoff reduction effectiveness, but the northwest facing façade is only slightly less effective, indicating how this system could be effectively deployed on building facades in any orientation.

Chapter 5. Description of Research Design and Methods

5.1 Introduction: Proof of Concept, Semi-controlled Field Experiment

This dissertation demonstrates the feasibility of growing food in a living façade vertical garden. It was conceived and implemented as a semi-controlled field experiment in the real world setting of the existing south and west façade areas of the Robert L. Preger Intelligent Workplace (IW) on the campus of Carnegie Mellon University. The IW is a 7000 SF living and lived-in laboratory dedicated to the research, demonstration and development of building systems integration for increasing energy efficiency and environmental effectiveness within the built environment. It is a living lab designed to be a flexible platform for building systems research and innovation while occupied with faculty and graduate student researchers. The steps necessary to conduct this experiment were to design, test, analyze and conclude the system installation, operation, performance and disassembly. These steps, including methods and details, are outlined in Table 5.1 below.

Table 5.1 Conceptual Diagram of Research Objectives, Methods and Details.

Objectives	Methods	Details
DESIGN Design, Fabricate, Install, Operate, and Maintain a Food Producing Living Facade	Proof of Concept Design Installation and Operation	Soil Based Panel and Trellis System
		Temperature Sensor Installation
		Particulate Sensor Installation
		Rain Barrel and PV solar irrigation system Installation
TEST Building Performance MRV	Semi-Controlled Field Experiment Data Collection	Food Production
		Façade Temperature (Exterior & Interior)
		Small Particulates
		Rainwater Irrigation
ANALYZE Data Analysis	Descriptive and Inferential Analysis	Food Weight, Quantity & Nutritional Value
		Hobo Sensor Façade Temperature Monitoring & Infra-Red Photography
		Small Particulate Monitoring
		Average Rainwater Usage
CONCLUDE Cradle to Cradle Dismantle System	Design for Disassembly	Biological Components to be composted
		Technical Components to be reused or recycled

The intention is to document the causal effect between a food producing living façade installation and façade temperature, small particulate levels and use of stored rainwater. Efforts were made to control for the unintended influence of the open floor plan within the IW on the temperature and air quality measurements within the research and control office spaces. Measured, recorded and verified data results determined the value of this form of green infrastructure in addressing the two critical issues of climate change and urban food security.

Design included all the work necessary to design, fabricate, install, operate, and maintain the food producing living façade. The test step included measuring, recording and verifying the building performance impact of food production, façade temperature reduction, air-quality benefit in terms of small particulate reduction, and the use of captured, stored rainwater as the primary source of irrigation. To analyze this data, a direct descriptive analysis was used. The quantified results of the measured performance were graphed, analyzed and conclusions were drawn. The final step to conclude this research study was to disassemble the food producing living façade system by breaking it down into its biological components and technological components. Design for Disassembly is a process of predesigning a reverse-process for disassembly at the end of the useful life of the system. Separating the components into biological and technological materials incorporates aspects of Cradle to Cradle design. The biological components were composted and the technological components were re-used, recycled or disposed of properly.

5.2 Design: Proof of Concept Design Installation and Operation

This research project was developed to demonstrate a facade retrofit strategy for creating a bioclimatic façade system focused on the design, construction and operation of a food producing living façade (FPLF) vertical garden on an existing, occupied-building. It is a proof-of-concept, applied research field project. The concept for this retrofit strategy to create a bioclimatic façade on an existing building to enhance overall building performance was conceived while working on the Smart Façade and GPIC/EEB HUB research projects conducted at Carnegie Mellon University (Aziz, 2009 & 2010).

The design of this food producing living façade research project was developed with a primary focus on food (biospherics), and the related building performance benefits of facade surface temperature reduction (energetics), small particulate reduction (atmospherics) and rainwater irrigation (hydrospherics). As such, this research project demonstrates and generates measured, recorded and verified data on the veracity of this systems integration retrofit design approach for improving total building performance in the existing, aging building stock, using a food producing living façade vertical garden installation.

5.2.1 Soil Based Panel and Trellis System

After a review of all the green façade and living wall options, the design and implementation of this food producing living façade project was intended to:

1. Demonstrate a full-scale example of a bioclimatic façade retrofit focused on creating a food producing vertical garden

2. Achieve a design for disassembly goal of creating an installation based on the cradle to cradle design concept, where biological components are composted and technological components are re-used or recycled to the maximum extent possible
3. Utilize a modular, low-cost, practical, scalable system that could be hauled up four stories on a passenger elevator and installed by a single individual
4. Establish a simple, straightforward system using off the shelf materials and techniques that is affordable and easily replicable as well as easy to operate and maintain by virtually anyone.
5. Pattern the layout on the proportion and rhythm of the existing IW façade in terms of vertical and horizontal elements (the spandrel, kick plate, viewing plane and transom areas identified in Figures 5.1, 5.2 and 5.3)
6. Require no fossil fuel energy and minimal organic fertilizer inputs

To achieve these project goals, the Living, Bioclimatic Facades for Sustainability, Human Health and Performance framework developed by the CMU Center for Building Performance and Diagnostics (CBPD), guided the design of this research project. It was this framework that was originally utilized to create the existing high-performance building façade of the Robert L. Preger Intelligent Workplace (IW) living and lived-in laboratory on top of Margaret Morrison Carnegie Hall on the Carnegie Mellon University campus in the Oakland section of the City of Pittsburgh.

The framework features the interior space, the exterior space and the integral space, which is the space within the façade assembly itself, diagrammed as though in cross-section perpendicular to the façade. This conceptual framework is illustrated in Figure 5.1 below. The surface elements of the facade include the spandrel panel (below the interior floor level), bruestrung (kick plate area of the lower wall), viewing field of the middle wall window band, and the transom area of the upper wall.

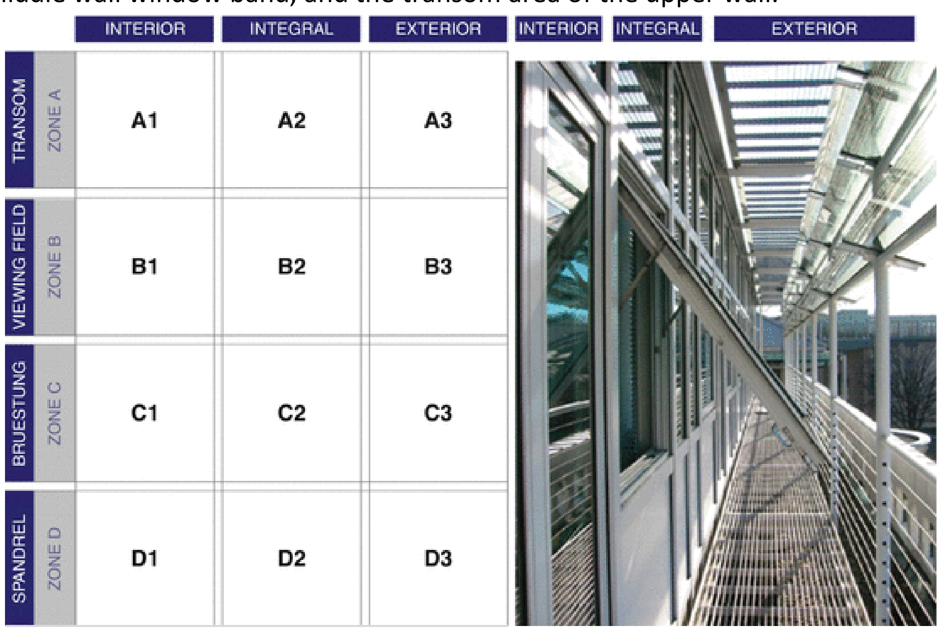


Figure 5.1 Facades and Enclosures, Building for Sustainability (Hartkopf, Aziz, & Loftness, 2013, p. 164).

It is this conceptual façade system, as articulated on the IW façade enclosure as shown in Figures 5.1 and 5.2, that provided the conceptual and dimensional framework for the design, installation and operation of this food producing living façade (FPLF) research project. The unique benefit of being able to install this research project at the IW is that the theoretical, idealized principles and guidelines illustrated in these diagrams are already inherent in the existing façade. As such, the FPLF is literally a "flowering" of this idealized bioclimatic façade design concept and physically demonstrates the principal guidelines, such as "Access to Nature".

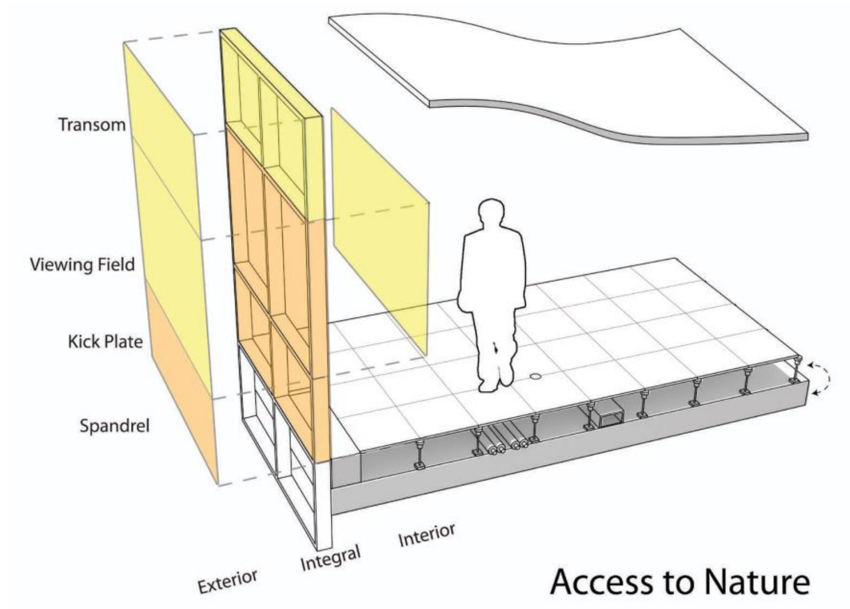


Figure 5.2 Elements of a High-Performance Bioclimatic Façade allowing Access to Nature (Center for Building Performance and Diagnostics Carnegie Mellon University, 2010)

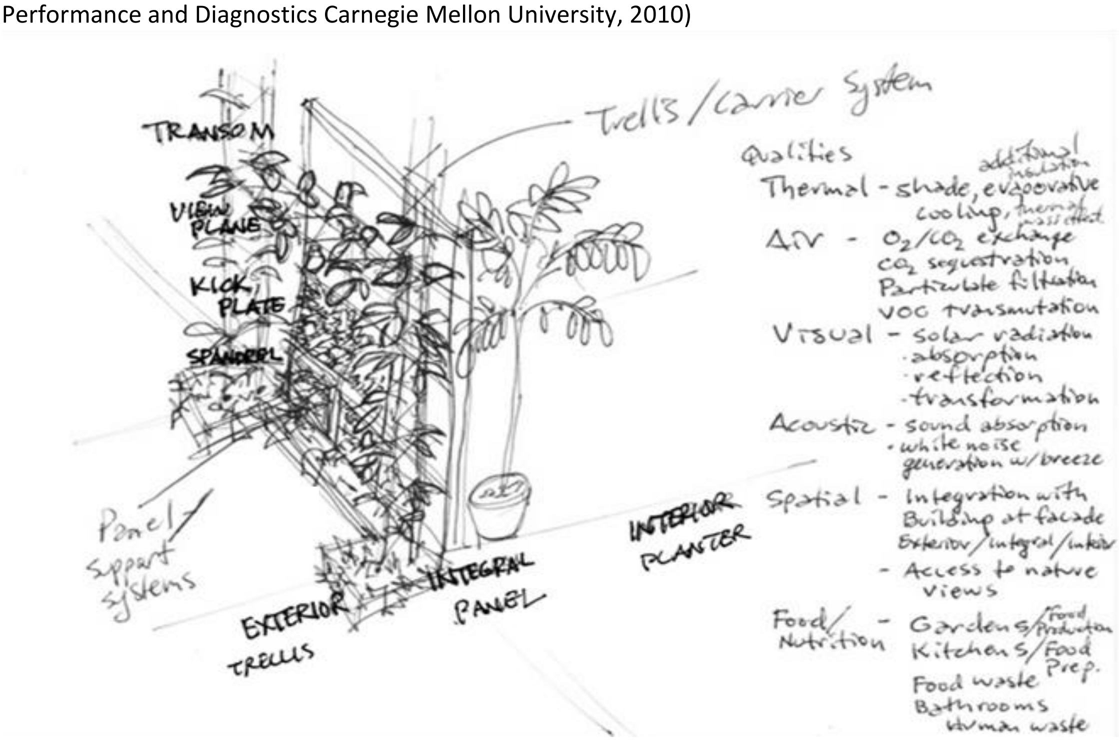


Figure 5.3 Access to Nature at the bioclimatic food producing living façade vertical garden installation showing external, integral and internal plant applications as well as listing the potential indoor environmental quality benefits, original sketch, Leininger, 2012

The organizing sketch for this research project installation shown in Figure 5.3 clearly illustrates this point and the maturing of these concepts of high-performance, dynamic façade layering, using living systems and systems integration techniques for achieving enhanced building performance outcomes. Those enhanced outcomes, in terms of the Indoor Environmental Qualities of Thermal, Acoustic, Visual, Spatial and Air qualities are listed in the sketch in Figure 5.3, along with the additional category of Food and Nutrition/Nutrient quality, based on the gustatory sense, or sense of taste.

To accomplish these objectives and realize the design framework shown in the sketch and diagrams above, all building materials and plants were purchased locally at home supply and agricultural supply stores. An effort was made to consciously select biological materials for as much of the system design and fabrication as possible, due to the lower embodied energy of these materials and their ability to biodegrade. Metal and plastic components were used sparingly, with the goal to reuse or recycle as much of those technological materials as possible. Table 5.2 shows the primary construction materials consisting of the biological and technological components used to create this system.

Table 5.2 Living Façade Fabrication Materials List

No.	Material Description	Application
1	1x8 Pine boards	Planting Boxes
2	1x2 Pine furring strips	Trellis Structure
3	deck screws	Wood Connectors
4	2x4 galvanized fencing	Trellis
5	¼” galvanized hardware cloth	Planting Box Soil Cover
6	metal staples	Hardware Cloth Connectors
7	zip cable ties	Trellis Connectors and Anchors

Wood was selected because it will degrade slowly over time, can be composted and grows on current solar income. The metal fencing, hardware cloth and screws can be re-used or recycled. The metal staples and plastic zip ties can be recycled or disposed of as municipal waste. These basic materials, assembled using hand tools and hand-held power tools, are the constituent elements that comprise the fabrication and installation of this food producing living façade research project.

In a temperate climate zone, the ideal layout to take advantage of passive solar design is to orient the building with a long east-west axis creating a large southern exposure. The IW, due to its location on top of the existing Margaret Morrison Carnegie Hall (MMCH) footprint, has an orientation perpendicular to the ideal with a long north-south axis resulting in large east-west exposure. This creates large cooling loads in the summer when the sun rises north of east and sets north of west, allowing low angle direct gain early in the morning and late into the afternoon when the daily temperature and heat gain is at its highest.

Automated, louvered solar shades on the long east and west façades were designed to control solar gain and glare, powered by small photovoltaic cells mounted on the louvers. The location, layout and design for the west façade and south façade installations of this system are illustrated in the floor plan, elevation, axonometric and section drawings, and photographs shown below (Figures 5.4 -5.13). A typical office bay along the west façade was selected for the semi-controlled field experiment location.

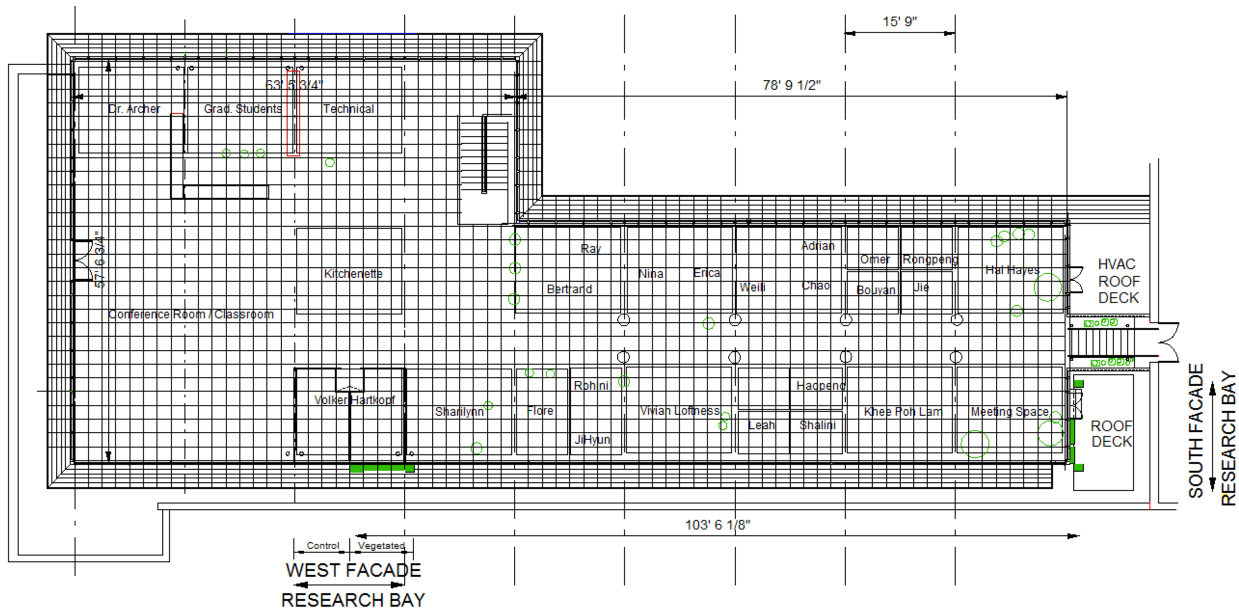


Figure 5.4 Intelligent Workplace floorplan showing west and south façade green wall research installations, Leininger, 2012

Half of the office space façade remained in its existing condition as a control, and the other half was covered by the hybrid panel and trellis living façade system (Figure 5.7).

Figure 5.5 The IW on top of MMCH, West Façade

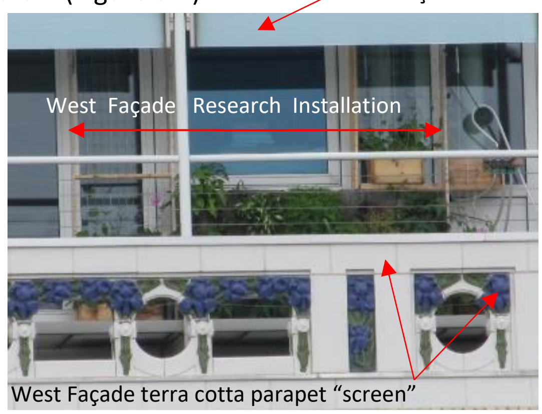


Figure 5.6 West Facing Living Façade Detail

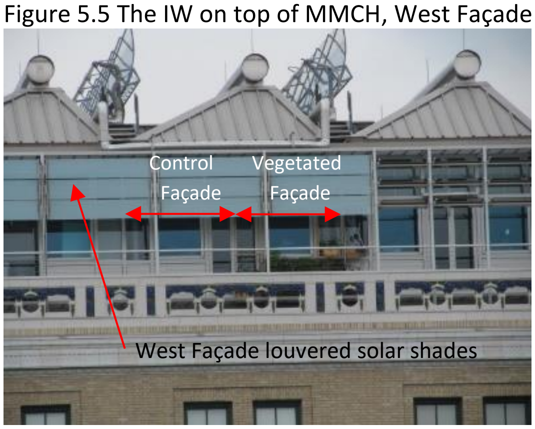


Figure 5.7 West Facing Research Facade

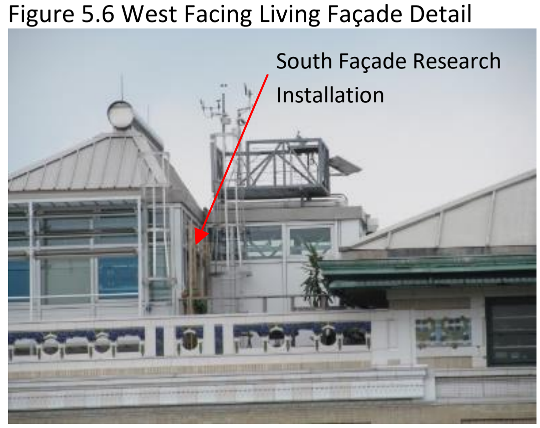


Figure 5.8 South Facing Research Facade

The second, uncontrolled field study was located on the short south façade, next to the outdoor roof deck. There are no solar louvers on this south façade. These two living façade research locations shown on the overall floor plan above are clearly visible in the photographs in Figures 5.5-5.8. The specific locations of the food producing living façade installations on the south and west facades of the IW are more clearly shown in the axonometric illustration, Figure 5.9. The South façade research installation was located adjacent to an open public conference space inside the IW and an outdoor roof deck meeting space between the IW and the top floor of MMCH.

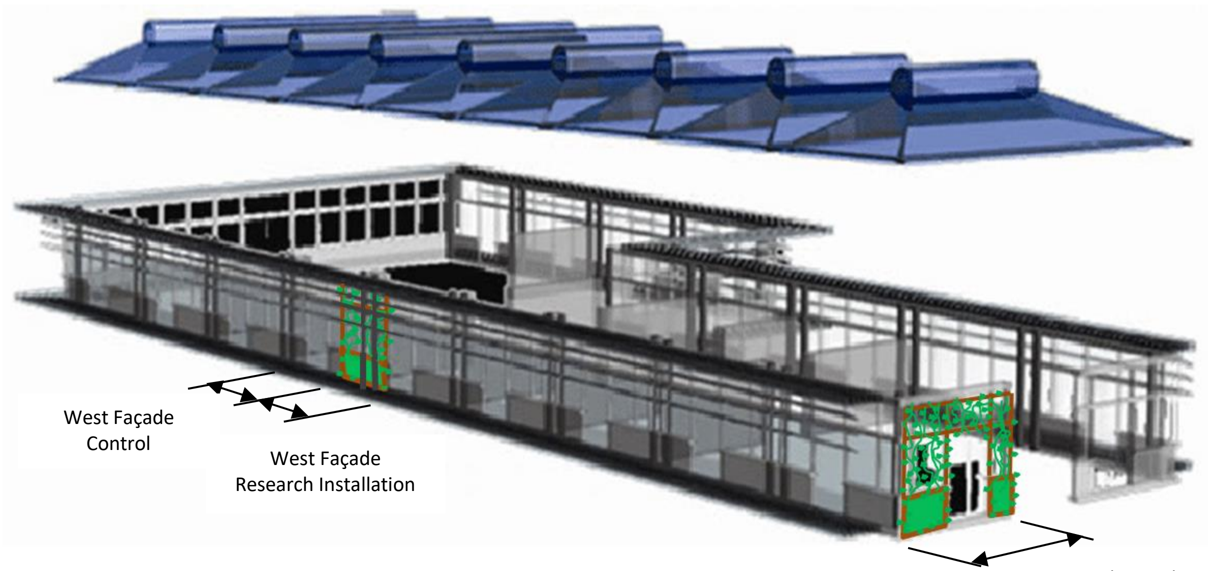


Figure 5.9 Axonometric of IW Showing Living Façade Research Areas, Leininger, 2012

The south façade research location was chosen because it is a public location, has easy access due to the existing roof deck and an existing roof drain downspout readily available to redirect into rain barrels. There was enough room on the roof deck to locate two rain barrels without any need for extensive modification or constraint.

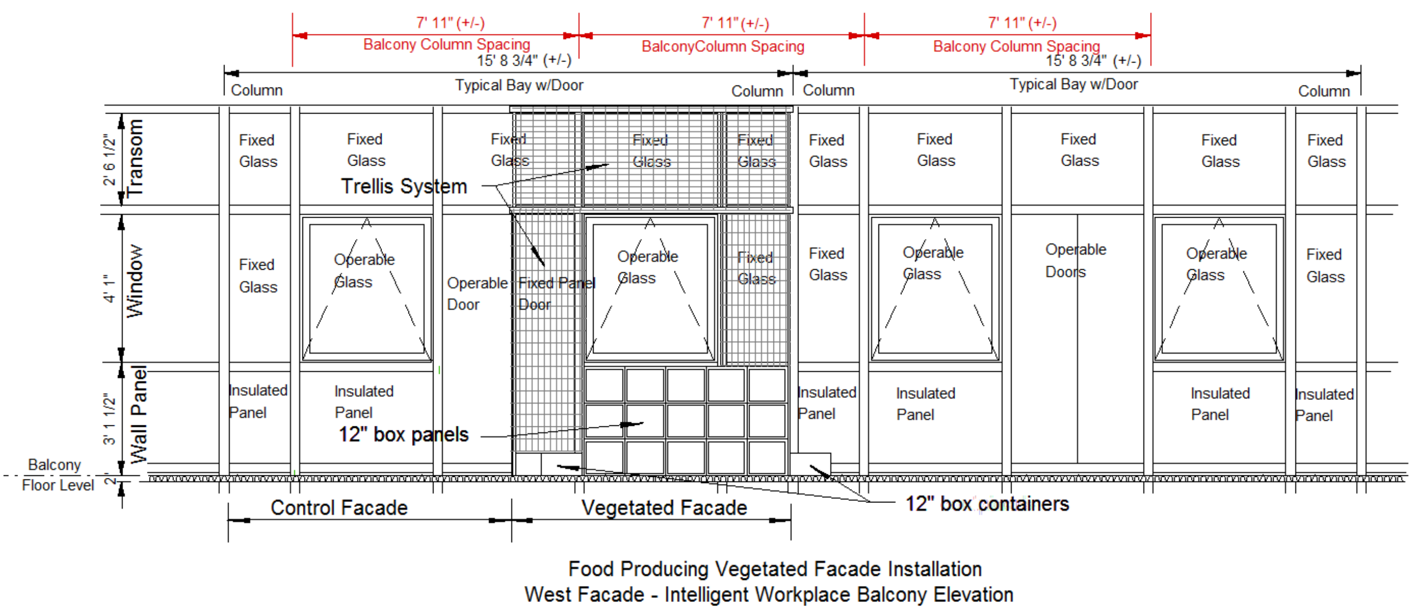


Figure 5.10 Exterior Living West Façade Elevation Layout Diagram Showing Specific Panel and Trellis Locations, Leininger, 2012

The west façade research bay was the location of the semi-controlled field study. The elevation drawing above in Figure 5.10 shows that the food producing living façade on the west façade was located on half of the façade outside the office of Professor Hartkopf, with the other half of the façade outside his office functioning as the control. Professor Hartkopf's office is laid out symmetrically relative to the façade openings and building structure, occupying the western side of bay 10 of the IW floorplan, Figure 5.11.

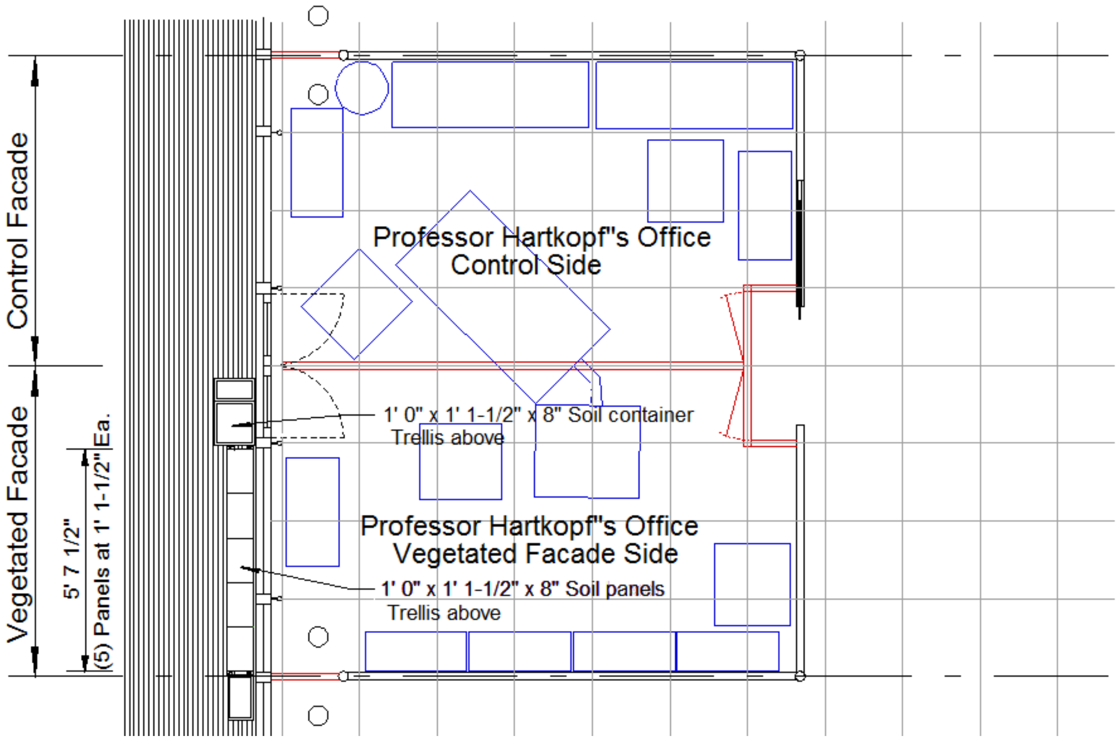


Figure 5.11 West Façade Research Bay Floor Plan, Leininger, 2012

The red lines on the floor plan diagram in Figure 5.11 represent the plastic membrane that was used to separate the research façade space from the control façade space and the rest of the IW due to the open floor plan. The walls are movable partitions; office furniture is shown in blue. The south façade research bay floor plan is shown in Figure 5.12 below.

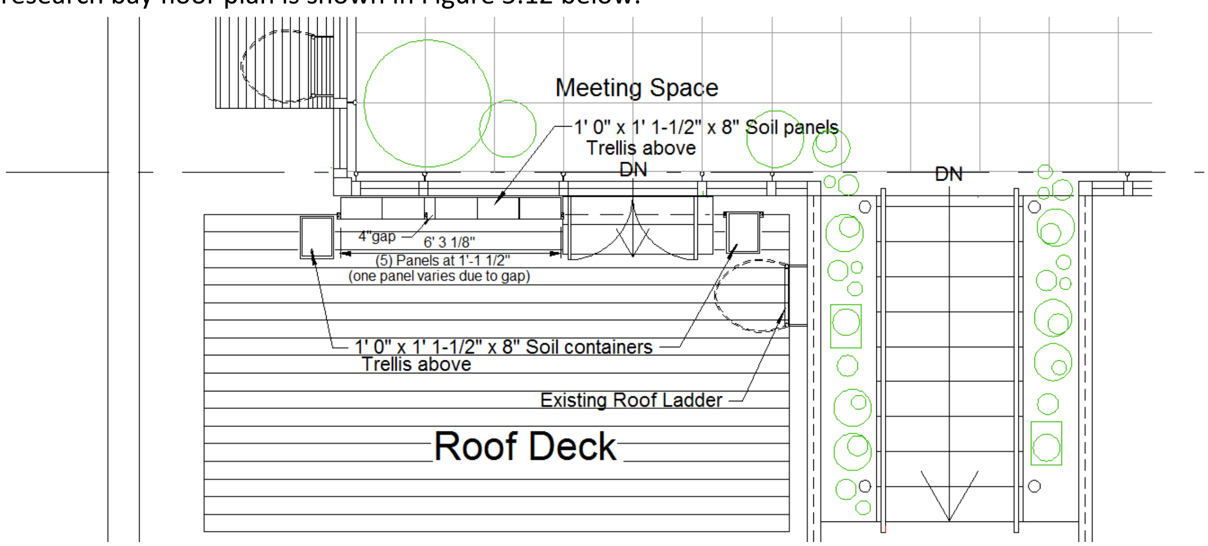


Figure 5.12 South Façade Research Bay Floor Plan, Leininger, 2012

The south façade research installation was an uncontrolled field study because there was no additional south facing façade area that could be used as a control. In addition, the public nature of the open floor plan meeting space that is inside the south façade made isolating that area from the rest of the IW office space impossible.

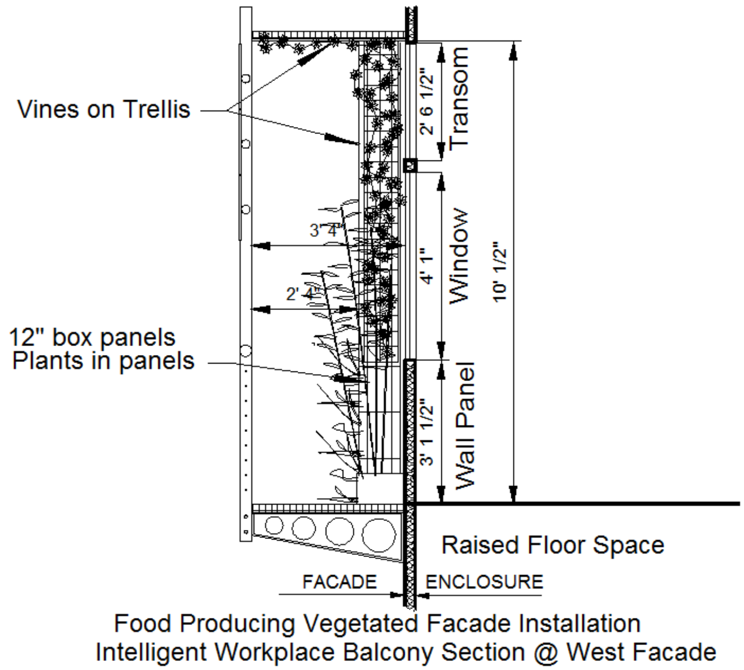


Figure 5.13 West Façade Research Bay Typical Wall Section, Leininger, 2012

The west façade research bay wall section shown in Figure 5.13 depicts the typical layout of the living façade panel and trellis research installation. The balcony is cantilevered over the existing MMCH roof, adjacent to the interior raised floor of the IW. The panels are located outside the insulated wall panel, with the trellis covering the window and glazed transom areas. The hybrid panel and trellis system illustrated here provides the soil system for rooting the plants in the panels and soil containers, while the trellis system provides a framework for the vining plants to cover the majority of the façade, which is glazed, with leaf cover as well.

Detailed dimensions and material configurations are shown in the planter box details, Figures 5.14 and 5.15. The 1x8 (3/4-inch x 7-1/4-inch nominal) pine boards made up the structure of the box, which was then covered in 1/4-inch galvanized metal hardware cloth. The boards were screwed together for future disassembly and the hardware cloth was stapled to the wood. The irrigation hose areas were kept open with 1-inch diameter pvc pipe which was perforated for water to flow from the irrigation hoses to the soil inside the box panel. When these boxes were stacked together, the 1-inch diameter irrigation holes aligned to accommodate the irrigation hoses.

The preassembly of these boxes against the wall panels of the IW façade, to gauge alignment and number of boxes required to completely cover the façade, is shown in Figure 5.16. The axonometric image, Figure 5.17, illustrates a typical planter box fully planted with vegetables, such as tomatoes, and other plants, such as sedum, which act like a ground cover to fill in the spaces between the vegetable plants. Once the panel boxes were planted and stacked in place, vertical 1x2 (3/4-inch x 1-1/2-inch nominal) furring strips were screwed to the boxes for the trellis.

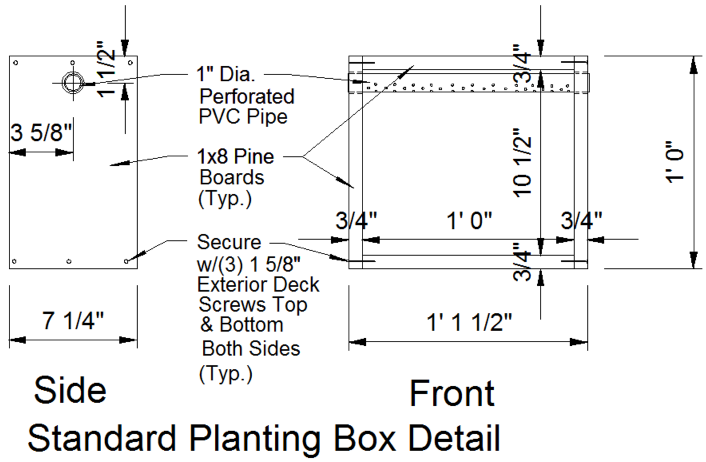


Figure 5.14 Standard Planting Box Detail Drawing showing structure, Leininger, 2012

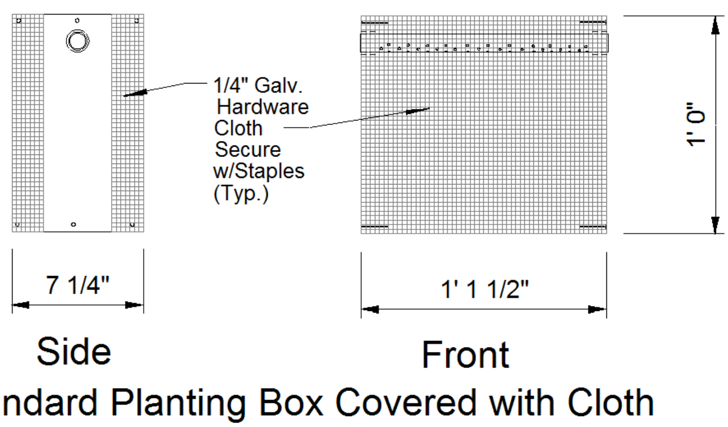


Figure 5.15 Standard Planting Box Detail Drawing showing hardware cloth enclosure, Leininger, 2012

Figure 5.16 Empty Green Façade Planting Box Panels

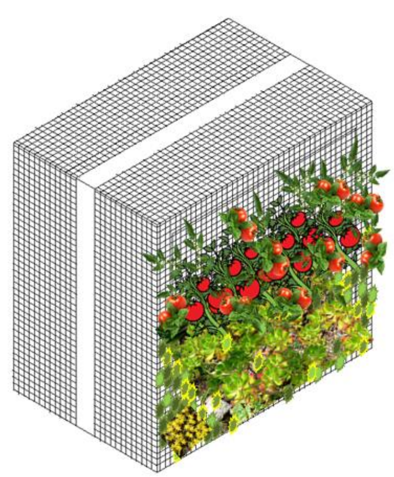


Figure 5.17 Typical Planting Box Axonometric Drawing, Leininger, 2012

Figure 5.18 Photo images of Green Façade Wooden Panel Module construction and planting steps and façade installation.

The images shown in figure 5.18 illustrate the steps in assembling and planting the soil panels. The façade photos show the original mock up the entire system, with the original transplants and including the trellis structure, along the west façade research bay in the Fall of 2012. The system in the foreground of both photos (*) was moved in 2013 to the South Façade to expose the control façade.

Figure 5.19 Planted panel installation on South Façade

Figure 5.20 Covering planters with hardware cloth

Figure 5.21 Fabricated soil in a planter from a 2009 research project conducted at the Almono Brownfield site

Figure 5.22 The components of fabricated soil (Kefeli, 2013)

The photos in Figures 5.19 and 5.20 show the south façade research bay installation and the installation of the galvanized metal hardware cloth on a transplanted planter box panel. Figures 5.21 and 5.22 show the fabricated soil components and the in-situ research application of a specific fabricated soil recipe in a planter bed at the ALMONO brownfield site in Hazelwood, from a grant funded research project in 2009. This tested, fabricated soil was re-used as the growing media for this FPLF research project. The construction of the boxes was accomplished with simple hand-held tools and power tools, as shown in Figure 5.23. This process generated sawdust as a waste component, which was used in the production of the fabricated soil, turning that waste into a resource (Figure 5.24).

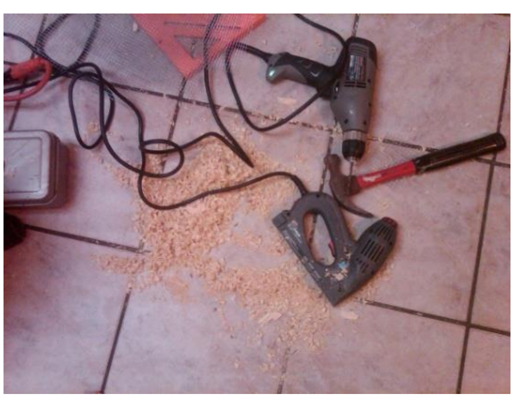


Figure 5.23 Planter box construction using simple hand tools and hand held power tools

Figure 5.24 Sawdust waste from construction used in fabricated soil mix

The compost used in the fabricated soil and in the refreshing of the soil in the planter boxes annually, was generated in a backyard compost pile. That compost was passed through a ¼ inch by ¼ inch screen prior to use (Figures 5.25 and 5.26). The process of spring planting at the south and west façade research installations is shown in Figures 5.27 and 5.28.


Figure 5.25 Screening compost from the pile


Figure 5.26 Compost, screened and ready


Figure 5.27 Planting along the west façade


Figure 5.28 Planting along the south façade

Figures 5.29 and 5.30 illustrate the south and west FPLF installations after initial planting in the spring of 2013. This was the first growing season where harvested data was collected and quantified. This same basic process was conducted every season between 2013 and 2018. No fertilizer was used until the final two growing seasons in 2017 and 2018. Granular organic fertilizer was added during each of those seasons at the time of planting, mixed into the soil and fresh compost.


Figure 5.29 West Façade fully planted


Figure 5.30 South Façade fully planted

5.2.2 Temperature Sensor Installation

Documentation of the thermal performance of the food producing living façade installations was provided by the strategic installation of temperature sensors at specific locations on the exterior and interior façade locations.   Sensors were also installed, for comparative analysis, at the same locations on the control façade, as part of the semi-controlled field experiment. Additional documentation of the thermal performance of the FPLF was provided by thermal imaging.

Sensor installation was made using Onset Data Loggers and Hobo TMC6-He temperature sensors. Four temperature sensors were connected to each of the four channel data loggers. One data logger was located on each side of the façade: one outside and one inside each FPLF installation (south and west façades), with one outside and one inside the control façade (west façade). The specific data logger and temperature sensor models used are shown in Figures 5.31 - 5.33.

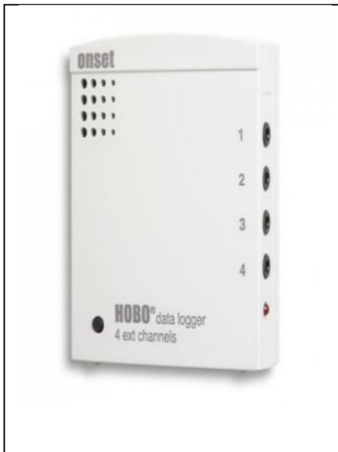


Figure 5.31 Onset Data Logger	Figure 5.32 Hobo TMC6-He Temeprature Sensor	Figure 5.33 Omega Outdoor Temperature Sensor

The four sensor locations on the exterior of the south and west FPLF installations were positioned as follows:

1. One foot off the façade (face of the plants)
2. Face of façade (immediately behind the plant panels)
3. Face of the fixed glass window
4. Face of the fixed glass balcony access door

The four sensor locations on the exterior of the west control façade were positioned as follows:

1. One foot off the façade
2. Face of the façade
3. Face of the fixed glass window
4. Face of the fixed glass balcony access door

The four sensor locations on the interior of both the west control façade and the south and west FPLF installations were positioned as follows:

1. One foot off the façade

2. Face of the façade
3. Face of the fixed glass window
4. Face of the fixed glass balcony access door

The specific locations of the four data loggers with four temperature sensors each are illustrated on the floor plan layout shown in Figure 5.34. The intention in selecting these specific sensor layout locations was to measure temperature movement across the FPLF and the control façade looking for measurable differences. This placement would document if there was a measurable benefit of temperature reduction due to the FPLF not only to the exterior façade surface, but also on the heat transfer effect to the interior façade surface as well as the interior space.

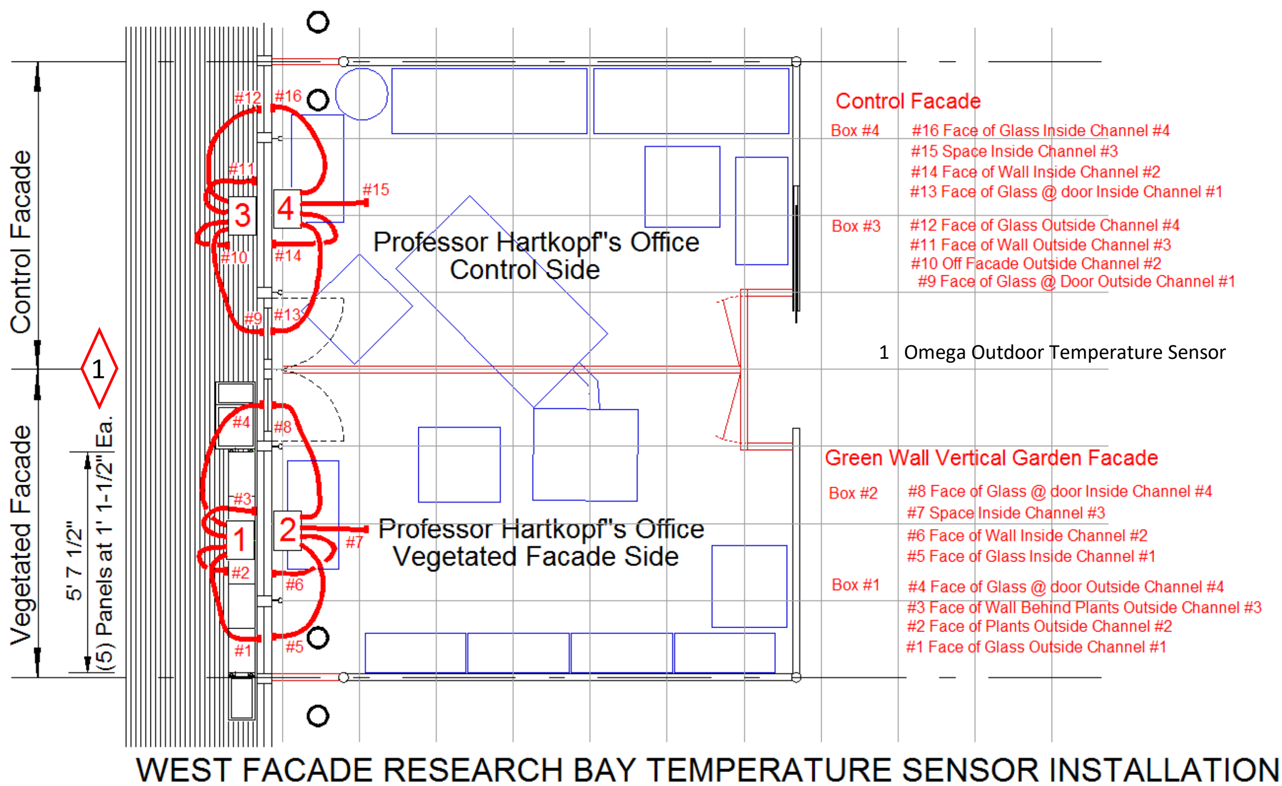


Figure 5.34 West Façade Research Bay Temperature Sensor and Data Logger Layout, Leininger, 2012

Professor Hartkopf's office was isolated from the adjacent work areas of the open floor plan with plastic sheeting to enclose the upper ceiling area and split the office space in half down the middle. This aligned with the center of the double French door which provides access to the exterior perimeter balcony where the FPLF structure was located. The isolation of Professor Hartkopf's office space, and the separation of it down the middle, was done in an attempt to control for any variables that would influence the temperature sensor measurements, other than the influence of the FPLF contrasted with the control façade. The elevation and section drawings on the next page, Figures 5.35 and 5.36, illustrate in additional detail the location of the data loggers and associated temperature sensors. The interior arrangement of the sensors is identical to the exterior arrangement. The wall section shown in Figure 5.36 illustrates the complimentary and balanced locations on the interior and exterior of the facade.

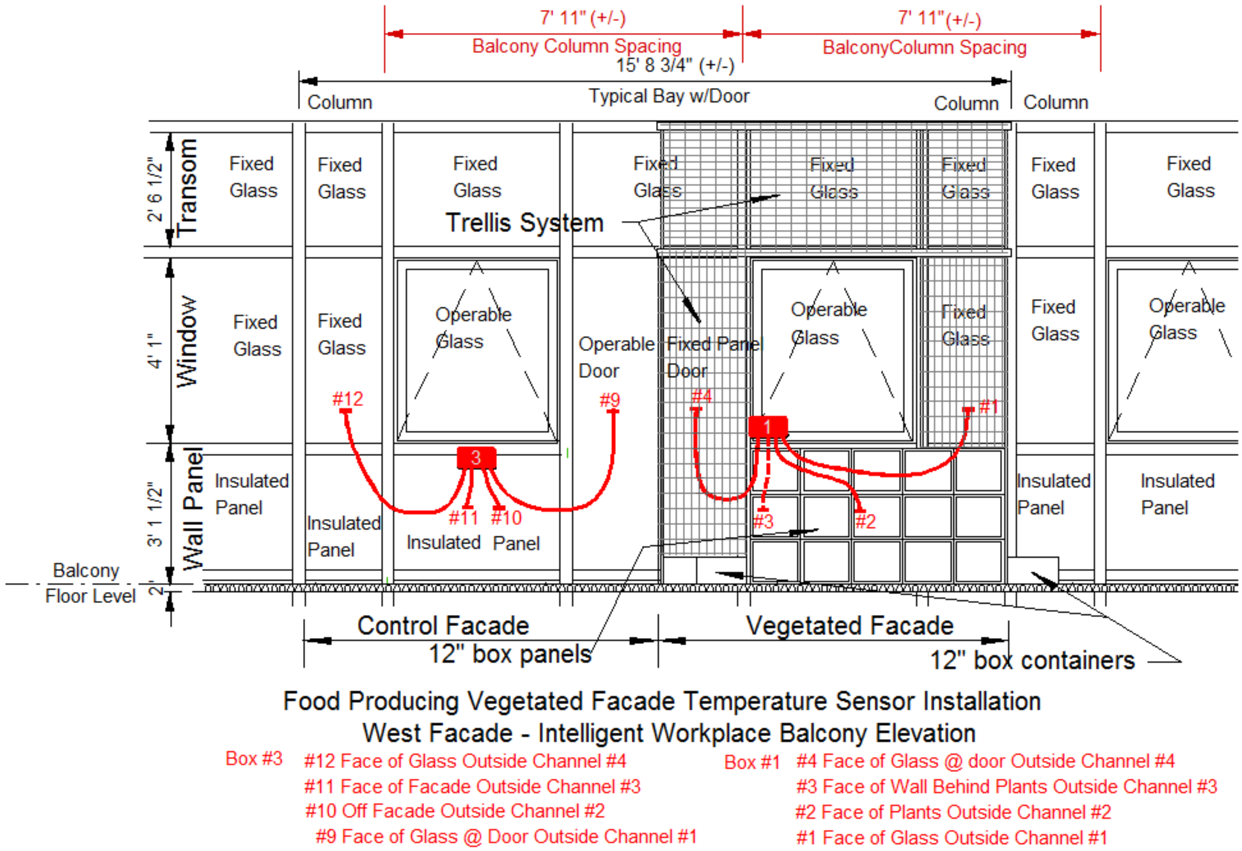


Figure 5.35 Exterior Living Façade Elevation Layout Diagram Showing temperature sensor and data logger locations, Leininger, 2012

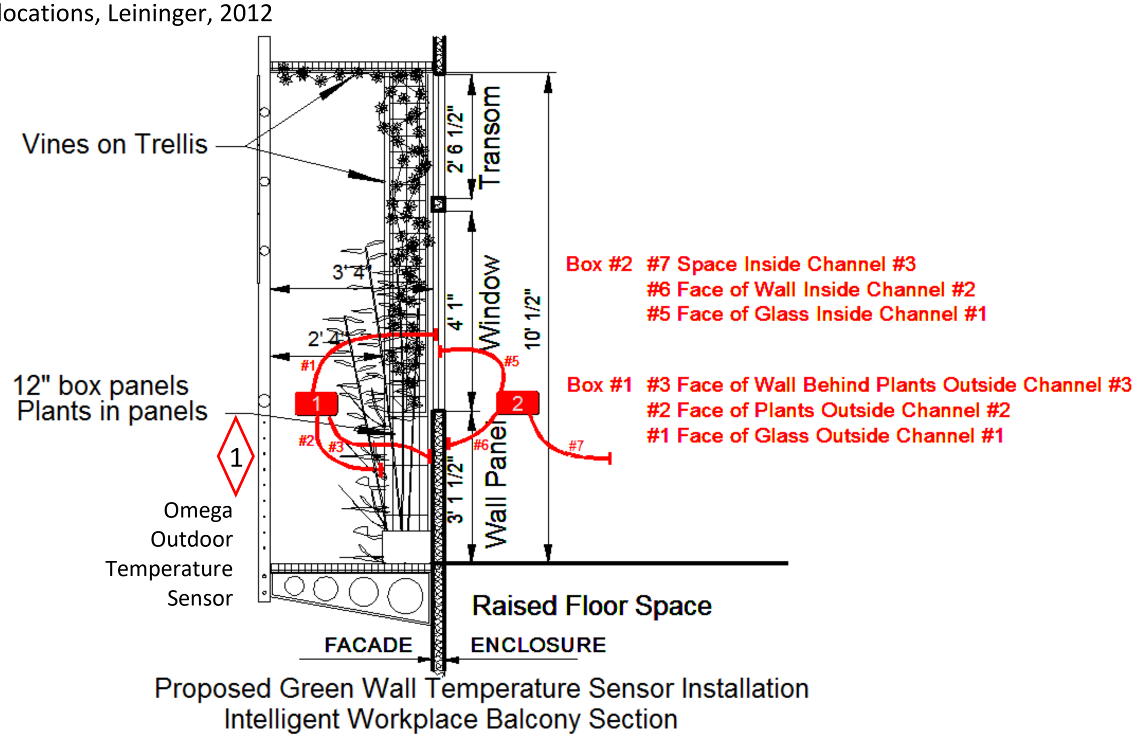


Figure 5.36 Building Envelope Section showing outdoor and indoor temperature sensor locations, Leininger, 2012

The photos in Figures 5.37-5.42 show the dataloggers and temperature sensors on the exterior and interior of the food producing living façade and the control façade on the west façade research bay, as per the drawings in Figures 5.34 and 5.35.

Figure 5.37 Control Façade interior

Figure 5.38 FPLF interior

Figure 5.39 Control Façade exterior

Figure 5.40 FPLF exterior

Figure 5.41 West Control and FPLF

Figure 5.42 West Control and FPLF (detail)

The next set of photos, Figures 5.43-5.46, show the dataloggers and temperature sensors on the exterior and interior of the food producing living façade installation on the south façade research bay, positioned similar to the drawings in Figures 5.35 and 5.36.

Figure 5.43 South Façade exterior

Figure 5.44 South Façade interior

Figure 5.45 South Façade exterior

Figure 5.46 South Façade (detail of data logger)

5.2.3 Small Particulate Sensor Installation

The IW is equipped with a building-wide energy management and optimization system from Aircuity, called Optinet™. The Aircuity Optinet™ air quality monitoring system utilizes nano-tubing to continuously sample air at multiple locations throughout the IW. Four additional monitoring locations were added to the central trunk of the monitoring system to collect air quality samples for the FPLF semi-controlled research study, as shown in Figures 5.47 and 5.48.

Figure 5.47 Connecting nano-tubing underfloor

Figure 5.48 Air Data Router and Optinet cable (Aircuity, Inc., 2008, p. 2)

The west façade research bay floor plan and elevation drawings shown in Figures 5.49-5.51 indicate the specific locations for these four additional monitoring locations and approximate nano-tubing layout.

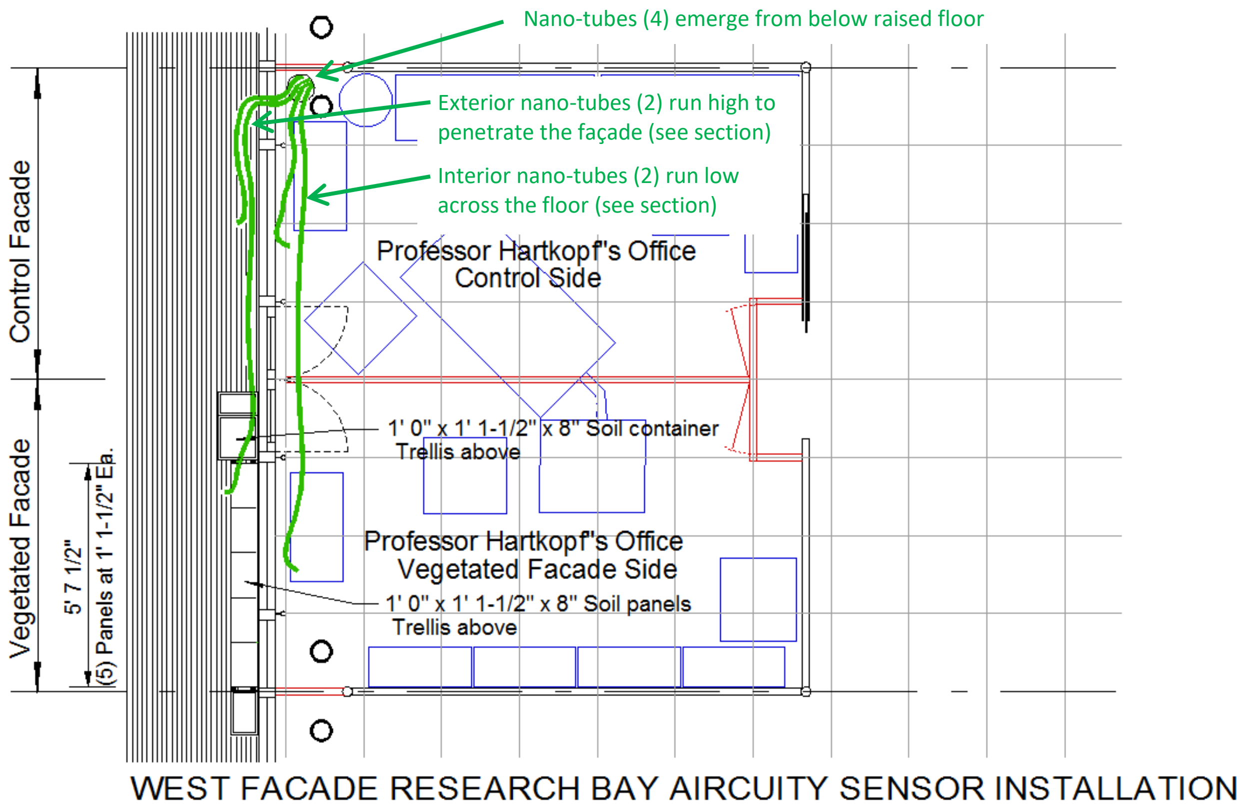


Figure 5.49 West Façade Research Bay Floor Plan showing Aircuity Optinet^{TM} sensor nano-tube layout, Leininger, 2013

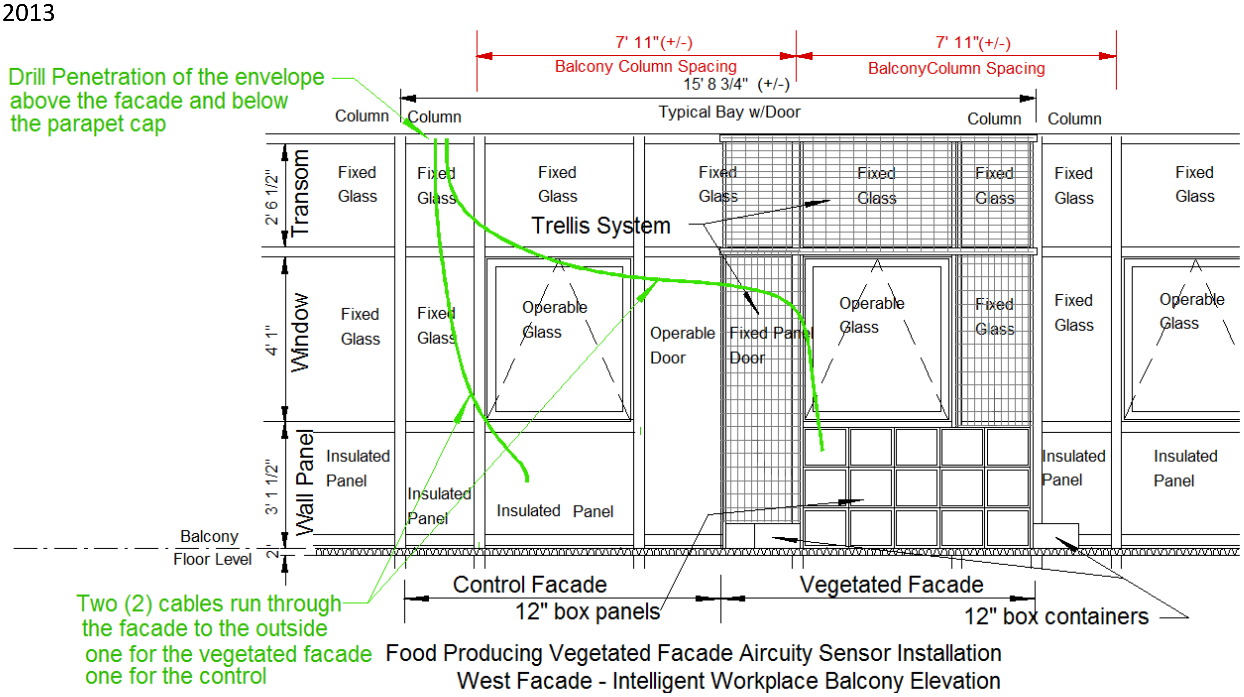


Figure 5.50 Exterior West Façade Research Bay Elevation showing Aircuity sensor nano-tube layout, Leininger, 2013

The relative locations of the interior and exterior ends of the nano-tubes are shown in the building envelope section, Figure 5.50. As noted above, the four nano-tubes emerge from below the raised floor, with the two interior nano-tubes positioned low along the floor, rising up approximately one foot above the floor to collect interior air samples, and the two exterior nano-tubes running up to above the transom windows to penetrate the building envelope before running back down to the exterior living and control facades approximately one foot above the balcony floor. To simplify the section for clarity, only one nano-tube is shown on the interior and exterior, although there were two on each side as noted.

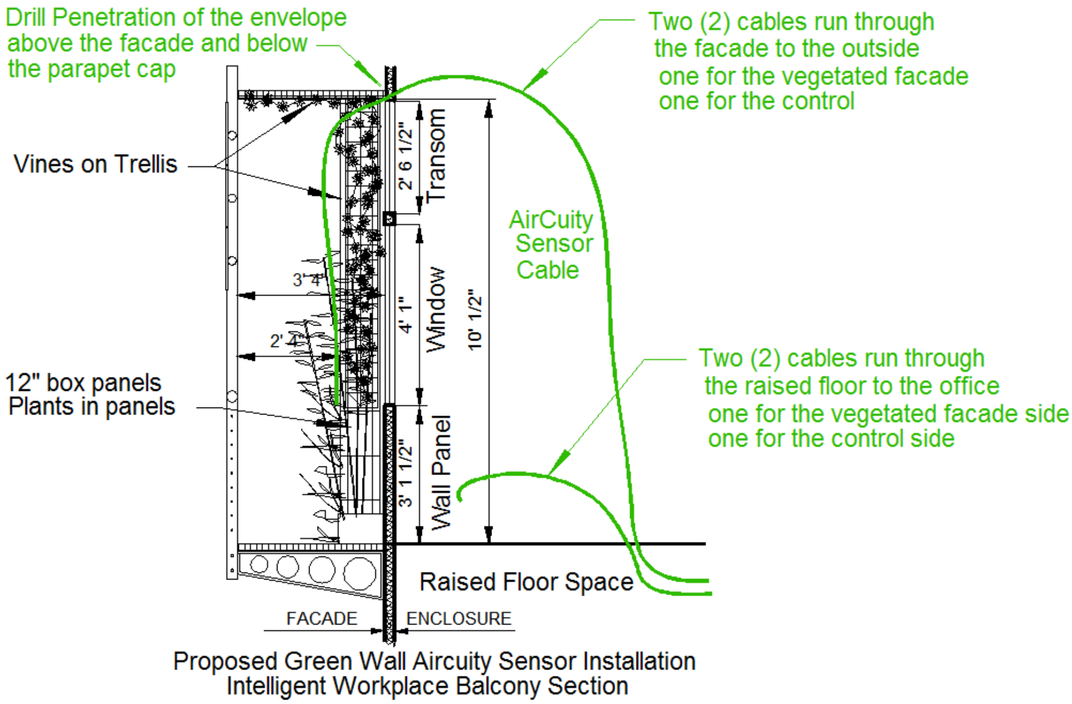


Figure 5.51 West Façade Research Bay Building Envelope Section showing outdoor and indoor Aircuity sensor locations, Leininger, 2013

Connecting the new nano-tube runs to the existing Aircuity system involved accessing the raised floor space under the IW structural floor tiles. Four new tubes were connected to the distribution box and run under the floor to the west façade area. At that point they emerged from under the floor through a pre-cut round diffuser access location in Dr. Hartkopf's office, the site of the semi-controlled field experiment. As noted on the drawings in Figures 5.48-5.50, two nano-tubes were kept low to the floor and run along the inside of the façade, with one staying in the control space, and the other running through the plastic sheeting to the FPLF research installation side of the office space. The interior nano-tubes were connected to heavy blocks near the air sample collection end to keep them upright and pointing into the air approximately 12-18 inches above the floor level.

The other two nano-tubes ran up the interior of the façade to the metal enclosure above the transom glazing where two small diameter holes, the size of the nano-tube diameter, were drilled allowing exterior access. Those two remaining nano-tubes were extended to the exterior through the drilled holes and ran down the façade, one on the control side and one on the research side. They extended down to between 12-18 inches above the exterior balcony floor level. The control façade nano-tube was secured to the façade with tape. The nano-tube located on the FPLF was secured to the galvanized metal wiring of the trellis section of the installation and then hung down to a collection location immediately adjacent to the face of the plants on the front of the soil-based panel system. This installation process is illustrated in the photos in Figures 5.52-5.57 below.

Figure 5.52 Nano-tube access

Figure 5.53 Connecting nano-tubing underfloor

Figure 5.54 Nano-tubes thru façade

Figure 5.55 Nano-tube air sampling end anchored to block

Figure 5.56 Nano-tube @ Control

Figure 5.57 Nano-tube @ FPLF

5.2.4 Rain Barrel and PV Solar Irrigation System Installation

The components of the rainwater storage and irrigation system (Figures 5.58-5.65), along with the Onset temperature sensors and data loggers and the Aircuity system nano-tubes, were the only part of the FPLF system not purchased locally. These components were purchased online, including the two plastic rain barrels, the two small photovoltaic panels, and the two Onset soil moisture sensors. The two irrigation pumps, 6-volt rechargeable battery, solar charge controller and switches, were purchased locally. The rain barrels were connected to an existing roof drain scupper by replacing an existing metal downspout with flexible ABS plastic 6-inch diameter elephant trunk drain pipe. This flexible drain pipe downspout was connected to one of the rain barrels with a smaller diameter overflow hose connecting the first rain barrel to the second one. The first rain barrel was elevated on two small plastic crates to help the flow.

Figure 5.58 Photovoltaic supply

Figure 5.59 Two rain barrels with flexible donwspout

Figure 5.60 Irrigation pumps

Figure 5.61 Weather tight control and pump boxes

The photovoltaic panels were connected to the rechargeable battery and the water pumps by means of a manual on/off main switch and then two toggle switches so both pumps could be manually turned on separately or at the same time. The south façade research bay and the west façade research bay each had a separate pump connected to one of the rain barrels for individual irrigation. The controls and battery, as well as the pumps, were each placed in separate individual weather-tight containers for exterior use.

Figure 5.62 Irrigation pumps

Figure 5.63 Manual control swithces

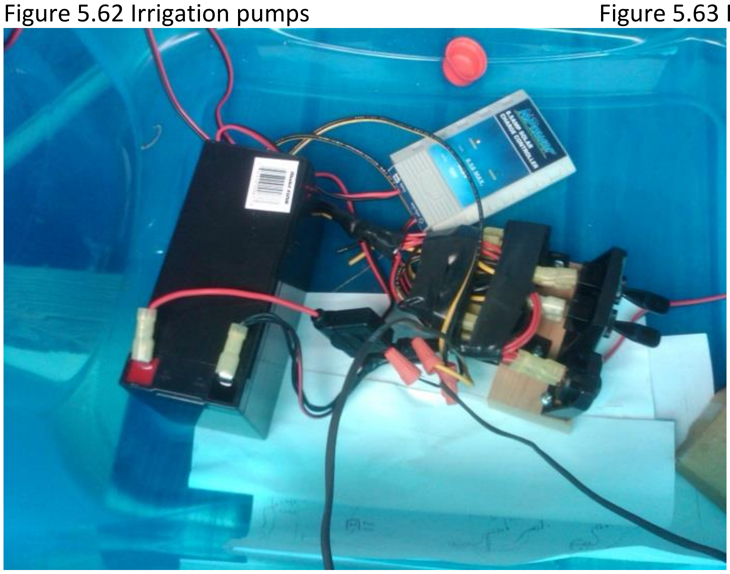


Figure 5.64 Wiring connections to the battery

Figure 5.65 Solar charge controller

To automate the control for the irrigation system, two Onset SMC-5 soil moisture sensors were deployed, one for each installation. The soil moisture sensors were located in the central soil panel of each installation and then linked back to the Onset U30 weather station. The weather station was then wired to the solar pump control switches to call for irrigation when the soil dried out. The goal was to call for irrigation water only when needed. Irrigation optimization with the control system would minimize wasting of water, use only as much stored rain water as necessary, and preserve the limited water supply. This minimized the chance of the rain barrels running dry during a prolonged period without rain. The photos below in Figures 5.66-5.71 show the soil moisture meters and weather station in place.

Figure 5.66 ECHO EC-5 Soil Moisture Sensor
https://www.onsetcomp.com/products/sensors/s-smc-m005

Figure 5.67 Hobo U30 Remote Monitoring System
http://www.connectingthings.com/produkt/hobo-u30-nrc-datalogger/

Figure 5.68 Irrigation hose connection to West Facade

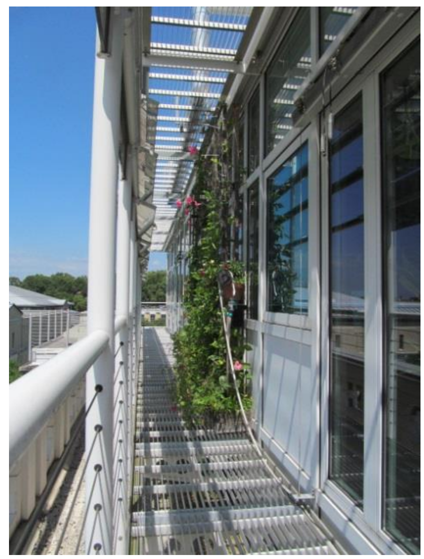


Figure 5.69 West Façade

Figure 5.70 The soil moisture sensor connected to the U30

Figure 5.71 Drip Irrigation supply

5.3 Test: Semi-Controlled Field Experiment Data Collection

This was a seven-year, longitudinal, field applied, observational study. It was developed as a full-scale application to show the repeated use of a food producing living façade over the full life cycle of the system. To establish the veracity of growing food producing plants as part of a living façade vertical garden system, replication of the work would have to be accomplished over multiple growing seasons. To document that such a system would also provide other well-established building performance and occupant benefits, a series of cross-sectional studies was performed collecting temperature and air quality data over shorter time periods, from one week to one year long. The entire research project ran from the summer of 2012, to the summer of 2019, when the system was decommissioned, disassembled, and broken down into its biological and technological components.

Testing the idea that living facades could be planted with food producing plants required a multi-faceted approach. To begin with, the system had to work. To be able to measure food production on a food producing façade required healthy plants that would flower, set fruit, and be vigorous enough to grow that fruit to maturity. This required a fertile growing media (fabricated soil) using fresh compost as part of the soil mix, and replenishing it each season. It required beginning with healthy plants for transplant. It required a secure, steady source of irrigation. It required checking on the plants daily to ascertain their progress and need for irrigation. Only if all of these things worked successfully could the produce be harvested, and the system fitted with temperature and air quality sensors to measure the performance of the system.

In order to test the primary hypothesis of this research project, to determine whether or not food producing plants can survive and thrive to maturity as part of a living façade system, food production harvesting and documentation was the primary focus of this research. It was important to show that this study was replicable, using simple tools and techniques, and that the same methods repeated over multiple growing seasons could produce the same or similar results. Documenting the success and variation of production over multiple growing seasons would help establish performance variability and success of such a system over its full life cycle.

Documentation of the other building performance benefits, including the temperature and air quality benefits, was conducted as a series of cross-sectional studies, because once those performance benefits were either confirmed or refuted, there was no need to continue to collect that data. Therefore, this data was collected only during a short part of the longer overall study. Documenting the long term, repeated food producing viability of this system is the primary original contribution of this research project.

5.3.1 Food Production

The specific food producing and non-food producing plants that were selected for use in this research project are listed in Tables 5.3-5.6. The decision was made to intentionally select a polyculture that would include companion planting focused on food and flower production, as well as inedible and non-flowering ground cover plants, including several species of sedum. This mix was selected in an attempt to ensure that even when the food producing plants were not producing, there would be plants of interest within the living façade system, including plants with a variety of flower, leaf and stem colors and textures. In addition, the sedum acted as a ground cover filling in the gaps and covering the metal hardware cloth, while the vines provided a canopy of leaves and flowers continuously throughout the growing season.

Table 5.3 Vegetables

No.	Common Name	Scientific Name
1	Hybrid Cherry Tomatoes	Solanum lycopersicum
2	Roma Tomatoes	Solanum lycopersicum 'Roma'
3	Heirloom Tomatoes	Lycopersicon esculentum
4	Sweet Banana Peppers	Capsicum annuum 'Banana Pepper'
5	Jalapeno Peppers	Capsicum annuum 'Jalapeño'
6	Green Peppers	Capsicum annuum Group
7	Red Peppers	Capsicum
8	Hot Shot Peppers	Capsicum annuum
9	Salsa Peppers	Capsicum annuum
10	Little Chili Peppers	Capsicum frutescens 'Siling labuyo'
11	Spring Peas	Pisum sativum
12	Kentucky Wonder Green Beans	Phaseolus vulgaris 'Kentucky Wonder'
13	Scarlet Runner Beans	Phaseolus coccineus

Table 5.4 Herbs

No.	Common Name	Scientific Name
1	Purple Basil	Ocimum basilicum
2	Sweet Basil	Ocimum basilicum
3	Sage	Salvia officinalis
4	Mint	Mentha

Table 5.5 Fruit

No.	Common Name	Scientific Name
1	Strawberries	Fragaria × ananassa
2	Rhubarb	Rheum rhabarbarum
3	Cantaloupe	Cucumis melo reticulatus

Table 5.6 Ornamentals

No.	Common Name	Scientific Name
1	Rocktrumpet	Mandevilla
2	Orange Lilly	Lilium bulbiferum
3	Mossy Stonecrop	Sedum acre
4	Cliff Stonecrop	Sedum glaucophyllum
5	Reflexed Stonecrop	Sedum reflexum or Sedum rupestre

A selection of the plants listed above, both on the vine and harvested, is shown in the photos in Figures 5.72-5.78. This primary data was collected as the crops ripened over the length of the growing season for six consecutive growing seasons (2013-2018). Collecting and documenting food production on this living façade system was critical to the success of the study.


Figure 5.72 Roma Tomatoes


Figure 5.73 Jalapeno Peppers


Figure 5.74 Purple Basil


Figure 5.75 Green Pole Beans


Figure 5.76 Cantelope


Figure 5.77 Strawberries

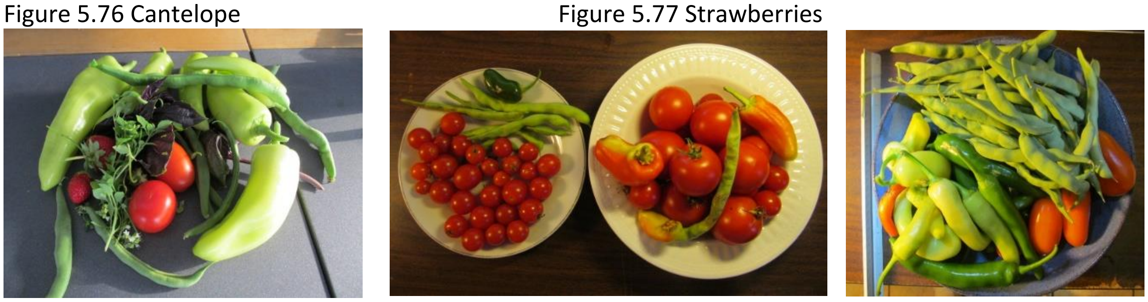


Figure 5.78 Harvested vegetables and herbs

5.3.2 Façade Temperature

Temperature data collection was conducted on the research and control façade areas over a series of one-week collection periods at several times of the year. The first period was taken in August 2013 to show typical summer temperature conditions and response. The second period was taken in September 2013 to show late summer approaching fall conditions. The third period was taken during February 2014 to show how the dormant systems responded to winter temperature conditions. Finally, a fourth period was taken during March 2014 to show response to spring temperature conditions. The four, one-week long, testing periods provided enough detail to compare the research installation with the control façade during different seasons to indicate the benefit of the performance of the food producing living façade system. The photos below, Figures 5.79 – 5.82, show façade temperature data collection being downloaded from the data loggers on the living and control facades.


Figure 5.79 Control Façade interior


Figure 5.80 Living Façade interior


Figure 5.81 Control Façade exterior

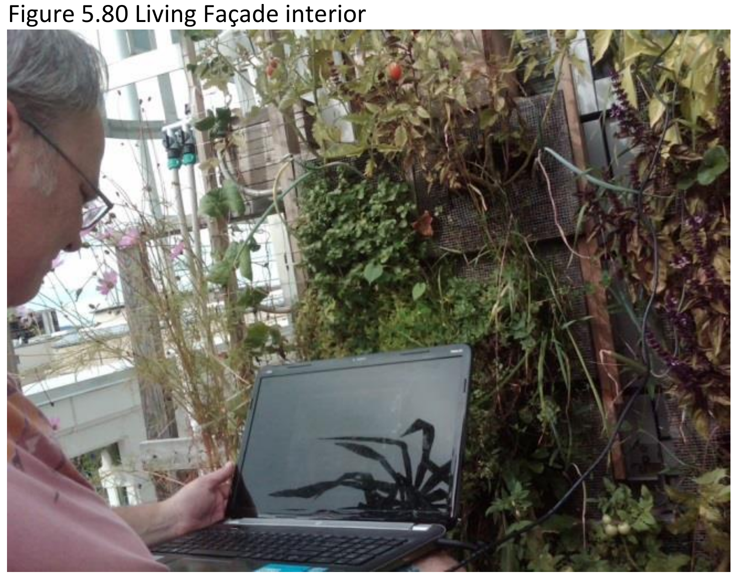


Figure 5.82 South Living Façade exterior

5.3.3 Small Particulates

Due to the Aircuity Optinet^{TM} system being fully automated, collecting data samples every minute and automatically storing this data in a database, the most important issue for good data collection was isolating the interior office space to the greatest extent possible. This was accomplished by tenting the office space with plastic above the office partitions, across the face of the radiant cooling panels at the lower ceiling surface, and down the middle of the office space to separate the research side from the control side.

This separation is shown in the first three photos below (Figures 5.83-5.87) on the west façade research bay floor plan. The new plastic sheet doorway, just inside the sliding glass interior office pocket door (note the round door handle in Figures 5.84 and 5.86), is held in place with Velcro squares when closed. Figure 5.86 shows the overall office partitions from inside the IW.


Figure 5.83 Research side

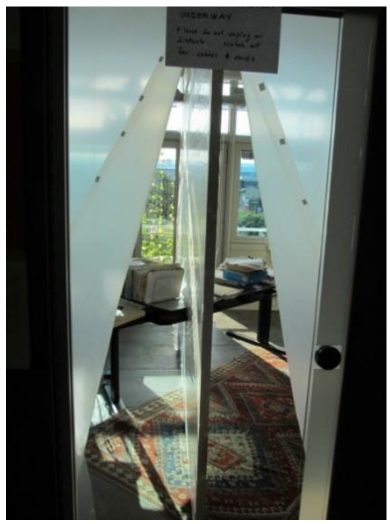


Figure 5.84 Plastic divider access

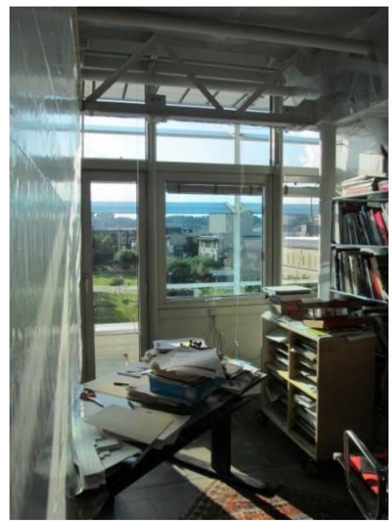


Figure 5.85 Control side


Figure 5.86 Plastic access doors


Figure 5.87 Professor Hartkopf's office area behind partitions

Tenting of the interior of the office is shown in Figures 5.83-5.93. In Figure 5.89 direct solar gain is seen shining on the plastic enclosure from the skylights in the roof of the IW. This sunlight is shining through the sloping plastic sheeting shown in Figure 5.88 from inside the office, and through the same sheet of plastic shown from outside the office, inside the IW, in Figure 5.90. Since this direct gain affected the control side and not the research side, the offending skylight (Figure 5.91) was covered (Figure 5.92). This was done in an attempt to minimize outside influences to the greatest extent possible.


Figure 5.88 Enclosing the office space


Figure 5.89 Enclosing the office space


Figure 5.90 Unwanted daylight


Figure 5.91 Plastic enclosure above partition

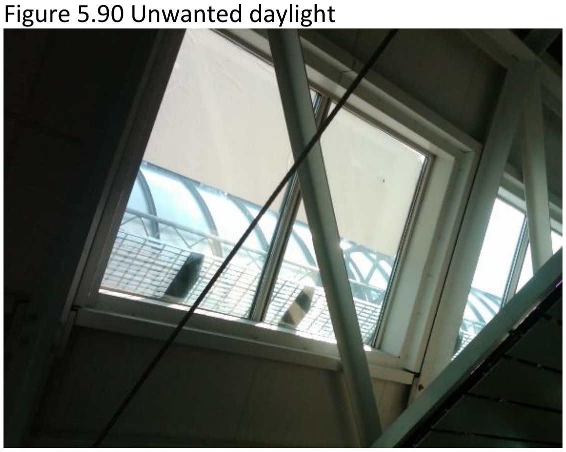


Figure 5.92 Skylight source


Figure 5.93 Blocking unwanted direct gain sunlight

5.3.4 Rainwater Irrigation

The food producing living façade system was equipped with two rain barrels for the primary water source and a photovoltaic solar energy powered rechargeable battery to run the two irrigation pumps, using soil moisture meters as the control to call for water only when needed. The limits of this system gradually became evident. Control with the soil moisture meters was difficult to calibrate and there was no specific way to measure water use. The challenge with calibrating the system was gauging how long the system could remain on to satisfy the need for irrigation, without running down the battery. The inability to be on site all day every day to check on the system as it was operating became a limiting factor. Measuring daily water use could have been accomplished by marking each rain barrel each day and measuring daily use, as each barrel serviced each separate system. The ability to check on the plants only once each day at the end of the day, and the need to do so to verify that the plants were surviving and thriving, led to an irrigation routine based on hand watering with gallon jugs filled from the rain barrels. Data collection for the measuring of water use by each research installation was therefore based on the average number of gallons of water used to irrigate each system each day. The photos in Figures 5.94 and 5.95 show the soil moisture sensor cable connected to the HOBO U30 Weather Station during the system set up process.

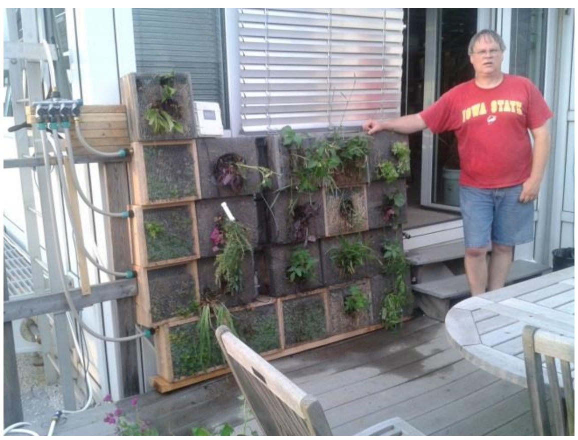


Figure 5.94 Intial irrigation control set up

Figure 5.95 HOBO U30 Weather Station connected to sensor cable

5.4 Analyze: Descriptive and Inferential Analysis

Data was collected to test the ability of a living façade to produce food as part of a vertical garden system, while simultaneously providing the building performance benefits of reduced façade temperature, improved air quality, and utilization of collected rain water for irrigation. The aim of this research study was to measure, record and verify performance, comparing the collected data to the existing research and adding to that literature with original results that have not previously been collected or recorded. To that end, the data that was collected has been analyzed, using the methods described and shown below, in these four categories: food production, façade temperature, small particulate levels and water use. Each of these categories will be reviewed in the sections that follow.

5.4.1 Food Weight, Quantity & Nutritional Value

Vegetables, herbs and fruit grown on the living façade system were harvested as they ripened. Each harvest was identified by which façade it was harvested from and on which day. Every vegetable and piece of fruit, and small bundles of herbs, were arranged on single letter sized (8.5” x 11.5”) sheets of white paper, numbered and then weighed. Each sheet of paper was photographed, and then weight and quantity were recorded one by one in a spreadsheet database. Production was broken down by weight, by quantity, by façade and by month. Replicability and fluctuations in productivity over the six growing seasons have been graphed as well. The goal was to quantify potential production levels attainable on a consistent basis with this type of system in this climate region, as well as to look at the potential for variety in the production output of such a system, in terms of the diversity of potential future plantings.

Examples of this process of data analysis for the food production attained by this system are shown in Figures 5.96 and 5.97. The scale used to weigh the produce was a simple digital kitchen scale, the Royal eX1 Exacta scale purchased at a local kitchen appliance store. In 2016, after 3 seasons of use, this scale quit functioning and a new Hamilton Beach small digital kitchen scale was purchased. The partial database shows how the individual production numbers were recorded and aggregated.

Figure 5.96 Food weight and Quantity

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Date of Harvest	Location	Hybrid Cherry Tomatoes	Hybrid Cherry Tomatoes	Hybrid Cherry Tomatoes	Roma Tomatoes	Roma Tomatoes	Roma Tomatoes	Heirloom Tomato	Heirloom Tomato	Heirloom Tomato	Sweet Banana Peppers	Sweet Banana Peppers	Sweet Banana Peppers	Jalapeno Peppers	Jalapeno Peppers	Jalapeno Peppers	Green Beans	Green Beans	Green Beans
2			assigned no	quantity	weight	assigned no	quantity	weight	assigned no	quantity	weight	assigned no	quantity	weight	assigned no	quantity	weight	assigned no	quantity	weight
3																				
4	09/30/13	SW	1	1	0.1													1	1	0.2
5	09/30/13	SW	2	1	0.3													2	1	0.3
6	09/30/13	SW	3	1	0.3													3	1	0.3
7	09/30/13	SW	4	1	0.3													4	1	0.3
8	09/30/13	SW	5	1	0.3													5	1	0.2
9	09/30/13	SW	6	1	0.3													6	1	0.3
10	09/30/13	SW	7	1	0.3													7	1	0.4
11	09/30/13	SW	8	1	0.4															
12	09/30/13	SW	9	1	0.4															
13																				
14	09/30/13	SW				1	1	0.3												
15	09/30/13	SW				2	1	0.4												
16	09/30/13	SW				3	1	0.4												
17	09/30/13	SW				4	1	0.5												
18	09/30/13	SW				5	1	0.4												
19	09/30/13	SW				6	1	0.5												
20	09/30/13	SW				7	1	0.5												
21	09/30/13	SW				8	1	0.4												
22																				
23	09/30/13	WW	1	1	0.3															
24	09/30/13	WW	2	1	0.4															
25																				
26	09/30/13	WW				1	1	0.4												
27	09/30/13	WW				2	1	0.6												
28																				
29	09/30/13	WW							1	1	2.0									

Figure 5.97 Food Production Harvest spreadsheet

The totals and aggregated data in the master database were then taken and further tallied in the categories mentioned above, by façade, by variety and by month, to ascertain any patterns of production and response to façade orientation. Potential modifications to the selection of specific varieties for specific areas on the façade is one potential use for this kind of data discretization.

In addition to the data on weight and quantity of vegetables, fruit and herbs produced, a nutritional analysis was completed for the following select crops:

1. Cherry Tomatoes
2. Roma Tomatoes
3. Sweet Banana Peppers
4. Jalapeno Peppers
5. Green Pole Beans

The nutritional analysis was conducted on produce from the research facades and was compared against the same varieties procured from the local grocery store as a "typical" example for each variety. The images below in Figure 5.98 shows the Cherry Tomatoes sample and the resulting nutritional analysis original report from Skyview Laboratory, Inc. These results have been put into a spreadsheet for comparative analysis in the results chapter.

SKYVIEW LABORATORY, INC.
P.O. BOX 273
JENNERSTOWN, PA 15547
814-629-5441
ROUGHAGE ANALYSIS

SAMPLE NUMBER: 99188
SAMPLE TYPE : CHERRY TOMATOES
: RESEARCH
DATE RECEIVED: 9/20/2019
CLIENT'S NAME: CHRIS LEININGER
640 GALEY BOULEVARD
BEAVER PA 15009
SAMPLE DATE: / /
FARM NAME : 7-2016 7-2018 MEXICO
DATE REPORTED: 10/ 4/2019
COPY TO:
00000
DATE ANALYZED: 9/20/2019
ANALYSIS TYPE: C

	AS SAMPLED	DRY MATTER	EXPECTED RANGE
MOISTURE,% :	73.4		
DRY MATTER,% :	26.6		
CRUDE PROTEIN,% :	4.5	17.0	
DIGEST. PROT.,% :	3.0	11.2	
CA,% :	0.06	0.22	
P,% :	0.09	0.35	
MG,% :	0.05	0.17	
K,% :	0.62	2.34	
S,% :	0.04	0.16	
NA,% :	0.05	0.19	
IRON, PPM :	10	37	
MANGANESE, PPM :	3	12	
COPPER, PPM :	1	3	
ZINC, PPM :	3	12	
OTHER			
COBALT ppm		0.45	
MOLYBDENUM ppm		0.40	
ALUMINUM ppm		< 1.5	

APPROVED

SKYVIEW LABORATORY, INC.
P.O. BOX 273
JENNERSTOWN, PA 15547
814-629-5441
ROUGHAGE ANALYSIS

SAMPLE NUMBER: 99187
SAMPLE TYPE : CHERRY TOMATOES
: CONTROL
DATE RECEIVED: 9/20/2019
CLIENT'S NAME: CHRIS LEININGER
640 GALEY BOULEVARD
BEAVER PA 15009
SAMPLE DATE: / /
FARM NAME : 9-10-2019
DATE REPORTED: 10/ 4/2019
COPY TO:
00000
DATE ANALYZED: 9/20/2019
ANALYSIS TYPE: C

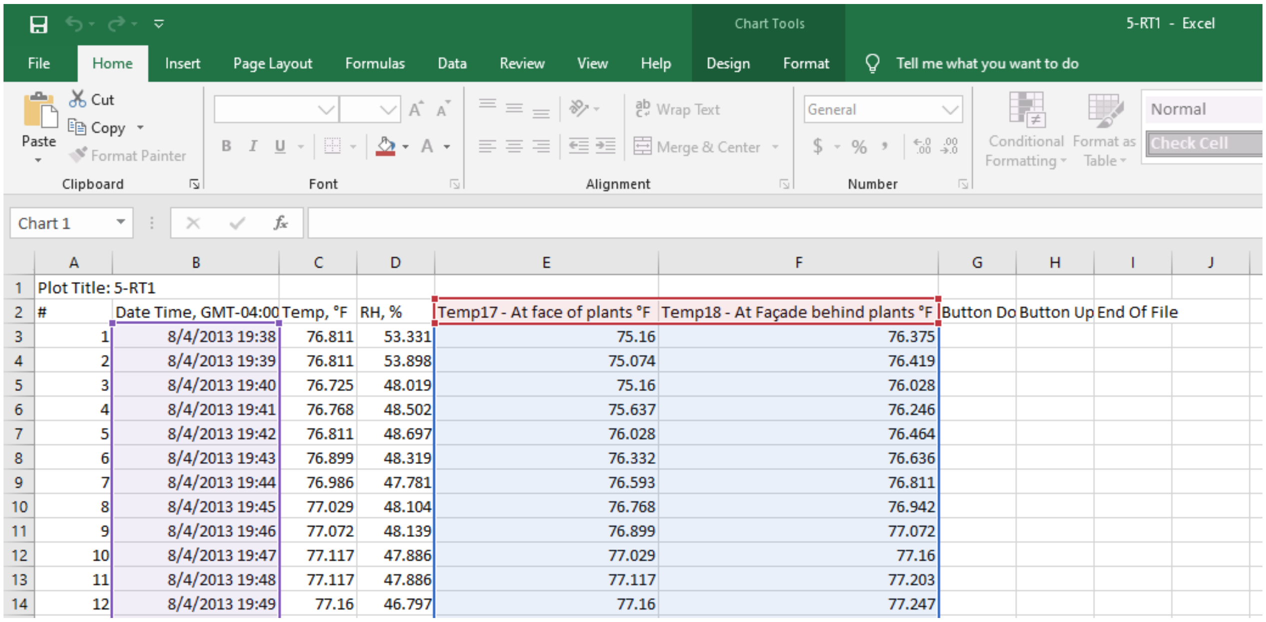
	AS SAMPLED	DRY MATTER	EXPECTED RANGE
MOISTURE,% :	73.4		
DRY MATTER,% :	26.6		
CRUDE PROTEIN,% :	3.5	13.3	
DIGEST. PROT.,% :	2.4	8.9	
CA,% :	0.06	0.23	
P,% :	0.11	0.40	
MG,% :	0.05	0.20	
K,% :	0.61	2.31	
S,% :	0.05	0.17	
NA,% :	0.06	0.24	
IRON, PPM :	10	39	
MANGANESE, PPM :	3	12	
COPPER, PPM :	2	8	
ZINC, PPM :	7	26	
OTHER			
COBALT ppm		0.29	
MOLYBDENUM ppm		0.78	
ALUMINUM ppm		< 1.5	

APPROVED

Figure 5.98 Nutritional value analysis done by Skyview Laboratory, Inc. (These reports shown in detail in chap. 6)

5.4.2 Hobo Sensor Façade Temperature Monitoring & Infra-Red Photography

The façade temperature data collected by the Onset sensors and HOBO data loggers was automatically saved into a spreadsheet format (Figure 5.99). Each week-long data collection period was identified for each sensor, with the control and research data for each sensor location being compared for analysis. For instance, on the exterior, the temperature collected one foot off the façade, which is at the face of the plants for the research installation, was shown along with the temperature at the façade, which is just behind the plant panels on the research installation, on one graph for the research side and the control side. These two graphs were then shown side by side to illustrate the difference. An example at the living façade is shown in Figure 5.100. Additionally, Infra-Red photographs were taken of each façade using a FLIR Thermal Imaging Camera to illustrate these temperature differentials (Figure 5.101).



	A	B	C	D	E	F	G	H	I
1	Plot Title: 5-RT1								
2	#	Date Time, GMT-04:00	Temp, °F	RH, %	Temp17 - At face of plants °F	Temp18 - At Façade behind plants °F	Button Do	Button Up	End Of File
3	1	8/4/2013 19:38	76.811	53.331	75.16	76.375			
4	2	8/4/2013 19:39	76.811	53.898	75.074	76.419			
5	3	8/4/2013 19:40	76.725	48.019	75.16	76.028			
6	4	8/4/2013 19:41	76.768	48.502	75.637	76.246			
7	5	8/4/2013 19:42	76.811	48.697	76.028	76.464			
8	6	8/4/2013 19:43	76.899	48.319	76.332	76.636			
9	7	8/4/2013 19:44	76.986	47.781	76.593	76.811			
10	8	8/4/2013 19:45	77.029	48.104	76.768	76.942			
11	9	8/4/2013 19:46	77.072	48.139	76.899	77.072			
12	10	8/4/2013 19:47	77.117	47.886	77.029	77.16			
13	11	8/4/2013 19:48	77.117	47.886	77.117	77.203			
14	12	8/4/2013 19:49	77.16	46.797	77.16	77.247			

Figure 5.99 Façade temperature spreadsheet; this image is shown as an example of the data collection process.

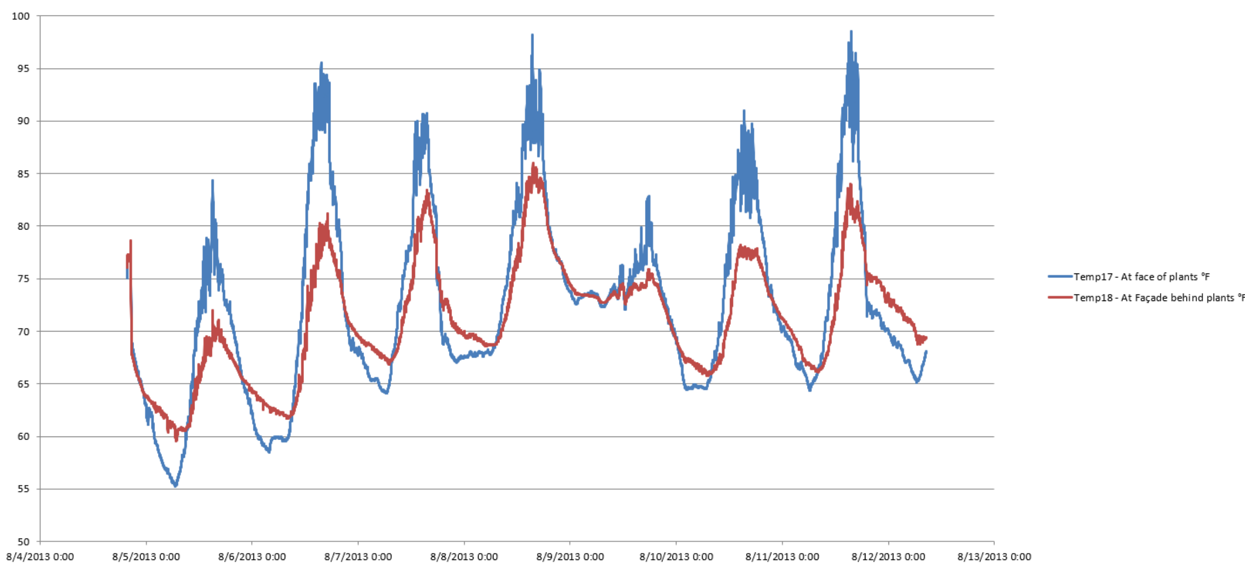


Figure 5.100 Living Façade temperature graph; this image is shown as an example of data representation.

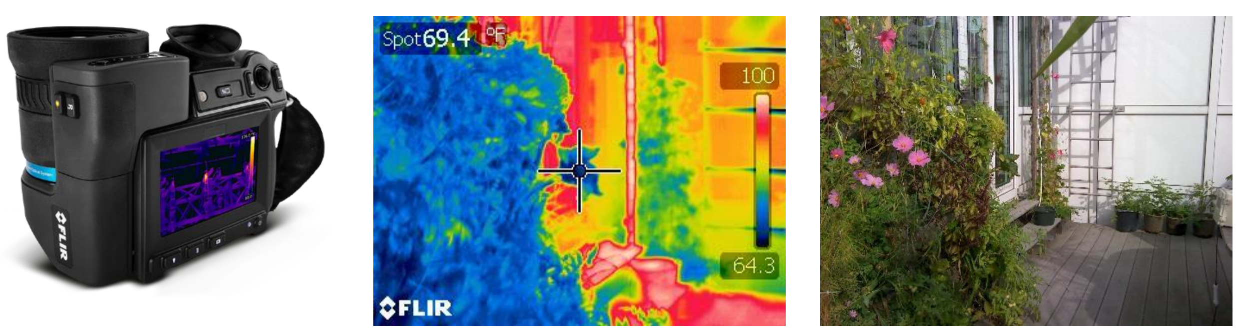
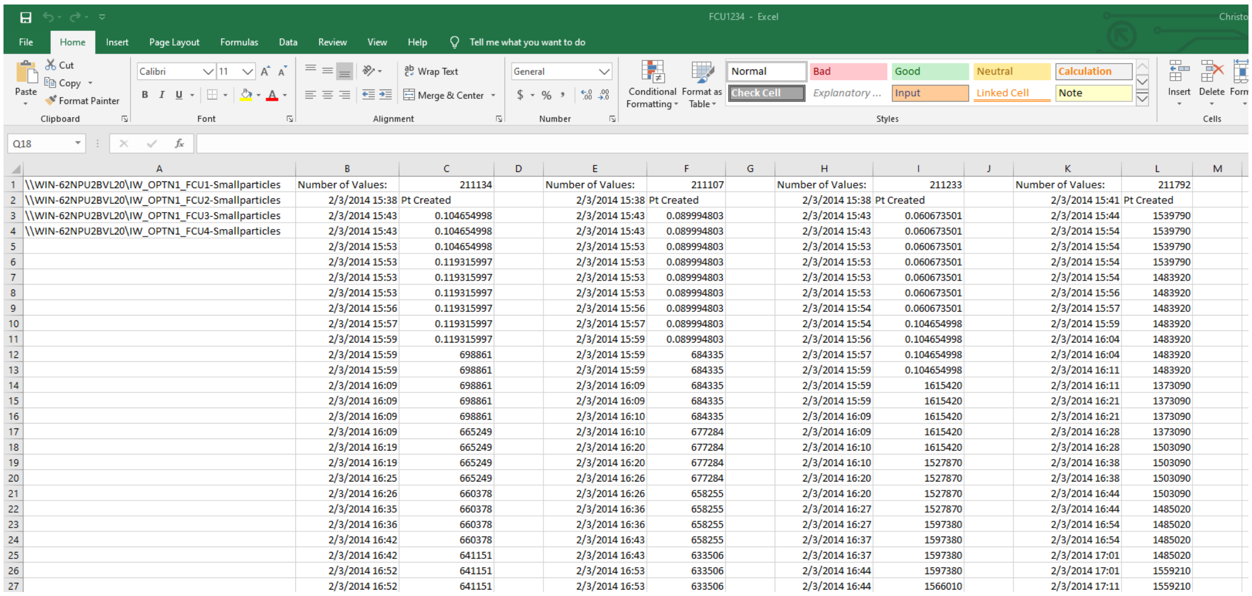


Figure 5.101 Infra-Red Thermal Imaging using FLIR T1020 HD Thermal Imaging Camera, South Façade (https://www.flir.com/)

5.4.3 Aircuity Small Particulate Monitoring

The small particulate data was collected automatically through the Aircuity Optinet™ system as noted above and stored in a spreadsheet database (Figure 5.102). This data was originally graphed automatically using a system developed in house at the CBPD using the output from the four specific sensors installed in the west façade research bay. An example of the graphing is shown in Figure 5.103.



	A	B	C	D	E	F	G	H	I	J	K	L
1	\\WIN-62NPU2BVL20\IW_OPTN1_FCU1-Smallparticles	Number of Values:	211134		Number of Values:	211107		Number of Values:	211233		Number of Values:	211792
2	\\WIN-62NPU2BVL20\IW_OPTN1_FCU2-Smallparticles	2/3/2014 15:38	Pt Created		2/3/2014 15:38	Pt Created		2/3/2014 15:38	Pt Created		2/3/2014 15:41	Pt Created
3	\\WIN-62NPU2BVL20\IW_OPTN1_FCU3-Smallparticles	2/3/2014 15:43	0.104654998		2/3/2014 15:43	0.089994803		2/3/2014 15:43	0.060673501		2/3/2014 15:44	1539790
4	\\WIN-62NPU2BVL20\IW_OPTN1_FCU4-Smallparticles	2/3/2014 15:43	0.104654998		2/3/2014 15:43	0.089994803		2/3/2014 15:43	0.060673501		2/3/2014 15:54	1539790
5		2/3/2014 15:53	0.104654998		2/3/2014 15:53	0.089994803		2/3/2014 15:53	0.060673501		2/3/2014 15:54	1539790
6		2/3/2014 15:53	0.119315997		2/3/2014 15:53	0.089994803		2/3/2014 15:53	0.060673501		2/3/2014 15:54	1539790
7		2/3/2014 15:53	0.119315997		2/3/2014 15:53	0.089994803		2/3/2014 15:53	0.060673501		2/3/2014 15:54	1483920
8		2/3/2014 15:53	0.119315997		2/3/2014 15:53	0.089994803		2/3/2014 15:53	0.060673501		2/3/2014 15:56	1483920
9		2/3/2014 15:56	0.119315997		2/3/2014 15:56	0.089994803		2/3/2014 15:54	0.060673501		2/3/2014 15:57	1483920
10		2/3/2014 15:57	0.119315997		2/3/2014 15:57	0.089994803		2/3/2014 15:54	0.104654998		2/3/2014 15:59	1483920
11		2/3/2014 15:59	0.119315997		2/3/2014 15:59	0.089994803		2/3/2014 15:56	0.104654998		2/3/2014 16:04	1483920
12		2/3/2014 15:59	698861		2/3/2014 15:59	684335		2/3/2014 15:57	0.104654998		2/3/2014 16:04	1483920
13		2/3/2014 15:59	698861		2/3/2014 15:59	684335		2/3/2014 15:59	0.104654998		2/3/2014 16:11	1483920
14		2/3/2014 16:09	698861		2/3/2014 16:09	684335		2/3/2014 15:59	1615420		2/3/2014 16:11	1373090
15		2/3/2014 16:09	698861		2/3/2014 16:09	684335		2/3/2014 15:59	1615420		2/3/2014 16:21	1373090
16		2/3/2014 16:09	698861		2/3/2014 16:10	684335		2/3/2014 16:09	1615420		2/3/2014 16:21	1373090
17		2/3/2014 16:09	665249		2/3/2014 16:10	677284		2/3/2014 16:09	1615420		2/3/2014 16:28	1373090
18		2/3/2014 16:19	665249		2/3/2014 16:20	677284		2/3/2014 16:10	1615420		2/3/2014 16:28	1503090
19		2/3/2014 16:19	665249		2/3/2014 16:20	677284		2/3/2014 16:10	1527870		2/3/2014 16:38	1503090
20		2/3/2014 16:25	665249		2/3/2014 16:26	677284		2/3/2014 16:20	1527870		2/3/2014 16:38	1503090
21		2/3/2014 16:26	660378		2/3/2014 16:26	658255		2/3/2014 16:20	1527870		2/3/2014 16:44	1503090
22		2/3/2014 16:35	660378		2/3/2014 16:36	658255		2/3/2014 16:27	1527870		2/3/2014 16:44	1485020
23		2/3/2014 16:36	660378		2/3/2014 16:36	658255		2/3/2014 16:27	1597380		2/3/2014 16:54	1485020
24		2/3/2014 16:42	660378		2/3/2014 16:43	658255		2/3/2014 16:37	1597380		2/3/2014 16:54	1485020
25		2/3/2014 16:42	641151		2/3/2014 16:43	633506		2/3/2014 16:37	1597380		2/3/2014 17:01	1485020
26		2/3/2014 16:52	641151		2/3/2014 16:53	633506		2/3/2014 16:44	1597380		2/3/2014 17:01	1559210
27		2/3/2014 16:52	641151		2/3/2014 16:53	633506		2/3/2014 16:44	1566010		2/3/2014 17:11	1559210

Figure 5.102 Aircuity Optinet™ small particulate data spreadsheet; this image is an example of the data record.

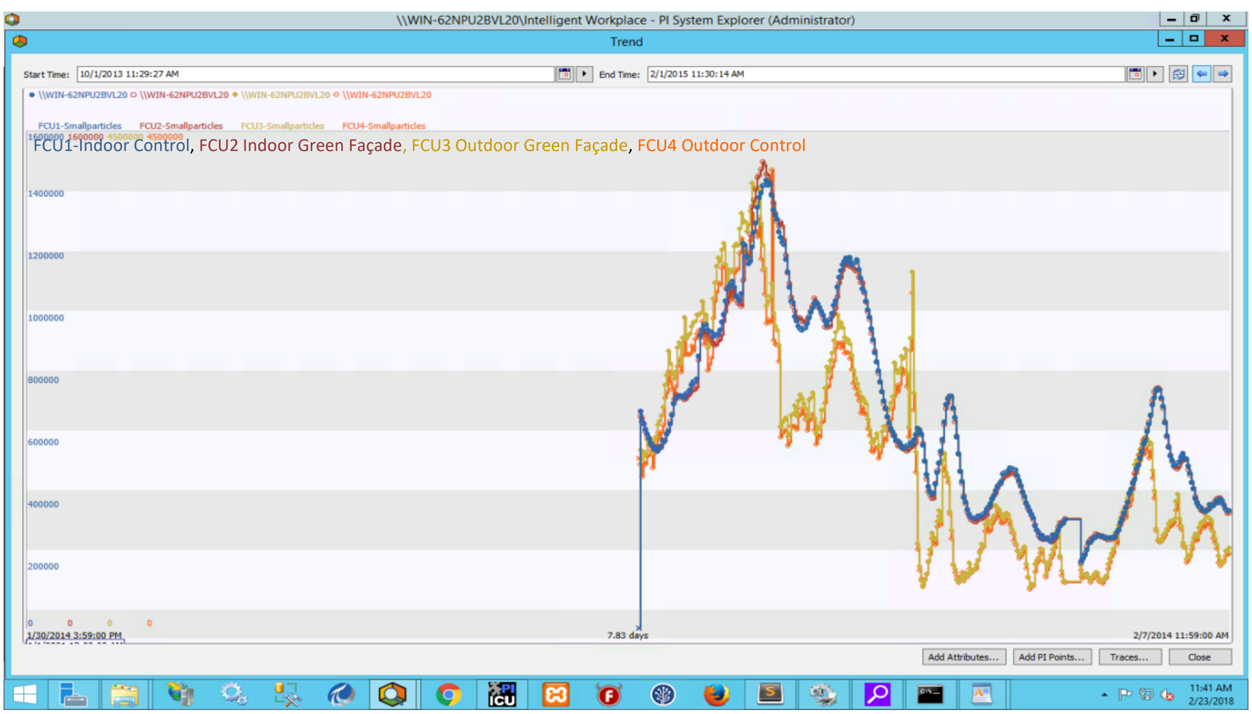


Figure 5.103 1-30-2014 through 2-7-2014, Indoor and outdoor PM2.5 particulate levels are nearly identical for both the green façade and the control façade; this image is an example of the original data representation.

5.4.4 Average Rainwater Usage

The average irrigation requirements were measured in gallons which became not only the measure but also the water delivery system. The need to check the condition of the plants at least once a day, along with the inability to check on the system multiple times each day, led to a late day irrigation routine using gallon jugs. The average number of gallons required for each research installation per day, seven days a week gives the total gallons of water used per system. Divided by the panel area of each installation, this provides the water usage per unit of area. Calculating the total annual rainfall from the rooftop area of the IW would determine if the rainwater available would be enough to irrigate a green façade covering the entire exterior façade. Figures 5.104-5.107 show the system and watering jugs.

Quantifying irrigation water usage, and comparing the amount available to how much surface area of food producing living façade it could support, is an important aspect of this study. In Pittsburgh, and many other older cites located in temperate climate regions, Combined Sewer Overflows (CSO's) from combined storm water and sewer systems can be generated by as little as one-tenth of an inch of rainfall (3 Rivers Wet Weather, 2016). Installing a FPLF would be one way to reduce the volume and speed with which rainfall moves through the storm water system, reducing pressure on that already overwhelmed system, and producing the other building and urban environment benefits discussed here. In the results chapter of this dissertation these calculations are quantified and discussed.

Figure 5.104 Gallon Jugs for irrigation

Figure 5.105 South façade irrigation

Figure 5.106 West façade irrigation (detail)

Figure 5.107 West façade irrigation

5.5 Conclude: Design for Disassembly

The concept of design for disassembly has been an important part of this research study, with a focus of illustrating a cradle to cradle life cycle for all the materials used to fabricate and operate this system. As all material used for this system were purchased from local purveyors, the upstream embodied energy within these materials is typical for the current state of the industry. The design, fabrication, installation, operation, and maintenance were conceived and implemented with the goal of disassembly at the time of decommissioning, with biological components being separated out for composting, and technological components being separated out for re-use or recycling to the maximum extent possible. This approach eliminates the creation of waste, instead turning all end-of-life materials into feedstock and a useful input resource for other processes.

In the summer of 2019, after six full growing seasons, the food producing living façade system at CMU was decommissioned and disassembled. The system components were held together with screws and zip ties, which were removed, with the wood and soil panels being composted and the galvanized fencing, hardware cloth being retained for re-use and/or recycling. The photos below show the disassembly of the south and west façade research systems (Figures 5.108-5.112), and the removal of components to an off-campus location for processing (Figures 5.113 and 5.114).

Figure 5.108 South façade system disassembly

Figure 5.109 South façade system disassembly

Figure 5.110 Disassembly

Figure 5.111 Decommissioned west façade system

Figure 5.112 After removal

Figure 5.113 West façade system components pre-processing

Figure 5.114 South façade system components pre-processing

5.5.1 Biological Components to be composted

The composting of biological components and products of the food producing living façade vertical garden began before the decommissioning of the system. At CMU there is already a university-wide recycling protocol for biological components created in kitchens and kitchenettes all across campus (Figure 5.115). Excess, inedible biomass generated by the vertical garden annually was periodically composed through the university composting system.

At the time of system decommissioning and disassembly, the biological and technological components were taken to an off-campus location for processing. Figures 5.116 and 5.117 below show the soil filled panels being disassembled with the wood and soil being composted. This is the same residential scale compost pile from which the compost used to create the growing medium was taken. This is a great illustration of the compost and other biological components provided initially returning to the original compost pile to create new compost for the next system.

Figure 5.115 IW compost

Figure 5.116 Preliminary processing

Figure 5.117 Biological components compost

5.5.2 Technological Components to be reused or recycled

The technological components of the system were taken apart and separated, as shown in Figures 5.118-5.120. The galvanized fencing was rolled up for re-use in a future food producing living façade vertical garden system. The metal hardware cloth will be re-used in new panel boxes or can be recycled. The screws will also be re-used or recycled. The perforated pvc pipe will be used for future irrigation systems. The plastic zip ties were recycled. At the end of the life cycle of this system no waste was generated.

Figure 5.118 Technological components

Figure 5.119 Screws, zip ties and pvc pipe

Figure 5.120 Metal hardware cloth

Chapter 6. Food Producing Living Façade Data Collection, Analysis and Results

This dissertation gathered data from the design, construction and operation of a food-producing living façade to prove that living façades in temperate climates can generate fresh produce, reduce façade temperature during the summer, reduce fine particulates in the air, and utilize harvested rainwater for primary irrigation. In order to address these four hypotheses, the following data was collected over six growing seasons on the west façade of the Intelligent Workplace at Carnegie Mellon University, with field comparisons of the performance of a food producing living façade versus a control façade area with no plants, to determine:

- Food production across six growing seasons, measured by weight
- Continuous façade temperature differentials in August and September, outdoors and indoors, measured by Hobo temperature sensors and Infra-Red photography, to be translated into reduced heat gain calculations and cooling load implications
- Particulate matter $PM_{2.5}$ readings for six months in micrograms/m^3, measured by Aircuity sensors outdoors and indoors, to calculate the potential reductions by the living façade
- Rainwater use in liters/day, measured by season for the six growing seasons compared to roof runoff that would burden a city storm system

The west façade provided space to conduct this semi-controlled field experiment with a food producing living façade installed adjacent to the existing thermally insulated aluminum faced façade, each exposed to the same climate conditions (sun, wind, temperature and rain). In addition, the indoor space was enclosed and divided to isolate the living and control façade areas.

A second food producing living façade was also built on the south façade of the Intelligent Workplace but without an adjacent control façade area for temperature and particulate matter comparisons. In addition, the interior space near the south façade is an informal meeting space with public outdoor roof access which could not be controlled for limiting access, creating no ability to provide air sampling sensors to measure small particulates on the south façade. As a result, only three data sets were collected on the performance of the south façade research installation (with no adjacent control for comparison):

- The potential for food production for six growing seasons, measured by weight
- Continuous façade temperature differentials for a typical week in late summer and again in early fall, outdoors and indoors, measured by Hobo thermocouples and infra-red photography to be translated into reduced heat gain calculations and cooling load implications
- Rainwater use in liters/day, measured by season for the six growing seasons compared to roof runoff that would burden a city storm system

The data for each of these variables was structured into a data set for analysis and this chapter gives the results of that analysis by outcome variable. The data collected and analyzed tested the veracity of incorporating food producing plants into a living façade as a source of local food production, while simultaneously reducing building façade temperature (inside and out), small particulate levels (inside and out), and utilizing stored rainwater. Additional observed and photographed benefits of habitat creation and biodiversity have been included at the end of this chapter.

The same number and type of each food producing plant were planted on each façade in similar locations and configurations. The south and west façade planting plans shown in Figures 6.1 and 6.2 for May 2014 are an example.

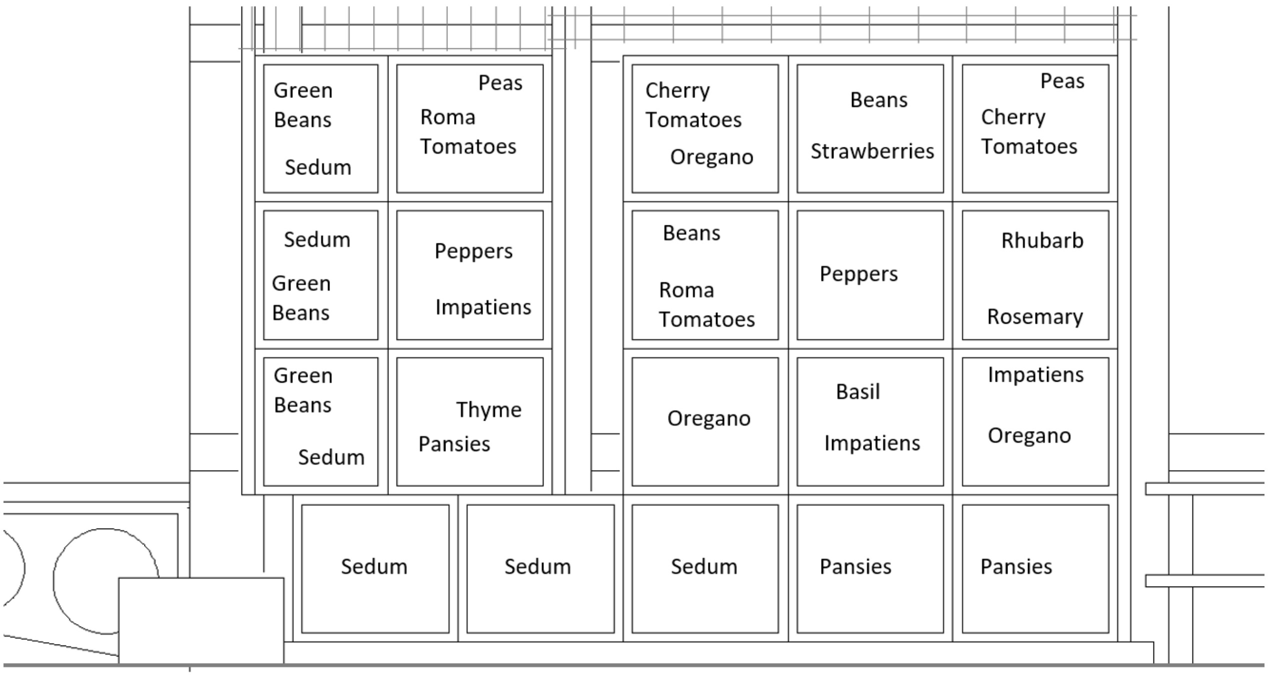


Figure 6.1 South Façade Planting Diagram (May 2014).

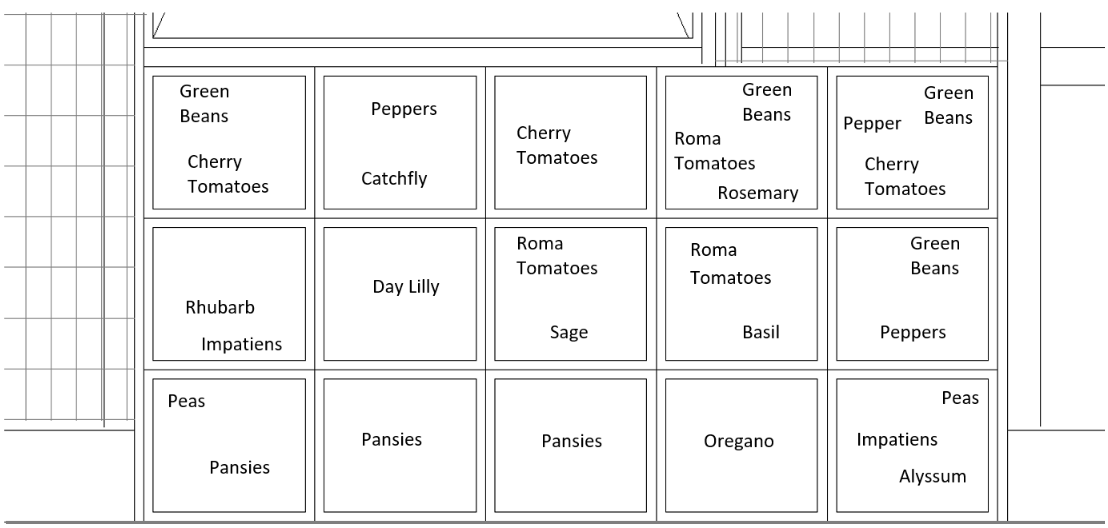


Figure 6.2 West Façade Planting Diagram (May 2014).

The west façade research bay contained 1.39 m^2 (15 ft^2) of soil filled panels. The south façade research bay contained 1.76 m^2 (19 ft^2) of soil filled panels. To normalize for the differences in the total area between these two research installations for the purposes of documenting the food production on each façade for comparative analysis, the food producing plants on the south façade were planted within the same total area as the west façade installation, 1.39 m^2 (15 ft^2). The additional 0.37 m^2 (4 ft^2) on the south façade installation was planted with non-food producing plants.

In this way the same number and type of plants were planted in the same total area on both façades , to normalize the calculations per unit area for comparison purposes. These numbers are used to calculate the food production per unit of area for this system for each production season. The total combined area of both façades planted with food producing plants was 2.78 m^2 (30 ft^2).

The same number and type of food producing crops planted on both façades each year included:

- 6 Cherry Tomato plants
- 6 Roma Tomatoes plants
- 2 Heirloom Tomato plants
- 6 Sweet Banana Pepper plants
- 6 Hot Pepper plants
- 18 Green Bean plants

In the first season, the Sweet Banana Peppers were separated from the Hot Peppers by façade, as a precaution, to keep the Sweet Banana Peppers from becoming hot. Upon investigation it became clear that this was not a concern. Plants were sourced at local retailers, and not all the same species were available each year.

In 2015 and 2018 the only Heirloom Tomato plants available were large varieties that could not be supported on the living façade. In 2016, there were no Roma Tomato plants available locally. These variations in planting created the fluctuations in total harvest indicated and the tables and charts shown below. These variations in the planting each year due to local availability were identical on each façade.

Calculations for the irrigation requirements for each façade were based on the total square footage of each façade, as all plants on both façades were irrigated every day. These differences are important when calculating total food production and total irrigation per unit area for comparison purposes.

In summary, the overall results of the research study indicate that:

- A maximum average production of 2.64 kilograms of produce per square meter of façade panel can be generated annually (0.54 lbs./ft^2)
- Façade surface temperatures can be reduced by 11 to 27.5 degrees Celsius (20 to 50 degrees Fahrenheit)
- $PM_{2.5}$ particulate levels can be reduced by 5.5% on average outdoors and 1.6% on average indoors
- Roof rainwater runoff can be redeployed for primary irrigation at an average rate of 14.26 liters per square meter per day (0.35 gallons per square foot per day)

The broader impact of these contributions is discussed at the end of each section.   Before and after photographs of the south façade research installation (Figure 6.3) and the west façade research installation (Figure 6.4, control on the left, living façade on the right) are shown below.

Figure 6.3 South Façade before & after.

Figure 6.4 West Façade before & after.

6.1 Food Production on Living Façades in a Temperate Climate

The primary hypothesis of this dissertation is that building façades can produce measurable amounts of fresh produce when outfitted with living façade assemblies planted with food producing plants. Quantification of fresh produce harvested from the south and west façade research installations was systematically documented to test this hypothesis.

Figure 6.5 South Façade detail 2013.

Figure 6.6 West Façade detail 2013.

As the produce reached maturity on the vine, as shown in Figures 6.5 and 6.6, it was harvested and then documented. The crops which were the primary focus for quantification of food production potential were Tomatoes, Peppers and Beans.   Additional crops were planted intermittently (some years but not every year) to illustrate the potential for crop diversification in future research studies. The produce was harvested, rinsed as necessary, laid out on letter sized sheets of white paper, numbered, weighed, and photographed, as shown in Figure 6.7.

Figure 6.7 Examples of food harvested. Produce was weighed, numbered and photographed.

Once the produce was documented, the quantity and weight of individual pieces of produce were compiled into a spreadsheet and summed by façade, month and year. These aggregated totals were then entered into tables and graphed looking for variations in production levels due to façade orientation from month to month and year to year.

The research documented that fresh produce could be successfully harvested from a living façade, as part of a polyculture garden which included fruits, vegetables, herbs and flowers. The goal was not to maximize food production, but instead to integrate food production into a living façade that also provided access to nature and visual interest, including from non-edible, flowering and succulent, plants.

Documentation of the potential for food production as integrated into a living façade was chosen as a deliberate strategy over the maximization of one or two vegetable crops within a monocultural urban agricultural system. Intentionally prompting crop and species diversity within a small scale, urban, living façade application was an important consideration, as well as design and production outcome of this field experiment.

Accumulating this data consistently over six consecutive growing seasons enabled the documentation of production variations, including both decline and recovery of total production over time. Official climate data for Pittsburgh, including temperature and precipitation, are included for comparative analysis with measured and recorded research data.

Six growing seasons also allowed for the completion of one full life cycle for the project, specifically the compostable soil panel assemblies. This was the estimated length of time it would take for the soil filled pine board planting box modules to begin to break down beyond repair, when the modules would need to be replaced individually, or the entire system disassembled and removed.

6.1.1 Weight and Weight per Area Production Tables and Graphs

The measured weight and weight per unit of area in aggregate, and for each plant variety, per façade, were the primary metrics for determining the food production value of these FPLF research installations. Total production of both façades gives critical insights into the average production possible on south and west façades, and will be used to determine the number of building occupants who can be supported with the nutritional requirement of 400 grams of fresh fruit and vegetables daily.

Quantifying the total weight per unit of area is the metric that allows for calculating the food production benefits of scaling up this system for larger scale applications. Tables 6.1 and 6.2 show the total food production in weight and in weight per area, per façade per year, with aggregates for both façades combined per year at the bottom.

Evaluating the data in Tables 6.1 and 6.2 and the associated graphs in Figures 6.8 through 6.11, several patterns begin to emerge. Years 2013 and 2017 have almost identical total production numbers with 7,192.26 and 7,349.00 combined grams of food respectively.

The total weight drops the second year (2014), rebounds the next year but not as high as the first year, drops again to an almost identical level with the second year, rebounds again to higher than the first year, and then drops back down again in 2018. 2017 has the highest production in terms of total weight, with the west façade producing more weight for the first two seasons and the south façade producing more weight for the final four seasons.

The comparisons of south and west total production reveals that both orientations are capable of yielding the same average weight production.

Table 6.1 Living Façade Food Production Totals by Weight per Year.

	2013	2014	2015	2016	2017	2018	Avg.
Total West Façade Food Production (grams)	**3696.77**	**2235.51**	**2532.46**	**1861.40**	**3626.00**	**2173.00**	**2687.52**
Total West Façade Food Production (pounds)	8.15	4.93	5.58	4.10	7.99	4.79	5.92
Total South Façade Food Production (grams)	**3495.49**	**1963.61**	**3752.89**	**2358.00**	**3723.00**	**2653.00**	**2991.00**
Total South Façade Food Production (pounds)	7.71	4.33	8.27	5.20	8.21	5.85	6.60
Total Food Production (grams)	**7192.26**	**4199.12**	**6285.35**	**4219.40**	**7349.00**	**4826.00**	**5678.52**
Total Food Production (pounds)	15.86	9.26	13.85	9.30	16.20	10.64	12.52

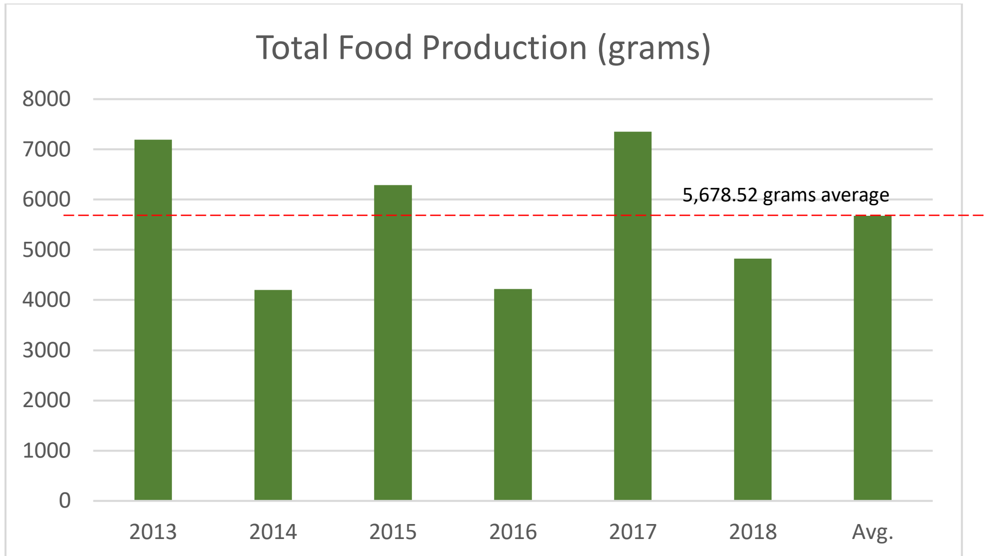


Figure 6.8 Total Food Production (grams).

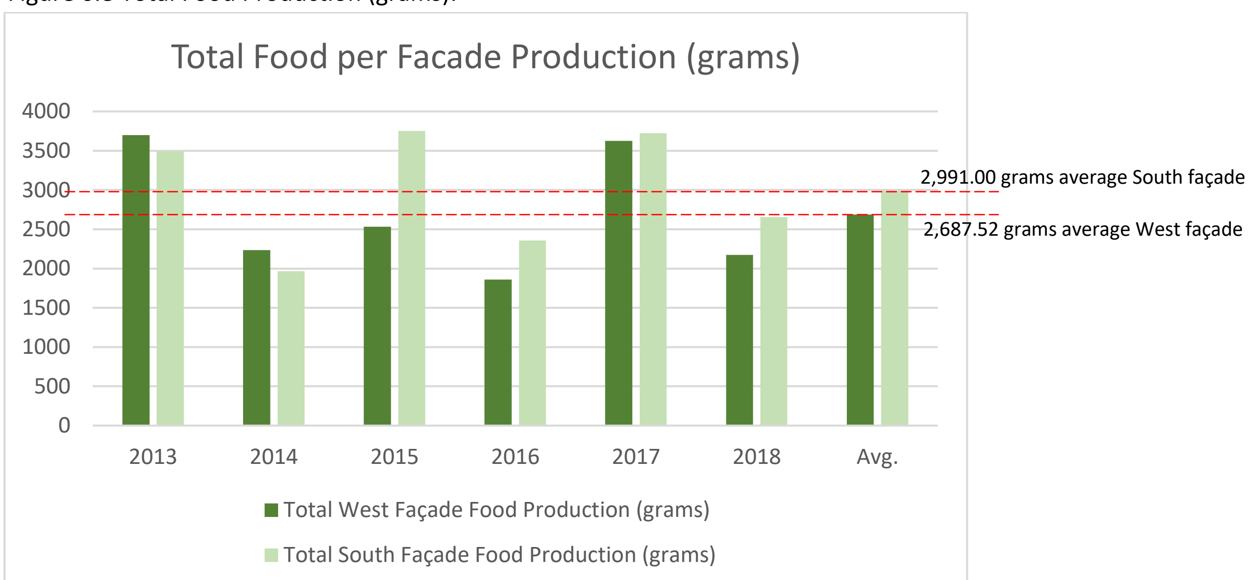


Figure 6.9 Total Food Production per Façade (grams).

Most significant for the ongoing design of food-producing living façades in climates similar to Pittsburgh is the weight of food produced per unit area on south and west facing façades. Table 6.2 shows the total food production in weight per unit of area per façade per year, with aggregated averages for both façades combined into an overall total.

On this chart, the largest production overall was in 2017 at 2.64 Kg/m^2 (the south and west façade production combined), but the largest production per area per façade is on the south facade in 2015 at 2.70 Kg/m^2. This table shows that total production weight per unit of area is larger for the west façade in the first two years, but larger for the south façade during the final four years. Figure 6.10 shows Total Food Production per unit area in Kg/$m^2$and Figure 6.11 shows Total Food Production per unit area per Façade in Kg/m^2 per growing season.

Table 6.2 Living Façade Food Production Totals by Weight per Unit of Area per Year.

	2013	2014	2015	2016	2017	2018	Avg
Total West Façade Food Production (kg/m^2)	**2.66**	**1.61**	**1.82**	**1.34**	**2.61**	**1.56**	**1.93**
Total West Façade Food Production (lbs/ft^2)	0.54	0.33	0.37	0.27	0.53	0.32	0.40
Total South Façade Food Production (kg/m^2)	**2.51**	**1.41**	**2.70**	**1.70**	**2.68**	**1.91**	**2.15**
Total South Façade Food Production (lbs/ft^2)	0.51	0.29	0.55	0.35	0.55	0.39	0.44
Total Food Production (kg/m^2)	**2.59**	**1.51**	**2.26**	**1.52**	**2.64**	**1.74**	**2.04**
Total Food Production (lbs/ft^2)	0.53	0.31	0.47	0.31	0.54	0.36	0.42

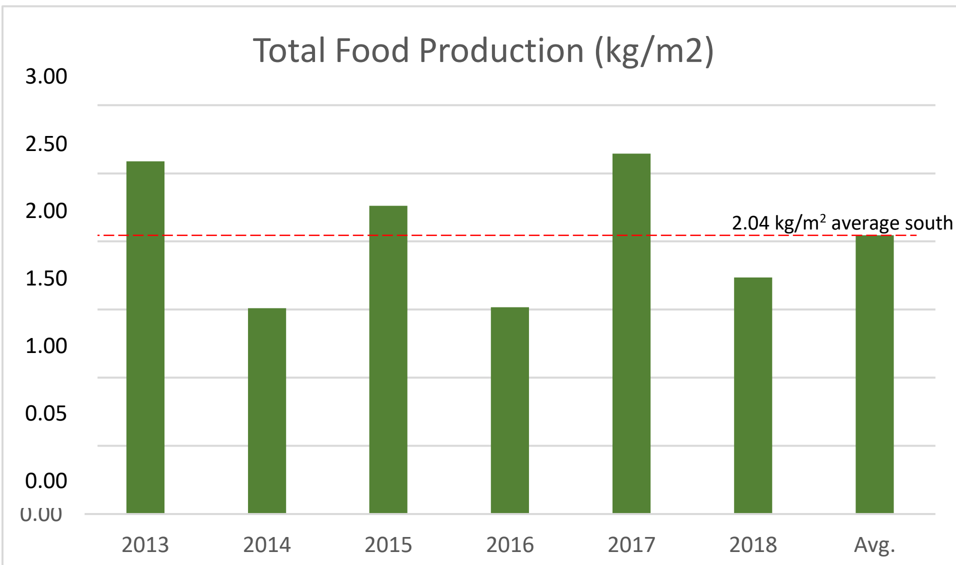


Figure 6.10 Total food production per unit of area (kg/m^2)

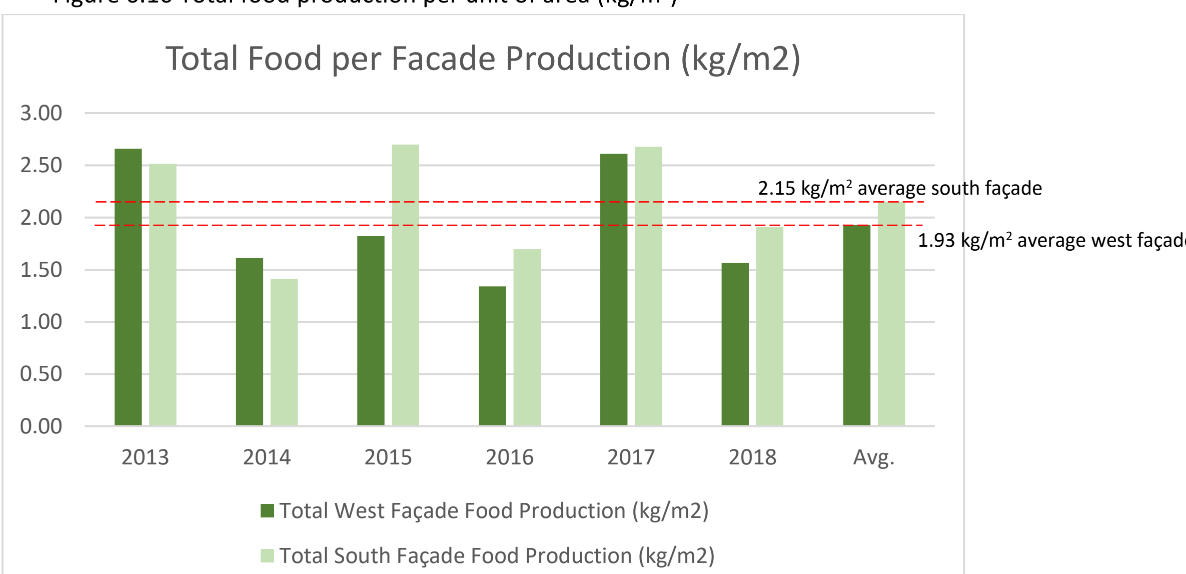


Figure 6.11 Total food production per unit area per façade (kg/m^2)

Production variations year to year follow a similar pattern with both façades decreasing or increasing production more or less to the same extent. There is no statistical significance overall to the differences in production on the west and south façades .

An examination of the difference in the total production in 2015, when the south façade outperformed the west façade by 32.5%, revealed a difference in Green Bean production that year, as shown in Figure 6.17. The Green Beans were all planted two weeks earlier in 2015 than in the two previous growing seasons, which yielded increased green bean production overall. The green beans on the west Façade became infected, however, with a white powdery reaction, which reduced overall production.

The climate conditions in Pittsburgh allow for a six or seven month long total growing season from May through late October or early November. The Koppen Climate classification subtype for Pittsburgh is Dfb, meaning it has a Warm Summer Continental Climate (Weatherbase, 2020). The US Forest Service places the Western Allegheny Plateau where Pittsburgh is located in the Humid Temperate Domain, Hot Continental Division, Eastern Broadleaf Forest (Oceanic) Province (U.S. Forest Service, 2016). Average weather conditions in Pittsburgh over a forty-one-year period are shown in Table 6.3, including amount of sunshine, clouds and rain per month (NWS, 2020).

Table 6.3 Weather Chart of 41-year averages of conditions in Pittsburgh during the months of the growing season (Weatherbase, 2020)

Weather Condition	Annual	May	June	July	August	September	October	November
% Sunshine	45	50	56	57	55	55	51	36
# Sunny Days	58	5	5	5	7	7	8	4
# Partly Cloudy Days	103	9	12	13	11	10	9	6
# Cloudy Days	204	17	13	13	13	13	14	20
Precipitation (in.)	38.2	4.0	4.3	3.8	3.2	3.1	2.3	3.2

Weather records for Pittsburgh covering average temperature and total precipitation per month and annually for each of the six growing seasons are shown below. Table 6.4, Figure 6.12 and Figure 6.13 show the average temperature in ^{o}F per month and annually for 2013-2018.

Table 6.4 Pittsburgh Annual Temperature in ^{o}F per month and annually, 2013-2018 (NWS, 2020)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2013	31.5	28.7	35.9	52.4	62.5	69.4	73.4	70.7	64	56.3	39.4	34.2	51.5
2014	22.1	25.7	34.5	52.2	62	70.6	70.5	70	64.1	53.7	38.8	35.5	50
2015	25.3	18.3	35.8	52.9	66.1	70.4	73.3	71.3	69.6	53.9	48.6	44.5	52.5
2016	26.7	33.6	48	51.3	61.2	71.6	75.5	76	69.5	56.6	46.5	33.6	54.2
2017	34.6	40.6	39.9	57.3	60.6	69.7	73.7	70.3	66.4	58	42	30.6	53.6
2018	25.6	38.8	34.8	46.3	69	70.8	73.5	73	69.7	53.4	37.3	34.9	52.3

The temperature data indicates variance of 1.4 - 11.3^{o}F (0.78 – 6.28^{o}C) in average monthly temperatures from May to November, while rainfall varies 2.22 - 7.92 inches (56 – 201 mm). These differences are substantial, but the microclimate effect, and daily irrigation, mitigate these differences.

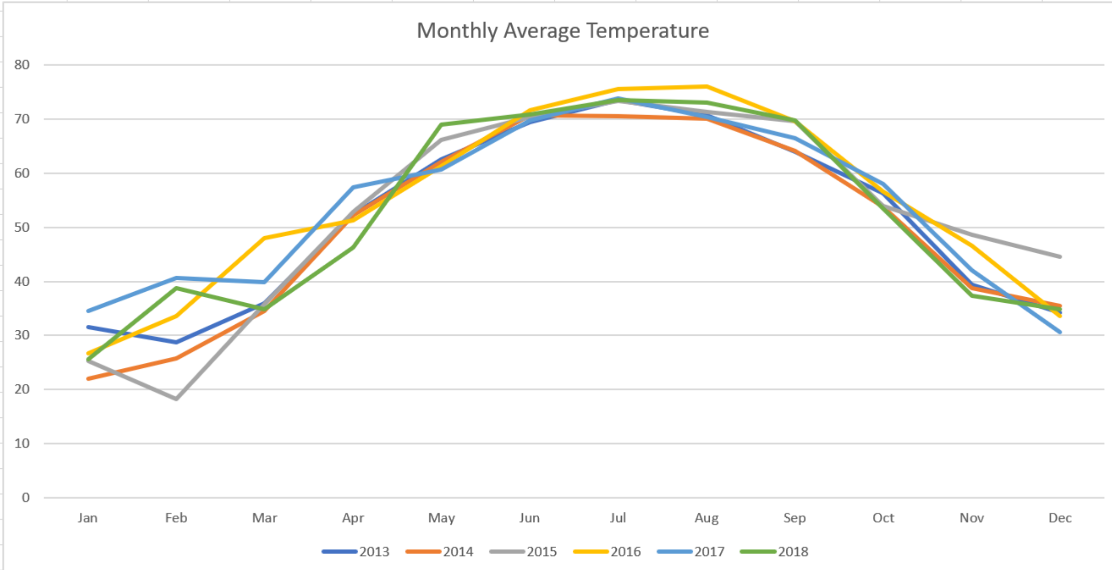


Figure 6.12 Monthly average temperature in °F, Pittsburgh from 2013 through 2018, the years of the study.

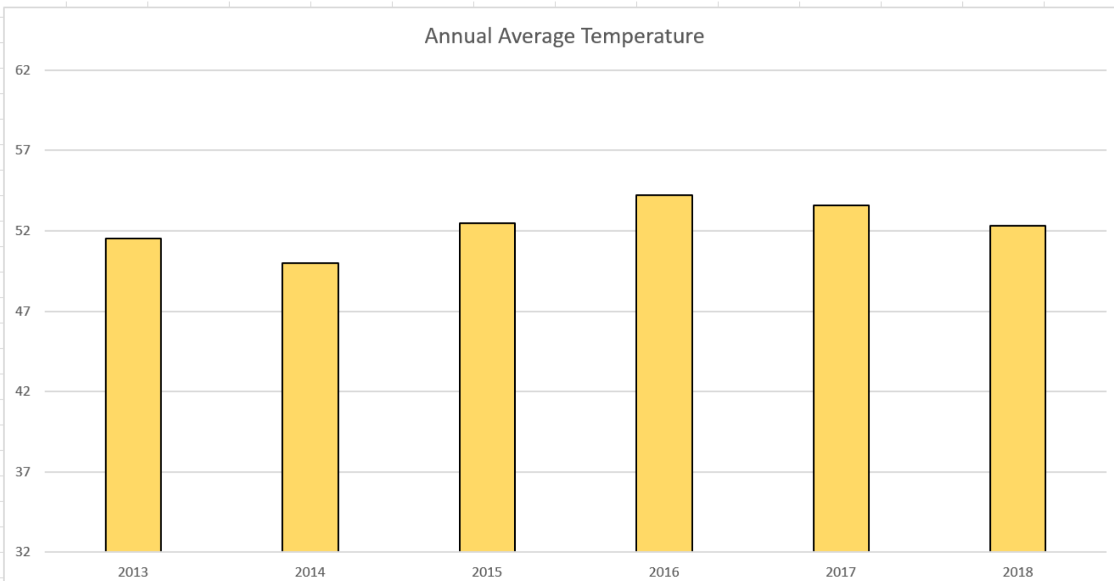


Figure 6.13 Annual average temperature in °F, Pittsburgh from 2013 through 2018, the years of the study.

Total rainfall in inches per month and annually, 2013-2018, is shown in Table 6.5, Figure 6.14 and 6.15.

Table 6.5 Pittsburgh Annual Precipitation in Inches per month and annually, 2013-2018 (NWS, 2020)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2013	2.44	2.13	2.17	3.27	2.33	5.48	6.16	1.78	2.31	2.35	2.97	3.26	36.65
2014	2.18	2.25	1.87	4.47	4.32	4.05	5.19	5.05	0.97	1.89	1.97	2.63	36.84
2015	2.25	1.55	4.01	3.95	2.72	7.34	3.61	2.29	5.08	3.34	1.38	3.04	40.56
2016	1.79	3.14	2.83	2.25	3.61	3.1	3.12	3.29	3.08	3.94	1.43	3.43	35.01
2017	3.54	1.46	5.02	3.54	5.15	3.78	6.42	2.63	0.58	4.11	4.15	1.77	42.15
2018	4.28	7.04	2.96	4.43	2.83	6.1	3.96	4.53	8.5	3.59	4.57	4.29	57.83

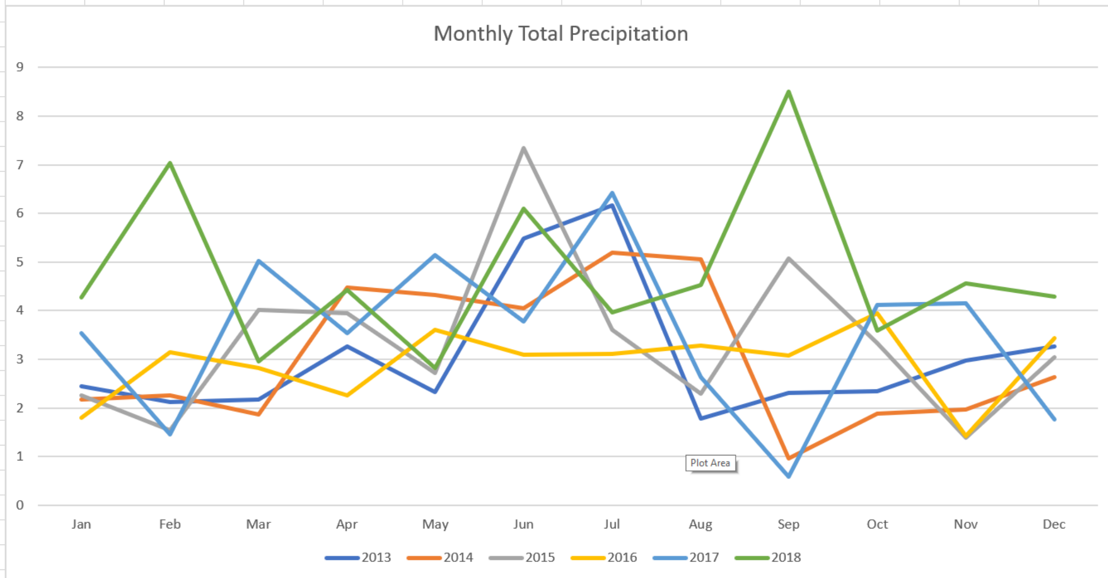


Figure 6.14 Month total precipitation in inches, Pittsburgh from 2013 through 2018, the years of the study.

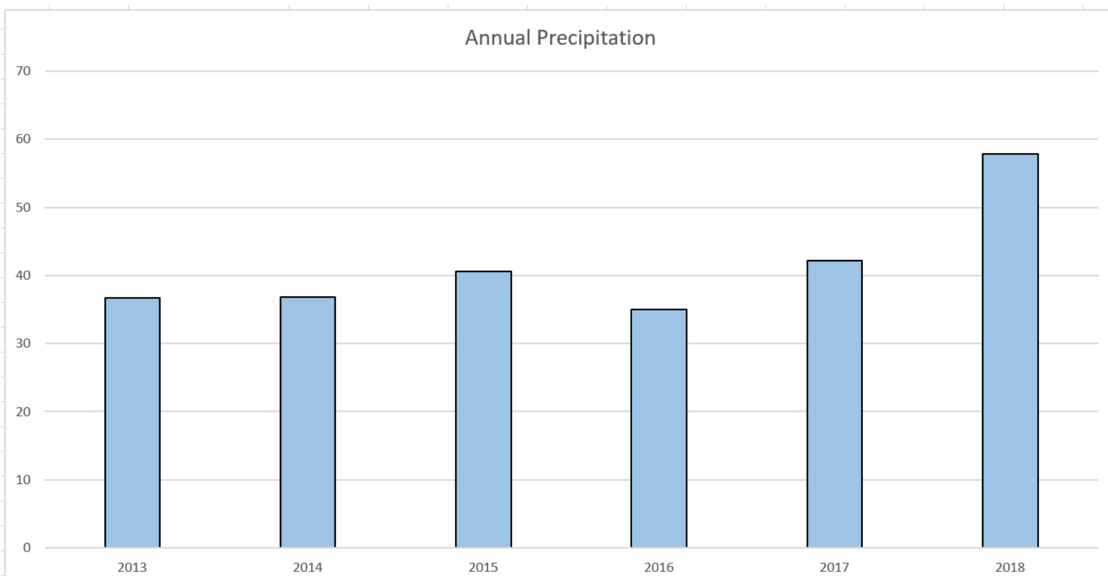


Figure 6.15 Annual Precipitation in Pittsburgh from 2013 through 2018, the years of the study.

Specific crop production that can be achieved in this climate zone is shown in Figures 6.16 through 6.21 in weight per unit of area per façade per year, providing a detailed breakdown of tomato, pepper and bean production for all six growing seasons, with averages. Indications are that each façade is better at growing certain crops and that instead of one façade orientation always being better overall at food production, the two orientations appear to balance each other out by providing a wider range of desirable conditions for a wider range of crops than just one façade orientation alone could achieve. This diversity is beneficial for addressing food insecurity by providing the fresh produce necessary to meet the 400-gram daily requirement for fruit and vegetables. The weight per unit area provides information for how much produce could be generated if this system was implemented in larger applications. This research can also inform community planners and architects about selecting specific crops to be planted in various configurations in community projects for specific outcomes.

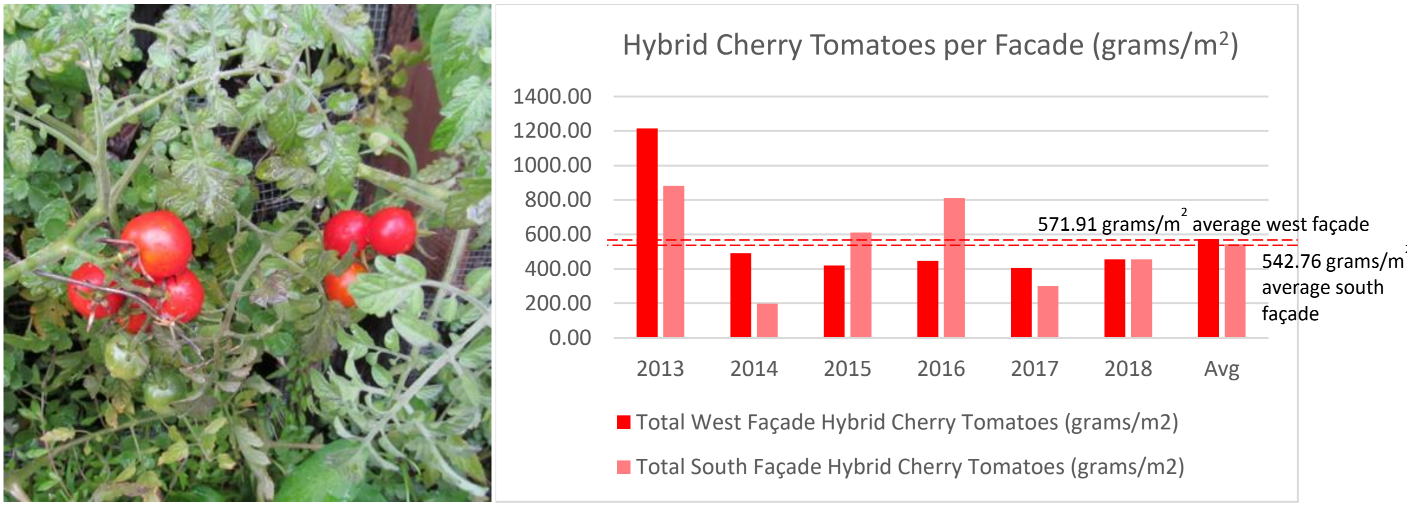


Figure 6.16 Comparison of Hybrid Cherry Tomatoes per façade (grams/m^2) per season

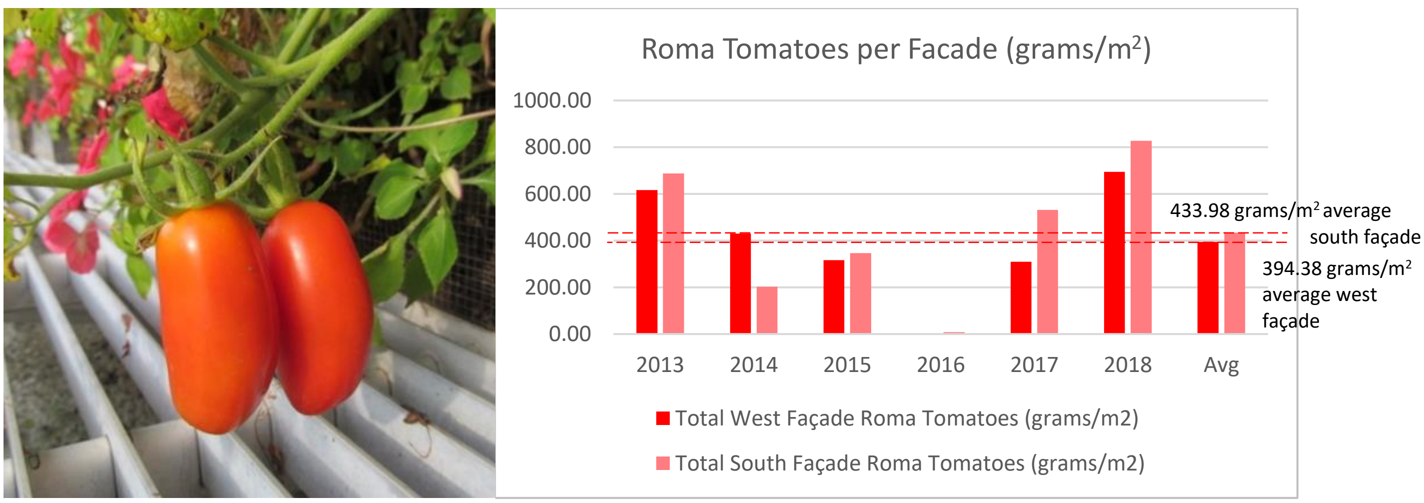


Figure 6.17 Comparison of Roma Tomatoes per façade (grams/m^2) per season

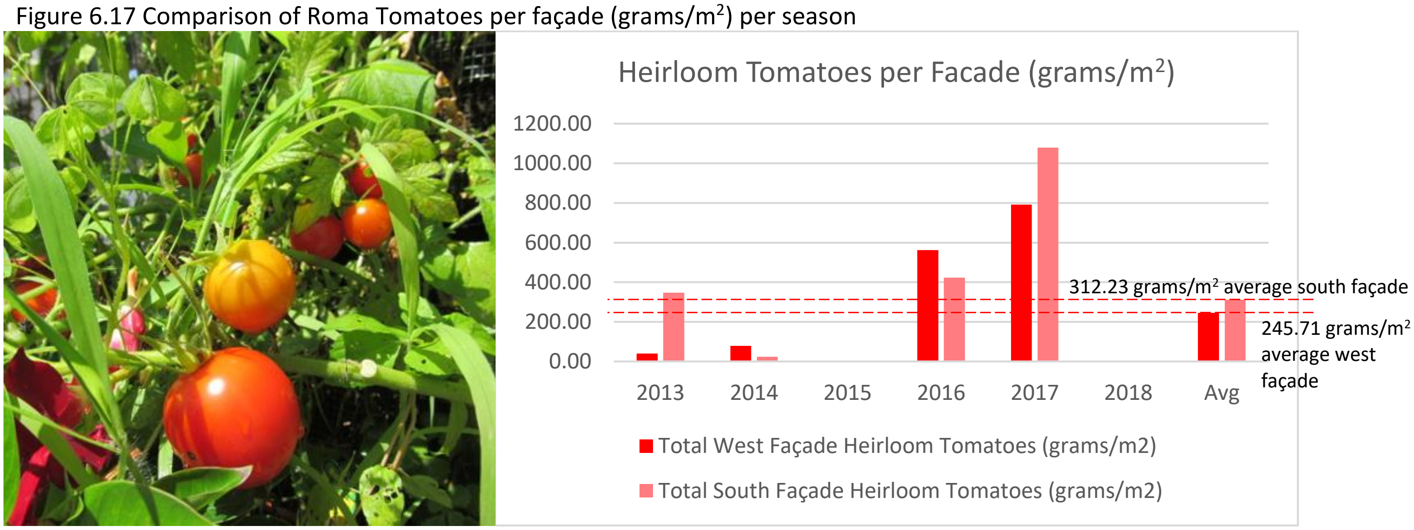


Figure 6.18 Comparison of Heirloom Tomatoes per façade (grams/m^2) per season

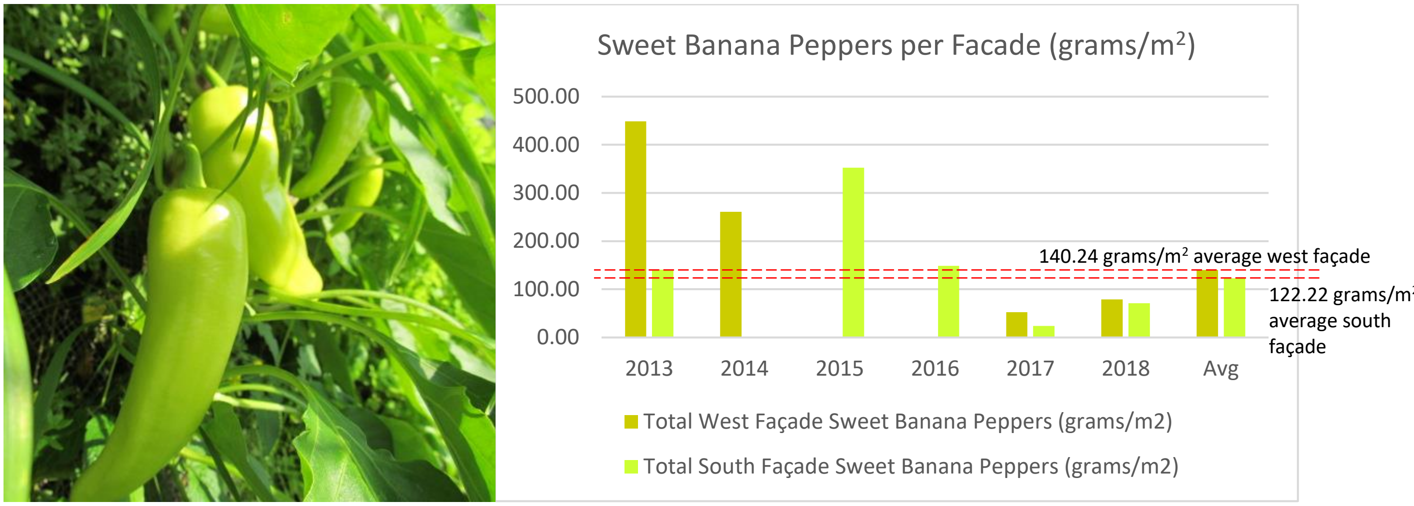


Figure 6.19 Comparison of Sweet Banana Peppers per Façade (grams/m^2) per season

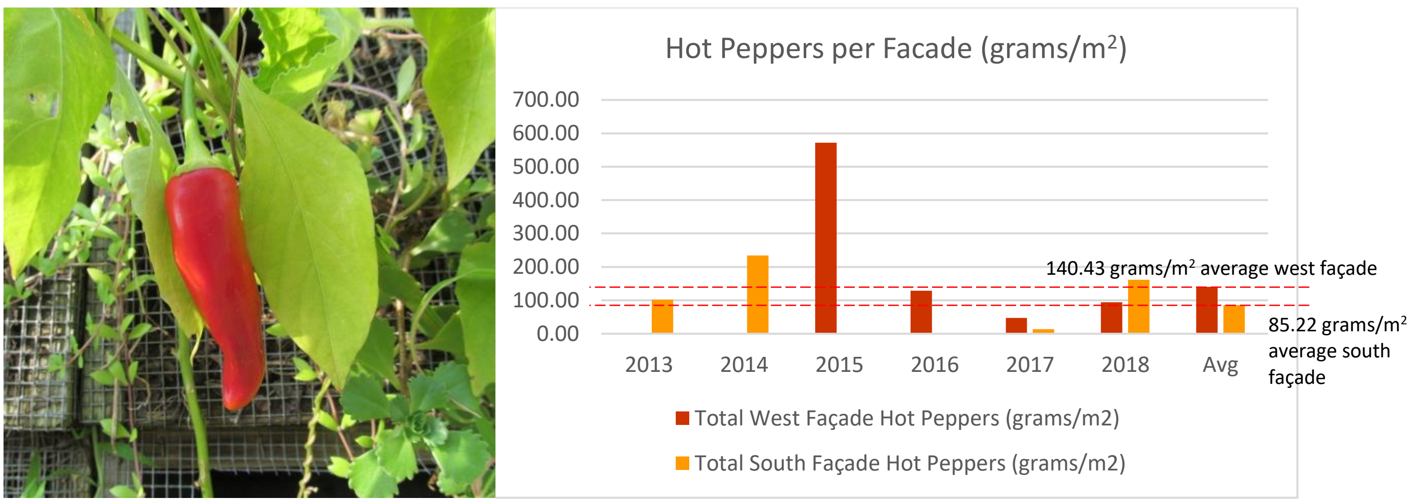


Figure 6.20 Comparison of Hot Peppers per Façade (grams/m^2) per season

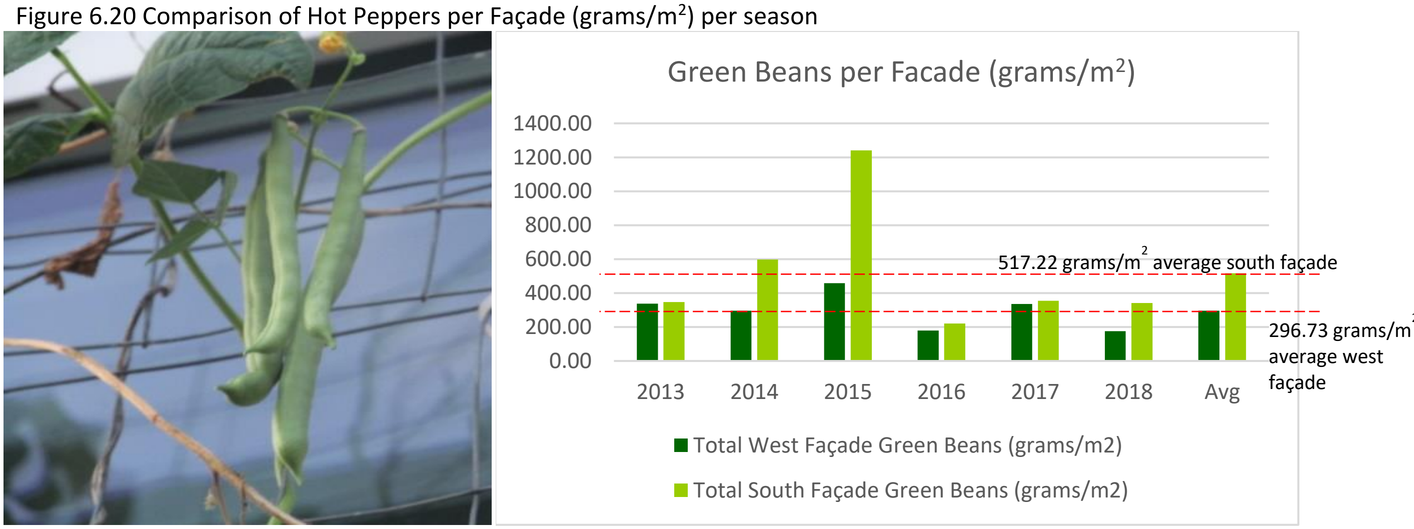


Figure 6.21 Comparison of Green Beans per Façade (grams/m^2) per season

6.1.2 Nutritional Value (fruits and vegetables)

Quantification of fresh produce per unit of area harvested from the food producing living façade as well as the verification of the nutritional value of this produce as equivalent to what is available currently in the marketplace, are critical metrics in determining how many people can meet their needs for fresh fruit and vegetables from the large-scale implementation of this research verified system. The World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) in 2003 launched an initiative to promote fruit and vegetable consumption for improved worldwide health. In the associated workshop report, *Fruits and Vegetables for Health*, 400 grams of fruits and vegetables is established as the minimum daily requirement to maintain good human health.

Specifically, the report *"recommends a minimum of 400g of fruit and vegetables per day (excluding potatoes and other starchy tubers) for the prevention of chronic diseases such as heart disease, cancer, diabetes and obesity, as well as for the prevention and alleviation of several micronutrient deficiencies, especially in less developed countries"* (World Health Organization, 2004, p. 18). Calculations of total grams of food produced divided by 400 grams per day, reveal how many building occupants could meet their minimum daily requirements for how many days. These implications of the research results will be further discussed in the next chapter.

Food production is about quality as well as quantity. Providing additional quantities of fresh, locally grown produce where none is currently available, especially in so-called 'food deserts' is important, but that food must provide nutritional value. To verify that the fresh produce grown on the living façade research installations at the IW contained the basic nutritional value expected of typically available grocery store produce, research samples harvested in the field and commercial samples purchased at local stores were sent to a commercial laboratory where they were analyzed. The specific produce samples compared were:

- Jalapeno Hot Peppers
- Mild Sweet Peppers
- Cherry Tomatoes
- Roma Tomatoes and
- Green Beans

The research and store samples (control) were chopped, measured into more than one cup amounts, placed into zip lock bags, frozen, packed in dry ice, and sent to Sky View Laboratories Inc. for testing. This testing facility was recommended by the local county extension office. Tables 6.6 and 6.7 contain the data results of the produce comparisons. The 'As Sampled' column contains the data results conducted on the wet sample. The 'Dry Matter' column contains the results conducted on the dry material. The Dry Matter results are better for comparative purposes.

These results show that the research samples are very similar in nutritional value to the control samples. Two samples, the Mild Sweet Peppers research sample and the Green Beans control sample have elevated Aluminum levels compared to the other samples, at 9.85 ppm and 45.30 ppm respectively, compared to <1.5 ppm typically. These levels are not considered excessive for food sources. If green beans sold locally contain 45.30 ppm of Aluminum and that is acceptable, then the sweet peppers grown on the research façade (clad with aluminum facia panels) containing 9.85 ppm of Aluminum would be equally acceptable.

Table 6.6 Nutritional values of research and control samples of Jalapeno Hot Peppers, Sweet Peppers and Cherry Tomatoes (Skyview Laboratory Inc., 2019)

REFERENCE NUMBER	99183		99184		99185		99186		99187		99188	
SPECIES	Jalapeno Hot Peppers Green Control		Jalapeno Hot Peppers Red Research		Sweet Peppers Control		Mild Sweet Peppers Research		Cherry Tomatoes Control		Cherry Tomatoes Research	
CONDITION	As Sampled	Dry Matter	As Sampled	Dry Matter	As Sampled	Dry Matter	As Sampled	Dry Matter	As Sampled	Dry Matter	As Sampled	Dry Matter
MOISTURE, %	86.7		81.0		88.6		82.9		73.4		73.4	
DRY MATTER, %	13.3		19.0		11.4		17.1		26.6		26.6	
CRUDE PROTEIN, %	1.8	13.3	1.9	10.1	1.0	8.7	1.7	10.1	3.5	13.3	4.5	17.0
DIGEST. PROTEIN, %	1.2	8.8	1.3	6.9	0.7	6.0	1.2	6.9	2.4	8.9	3.0	11.2
CA, %	0.04	0.27	0.04	0.21	0.01	0.13	0.04	0.23	0.06	0.23	0.06	0.22
P, %	0.04	0.32	0.05	0.26	0.03	0.25	0.06	0.35	0.11	0.40	0.09	0.35
MG, %	0.03	0.21	0.03	0.18	0.01	0.12	0.05	0.32	0.05	0.20	0.05	0.17
K, %	0.29	2.20	0.41	2.16	0.23	2.00	0.39	2.26	0.61	2.31	0.62	2.34
S, %	0.03	0.19	0.03	0.18	0.01	0.12	0.05	0.28	0.05	0.17	0.04	0.16
NA, %	0.02	0.14	0.03	0.14	0.01	0.05	0.04	0.24	0.06	0.24	0.05	0.19
IRON, ppm	6	47	7	39	5	44	8	49	10	39	10	37
MANGANESE, ppm	1	11	2	11	1	11	3	15	3	12	3	12
COPPER, ppm	2	13	2	13	1	9	1	5	2	8	1	3
ZINC, ppm	2	16	2	26	3	23	4	25	7	26	3	12
		APPROVED		APPROVED		APPROVED		APPROVED		APPROVED		APPROVED
COBALT. ppm		0.30		0.32		0.44		0.41		0.29		0.45
MOLYBDENUM, ppm		<0.3		<0.3		0.85		0.39		0.78		0.40
ALUMINUM, ppm		3.02		<1.5		<1.5		9.85		<1.5		<1.5

Table 6.7 Nutritional values of research and control samples of Roma Tomatoes and Green Beans (Skyview Laboratory Inc., 2019)

REFERENCE NUMBER	99189		99190		99191		99192	
SPECIES	Roma Tomatoes Control		Roma Tomatoes Research		Green Beans Control		Green Beans Research	
CONDITION	As Sampled	Dry Matter	As Sampled	Dry Matter	As Sampled	Dry Matter	As Sampled	Dry Matter
MOISTURE, %	94.3		31.6		92.4		85.7	
DRY MATTER, %	5.7		68.4		7.6		14.3	
CRUDE PROTEIN, %	1.0	17.0	12.2	17.8	1.6	20.4	3.6	25.3
DIGEST. PROTEIN, %	0.6	11.2	8.0	11.7	1.0	13.3	2.3	16.3
CA, %	0.02	0.37	0.62	0.91	0.07	0.98	0.12	0.81
P, %	0.03	0.55	0.24	0.35	0.04	0.53	0.08	0.55
MG, %	0.01	0.25	0.20	0.29	0.03	0.43	0.06	0.41
K, %	0.16	2.74	1.70	2.48	0.18	2.34	0.29	2.06
S, %	0.01	0.23	0.18	0.27	0.03	0.38	0.05	0.34
NA, %	0.02	0.28	0.29	0.43	0.03	0.39	0.04	0.28
IRON, ppm	4	73	38	55	9	113	13	89
MANGANESE, ppm	1	15	6	9	3	35	3	18
COPPER, ppm	0	4	10	14	1	15	2	11
ZINC, ppm	1	18	22	32	3	41	8	57
		APPROVED		APPROVED		APPROVED		APPROVED
COBALT. ppm		0.33		0.31		0.41		0.40
MOLYBDENUM, ppm		0.15		0.98		0.83		0.57
ALUMINUM, ppm		<1.5		<1.5		45.30		<1.5

The nutritional analysis shows that the fresh vegetables produced on the food producing living façade are nutritionally equivalent to the store-bought control samples. **The average level of production in**

climates similar to Pittsburgh, for south, west and east orientation façades would be 2.04 Kg/m^2 per growing season. If six months is the average growing season, 2040 grams/m^2 divided by 180 days yields 11.33 grams/m^2 per day, requiring 35.3 m^2 of façade (380 ft^2) per person to meet daily requirements. These results provide a baseline for future studies to verify how to maximize food production on living façades . There are many more benefits to local food production, including: freshness due to harvesting when ripe, reductions in the use of pesticides, herbicides, preservatives; reduction in miles traveled, packaging and handling. A detailed analysis of the upstream and downstream benefits and impacts of this form of local urban agriculture was beyond the scope of this study.

6.2 Thermal Performance of a Food Producing Living Façade in a Temperate Climate

A second hypothesis in this dissertation is that food producing living façades will reduce the façade surface temperature, compared to a control of that same façade, which in turn will reduce conductive heat gain and total cooling load. To compare the thermal performance of the living façade relative to the existing control façade, 16 temperature sensors were placed on the opaque and transparent portions of both façades , internally and externally. The locations are illustrated in the temperature sensor layout plan and section shown in Figures 6.22 and 6.23. This layout diagram is shown here again as a reference for the temperature sensor numbers which are indicated on each graph for comparative analysis.

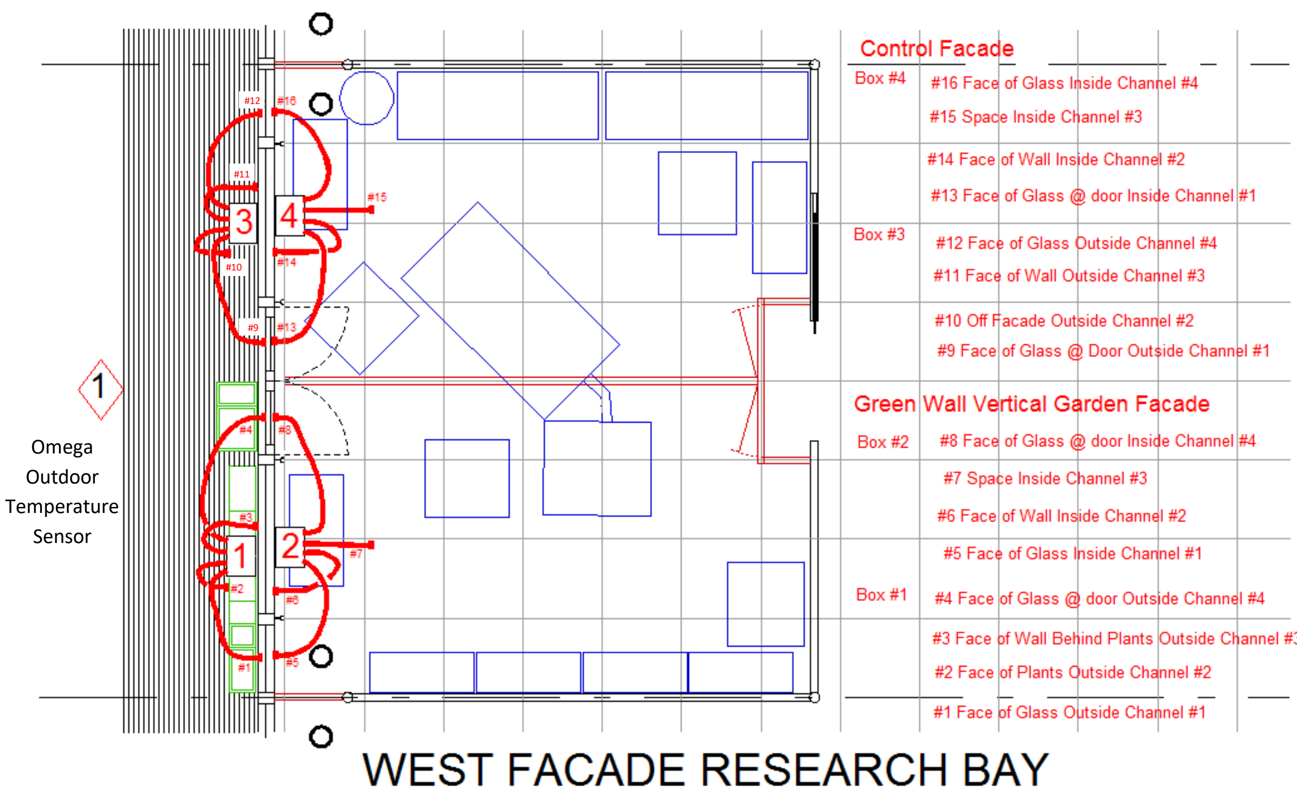


Figure 6.22 Temperature sensor layout in plan.

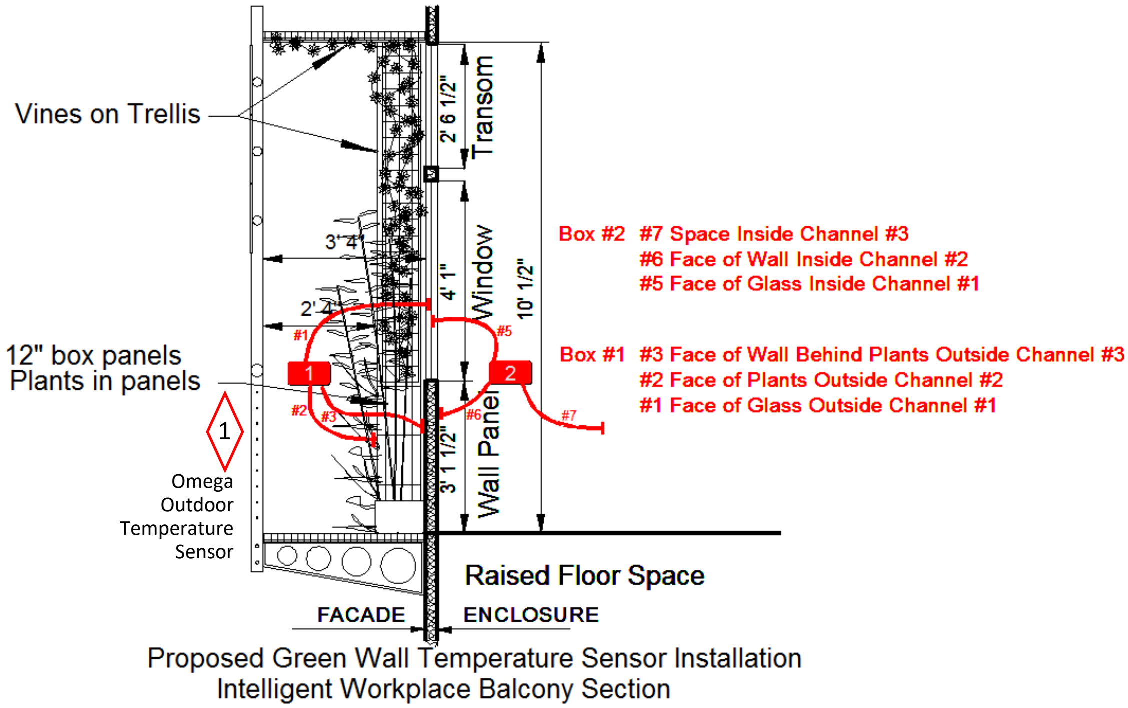


Figure 6.23 Building envelope section showing outdoor and indoor temperature sensor locations.

Each Onset Hobo™ data logger was numbered, boxes 1-4 shown on the floor plan diagram, and connected to four temperature sensors. An identical layout of sensors was established for the living research façade and the control façade both on the exterior and the interior. That arrangement allowed for one sensor to be on the opaque part of the façade, one on the fixed window glass, and one on the door glass on the exterior and interior for each façade.

In addition, one sensor hung inside the space of each research area, approximately 0.5 meters above the floor (18 inches) and 0.667 meters (24 inches) from the façade. This allowed for direct comparison of façade surface temperature conditions for the glazed and opaque areas of the living façade relative to the control façade.

6.2.1 Measured Façade Temperatures

Temperature data collection was conducted on the research and control façade areas over two one-week periods in August and September 2013 to show typical summer and late summer conditions. The two, one-week long testing periods were recorded to document the benefit of the performance of the food producing living façade installation compared to the control façade.

Week-long opaque façade temperature measurements for the week of August 5-11, 2013, including the outdoor temperature conditions are shown in Figure 6.24. Comparison of outside air temperature and the high and low opaque surface temperatures are shown. The significance of the living façade to reduce surface temperatures is clearly evident in blue, with air temperature in yellow and unshaded surface temperatures in red. An indication of sun/cloud cover for the Pittsburgh region for that week is shown in the historic weather chart shown in Figure 6.25.

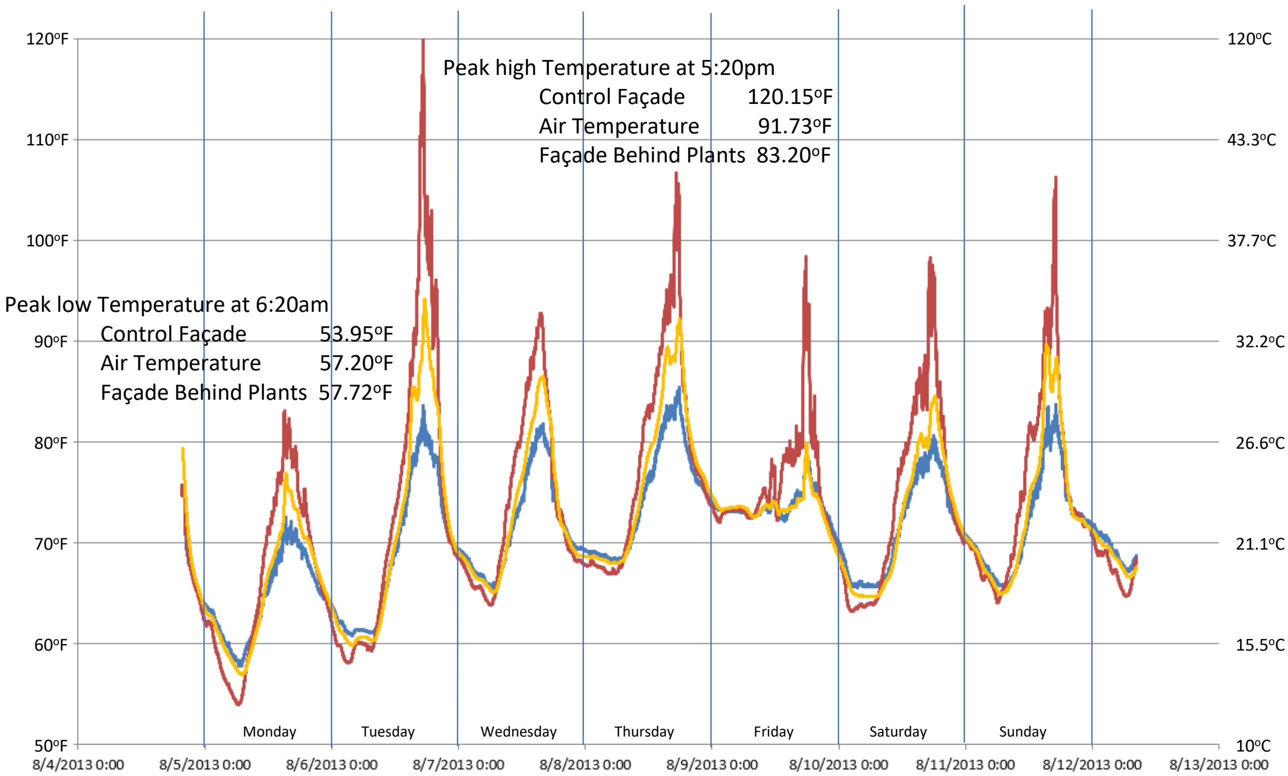


Figure 6.24 Exterior Opaque Façade Surface and Air Temperatures, Aug. 5-11, 2013

n=10,858; p-value < 0.001

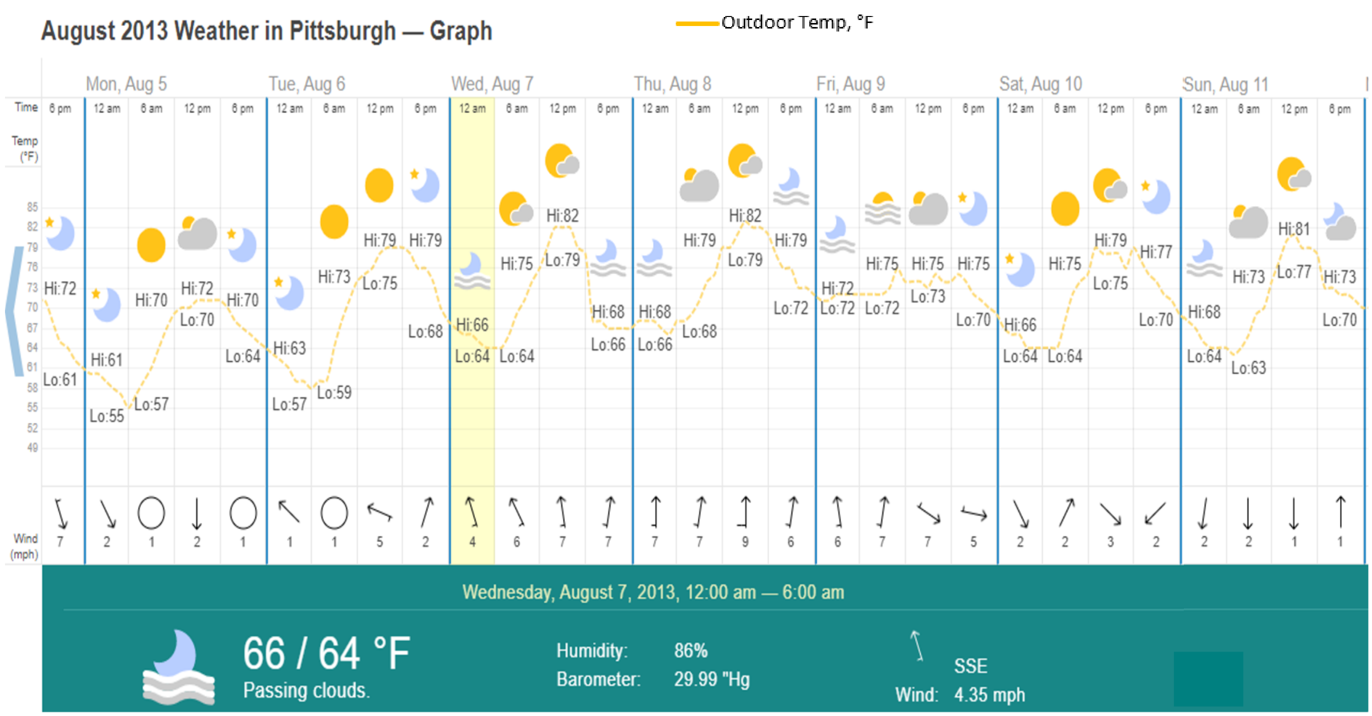


Figure 6.25 Pittsburgh historic weather chart, August 5-11, 2013 (timeanddate.com, 2020)

On August 6, 2013, at 5:20pm, the surface temperature on the control façade reached a high of 120.15°F (48.97°C), while the surface temperature on the living façade behind the plants reached a high of 83.20°F (28.44°C), a difference of 36.95°F (20.53°C), when the outside air temperature measured one meter (three feet) off the west façade reached a high temperature of 91.73°F (33.18°C). The indoor surface temperature at the control façade at 5:20 pm reached a high of 80.10°F (26.72°C), with an indoor air temperature of 81.15°F (27.31°C), while the indoor living façade surface temperature reached a high of 76.25°F (24.58°C), with indoor air temperature of 80.18°F (26.77°C), a difference of surface temperature between the living and control façades of 3.85°F (2.14°C), shown in Figure 6.27. Even on cooler days, such as August 9th, at 5:44pm, with a high outside air temperature of 78.77°F (25.98°C), the control façade warmed up rapidly to a high of 98.38°F (36.88°C), while the façade surface temperature behind the plants reached 77.95°F (25.53°C), a 20.43°F (11.35°C) differential.

A statistical analysis of this one week of continuous exterior façade surface temperature measurement (n=10,857) revealed that the living wall stayed 10-36.95°F (5.56-20.53°C) cooler than the control wall throughout a mixed partly sunny and partly cloudy summer week ($p<0.001$).

Internal surface temperatures were measured on the inside surface of the opaque portion of the living and control façades, as shown in Figure 6.26. The inside surface of the opaque portions of the living wall façade were at least 1-3.85°F cooler (0.55-2.14°C) than the control façade. While significant, these differentials are minimized by the mechanical conditioning system which is shared in the two test chambers. Nonetheless, the 10-36.95°F (5.56-20.53°C) differential in outdoor surface temperatures for the opaque panels of the living façade and the control façade would translate into measurable cooling energy savings.

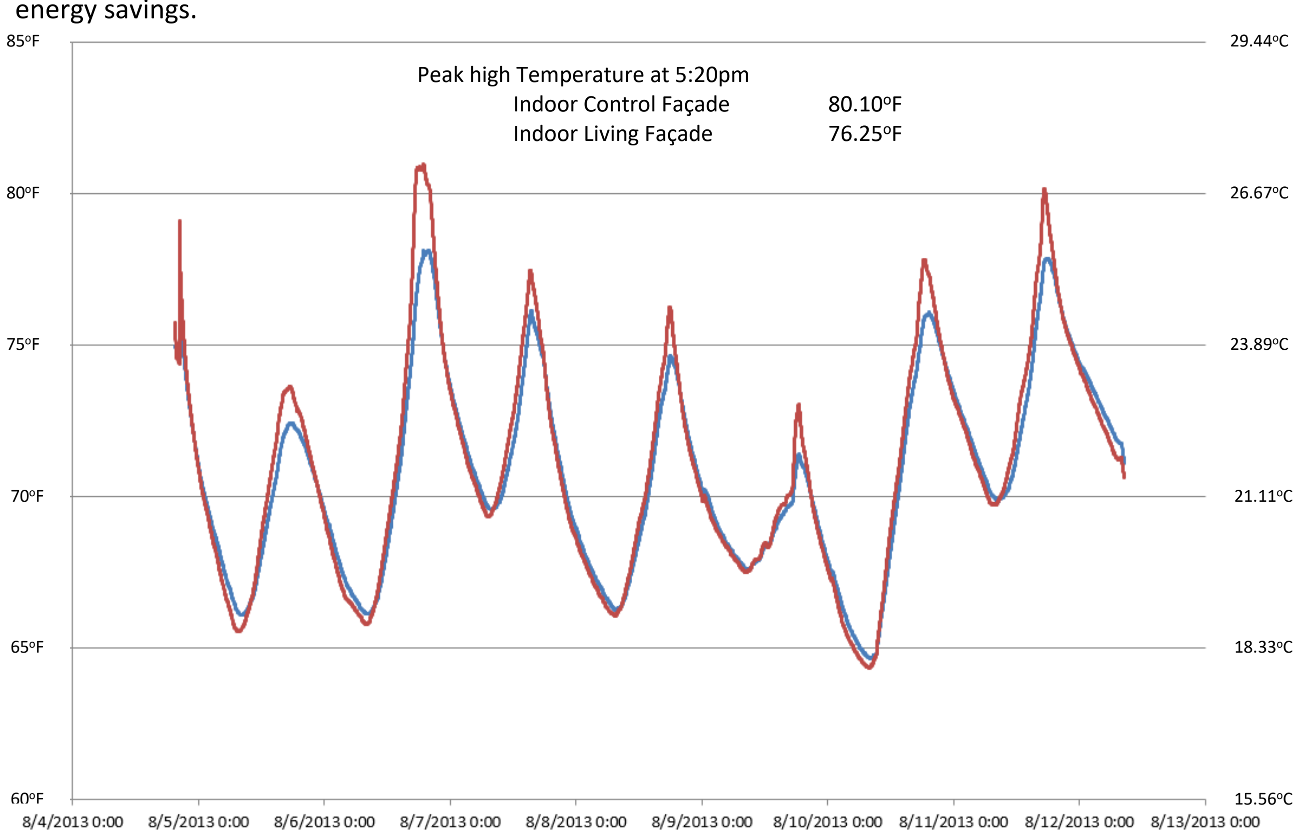


Figure 6.26 Interior Opaque Façade Surface Temperatures at the living and control façades, Aug. 5-11, 2013.

Researchers have documented façade surface temperature reductions of up to 27°F (15°C) due to Vertical Greenery Systems (VGS) compared to a control façade without greenery (Stec et. al., 2005; Wong, et. al., 2010; Perini, et. al., 2011; Fang, et. al., 2011). Researchers have also documented that reducing façade surface temperatures due to VGS can result in a 20% reduction in demand for cooling (Stec, et. al., 2005; Akbari et. al., 2001).

In a simplified static heat gain calculation shown below, the control façade has a peak 40°F delta temperature (22.2°C) between exterior and interior surface temperatures, while the living façade has a peak 7°F delta temperature (3.9°C) exterior to interior, as well as a slightly lower U value due to the addition of boxes filled with earth.

Simplified Peak Heat Gain Calculations for Comparative Analysis
Conductive heat gain calculations were performed for using the equation Q = U x A x ΔT, where:

U = value of transmittance
A = area of façade
ΔT = temperature differential between the interior and exterior façade surfaces

8/6/2013 5:20 pm	Control Façade Outside	120.15°F	ΔT = 40.054°F
	Control Façade Inside	80.096°F	
	Living Façade Outside	83.199°F	ΔT = 6.953°F
	Living Façade Inside	76.246°F	

The opaque façade of the Intelligent Workplace is a white insulated panel with aluminum facia and a thermal break. The effective U-value is a measured 0.06 Btu/hr-ft^2-°F (0.34 W/m^2-°C) equal to an R-value of 1/0.06 or 16.66 hr-ft^2-°F/Btu.

R-value of IW opaque façade panel is R 16.67;
R-value of inside air film is R 0.68;
R-value of outside air film is R 0.17;
Total R-value = 16.67+0.68+0.17 = 17.52; Total U-value = 1/17.52 = 0.057 Btu/hr-ft^2-°F

Q_{OC} = U x A x ΔT; **For Opaque Control Façade** ΔT = 120.15°F – 80.096°F = 40.054°F
Q_{OC} = 0.057 Btu/hr-ft^2-°F x (3'-1.5" x 5'-7.5") x 40.054°F
Q_{OC} = 0.057 Btu/hr-ft^2-°F x (3.125' x 5.625') x 40.054°F
Q_{OC} = 0.057 Btu/hr-ft^2-°F x (17.58ft^2) x 40.054°F = 40.13 Btu/hr

R-value of dirt is R-0.1875 avg. x 8 inches = 1.5 (1.125 or 25% of 1.5 will be used due to air gaps);
Total R-value = 16.67+1.125+0.68+0.17 = 18.65; Total U-value = 1/18.65 = 0.054 Btu/hr-ft^2-°F
Q_{OL} = U x A x ΔT; **For Opaque Living Façade** ΔT = 83.199°F – 76.246°F = 6.953°F
Q_{OL} = 0.054 x 17.58ft^2 x 6.953°F = 6.60 Btu/hr

The total peak heat transfer of 6.60 Btu/hr is an 83.55% reduction from 40.13 Btu/hr (representing a significant reduction in conductive heat gain at the moment of highest temperature of the day). Peak load reductions are critical for sizing of equipment and for managing electricity service in a warming climate.

Heat gain through the façade is vector driven, flowing from higher temperature to lower temperature. To capture the benefits of living walls on annual cooling loads, the length of each day's heat gain period was identified. The heat gain period was defined as when the exterior façade surface temperature was higher than the interior façade surface temperature at the living and control façades respectively.

Table 6.8 Opaque living and control façade heat gain and average ΔT calculations, Aug. 5-11, 2013.

Date	Façade	Length of Heat Gain Period	% Reduction Length of Heat Gain Period	Avg ΔT °F	% Reduction ΔT °F
8/5/2013	LF	0hr 27min	94.38%	0.84	79.21%
	CF	8hr 0min		4.22	
8/6/2013	LF	8hr 53min	16.46%	3.03	75.17%
	CF	10hr 38min		12.21	
8/7/2013	LF	8hr 49min	23.00%	3.37	55.15%
	CF	11hr 27min		7.52	
8/7/2013 pm to 8/10/2013 am	LF	50hr 32min		4.48	40.09%
	CF	47hr 42min	5.61%	7.47	
8/10/2013	LF	16hr 41min		2.74	67.76%
	CF	13hr 15min	20.58%	8.50	
8/11/2013	LF	7hr 17min	22.93%	3.17	63.72%
	CF	9hr 27min		8.76	

During the week of August 5-11, 2013, daily heat gain periods were identified for each façade. On August 5th the control façade had a heat gain period of 8 hours, while the living façade had almost no heat gain period, lasting only 27 minutes. This was a reduction of the heat gain period by 94.38%. Interestingly, this was on a day when the official high temperature was 72°F, and the high temperature measured one meter off the façade reached 78°F. On August 6, 7 and 11, the heat gain periods were reduced at the living façade by 16.46%, 23% and 22.93% respectively. Heat gain periods were shorter for the control façade than for the living façade on two occasions by 5.61% and 20.58%. These were when the heat gain periods went into overnight hours with a warm low temperature which allowed the control façade to cool off more quickly than the living façade. The average reduction in heat gain periods for this typical summer week in Pittsburgh was 21%. Capturing the length of heat gain periods helps to confirm the reductions in cooling loads identified by researchers completing controlled hot box experiments. During all heat gain periods the reduction in heat gain deltas on the FPLF was 40%-80%.

These peak and annual cooling load findings relate to introducing living walls in front of opaque portions of the façade. However, the food producing living façade was a hybrid panel and trellis system with vining plants extending above the opaque panels to cover the fixed vision glass areas in the Intelligent Workplace as well. In an equally warm week in September 2013, measurements of the exterior façade glass surface temperatures indicated that the vines from the living façade also reduced peak façade temperatures by 10°F (5.6°C) as shown in Figure 6.27. However, night-time radiant exchange from the glass surface to the clear sky, that might help reduce cooling loads, was only reduced by 1.5 °F (0.84 ° C) keeping glass surface temperatures at 52.5°F (11.4°C) while air temperatures where 50°F (10°C) and the HVAC systems were off. Weather conditions for the week are shown in Figure 6.28.

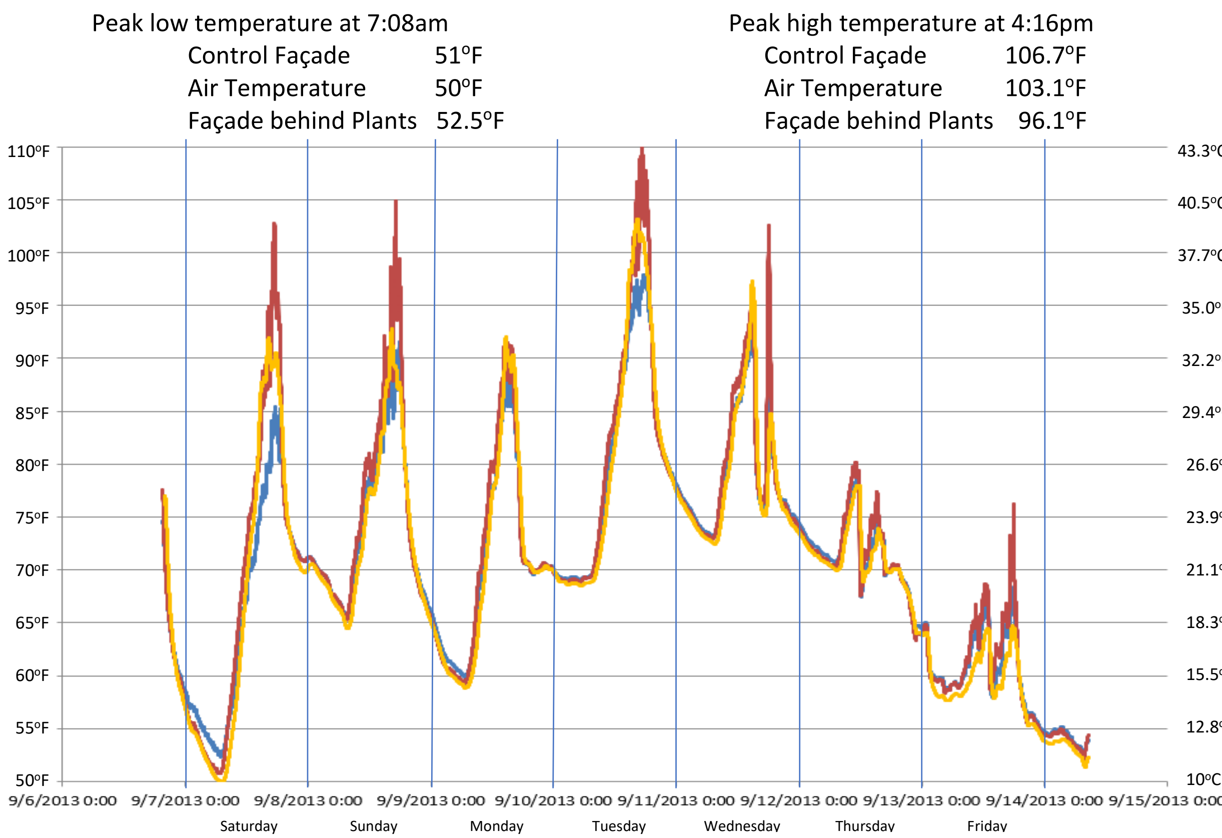


Figure 6.27 Exterior glazed façade surface temperatures, September 7-13, 2013.

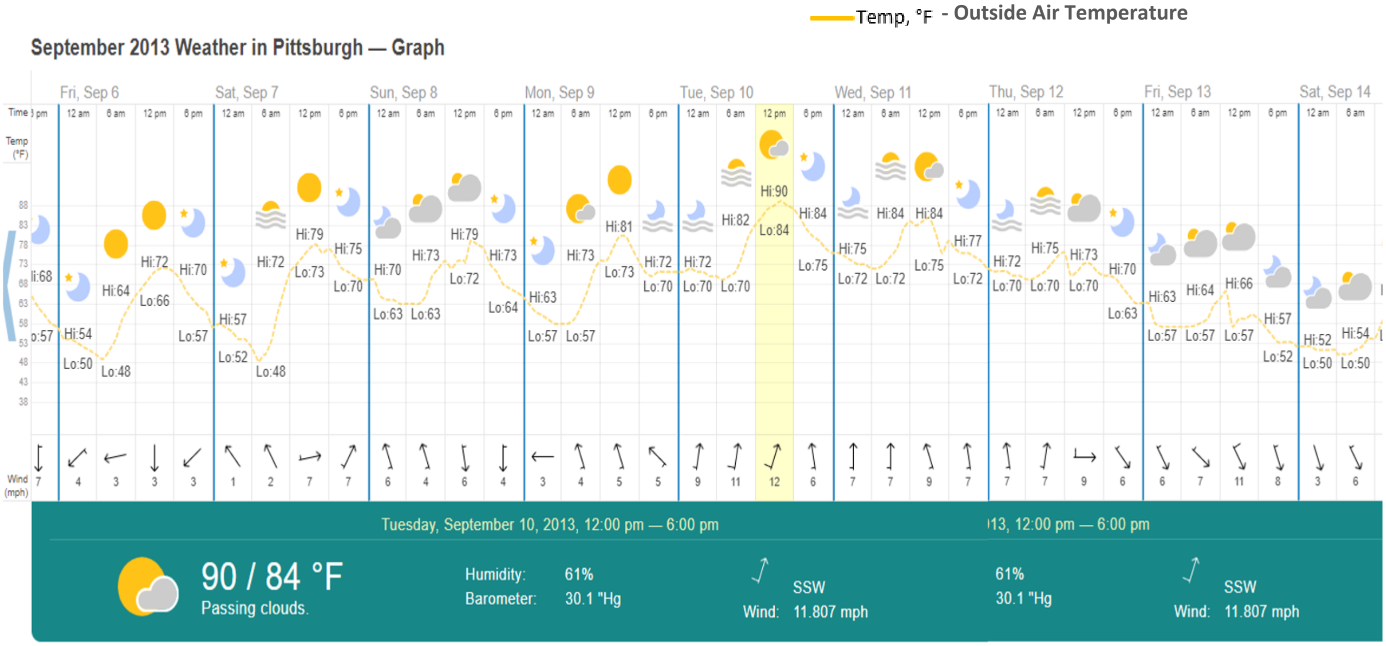


Figure 6.28 Record of Pittsburgh weather for the week of September 6 to 13, 2013 (timeanddate.com, 2020)

Internal surface temperatures were measured on the inside surface of the glazed portion of the living and control façades, as shown in Figure 6.29 below.

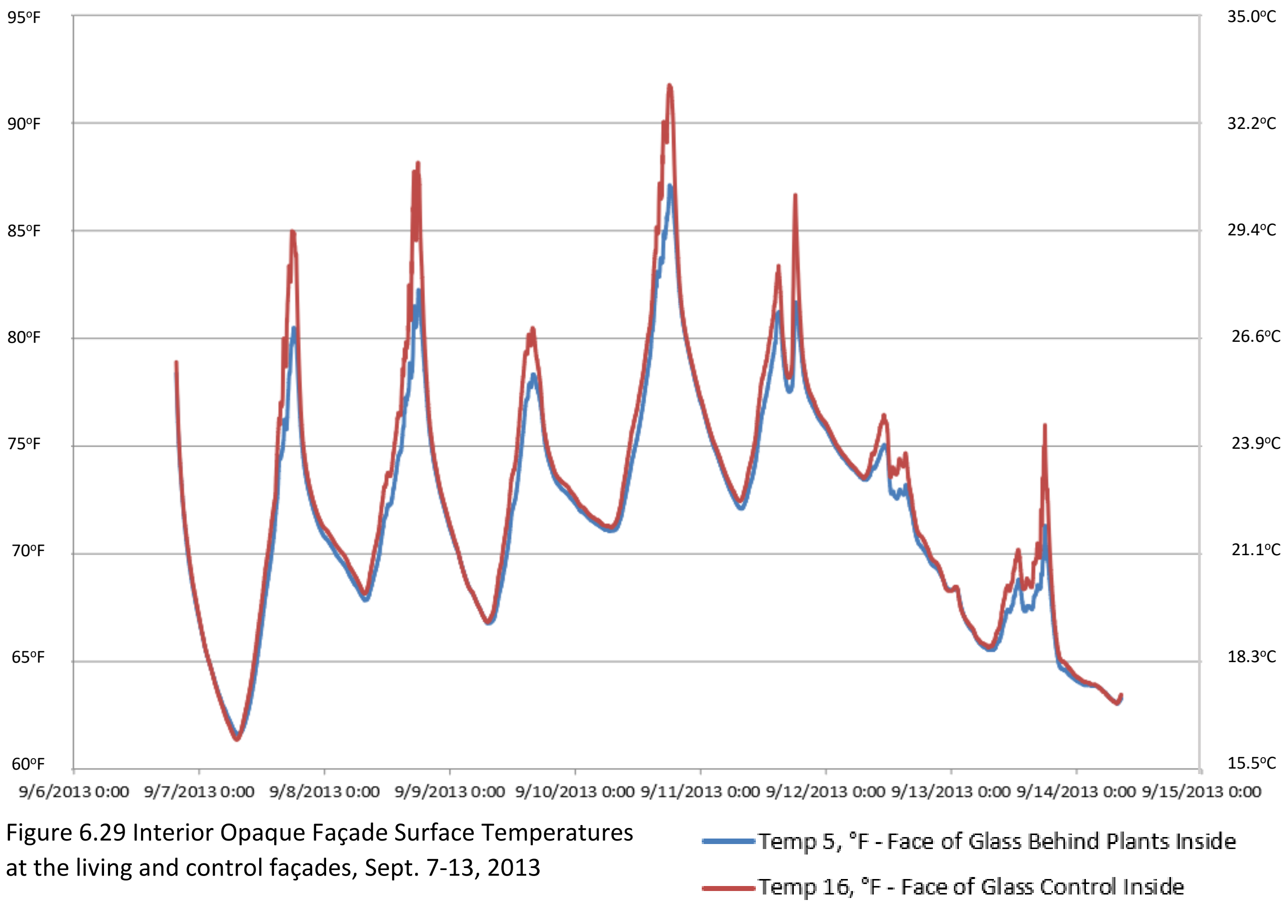


Figure 6.29 Interior Opaque Façade Surface Temperatures at the living and control façades, Sept. 7-13, 2013

The inside surface of the fixed glazed portions of living wall façade were at least 1-3ºF cooler (0.55-1.66ºC) than the control façade. While significant, these differentials are minimized by the mechanical conditioning system which is shared in the two test chambers.

The delayed onset of the temperature increase on the window glass behind the vines prevented the glass surface from heating up as rapidly and delayed the decrease in surface temperature of the glass when compared to the control façade as the air temperature dropped. This illustrates the benefit of the plants in dampening the severity of temperature swings.

On warm days, reducing the temperature differentials between the exterior and interior surface of the building façade will reduce conductive heat gain, and therefore peak and total cooling load. To quantify the impact on total cooling load, the average temperature differential between the exterior and interior surface of the glazing at the living façade behind the plants was compared to the exterior and interior surface of the glazing at the control façade. This illustrates the magnitude of the potential for heat gain reduction, and therefore the potential for peak and total cooling load reduction, from the glass area itself, inclusive of improved shading coefficients.

As with the measured opaque façade data above, the glazed façade surface conductive peak heat gain calculations can be illustrated by the peak temperature differential between interior and exterior glazed surfaces in the control façade and the living façade.

9/10/2013 4:16 pm	Control Façade Outside	106.7°F	$\Delta T = 19.8^{\circ}F$
	Control Façade Inside	86.9°F	
	Living Façade Outside	96.1°F	$\Delta T = 12.5^{\circ}F$
	Living Façade Inside	83.6°F	

The glazing assembly of the Intelligent Workplace, for reference, is a double glazed, low-e, argon gas filled system with thermally broken frames (with 0.64 visible transmission and 0.34 SHGC). The effective U-value is a measured 0.29 Btu/hr-ft^2-$^{\circ}$F (1.65 W/m^2-$^{\circ}$C) equal to an R-value of 3.45 hr-ft^2-$^{\circ}$F/Btu. It was assumed that the insulating value of the plant vines was low and considered negligible, so the same calculation was used for the Living Façade (LF) and the Control Façade (CF). A 34.90% reduction in peak conductive heat gain through the glazed façade areas, was calculated based on the recorded surface temperatures of the day, with vines providing dappled shade in front of the living façade glazing. Heat gain periods were identified, defined as when the exterior surface of the glazing became higher in temperature than the interior surface (Table 6.9). This allowed for a comparison of the average temperature differential over a six day period of warm temperatures. When nighttime cooling hours are factored in, an average of 3.4% effective reduction in heat gain periods was recorded for the glazed areas of the living façade, with an average of 10% effective reduction in ΔT.

Table 6.9 Glazed living and control façade heat gain and average ΔT calculations, Sept. 7-13, 2013.

Date	Façade	Length of Heat Gain Period	% Reduction Length of Heat Gain Period	Avg ΔT $^{\circ}$F	% Reduction ΔT $^{\circ}$F
9/7/2013 Daytime	LF	8hr 59min		2.69	66.22%
	CF	8hr 46min	2.41%	7.96	
Late 9/7/2013 Early 9/8/2013	LF	2hr 1min		0.34	
	CF	0hr 36min	70.25%	0.07	78.56%
9/8/2013 Daytime	LF	10hr 42min		5.74	17.62%
	CF	9hr 46min	8.72%	6.96	
9/9/2013 Daytime	LF	8hr 1min	0.21%	5.84	5.49%
	CF	8hr 2min		6.18	
9/10/2013 thru 9/11/2013	LF	30hr 59min		5.40	8.65%
	CF	19hr 24min 10hr 25 min	3.77%	5.91	
9/11/2013 Evening	LF	1hr 33min		2.97	57.75%
	CF	1hr 17min	17.20%	7.02	
9/12/2013 Morning	LF	3hr 5min	0.54%	2.20	1.66%
	CF	3hr 6min		2.23	
9/12/2013 Afternoon	LF	1hr 44min	27.27%	1.12	
	CF	0hr 20min 2hr 3min		0.83	26.08%
9/12/2013 Evening	LF	0hr 45min		0.20	
	CF	0hr 13min	71.11%	0.12	36.59%

During the week of September 7-13, 2013, nine different heat gain periods were identified, of differing durations, for each façade. The first one on September 7th shows a typical or expected pattern where the day warmed up over a relatively long period of time, nearly 9 hours for both the living and control, and then cools down. The living façade had a slightly longer heat gain period, lasting 13 minutes or 2.41% longer than the control façade. Even with a slightly longer heat giant period, the average ΔT for the living façade was 2.69°F compared to 7.96°F for the control, a reduction of 66.22%. This reduction in average temperature differential due to the living façade, over a nearly identical length of time, indicates the potential cooling load reduction implications at the façade glazing.

A second heat gain period of very short duration occurred during the overnight hours of September 7th to 8th. The glazing behind the living façade cooled down more slowly than the control façade glazing, therefore when there was a subtle increase in the outside air temperature after midnight, the heat gain period for the living façade was just over two hours, but only 37 minutes for the control façade, a reduction of 70.25%. The remaining seven heat gain periods are of nearly identical duration, with three of those being shorter at the living façade and four being shorter at the control façade. The average temperature differential was reduced at the living façade for the first five of those seven heat gain periods. This variability in the length of heat gain and average temperature differential reduction between the living and control façades is due to the relatively quick cool down of the exterior glazing as the temperature falls, and the dual temperature spikes on the last two days of the week, September 11th and 12th.

These simplified calculations of the conductive heat gain at the opaque and glazed façade areas during the peak heat of the day have direct implication for cooling load savings. Peak heat gain reductions of 85.33% at the opaque façade in August and 34.90% at the glazed façade in September illustrates the potential cooling benefit of food producing living façade applications on a west facing façade during the summer period in Pittsburgh. The impact of food producing living façades for reducing annual load contributions is an average of 21% for opaque façade areas and 3.4% for glazed façade areas. A lag effect is also indicated in the living façade data that illustrates a reduction in the rate of heat gain during the day and heat loss at night, increasing the length of time that the living façade stays within the thermal comfort zone, between 68-78°F, as compared to the control façade.

Building A Typical Temperature Profile for Food Producing Living Façades

To better understand the cooling load reduction potential of food producing living façade applications in temperate continental regions similar to Pittsburgh, the measured surface temperature data was averaged hourly for the opaque and glazed door façades using the August data, and for the opaque and glazed façade areas using the September data.

Typical Day Opaque Façade Comparison - August

West façade surface temperatures taken at the white aluminum opaque panels and outside air temperature were measured every minute from August 5-11, 2013, and then averaged hourly as shown in Table 6.10. The comparison of the food producing living façade and control façade opaque surface temperature measurements contrasted with the outside air temperature measured one meter off the façade, indicate when the living façade is warmer than the control façade (shown in red) and cooler than the control façade (shown in green). The red indicates where night and early morning sky radiant heat loss is being retarded by the living façade, and green indicates where heat gain is being reduced. The p-values for each hourly average comparison indicate statistical significance of these results for each hour of the "typical day", where n=420 per hour.

Table 6.10 Average Hourly Exterior Opaque West Façade Surface Temperatures and Outside Air Temperature for a "Typical Day" in August (average of 7 days of data measured from August 5-11, 2013).

Typical Day August	Exterior Opaque Living Façade	Exterior Opaque Control Façade	Outside Air Temp	p-value
12-1am	68.31	67.09	67.91	<0.001 Significant
1-2am	67.59	66.03	67.13	<0.001 Significant
2-3am	66.79	64.96	66.38	<0.001 Significant
3-4am	66.27	64.49	65.74	<0.001 Significant
4-5am	66.02	64.44	65.46	<0.001 Significant
5-6am	65.64	64.01	65.17	<0.001 Significant
6-7am	65.39	63.84	64.84	<0.001 Significant
7-8am	65.66	65.02	64.94	P=0.05 Significant
8-9am	66.43	67.41	65.96	<0.001 Significant
9-10am	67.73	70.17	67.61	<0.001 Significant
10-11am	69.44	73.17	69.76	<0.001 Significant
11-12pm	71.34	76.57	72.16	<0.001 Significant
12-1pm	72.67	78.13	74.09	<0.001 Significant
1-2pm	74.28	80.95	75.82	<0.001 Significant
2-3pm	76.13	84.17	78.46	<0.001 Significant
3-4pm	77.93	87.11	82.56	<0.001 Significant
4-5pm	78.20	89.34	81.91	<0.001 Significant
5-6pm	78.67	91.84	83.26	<0.001 Significant
6-7pm	76.66	83.90	80.02	<0.001 Significant
7-8pm	74.92	79.63	76.96	<0.001 Significant
8-9pm	73.23	74.71	74.68	<0.001 Significant
9-10pm	71.68	72.04	72.47	<0.001 Significant
10-11pm	70.79	70.38	70.99	<0.001 Significant
11-12am	70.11	69.31	69.90	<0.001 Significant

Figure 6.30 shows the hourly averages graphed with the area of significance highlighted in yellow, showing the living façade cooler than both the control façade and the outside air temperature. The boxplots shown in Figure 6.31 illustrate the range of temperatures every four hours over the course of the "Typical Day", using the data measured over the week of August 5-11, 2013. An averaged "Typical Day" reveals that the living façade never exceeds the comfort zone limit of 25.6°C (78°F) as shown in Figure 6.30. The yellow area shows the period of time that the control façade is hotter than the living façade. The control façade exceeds the comfort zone from 1 to 8pm. The living façade is cooler than the outside air from approximately 10am to 10pm. To further profile thermal performance for typical August days in Pittsburgh, box plots of statistically significant façade surface temperatures and outside air temperatures are shown for six one hour periods, see Figure 6.31.

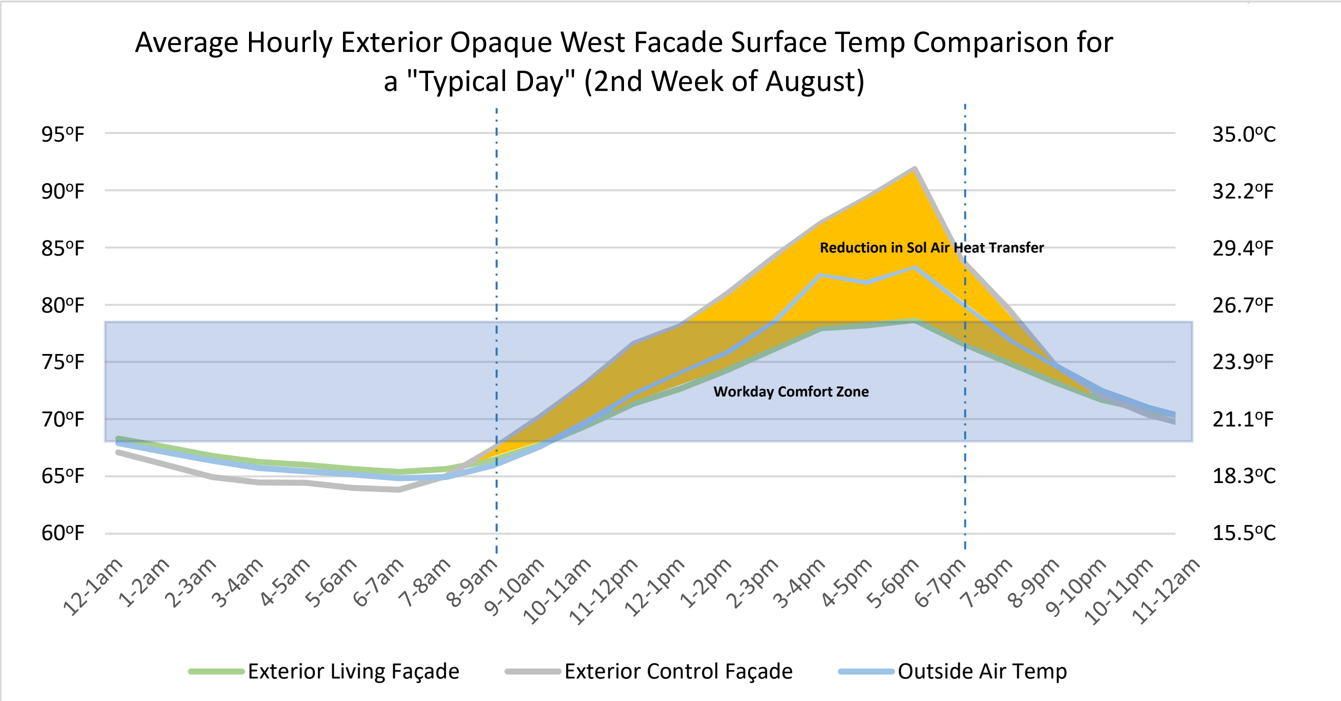


Figure 6.30 Average Hourly Exterior Opaque West Façade Surface Temperatures and Outside Air Temperature for a "Typical Day" in August (average of 7 days of data measured from August 5-11, 2013).

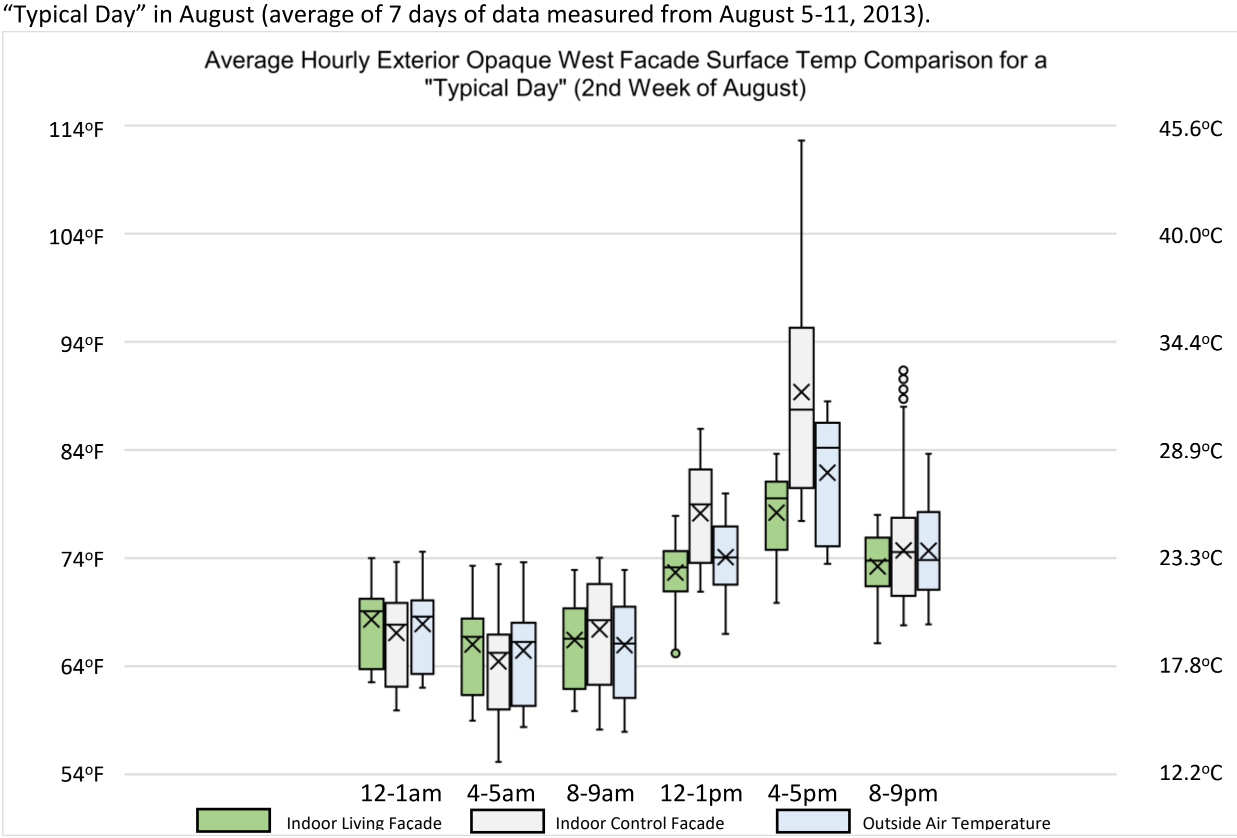


Figure 6.31 Average Hourly Exterior Opaque West Façade Surface Temperatures and Outside Air Temperature Comparison Boxplots for a "Typical Day" in August (average of 7 days of data measured from August 5-11, 2013).

Food producing living façades have 4.56°C (8.2°F) lower temperatures during the hottest hour from 4-5 pm ($p<0.001$). Food producing living façades have 3.11°C (5.6°F) lower temperatures during the noon hour from 12-1 pm ($p<0.001$). During the remaining hours, the deltas are less dramatic but still significant, while 12-1am and 4-5am hours reveal cooler temperatures on the control façade. Soil-based living façade panels with food producing plants on opaque building façades keep typical August summer day surface temperatures at or below air temperatures as compared to a 0.36-13.17°F (0.2-7.31°C) rise in surface temperatures on conventional light colored building façades, contributing to cooling loads during the daytime hours. Applications on dark façades would provide an even greater benefit.

Typical Day Glazed Door Façade Comparison - August

Hourly average glazed door surface temperature measurements and outside air temperature measured one meter off the façade, shown in Table 6.11, indicate when the living façade is warmer than the control (shown in red) and cooler than the control (shown in green). P-values indicate statistical significance from 10-3pm and 5-6pm, n=420 per hour. Figures 6.32 and 6.33 show the "typical day" graph and boxplots. Both façades exceed the comfort zone from 10am to 8pm, with the living façade performing slightly cooler than the control façade.

Table 6.11 Average Hourly Exterior Glazed Door West Façade Surface Temperatures and Outside Air Temperature for a "Typical Day" in August (average of 7 days of data measured from August 5-11, 2013).

Typical Day August	Exterior Glazed Door Living Façade	Exterior Glazed Door Control Façade	Outside Air Temp	p-value
12-1am	67.70	67.38	67.91	0.228 Not Significant
1-2am	66.73	66.38	67.13	0.203 Not Significant
2-3am	65.72	65.35	66.38	0.240 Not Significant
3-4am	65.13	64.83	65.74	0.370 Not Significant
4-5am	65.03	64.77	65.46	0.438 Not Significant
5-6am	64.68	64.38	65.17	0.3943 Not Significant
6-7am	64.41	64.19	64.84	0.5434 Not Significant
7-8am	65.46	65.53	64.94	0.829 Not Significant
8-9am	68.04	68.37	65.96	0.276 Not Significant
9-10am	71.09	71.61	67.61	0.066 Not Significant
10-11am	74.26	75.00	69.76	P=0.006 Significant
11-12pm	77.62	78.58	72.16	<.001 Significant
12-1pm	79.18	80.06	74.09	P=0.004 Significant
1-2pm	81.55	82.80	75.82	<0.001 Significant
2-3pm	84.11	85.34	78.46	<0.001 Significant
3-4pm	87.95	88.10	82.56	0.719 Not Significant
4-5pm	89.02	89.73	81.91	0.203 Not Significant
5-6pm	90.49	92.38	83.26	P=0.0010 Significant
6-7pm	84.11	85.05	80.52	0.124 Not Significant
7-8pm	80.72	81.33	76.96	0.279 Not Significant
8-9pm	76.12	75.73	74.68	0.330 Not Significant
9-10pm	72.49	72.20	72.47	0.170 Not Significant
10-11pm	70.85	70.55	70.99	0.142 Not Significant
11-12am	69.79	69.51	69.90	0.175 Not Significant

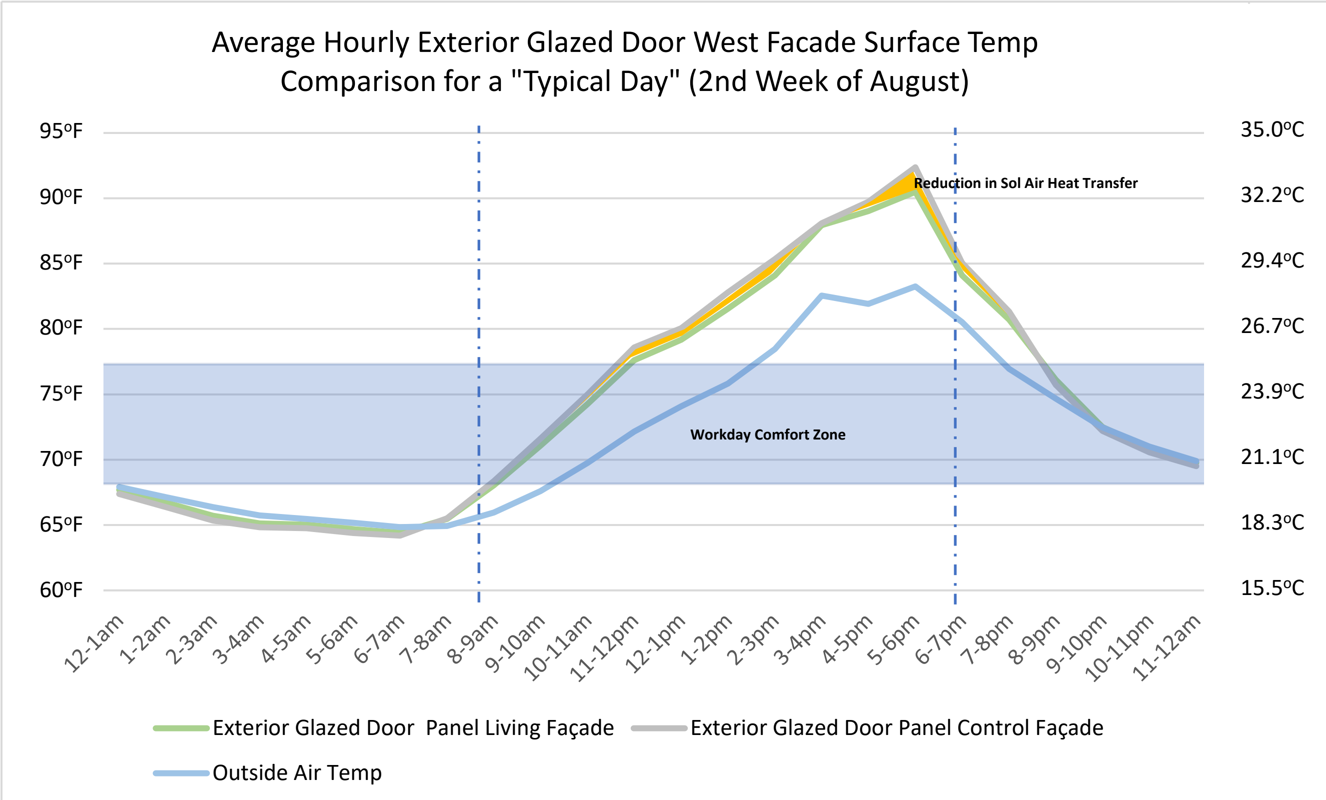


Figure 6.32 Average Hourly Exterior Glazed Door West Façade Surface Temperatures and Outside Air Temperature for a “Typical Day” in August (average of 7 days of data measured from August 5-11, 2013).

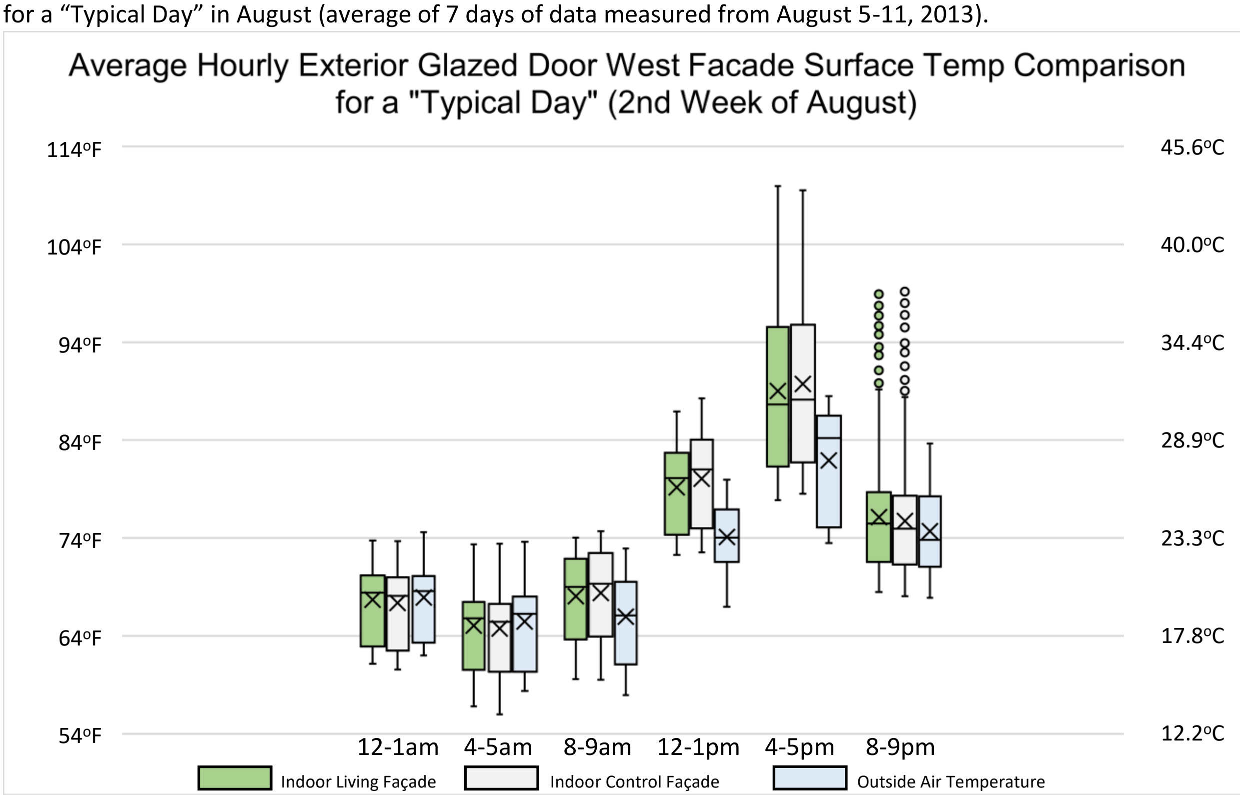


Figure 6.33 Average Hourly Exterior Glazed Door West Façade Surface Temperatures and Outside Air Temperature Comparison Boxplots for a “Typical Day” in August (average of 7 days of data measured from August 5-11, 2013).

FPLF plant vines covering glazed façade doors keep typical summer day glazed surface temperatures at or below glazed door control façade surface temperatures by 0.61-1.89°F (0.31-1.04°C) during the daytime hours.

Typical Day Opaque Façade Comparison - September

Hourly average opaque surface temperature measurements, contrasted with the outside air temperature measured one meter off the façade, shown in Table 6.12, indicate when the living façade is warmer than the control façade (shown in red) and cooler than the control façade (shown in green). P-values indicate statistical significance every hour of the day except from 8-9am and 8pm-12am, where n=420 per hour. Figures 6.34 and 6.35 show the "typical day" graph and boxplots; similar to August.

Table 6.12 Average Hourly Exterior Opaque West Façade Surface Temperatures and Outside Air Temperature for a "Typical Day" in September (average of 7 days of data measured from September 7-13, 2013).

Typical Day September	Exterior Opaque Living Façade	Exterior Opaque Control Façade	Outside Air Temp	p-value
12-1am	68.59	67.75	67.80	P=0.047 Significant
1-2am	67.55	66.41	66.70	P=0.011 Significant
2-3am	66.84	65.57	65.56	P=0.007 Significant
3-4am	66.34	65.00	64.88	P=0.006 Significant
4-5am	65.76	64.28	64.32	P=0.003 Significant
5-6am	65.34	63.97	63.82	P=0.006 Significant
6-7am	65.06	63.71	63.59	P=0.007 Significant
7-8am	65.03	63.98	63.39	P=0.032 Significant
8-9am	65.80	66.67	64.74	0.070 Not Significant
9-10am	67.22	69.86	67.75	<0.001 Significant
10-11am	69.16	73.02	70.90	<0.001 Significant
11-12pm	70.89	75.50	74.43	<0.001 Significant
12-1pm	71.52	76.48	75.91	<0.001 Significant
1-2pm	72.43	78.47	77.76	<0.001 Significant
2-3pm	74.16	81.47	82.15	<0.001 Significant
3-4pm	74.92	82.15	83.91	<0.001 Significant
4-5pm	74.86	83.21	83.04	<0.001 Significant
5-6pm	74.63	85.67	80.84	<0.001 Significant
6-7pm	73.63	80.69	79.20	<0.001 Significant
7-8pm	71.45	73.62	74.76	<0.001 Significant
8-9pm	70.25	71.03	71.45	0.124 Not Significant
9-10pm	69.55	69.93	70.02	0.431 Not Significant
10-11pm	68.88	68.64	68.87	0.622 Not Significant
11-12am	68.33	67.99	67.98	0.487 Not Significant

An averaged "Typical Day" reveals that the living façade never exceeds the comfort zone limit of 25.6°C (78°F) as shown in Figure 6.34. The yellow area shows the period of time that the control façade is hotter than the living façade. The control façade exceeds the comfort zone from 1 to 6:30pm. The living façade is cooler than the outside air from approximately 8:30am to 10pm. To further profile thermal performance for typical September days in Pittsburgh, box plots of statistically significant façade surface temperatures and outside air temperatures are shown for six one hour periods, see Figure 6.35.

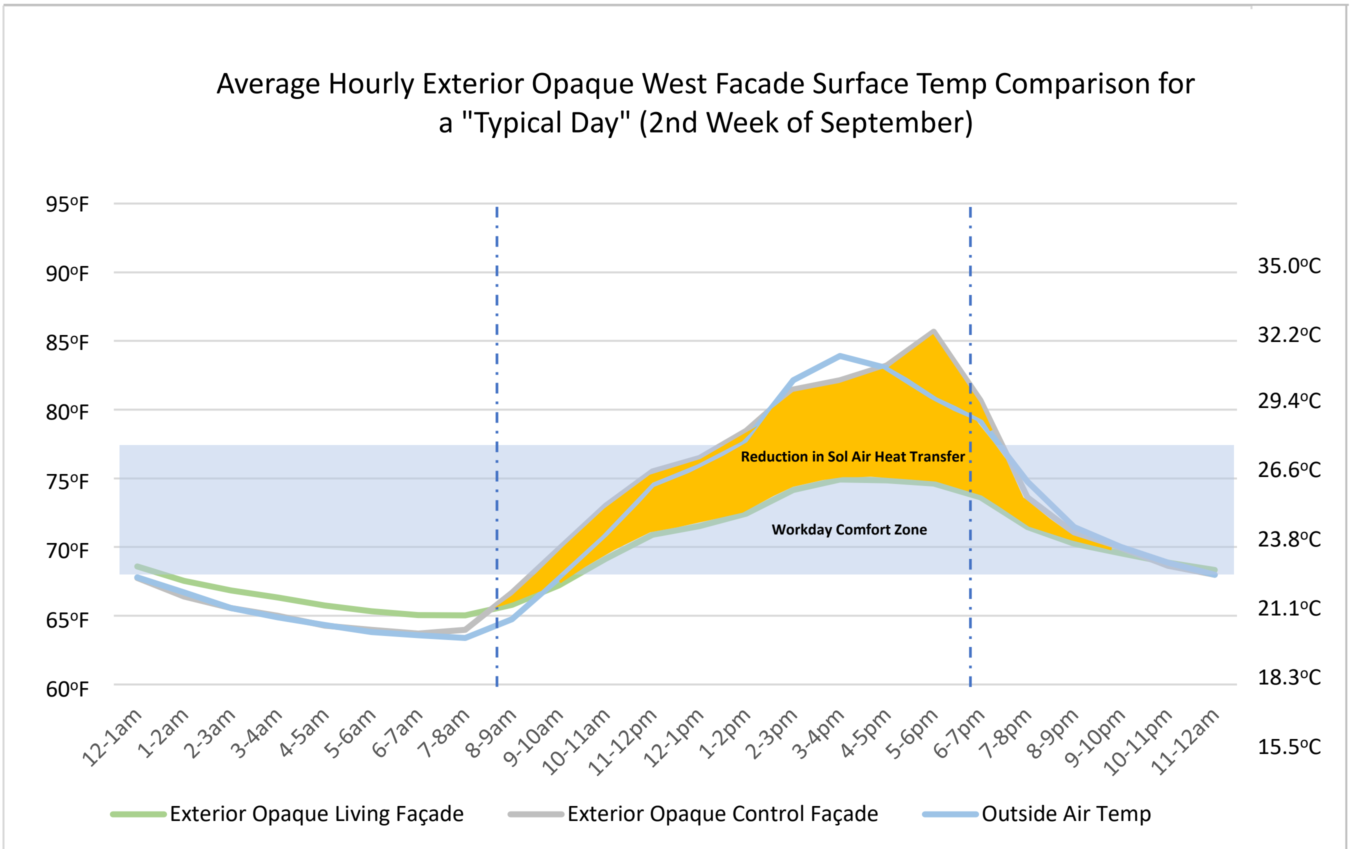


Figure 6.34 Average Hourly Exterior Opaque West Façade Surface Temperatures and Outside Air Temperature for "Typical Day" in September (average of 7 days of data measured from September 7-13, 2013).

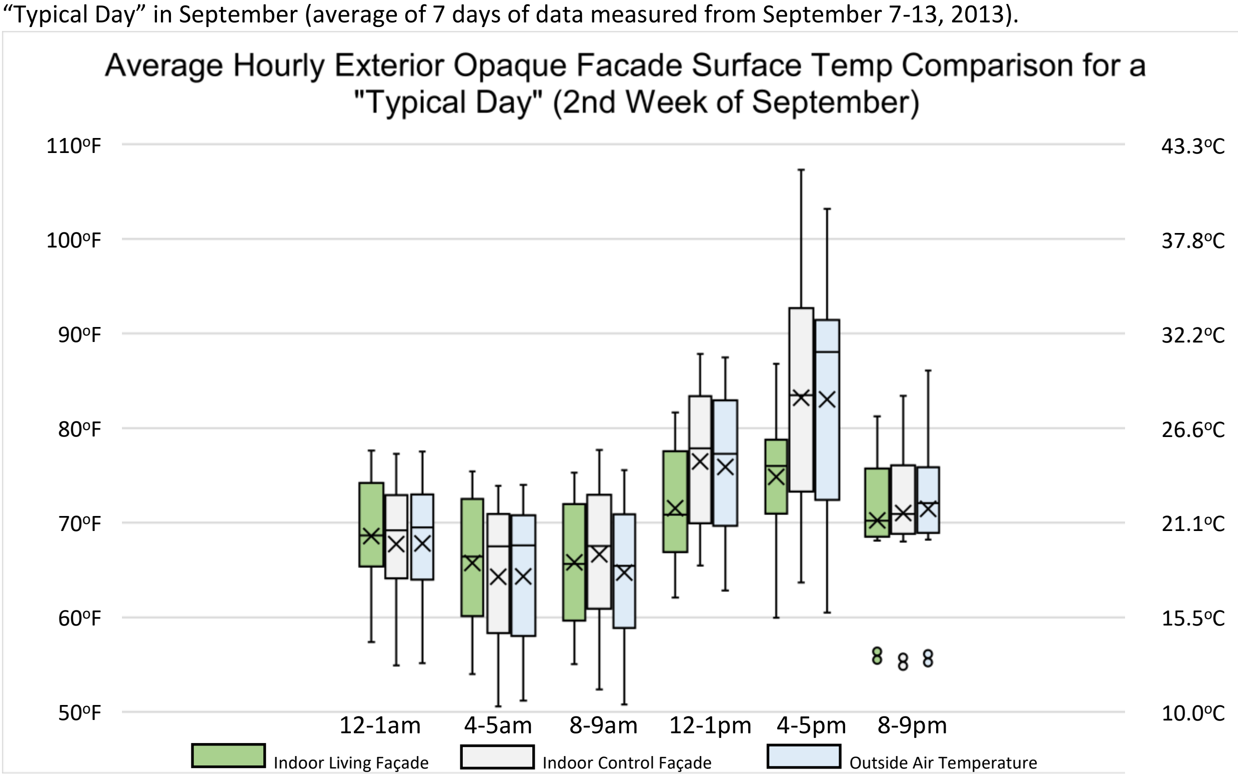


Figure 6.35 Average Hourly Exterior Opaque West Façade Surface Temperatures and Outside Air Temperature Comparison Boxplots for a "Typical Day" in September (average of 7 days of data measured from Sept. 7-13, 2013).

The introduction of soil-based living façade panels with food producing plants on opaque building façades keeps typical September summer day surface temperatures at or below air temperatures. This is compared to a 0.38-11.04°F (0.21-6.14°C) rise in surface temperatures on conventional light colored building façades which contributes to cooling loads during the daytime hours.

Glazed West Façade with and without Living Façade September

Hourly average glazed surface temperature measurements mirror the findings of August, indicating that the glazed areas of the living façade are slightly warmer than the unshaded glazed areas at night (shown in red, but without statistical significance) and cooler during the day (shown in green with statistical significance). P-values indicate statistical significance from 9am-7pm, where n=420 per hour. Figures 6.36 and 6.37 show the "typical day" graph and boxplots.

Table 6.13 Average Hourly Exterior Glazed Façade Surface Temperatures and Outside Air Temperature for a "Typical Day" in September (average of 7 days of data measured from September 7-13, 2013).

Typical Day September	Exterior Glazed Living Façade	Exterior Glazed Control Façade	Outside Air Temp	p-value
12-1am	68.59	68.10	67.80	0.259 Not Significant
1-2am	67.37	66.76	66.70	0.179 Not Significant
2-3am	66.48	65.93	65.56	0.249 Not Significant
3-4am	65.96	65.41	64.88	0.262 Not Significant
4-5am	65.32	64.70	64.32	0.203 Not Significant
5-6am	64.88	64.36	63.82	0.291 Not Significant
6-7am	64.60	64.09	63.59	0.292 Not Significant
7-8am	64.65	64.44	63.39	0.657 Not Significant
8-9am	66.80	67.44	64.74	0.179 Not Significant
9-10am	69.77	71.10	67.75	<0.001 Significant
10-11am	72.94	74.79	70.90	<0.001 Significant
11-12pm	75.47	77.34	74.43	<0.001 Significant
12-1pm	76.06	78.02	75.91	<0.001 Significant
1-2pm	77.39	79.93	77.76	<0.001 Significant
2-3pm	79.99	82.97	82.15	<0.001 Significant
3-4pm	80.75	84.07	83.91	<0.001 Significant
4-5pm	79.74	83.92	83.04	<0.001 Significant
5-6pm	80.15	85.75	80.84	<0.001 Significant
6-7pm	78.72	82.12	79.20	<0.001 Significant
7-8pm	74.06	73.83	74.76	0.696 Not Significant
8-9pm	71.47	71.16	71.45	0.552 Not Significant
9-10pm	70.47	70.15	70.02	0.518 Not Significant
10-11pm	69.35	68.96	68.87	0.430 Not Significant
11-12am	68.66	68.32	67.98	0.497 Not Significant

An averaged "Typical Day" reveals that the living façade exceeds the comfort zone limit of 25.6°C (78°F), from 1 to 6pm, and is cooler than the outside air for approximately the same time as shown in Figure 6.36. The yellow area shows the period of time that the control façade is hotter than the living façade. The control façade exceeds the comfort zone from 11am to 6:30pm. Box plots of façade surface temperatures and outside air temperatures are shown for six one hour periods in Figure 6.37.

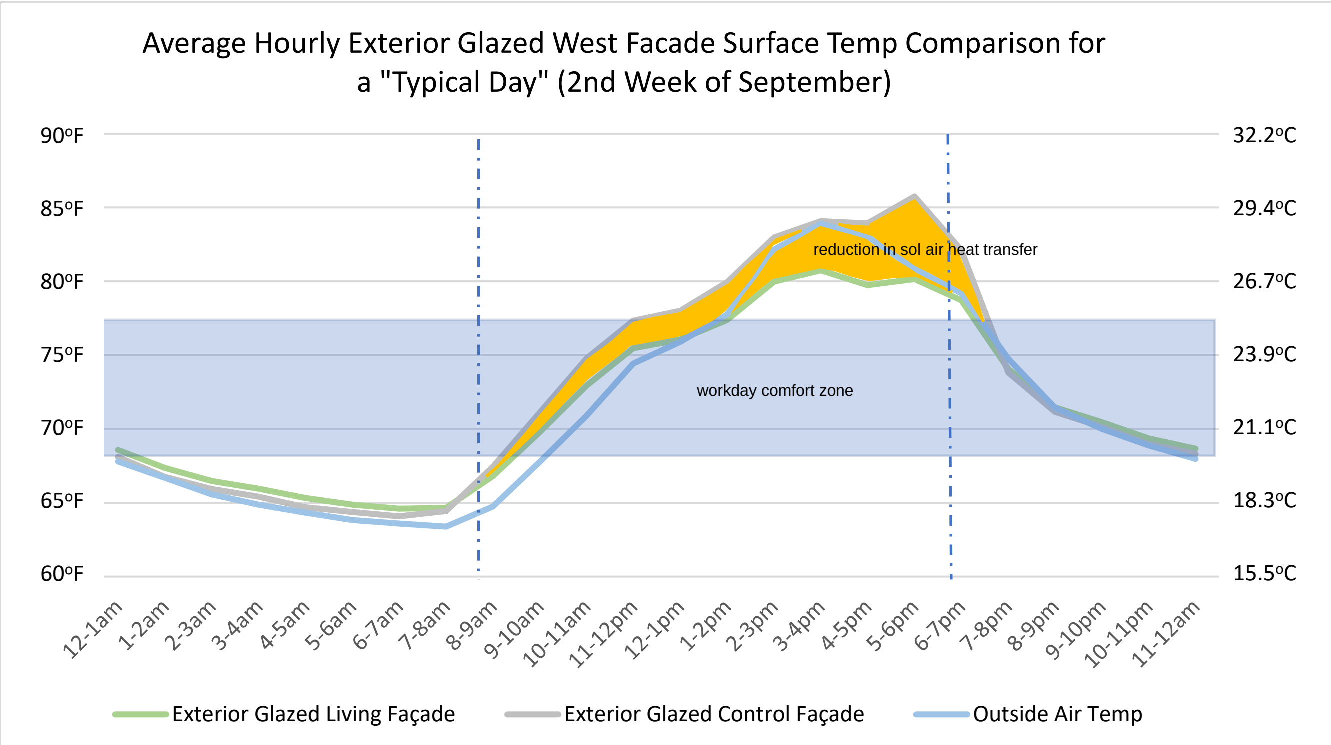


Figure 6.36 Average Hourly Exterior Glazed Façade Surface Temperatures and Outside Air Temperature for a "Typical Day" in September (average of 7 days of data measured from September 7-13, 2013).

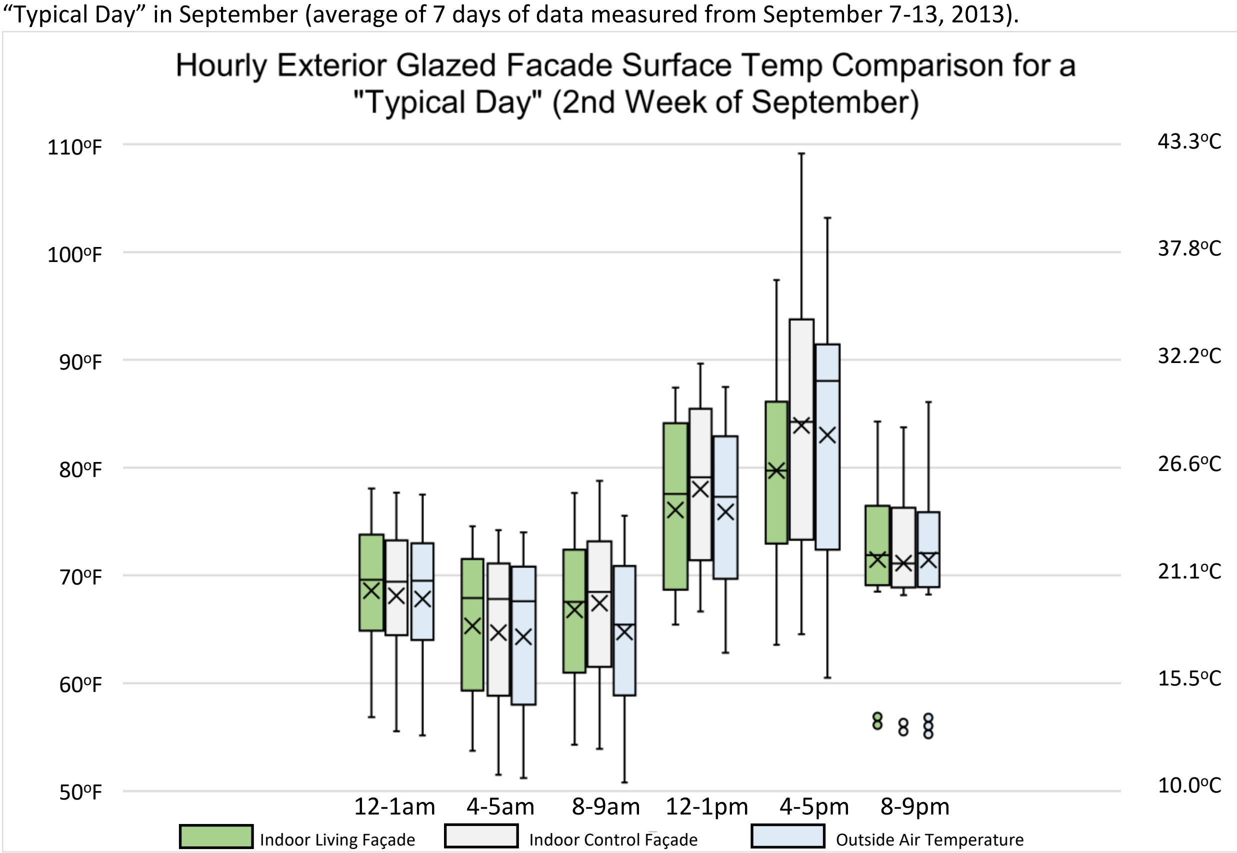


Figure 6.37 Average Hourly Exterior Glazed West Façade Surface Temperatures and Outside Air Temperature Comparison Boxplots for a "Typical Day" in September (average of 7 days of data measured from Sept. 7-13, 2013).

FPLF's with vines extending to cover glazed façade areas keep typical summer day glazed surface temperatures at or below glazed control façade surface temperatures by 0.64-5.6^{o}F (0.36-3.11^{o}C) during the daytime hours.

The hourly average temperature data compressed from the second week of August and the second week of September shows a progression of benefit. The most significant façade surface temperature reduction benefit was at the opaque façade in both August and September. The food producing living façade hourly average surface temperature reduction at the opaque façade in August was up to 13.17^{o}F (7.31^{o}C) and in September it was up to 11.04^{o}F (6.14^{o}C). The next most significant benefit was shown in the data recorded at the glazed façade areas measured in September, showing a surface temperature reduction of up to 5.6^{o}F (3.11^{o}C). The least significant benefit was shown in the data recorded at the glazed door façade areas measured in August, showing a surface temperature reduction of up to 1.89^{o}F (1.04^{o}C).

The surface temperature reduction benefit due to the food producing living façade is the most significant at the opaque façade due to the soil and plant panels, which provide additional thermal mass in the soil and irrigation water, as well as additional evaporative cooling due to evapotranspiration by the plants. The shading and evaporative cooling effects were beyond the limitations of this study, and therefore not measured, but should be the focus of future research.

The benefit of a food producing living façade to shade glazed façade areas could be enhanced by increasing leaf area coverage, see Figures 6.38-6.41. The glazed door panel has nearly twice as much glass area as the glazed vision panel, and with the glass surface heating up more significantly than the opaque white aluminum façade panel, as shown in Figures 6.38 and 6.39, the glazed door panel generated the least significant surface temperature reduction benefit. Maximizing vine coverage at the glazing was not the focus of this study, but additional research in this area, including understanding the dynamic effects of bio-shading, should be pursued.

Figure 6.38 Fixed Glazed Panel Living Façade

Figure 6.39 Glazed Door Panel Living Façade

Figure 6.40 Glazed Transom Panel Living Facade

Figure 6.41 Close up of Plants at base of Glazed Door Panel

The infrared photographs from August 2013, Figures 6.42 and 6.43 clearly indicate how the façade glazing is hotter than the white aluminum façade panels at the west facing control façade, by about 20°F (11.11°C). A more detailed analysis of surface temperature comparisons of the food producing living façade to the control façade using infra-red photography is contained in Section 6.2.2.

Figure 6.42 West Facing Control Façade opaque and glazed façade.

Figure 6.43 Infra-red photo indicating the glazing is approximately 20°F (11.11°C) hotter than the adjacednt white aluminum façade panel.

6.2.2 Infrared Thermal Imaging Analysis of Façade Temperatures

The thermal performance of the food producing living façade was also captured through thermal imaging photography using an advanced FLIR infra-red camera. Thermal imaging helps visualize the temperature differences between the plants on the living façade and the control façade at both the opaque and glazed façade panels, as documented by the façade temperature sensor data reviewed above. The FLIR camera captures a photograph and an infra-red image detail of the center of that (shown side by side in Figures 6.42 through 6.49).

The exterior photos below were taken on August 31, 2013, between 4:22 and 4:56 pm. The thermal image photos show a temperature reading at the center, and establish the high and low temperature range on the right side of each photo. The coolest areas are those covered by plants and soil. The largest range of hottest to coolest areas, shown in Figure 6.44, was taken at 4:38 pm on the south façade, running from 83.3 °F (28.5°C) to 149 °F (65°C), a difference of 65.7°F (36.5°C). The spot temperature on the plant leaf in the light blue color range is at 95.4 °F (34.7°C), a reduction of 53.6 °F (30.3°C) below the hottest façade areas.

The smallest range of hottest to coolest, shown in Figure 6.49, was taken at 4:56 pm on the west façade, running from 76.1°F (24.5°C) to 91.2°F (32.9°C), a difference of 15.1°F (8.4°C). This is due to the photo showing all living façade plants. The spot temperature of 79.9°F (26.6°C) on the opaque west facing living façade is 25.1°F (14°C) lower than the same location on the opaque control façade, which is 105°F (40.6°C). These photos confirm that food producing living façades can result in as high as a 65.7°F (36.5°C) differential in surface temperatures for opaque façades on a sunny day, while measured data revealed an average surface temperature penalty for opaque façade areas of 10-40°F (5.56-22.22°C).

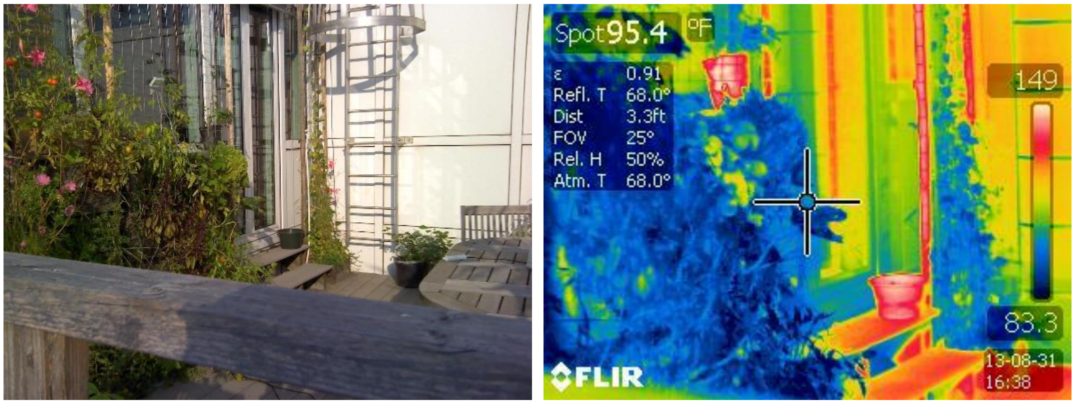


Figure 6.44 Regular photo and thermal image showing 65.7°F overall temperature range, 53.6°F spot range.

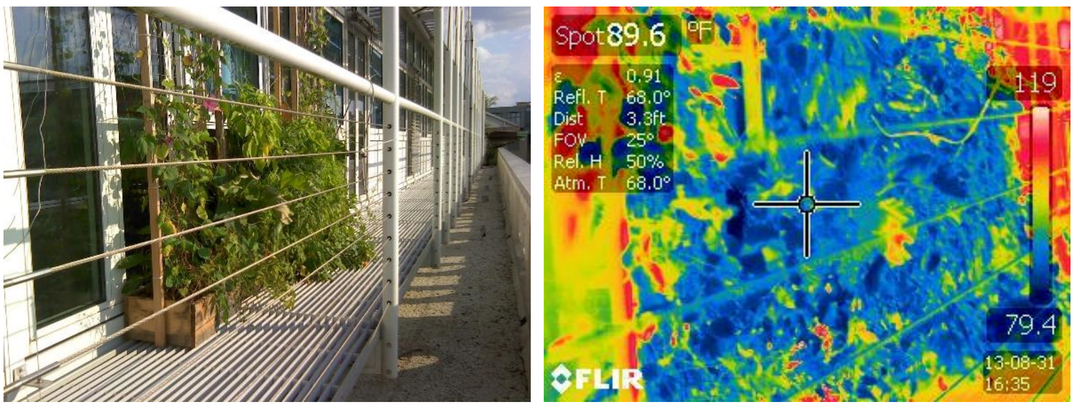


Figure 6.45 Regular photo and thermal image showing 39.6°F overall temperature range, 29.4°F spot range.

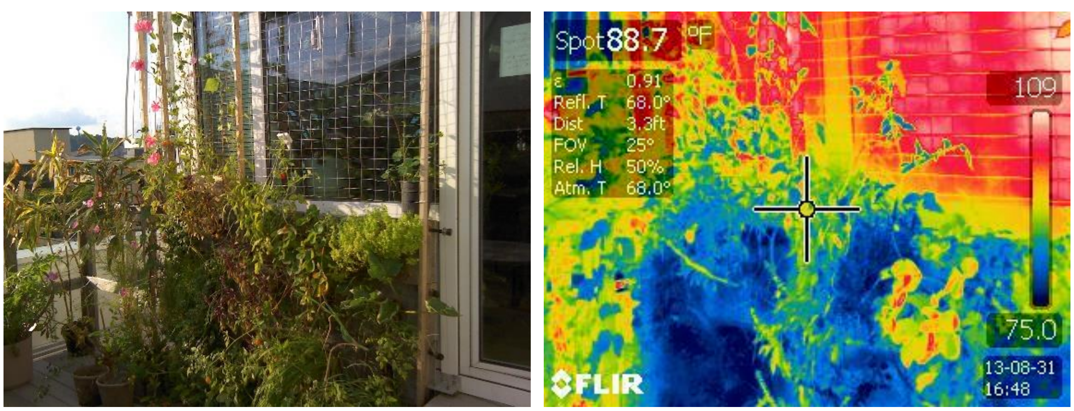


Figure 6.46 Regular photo and thermal image showing 34°F overall temperature range, 20.3°F spot range.

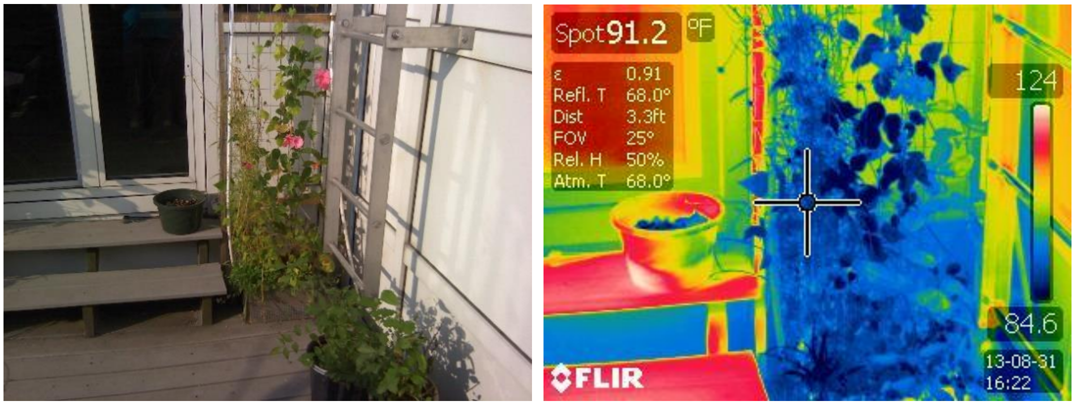


Figure 6.47 Regular photo and thermal image showing 39.4°F overall temperature range, 32.8°F spot range.

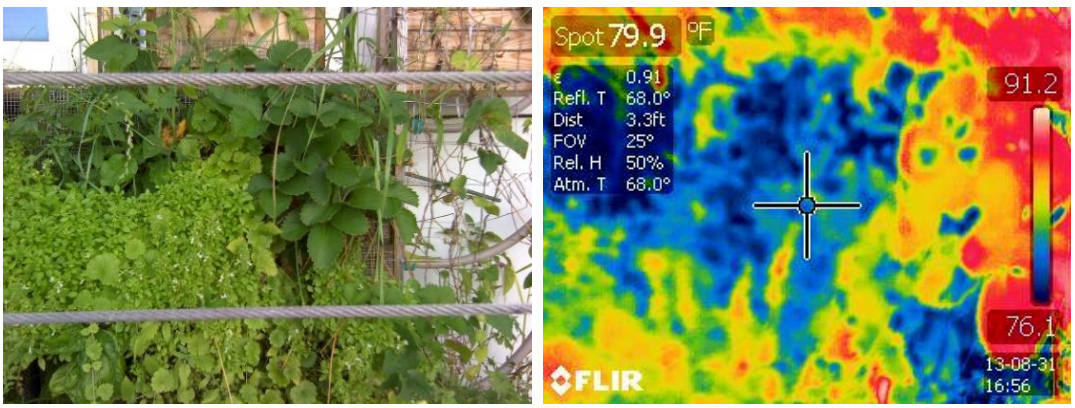


Figure 6.48 Regular photo and thermal image showing 15.1°F overall temperature range, 11.3°F spot range.

Figure 6.49 Regular photo and thermal image showing 14°F overall temperature range, 2°F spot range at the opaque control façade

Thermal images can also be used to show conductive heat transfer on the inside of the façade, through both opaque and glass areas. Figures 6.50 and 6.51 illustrate that the inside surface of the glazed areas of the living façade are 2.7°F cooler as compared to the control façade, and the inside surface of the opaque areas of the living façade are to 4.4°F cooler than the control. This would improve the radiant environment for building occupants which would also reduce the cooling demand, albeit not calculated.

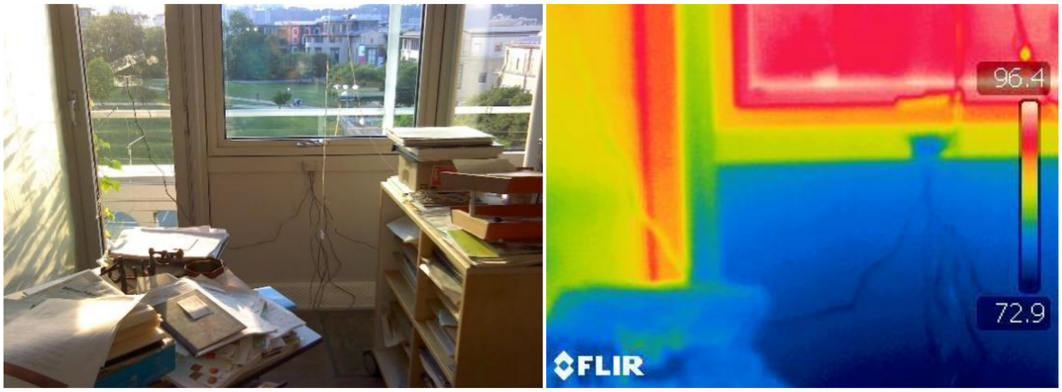


Figure 6.50 Regular photo and thermal image showing 23.5°F overall temperature range, 2.7°F high temperature differential. Living façade is cooler than the control façade.

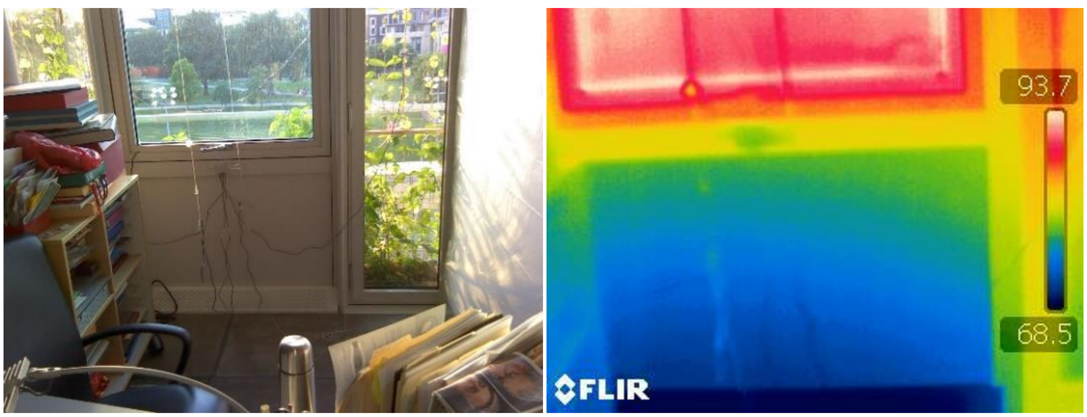


Figure 6.51 Regular photo and thermal image showing 25.2°F overall temperature range, 4.4°F low temperature differential. Living façade is cooler than the control façade.

6.3 Air Quality Performance of a Food Producing Living Façade in a Temperate Climate

The third hypothesis of the thesis is that living façades will improve air quality by decreasing amounts of airborne small particulates. Measurement of air quality performance focused on small particulate level reduction, due to the specific problems that small particulates ($PM_{2.5}$) pose for the air quality of the City of Pittsburgh. Small particulate levels were monitored both outside and inside of the living and control façades on the west, in an attempt to document a reduction of small particulates outside, and potential correlation with reduced levels inside.

The National Ambient Air Quality Standards published by the EPA states that primary levels should be no greater than 12.0 μg/m^3 and secondary levels no greater than 15.0 μg/m^3 calculated as an annual average. The 24-hour primary and secondary combined readings should be no greater than 35.0 μg/m^3. These levels are shown in Table 6.14 below. Primary is referred to by the NAAQS as the health-related standard, and is explained as the primary emissions source. Secondary is listed as the welfare-related standard, and is explained as the secondary source that develops when the primary emissions mix with other airborne substances.

Table 6.14 The National Ambient Air Quality Standards chart for Particle Pollution (USEPA, 2020).

Pollutant [links to historical tables of NAAQS reviews]		Primary/ Secondary	Averaging Time	Level	Form
Particle Pollution (PM)	$PM_{2.5}$	primary	1 year	12.0 μg/m³	annual mean, averaged over 3 years
		secondary	1 year	15.0 μg/m³	annual mean, averaged over 3 years
		primary and secondary	24 hours	35 μg/m³	98th percentile, averaged over 3 years
	PM_{10}	primary and secondary	24 hours	150 μg/m³	Not to be exceeded more than once per year on average over 3 years

https://www.epa.gov/criteria-air-pollutants/naaqs-table

Table 6.15 shows the average levels of $PM_{2.5}$ in micrograms per cubic meter (μg/m³) measured for the Living and Control Façades during the seven-month period of February to August 2014. The months of April through August were used for detailed analysis as they are the primary months of the growing season available from the data collected.

Over a seven month period (times when operable windows might be in use), the living façade slightly outperforms the control façade every month indoors and outdoors, except in April when the indoor level for the living façade is slightly higher than for the control façade (Table 6.15). All results are well below the NAAQS standards, and are also below the 3.2 μg/m³ recommendation of the American Lung Association (American Lung Association, 2020).

Table 6.15 $PM_{2.5}$ Averages (μg/m³)

Month & Year	Indoor			Outdoor		
	Living Façade	Control Façade	p-value	Living Façade	Control Façade	p-value
Feb 2014	0.6028	0.6147	<0.001 Significant	1.2279	1.3072	<0.001 Significant
Mar 2014	0.4096	0.4139	<0.001 Significant	0.9137	0.9715	<0.001 Significant
Apr 2014 n=15,553	0.5130	0.5114	0.643 Not Significant	0.8438	0.8848	<0.001 Significant
May 2014 n=16,128	0.7220	0.7332	0.041 Significant	1.0886	1.1329	<0.001 Significant
Jun 2014 n=15,605	1.1676	1.1784	0.197 Not Significant	1.7333	1.8240	<0.001 Significant
Jul 2014 n=16,126	1.1379	1.1437	0.490 Not Significant	1.6417	1.7278	<0.001 Significant
Aug 2014 n=15,905	1.0733	1.1257	0.382 Not Significant	2.0149	2.2853	<0.001 Significant

The graphs shown in Figures 6.52 through 6.56 illustrate the results comparing the indoor and outdoor living versus control façade comparisons per month for April through August.

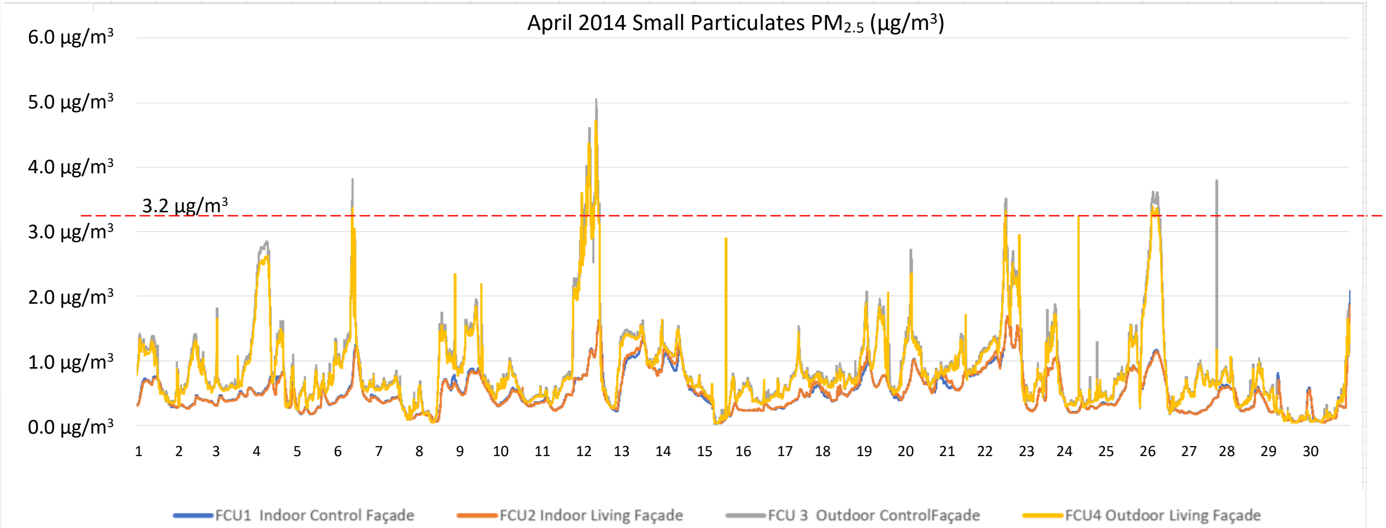


Figure 6.52 April 2014 (red dashed line indicates 3.2 µg/m^3), n=15,553, p<0.001

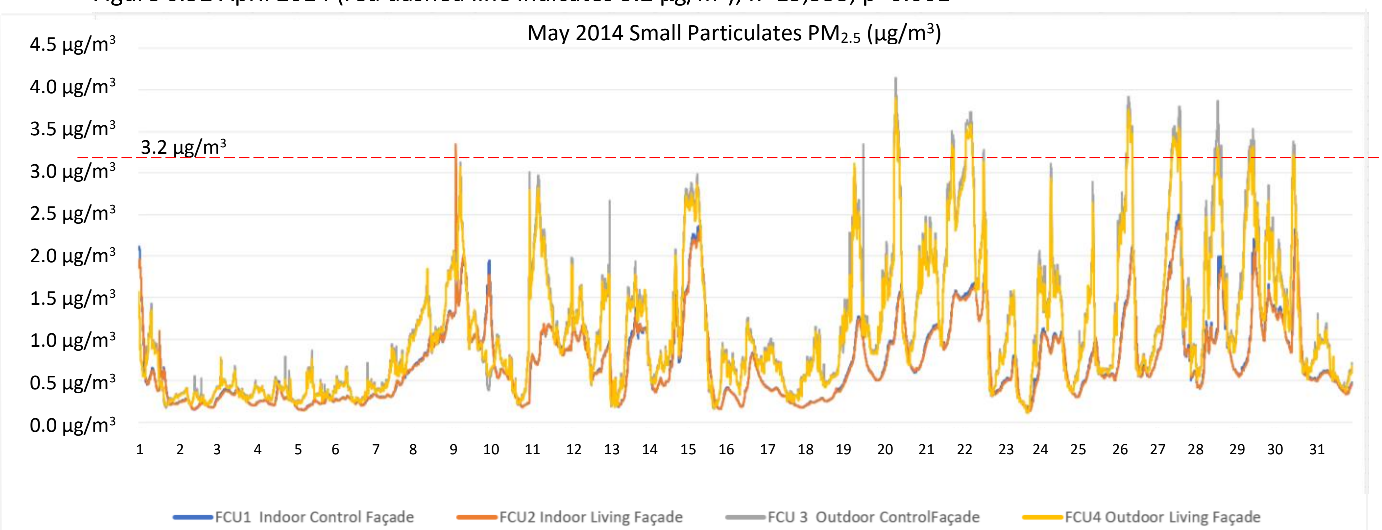


Figure 6.53 May 2014 (red dashed line indicates 3.2 µg/m^3), n=16,128, p<0.001

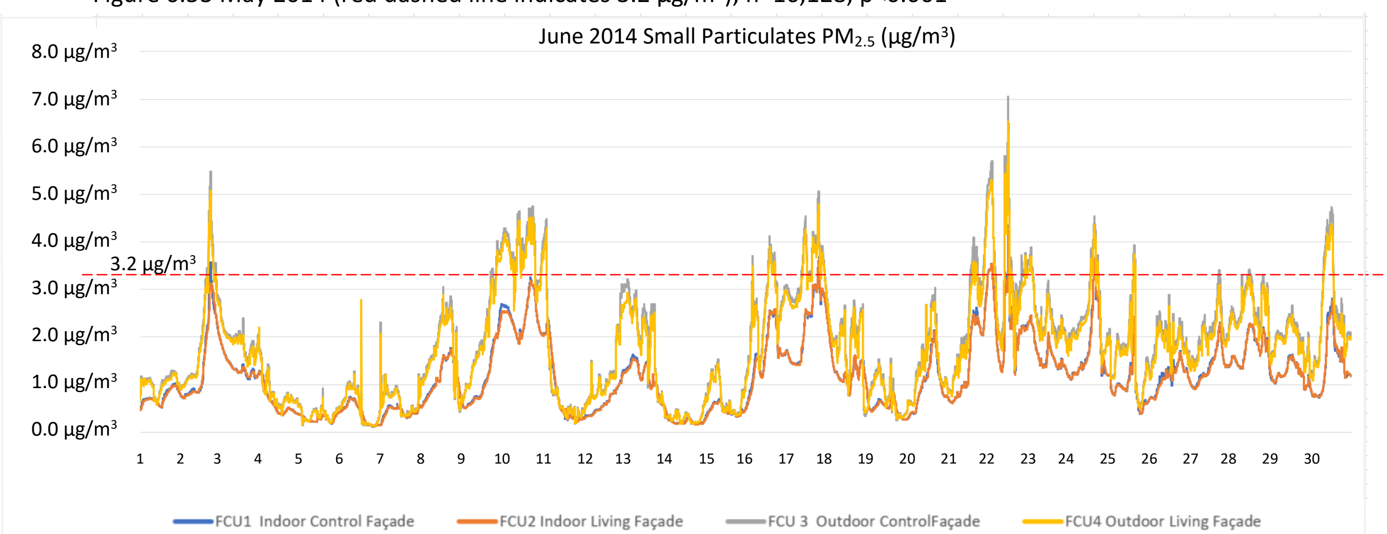


Figure 6.54 June 2014 (red dashed line indicates 3.2 µg/m^3), n=15,605, p<0.001

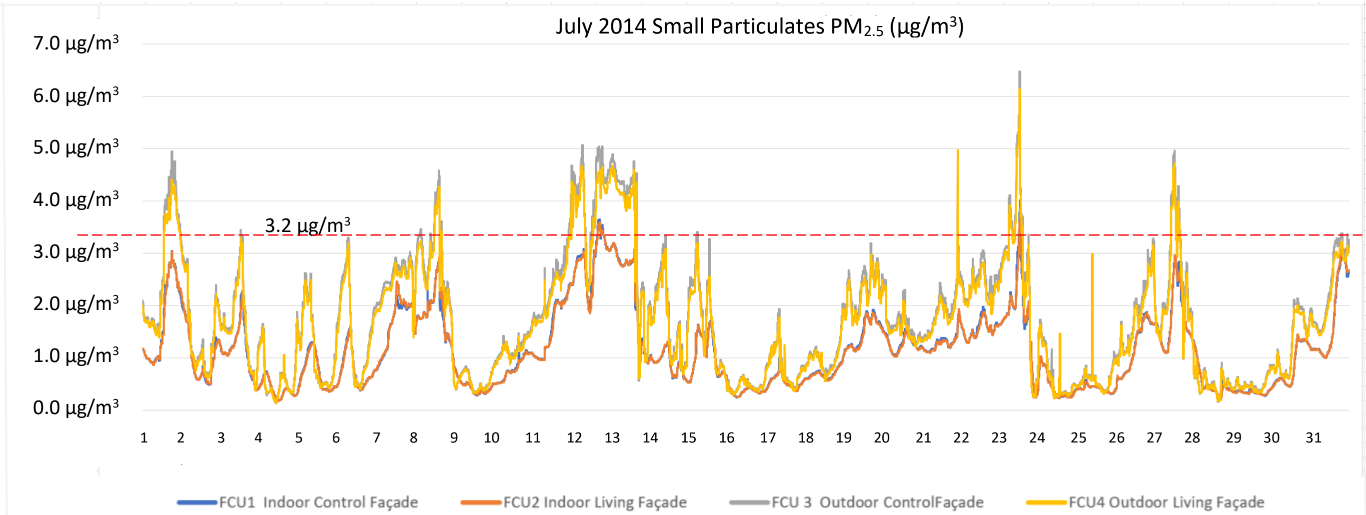


Figure 6.55 July 2014 (red dashed line indicates 3.2 µg/m^3), n=16,126, p<0.001

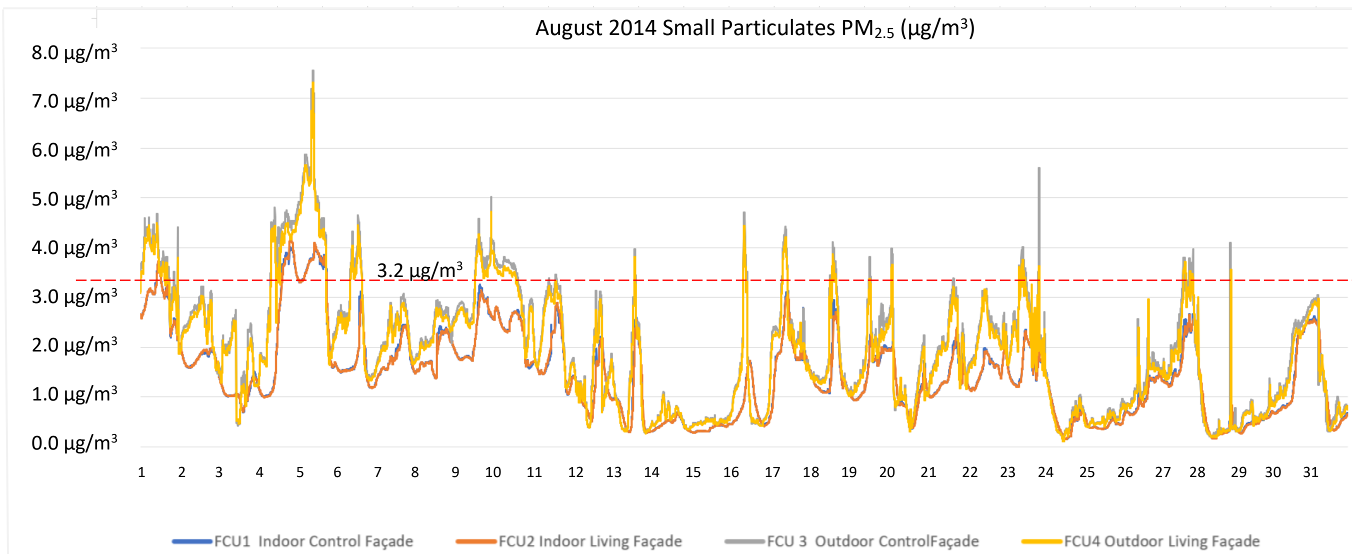


Figure 6.56 August 2014 (red dashed line indicates 3.2 µg/m^3), n=15,905, p<0.001

These graphs show that one day spikes sometimes reach up to 7.0 µg/m^3, well below the NAAQS standards, but periodically exceed the 3.2 µg/m^3 recommended for healthy lung function by the American Lung Association.

Boxplot analysis was undertaken to test the statistical significance of these results for the entire seven-month period, from February to August 2014, both indoor and outdoor, as shown in Figures 6.57 and 6.58 below. Samples were taken every few minutes for seven months, n=209,295. The data for the living and control façades are presented as side-by-side boxplots, for the exterior and interior opaque façade areas.

The five-number summary for each façade, including the minimum, first quartile, median, third quartile and maximum, are shown next to each boxplot. The exterior and interior façade measurements are statistically significant, both P<0.001. The majority of both the indoor and outdoor measurements fall below 3.2 µg/m^3 recommended for healthy lung function by the American Lung Society.

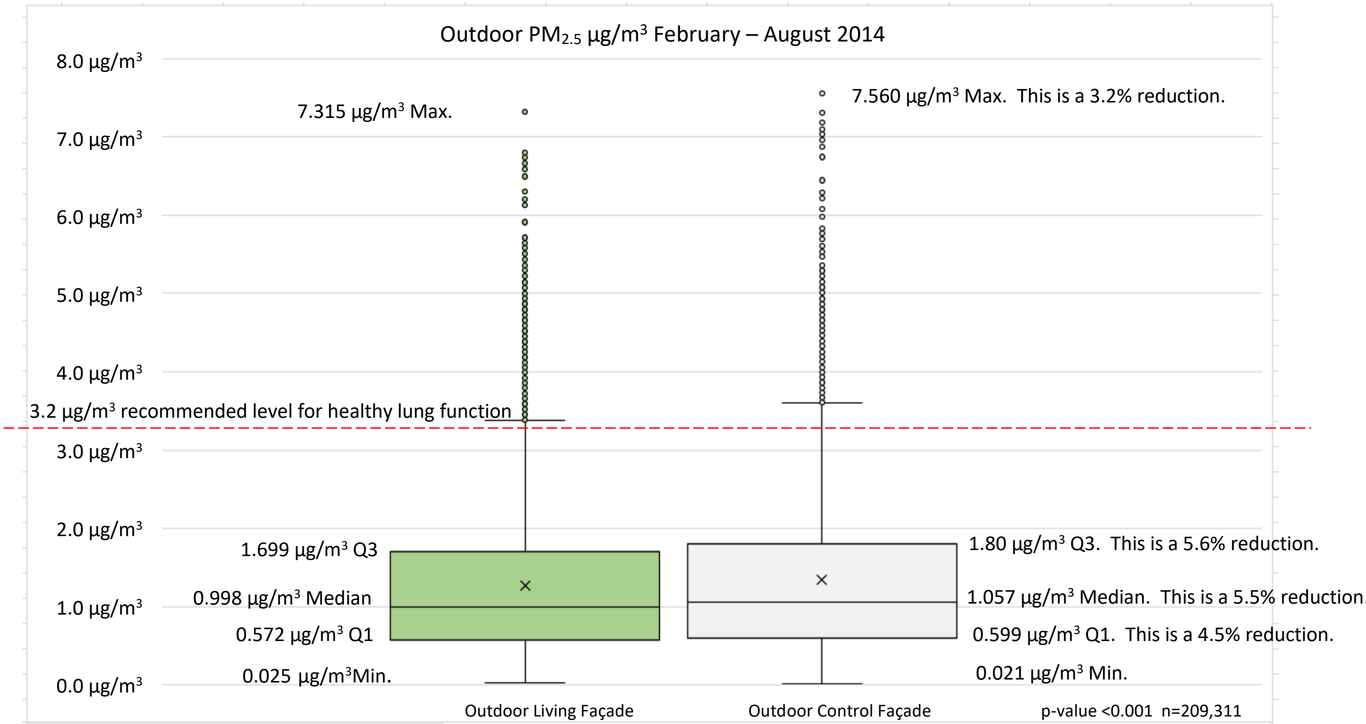


Figure 6.57 Outdoor West Façade $PM_{2.5}$ µg/m³ at Living and Control Façades February – August 2014 n=209,295, p<0.001

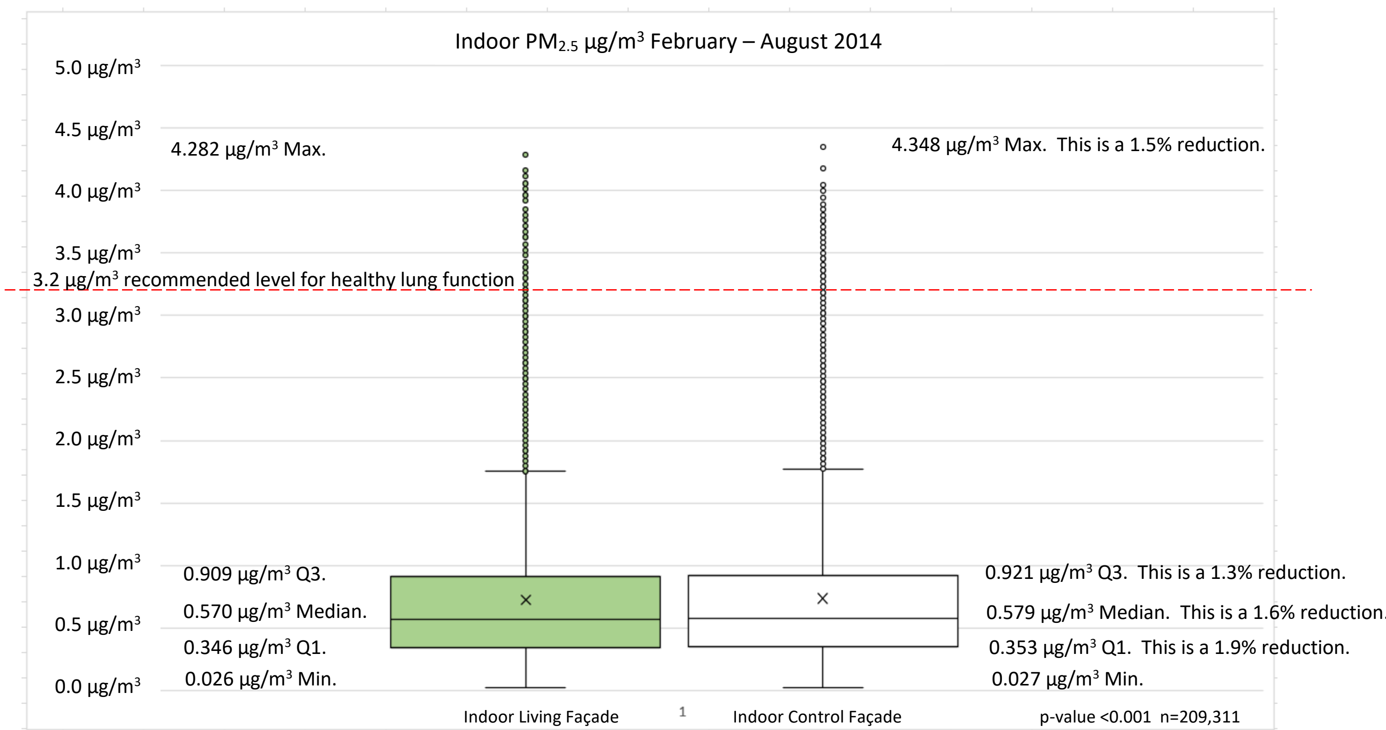


Figure 6.58 Indoor West Façade $PM_{2.5}$ µg/m³ at Living and Control Façades February – August 2014 n=209,295, p<0.001

A side-by-side comparison of all seven months shown as separate boxplots is shown in Figure 6.59. The number of samples, averages and p-values for each month are listed in Table 6.14 above. The data is statistically significant for all the exterior data for each month, but is statistically significant on the interior only for the months of February, March and May.

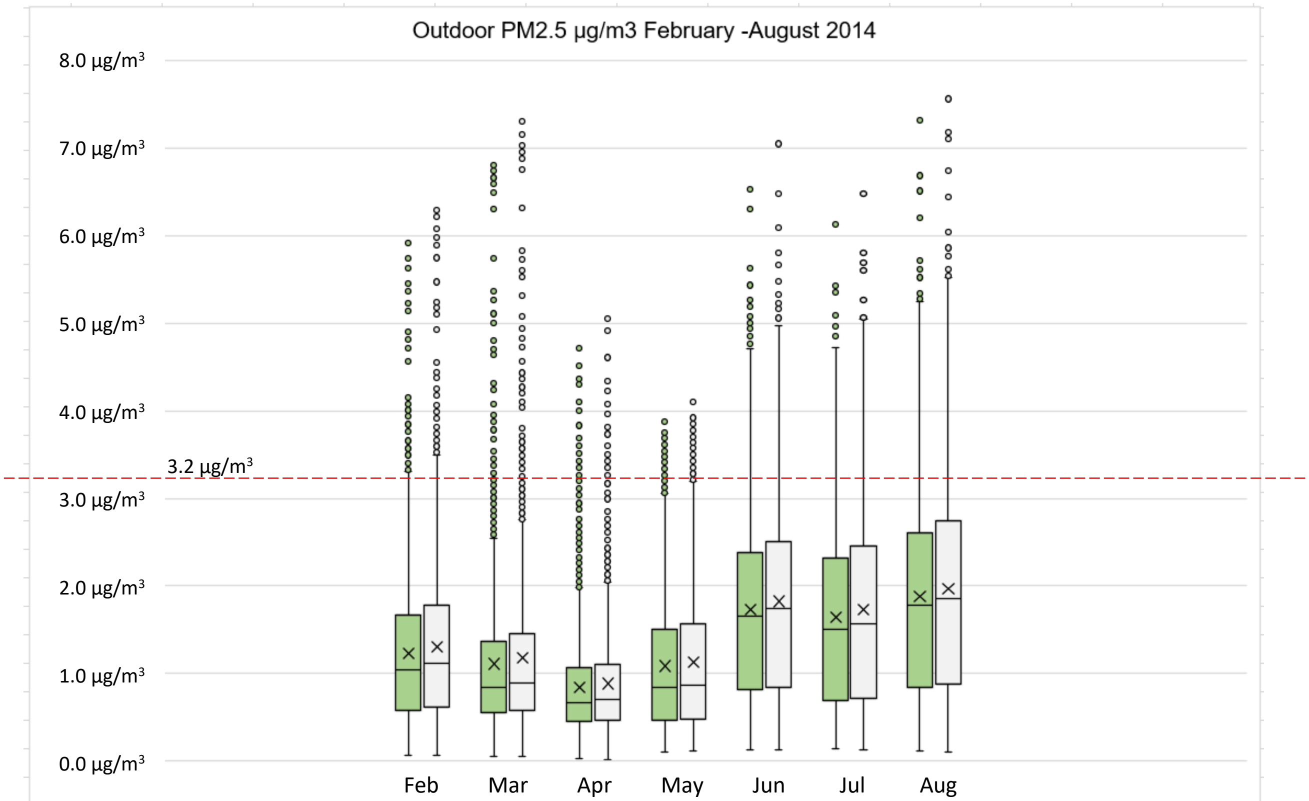


Figure 6.59 Outdoor West Façade $PM_{2.5}$ µg/m³ at Living and Control Façades monthly comparison February – August 2014 (number of samples and p-values per month are listed in table 6.14 above)

The side-by-side comparison of these boxplots for the living and control façades each month helps to illustrate the fluctuating levels of small particulates over a significant portion of the year (Figure 6.59). During February and March, plants are usually still dormant or have died back, and yet the performance difference of the living façade shows statistically significant lower levels of particulates. The majority of all measurements once again show outdoor levels of small particulates that fall well below the 3.2 µg/m³ threshold (American Lung Association, 2020).

To better see these results and the slight benefit provided by the living façade in comparison to the levels measure at the control façade, one typical day in July was selected to graph in more detail (Figures 6.60 and 6.61). The outdoor living and control façade are shown in Figure 6.61 indicating levels fluctuating from between 1.3 and 2.6 µg/m³, with the control façade slightly higher than the living façade, by one or two tenths, and showing more peaks, indicating perhaps that the living façade has more resiliency to fluctuations in the air.

The indoor air comparison between the living and control façades is similar, with a flatter curve ranging from between 1.0 and 1.6 µg/m³. Again, the indoor living façade sensor does not react as strongly as the control façade sensor to the slight spike that occurs around 1:30 pm. This may indicate a translation of the benefit of the living façade to the interior of the office space.

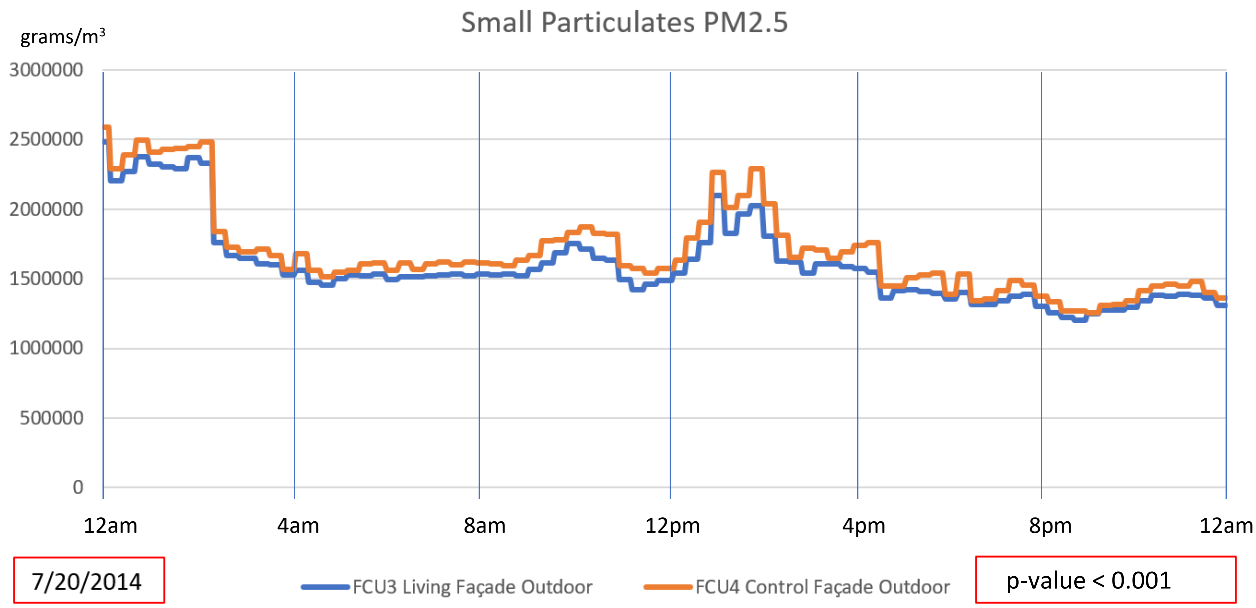


Figure 6.60 Outdoor PM2.5 levels Living Façade (blue) vs. Control Façade (orange), July 20, 2014 (24-hour period)

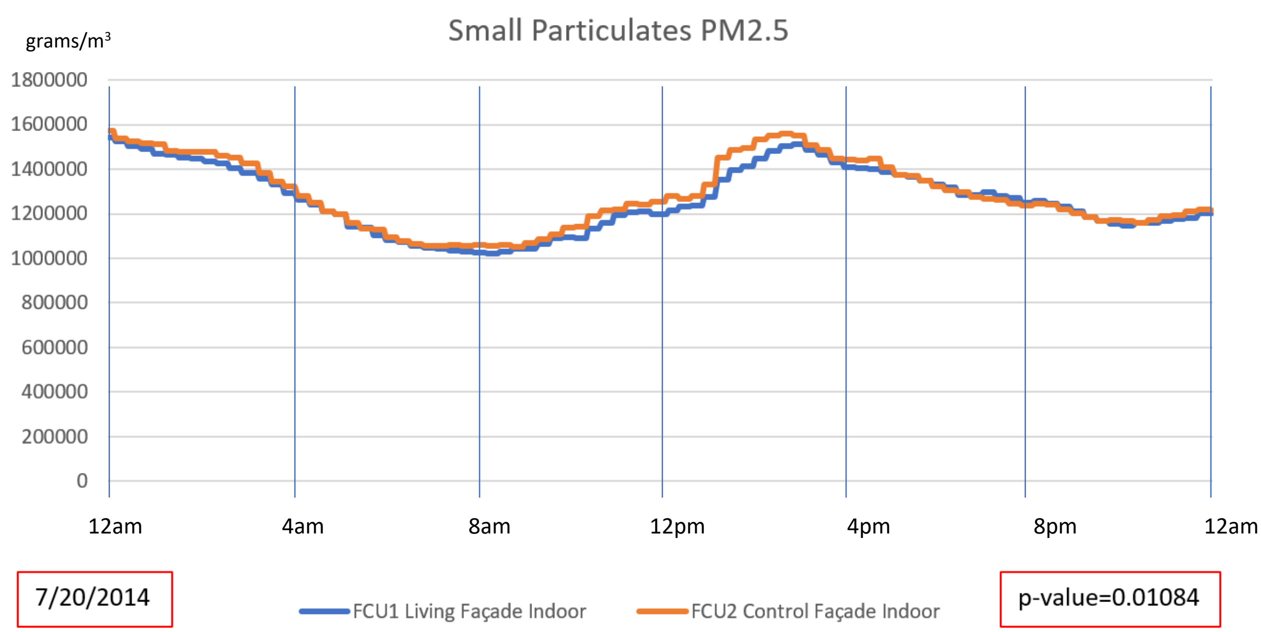


Figure 6.61 Indoor PM2.5 levels Living Façade (blue) vs. Control Façade (orange), July 20, 2014 (24-hour period)

Statistical analysis of these detailed graphs from July 20th yielded p-values <0.001 for the outdoor façade comparison, and 0.011 for the indoor comparison, indicating that these results are statistically significant.

The map shown in Figure 6.62 below features the readings from multiple air monitoring stations across the uptown neighborhoods of Pittsburgh. Standards indicate average readings for primary sources at 12 micrograms per cubic meter (µg/m^3) over a three-year period, and 15 µg/m^3 for secondary sources over a three-year period. The average of a combination of primary and secondary sources over a 24-hour period yields 35 µg/m^3. The range of numbers shown on this map goes from zero (good) to 500 µg/m^3

(hazardous), with the majority falling on the good range of 0-50 µg/m^3 (see the National Ambient Air Quality Standards chart, Table 6.14, above). The reading of 56 µg/m^3 closest to the IW and MMCH is probably influenced by the wood shop exhaust coming from the basement of the College of Fine Arts building. The relatively low readings recorded by the IW sensors on the west facing living façade and control façade of between 1 and 2.6 µg/m^3 seem to be influenced by the high parapet of the original roof structure, rising above and helping to protect the façade balcony area, as well as the solar shade louvers and overhead louvered grate that protect the upper portions of the façade from airborne deposition. The graphs show that the living façade does have lower levels of $PM_{2.5}$ in general, but both façades show data in the low end of the good range. Developing additional charts selected over the entire course of the growing season should show if this is a consistent pattern of the results are indeed more mixed and less indicative of any benefit provided by the food producing living façade.

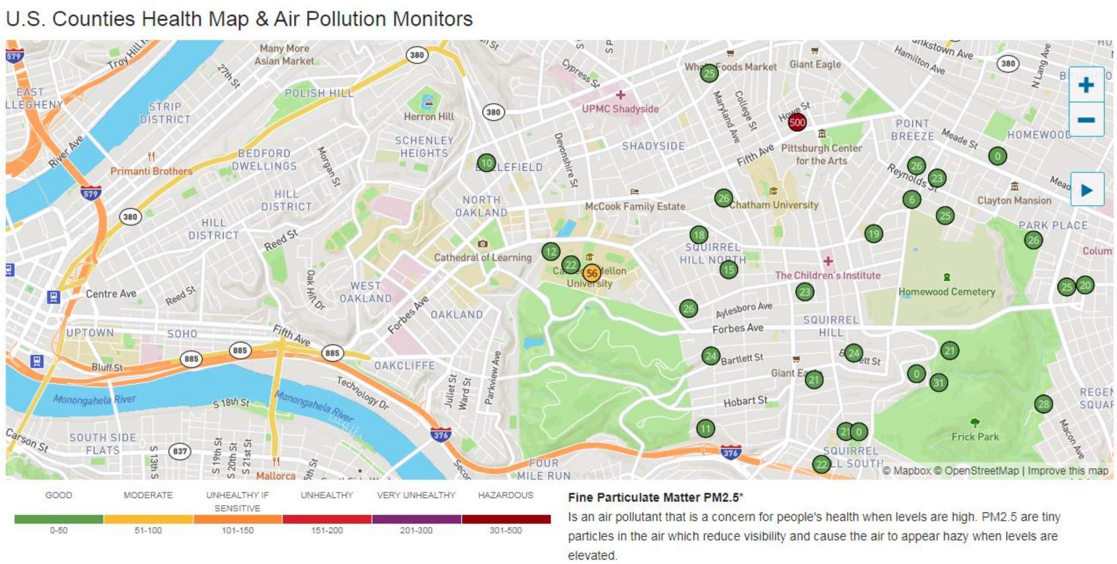


Figure 6.62 Map of readings from multiple air monitoring stations across the uptown neighborhoods of Pittsburgh (wunderground.com, 2020)

6.4 Rainwater Capture for Local Irrigation of the Food Producing Living Façade in a Temperate Climate

Similar to numerous US cities with combined storm sewer systems, Pittsburgh critically needs to manage a percent of its storm water on site to minimize overflow conditions. Capturing and storing rainwater to irrigate a food producing living façade can significantly reduce storm water runoff in temperate climate cities.

Rainwater falling on the roof of the IW was collected in two, forty-five-gallon rain barrels to be used as the primary irrigation source for the food producing living façade vertical garden assembly installations. These rain barrels were connected to two pumps for automatic irrigation, one for the south façade installation and one for the west façade installation. These pumps were powered by two small photovoltaic solar panels that charged a 6-volt rechargeable battery. The system was controlled by one soil moisture sensor placed in one soil panel in each of the vertical garden installations, connected to a data logger and weather station controller, with manual override toggle switches.

Irrigation for the living façade assemblies was integrated with rainwater capture and storage to address predictable periods of no rain, with enough photovoltaic power to pump and regulate water distribution automatically using the soil sensors. Ensuring that the battery was sufficiently charged to power consistent irrigation across the greater distance to the west façade living façade, was also critical. While gravity flow can distribute water vertically, horizontal flows of up to 30 meters (100 feet) required electric pumps.

A living façade with well-established, healthy plants that are able to bear produce should be irrigated based on consistent soil moisture readings and responsive supply. The demand for water as called for by the soil moisture sensors for the south and west living façades is shown in Figure 6.63 below. The differences in demand cycles for the two orientations is a function of the intensity and direction of the sun and wind exposure at different times of the day.

The sensor called for irrigation when the moisture content was just above one tenth of a cubic meter of water per cubic meter of soil (0.1 m^3/m^3) and irrigated to the level of just above two tenths of a cubic meter of water per cubic meter of soil (0.2 m^3/m^3).

The pattern of readings for irrigation demand suggested that watering once every 24 hours was adequate for keeping the food producing plants sufficiently moist, but two days without irrigation caused the plants leaves to begin to wilt. An uneven pattern of irrigation through an automated system led to an undesirable condition called "blossom end rot" on the bottom of the Roma tomatoes (Figures 6.64 and 6.65). As a result, daily hand watering of the system using captured rainwater was implemented during the growing season.

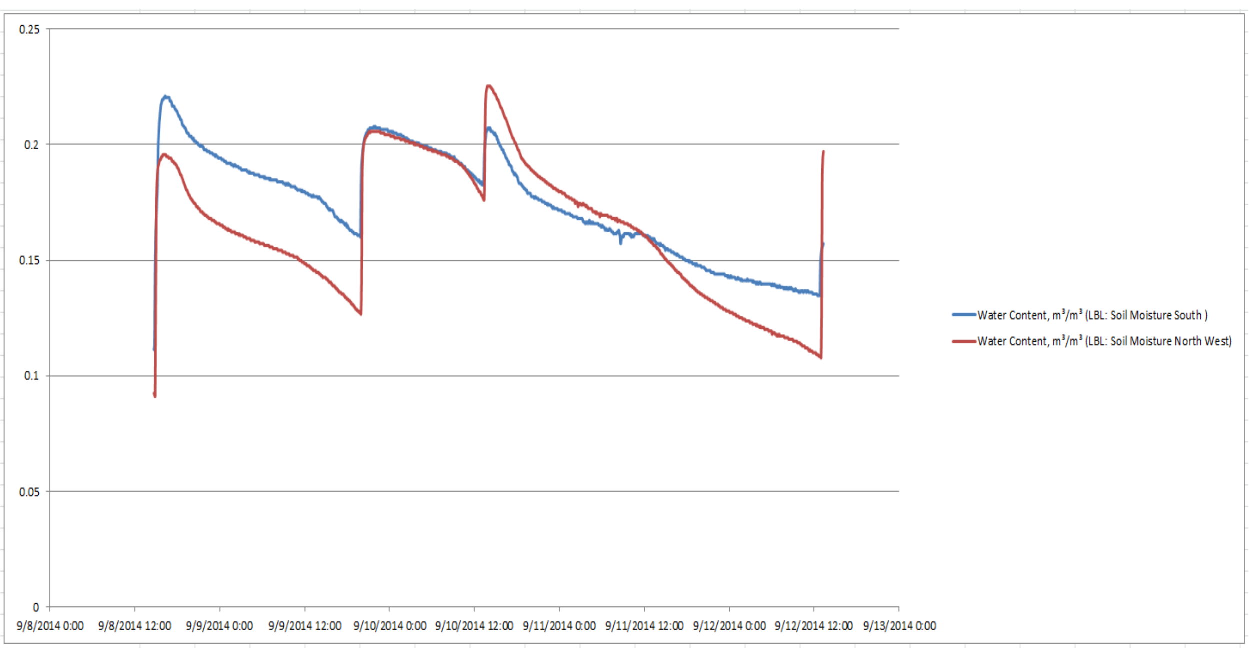


Figure 6.63 Soil Moisture Sensor Trials

Figures 6.64 and 6.65 Blossom End Rot on Roma Tomatoes, July 2014

6.4.1 Average Rainwater Capture for Irrigation

The west façade research bay contained 1.39 m^2 (15 ft^2) total of soil filled panels. The south façade research bay contained 1.76 m^2 (19 ft^2) total of soil filled panels. These numbers are used to calculate the irrigation per unit of area for this system. The west and south façade research installations when added together contain a total of 3.15 m^2 (34 ft^2) of soil filled panels.

Watering the FPLF installations once a day every day during the growing season redeploys 14.26 liters of water per square meter (0.353 gal/ft^2). This totaled 26.5 liters (7 gallons) of water daily for the south façade installation and 18.9 liters (5 gallons) daily for the west façade installation, which was both smaller in area and more shaded.

- 26.5 liters per 1.76m^2 per day = **15.06 liters/m^2** per day (7 gallons per 19ft^2 = 0.368 gal/ft^2) south façade
- 18.9 liters per 1.39 m^2 per day = **13.6 liters/m^2** (5 gallons per 15ft^2 = 0.333 gal/ft^2) west façade
- 45.4 liters per 3.15 m^2 per day = **14.26 liters/m^2** (12 gallons per 34ft^2 = 0.353 gal/ft^2) both avg.

In general, the growing season lasts 214 days, from May 1st to Dec 1st each year, nearly 60% of the year. In some years, frost would occur before December 1st, but irrigation would continue usually through the last harvest and until the plants died in the first hard freeze of the season. Total water needed for the entire growing season is calculated below based on the daily use outlined above:

> 214 days x 45.4 liters per day = **9,716.5 liters** (214 days x 12 gallons per day = 2,568 gallons) total water needed for each growing season.

Rainwater harvesting for food producing living façades is limited to the total water storage capacity, with overflow released to the storm sewer. The test configuration demand for 45.4 liters (12 gallons) per day for thirty days is 1,362 liters (360 gallons) or 432.38 liters/m^2 (10.58 gal/ft^2), which would require fully filling both 170-liter (45 gallon) rain barrels four times a month. Given rainfall in the City of Pittsburgh of between 5.75 and 10 .46 centimeters (2.25 and 4.12 inches) per month on average during the growing season, between 58.27 and 105.12 liters/m^2 (1.43 and 2.58 gal/ft^2) of rooftop generated rainwater is available. These calculations show that the FPLF will use all the roof generated rainfall available, on average. The IW has a roof area of approximately 602 m^2 (6,477 ft^2 or 932,688 in^2). Total monthly rainfall amounts are calculated in Table 6.16 below.

Table 6.16 Monthly rainfall accumulation generated by the roof of the Intelligent Workplace.

Month	Days	Rain Volume Calculation	Volume	Amount	Amount/Area
May	31	932,688 sq. in. x 3.80 in. of rain =	3,544,214.4 cu in	15,342.92 gal 58,079.27 liters	2.37 gal/ft^2 96.57 liters/m^2
June	30	932,688 sq. in. x 4.12 in. of rain =	3,855,034.56 cu in	16,688.46 gal 63,172.69 liters	2.58 gal/ ft^2 105.12 liters/m^2
July	31	932,688 sq. in. x 3.96 in. of rain =	3,693,444.48 cu in	15,988.94 gal 60,524.72 liters	2.47 gal/ ft^2 100.64 liters/m^2
Aug	31	932,688 sq. in. x 3.38 in. of rain =	3,152,485.44 cu in	13,647.12 gal 51,659.97 liters	2.11 gal/ ft^2 85.97 liters/m^2
Sept	30	932,688 sq. in. x 3.21 in. of rain =	2,993,928.48 cu in	12,960.73 gal 49,061.70 liters	2.00 gal/ ft^2 81.49 liters/m^2
Oct	31	932,688 sq. in. x 2.25 in. of rain =	2,098,548.00 cu in	9,084.62 gal 34,389.03 liters	1.43 gal/ ft^2 58.27 liters/m^2
Nov	30	932,688 sq. in. x 3.02 in. of rain =	2,816,717.76 cu in	12,193.58 gal 46,157.72 liters	1.88 gal/ ft^2 76.60 liters/m^2
Totals	214			95,906.37 gal 363,045.10 liters	2.12 gal/ ft^2 avg. 86.38 liters/m^2 avg.

Depending on variations in actual rainfall frequency, there may be periods of time when rainwater irrigation must be supplemented with an additional water source. The 340 liters (90 gallons), when used at a rate of 45.4 liters per day (12 gallons), would be used up within 7.5 days. Limitations in fully draining every last bit of water stored in the rain barrels would reduce that period of time to perhaps less than 6 days. In a typical year in Pittsburgh the number of consecutive days without rainfall would only be a few. In 2019, the longest period without rainfall was 6 consecutive days. In 2016 it was 8 days and in 2015 there was a dry period lasting 9 days in August and 8 days in June. In 2012 Western Pennsylvania experienced conditions that officially ranged from Abnormally Dry to Moderate Drought. Historically, the longest period without rainfall on record for the City of Pittsburgh is 26 consecutive days, recorded in November, 1874. To ensure adequate irrigation water supply, additional storage or access to potable water is necessary as a backup due to unpredictable variations in rainfall.

In conclusion, the food producing living façades in the IW test bed were able to effectively redeploy **815.24 gallons / m^2 of wall area** (214 days x 12 gallons per day = 2,568 gallons of water needed total; 2,568 gallons / 3.15 m^2 of wall area = 815.24 gallons / m^2 of wall area). This represents the ability to **redirect 0.063 inches of rain per m^2 of roof** to **3.15 m^2 of façade** given **90 gallons of on-site storage**. **This would be provided by 5.1 m^2 of roof** (55 ft^2 of roof), with **on-site water storage** to address rainfall variability **at 28.6 gallon storage per m^2 façade**. Thus, one hundred percent of the rain that falls on a typical commercial building roof in Pittsburgh during the growing season would be utilized by the full scale implementation of a food producing living façade or façades on a majority of that building.

6.5 Biodiversity Benefits of the Food Producing Living Façade in a Temperate Climate

Food producing living façades also contribute to biophilic advantages and biodiversity. The food producing living façade developed in this thesis represents increased access to nature, with all of its dynamic, circadian and aesthetic qualities. Considering the extent of work and living environments that have no visual or physical connection to nature, in spaces too deep or too tall, the introduction of food producing living façades that bring full sensory experience to every floor is an important contribution to the quality of the indoor environment.

Food producing living façades are invaluable to biodiversity and the survival of native pollinators and insect populations (Figures 6.69 and 6.73). Birds were attracted to the living façades, such as Robins (Figures 6.66 and 6.68). The Robin is not only a predator, but can also be prey for the Hawk that has been known to visit the fourth-floor balcony of the IW, sitting on the railing, looking for its next meal (Figure 6.67).

Figure 6.66 American Robin *Turdus migratorius*

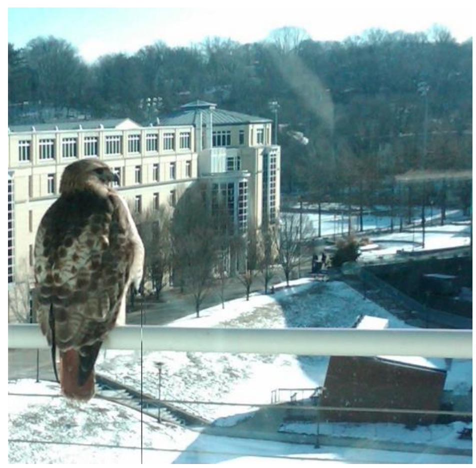


Figure 6.67 Hawk *Species Unknown*

Figure 6.68 Robin’s nest

Figure 6.69 Yellow Garden Spider
Agriope aurantia

Across the six seasons studied in this thesis, a variety of insects were observed, including spiders, wasps, bees, grasshoppers and a praying mantis. Beneficial insects such as the Yellow Garden Spider (Figure 6.69) and Northern and European Paper Wasps (Figures 6.70 and 6.71), are attracted to the vertical gardens and help control pests, such as the Grasshopper (Figure 6.72). The Praying Mantis (Figure 6.73) is another beneficial insect capable of removing a number of pests from the garden.

Figure 6.70 European Paper Wasp
Polistes fuscatus

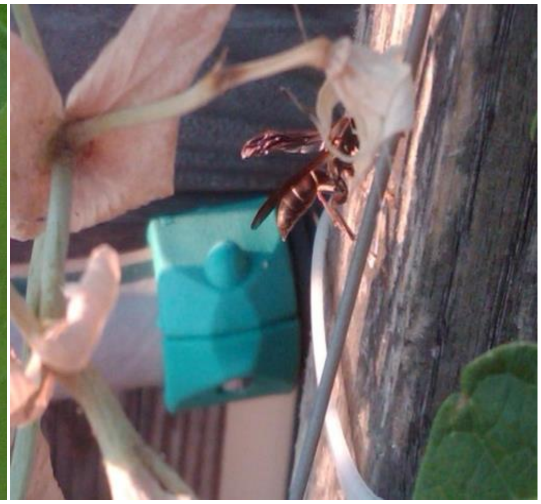


Figure 6.71 Northern Paper Wasp
Polistes dominula

Figure 6.72 Grasshopper *Species uncertain*

Figure 6.73 Praying Mantis Mantis religiosa

The additional benefits of biophilia and biodiversity, as the photographs above illustrate, address critical losses of contiguous natural settings in the existing built environment. Installed throughout the city, food producing living façades can provide additional opportunities for urban agriculture, potentially addressing the critical issue of urban food deserts, as well as environmental education, ecological restoration and remediation, as part of an expanding system of green infrastructure. Given that there is often very little land available for parks and green space in cities, it is critical for the façades of city buildings to be re-visioned as vertical gardens to maintain and increase the diversity of species that ensure biodiversity in cities.

Chapter 7 Conclusions

Executive Summary/Abstract

The built environment uses significant and increasing amounts of energy, more than 1000 times the energy density per unit area of the natural environment, contributing to urban heat island effect. Simultaneously, population growth and urban development have outpaced food production globally. In response, there has been a growing trend to further develop the ancient tradition of incorporating plants into the built environment via green roofs, green façades, urban agriculture and other green infrastructure. Research is limited, however, into the application of growing food producing plants on a living façade to improve total building performance. This dissertation investigates the role of integrating food producing plants into a living façade to positively impact four outcomes: food production, thermal performance, air quality and rainwater management in a temperate climate.

The design, construction, operation and end-of-life disassembly and recycling of a food producing living façade on the south and west of the Robert L. Preger Intelligent Workplace at Carnegie Mellon University successfully demonstrates the critical value of living façades for the Pittsburgh climate. A maximum average production of 2.64 kilograms of produce per square meter of façade panel can be generated annually (0.54 lbs./ft2) which could effectively meet 7-14% of summer nutritional demands for building occupants. The façade temperatures can be reduced between 10^{o}F - 36.95^{o}F (5.56^{o}C - 20.53^{o}C) with approximately 20% reduction in cooling energy, and positive impact on reducing urban heat island effect. A living façade can effectively scrub pollutants from the natural ventilation air stream, measured at a maximum of 5.6% reduction in $PM_{2.5}$ for the living façade compared to the control façade. An average of 14.26 liters of rainwater per square meter of façade per day (0.35 gal/ft^2/day) can effectively redirect all the rainfall on the roof from storm drains into primary irrigation. In addition, observational studies revealed enhanced access to nature for building occupants, wildlife habitat and biodiversity.

7.1 Key Challenges Addressed by Food Producing Living Façades and Hypotheses

There are many challenges that can be met by increasing vegetation in cities through urban gardens, green roofs and living façades. This thesis identified a set of four challenges to establish the hypothesis and metrics for food producing living façades to address food shortages, heat increases, air quality challenges and flooding in cities around the world.

Alongside rapid urbanization around the world, there is a growing gap between increasing human population and food production. Over 1.7 million global deaths each year (2.8%) are attributed to low fruit and vegetable consumption (World Health Organization, 2004). The percentage in the U.S. is also striking, with over 11.1% of all US Households identified as “Food Insecure” (USDA, 2018) including 9-12% of Pennsylvania households (Coleman-Jensen, Rabbit, Gregory, & Singh, 2018) and 13.7% of Allegheny County households (Sundaram, 2018). The vertical surfaces of buildings provide a significant opportunity for urban food production, while also reducing surface temperatures, improving air quality and rainwater management – the subject of this research.

Buildings in the U.S. use 76% of all electricity (Mazria & AIA, 2006); 10% for cooling in 2019 (EIA, 2020), with 9.6% of component loads due to heat gain on building surfaces (Huang & Franconi, 1999). Air Conditioning accounts for 15% of total energy costs for commercial buildings (ASi Controls, 2014). Cooling loads in the U.S. contribute 117 Million metric tons of CO2 per year, as well as other greenhouse gasses and pollutants (US Department of Energy, 2021). Air conditioning contributes 20% or more to peak power demand, challenging grid reliability (Energy Storage Center, 2013).

This leads to high façade surface temperatures and increased air conditioning exhaust which contributes to and exacerbates urban heat island effect. Annually in the U.S., 600-700 people die due to heat waves. *"Heat wave mortality risk increased 2.5% for every 1°F increase in heat wave intensity and 0.38% for every 1-day increase in heat wave duration."* (Anderson, 2010).

Air pollution kills an estimated 7 million people worldwide annually (World Health Organization, 2020). Forty-five percent of the U.S. population live in counties with unhealthy levels of particulate or ozone pollution (Hahn, 2020). Pittsburgh consistently ranks among the top ten worst cities in the U.S. for small particulates (Lynn, 2020). The lack of landscape in urban environments is correlated with a 4% increase in fine (PM_{10}) and ultra-fine ($PM_{2.5}$) dust particles (Kohler M. , 2008).

In natural ecosystems, evaporation accounts for 80% of water, with 1% going to runoff, while in the built environment evaporation is only 25%, with 70% going to runoff (Dreiseitl, 2005). In cities with combined storm sewers, the immediate runoff quantities result in combined sewer overflows (CSOs). In Pittsburgh as little as $1/10^{th}$ of an inch of rain (2.54 mm) can cause CSO's (Knauer, 2003).

Present rainwater management allows immediate building and site runoff into urban storm sewer systems resulting in increased flooding. Storm water management with grey infrastructures also increases the frequency and severity of drought compromising the hydrological cycle due to the lack of natural groundwater recharge (Lyle, 1999; Schmidt, 2009 and Dreiseitl, 2005).

Bringing nature into the city is a tradition as old as the hanging gardens of Babylon, but it is only in the late twentieth and early twenty-first centuries that this concept has matured into a strategy for incorporating plants and living systems into a performance-based approach to the design and functioning of the built environment. In Pittsburgh, the Phipps Conservatory Center for Sustainable Landscapes exemplifies this new approach integrating green roofs, indoor green walls, on site water treatment with other advanced sustainable features (Phipps Conservatory, 2021).

This new approach also includes the introduction of urban agriculture not only on land within the city, but also on top of and integrated with the green roofs and green façades of local commercial and residential buildings. Bringing productive landscape and agriculture right into the city, integrated within the building envelope itself, provides a new opportunity to increase food production on previously unproductive urban surfaces. The challenges are to quantify how much food can be produced in a temperate climate and what other benefits might be gained alongside food production.
This research answers one overriding hypothesis with three sub-hypotheses:

Living façades will increase urban food production, while simultaneously functioning to decrease urban heat, improve urban air, and decrease storm water runoff.

1: Living façades will increase urban food production, producing measurable amounts of fresh vegetables, fruit and herbs.

2: Food producing living façades will decrease façade surface temperatures during the heat of the day in summer.

3: Food producing living façades will improve air quality by reducing $PM_{2.5}$ particulates at the building façade.

4: Food producing living façades will decrease storm water runoff through the collection and redeployment of rainwater for irrigation.

7.2 A Taxonomy of Choices for Configuring Living Façades

To quantify the potential of living façades to increase urban food production and offer other environmental benefits, it is important to distinguish the types of living wall configurations and background research on their relative performance impacts. A review of more than ninety research articles helped to define types of vertical greenery systems (VGS), design variables, performance metrics and outcomes. In the book *Vertical Greenery for the Tropics,* (Wong N. H., 2009) Vertical Greenery Systems (VSG's) were defined in two general categories:

- Green Façades are support systems or trellises that are coupled with the ground
- Living Walls are containers and carrier systems with panels of growing medium to support a broader range of plant types.

In a definitive paper produced at the Queensland University of Technology Centre for Subtropical Design, *Living Walls – A Way to Green the Built Environment* (Loh, 2008), three basic green wall systems are defined.

- Panel Systems (like the Carrier System described above)
- Felt Systems, with pockets hung from a backing support
- Container and/or Trellis Systems, with a ground container to support the growth of vines

The system used at this experimental research on the south and west façades of the Intelligent Workplace living lab in Pittsburgh was a hybrid panel and trellis system, with the soil panels providing the fabricated soil mix to grow the polyculture of plants used in this study. The research installations employed a diversity of horticultural and ornamental plants and vines for cooling, air treatment and seasonal transparency of the glazed areas, and used photovoltaics to power the automated drip irrigation system using stored rainwater. The experimental installation was evaluated over six growing seasons, using a range of instruments to quantify the performance benefits of food producing living façades.

7.3 Background Literature on Living Food Producing Façades

Twenty-one papers of precedent research on living façades and more significantly food producing façades were reviewed to determine critical test bed configuration and performance measurements for food, heat, air and water impacts, with an identification of the climate region where these studies were conducted.

A majority of the research on green walls and living façades has been focused on the temperate climate region, which is the dominant climate type in the United States and in Europe. While there is a growing body of research on living façades, there is remarkably little research to date on food producing façades. Two studies will be elaborated on here.

At the time of this research, only two studies had been completed quantifying the benefits of food production on the vertical faces of buildings. At Penn State University, Nagle et al. identified that a range of 1.5– 12.7 kg/m2 of herbs and collard greens can be produced on panel based living façades in a temperate climate (Nagle, Echols, & Tamminga, 2017). At the Swedish University of Agricultural Sciences, Martensson et al. identified that edible perennials - Chives, Lesser Calamint, and Wild Strawberry – could thrive over winter in a living wall system in Malmo, Sweden (Martensson, Wuolo, Fransson, & Emilsson, 2014). These two studies offer insight into the production capability of food producing walls and the potential durability and vitality of horticultural plants as components of a living façade in cold and temperate climates. Critical validation of the veracity and replicability of these results is the purpose of this study.

A review of more than a dozen green façade and living wall studies related to thermal performance benefits, these five illustrate the typical findings. Akbari et al., identified that *"urban trees and high albedo surfaces can…reduce national energy use in air conditioning by 20% and save over $10B per year in energy use and improvement in urban air quality."* (Akbari, Pomerantz, & Taha, 2001). A field study of trellis and panel Vertical Greenery Systems (VGS) by Wong et al., identified that living walls reduced surface temperatures by 5°C (9°F) on average. In a subsequent simulation study, Wong et al. identified heat gain reductions of 10%-74% based on the extent of vertical greenery coverage (Wong N. H., 2008).

A field study of green façade exterior surface temperature differentials on a building in Northern Greece determined the average reduction was 5.7°C (10.3°F) (Eumorfopoulou & Kontoleon, 2009). An energy simulation study on the same building identified cooling load reductions of 18% on the east façade, 8% on the south, 18% on the west and 5% on the north (Kontoleon & Eumorfopoulou, 2010). Tilley et al., identified an average façade surface temperature reduction of 11°C (20°F) in green façade test cells at the University of Maryland, with a maximum of 14°C (25°F) cooler than the bare wall control (Tilley, Price, Matt, & Marrow, 2012). Perini et al., identified 17%-40% energy savings in cooling with vertical greenery systems on the south façade of an office building in Genoa, Italy (Perini, Bazzocchi, Croci, Magliocco, & Cattaneo, 2017). These findings show the surface temperature reduction and potential cooling load reduction benefit generated by green façades and living walls planted with non-edible plant varieties. Verifying that horticultural plants will yield similar façade surface temperature reductions is the second point of this study.

The four studies reviewed on the benefit of plants relative to small particulate reduction, illustrate the major findings in this area. Kohler identified a 4% reduction in annual dust-fall (PM_{10} and $PM_{2.5}$) through a maximization of green façades (trellis) and living walls (panel) in dense urban environments (Kohler M. , 2008). Variation in leaf texture and surface characteristics of three tree species, and the use of daily irrigation to increase the opportunity for wet deposition, are effective mechanisms for reducing $PM_{2.5}$ in urban environments (Wang, Gong, Liao, & Wang, 2015). The performance of four different evergreen plant species to reduce fine and ultra-fine dust particles (PM_{10} and $PM_{2.5}$) when planted in a vertical greening system was studied by Perini, et al. Shrubby, non-edible plants indicated that waxy leaves (*T. jasminoides*) collected the highest number of particulates, whereas plants with hairy leaves (*P. frucitosa*) were less effective (Perini, Ottele, Giulini, Magliocco, & Roccotiello, 2017). Petit et al. identified that fern species had a single pass removal efficiency of 46% for $PM_{0.3\text{-}0.5}$ and 92% for $PM_{5\text{-}10}$ when integrated into a bio-wall HVAC filtration system (Petit, Irga, Abdo, & Torpy, 2017). These studies show that small tree and shrub species produce leaves that provide effective surface area for small particulate deposition, effectively reducing airborne levels. Verifying that horticultural plant leaves can provide similar benefits in terms of improving air quality by reducing $PM_{2.5}$, while producing measurable amounts of fresh produce, is the third important aspect of this study.

The two most relevant studies on rainwater absorption by living façades illustrate their potential value as green infrastructure. Living façade panels planted with sedum angelina, sedum ternatum, sem-pervivum tectorum, and ajuga reptans reduced rainwater runoff an average of 52-68% (Kew, Pennypacker, & Echols, 2014). Connelly et al. identified that different vining plants will absorb different rain quantities, with Silverlace at 2.83 L/m^2 (0.07gal/ft^2), vine, Evergreen clematis at 4.28 L/m^2 (0.11gal/ft^2), and Oriental bittersweet at 5.58 L/m^2 (0.14gal/ft^2) (Connelly, Compton-Smith, Rousseau, & Huston, 2012).

7.4 Food Producing Living Façades – System Design and Food Production

After a review of living façade designs and precedent research, the design and implementation of the Intelligent Workplace food producing living façade project was developed to contribute a semi-controlled field experiment on the existing south and west façade areas of the Robert L. Preger Intelligent Workplace (IW) on the campus of Carnegie Mellon University. The IW is a 7,000 square foot living and lived-in laboratory dedicated to the research, demonstration and development of building systems integration for increasing energy efficiency and environmental effectiveness within the built environment. It is designed to be a flexible platform for building systems research and innovation, while occupied with faculty and graduate student researchers (Hartkopf, Loftness, & Aziz, 2005).

The steps necessary to conduct this experiment were to design, test, analyze and conclude the system installation, operation, performance and disassembly. The aim of this research study was to measure, record and verify performance, comparing the field data results to existing research and contributing original results not previously collected or recorded. The four sections that follow outline the data sets, analysis methods and results that confirm food producing living façades contribute measurable food production, heat gain reduction, air quality improvement and rainwater redeployment.

Food Producing Living Façades generate an average of 2 kg/m^2 of nutrition per growing season.

The primary hypothesis of this dissertation is that building façades can produce measurable amounts of fresh produce when updated with living façade assemblies planted with food producing plants. Quantification of fresh produce harvested from the south and west façade research installations was systematically documented to test this hypothesis. The same number and type of food producing crops planted on both façades each year included:

- 6 Cherry Tomato plants
- 6 Roma Tomatoes plants
- 2 Heirloom Tomato plants
- 6 Sweet Banana Pepper plants
- 6 Hot Pepper plants
- 18 Green Bean plants

Production was broken down by weight, by quantity, and by façade orientation. Replicability and fluctuations in productivity over the six growing seasons were captured and graphed as well. The goal was to quantify potential production levels attainable on a consistent basis with this type of system in this climate region, as well as to look at the potential for variety in the production output of such a system, in terms of the diversity of potential future plantings.

Vegetables, herbs and fruit grown on the living façade system were harvested as they ripened. Every vegetable and piece of fruit, as well as small bundles of herbs, were arranged on single letter sized (8.5 inch x 11.5 inch) sheets of white paper, numbered and then weighed. Each sheet of paper was photographed, and then weight and quantity were recorded in a spreadsheet database.

There are several significant conclusions drawn from this 6-year experimental study confirming that living food producing façades can produce an average of 2 kg/m^2 of nutritious fruits and vegetables for south and west orientations in the temperate climate of Pittsburgh.

- Food producing living façades can produce a maximum of 2.64 $kilograms/m^2$ of fresh produce (0.54 $lbs./ft^2$) and a six-season average of 2.04 kg/m^2 across south and west façades in a temperate climate.
- To achieve 400 grams daily of fresh fruit and vegetable production during the growing season, approximately 37 m^2 (400 ft^2) of façade would be needed per person to provide for a nutritional diet that meets WHO standards.
- Food producing living façades produce showed similar nutrient levels as store bought produce, but will support local economies and reduce embodied energy – and tastes better.

7.5 Food Producing Living Façades – Façade surface temperatures reduction

Food producing living façades reduce exterior façade surface temperatures 5.56^oC-20.53^oC (10^oF-36.95^oF).

A second hypothesis in this dissertation is that food producing living façades will measurably reduce façade surface temperature, compared to a control of that same façade, which in turn will reduce conductive heat gain and total cooling load. Temperature data was collected for the research and control façade areas over two one-week periods in August and September 2013 to show typical summer and late summer conditions.

- Air temp 1 meter away from west façade – indoors and outdoors (HOBO and Omega sensors)
- Exterior and interior surface temp - opaque west façade (HOBO U12 data logger and sensors)
- Exterior and interior surface temp - glazed west façade (HOBO U12 data logger and sensors)
- Thermographic Imaging of exterior façade (FLIR Thermal Imaging Camera)

The opaque façade temperature measurements for the week of August 5-11, 2013, reveal a number of statistically significant findings:

- The average temperature differential (ΔT) during heat gain periods was reduced by 40% to 79% for the living façade compare to the control.
- Peak exterior façade surface temperature was reduced by 20.5^{o}C (37^{o}F) on the hottest day.
- At night, the living façade kept the façade surface temperature an average 4.74^{o}C (3.77^{o}F) warmer than the control façade as temperatures dropped below comfort
- The food producing living façade reduced the length of heat gain periods for the living façade 23% to 94% on hot days.
- The length of heat gain periods was shorter for the control façade on cooler days, due to the thermal lag of the living façade.

In an effort to understand the implication of these temperature differentials for building cooling loads, the hour-by-hour comparison of the temperature changes were averaged to create a “Typical Summer Day”. On an averaged “Typical Summer Day” living façade temperatures never exceed the comfort zone upper limit of 25.6^{o}C (78^{o}F), while the control façade exceeds the comfort zone from 1 to 8 pm. The area between the exterior surface temperatures of the living façade compared to the control represent the potential contribution to the cooling load.

As a field research study in an occupied building, it was not possible to fully isolate the control and living façade test areas from the mechanical systems. However, the continuous minute by minute monitoring of interior and exterior surface temperatures for two summer weeks with a mix of sun and overcast days allowed for a statistically significant profile of surface temperatures and temperature differentials to be developed for living façades in a temperate climate. Other researchers have identified that reductions in surface temperatures and temperature differentials correspond to a reduction in air conditioning loads of 20% (Stec, Van Passen, & Maziarz, 2005) (Akbari, Pomerantz, & Taha, 2001) or greater, between 35%-68% in various cities globally (Alexandri & Jones, 2008).

7.6 Food Producing Living Façades – Air quality improvement via small particulate reduction

Food producing living façades generate 3.2%-5.6% reductions in $PM_{2.5}$ at the exterior façade.

The third hypothesis on the value of living façades was the ability to reduce outdoor air pollutants. Measurement of air quality performance focused on small particulate levels ($PM_{2.5}$) critical for improving the air quality of cities with high traffic and industrial pollution, such as Pittsburgh.

The small particulate data was collected with the IW Aircuity Optinet™ system that utilizes nanotube technology to take air samples every few minutes. Samples were pulled to a robust central sensor suite from locations on the exterior and interior of the façade.

Analysis of the exterior data for the entire seven-month period, from February to August 2014, revealed statistically significant but modest improvements in air quality due to the living façade.

- Over the monitoring period from February to August, $PM_{2.5}$ levels were 3.2% to 5.6% lower at the surface of the living façade ($p<0.001$).
- Neither façade exceeds the federal NAAQS levels of 35µg/m^3 over 24 hours, or 15µg/m^3 as an annual mean.
- Rarely does either façade exceed the American Lung Association's recommended level of 3.2µg/m^3.

7.7 Food Producing Living Façades – Rainwater Runoff Reduction

Food producing living façades can absorb 14 liters of water per m^2 per day.

To benefit the significant number of temperate climate cities with challenges of storm sewer overflow in heavy rains, quantifying irrigation water usage relative to surface area of food producing living façade was an important aspect of this study. The average irrigation requirements were measured in liters (gallons) per day throughout the growing season from May 1 to December 1, over six growing seasons.

Irrigation for the living façade assemblies was integrated with rainwater capture and storage to address predictable periods of no rain. Since rainfall is never consistent, roof rainwater capture was stored in two 45-gallon rain barrels, with an overflow capability to the building drains. To establish water requirements of the FPLF, Echo EC-5 moisture sensors were attached to a HOBO U30 monitor system which triggered the pump to turn on and off as required, and established the optimum watering quantities for the remaining seasons.

The pattern of readings for irrigation demand suggested that watering once every 24 hours was adequate for keeping the food producing plants sufficiently moist, but two days without irrigation caused the plants leaves to begin to wilt. Although solar panels were added to power the pumps for the drip irrigation system, an uneven pattern of irrigation through the automated system led to an undesirable condition called "blossom end rot" on the bottom of the Roma tomatoes. As a result, daily hand watering of the system was implemented during the growing season.

The results are significant. Food producing living façades in temperate climates can effectively redeploy 14.26 liters/m^2 (0.35 gallons/ft^2) per day of rainfall for the 214-day growing season, from May 1st to December 1st each year in the Pittsburgh climate.

This means that every 1 m^2 of living façade can absorb the rainwater from 5 m^2 of roof (54 ft^2 of roof), in combination with on-site water storage to address rainfall variability, significantly reducing storm water runoff. In the Pittsburgh climate, rainwater storage should be sized at 28.6 gallons storage per m^2 façade.

7.8 Food Producing Living Façades - Increase Biodiversity

Food producing living façades provided additional habitat where a mix of species were observed.

Food producing living façades also contribute to biophilic advantages and biodiversity. The food producing living façade developed in this thesis represent increased access to nature, with all of its dynamic, circadian and aesthetic qualities. Across the six seasons studied in this thesis, a variety of birds, spiders and insects were observed:

- American Robin
- Hawk
- Grasshopper
- Praying Mantis
- Yellow Garden Spider
- European Paper Wasp
- Northern Paper Wasp

Considering the extent of work and living environments that have no visual or physical connection to nature, in spaces too deep or too tall, the introduction of food producing living façades that bring full sensory experience to every floor is an important contribution to the quality of the indoor environment.

7.9 Implications, Limitations and Future Research

Throughout the United States and around the world, major cities have been utilizing vacant lots and flat or low-slope roof tops to develop urban farms, education programs and jobs training to support this expanding sector of urban agriculture. The surface area of urban building rooftops is only a small proportion of the overall area of the building façade on multi-story buildings. Transforming building façades into food producing living façades would, in effect, create "new land' drastically increasing the area for food production within the urban environment.

Food producing living façades could provide the 400g/day of fresh vegetables needed per person to 7-14% of the occupants of a residential or commercial building floor, entire building, or group of buildings, during the 214-day growing season in Pittsburgh, 85,600 grams or 85.6 Kg per person, based on the 2.04Kg/m^2 average production documented in this dissertation. Application of the food producing living façade to three façades of the IW (a single-story building) totaling 122.25 m^2 of façade panels, would yield 250 Kg's (551 lbs.) of produce. This is enough to provide 400g/day of fresh fruit and vegetables for three individuals out of 22 occupants or 13% of that population.

Application of the food producing living façade to all four façades of Donner House (a six-story building when renovated) totaling 1,290 m^2 would yield 2,631 kg's (5,800 lbs.) of produce; enough for 30 individuals out of 239 occupants to meet their nutritional needs or 12.5% of that population. When applied to 33 buildings of the same scale on campus, the yield would be 86,823 kg's (191,411 lbs.) of produce; enough for 1,014 individuals out of 6947 occupants or 14.6% of the campus undergraduate population.

Application of the food producing living façade to 70 ten-story Buildings in Downtown Pittsburgh would yield 2,160,000 kg's (4,762,000 lbs.) of produce. This is enough for 25,233 individuals to meet their nutritional requirements out of 15,060 downtown residents or 168% of that population, or out of 457,000 workers downtown or 5.5% of that population. When applied to 25% of commercial building façades in the United States, 186 million m^2 of façade, would yield 379,440,000 Kg's (836.5 million lbs.) of produce which is enough for 4.4 million individuals to meet their nutritional needs out of 64 million working professionals in the U.S. (DPE, 2020) or 6.9% of that population.

The annual production from food producing living façades could meet 7-14% of the nutritional needs of the population locally, a potential source for the 9-12% of Pennsylvanians who are food insecure.

Food producing living façades could absorb 0.003 inches of rainfall per m^2 of roof per day for each m^2 façade throughout the 214-day growing season in Pittsburgh. Application of the food producing living façade to three façades of the IW (a single-story building) would absorb 465 gallons per day over 122.25 m^2 of façade (3.8 gal/m^2) utilizing 100% of the rainfall on the IW roof per day (on average). Applied to all four façades of Donner House (a six-story building when renovated) would absorb 4,902 gallons per day over 1,290 m^2 of façade utilizing 100% of the rainfall on the IW roof /day.

The annual rainwater absorption from food producing living façades would utilize 100% of rainfall falling on roofs of buildings with extensive living façade installations.

This research study was limited by the variability in plant availability, due to seasonal fluctuations in the local retail supply of horticultural plant starts. Additional limitations of the study included the inability to control for variables such as the unique geometries creating installation configuration differences between the south façade at the lower roof deck, without automated solar shading louvers, and the west façade at the balcony, at the same level as the interior floor level, which did feature the automated solar shading louvers. To limit the complexity and quantity of the variables collected to a singular focus on small particulates ($PM_{2.5}$), a multi-variable air quality analysis was not conducted.

There are a number of areas that could become the focus of future research immediately if funding was available. The research results presented here provide a baseline of data in the areas of urban food, heat, air and water, upon which numerous future research studies could expand. Maximizing food production for specific species and demographics to address food insecurity tailored to specific regional and cultural tastes is a key area for additional investigation. Investigating vegetation variability for shading, including maximizing leaf area index (LAI), dynamic bioshading, and total cooling load calculations, in both energy simulation modeling and field verification is also an important area for additional research. Design development of a commercially viable, modular, food producing living façade system with integrated irrigation, closed loop water applications, including aquaponics, and automated operation with building robotics and controls could elevate this approach to the scale of urban vertical farming. Examples of integrated irrigation and closed loop water cycling can be seen in the green façade research applications of Marco Schmidt at the Adlershof Physik in Berlin. This approach features living systems integration via design and engaging the hydrological cycle from tracing and using the water through interception, redeployment, runoff collection, storage, and final flow destination, including procuring additional irrigation water by collecting it in public water features that also provide recreational and therapeutic amenities, and perhaps fish production through aquaponics applications.

In addition, full scale human health implications related to reduced mortality linked to malnutrition, heat waves, small particulate related respiratory health, and CSO's should be investigated at the community scale. Integration with ongoing initiatives should also be explored such as the Pittsburgh Downtown 2030 District, P4 Initiative, applications of the United Nations Sustainable Development Goals within Pittsburgh by Covestro and other industry partners, and specific project applications such as in Aliquippa, Pennsylvania, as identified in an EPA USDA funded Local Foods, Local Places workshop in 2019. Opportunities currently exist to apply the baseline results from this dissertation at the local, state and federal levels. Each of these applications should be a field research project gathering appropriate performance data to verify the results of this study. Applications at a large enough scale would reach a critical mass that would begin to change the energy and environmental performance of the overall built environment, replacing fossil fuel energy and materials, with biology and design intelligence, while providing ecosystems services to urban populations.

References

3 Rivers Wet Weather. (2016). *About the Wet Weather Issue*. Retrieved from 3 Rivers Wet Weather: https://www.3riverswetweather.org/about-wet-weather-issue#:~:text=As%20little%20as%20one%2Dtenth,into%20our%20rivers%20and%20streams.&text=This%20extra%20volume%20of%20water,it%20reaches%20the%20treatment%20plant.

Abel, C. (2010). The Vertical Garden City: Towards a New Urban Topology. *CTBUH Journal, 11*, pp. 20-30. Retrieved from https://global.ctbuh.org/resources/papers/download/390-the-vertical-garden-city-towards-a-new-urban-topology.pdf

AEDC. (2019, August 28-29). Aliquippa Economic Development Corporation. *Invitation: Local Foods Local Places Workshop*, 1-3. Aliquippa, PA, USA: AEDC.

Agritecture. (2018, September 17). *Greenbelly: Turning City Walls into Veritcal Farms*. Retrieved from https://www.agritecture.com/blog/2018/9/17/greenbelly-turning-city-walls-into-vertical-farms

Aircuity, Inc. (2008). *airgenuity.ca.* Retrieved from Optinet System Overview pdf: http://www.airgenuity.ca/resources/data/OptiNet-System-Overview.pdf

Akbari, H., Pomerantz, M., & Taha, H. (2001). Cool Surafaces and Shade Trees to Reduce Energy Use and Improve Air Quality in Urban Areas. *Solar Energy, 70*(3), 295-310. doi:10.1016/S0038-092X(00)00089-X

Alexandri, E., & Jones, P. (2008). Temperature Decrease in an Urban Canyon Due to Green Walls and Green Roofs in Diverse Climates. *Building and Environment, 43*(4), 480-493. doi:10.1016/j.builden.2006.10.055

American Lung Association. (2020). *State of the Air Pennsylvania: Allegheny* . Retrieved from American Lung Association State of the Air: https://www.stateoftheair.org/city-rankings/states/pennsylvania/allegheny.html

Amir, A., Yeok, F., Abdullah, A., & Rahman, A. (2011). The Most Effective Malaysian Legume Plants as Biofacade for Building Wall Application. *Journal of Sustainable Development, 4*(1), 103-111. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.665.3215&rep=rep1&type=pdf

Anderson, G., & Bell, M. (2010). Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities. *Environmental Health Perspectives, 119*(2), 210-218. doi:10.1289/ehp.1002313

Anderson, R. (2009). *The Business Logic of Sustainability [Video file]*. Retrieved from Tedx Talks: https://www.ted.com/talks/ray_anderson_the_business_logic_of_sustainability?language=en

Anderson, R. C. (1998). *Mid-Course Correction: Toward a Sustainable Enterprise :The Interface Model.* Peregrinzilla Press.

Ariaudo, F., Corgnati, S., Fracastoro, G., & Raimondo, D. (2009, June). Cooling Load Reduction by Green Walls: Results from an Experimental Campaign. *4th International Building Physics Conference.* Retrieved from https://www.researchgate.net/publication/273131709

ASi Controls. (2014, May 23). Retrieved from What Drives Energy Use in Commercial Buildings: http://www.asicontrols.com/controlling-energy-costs-commercial-building/

Babak, R., Tenpierik, M., & van den Dobbelsteen, A. (2015, May). The Impact of Greening Systems on Building Energy Performance. *Renewable and Sustainable Energy Reviews, 45*, 610-623. doi:10.1016/j.rser.2015.02.011

Bajcinovci, B., & Jerliu, F. (2016). Achieving Energy Efficiency in Accordance with Bioclimatic Architecture Principles. *Environmental and Climate Technologies, 18*, pp. 54–63. doi:10.1515/rtuect-2016-0013

Bartczak, B., & Dunbar, C. (2009). *Living Walls in the Built Environment.* Colorado State University.

Bass, B. (2007). *Green Roofs and Green Walls: Potential Energy Savings in the Winter (Report on Phase 1).* Troronto, Canada: Adaptation & Impacts Research Division, Environment Canada at the University of Toronto Centre for Environment. Retrieved from http://www.upea.com/

Bass, B., & Baskaran, B. (2003). *Evaluating Rooftop and Vertical Gardens as an Adaptation Strategy for Urban Areas.* Institute for Research in Construction, National Research Council Canada. Retrieved from http://irc.nrc.cnrc.gc.ca/ircpubs

Beaver, J. (2012). Conception of Fabricated Soil for Green Roofs and Green Walls. *Slippery Rock University Student Symposia.*

Belko, M. (2016, August 23). Granite replacing green: PNC's leafy creation Downtown will come to an end. *Pittsburgh Post-Gazette*. Retrieved from https://www.post-gazette.com/local/city/2016/08/23/PNC-s-green-wall-being-dismantled/stories/201608230085

Benefits of Green Roofs in Winter, 62, 1. (2006). Retrieved from Environzine- Environment Canada's Online Newsmagazine: http://ec.europa.eu/environment/etap

Benfey, C. (2019, December). *Harpers Magazine.* Retrieved from Burning Down the House: A Gothic Life of Frank Lloyd Wright: https://harpers.org/archive/2019/12/plagued-by-fire-the-dreams-and-furies-of-frank-lloyd-wright-paul-hendrickson/

Berlin Senate for Urban Development. (n.d.). *Institute of Physics in Berlin-Adlershof: Urban Ecological Model Projects.* [Pamphlet]. Berlin.

Blanc, P. (2008). *The Vertical Garden: From Nature to the City.* New York: Norton, W. W. & Company, Inc.

Bohn, K., & Viljoen, A. (2011). The Edible City: Envisioning the Continuous Productive Urban Landscape (CPUL). *Field, 4*(1), 160–161. Retrieved from https://www.academia.edu/5294471/The_Edible_City_Envisioning_the_Continuous_Productive_Urban_Landscape_CPUL_

Brady, N., & Weil, R. (2004). *Elements of the Nature and Properties of Soils, 2nd. Ed.* N.J.: Pearson Prentice Hall.

Braungart, M. (2012, September). C2C A Building Like a Tree. Presentation at Carnegie Mellon University. Pittsburgh, PA.

Brown, R., & Koomey, J. (2002). *Electricity Use in California: Past Trends and Present Usage Patterns.* Berkeley, CA: Ernest Orlando Lawrence Berkeley National Laboratory, University of California.

Browning, W., Ryan, C., & Clancy, J. (2014). *14 Patterns of Biophilic Design.* New York: Terrapin Bright Green LLC.

Cameron, R., Taylor, J., & Emmett, M. (2014). What's 'Cool' in the World of Green Facades? How Plant Choice Influences the Cooling Properties of Green Walls. *Building and Environment, 73*, 198-207. Retrieved from http://dx.doi.org/10.1016/j.buildenv.2013.005

Cardinale, N., & Ruggiero, F. (2000). Energetic Aspects of Bioclimatic Buildings in the Mediterranean Area: a Comparison between Two Different Computation Methods. *Energy and Buildings, 31*(1), 55-63. doi:org/10.1016/S0378-7788(99)00005-5

Carnegie Museum of Natural History. (2016). We Are Nature: Welcome to the Anthopocene [Exhibition Pamphlet]. Pittsburgh, PA.

Center for Building Performance and Diagnostics Carnegie Mellon University. (2010, November 17-19). Greenbuild Conference Poster Presentation. *10 Strategies: Living, Bioclimatic Facades for Sustainability, Human Health & Performance*. Chicago, IL.

Center for Building Performance and Diagnostics, Carnegie Mellon University. (1987). Total Building Performance Matrix. Pittsburgh, PA.

Center for Building Performance and Diagnostics, Carneigie Mellon University . (2004). *Guidelines for High Performance Building*. Retrieved from http://cbpd.arc.cmu.edu

Center for Maximum Potential Building Systems (CMPBS) and Health Care Without Harm. (2007). *Connection to the Natural World: Places of Respite (Version 2.2)*. Retrieved from http://www.gghc.org/documents/TechBriefs/GGHC_TechBrief_Places-of-Respite.pdf

Center for Urban Education about Sustainable Agriculture (CUESA). (2019). *How Far Does Food Travel to Get to Your Plate.* Retrieved from https://cuesa.org/learn/how-far-does-your-food-travel-get-your-plate

Cervinka, R., Roderer, K., & Hefler, E. (2011). Are Nature Lovers Happy? On Various Indicators of Well-Being and Connectedness with Nature. *Journal of Health Psychology, 17*(3), 379-388. doi:10.1177/1359105311416873

Coleman-Jensen, A., Rabbit, R., Gregory, C., & Singh, A. (2018). *Household Food Security in the United States in 2018.* U.S. Department of Agriculture, Economic Research Service.

Coma, J., Chafer, M., Perez, G., & Cabeza, L. (2020). How Internal Heat Loads of Building Affect the Effectiveness of Vertical Greenery Systems: An Experimental Study. *Renewable energy, 151*, 919-930. Retrieved from https://doi.org/10.1016/j.renene.2019.11.077

Connelly, M., Compton-Smith, J., Rousseau, N., & Huston, C. (2012). *Rainwater Interception Capacity of Green Façades Final Report.* British Columbia Institute of Technology, School of Construction and the Environment. Vancouver: BCIT Centre for Architectural Ecology.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., . . . van den Belt, M. (1997). The Value of the World's Ecosystem Services and Natural Capital. *Nature, 387*, 253-260. doi:10.1038/387253a0

Covestro North America. (2019). *Covestro announces THINC30 lineup for 2019*. Retrieved September 2019, from covestro.us: https://www.covestro.us/en/media/news-releases/2019-news-releases/2019-04-23-thinc30-lineup

Croce, F., Katrini, E., Ramesh, S., & Magnusen, K. (2012). Integrated Systems Approach for Improved Energy Performance Human Comfort and Campus Quality: Comparing Extension and Retrofit Opportuities at Donner House Dormitory. Pittsburgh, PA: Course 48-723 Performance of Advanced Building Systems, Carnegie Mellon University.

Culgan, R., & Deppen, C. (2018, October 15). *Fresh Divide: Inside Pittsburgh's Food Deserts, Where Buying Milk or Veggies is Impossible*. Retrieved July 20, 2019, from TheIncline: https://archive.theincline.com/2018/10/15/fresh-divide-inside-pittsburghs-food-deserts-where-buying-milk-or-veggies-is-impossible/

Culley, P. (2018). *Designing with Nature as Practice Presentation.* Pittsburgh, PA: Carnegie Mellon University.

Currie, B. A., & Bass, B. (2008). Estimates of Air Pollution Mitigation with Green Plants and Green Roofs Using the UFORE Model. *Urban Ecosyst, 11*, 409–422. doi:10.1007/s11252-008-0054-y

Cusick, D. (2020, July 16). Chicago Learned Climate Lessons from Its Deadly 1995 Heat Wave. Retrieved from https://www.scientificamerican.com/article/chicago-learned-climate-lessons-from-its-deadly-1995-heat-wave1/#:~:text=By%20the%20end%20of%20the,Harvey%20(107)%2C%20combined.

Dahanayake, K., & Chow, C. (2018). Comparing Reduction of Building Cooling Load through Green Roofs. *Building Simulation, 11*, 421-434. doi:10.1007/s12273-017-0415-7

Davis, M., & Himer, S. (2015). The Potential for Vertical Gardens as Evaporative Coolers: An Adaptation of the 'Penman Monteith Equation'. *Building and Environment, 92*, 135-141. doi:10.1016/j.buildenv.2015.03.033

Davis, M., Ramirez, F., & Perez, M. (2016). More than just a Green Façade: Vertical Gardens as Active Air Condtioning Units. *Procedia Engineering, 145*, 1250-1257. doi:10.1016/j.proeng.2016.04.161

Davis, M., Ramirez, F., & Vallejo, A. (2015). Vertical Gardens as Swamp Coolers, International Conference on Sustainable Design, Engineering and Construction. *Procedia Engineering, 118*, 145-159.

Davis, M., Tenpierik, M., Remirez, F., & Perez, M. (2017). More than Just a Green Façade: The Sound Absorption Properties of a Vertical Garden with and without Plants. *Building and Environment*, pp. 64-72. doi:10.1016/j.buildenv.2017.01.010

Deforest, A. (2010). Down (Town) on the Farm. *Sustainable Industries*, pp. 24-30. Retrieved from http://sustainableindustries.com/articles/2010/08down-town-farm

Department for Professional Employees - AFL-CIO. (2020, January 10). *The Professional and Technical Workforce: By the Numbers*. Retrieved January 4, 2020, from dpeaflcio.org: https://www.dpeaflcio.org/factsheets/the-professional-and-technical-workforce-by-the-numbers

Dimoudi, A., & Nikolopoulou, M. (2003). Vegitation in the Urban Enviornoment: Microclimatic Analysis and Benefits. *Energy and Buildings, 35*(1), 69-76. doi:org/10.1016/S0378-7788(02)00081-6

Djedjig, R., Bozonnet, E., & Belarbi, R. (2014, October). A hygrothermal model of green walls interactions in street canyons. *Third International Conference on Countermeasures to Urban Heat Island.* Venice, Italy. Retrieved from https://www.researchgate.net/publication/268801813

Dreiseitl, H. (2005, April 26). Planning, Building and Designing with Water. *Waterways*, 92. Pittsburgh, Pennsylvania, USA: Atelier Dreiseitl.

Drummond, M., & Loveland, T. (2010). Land-use Pressure and a Transition to Forest-Cover Loss in the Eastern United States. *BioScience, 60*(4), pp. 286-298.

Dunnett, N., & Kingsbury, N. (2008). *Planting Green Roofs and Living Walls* (2nd ed.). Portland, OR: Timber Press, Inc.

Ecological Footprint. (2019). Retrieved January 16, 2019, from Wikipedia: https://en.wikipedia.org/wiki/Ecological_footprint

Ecosystem. (2019). Retrieved Februrary 21, 2019, from Wikipedia: https://en.wikipedia.org/wiki/Ecosystem

EIA. (2019, July 10). *U.S. Electricity Flow, 2018.* Retrieved from Energy Information Adminstration: https://www.eia.gov/totalenergy/data/monthly/pdf/flow/electricity.pdf

EIA. (2020, January 10). *Commercial Buildings Energy Consumption Survey 2003 Data*. Retrieved 2011, from Energy Information Administration: https://www.eia.gov/consumption/commercial/data/2003/

Energy Innovation Center. (2020). *Energy Innovation Center*. Retrieved January 10, 2020, from eicpittsburgh.org: http://www.eicpittsburgh.org/

Energy Solutions Center. (2008). *What is the Shading Coefficient*. Retrieved September 20, 2020, from Glass on Web: https://www.glassonweb.com/news/what-shading-coefficient

Energy Storage Center. (2013, February 24). *Reduction of Peak AC Demand*. Retrieved from The ESA Blog: https://energystorage.org/reduction-of-peak-ac-demand/#:~:text=In%20many%20regions%20of%20the,demand%20(May%2DOctober).

EPA. (2020, January 10). *U.S. Environmental Protection Agency Smart Growth Local Foods Local Places*. Retrieved August 27, 2019, from epa.gove: https://www.epa.gov/smartgrowth/local-foods-local-places

Ernst Haeckel. (2019). *Wikipedia*. Retrieved February 20, 2019, from https://en.wikipedia.org/wiki/Ernst_Haeckel

Etchells, F., & Corbusier, L. (1968). *Towards a New Architecture.* New York: Dover Publications.

Eumorfopoulou, E. A., & Kontoleon, K. J. (2009). Expirmental Approach to the Contribution of Plant-Covered Walls to the Thermal Behaviour Building Envelopes. *Building and Environmnet, 44*, 1024-1038. doi:10.1016/j.buildenv.2008.07.004

Farid, F., Ahmad, S., Raub, A., & Shaari, M. (2016). Green “Breathing Facades” for Occupants’ Improved Quality of Life. *Procedia - Social and Behavioral Sciences, 234*, 173 – 184. doi:10.1016/j.sbspro.2016.10.232

Feng, W., Xiaosong, Z., Junjie, T., & Xiuwei, L. (2011). The Thermal Performance of Double Skin Façade with Tillandsia Usneoides Plant Curtain. *Energy and Buildings, 43*(9), 2127-2133. Retrieved from https://doi.org/10.1016/j.enbuild.2011.04.021

Ferrante, A., & Mihalakakou, G. (2001). The Influence of Water, Green and Selected Passive Techniques on the Rehabilitation of Historical Industrial Buildings in Urban Areas. *Solar Energy, 70*(3), 245-253. doi:org/10.1016/S0038-092X(00)00100-6

Field, C., Behrenfeld, M., Randerson, J., & Falkowski, P. (1998). Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science, 281*, pp. 237-240. doi:10.1126/science.281.5374.237

Fischetti, M. (2008). *How Do Green Roofs Work?* Retrieved from http://www.scientificamerican.com/article.cfm?id=living-cover

Fitch, J. M. (1972). *American Building 2: The Environmental Forces That Shape It* (2nd ed.). New York: Schocken Books.

Fitch, J. M. (1999). *American Building: The Environmental Forces That Shape It.* (New ed.). New York: Oxford Press.

Food and Agriculture Organization of the United Nations. (2009, March 3). High-Level Expert Forum 2050 Global Agriculture. *How to Feed the World 2050.* Rome. Retrieved from http://www.fao.org/fileadmin/templates/wsfs/docs/expert_paper/How_to_Feed_the_World_in_2050.pdf

Forman, Mostafavi, & Christensen. (2012). Roots to Our Ecology and Built Future. In *Instigations Engaging Architecture, Landscape and the City.* Cambridge, MA: Harvard University Graduate School of Design.

Fox, J., & De Pooter, N. (2017). The Effect of Building Facades on Outdoor Microclimate –Dependence Model Development Using Terrestrial Thermography and Multivariate Analysis. *Procedia Engineering, 180*, pp. 1326-1334. doi:10.1016/j.proeng.2017.04.295

Gerhardt, C., & Vale, B. (2010). *Comparison of Resource Use and Environmental Performance of Green Walls with Façade Greenings and Extensive Green Roofs.* School of Architecture, University of Wellington.

Ghazalli, A. J., Brack, C., Bai, X., & Said, I. (2019). Physical and Non-Physical Benefits of Vertical Greenery Systems: A Review. *Journal of Urban Technology, 26*(4), 53-78. doi:10.1080/10630732.2019.1637694

Glasshouse Museum. (2009, April 21). *Green Box: The Sustainable Garden-House of the Future. [Pamphlet].* New York City.

Global Footprint Network. (2020). *Glossary*. Retrieved February 20, 2020, from https://www.footprintnetwork.org/resources/glossary/?_ga=2.20207736.1114422926.1609104186-1450512685.1609104186

Gorsevski, V., Quattrochi, D., & Luvall, J. (1997). Air Pollution Prevention Through Urban Heat Island Mitigation: An Update on the Urban Heat Island Pilot Project. Retrieved from https://www.researchgate.net/publication/237338072_Air_Pollution_Prevention_Through_Urban_Heat_Island_Mitigation_An_Update_on_the_Urban_Heat_Island_Pilot_Project

Gray, R. (2015). Building a Research Agenda for Creating Sustainable and Inclusive Communities for All. *Cityscape: A Journal For Policy and Development, 17*(2).

Greater Pittsburgh Community Food Bank. (2016, April). *Hunger Profile Allegheny County.* Retrieved from https://www.pittsburghfoodbank.org/wp-content/uploads/2018/04/Allegheny-hunger-profile-April-2016.pdf

Green and Energy Efficient Roofs Subcommittee-Roofs. (2010). Retrieved from http://consensus.fsu.edu/FBC/2010-Florida-Energy-Code/Green%20and%20Energy%20Efficient%20Roofs%20Research.pdf

Green Roofs for Healthy Cities. (2007). Retrieved from Bibliography of Green Roof Articles in English: http://www.greenroofs.org

Green Roofs in Winter: Hot Design for a Cold Climate. (2005, November 26). *ScienceDaily*.

Greenbuild Conference Poster Presentation. (2010, November 17-19). Chicago, IL.

Greenscreen. (2015, September 3). *Considerations For Advanced Green Facade Design*. Retrieved February 1, 2018, from http://greenscreen.com/docs/Education/greenscreen_Advanced%20Green%20Facade%20Design_White%20Paper.pdf

Grinde, B., & Patil, G. (2009). Biophilia: Does Visual Contact with Nature Impact on Health and Well-Being? *Int. J. Environ. Res. Public Health*, 2332-2343. doi:10.3390/ijerph6092332

Grobman, Y., & Elimelech, Y. (2016). Microclimate on Building Envelopes: Testing Geometry Manipulations as an Approach for Increasing Building Envelopes' Thermal Performance. *Architectural Science Review, 59*(4). doi:10.1080/00038628.2015.1025688

Hahn, J. (2020, April 21). *Sierra National Magazine of the Sierra Club*. Retrieved from Nearly Half of the US Population is Breathing Dirty Air: https://www.sierraclub.org/sierra/nearly-half-us-population-breathing-dirty-air-american-lung-association-state-of-the-air

Hartkopf, V. (2005, April 28). Water in the Built Environment [Slide Presentation]. *Economicology Meeting.* Acquinas College. Grand Rapids, MI.

Hartkopf, V. (2011, October 21). Systems Integration for High Performance Buildings Communities, Urbanities, Regions [Slide Presentation]. *International Conference for Enhanced Building Operations*. New York City.

Hartkopf, V., & Loftness, V. (1999). Global Relevance of Total Building Performance. *Automation in Construction, 8*(4), 377-393. doi:org/10.1016/S0926-5805(98)00085-5

Hartkopf, V., & Loftness, V. (n.d.). *Transforming the Built Environment through the Internet of Things [Slide presentation].* Vienna.

Hartkopf, V., Aziz, A., & Loftness, V. (2013). Facades and Enclosures, Building for Sustainability. In V. Loftness, & D. Haase (Eds.), *Sustainable Built Environments.* New York: Springer.

Hartkopf, V., Loftness, V., & Aziz, A. (2005). The Robert L. Preger Intelligent Workplace and the Building as Power Plant / Invention Works at Carnegie Mellon University. In D. Clements-Croome, *Creating the Productive Workplace* (pp. 324-333). New York: Taylor & Francis. Retrieved from https://www.researchgate.net/publication/279190533_Creating_the_Productive_Workplace

Hartkopf, V., Yang, X., & Aziz, A. (2009). *Case-studies of High Performance Sustainable Buildings.* Paris: UNEP Sustainable Buildings & Climate Initiative. Retrieved from https://www.scribd.com/document/40966506/Paris-Case-Studies-Summary

Hawken, P. (1993). *The Ecology of Commerce: A Declaration of Sustainability.* New York: HarperCollins.

Hirst, J., Morley, J., & Bang, K. (2008). Functional Landscapes: Assessing Elements of Seattle Green Factor. *Internship Report*.

Huang, J., & Franconi, E. (1999). *Commercial Heating and Cooling Loads Component Analysis.* University of California, Building Technologies Department. Berkeley: Lawrence Berkeley National Laboratory.

Ignatius, M. (2015). *Urban Microclimate Analysis with Consideration of Local Ambient Temperature, External Heat Gain, Urban Ventilation, and Outdoor Thermal Comfort in the Tropics*. Retrieved June 10, 2018

Iowa Public Television. (2018, May 8). *George Washington Carver: An Uncommon Life.* Retrieved from YouTube: https://www.youtube.com/watch?v=_3CVmluYFtI

Ip, K., Lam, M., & Miller, A. (2010). Shading performance of a vertical deciduous climbing plant canopy. *Building and Environment, 45*, 81-88. doi:10.1016/j.buildenv.2009.05.003

Irwin, G. (2010, October 1). *Green Wall Research, Full Steam Ahead! [Online]* . Retrieved from www.greenroofs.com .

Jackson, W. (2013). Global Food Systems, Global Food Systems Forum: Food 2025, University of California Agriculture and Natural Resources,. Retrieved from https://www.youtube.com/watch?v=SE7_8MsTepY

Jan Ingenhousz. (2017). *Wikipedia*. Retrieved December 8, 2017, from https://en.wikipedia.org/wiki/Jan_Ingenhousz

Jones, N. (2011). *Human Influence Comes of Age: Geologists debate epoch to mark effects of Homo sapiens*. Retrieved January 22, 2018, from Nature: https://www.nature.com/news/2011/110510/full/473133a.html

Kaminski, M. (2011). *Landscaping with Native Plants, EPA Fact Sheet*. Retrieved from http://www.epa.gov/greenacres/nativeplants/factsht.html

Kannamma, D., & Sundaram, A. (2014). Design Best Practice Methods to Minimize the Impact of Building Material on Urban Microclimate. *30th International PLEA Conference, 16-18 December 2014.* Ahmedabad: CEPT University.

Kazemi, F. M. (2014). Evaluation of the Roles and Effects of Growing Media on Green Roofs and Green Walls in Arid and Semi-arid Climates. (E. Ltd., Ed.) *Elsevier Editorial for Building and Environment Draft Manuscript*.

Kazemi, F. M. (2014). Evaluation of the Roles and Effects of Growing Media on Green Roofs and Green Walls in Arid and Semi-arid Climates. *Elsevier Editorial for Building and Environment Draft Manuscript*.

Kefeli, V. (2004). *Biological Processes in the Native and Fabricated Soil for Green Biomass Accumulation.*

Kefeli, V. M. (2011). *Regenerative Cycles in Biomass Formation and Bio-Fuel Production.* Beaver, PA: Sustainable Home Designs, LLC.

Kefeli, V., Leininger, C., Mastalski, S., Rihn, B., & Epley, D. (2013, April). The ReDirt Project: Creating Fabricated Soil from Waste River Silt for Urban Brownfield Regeneration at the ALMONO Site in Hazelwood, Pittsburgh, Pennsylvania. *Internatiional Journal of Applied Science and Technology, 3*(4), 100-117. Retrieved from http://www.ijastnet.com/journal/index/454

Kellert, S. R. (2008). *Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life.* New York: Wiley Co.

Kemper, N. (2018, April 18). *Vivian Loftness on Biophilia and Why We Must Design Buildings Connected to Nature*. Retrieved from http://commonedge.org/vivian-loftness-on-biophilia-and-why-we-must-design-buildings-connected-to-nature/

Kew, B., Pennypacker, E., & Echols, S. (2014). Can Greenwalls Contribute to Stormwater Management? A Study of Cistern Storage Greenwall First Flush Capture. *Journal of Green Building, 9*(3), 85-99. Retrieved from http://meridian.allenpress.com/jgb/article-pdf/9/3/85/1765666/1943-4618-9_3_85.pdf

Klein-Banai, C. (2015). *Public Health and Sustainability*. Retrieved January 14, 2018, from https://cnx.org/contents/YISu827b@2/Public-Health-and-Sustainability

Knauer, J. (2003). *Water Quality Report.* Pittsburgh, PA: Studio for Creative Inquiry Press.

Kohler, C., Shukla, Y., & Rawal, R. (2017). *Calculating the Effect of External Shading on the Solar Heat Gain Coefficient of Windows.* Energy Technolgies Area. Berkeley, USA: Lawrence Berkley National Laboratory.

Kohler, M. (2006). Long-Term Vegetation Research on Two Extensive Green Roofs in Berlin. *Urban Habitats, 4*(1), 3-26. Retrieved from http://www.urbanhabitats.org/v04n01/berlin_full.html

Kohler, M. (2008). Green Facades—a View Back and Some Visions. *Urban Ecosystems, 11*(4), 423–436. doi:10.1007/s11252-008-0063-x

Kohler, M. (2011). *Manfried Kohler Publications*. Retrieved from http://www.gruendach-mv.de/publications.htm

Kontoleon, K., & Eumorfopoulou, E. (2010). The Effect of the Orientation and Proportion of a Plant-Covered Wall Layer on theTthemal Performance of a Building Zone. *Building and Environment, 45*, 1287–1303. doi:10.1016/j.buildenv.2009.11.013

Kuo, F. (2003). *The Role of Arboriculture in a Healthy Social Ecology: Social Aspects of Urban Forestry*. Retrieved from http://nrs.fs.fed.us/pubs/jrnl/2003/nc_2003_kuo_001.pdf

LaBar, J. (2018, January 9). *One of the Greenest Buildings in the World Marks Five Year Anniversary*. Retrieved October 6, 2019, from phipps.conservatory.org: https://www.phipps.conservatory.org/press-room/press-releases/one-of-the-greenest-buildings-in-the-world-marks-five-year-anniversary

Lam, K. P. (2008, October 21). Urban Heat Island. *Presentation given at Carnegie Mellon University*.

Lang, A., Chailakhyan, M., & Frolova, A. (1977). Promotion and Inhibition of Flower Formation in a Dayneutral Plant in Grafts with a Short-Day Plant and a Long-Day Plant. *Proceedings of the National Academy of Science*, *74, No. 6*, pp. 2412-2416. doi:10.1073/pnas.74.6.2412

Lee, H. &. (2006). Aesthetics and Cooling – Green Roofs and Walls: Research on the scenic Meaning of Rooftop Greening with Semantic Differential Measure and Join-Count Statistics. *2006 Greening Rooftops for Sustainable Communities Confereence Proceedings.*

LEED v4: The Future of Green Building is Here. (2016). Retrieved July 6, 2016, from http://www.usgbc.org/leed-v4

Leng, O., & Sia, A. (Eds.). (2002). *Handbook on Skyrise Greening in Singapore,.* National Park Board and the Centre for Total Building Performance at National University of Singapore.

Li, J., Zheng, B., Shen, W., Xiang, Y., Chen, X., & Qi, Z. (2019). Cooling and Energy-Saving Performance of Different Green Wall Design: A Simulation Study of a Block. *Energies, 12*(2912), 1-17. doi:10.3390/en12152912

Liebard, A., & de Herde, A. (n.d.). *Bioclimatic Facades.* Bonneville, France: Somfy Architecture. Retrieved from https://docplayer.net/18002610-Bioclimatic-facades-alain-liebard-andre-de-herde.html

Lincoln, A. (1859, September 30). An Address by Abraham Lincoln Before the Wisconsin State Agricultural Society. Milwaukee, Wisconsin.

Littlefair, P. (2001). Daylight, Sunlight and Solar Gain in the Urban Environment. *Solar Energy, 70*(3), 177-185. doi:10.1016/S0038-092X(00)00099-2

Loftness, V., Cochran, E., & Srivastava, R. (2013). *Building Investment Decision Support for Six Energy Efficient Lighting Retrofits: Recommendations for Triple Bottom Line Saving Recommendations for Triple Bottom Line Savings, EEB Hub Report, A U.S. DOE Energy Innovation Hub.* Center for Building Performance and Diagnostics. Pittsburgh, PA: Carnegie Mellon University.

Loftness, V., Hakkinen, B., Adan, O., & Nevalainen, A. (2007). Elements That Contribute to Healthy Building Design. *Environmental Health Perspectives, 115*(6). doi:10.1289/ehp.8988

Loftness, V., Hartkopf, V., & Aziz, A. (2011). Building Investment Decision Support (BIDSTM) for Green Builkding Technologies. In S. Lahlow (Ed.), *Systems Innovation for Sustainability 4: Case Studies in Sustainable Consumption and Productions- Energy Use and the Built Environment* (pp. 108-135). Sheffield, United Kingdom: Greenleaf Publishing. doi:10.432/9781351279321

Loftness, V., Hartkopf, V., & Lam, K. P. (2006, June 4-6). Sustainability and Health are Integral Goals for the Built Environmentrmance. *Healthy Buildings 2006*. Lisbon, Portugal.

Loftness, V., Hartkopf, V., Guretekin, B., Hua, Y., Qu, M., Snyder, M., . . . Yang, X. (2013). *Building Investment Decision Support (BIDS): Cost Benefit Tool to Promote High Performance Components, Flexible Infrastructures and Systems Integration for Sustainable Commercial Buildings and Productive Organizations.* Pittsburgh, PA: Carnegie Mellon University Center for Building Performance and Diagnostics. Retrieved from https://www.brikbase.org/sites/default/files/aiab080586_01.pdf

Loftness, V., Lam, K. P., & Hartkopf, V. (2005). Education and Environmental Performance-Based Design: A Carnegie Mellon Perspective. *Building Research and Information, 33*(2), 196-203. doi:DOI: 10.1080/0961321042000325336

Loh, S. (2008). Living walls - a way to green the built environment. *Environment Design Guide, TEC(26)*, 1-7.

Lopez-Rodriguez, G., Perez-Esteban, J., Ruiz-Fernandez, J., & Masaguer, A. (2016). Behavior and Evolution of Sustainable Organic Substrates in a Vertical Garden. *Ecological Engineering, 93*, 129-134. doi:10.1016/j.ecoleng.2016.05.020.

Lundholm, J. (2006). Green Roofs and Facades: A Habitat Template Approach. *Urban Habitats, 4*(1), 87-101. Retrieved from http://www.urbanhabitats.org/v04n01/habitat_pdf.pdf

Lyle, J. T. (1994). *Regenerative Design for Sustainable Development.* New York: John Wiley & Sons.

Lynn, H. (2020, April 22). Report: Pittsburgh ranked 8th worst for air polution among US cities. Retrieved from https://www.pghcitypaper.com/pittsburgh/report-pittsburgh-ranked-8th-worst-for-air-pollution-among-us-cities/Content?oid=17179037

Maclean, H. P. (1993). *Fusing Concept with Practice:.* AIA.

Manso, M., & Castro-Gomez, J. (2015). Green Wall Systems: A Review of Their Characteristics. *Renewable and Sustainable Energy Reviews, 41*, 863-871. doi:10.1016/j.rser.2014.07.203

Martensson, L. M., Wuolo, A., Fransson, A. M., & Emilsson, T. (2014). Plant Performance in Living Wall Systems in the Scandinavian Climate. *Ecological Engineering, 71*, 610-614. doi:10.1016/j.ecoleng.2014.07.027

Matson, J. (2012, May 1). *Scientific American.* Retrieved from Food Deserts Leave Many Americans High and Dry: https://www.scientificamerican.com/article/high-and-dry-in-the-food/

Matt, S. (2012). *Green Facades Provide Habitat for Arthropods on Buildings in the Washington, D.C. Metro Area.* (Unpublished master's thesis). University of Maryland, College Park, MD.

Mazria, E., & AIA. (2006, July 7). Retrieved January 22, 2018, from Architects and Climate Change: http://filelibrary.associationsites.com/aia/collection/Walk_the_Walk/Supporting_Docs/architectsandclimatechange.pdf

McCart, M. (2019). Mapping Hunger: Where are Pittsburgh's Food Deserts? *Pittsbrugh Post-Gazette*. Retrieved March 26, 2019, from https://newsinteractive.post-gazette.com/food-deserts/

Metabolism. (2019). *Wikipedia*. Retrieved February 20, 2019, from https://en.wikipedia.org/wiki/Metabolism

Millennium Ecosystem Assessment. (2005). *Living Beyond Our Means Natural Assets and Human Well Being Statement from the Board.* Retrieved June 15, 2019, from https://www.millenniumassessment.org/documents/document.429.aspx.pdf

Mok, K. (2017, June 8). *World's Largest Vertical Garden Hosts 115,000 Plants to Create "Living Building" (Video)*. Retrieved from https://www.treehugger.com/green-architecture/santalaia-vertical-garden-building-paisajismo-urbano-groncol.html

Nagengast, A. L. (2013). Energy Performance Impacts from Competing Low-slope Roofing Choices and Photovoltaic Technologies [Unpublished doctoral dissertation]. Carnegie Mellon University.

Nagle, L., Echols, S., & Tamminga, K. (2017). Food production on a living wall: Pilot study. *Journal of Green Building, 12*(3), 23-38. doi:10.3992/1943-4618.12.3.23

Napier, J. (2015). Climate Based Façade Design for Business Buildings with Examples from Central London. *Buildings, 5*, pp. 16-38. doi:10.3390/buildings5010016

National Geographic. (2019, 04). Cities of the Future. *National Geogrpahic Magazine Special Issue: Cities*, p. 21.

National Institute of Food and Agriculture. (2010). *Agriculture and Food Research Initiative Competitive Grants Program Sustainable Bioenergy FY 2010 Request for Applications [Initial Announcement] .* United States Department of Agriculture, Washington, DC.

Nedlaw Living Walls. (2018, April 4). Living Wall Biofilter. *Nedlaw Interactive Brochure 04.18*, 1-12. Breslau, Ontario, Canada: Nedlaw Group. Retrieved 2018, from http://nedlawlivingwalls.com/wp-content/uploads/sites/4/2018/04/Nedlaw_Interactive_Brochure_04.18.pdf

Nikolopoulou, M., Baker, N., & Steermers, K. (2001). Thermal Comfort in Outdoor Urban Spaces: Understanding the Human Parameter. *Solar Energy, 70*(3), 227-235. doi:org/10.1016/S0038-092X(00)00093-1

NWS. (2020). *NWS Pittsburgh Records Climate Data.* Retrieved from National Weather Service: https://www.weather.gov/pbz/pit_records

Oak Ridge National Laboratory. (2001). *Worldwide Historical Estimates of Leaf Area Index, 1932-2000 (ORNL/TM-2001/268).*

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R., Doshi, H., Dunnett, N., . . . Rowe, B. (2007). Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. *57*(10), 823-833. doi:10.1641/B571005

Odum, E. P. (1993). *Ecology and Our Endangered Life-Support Systems* (2nd ed.). Sutherland, MA: Sinauer Associates, Inc.

Olgyay, V. (1963). *Design with Climate: Bioclimatic Approach to Architectural Regionalism.* Princeton, NJ: Princeton University Press.

Onder, S., & Dursun, S. (2011). Global Climate Changes and Effects on Urban Climate of Urban Green Spaces. *International Journal of Thermal and Environmental Engineering, 3*(1), 37-41. doi:10.5383/ijtee.03.01.006

Organic Architecture. (2020). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Organic_architecture

Orr, D. (1994). *Earth in Mind: On Education, Environment, and the Human Prospect.* Washington, DC: Island Press.

Othman, A., & Sahadin, N. (2016). Vertical Greening Façade as Passive Approach in Sustainable Design. *222*, 845-854. doi:10.1016/j.sbspro.2016.05.185

Ottele, M., Perini, K., Fraaij, A., Haas, E., & Raiten, R. (2011). 6.2 Comparative life cycle analysis for green facades and living wall systems. In M. Ottele, *The Green Building Envelope Vertical Greening* (pp. 210-232). Rotterdam: University of Delft. Retrieved from https://repository.tudelft.nl/islandora/object/uuid%3A1e38e393-ca5c-45af-a4fe-31496195b88d

Ottele, M., Van Bohemen, H. D., & Fraaij, A. L. (2010). Quantifying the Deposition of Particulate Matter on Climber Vegetation on Living Walls. *Ecological Engineering, 36*(2), 154-162. doi:10.1016/j.ecoleng.2009.02.007

Overbey, D. (2015, May 18). *Comparing Solar Heat Gain Coefficients (SHGC) and Shading Coefficients (SC)*. Retrieved from Walls & Ceilings: https://www.wconline.com/blogs/14-walls-ceilings-blog/post/89661-comparing-solar-heat-gain-coefficients-shgc-and-shading-coefficients-sc

Park, J., Leininger, C., Hartkopf, V., & Kviz, B. (2013). Campus Food Waste Management: Developing a Comprehensive Food Waste Management System for Green Campus. *AASHE Conference & Expo* (pp. 1-32). Nashville: Association for the Advancement of Sustainability in Higher Education.

Paull, N., Krix, D., Torpy, F., & Irga, P. (2020). Can Green Walls Reduce Outdoor Ambient Particulate Matter, Noise Pollution and Temperature? *International Journal of Environmental Research and Public Health, 17*(5084), 1-19. doi:doi:10.3390/ijerph17145084

PDT Architects. (2017). *Living Facades.* Retrieved June 10, 2018, from http://pdt.com.au/think-tank/living-facades-blg-21

Peck, S. &. (2009). *Green Wall Research Funding Awarded BCIT (Press Release)* . Retrieved from http://www.greenroofs.org

Peck, S. W., Callaghan, C., Kuhn, M., & Bass, B. (1999). *Greenbacks from Green Roofs: Forging a New Industry in Canada.* Status Report on Benefits, Barriers and Opportunities for Green Roof and Vertical Garden Technology Diffusion, Canada Mortgage and Housing Corporation. Retrieved from https://commons.bcit.ca/greenroof/files/2012/01/Greenbacks.pdf

Peck, S., & Kuhn, M. (2003). *Design Guidelines for Green Roofs.* Toronto: Ontario Association of Architects.

Perez, G., Coma, J., Martorell, I., & Cabeza, L. (2014). Vertical Greenery Systems (VGS) for energy saving in buildings: A review. *Renewable and Sustainable Energy Reviews, 39*, 139-165. doi:10.1016/j.rser.2014.07.055

Perini, K., Bazzocchi, F., Croci, L., Magliocco, A., & Cattaneo, E. (2017). The Use of Vertical Greening Systems to Reduce the Energy Demand for Air Conditioning, Field Monitoring in Mediterranean Climate. *Energy and Buildings, 143*, 35-42. doi:10.1016/j.enbuild.2017.03.036

Perini, K., Ottele, M., & Raiteri, R. (2011). Greening the Building Envelope, Façade Greening and Living Wall Systems. *Open Journal of Ecology, 1*(1), 1-8. doi:10.4236/oje.2011.11001

Perini, K., Ottele, M., Fraaij, A. L., Haas, E. M., & Raiteri, R. (2011). Vertical Greening Systems and the Effect on Air Flow and Temperature on the Building Envelope. *Building and Environment, 46*(11), 2287-2294. doi:10.1016/j.buildenv.2011.05.009

Perini, K., Ottele, M., Giulini, S., Magliocco, A., & Roccotiello, E. (2017). Quanitfication of Fine Dust Deposition on Different Plant Species in a Vertical Greening System. *Ecological Engineering, 100*, 268-270. doi:10.1016/j.ecolenj.2016.12.032

Petit, T., Irga, P., Abdo, P., & Torpy, F. (2017). Do the Plants in Functional Green Walls Contribute to Their Ability to Filter Particulate Matter? *Building and Environment, 125*, 299-307. doi:10.1016/j.buildenv.2017.09.004

Phipps Conservatory. (2021). *Phipps Green Innovation*. Retrieved from Center for Sustainable Landscapes: https://www.phipps.conservatory.org/green-innovation/at-phipps/center-for-sustainable-landscapes-greenest-building-museum-garden-in-the-world

Pittsburgh Downtown Partnership. (2016). *2016 State of the Downtown Report.* Pittsburgh, PA: Pittsburgh Downtown Partnership. Retrieved 2018, from https://downtownpittsburgh.com/wp-content/themes/downtownpittsburgh/downloads/state-of-downtown-report-2016-web-final.pdf

Prazak, J., Sir, M., & Tesar, M. (1994). Estimation of Plant Transpiration from Meteorological Data under Conditions of Sufficient Soil Moisture. *Journal of Hydrology, 162*(3-4), 409-427. doi:10.1016/0022-1694(94)90239-9

Previtali, M. e. (2013). Rigorous Procedure for Mapping Thermal Infrared Images on Three-Dimensional Models of Building Façades. *Journal of Applied Remote Sensing, 7(1):073503*.

Price, J. W. (2010). *Green Facade Energetics.* (Unpublished Master's Thesis). University of Maryland, College Park, MD.

Rachel Carson Institute. (2019). *Brochure*. Pittsburgh, PA: Chatham Univeristy.

Radi, M., Dodig, M. B., & Auer, T. (2019). Green Facades and Living Walls—A Review Establishing the Classification of Construction Types and Mapping the Benefits. *Sustainability, 11*. doi:10.3390/su11174579

Raji, A., Tenpierik, M., & Van Den Dobbelsteen, A. (2015). The Impact of Greening Systems on Building Energy Performance: A Literature Review. *Renewable and Sustainable Energy Reviews, 45*, 610-623. doi:10.1016/j.rser.2015.02.011

Romm, J. J., & Browning, W. D. (1998). *Greening the Building and the Botton Line: Increasing Productivity Through Energy-Efficient Design.* Snowmass, CO: Rocky Mountain Institute.

Rosasco, P., & Perini, K. (2013). Cost-Benefit Analysis for Green Facades and Living Wall Systems. *Building and Environment, 70*, 110-121. doi:10.1016/j.buildenv.2013.08.012

Roulet, C. A. (2001). Solar Energy and Global Heat Balance of a City. *Solar Energy, 70*(3), 255-261. doi:org/10.1016/S0038-092X(00)00098-0

Santamouris, M., Papanikolaou, N., Livada, I., Argiriou, A., & Assimakopoulos, D. N. (2001). On the Impact of Urban Climate on the Energy Consumption of Buildings. *Solar Energy, 70*(3), 201-216. doi:org/10.1016/S0038-092X(00)00095-5

Sayre, R., Comer, P., Warner, H., & Cress, J. (2009). *A New Map of Standardized Terrestrial Ecosystems of the Conterminous United States: U. S. Geological Survey Professional Paper 1768.* Retrieved from https://pubs.usgs.gov/pp/1768

Scarpa, M., Mazzali, U., & Peron, F. (2014). Modeling the energy performance of living walls: Validations against field measurements in termperate climate. *Energy and Buildings, 79*, 155-163. Retrieved from http://dx.doi.org/10.1016/j.enbuild.2014.04.14

Schiller, S. (2010). The Thermal Benefits of Green Walls on Buildings and in Urban Canyons. *Summary 3 for the class 48-722 Building Performance Modeling.* Pittsburgh, PA: Carnegie Mellon University.

Schmelzer, P. (. (2005, November 29). *Green Roof Study Results for Cold Climates [Online Post]*.

Schmelzer, P. (2005, November 29). *Online Post.* Retrieved from Green Roof Study Results for Cold Climates.

Schmidt. (2005). The Interaction between Water and Energy of Greened roofs. (pp. 1-9). Basel: World Green Roof Congress. Retrieved from http://www.gebaeudekuehlung.de/Basel2005.pdf

Schmidt, M. (2009). Rainwater Harvesting for Mitigating Local and Global Warming. *Fifth Urban Research Symposium*, (pp. 1-15). Marsielle, France. Retrieved from http://www.gebaeudekuehlung.de/URS2009Marseille.pdf

Schmidt, M., Reichmann, B., & Steffan, C. (2007). Rainwater Harvesting and Evaporation for Stormwater Management and Energy Conservation. (pp. 1-4). Berlin: International Congress on Environmental Planning and Management. Retrieved August 17, 2013, from https://www.researchgate.net/profile/Marco_Schmidt4/publication/267260946_Rainwater_harvesting_and_evaporation_for_stormwater_management_and_energy_conservation/links/5630f09308ae13bc6c354a81/Rainwater-harvesting-and-evaporation-for-stormwater-management-

Sharp, R. (2007). Green Walls and Green Roof Gardens: Green Walls in Vancouver. *2007 Greening Rooftops for Sustainable Communities Conference Proceedings.* Minneapolis, MN.

Sharples, S., & Bensalem, R. (2001). Airflow in Courtyard and Atrium Buildings in the Urban Environment: A Wind Tunnel Study. *Solar Energy, 70*(3), 237–244. doi:10.1016/S0038-092X(00)00092-X

Shashua-Bara, L., & Hoffman, M. (2003). Geometry and orientation aspects in passive cooling of canyon streets with trees. *Energy and Buildings, 35*(1), 61-68. doi:org/10.1016/S0378-7788(02)00080-4

Skyview Laboratory Inc. (2019). *Nutritional Analysis of Living Facade vs. Conventional Produce Samples.* Boswell, PA: Skyview Laboratories Inc.

Small Wright, M. (1993). A Garden as Defined by Nature. In *The Perelandra Garden Workbook.* Jeffersonton, VA: Perelandra Ltd.

Solar Insolation Levels in North America. (2010). Retrieved October 25, 2010, from http://www.solarpanelsplus.com/solar-insulation-levels/

SOMFY Architecture. (2009). *Somfy Solutions for the Development of Bioclimatic Façade.* Cluses Cedex, France: SOMFY Living Architecture. Retrieved from https://service.somfy.com/downloads/buildings/brochure_bcf_en.pdf

St. John, A. (2011). *A Sustainability Laboratory: Scalo Solar Solutions completes a sustainability demonstration project.* Retrieved from http://www.professionalroofing.net/Articles/A-sustainability-laboratory--09-01-2011/1957

Stav, Y. (2008). *Living Walls and Their Potential Contribution to Sustainable Urbanism in Brisbane.* Confirmation of Candidature Report, Queensland University of Technology, School of Design, Brisbane, Australia.

Stec, W., Van Passen, A., & Maziarz, A. (2005). Modelling the Double Skin Façade with Plants. *Energy and Buildings, 37*, pp. 419-427. doi:10.1016/j.enbuild.2004.08.008

Steffen, W., Rockstrom, J., Richardson, L., Leton, T., Folke, C., Liverman, F., . . . Winkelmann, R. (2018). Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, p. 8252/8259. doi:10.1073/pnas.1810141115

Stenning, L. &. (2008, October). Seattle Green Factor: Improving Green Infrastructure Parcel by Parcel. Washington University. Retrieved from Master Studio Presentation, Washington University.: http://greenfutures.washington.edu/powerpoints/Seattle_Green_Factor_Stenning_Philipsen.pdf

Stokols, D. (1995). Culture Change: Translating Social Ecological Theory into Guidelines for Community Health Promotion. *American Journal of Health Promotion*, 282-298.

Straube, J. (2008). *Can Highly Glazed Building Façades Be Green?* Retrieved August 3, 2018, from Building Science Corporation: https://buildingscience.com/documents/insights/bsi-006-can-fully-glazed-curtainwalls-be-green

Suklje, T., Medved, S., & Arkar, C. (2016). On Detailed Thermal Response Modeling of Vertical Greenery Systems as Cooling Measure for Buildings and Cities in Summer Conditions. *Energy, 115*, 1055-1068. doi:10.1016/j.energy.2016.08.095

Sunakorn, P., Pakarnseree, R., & Davivongs, M. L. (2006). The Application of Plants on Parking Structures to reduce CO2. *Paper presented at the iNTA Conference 2006 - Harmony in Culture and Nature*.

Sundaram, A. (2018, August 26). The Meal Gap: Thousands of 'Food Insecure' Families are Forced to Make Tough Decisions Daily. *Pittsburgh Post-Gazette*. Retrieved from https://www.post-gazette.com/news/health/2018/08/26/food-stamps-snap-federal-aid-farm-bill-pittsburgh-hunger-meal-gap-food-insecurity/stories/201807230106

Sung, D. (2016). A New Look at Building Facades as Infrastructure. *Engineering, 2*, 63–68. doi:10.1016/J.ENG.2016.01.008

Susorova, I., Azimi, P., & Stephens, P. (2014). The Effects of Climbing Vegetation on the Local Microclimate, Thermal Performance, and Air Infiltration of Four Building Facade Orientations. *Building and Environment, 76*, 113-124. doi:10.1016/j.buildenv.2014.03.011

Takakura, T., Kitabe, S., & Goto, E. (2000). Cooling Effect of Greenery Cover Over a Building. *Energy and Buildings, 31*(1), 1-6. doi:10.1016/S0378-7788(98)00063-2

Templeton, D. (2015, February 10). *Pittsburgh Post Gazette.* Retrieved from How Polluted is Pittsburgh Region? A CMU Professorhelps Shed Light on Air Quality: https://www.post-gazette.com/news/environment/2015/02/11/Carnegie-Mellon-University-professor-makes-new-pollution-maps-public/stories/201502110023

Terrapin Bright Green. (2020). *14 Patterns of Biophilic Design.* Retrieved from https://www.terrapinbrightgreen.com/report/14-patterns/

Terrapin Bright Green, L. (2012). *The Economics of Biophilia*. Retrieved from http://www.terrapinbrightgreen.com/downloads/The%20Economics%20of%20Biophilia_Terrapin%20Bright%20Green%202012e_1.pdf

Thayer, B. (1995). Daylighting and Productivity at Lockheed. *Solar Today, May/June*, 26-29.

Theodosiou, T. (2003). Summer Period Analysis of the Performance of a Planted Roof as a Passive Cooling Technique. *Energy and Buildings, 35*(9), 909-917. doi:10.1016/S0378-7788(03)00023-9

Thomazelli, R. C. (2017). Acoustic Properties of Green Walls: Absorption and Insulation. *Proceedings of Meetings on Acoustics. 28, 015017.* Buenos Aires, Argentina: 22nd International Conference on Acoustics Acoustics for the 21st Century.

Tilley, D. (2012). *Renewable Power Rhythm:The Rhythm of Power Availability in the Post-Prosperous Way Down World*. Retrieved from http://prosperouswaydown.com/renewable-power-rhythm/

Tilley, D., & Price, J. (2010). Effect of Vertical Vegetation on Thermal Balance of Buildings. *Cities Alive: 8th Annual Green Roof & Wall Conference.* Vancouver, Canada.

Tilley, D., Price, J., Matt, S., & Marrow, B. (2012). *Vegetated Walls: Thermal and Growth Properties of Structured Green Facades.* Final Report to Green Roofs for Healthy Cities—Green Walls Group. doi:10.13140/RG.2.2.24238.56646

timeanddate.com. (2020). *Past Weather in Pittsburgh, Pennsylvania, USA - August 2013.* Retrieved from timeanddate.com: https://www.timeanddate.com/weather/usa/pittsburgh/historic?month=8&year=2013

Timur, O. B., & Karaca, E. (2013). Vertical Gardens. *Advances in Landscape Architecture*, 587-622. Retrieved from http://dx.doi.org/10.5772/55763

Toronto and Region Conservation Authority. (2010). *Low Impact Development Stormwater Management Planning and Design Guide: Version 1.* Toronto, Canada.

Troy, A., & Davis, S. (2016, January 13). *USDA Forest Service.* Retrieved from The Effect of Urban Tree Canopy on Microclimate and Heat Islands: https://www.fs.fed.us/research/docs/webinars/urban-forests/microclimate-heat-islands/slides-troy.pdf

Tundrea, H., & Budescu, M. (2013). Bioclimatic Architecture: A Sensible and Logical Approach Towards the Future of Building Development. *Bulletin of the Polytechnic Institue from IASI, 59*(63), 109-117.

U S Environmental Protection Agency. (n.d.). *epa.gov*. Retrieved July 23, 2012, from Fact Sheets on Designing for the Disassembly and Deconstruction of Buildings: https://www.epa.gov/smm/fact-sheets-designing-disassembly-and-deconstruction-buildings#:~:text=The%20Pilot%20formulated%20design%20for,disassembly%20and%20building%20material%20reuse.

U.S. Forest Service. (2016, September 16). *Ecoregions of the United States.* Retrieved January 4, 2020, from U.S.Forest Service - USDA: https://www.fs.usda.gov/rmrs/ecoregions-united-states

Union of Concerned Scientists. (2002). *1992 World Scientists Warning to Humanity.* Retrieved from https://www.ucsusa.org/resources/1992-world-scientists-warning-humanity

Unit 5: Human Population Dynamics. (2019, January 12). Retrieved from Section 4: World Population Growth Through History: https://www.learner.org/courses/envsci/unit/text.php?unit=5&secNum=4

United Nations. (1987). *Report of the World Commission on Environment and Development: Our Common Future (Brundtland Report).*

United Nations. (2004). *World Urbanization Prospects: The 2003 Revision.* New York: United Nations Department of Economic and Social Affairs/Population Division.

United Nations. (2020, January 10). *Agenda 21 Sustainable Development Goals Knowledge Platform*. Retrieved from sustainabledevelopment.un.org: https://sustainabledevelopment.un.org/outcomedocuments/agenda21

US Department of Energy. (2021). *Air Conditioning*. Retrieved 1 16, 2021, from Energy Saver: https://www.energy.gov/energysaver/home-cooling-systems/air-conditioning#:~:text=Air%20conditioners%20use%20about%206,into%20the%20air%20each%20year.

US Energy Information Administration. (2020, March 13). *Today in Energy*. Retrieved from EIA projects air-conditioning energy use to grow faster than any other use in buildings: https://www.eia.gov/todayinenergy/detail.php?id=43155#:~:text=Across%20the%20buildings%20sector%2C%20purchased,fuels%20met%20space%20heating%20needs.

USDA. (2012). *Characteristics and Influential Factors of Food Deserts.* U.S. Department of Agriculture, Economic Research Service. Washington, DC: Economic Research Service USDA. Retrieved 2018, from https://www.ers.usda.gov/webdocs/publications/45014/30940_err140.pdf

USDA. (2018). *Food Security and Economic Assistance*. Retrieved from Economic Research Service: https://www.ers.usda.gov/data-products/ag-and-food-statistics-charting-the-essentials/food-security-and-nutrition-assistance/#:~:text=The%20prevalence%20of%20food%20insecurity,food%20secure%20throughout%20the%20year.&text=Food%20insecurity%20increased%20f

USDA-NIFA. (2010). *Agriculture and Food Research Intiative Competitive Grants Program: Sustainable Bioenergy.* Washington, DC: USDA-National Institure of Food and Agriculture.

USEPA. (2020). *NAAQS Table*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/criteria-air-pollutants/naaqs-table

Van den Berg, A., Wesselius, J., Maas, J., & Tanja-Kijkstra, K. (2016). Green Walls for a Restorative Classroom Environment: A Controlled Evaluation Study. *Environment and Behavior, 49*(7), 791-813. doi:10.1177/0013916516667976

Van der Ryn, S., & Cowan, S. (1996). *Ecological Design.* Washington, DC: Island Press.

Venolia, C. (1988). *Healing Environments.* Celestial Arts.

Virtudes, A., & Manso, M. (2016). Benefits of Greenery in Contemporary City. *IOP Conference Series: Earth and Environmental Science, 44*, 1029-1038. doi:10.1088/1755-1315/44/3/032020

Wang, L., Gong, H., Liao, W., & Wang, Z. (2015). Accumulation of Particles on the Surface of Leaves During Leaf Expansion. *Science of the Total Environment, 532*, 420-434. doi:10.1016/j.scitotenv.2015.06.014

Weatherbase. (2020). *Pittsburgh, Pennsylvania Weather*. Retrieved from weatherbase.com: https://www.weatherbase.com/weather/weather-summary.php3?s=2527&cityname=Pittsburgh,+Pennsylvania,+United+States+of+America

Wells, M. (1982). *Gentle Architecture.* New York: McGraw-Hill.

What-when-how, In Depth Tutorials and Information. (2016). Retrieved August 1, 2016, from ARCHITECTURE (Social Science): http://what-when-how.com/social-sciences/architecture-social-science/

Wikipedia Commons. (2005). *File: Life Six Kingdoms*. Retrieved February 24, 2013, from https://commons.wikimedia.org/wiki/File:Life_Six_Kingdoms.png

Wilson, E. O. (1984). *Biophilia.* Cambridge, MA: Harvard College.

Wolf, K. (2005). Civic Nature: Valuation: Assessments of Human Functioning and Well-Being in Cities. *Forging Solutions: Applying Ecological Economics to Current Problems.* Tacoma, WA: Proceedings of the 3rd Biennial Conference of the U.S. Society for Ecological Economics.

Wolf, K. (November 1998). *Urban Nature Benefits: Pyscho-Social Dimensions of People and Plants, Human Dimensions of the Urban Forest (Fact Sheet 1).* Center for Urban Horticulture, University of Washington.

Wolf, K. (n.d.). *Urban Ecology*. Retrieved from Human Dimensions: To discover and understand human benefits of nature in cities: http://www.naturewithin.info/new.html

Wong, N. H. (2008). Integrating Greenery with Buildings to Enhance Green Building Design. [Slide presentation]. *International Green Building Conference.* Suntec City, Singapore.

Wong, N. H. (2009). Typologies of Vertical Greenery Systems. In T. P. Yok, K. Chiang, D. Chan, N. H. Wong, C. Yu, A. Tan, N. C. Wong, K. Chiang, & A. Tan (Eds.), *Vertical Greenery for the Tropics* (pp. 1-99). Singapore: Centre for Urban Greenery & Ecology. Retrieved April 15, 2011, from https://www.amazon.com/Vertical-Greenery-Tropics-Alex-Tan/dp/9810839731

Wong, N. H., Kwang, T. A., Chen, Y., Sekar, K., Tan, P. Y., Chan, D., . . . Wong, N. C. (2010). Thermal evaluation of vertical greenery systems for building walls. *Building and Environment, 45*(3), 663-672. doi:10.1016/j.buildenv.2009.08.005

World Health Organization. (2004). *Fruit and Vegetables for Health: Report of a Joint FAO/WHO Workshop.* Kolbe, Japan. Retrieved from https://apps.who.int/iris/bitstream/handle/10665/43143/9241592818_eng.pdf;jsessionid=6157C24C4CBEBA2A9228072D86917961?sequence=1

World Health Organization. (2021, January 5). *Health Topics*. Retrieved from Air Pollution: https://www.who.int/health-topics/air-pollution#tab=tab_2

wunderground.com. (2020, September 6). *Pittsburgh, PA Air Quality & Pollen*. Retrieved from wunderground.com: https://www.wunderground.com/health/us/pa/squirrel-hill-pittsburgh/15217

Yarn, K., Yu, k., Huang, J., Jou, W., & Wu, P. (2013, October). Utilizing a Vertical Garden to Reduce Indoor Carbon Dioxide in an Indoor Environment. *Wulfenia Journal, 20*(10), pp. 180-194.

Yazdanseta, A., & Norford, L. (2017). Estimating the Untapped Cooling Power of Green Walls as Evaporative Coolers for Buildings. *Building Simulation 2017: Proceedings of the 15th IBPSA Conference*, (pp. 116-125). San Francisco, CA. doi:10.26868/25222708.2017.028

Yuan, S., & Rim, D. (2018). Cooling Energy Saving Associated with Exterior Greenery Systems for Three US Department of Energy (DOE) Standard Reference Buildings. *Building Simuation, 11*, 625-631. doi:10.1007/s12273-018-0427-y