Reducing Energy Demands in Greenhouse Farming:

The Potential of Passive Solar Greenhouses in the U.S.

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Abstract

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Controlled environment agriculture has significantly enhanced agricultural productivity around the world. However, greenhouse farming operations in Western countries remain highly energy-intensive, with heating accounting for the majority of energy use. In the Netherlands, heating accounts for around 74% of total energy input. Passive solar greenhouses (PSGs) offer an energy-efficient alternative by utilizing direct sunlight as the sole heat source. Their design incorporates thermal mass, enabling high thermal gain and substantially reducing energy consumption. While PSGs are widely implemented in Asia, their adoption at a commercial scale in the United States has been limited.

This study investigates the feasibility of implementing PSGs across diverse U.S. climate zones by evaluating their thermal performance and energy-saving potential. Four locations representing different climate zones were selected for case studies. A passive solar greenhouse model was used for energy and lighting simulations, testing various combinations of wall assemblies, glazing materials, shading, ventilation, and night insulation strategies.

Results indicate that PSGs increase the duration of ideal internal temperatures in all four locations. They are particularly effective in cold and marine climates, where they significantly raise interior temperatures without supplemental heating. Their performance is less effective in hot climates. Given that heating accounts for the largest portion of energy use in conventional greenhouses, PSGs show strong potential for cold regions. As more than half of the U.S. falls within cold and marine zones, PSGs offer a promising solution for year-round vegetable production with minimal energy input.

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Chapter 1: Introduction

Food Systems and the Role of Greenhouses

The current food system contributes to 34% of the global carbon footprint (Crippa, 2021), and it is heavily dependent on centralized industrial agriculture and extensive transportation networks. The transportation alone accounts for nearly 20% of total food-system emissions (Li). Beyond emissions, land agriculture is also very water and resource-intensive. There have been many discussions on how to make the current food system more sustainable: providing healthy food to meet the demand of the growing population while reducing carbon emissions and resource demand. One strategy is localizing food production instead of relying on food to be produced elsewhere and travel long distances. However, agriculture often requires optimal climatic conditions, which many regions lack. To address this, controlled environment agriculture (CEA) has been developed in various sizes and forms to extend growing seasons and enable the cultivation of fresh produce. Greenhouses are the most common type of CEA and have been playing an important role in many European and Asian countries. The Netherlands is well-known for its productive agriculture under glass roofs. To produce the same amount of lettuce, the ones growing in Dutch greenhouses only use 1/10th of the land than growing outdoors (Viviano). In China, 370.1×10^4 hm2 of land is covered by passive solar greenhouses, which allow the northern regions to grow vegetables while the temperature drops below freezing

outside. In comparison, although the US has been a top agriculture exporter, most of the production is from land in certain regions with ideal climates. Industrialized agriculture is productive, yet it comes at the cost of high carbon emissions and water usage. US agriculture could be more energy and resource-efficient by adopting CEA at a large scale.

Greenhouse designs vary by region and the intended uses. The Venlo-style fully glazed type is popular among European growers. This type of greenhouse is heated, mechanically ventilated, and equipped with artificial lighting. The fully controlled environment is effective in increasing crop yield. The Netherlands is the top vegetable producer, and a large portion of the produce is grown in greenhouses. With advanced technology in environmental control, the Netherlands has developed an agricultural system that primarily uses Venlo-style greenhouses. With the productive growing process, there also comes a cost in energy and carbon emissions. Dutch agriculture contributes to 14% (32 Mton CO2-eq in 2016) of the country's greenhouse gas emissions (van Grinsven et al.). On the one hand, the fully controlled greenhouses have increased vegetable yields and allowed the crops to grow in regions with harsher climates. However, as global warming and climate change are at the forefront of complex issues the world faces, innovations in reducing the energy cost in CEA are needed. Although the Netherlands has been developing new ways to improve energy efficiency with advanced technology, on the other side of the world, passive solar greenhouses have already been used for decades to grow food with minimal energy consumption.

Passive solar greenhouses are popular in China and other regions in Asia and have allowed regions with cold climates to grow vegetables year-round. In contrast to the Venlo-style greenhouses, passive solar greenhouses adopt a more climate-accepting strategy with minimum to no energy input other than sunlight. The idea of passive solar energy for architectural use also existed in the US and was popular in the twentieth century. The following chapters of this paper will examine the potential of adopting passive solar greenhouses in the US.

Passive Solar Architecture in the United States

Experiments in the 20th Century and the Potential to Address Food Insecurity Today

The concept of passive solar energy has a long history. It was once extremely popular among engineers and architects during the 1940s to 1950s and again from the 1970s to the 1980s. There were various research and experimentations on harnessing solar energy through architectural design and materials. The development of such technology was tightly connected to the political and economic scene. The experimentations from the post-war period to the 1980s are both proof of the feasibility of applying passive solar technology in the United States and a proclamation of the off-grid lifestyle. While some built projects address the concerns for heating and cooling homes, others dived into agriculture and used the passive solar projects as a manifesto to create new ways of living. While the application of passive solar in residential buildings might not be the most suitable application today, the passive solar greenhouse has the potential to be applied in small farms in the urban environment to address the pressing food security and food injustice issues that many parts of the U.S.

face. This section examines the importance of passive solar technology in the twentieth century and evaluates its potential to be adopted in urban agriculture today.

During the post-war period, technologies related to energy production and transportation grew significantly. Oil was being extracted and transported across oceans to power the daily uses of buildings and cars. In the United States (U.S.), it was also the period when suburban development rapidly expanded. The U.S. participation in the war demanded a large supply of petroleum for military use between 1941 and 1945, which outstripped domestic production and led to fuel shortages. With the end of the war, the energy shortage was also averted. However, there was a growing concern about resource depletion and the future of human civilization. Fairfield Osborn expressed his concern about population growth in the book Our Plundered Planet: “the tide of the earth’s population is rising, the reservoir of the earth’s living resources is falling … there is only one solution: Man must recognize the necessity of cooperating with nature. He must temper his demands and use and conserve the natural living resources of this earth in a manner that alone can provide for the continuation of his civilization” (Osborn). During the 1970s, to cope with the terrors of the war, the debate over technology, and the complexity of modern life, architects began to take a more humanistic approach to modern architecture. This shift towards considering “the modern house could be both technological innovation and humanist retreat” can be both “experimental and dwelling” (Barber 96). Based on this concept, MIT produced several solar house experiments that focused on harnessing sunlight as the energy source.

Figure 1.1 MIT Solar House II, 1948 (MIT News Office and the MIT Museum)

During the 1940s to 1950s, some pioneer examples were built by engineers and architects to test the ideas of passive solar heating in single-family homes. In 1946, a group of engineers and architects designed and built the Experimental Dwelling, a house that was intended to be more of a laboratory than for residential purposes. The main purpose was to test the heat storage capability of chemical compounds. The south facade was divided into six panels with glazing. Each one tested a number of elements, including different storage compounds, the number of glass layers, the thickness of panel support, etc. However, the results were not ideal, and the experiment was stopped after eighteen months. In 1947, a fourth-year undergraduate studio incorporated this building to repurpose it to be a habitable solar-heated residence (Figure 1.1). With only 608 square feet, the house was carefully designed to maximize comfort through passive solar strategies. Due to the nature of this house previously as a laboratory, many caveats emerged to prevent it from achieving maximum performance. Although the house was not able to maintain 65-70 degrees for all seasons in Massachusetts, it did provide meaningful insights to indicate under what

conditions climate solar heating is competitive with fossil fuel heating. The result of this experiment was used in the subsequent years (Barber 102).

Figure 1.2 Dover Sun House. 1948 (energyhistory.yale.edu)

The architect Maria Telke and the engineer Eleanor Raymond designed Dover Sun House (Figure 1.2) in 1948. The large windows on the second floor functioned as heat collectors. Heat was collected and sent to the heat bin, which contains chemical salts, at the ground level. Telke and Raymond originally hoped that their energy storage system could heat the house for two to three days without sunlight. Although the building initially performed well and provided more consistent heating than active solar heating, numerous problems around construction and materials quickly arose. After five years, the house was unable to provide savings in heating costs. In 1954, the solar heating system was removed, and the experiment ended. Although the all-solar house did not work well, it “became an important symbol of an emergent discussion that was concerned with adjusting social systems in order to better account for environmental limits” (Barber 122). Daniel Barber also commented in the book A House in the Sun that the Dover Solar House “operated less as a technological solution to an economic problem, and more as a catalyst for a new kind of conversation – less as a way out of

conflicts in the political and economic sphere, and more as a means to open up the discussion of the future to a wider range of possibilities" (Barber 122). From this perspective, Dover Sun House was quite a successful experiment, especially considering a family lived in there, which makes the envisioned future through technological innovation more tangible for ordinary people.

Figure 1.3 Cape Cod Ark, 2004 (The Green Center)

The New Alchemy Institute was established in 1969 by a group of future-thinking researchers to explore organic agriculture, aquaculture, and bioshelter without relying on fossil fuels. Their mission is to "Restore the Lands, Protect the Seas, and Inform the Earth's Stewards" (The Journal of the New Alchemists). Unlike the two previous case studies that primarily focus on dwelling and building performance, New Alchemy Institute's experiments have a more ecological approach. Ark (Figure 1.3) is an experiment built by Hilde Maingay and Earle Barnhart to explore whether it is possible to grow food in the New England climate in a greenhouse without using fossil fuels or pesticides. The focus on self-sufficiency with knowledge from nature leads to an aquaponics operation in a greenhouse with both passive solar heating and solar panels. The project lasted from 1971 to 1991. Ark embodies a vision where humans do not

merely consume, waste, and pollute. It serves as living evidence that we can actively participate in a closed-loop system, ensuring our survival without harming other living beings or the climate.

The experiments from the 20th century not only provided insights into the technical realm of building technology but also brought a new perspective on how humans should live in relation to the natural world. American people's views of the natural environment in the 1950s were mostly focused on nature as a resource and waste sink. The major concern was resource depletion and the physical "limit". Both MIT Solar House and Dover Sun House are responding to the socio-economic environment at the time. The concern over resource depletion was also reflected in the initial ideas of self-sufficiency. In the 1970s, the view on nature shifted towards nature as a public good. The major concerns in this era were environmental degradation and climate change. New Alchemy Institute's experiments, although also focused on self-sufficiency, introduced ecological ideas. Ark was an exploration of how humans can be participants in the living system. This idea is quite a contrast to humans as resource takers from the 1950s. Today, we tend to associate the words "nature", "environment", and "climate change" with "sustainability". Sustainability encompasses more than the environmental aspect; social justice and equity are inseparable when discussing the idea of sustainability and the human-nature relationship. As passive solar explorations in the 20th century often aligned with the period's view on the human-nature relationship, how could passive solar be used today that could also align with current societal views and values?

It has been more than four decades since the establishment of the New Alchemy Institute and even longer since the solar house experiments, yet passive solar technology has not been improved or widely adopted. Part of the reason is that the HVAC systems have been improving, and their reliability in delivering comfort in all climates is needed. As more places in the U.S. are facing a housing crisis, increasing density and building more housing become a priority. This also limits the potential for applying passive solar energy to residential buildings since passive solar is only effective in certain orientations. However, the limitation in residential typology might open up opportunities for other typologies. One pressing issue for urbanization is food insecurity. Many cities have food deserts, where it is difficult for residents to access fresh and nutritious food. People living in the food deserts are often low-income and people of color, which reinforces the existing injustice experienced by marginalized communities. Passive solar technology has already been successfully implemented on a large scale in China, and it holds significant promise for small-scale agriculture as well. The following three case studies explore the potential to apply passive solar greenhouses to urban agriculture as a way to alleviate food insecurity.

Figure 1.4 Chinese solar greenhouse

The passive solar greenhouse (PSG) is a unique agricultural typology that originated in China and is also known as the Chinese solar greenhouse (CSG). CSGs use direct sunlight as the only heat source. With thermal mass, insulation, and other passive strategies, this invention has allowed northern China to produce fresh vegetables year-round. The first CSG was developed in the 1970s, and it has continuously evolved with new technologies and inventions. The design of solar greenhouses has improved significantly since the 1970s with innovations in materials and construction techniques. By 2017, Chinese solar greenhouses (CSGs) had enveloped 370.1×10^4 hm2 of land in China, accounting for approximately 33% of all greenhouses (Liu 2019). As an energy-efficient and climate-responsive typology, PSGs use architectural interventions, including form, orientation, and materials, to respond to climate conditions instead of relying on mechanical systems. CSGs can be found in all northern provinces, with climates ranging from mildly cold winters to extremely cold. The success of the low-tech passive solar greenhouses in China is partially due to government policy and

subsidies on controlled environment agriculture and economic incentives. The prevalence of such typology in China indicates its feasibility in various climates. However, widely applying passive solar greenhouses in the United States for large-scale farming might not be the most viable option due to maintenance and labor costs. Creating smarter passive solar greenhouses that incorporate automation and environmental controls could potentially allow passive solar greenhouses to be adopted in many locations in the U.S.

Aquaponics solar greenhouse, Heppenheim and Neuenburg am Rhein, Germany.

Figure 1.5 Greenhouse interior with growing beds and covered fish tanks, 2015 (Franz Schreier, the Aquaponic Solar Greenhouse, Neuenburg am Rhein, Germany)

With relatively low solar radiation and cold winters, Germany is a perfect place to experiment with passive solar greenhouses. This example incorporates the design of a Chinese solar greenhouse with an ETFE membrane and custom photovoltaic panels on the south-facing side. The solar panels integrate both energy transformation and shading to optimize the growing conditions for plants. The thoughtful design has allowed this greenhouse to function at -4°F (-20°C). The growing system is aquaponics,

which is very efficient in terms of water usage and nutrient cycles. To optimize the lighting conditions during low-light conditions, the greenhouse uses supplemental lighting and wavelength conversion film, which transforms green light into red light (Proksch 106). Incorporating both high-tech technologies and low-tech passive strategies allows this greenhouse to achieve high energy performance and crop yields. Adding electricity could be beneficial and allow the system to be more practical in regions with sub-optimal solar radiation rates.

GrowHaus and Flourish Farms, Denver, CO.

Figure 1.6 Interior of Flourish Farm's greenhouse with aquaponics beds, 2015 (JD Sawyer)

GrowHaus is a non-profit organization focusing on promoting community-led food justice initiatives, including expanding food access and reducing food insecurity in Elyria/Swansea neighborhood in Denver, CO. Flourish Farms is a 3,200 sq ft urban aquaponics farm located at the GrowHaus (The Aquaponic Source). Although Flourish Farms is not a passive solar greenhouse, it does successfully integrate aquaponics with the urban environment, an aspect that could be applied elsewhere. Flourish Farm was

established in 2011 and has been in operation with a good financial record. The farm donated 10% of its produce to GrowHaus in 2015 (Sawyer 2016). Aside from production, education is an important part of the programming for the Flourish Farm and GrowHaus. Next to the greenhouse is an education center that provides programs for both youth and adults in the community. This collaboration between urban farming and community organizations is effective in addressing food insecurity. A model like this could be applied to other cities where the population experiencing food insecurity can benefit from both increased access to fresh produce and related programs. The role of the farm, in this case, is beyond providing produce, but also functions as a node for connection and empowerment.

The three case studies above illustrate the potential directions of applying passive solar greenhouses in the U.S. to address the food desert issue. The large-scale application of the Chinese greenhouse indicates that a passive solar greenhouse can be applied in various northern climates. The second example of an aquaponics greenhouse in Germany suggests that incorporating both high-tech and low-tech methods can greatly increase productivity. The last example of GrowHaus and Flourish Farm in Denver shows the positive impact of incorporating urban agriculture with community organizations to expand access to fresh food. Other cities and food desert areas in the US can consider adopting passive solar greenhouses to grow food and empower the communities.

The experiments of passive solar houses and the New Alchemy Institute established a legacy of exploring self-sufficiency. Although the results were not ideal at

the time, they provided important information on feasibility, materials, and design. More importantly, they started the conversation on the possibility of living without fossil fuels. The vision they created is even more pertinent today as the world faces similar challenges on a larger scale. With rapid rates of urbanization, instead of applying passive solar to dwellings, it is more effective to use this technology for greenhouses and address the issue of food security and food deserts. In contrast to the passive solar experiments in the 20th century that stress completely passive, passive solar greenhouses have the potential to efficiently provide fresh food to urban areas with the combination of low-tech and high-tech methods.

Passive Solar Greenhouse

Passive solar greenhouses' designs vary in size, shape, and materials. However, they tend to follow seven principles as summarized by Lindsey Schiller in the book *The Year-round Solar Greenhouse*. In most of the US climates, keeping the interior environment warmer than the exterior during winter months and cold nights should be the priority.

The Seven Principles of Solar Greenhouse Design (Schiller)

- Orient the Greenhouse Toward the Sun

Most glazing areas should face south to obtain the maximum level of solar radiation.

- Insulate the areas that don't collect a lot of light

The north wall tends to lose a substantial amount of heat during cold months and at night. It is important to have a proper level of insulation to reduce heat loss.

- Insulate Underground

The perimeter of the greenhouse should be insulated to allow the soil to stay warmer than the exterior environment, which helps to stabilize the temperature inside.

- Maximize Light and Heat in the Winter

Maximizing natural lighting and heat with passive solar means is essential to growing during winter months. This is done by using proper glazing materials and angling the glazing for winter light collection.

- Reduce Light and Heat in the Summer

During summer, too much heat and light can cause damage to the plants. Shading is an effective strategy to reduce light levels.

- Use Thermal Mass

Thermal mass are materials that store the excess heat in the greenhouse collected during daytime and slowly radiate the energy into the greenhouse at night. This is essential to maintain a more stable temperature in the greenhouse.

- Ensure sufficient ventilation

Natural ventilation is needed to reduce heat and humidity, as well as maintain an adequate amount of carbon dioxide.

PSGs in China

In the summer of 2024, I visited Shandong, China, to explore passive solar greenhouses in the region. Shouguang, a small city in Shandong Province in Northeast China, is widely known as the “vegetable town” of the country. Agriculture is the region’s primary industry, with approximately 600,000 acres of land dedicated to vegetable farming. Annually, the area produces around 4.5 billion kilograms of vegetables (PR Newswire). Passive solar greenhouses (PSGs) are extensively used by local farmers to grow a variety of vegetables year-round. To maximize yield, many farmers cultivate crops both in open fields and inside PSGs. The region’s climate is well-suited for traditional, low-tech PSGs, which are built directly on the ground and feature an earth back wall for insulation. Generations of agricultural experience among local farmers have fostered a culture of continuous innovation rooted in traditional knowledge.

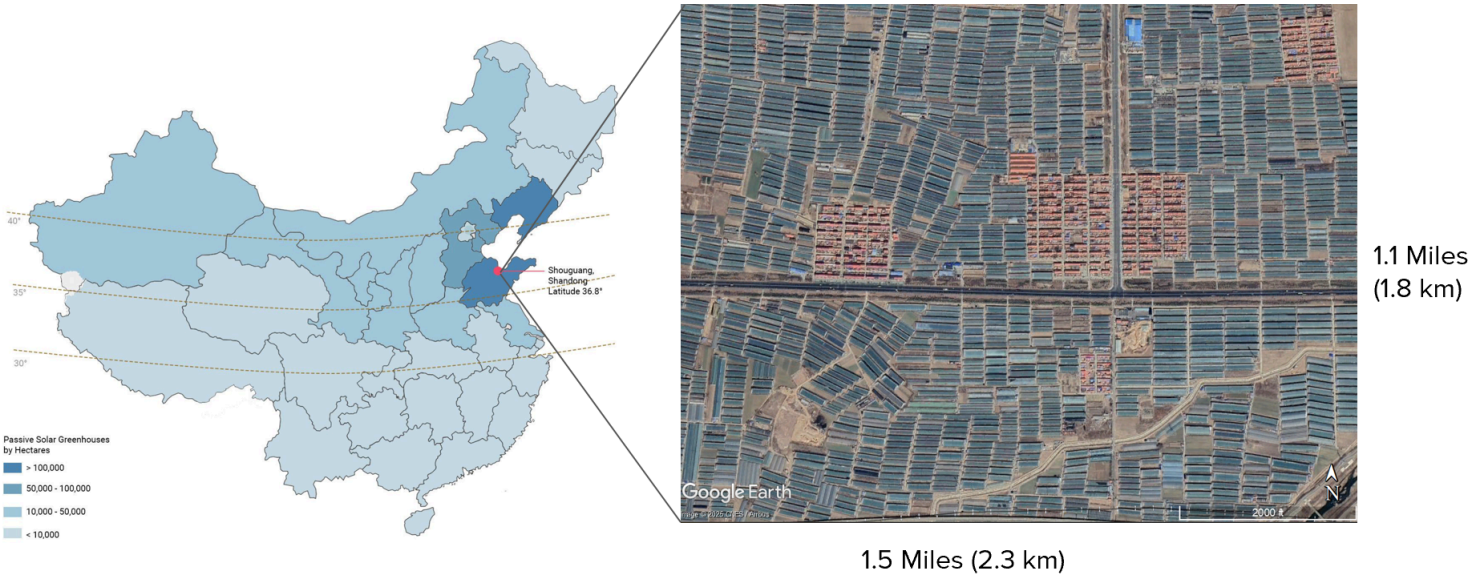


Figure 1.7 Aerial view of Shouguang. Passive solar greenhouses (blue) and residential areas (orange). Map data from http://data.sheshiyuanyi.com/AreaData/

The structure and materials used for passive solar greenhouses are homogeneous in this region. They are usually dug into the ground and have a north wall around 7m tall. The span

is around 15 to 20m. The length is in the range of 100 to 200m. Steel tubes combined with concrete columns (Figure 1.9) allow larger spans with less cost. Some greenhouses are built with steel trusses, which does not need columns (Figure 1.12).

These greenhouses all have simple vent control systems. There are typically two openings across the greenhouse: one at the top, the other at the bottom. The top one is connected to ropes, which are attached to a rod against the back wall (Figure 1.11, left). A motor is attached to the rod, which rotates the rod to open and close the vent at the top.

Figure 1.8 Exterior of a passive solar greenhouse

Figure 1.9 Interior with concrete columns

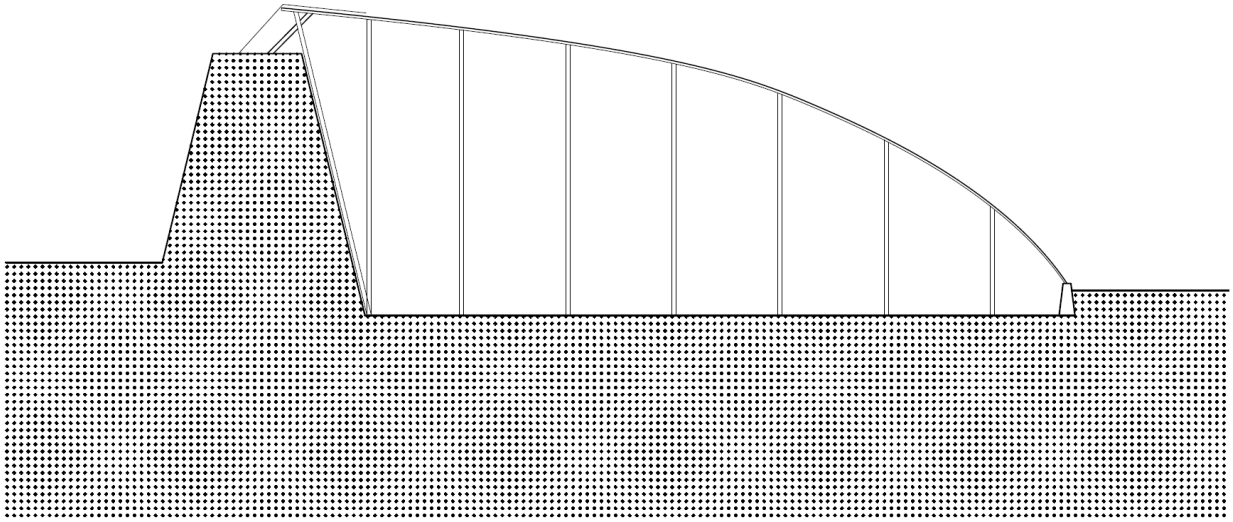


Figure 1.10 Typical section

Figure 1.11 Vent control system with rods and ropes (left). Entrance (right).

Figure 1.12 Interior of a steel truss PSG with supplemental lighting.

Chapter 2: Literature Review

Research on passive solar greenhouses has been conducted both in the technical design and historical aspects. A substantial amount of literature on PSGs is from Chinese scholars, potentially because of the large number of PSGs in China that are being used in commercial agriculture. Most publications focus on intricate aspects of PSGs while only a few sources provide a comprehensive overview. This literature review aims to develop a thorough understanding of the history of passive solar greenhouses, current research interest in the area, and the potential to incorporate natural lighting analysis in passive solar greenhouses.

The first group of literature provides an overview of passive solar greenhouses' mechanisms and applications. The articles outline passive solar design principles and their development in China. Chinese solar greenhouses were adopted in China in the 1970s. Two articles give an overview of the Chinese solar greenhouse and its application and evolution over the years. In "Structure, Function, Application, and Ecological Benefit of a Single-Slope, Energy-Efficient Solar Greenhouse in China", Gao et al. (2010) provided an overview of the function, characteristics, and benefits of the passive solar greenhouse. The article includes diagrams of four generations of solar greenhouses in China, which are very helpful in understanding the general structural changes over the years. The article concludes that solar greenhouses are essential for future low-carbon production, but more research on innovation and optimization is needed to continue to improve energy efficiency. The other article by Chen, published in

1994, discusses the development of solar greenhouse technology in China, including achievements and areas for improvement. Compared to Gao et al., Chen provides more details and suggestions on the technical aspects of Chinese solar greenhouses. The article states that Chinese solar greenhouses are different than the large-scale greenhouses in other countries, thus needing to develop a unique theoretical system for future research. Although published 16 years apart (2010 and 1994), both articles provide a comprehensive overview of the development of Chinese solar greenhouses while suggesting further research is needed.

In contrast to the large-scale usage of passive solar greenhouses in China, PSGs are more of a backyard project for hobby growers in North America. Schiller and Plinke's book *The Year-Round Solar Greenhouse: How to Design and Build a Net-Zero Energy Greenhouse (2016)* is a guidebook for anyone interested in building a small-scale PSG themselves. The book employs narratives, examples, images, and diagrams to comprehensively explain all aspects of passive solar greenhouses, assisting readers in making informed design and construction decisions. Schiller and Plinke build on the passive solar principles to provide more hands-on advice for construction and operation. This book is less about detailed research but more of a good resource for a basic understanding of PSGs. Considering that PSGs are less popular in North America than in China, this book is a valuable resource for growers who want to experiment with something new.

To understand the current state of academic passive solar greenhouse research, Ding conducted a bibliometric overview of the papers related to this topic between 2002

and 2023. The number of publications related to this topic is increasing, particularly after 2020. The author extracted information related to design strategies, including properties of thermal mass and insulation materials. While the author acknowledges the detailed aspects of PSGs in many papers, they also suggest that the findings are "focused on narrow facets of passive solar technologies, rather than providing clear, actionable guidance for practical design applications" (Ding 1). Following this claim, the paper concludes by suggesting future directions for research, including "standardized guidelines that assist practitioners in selecting and combining appropriate technologies based on specific regional climates, crop requirements, and economic constraints" (Ding 14). Ding's paper provides a high-level overview of passive solar greenhouse research that goes beyond the detailed components. This type of approach is rare in publications related to PSGs, and it is valuable for researchers to evaluate future research topics.

The conclusion of Ding's research inspires this project to use a more generalized approach to analyze PSGs' performance in different climates. The next section of the literature review dives into the two areas of focus: thermal performance and natural lighting analysis.

Energy performance and thermal quality in relation to the insulation and thermal mass are popular research subjects. Among these studies, many are experimental investigations conducted in PSGs in China using controlled environments with sensors. Some combine simulation-based research with experimental studies to compare results, while a few are solely simulation-based studies. The south roof and the north

wall are two components that play important roles in the thermal capacity of PSGs. External thermal insulation is often in the form of a blanket over the roof. The blanket is rolled down manually or automatically at night. Kim et al. concluded that an external covering quilt could reduce the heat loss of the unheated greenhouse by about 28.7%. Researchers have studied the material combination and control strategy of the insulation quilt (Rasheed et al., Chen et al.). Some researchers have also studied double-layer front roof insulation. Garzol and Blackwell found that using a glass or plastic film with an air layer in the middle can reduce heat loss by 32%. Teitel et al. used an aluminum insulation layer on the interior side and concluded that there is no significant difference in overall energy dissipation, but the insulation layer improved the temperature underneath. Preventing heat loss has been an essential area of research in the past decades and continues to draw interest since it is one of the essential factors in a passive solar greenhouse's thermal performance.

Thermal mass is another key component in solar greenhouses' performance. In passive solar greenhouses, the north wall is usually constructed with materials with high heat storage capacity. Common materials for thermal mass include concrete blocks and clay bricks. The north wall absorbs the heat from solar radiation during the daytime and releases it at night when the temperature is lower. In addition to the heat storage capacity, the north wall also has to be structurally sound, especially considering wind and snow loads. Several composite materials have been studied and proven to have improved heat storage capacity. Various phase change materials for the back wall have also been studied. Although phase change materials have high thermal capacity

and are effective in preventing the night temperature from dropping too low, they are also costly and difficult to construct. Liu et al. suggest that there is not yet a system to determine the most suitable north wall materials for solar greenhouses in northern China. There is a lot of room for innovation in insulation and thermal mass materials, considering that current materials are homogeneous across different regions. More variety, especially in biobased and local materials, could be researched. Zhang et al. used experimental methods to test straw block walls and compare heat transfer characteristics with typical clay bricks. The result shows that the straw block wall has higher thermal resistance than the clay blocks. This study suggests the potential of using biobased and agricultural waste materials for passive solar greenhouse construction. These researches on the thermal performance of PSGs provide valuable data and information that could be applied to digital simulations.

In addition to maintaining optimal temperature with passive means, obtaining ideal light levels is also crucial to plant growth. For a long time, it has been believed that blue and red spectrums in photosynthetic active radiation (PAR) lighting are the most essential spectrums for plant growth. However, as more and more recent research has shown, different aspects of plant growth are associated with multiple wavelengths in the entire light spectrum composition. Providing only the peak wavelength, red and blue, in PAR is not sufficient for the best yield. The intensity and spectral composition of lighting both affect plant growth.

While there is an established understanding of the relationship between light intensity and plant growth, the quality of light, in terms of spectral composition, has only

been drawing researchers' attention in the recent decade. Red and blue lights are presumed to be the most important for photosynthesis, yet green and other spectrums of light are responsible for the nuanced physiological and morphological responses (Ptushenko et al.). Multiple studies have shown that plants grow better under natural lighting than artificial lights, even when the illumination level is the same. Jung and Arar's study concludes that even for low-light tolerant plants, natural lighting fosters better growth (Jung and Arar). The percentage of each spectrum also contributes to the overall effect on plant growth. Jalal et al. studied lettuce growth under different fractions of red and blue lights. They examined the physiology, growth, and antioxidant activities in lettuce (Shiren et al.). In natural light settings, the color of the sky and light vary by location, times of the day, sky condition, and humidity. Since natural lighting is the primary choice for PSGs (because of no additional energy demand), it is beneficial to understand the spectrum composition of the light at different locations. An overview of the spectra of natural lighting can benefit PSG design and crop selection decisions.

Chapter 3: Project Scope and Methodology

Considering that PSGs are not widely adopted in the US, it would be beneficial to develop a more holistic understanding of the feasibility in terms of the environmental conditions that PSGs can achieve in US climates. This project aims to evaluate the optimal designs of PSGs across various climate zones in the US using digital simulation tools. The goal is to provide an overview, paving the way for more detailed research and a decision-making tool in the future. The project has two main goals: firstly, to adapt existing building simulation tools for use with passive solar greenhouses; secondly, to identify the most suitable designs and materials for PSGs in various selected climates.

The methodology for this study involves conducting case studies in four distinct locations: Seattle, WA; Chicago, IL; Tucson, AZ; and Arlington, VA. Each location undergoes a baseline climate and daylighting analysis, which is then compared to the ideal environmental and lighting conditions for greenhouse crops. This step helps

identify key aspects to focus on during design iterations. Subsequently, multiple iterations are developed for each location and compared to the baseline. The results are analyzed to provide insights and patterns that could inform design decisions for passive solar greenhouses in similar regions. The deliverables include a Grasshopper script for energy and lighting simulation, PSG designs and materials for each location, and analysis.

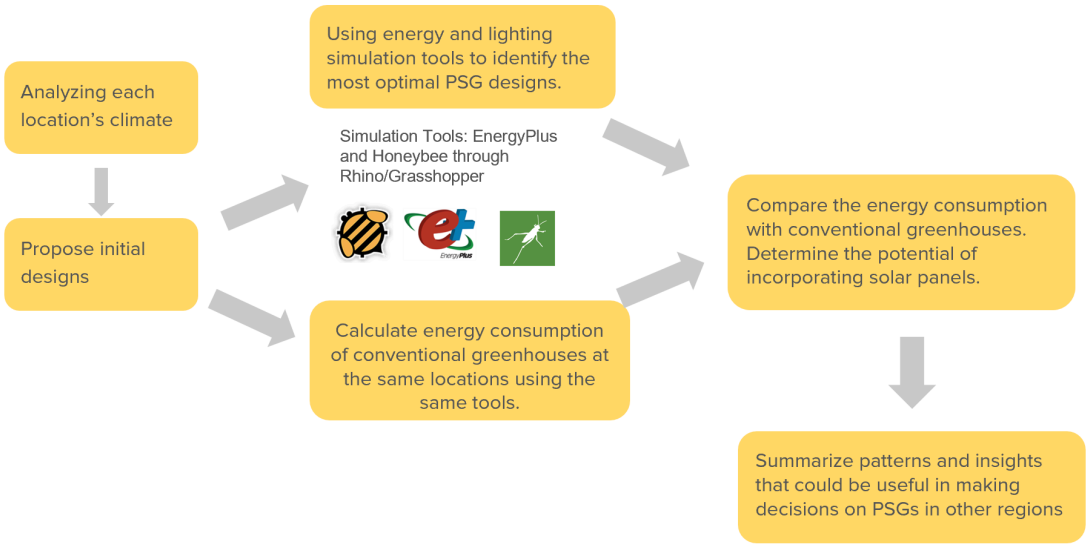


Figure 3.1 Methodology overview

Site Selection and Climate

To understand the designs and performance of PSGs in different climates, four locations in different climate zones (according to the IECC climate zone map) are selected for case studies. Seattle is in the marine zone, Chicago is in the cold/very cold zone, Tucson is in the hot dry/mixed dry zone, and Arlington is in the mixed humid zone.

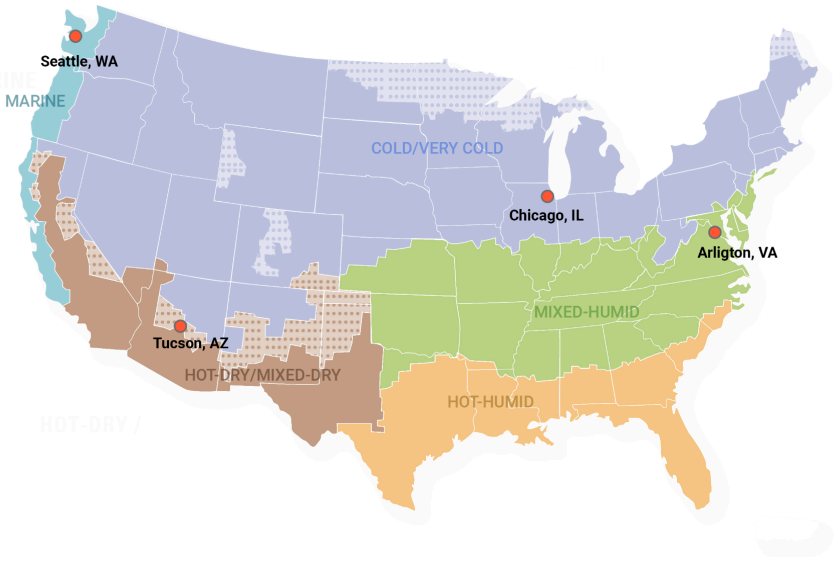


Figure 3.2 US climate zones with case study locations (based on Building America Climate Zone Map, U.S. Department of Energy)

Tools and Simulation Strategies

Each location has its unique challenges to be addressed by the greenhouse designs. The greenhouse model is built in Rhino, and the simulation is performed in the Grasshopper environment using the Honeybee plugin.

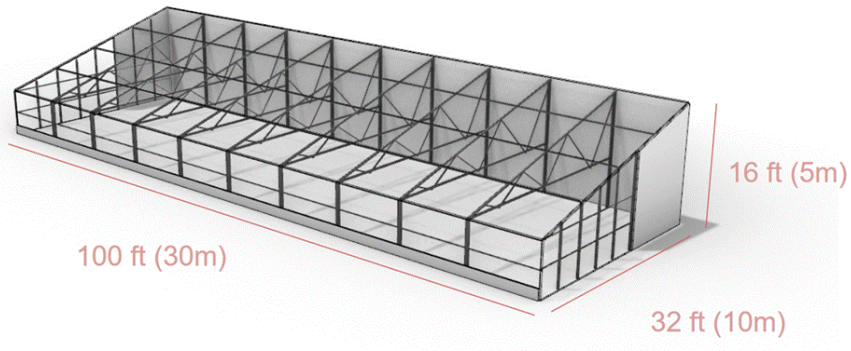


Figure 3.3 Model for simulation

The greenhouse structure is a steel truss frame. The design of the PSG consists of four sides and a sloped roof. The north wall is an opaque material, two sides are partially opaque, and the front wall and the roof are covered with glazing materials. On top of the glazing, there is a retractable insulation blanket and shading fabric. Several north wall assemblies and glazing materials are tested for each location to select the best. Besides materials, several controls are also being tested in the simulation, including shading, night insulation, passive ventilation, and exhaust fans.

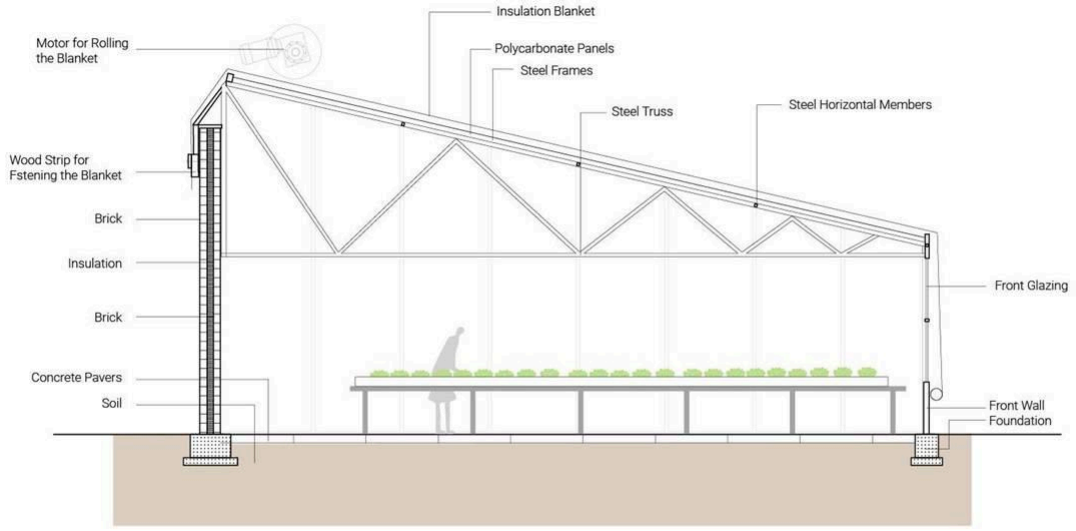


Figure 3.4 Section of the greenhouse

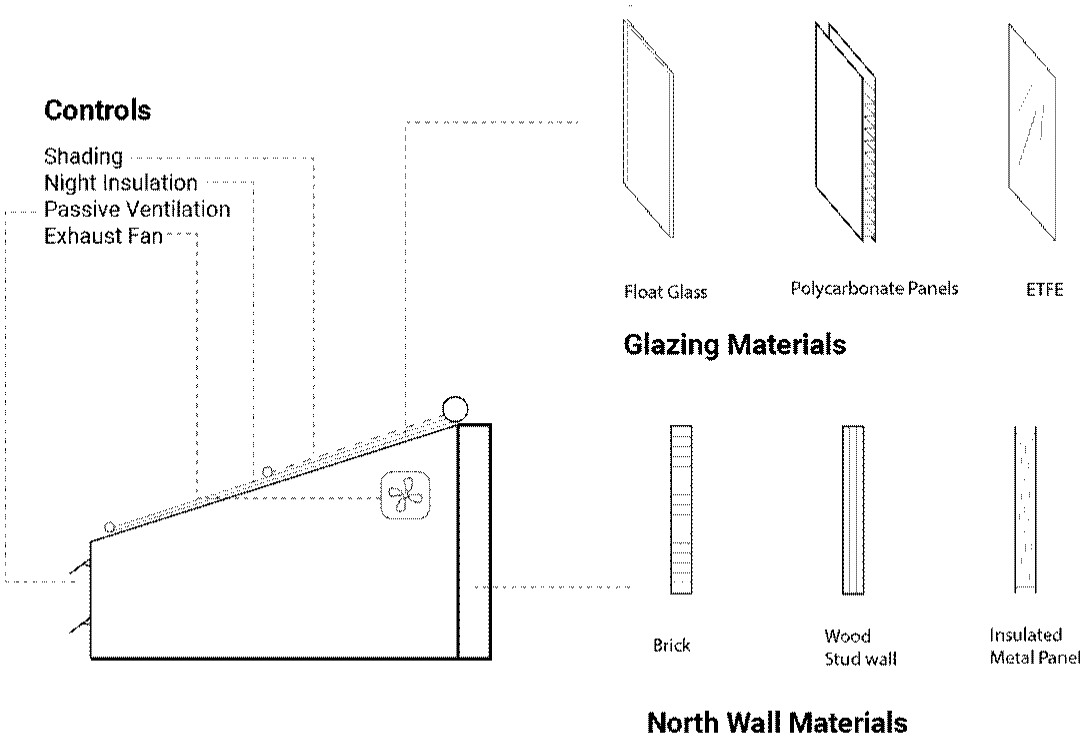


Figure 3.5 Areas of exploration

Table 3.1 Glazing options

Glazing Materials	Thickness (mm)	U Factor (W/m2K, Btu/h·ft2·F)		Solar Heat Coefficient (SHGC)	Visual Transmittance	Cost per SF ($)
PE (1 layer)	0.18	5.90	1.04	0.8	0.8	0.085
ETFE (1 layer)	0.05	0.24	0.04	0.8	0.9	3.5
Polycarbonate (double wall)	8	3.26	0.57	0.82	0.81	1.66
Plexiglass	16	2.50	0.44	0.8	0.87	4.07
Glass	4	5.80	1.02	0.8	0.9	6
PE (2 layer with air)		4.00	0.70	0.8	0.77	

For glazing, the materials in the table above are used for initial simulations. Based on performance and durability, two are selected for further investigation: ETFE and polycarbonate panels with double walls.

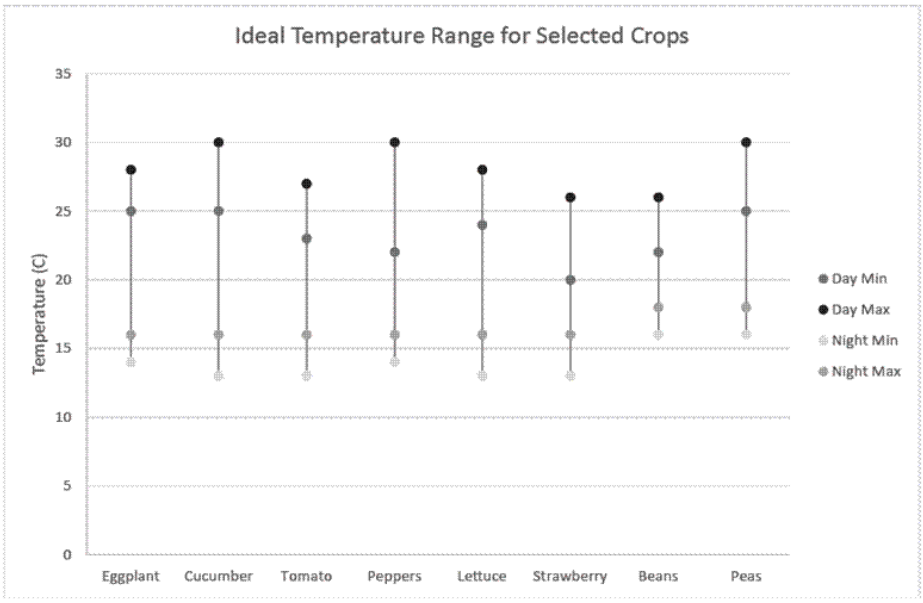


Figure 3.6 Ideal temperature range for selected greenhouse vegetables (Rabbi et al)

Figure 2.5 shows the ideal temperature range for growing common greenhouse vegetables. Crops have ideal temperature ranges for daytime and nighttime. For each growing stage, the temperature also varies. In general, the lower temperature inside the greenhouse should be around 10 °C, and the upper limit should be around 30 °C. Depending on the crops planted, the ideal temperature range changes. This project generalizes the temperature range to 10 to 30 °C to fit the needs of most vegetables that are commonly grown in greenhouses.

Simulation Setup

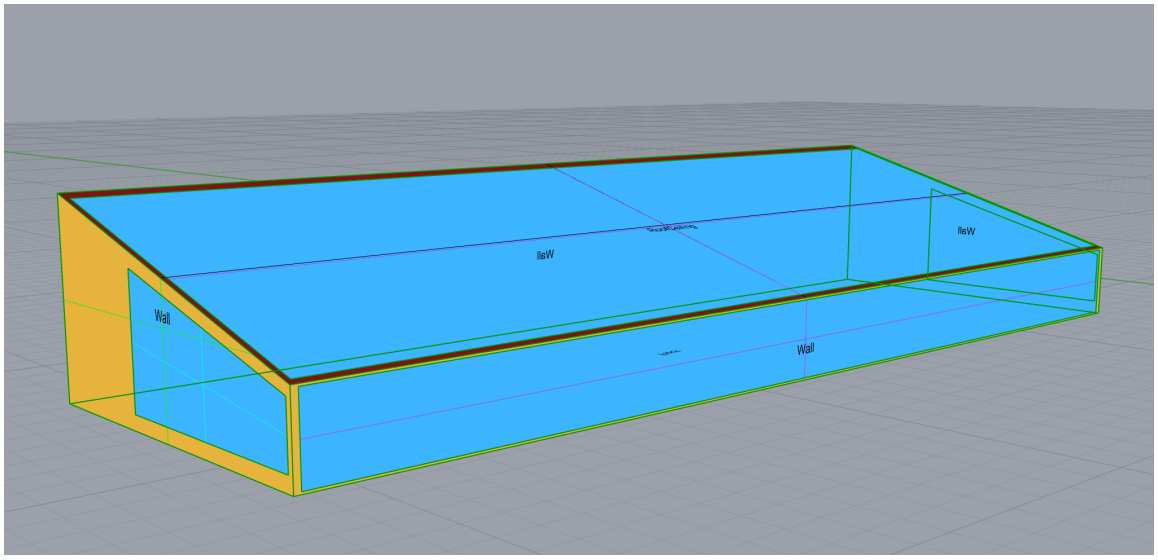


Figure 3.7 Energy simulation model

The energy simulation uses Honeybee plugins in Grasshopper. Since the program is designed to simulate buildings, many settings are changed with custom values to reflect the greenhouse environment. The first step is to model the geometry in Rhino and define it in Grasshopper. The geometry is separated into three categories: roof/ceiling, wall, and floor (ground) as shown in Figure 3.7. Then, glazing is added as operable and fixed openings. Then the program is defined with custom light/people/equipment settings. Wall and glazing materials are defined in the next section. For wall assemblies, bricks with 25mm and 50mm rigid insulation are selected (Figure 3.8).

Weather files are obtained from onebuilding.org. After running the simulation, the result data is separated into ranges. Visualizations are then created using the Ladybug plugin.

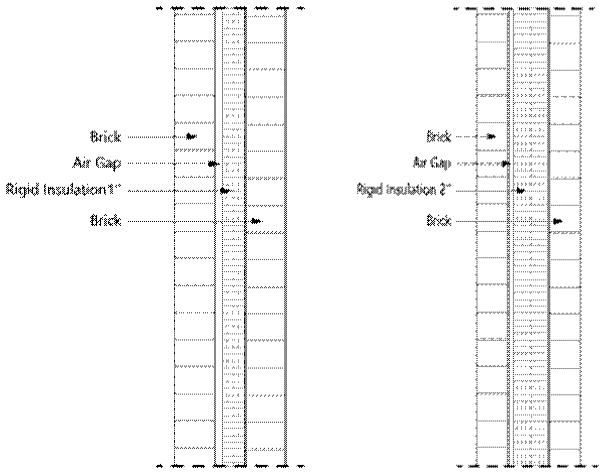


Figure 3.8 Wall sections

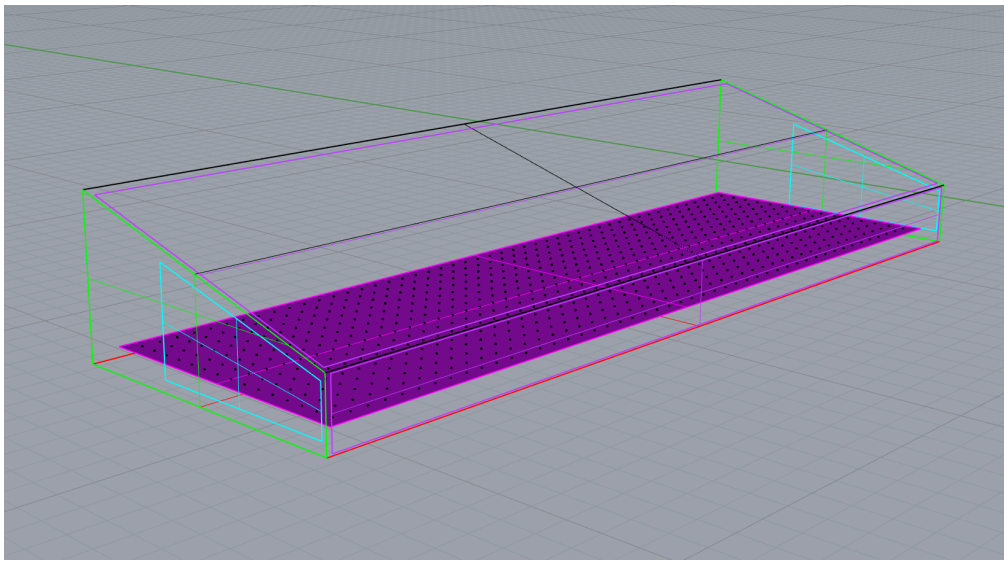


Figure 3.9 Lighting simulation model with the sensor grid

For lighting simulation, a sensor grid is placed inside the greenhouse at 2 feet above the ground level (Figure 3.9). Climate Studio is used to simulate the mean illuminance for every hour of the year in lux. The result is then multiplied by 0.0185 for PAR. Daily Light Integral (DLI) is the final result, which reflects the intensity of light within a day.

Baseline Conditions

The temperature in the weather data from each location is presented in the monthly charts in Figure 3.10. Each column represents a typical day in a month. The three lines on the blue area represent minimum, mean, and maximum, respectively. The yellow zone is the target temperature, 10 to 30°C. The percentage of the year in the target zone ranges between 50% and 66% among the four locations.

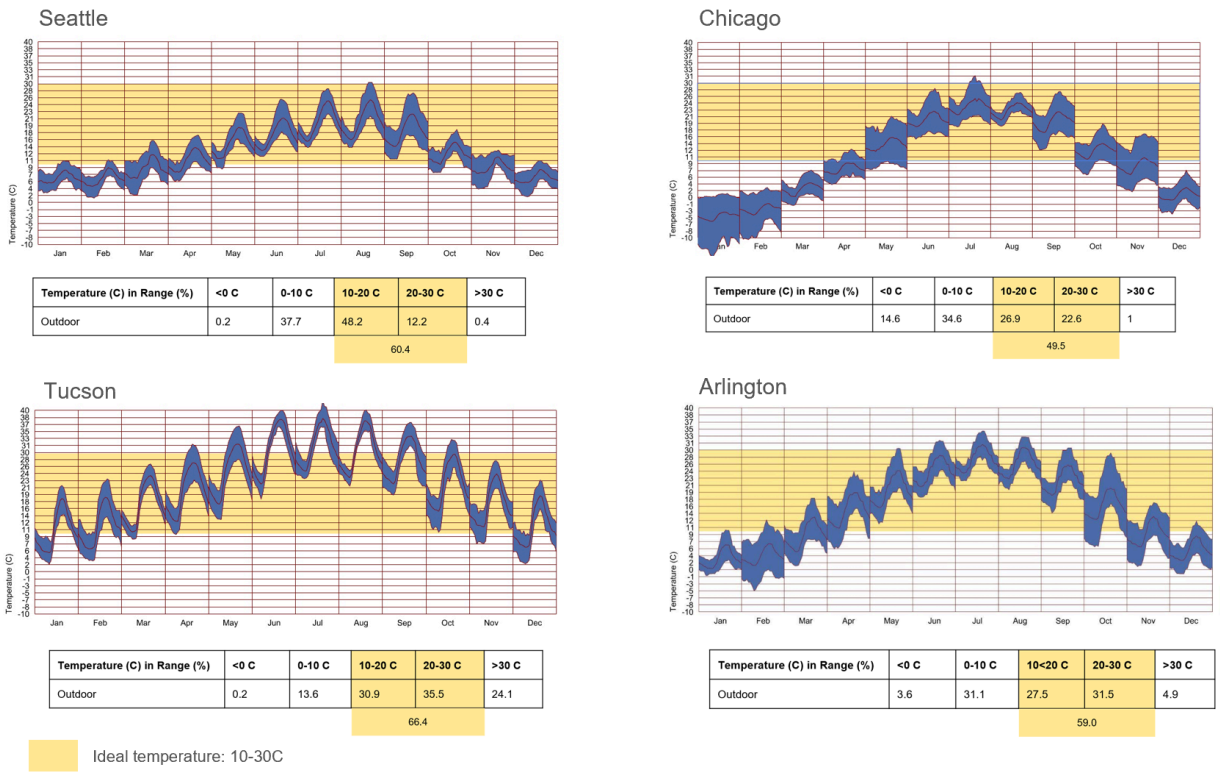


Figure 3.10 Monthly temperature charts of the four locations with the target temperature range highlighted

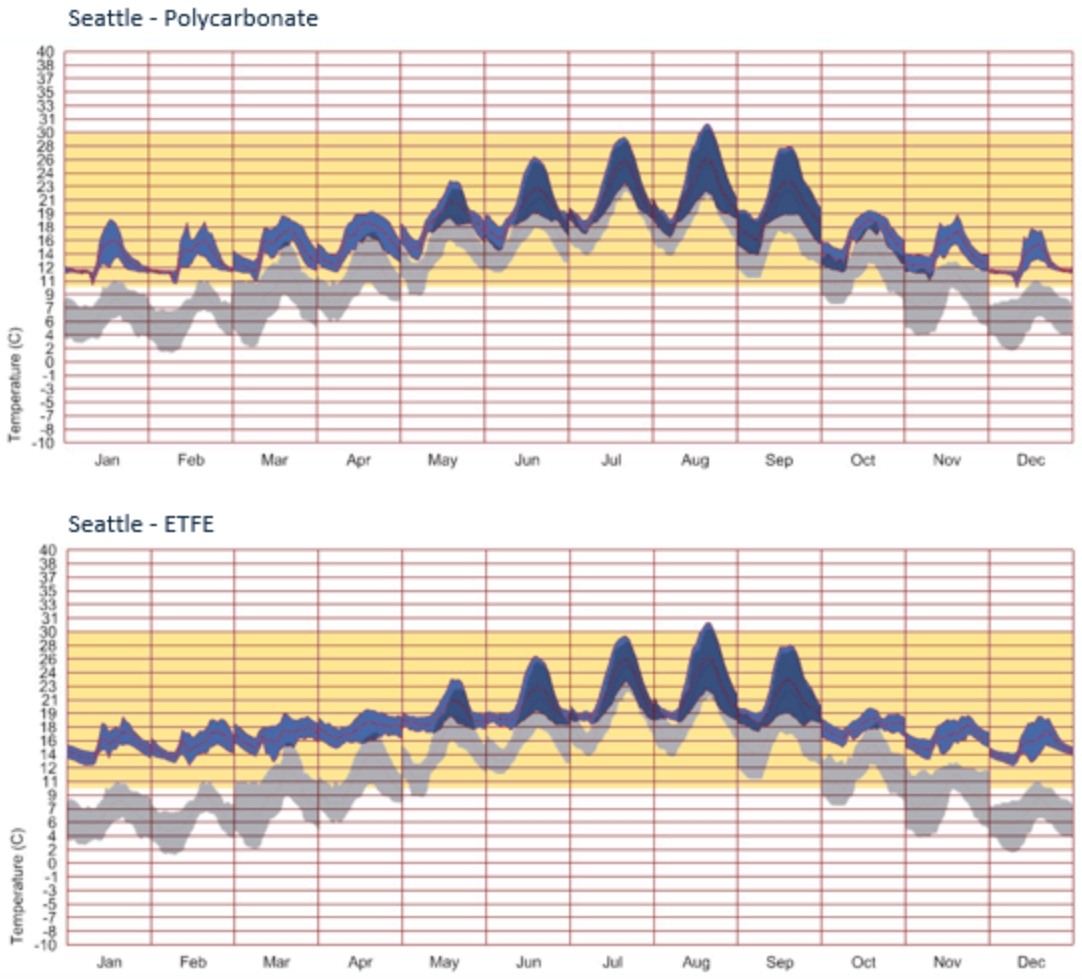
Chapter 4: Results

Seattle

Seattle is in the marine zone, meaning that the winter is mild, and summer is also not too hot. Although it is rare for the temperature to drop below freezing, heating is typically needed for vegetables to grow. The high temperature in summer is usually between 25 to 30°C, which is the ideal range for most vegetables. The final results show that both polycarbonate panels and ETFE are suitable materials for this climate with slight variations.

Table 4.1 Seattle greenhouse setting

Wall	Two layers of brick, 25mm Insulation, R=8 $ft^2 \cdot °F \cdot h/BTU$
Glazing	8mm Polycarbonate
Ventilation	Passive, fan
Night Insulation	On when night temperature is under 12 °C
Shade	No shade

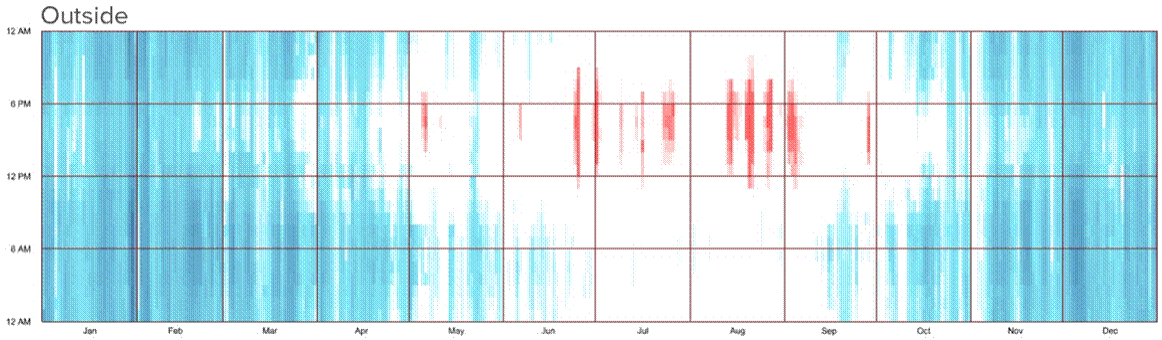


Temperature (°C) in Range (%)	<0 °C	0-10 °C	10-20 °C	20-30 °C	>30 °C
Outdoor	0.2	37.7	48.2	12.2	0.4
			60.4		
Indoor - ETFE	0.0	0.0	49.7	41.1	9.2
			90.8		
Indoor - Polycarbonate	0.0	0.1	68.0	25.7	6.3
			93.7		

Figure 4.1 Monthly temperatures inside the greenhouse in Seattle with the ideal zone highlighted.

Since the summer in Seattle is relatively mild, no shading is needed for cooling. When polycarbonate panels are used for glazing, 93.7% of the year, the temperature inside the greenhouse is between 10 to 30 °C. Within this range, 68% of the time is between 10 and 20 °C, and 25.7% of the time is between 20 and 30 °C. This is a

significant increase from 60.4% of the time outside. When ETFE is used for glazing while other settings stay the same, the amount of time between 10 and 30 °C is about the same. However, the percentage of time between 20 and 30 °C increased significantly from 25.7% to 41.1%. If the intended crop for growing prefers a lower temperature, then polycarbonate should be used. If the intended crop prefers a higher temperature, ETFE should be used. It is also worth mentioning that the amount of time over 30 °C increased for both materials compared to outside. This is predicted as greenhouses tend to trap heat during summer. The high temperature is, in fact, less of a concern since the maximum temperature in the graphs is just under 31 °C, which is acceptable for most crops.



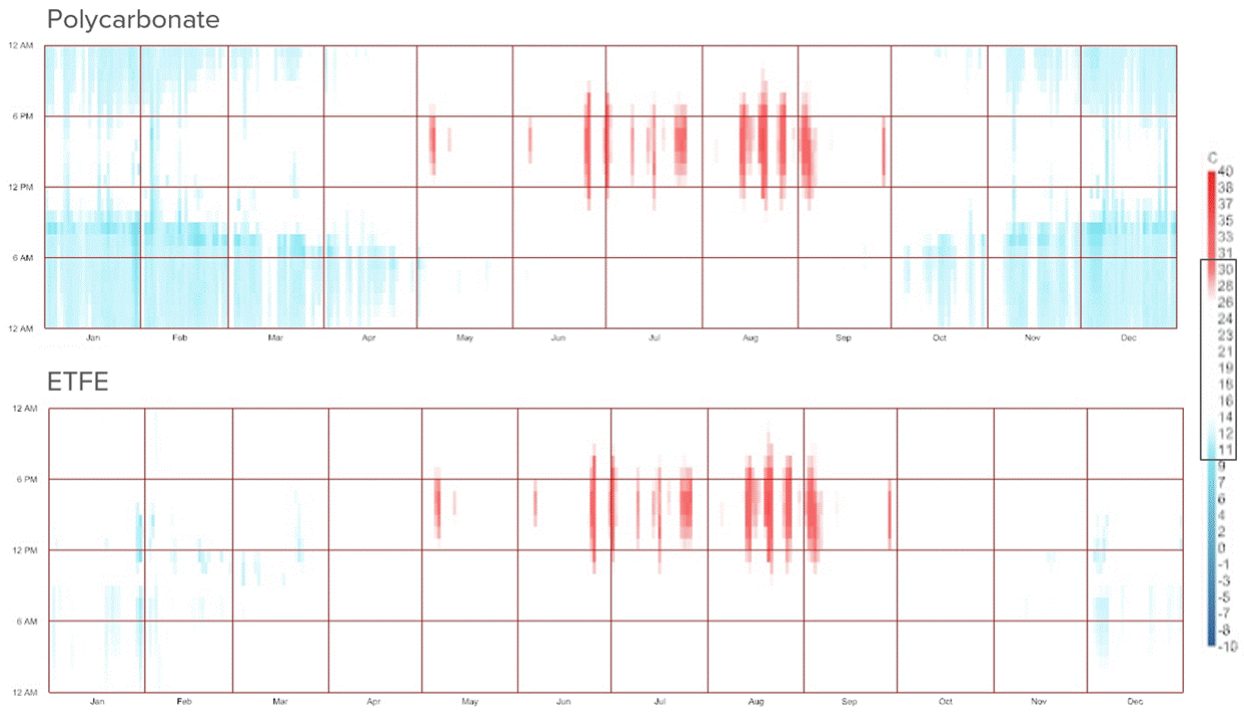


Figure 4.2 Seattle annual hourly temperature maps

Light

The Daylight Integral is a measurement that indicates the amount of light that falls on a surface in a day. The minimum daylight integral for sufficient lighting for growing is 12 mol/m-2/day for leafy greens, and 20 mol/m-2/day for fruiting vegetables. The Daylight Integral level in Seattle shows that there is enough sunlight in summer, but winter months do not have enough light for vegetables to grow. Therefore, supplemental lightings are needed to provide sufficient lighting.

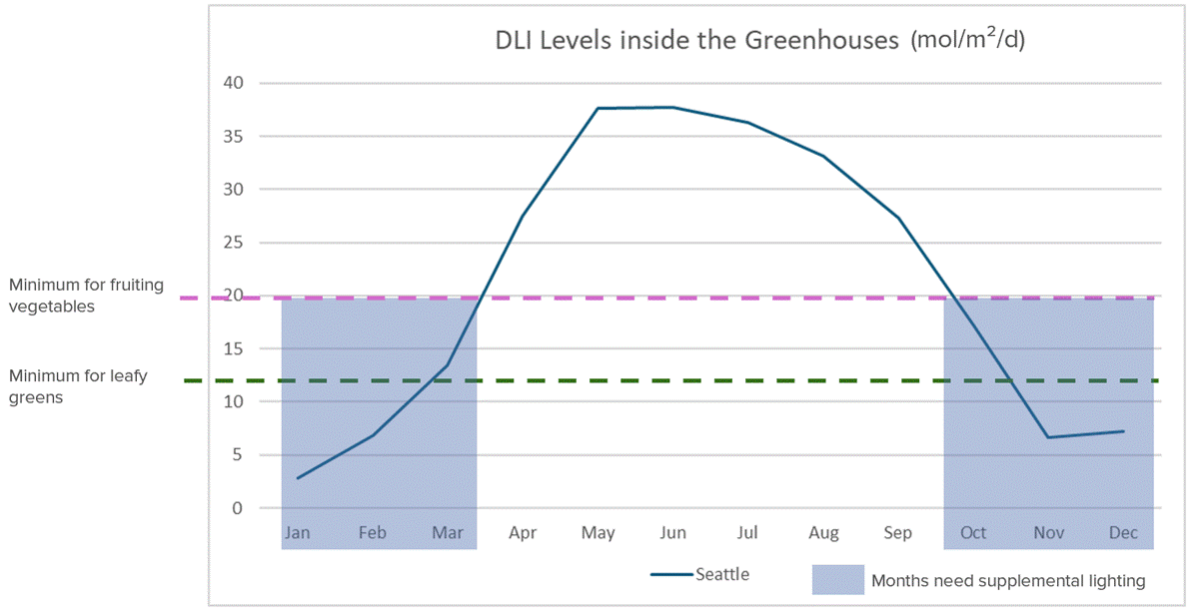


Figure 4.3 Daily Light Integral level inside the greenhouse in Seattle

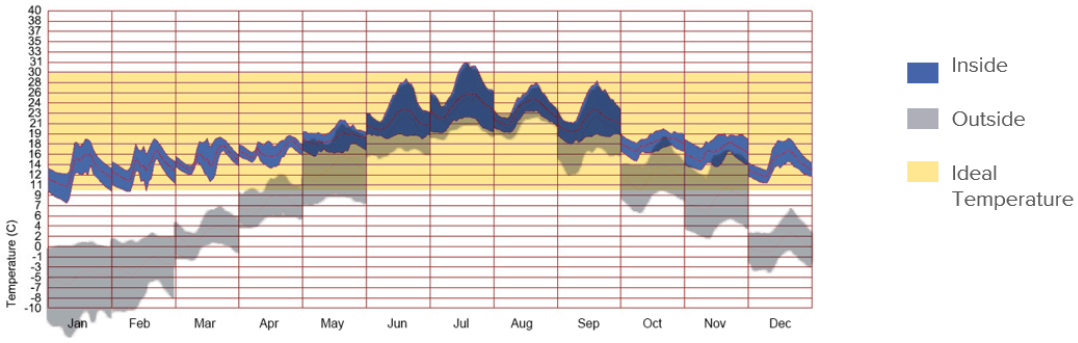
Chicago

Chicago is in the cold zone with a significant portion of the winter temperatures below 0 °C. The summer is also hot with outside temperatures above 30 °C. Only 49.5% of the hours of the year are in the target temperature zone. Both passive heating and cooling strategies are needed.

Table 4.2 Chicago greenhouse setting

Wall	Two layers of brick, 50mm Insulation, R=12 $ft^2 \cdot °F \cdot h/BTU$
Glazing	Single Layer ETFE
Ventilation	Passive, fan
Night Insulation	On when night temperature is under 12 C
Shade	50% opacity, July-Sept 10am-4pm

The glazing material used in Chicago is ETFE due to its high light transmittance with high insulation, which is ideal for a cold climate. The percentage of hours in the ideal temperature range rose to 95% inside the greenhouse. As shown in Figure 4.4, outside temperature from December through March is lifted from partially or completely below freezing to between 10 and 30°C. The temperature in summer stays mostly unchanged.



Temperature (°C) in Range (%)	<0 °C	0-10 °C	10-20 °C	20-30 °C	>30 °C
Outdoor	14.6	34.6	26.9	22.6	1
			49.5		
Indoor	0.0	0.5	51.5	43.5	4.5
			95.0		

Figure 4.4 Monthly temperatures inside the greenhouse in Chicago with the ideal zone highlighted.

The passive solar greenhouse is very effective at raising temperatures in the winter months. As shown in the annual hourly temperature graph, the blue colors are significantly reduced, but the red areas stayed very much the same.

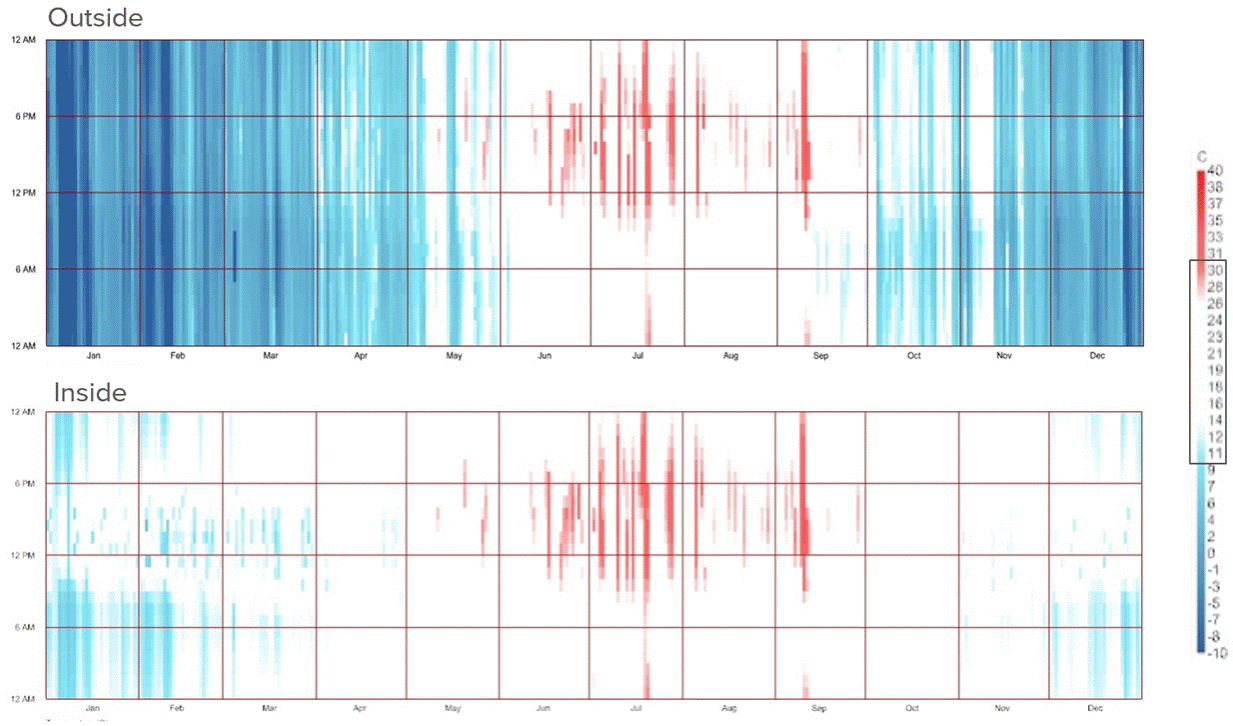


Figure 4.5 Annual hourly temperature in Chicago

The light levels in Chicago are higher than in Seattle, but supplemental lighting is still needed in January, February, and December.

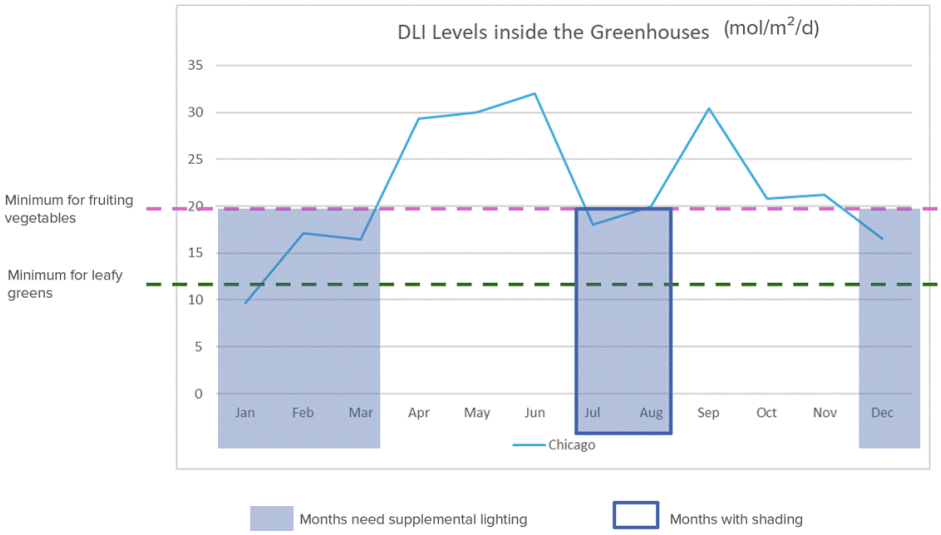


Figure 4.6 Daily Light Integral level in the greenhouse in Chicago

Arlington

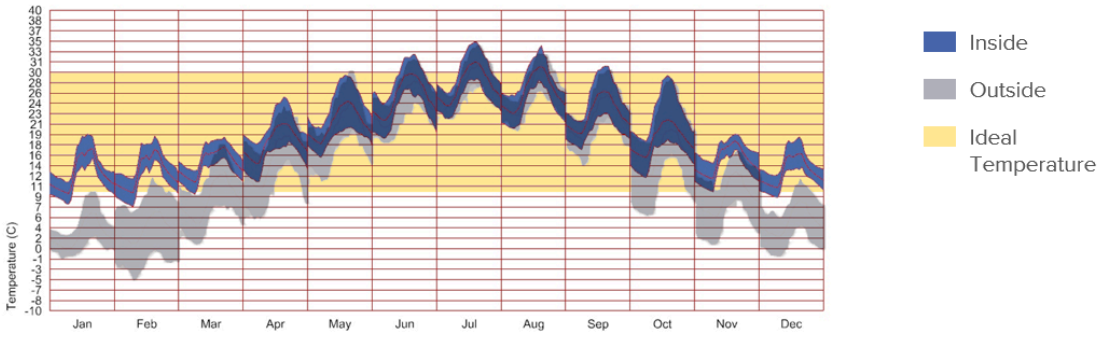
Arlington is in the mixed-humid climate zone. The temperature pattern throughout the year is similar to Chicago's but with a milder winter. 59% of the year, the temperature is between 10 and 30°C.

Table 4.3 Arlington greenhouse setting

Wall	Two layers of brick, 25mm Insulation, R=8 ft²·°F·h/BTU
Glazing	8mm Polycarbonate
Ventilation	Passive, fan
Night Insulation	On when night temperature is under 12 C
Shade	50% opacity, July-Sept 9am-4pm

The simulation result shows a similar pattern to Chicago. The winter months' temperature is raised, and the summer temperature stays mostly the same. Overall, 87.4% of the year is within the target temperature zone inside the passive solar

greenhouse. The challenge for Arlington is to balance the amount of shading with temperature. The temperature could be lowered with longer shading, but that also reduces the amount of daylight.



Temperature (°C) in Range (%)	<0 °C	0-10 °C	10<20 °C	20-30 °C	>30 °C
Outdoor	3.6	31.1	27.5	31.5	4.9
			59.0		
Indoor	0.0	3.1	48.4	38.7	9.8
			87.4		

Figure 4.7 Monthly temperatures inside the greenhouse in Arlington with the ideal zone highlighted.

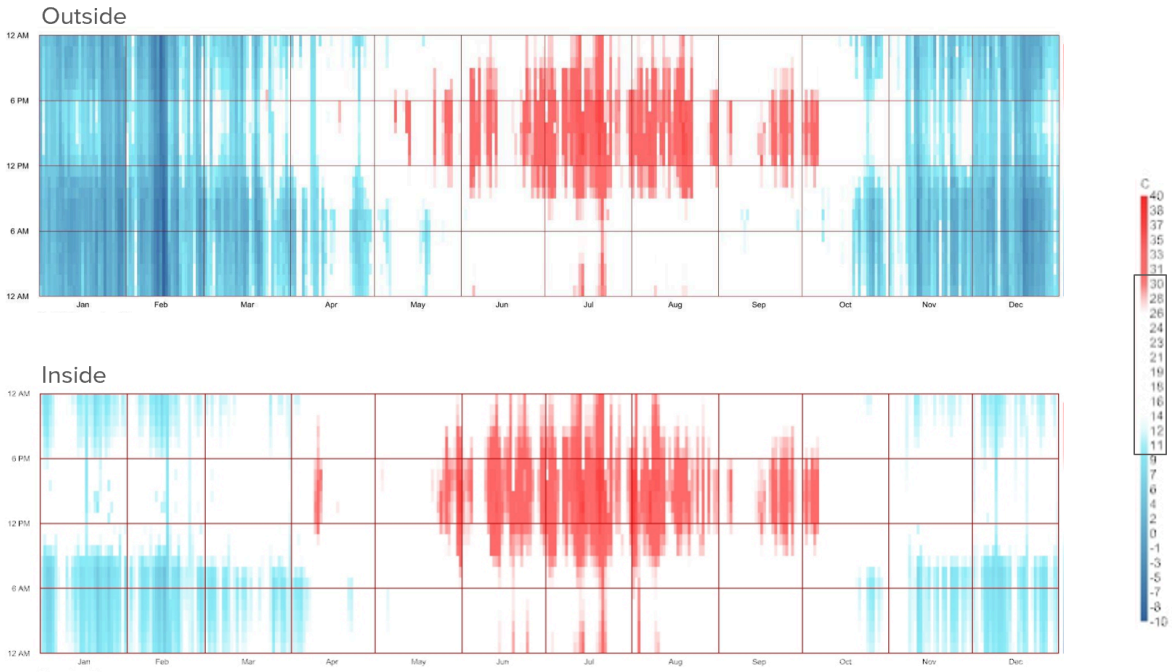


Figure 4.8 Annual hourly temperature in Arlington

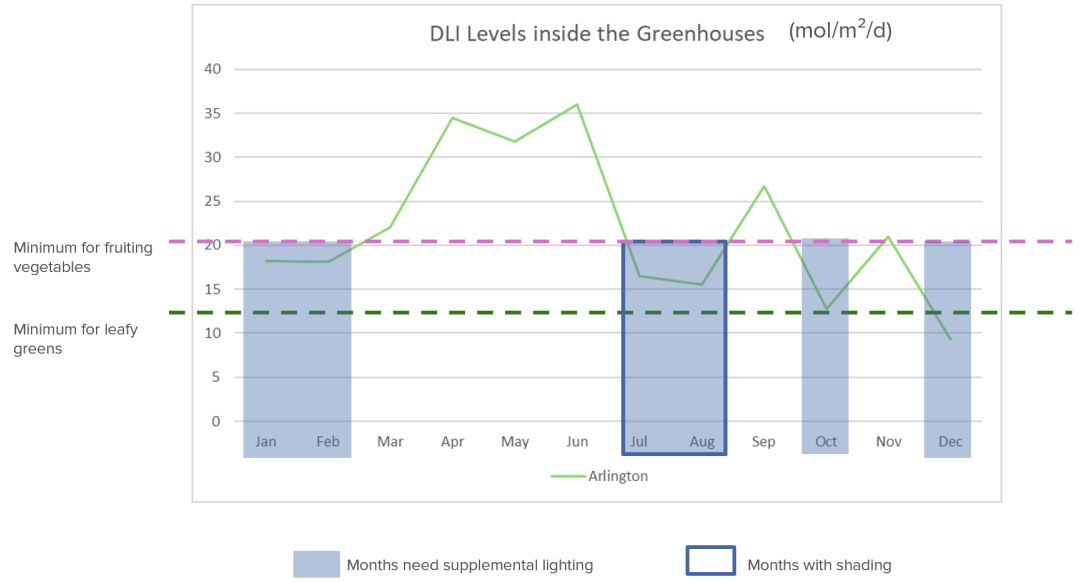


Figure 4.9 Daily Light Integral level in the greenhouse in Arlington

Tucson

Situated in the mixed-dry climate zone, Tucson's average temperature throughout the year is higher than the other three case study locations. There is also a big diurnal shift in temperature. 66.4 percent of the time is within the target temperature range. The rest of the time needs both heating and cooling. Summer months are significantly warmer than the other three locations, with the maximum temperature reaching 40°C.

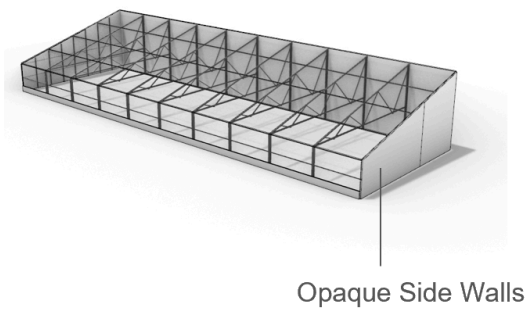


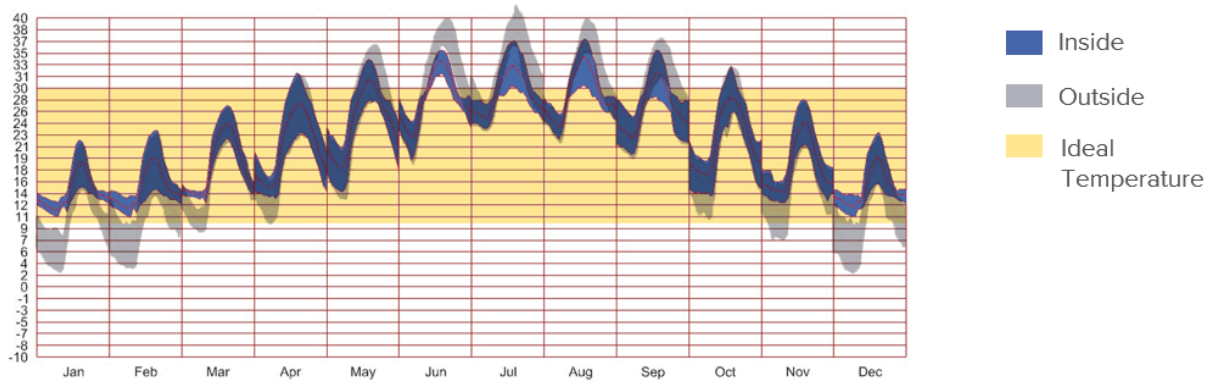
Figure 4.10 Tucson simulation model

Table 4.4 Tucson greenhouse setting

Wall	Two layers of brick, 50mm Insulation, R=12 $ft^2 \cdot °F \cdot h/BTU$
Glazing	8mm Polycarbonate
Ventilation	Passive + Fan
Night Insulation	On when night temperature is under 12 C
Shade	50% opacity, on May-September, 10am-4pm

The glazing material is polycarbonate panels, and the north wall is insulated with 50mm rigid insulation. Instead of having glazing on the side walls, Tucson's greenhouses have solid side walls to increase shading during summer months.

The passive solar greenhouse is effective in raising temperatures. During summer months, the percentage of time above 30°C is reduced from 24.1% outside to 11.3% due to shading and ventilation. The maximum temperature is between 35 to 37°C. This condition is warmer than ideal, but it is difficult to further cool the greenhouse without sacrificing the daylight. As shown in Figure 4.12, the amount of red areas from inside the greenhouse only reduced slightly from the outside, indicating that the effect of the passive solar greenhouse on cooling is limited in Tucson. Since Tucson has high DLI year-round, there is still an adequate amount of light inside the greenhouse after shading in summer months (Figure 4.13).



Temperature (C) in Range (%)	<0 C	0-10 C	10-20 C	20-30 C	>30 C
Outdoor	0.2	13.6	30.9	35.5	24.1
			66.4		
Indoor	0	0.2	39.9	48.6	11.3
			88.5		

Fig. 4.11 Monthly temperatures inside the greenhouse in Tucson with the ideal zone highlighted.

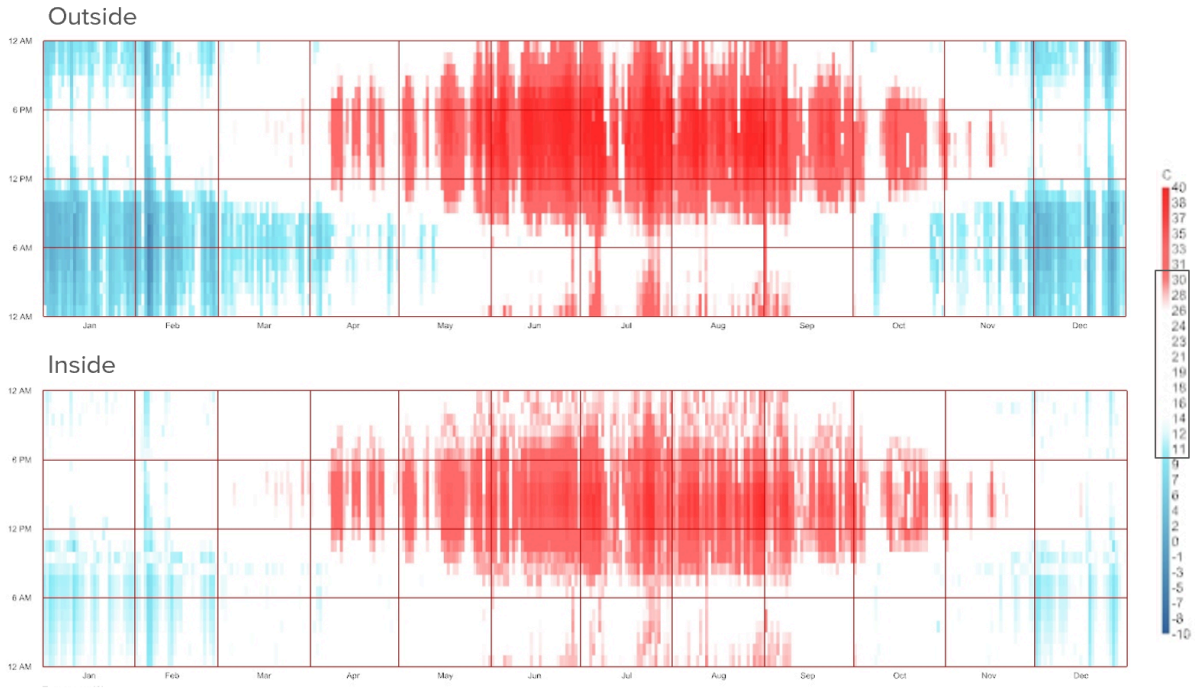


Figure 4.12 Annual hourly temperature chart in Tucson

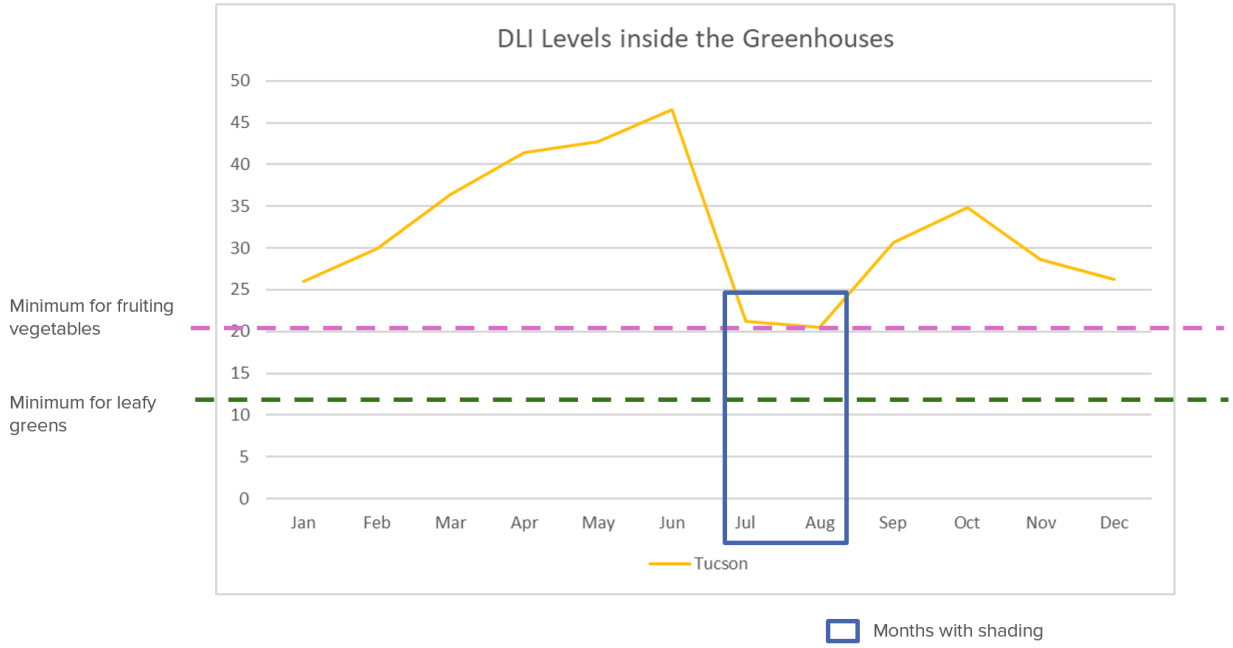
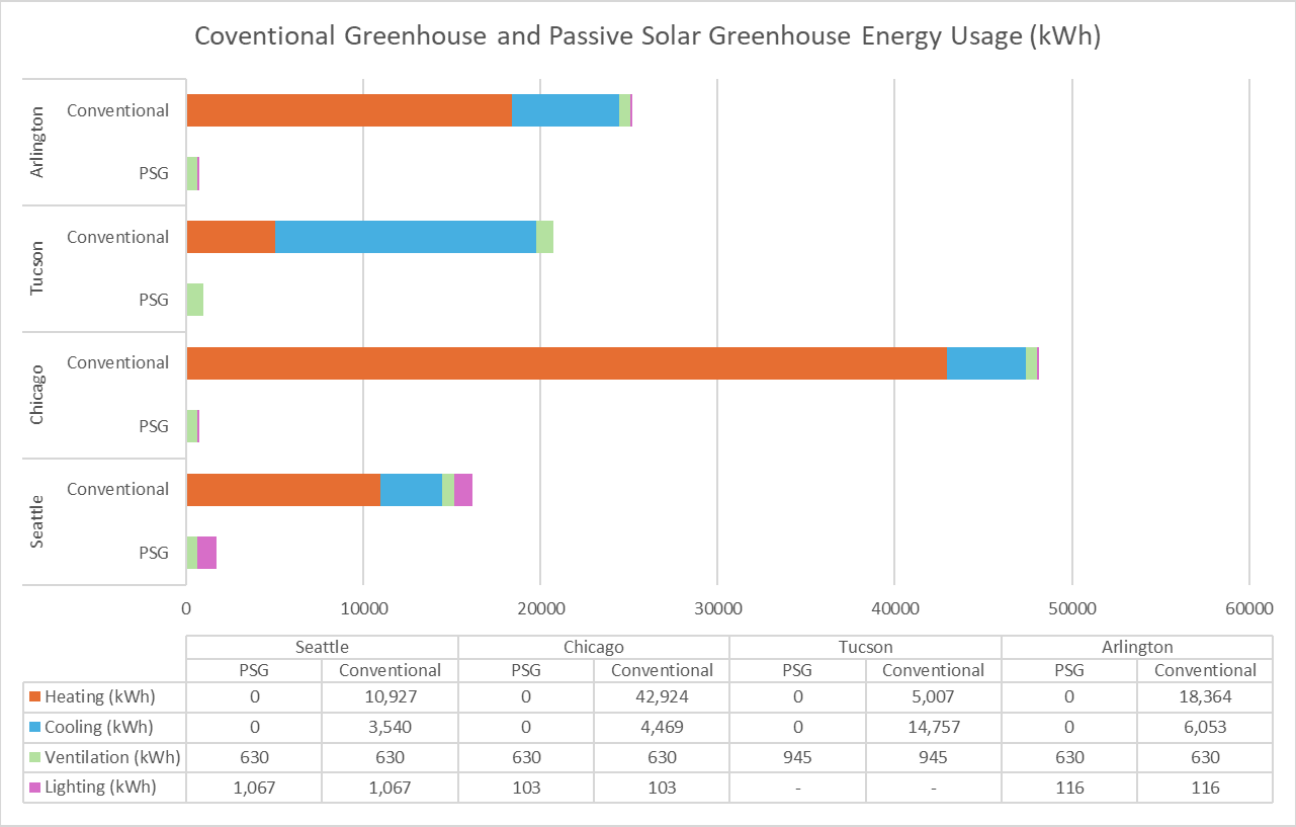


Figure 4.13 Daylight Integral levels inside the greenhouse in Tucson

Energy Use and Solar PVs

The energy usage of the conventional greenhouse is calculated using Climate Studio. The conventional greenhouse is modeled as a glass-covered greenhouse with the same square footage as the passive solar greenhouse. As shown in Figure 4.14., heating contributes the largest amount of energy consumption in greenhouses at three locations, and cooling is the largest in Tucson. Passive solar greenhouses do not need heating or cooling to regulate interior temperature; therefore, the total energy use is only a fraction of conventional greenhouses.



	Seattle		Chicago		Tucson		Arlington	
	PSG	Conventional	PSG	Conventional	PSG	Conventional	PSG	Conventional
Heating (kWh)	0	10,927	0	42,924	0	5,007	0	18,364
Cooling (kWh)	0	3,540	0	4,469	0	14,757	0	6,053
Ventilation (kWh)	630	630	630	630	945	945	630	630
Lighting (kWh)	1,067	1,067	103	103	-	-	116	116

Figure 4.14 Conventional Greenhouse and Passive Solar Greenhouse Energy Usage

Chapter 5: Conclusions

Table 5.1 Percentage of the year in the target temperature range (10 to 30 °C)

	Climate Zone	Outside	Inside Greenhouse	Difference
Seattle	Marine	60.4%	93.0%	32.6%
Chicago	Cold	45.5%	95.0%	45.5%
Arlington	Mix-humid	59.0%	87.4%	28.4%
Tucson	Mix-dry	66.4%	88.5%	22.1%

Overall, passive solar greenhouses can significantly increase the percentage of time that indoor temperatures remain within the target range—exceeding 85% in some cases. The extent of this improvement varies by climate zone. As shown in Table 5.1, these systems are most effective in cold and marine regions, where heating demands outweigh cooling needs. For instance, the target temperature coverage increased by 45.5% in Chicago and 32.6% in Seattle. In contrast, warmer climates such as Tucson and Arlington saw more modest improvements of 22.1% and 28.4%, respectively.

Given that over half of the U.S. falls within cold and marine climate zones, passive solar greenhouses present a promising solution for enabling year-round vegetable production in these regions. Furthermore, as discussed in Chapter 2, greenhouses in colder climates require substantially more energy for heating. Thus, implementing passive solar designs offers a cost-effective strategy to reduce this energy burden.

While heating and cooling dominate greenhouse energy use, lighting and mechanical ventilation also contribute. However, the energy required for these functions is relatively modest and can be feasibly supplied through solar photovoltaic (PV) systems, enhancing the overall sustainability of passive solar greenhouses.

Limitations and Future Opportunities

This study has several limitations that may affect the accuracy and generalizability of its findings. First, the energy consumption calculations do not account for electricity used by auxiliary systems such as sensors, controls, and motors for operating shading devices and thermal blankets. Second, the energy demands for lighting and mechanical ventilation were based on selected commercial products; using different equipment could yield varying results. Overall, this project serves as a broad assessment intended to demonstrate the potential of passive solar greenhouses across various U.S. climate zones, rather than a detailed case-specific analysis.

Future research could expand on this work in several meaningful directions. One key opportunity is to develop passive solar greenhouse designs better suited to hot climates. The results from Tucson suggest that the current design could benefit from enhancements such as passive cooling strategies and/or mechanical systems. Incorporating evaporative cooling into future energy models could improve accuracy and applicability in arid regions. Additionally, while this study does not address CO_2 enrichment, it plays a vital role in commercial greenhouse operations. Future studies

should explore CO_2 enrichment strategies and integrate their energy implications into comprehensive greenhouse energy modeling.

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Images
Figure 1.1: MIT Solar House II, MIT News Office and the MIT Museum.
https://web.mit.edu/solardecathlon/solar2.html

Figure 1.2: Eleanor Raymond and Maria Telkes, *Dover Sun House*, 1948, photograph, Dover, Massachusetts.
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Figure 1.3: Cape Cod Ark, The Green Center, https://newalchemists.net/portfolio/bioshelter-arks/

Figure 1.4: Chinese solar greenhouse exterior.

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Chapter 3: Project Scope and Methodology

Figure 3.2 base image
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Figure 3.6 data
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