PSGH White Paper #1

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Executive Summary

This white paper explores the critical role and transformative potential of 5th World's (5W) Passive Solar Greenhouse (PSGH) equipped with Climate Battery technology in addressing challenges including, but not limited to:

- Ensuring a year-round supply of nutrient-dense food
- Drastically reducing carbon footprints
- Creating aesthetically pleasing spaces tailored to individual needs
- Enhancing resilience in an increasingly unpredictable climate

Through the application of TRNSYS (Transient System Simulation Tool), a flexible software environment used to simulate the behaviour of dynamic and transient systems, the 5W PSGH design was evaluated against conventional style greenhouses (both insulated and non-insulated) in varied climatic conditions in North America: Kamloops, BC; Calgary, AB; London, ON; and Boulder, CO.

The analysis conducted on the thermodynamic output of TRNSYS highlights the remarkable energy efficiency of the 5W PSGH, which, on average, requires only 1.2% of the energy consumed by conventional greenhouses and 2.3% of that by conventional greenhouses with insulation. This marks a great stride towards minimizing operating costs, reducing environmental impact, and increasing thermal comfort of both plants and humans.

Beyond serving as an eco-friendly alternative to conventional greenhouses, the 5W PSGH presents itself as a strategic investment for a resilient future, tailored to your lifestyle and preferences. We work closely with our clients in an innovative and collaborative manner to implement features such as saunas, hot tubs, games rooms, and rainwater harvesting systems to create holistically designed multifunctional food-bearing spaces that go beyond traditional agriculture. We invite you to discover the benefits of the 5W PSGH through free discovery calls, where we can cultivate both a collaborative relationship and a resilient future.

Introduction

Historically speaking, human ingenuity in shelter design reflected a deep harmony with natural forces. For example, over 5,000 years ago, Iranian architects designed buildings with passive cooling systems, preserving winter ice well into the blistering summers for later use (Bahadori, 1978). The Greeks had planned their cities to be oriented towards the sun for maximum and equitable solar gain for all its inhabitants.

One doesn’t have to look far to see how far we have strayed from these passive principles. While ancient civilizations were able to engineer harmony with nature's offerings, modern practices, especially in the greenhouse sector, have diverged. In Alberta, Canada, about 82% of greenhouses consume a staggering 5×10^6 GJ of natural gas each year, translating to roughly 234,000 metric tons of CO_2 emissions (Spencer et al., 2018; Ellouze & Mirza, 2017). Beyond the environmental toll, the financial implications are harsh: Heating expenses routinely account for up to 35% of total production costs in Canadian greenhouses (Ahmed et al., 2019), a figure that's been on the rise. This isn't just a localised challenge either—it reflects a worldwide dilemma, illustrating a tension between increasing greenhouse energy demands and a global momentum towards regenerative and healthy living that prioritizes local solutions, nutrient dense food, and food and fuel security.

Amidst the global urge to cut back on emissions, and achieve self custody of nutrient-dense food, the idea of once again cooperating with nature is rapidly gaining prominence. This white paper delves into the promise of 5th World’s Passive Solar Greenhouse designs with a particular focus on our revolutionary Climate Battery design. Through case studies of our greenhouses in Kamloops, BC; Calgary, AB; London, ON; and Boulder, CO, we will elucidate the promise of our innovative design technology, and support those promises with the outputs of state-of-the-art thermodynamic modelling. Further, we will discuss why forward-thinking investors should view Passive Solar Greenhouses as more than just an eco-friendly asset: They are also a strategic, long-term investment that provides dividends beyond measure.

Our journey towards local-scale regenerative solutions sees us combine ancient wisdom with contemporary innovation, reminding us that the solutions for a brighter tomorrow often lie in the wisdom of yesteryears. This journey begins with reimagining our relationship with nature and harnessing its potential in a way that benefits us today and not only preserves, but creates resources for future generations.

The Anatomy of a Passive Solar Greenhouse

People have sought reliable sources of nutrient-dense food since ancient times. In an era devoid of modern medical luxuries, the Roman Emperor Tiberius was beset with illness, and his prescription was simple: A cucumber a day. However, meeting this simple requirement posed a challenge given the conditions needed for the cucumber to grow. Rising to the occasion was the design of the first greenhouse, crafted with thin translucent sheets of selenite, a crystalline variety of gypsum.

Fast forward to today, and greenhouses have proliferated far and wide. Stretching over an astounding nine million acres globally, these structures have become a ubiquitous part of our agricultural landscapes and backyard gardens. Yet, with vast expanses sheathed almost entirely in glazing, these contemporary greenhouses demand staggering energy inputs.

The term “passive-solar” may sound like a modern buzzword, but as discussed above, the principles are as ancient as human civilization itself. At its core, a passive solar design harnesses the sun's energy without relying on external, active mechanical systems. Instead, passive solar design leverages a dynamic interplay between the natural processes of solar and mechanically induced convection, conduction, and radiation[1], all carefully designed within architectural elements to modulate temperature, resulting in the optimal conditions for growth, food storage, and/or human comfort.

The architectural elements that modulate convection, conduction, and radiation in order to achieve optimal conditions for growth, food storage, and/or human comfort are as follows[2]:

- **Aperture:** The component through which sunlight enters a structure—essentially the ‘window’ for the sun.
- **Collector:** Directly absorbs the sunlight streaming through the aperture

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[1] For a primer on these processes, please refer to Appendix 1.

[2] For an expanded description of the architectural design elements considered in passive solar design, please refer to Appendix 2.

- **Thermal mass:** Materials that can capture and store heat
- **Distribution:** To distribute the heat generated by the collector
- **Control:** To regulate the amount of sunlight and /or heat that is permitted to stay in the structural system

Each of the above architectural elements holds the potential to profoundly influence the conditions within a greenhouse, determining both the success of fostering plant growth, and the energy expenditure required to sustain that plant growth. Over the past 12 years, 5th World co-founder and mechanical engineer, Rob Avis, has delved deep into this art and science of greenhouse design by studying, testing, and refining each of these architectural elements, pushing the boundaries of what's conventionally known and practised.

While many greenhouses focus merely on capturing sunlight, 5W greenhouses aim for a holistic balance: maximizing sunlight capture, ensuring efficient heat storage, and maintaining optimal conditions with the least energy expenditure. The 5W Passive Solar Greenhouse equipped with a Climate Battery (henceforth referred to as PSGH) has a unique advantage stemming from its precision-engineered design that not only optimizes each architectural element for superior energy efficiency and environmental control but also integrates them into a more balanced and effective system via the Climate Battery system; the result being an extended growing season, improved conditions for growing/storing crops, and significantly reduced energy consumption.

The Climate Battery Explained

The centrepiece of our greenhouse design strategy is the Climate Battery system, which integrates the architectural elements of passive solar design to redefine greenhouse efficiency and functionality. But, what is the Climate Battery, and how does it contribute to the efficiency of our greenhouses?

A Climate Battery is essentially a subterranean air-management and heat storage system. Picture it as a greenhouse’s energy reservoir that can be tapped into when outside ambient temperatures fall in the autumn, winter, and even anomalously cold days in the summer. Rather than letting excess heat escape into the atmosphere when there is an abundance, the Climate Battery captures it and waits until it is crucial for that heat to be distributed back into the greenhouse in order to maintain optimal growing conditions.

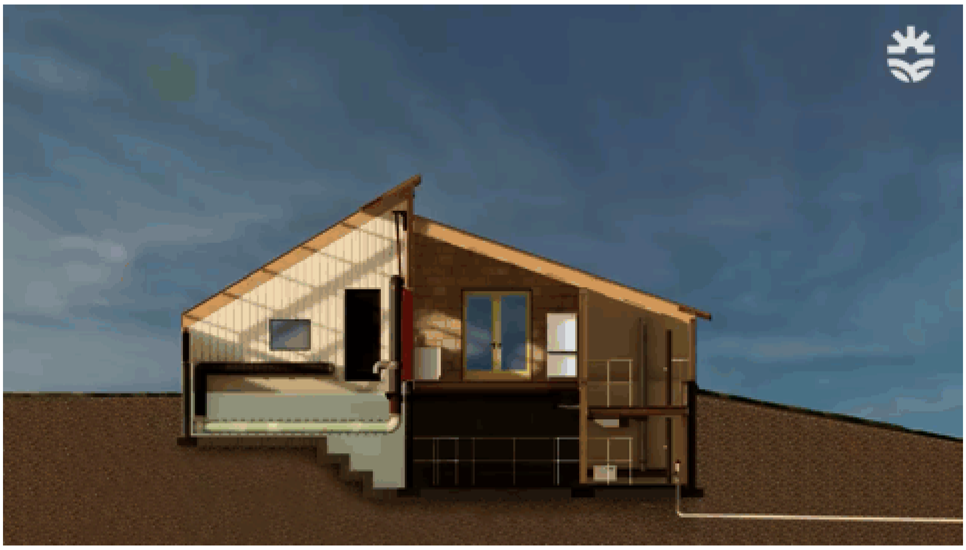

Figure 1. Graphic Representation of the Fifth World Passive Solar Greenhouse with Climate Battery and Integrated Root Cellars

The following table draws a comparison between conventional greenhouses, and the 5W PSGH with Climate Battery™ design technology.

Table 1. Comparison of Architectural Design Elements of Conventional Greenhouses and the 5W Passive Solar Greenhouse with Climate Battery

Architectural Element	Conventional Greenhouse	5th World’s Passive Solar Greenhouse with Climate Battery
Aperture	Typically made of a single layer of glass, plastic, or polycarbonate on all sides. While this design allows for a high degree of light penetration (i.e. the aperture is always fully open), it offers very little insulation, allowing heat to escape readily and easily. Can lead to excessive heat during the day, and rapid heat loss during the night.	In the northern hemisphere, the north, west, and east facing walls, plus the south facing knee-wall are all heavily insulated. The resultant aperture is limited to the south facing glazing for greenhouses in the Northern Hemisphere, and north facing glazing in the Southern Hemisphere. Our deliberately oriented and placed greenhouses maximize incoming sunlight, while minimizing heat loss.

Collector	With the entire structure acting as the aperture, the contents of the structure itself acts as a collector. Because there is little distinction between the collector and the rest of the structure, there is very little control over heat absorption and distribution.	Our precision crafted collector surfaces with low albedo are positioned strategically to absorb maximum sunlight, convert it to heat, and store that heat underground for later use.
Thermal Mass	While some traditional greenhouses may use thermal mass, their influence is diminished by the fact there is so little insulation to keep that heat in. Furthermore, that thermal mass does not hold heat for longer than overnight, limiting the influence it can exert during a longer time scale.	By incorporating thermal mass in our designs that include heavy insulation, the heat radiated from thermal mass stays in the greenhouse, modulating night time temperatures.
Distribution	Heat distribution is managed through forced convection via fans.	By capturing sunlight via our collector, and sending it to our Climate Battery™, heat is distributed underground to be extracted at a later time when it is colder. Furthermore, automated fans move air, and while distributing heat also prevent stagnation.
Control	Achieved through ventilation	Our advanced and fully automated control mechanisms open windows, doors, and vents, as well as turn on fans when certain conditions are met.

Closing the Loop: Harnessing Earth's Natural Thermostat

Our improvements over the traditional greenhouse go above and beyond extending the growing season—the 5W Passive Solar Greenhouses take efficiency a step further. Not only do our greenhouses nurture plants through passive means, but they also offer an ingenious solution to store the yield of your harvest. As an optional feature, we've integrated a series of three different root cellars, each tailored to cater to diverse storage needs:

1. **Cool and Humid Cellar:** With a cool and moist environment, this root cellar is perfect for root crops.
2. **Cool and Dry Cellar:** Ideal for grains, peas, canned goods, and the like, this cellar ensures your produce remains cool yet free from excessive moisture.
3. **Colder and Dry:** The coldest of the three cellars, this chamber is well suited for curing meats, storing cheese, and long-term storage of fine wines.

Each cellar utilizes an array of Earth Tubes for passive temperature and humidity control. During the summertime, the Earth Tubes draw air towards the greenhouse, naturally cooling it to the Earth's temperature. Conversely, during winter, the Earth's stable subsurface temperature gently warms the air, providing just the right environment for storage.

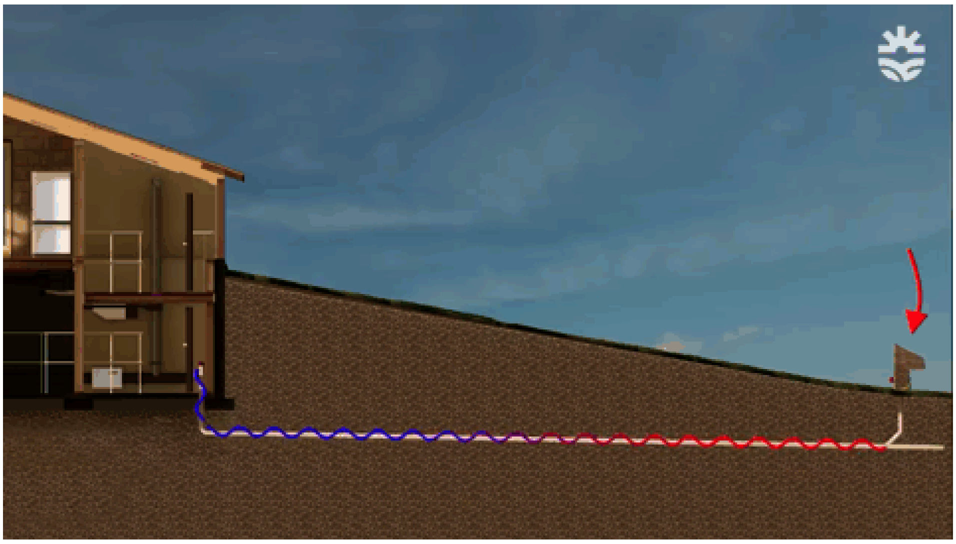

Figure 2. Earth tube system for passive cooling of root cellars

Furthermore, our system ensures that the gases released by the stored crops are put to productive use: We've innovatively designed the structure so that the gaseous compounds such as ethylene, carbon dioxide, and other gases emanating from the root cellars are directed toward the greenhouse, where they can be used to enhance plant growth. Therein lies the genius of our design, where we transform a potentially life-threatening problem into an enriching solution. The design of such a system demonstrates a harmonious balance, where waste is transformed into valuable resources for plant health and productivity.

From Theory to Thriving: Case Studies of Passive Solar Greenhouses in Action

This section explores the outputs of the thermodynamic modelling conducted by David Bradley, principal investigator at Thermal Energy System Specialists (TESS). The thermodynamic modelling was done with TRNSYS (pronounced 'tran-sis'), a flexible software environment used to simulate the behaviour of dynamic and transient systems. To learn more about TRNSYS, go HERE. TRNSYS was used to compare conventional-style greenhouses (with and without an insulated north wall in order to simulate a more efficient building without a climate battery) with the 5W PSGH with a Climate Battery. The greenhouses that were modelled had the following characteristics:

- Dimensions of 6.1m x 12.2m
- Oriented from west to east to maximize solar gain
- In the instances where insulation was modelled, the insulation had an R value of 17
- Each greenhouse was modelled to have two heaters, one located near the ground, and another at a height of 4.5m (14ft). These heaters were automatically turned on in the simulation in order to keep the greenhouse temperatures above 5°C (41°F) at all times
- Each greenhouse was equipped with a ventilation system that effectively capped the internal temperatures to a maximum of 40°C (104°F)

To investigate how the 5W Passive Solar Greenhouse performs in an array of climatic regions, the model was run with different typical meteorological year (TMY) files[3]. The performance of conventional-style greenhouses both with and without an insulated north wall, and the 5W Passive Solar Greenhouse with Climate Battery technology was explored in the following locations:

- Kamloops, British Columbia, Canada
- Calgary, Alberta, Canada
- London, Ontario, Canada
- Boulder, Colorado, United States

Both the temperature and the incoming solar radiation (henceforth referred to as insolation) within the TMYs for the listed locations above vary significantly both within and amongst locations within the modelling period. The variations in both metrics are critical in determining the thermal and energy performance of the three greenhouse designs explored in this paper and can be explored in Figure 3 (temperatures), Figure 4 (insolation), and Table 1. Please note that due to the nature of the TMY files, there are no

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[3] A TMY is a compilation of selected meteorological data for a specific location over a specific period (generally 20–30 years). The data in a TMY is not from a single year but is a composite of various individual months from different years, chosen to represent a 'typical' year for that location.

dates displayed, and rather, the x-axis of the subsequent plots in this paper are labelled with the Day of the Year, rather than dates.

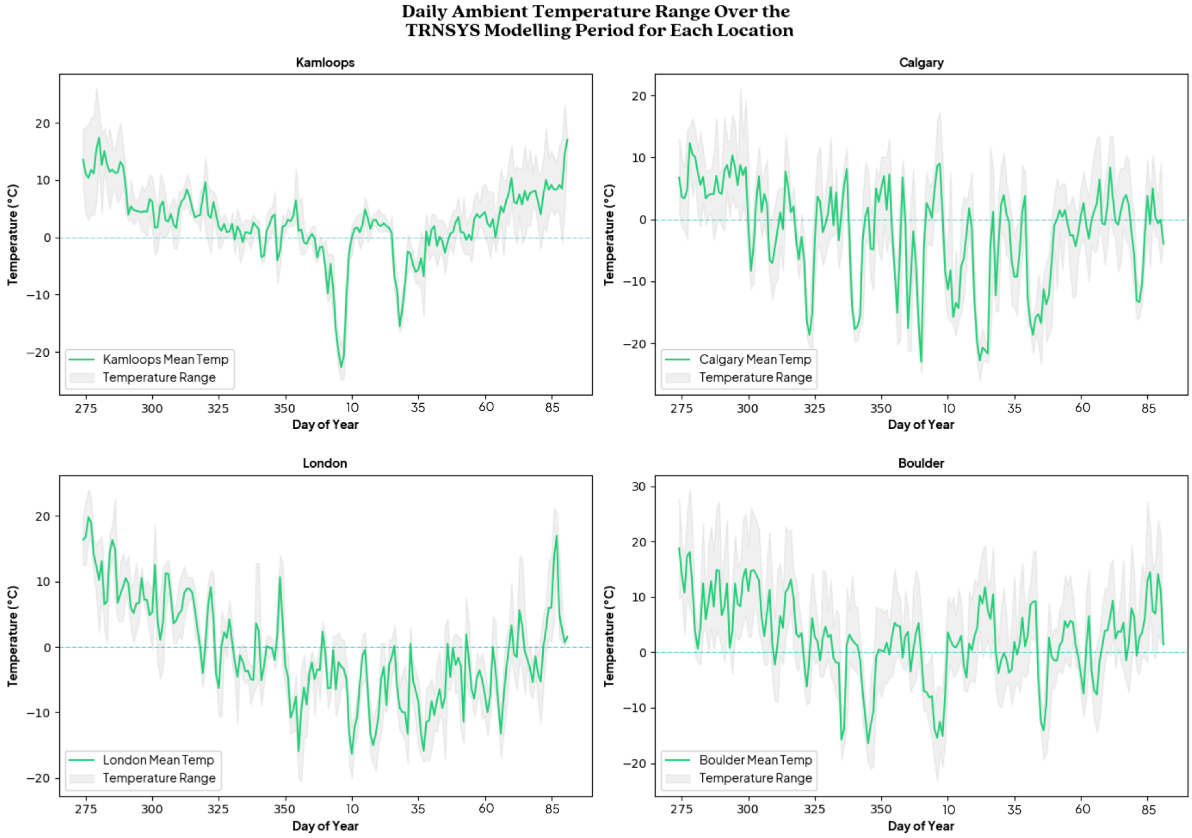

Figure 3. Temperature fluctuations in the TMY files used in the TRNSYS model for each location.

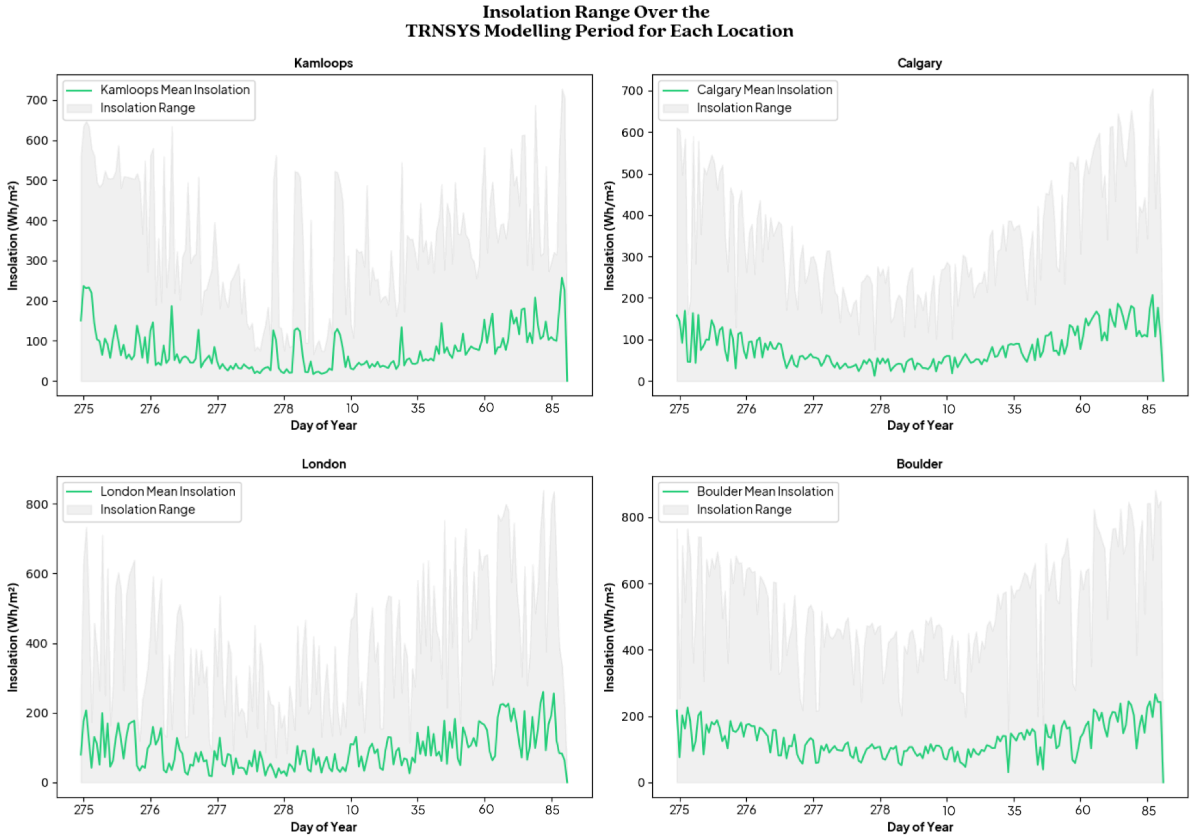

Figure 4. Insolation fluctuations in the TMY files used in the TRNSYS model for each location.

Table 2. Comparative Temperature and Insolation Variability Within the TMY of Each Studied Location

Location	Days with Avg Temp < 0°C (32°F)	Days with Avg Temp < -10°C (14°F)	Days with Avg Temp < -20°C (-4°F)	Std. Dev of Daily Temperatures (°C/°F)	Std. Dev of Avg Daily Temps (°C/°F)	Cumulative Insolation (Wh/m2)
Kamloops	44	6	2	2.2/4.0	6.4/11.6	336,655.3
Calgary	98	35	5	3.5/6.3	8.1/14.6	344,517.6
London	105	19	0	2.7/4.8	7.7/13.9	403,828.1
Boulder	55	12	0	4.5/8.1	7.2/13.0	564,248.7

Research Questions

While exploring the performance of greenhouses in these regions, the focus was primarily on investigating the following research questions:

1) How did energy usage compare between conventional greenhouses, conventional greenhouses with an insulated north wall, and Passive Solar

Greenhouses equipped with a Climate Battery throughout a typical meteorological year's winter season?

2) Under what climatic conditions did Passive Solar Greenhouses with a Climate Battery perform most effectively compared to conventional greenhouses and conventional greenhouses with an insulated north wall? This was evaluated based on:
    a) The maintenance of temperature within the greenhouses, particularly how Passive Solar Greenhouses managed temperature differences compared to the other two types.
    b) The overall energy expenditure required for maintaining optimal growing conditions within the Passive Solar Greenhouse versus the conventional greenhouses.

Kamloops, BC

Located in the semi-arid hills and sage-brush-covered grasslands of central British Columbia, Kamloops, with a Koppen-Geiger classification of BSk (semi-arid), experiences hot and dry summers, and mild (albeit long) winters. The growing season in Kamloops often begins in week 24 of the year, and generally ends around week 37, but frosts can occur in any month of the year. In terms of extremes, temperatures in the winter can fall to lows of approximately -40°C (-40°F), and highs of approximately 10°C (50°F); in the summertime, temperatures can exceed 40°C (104°F), yet also drop below 0°C (32°F).

In the TMY file for Kamloops, BC (Figures 3 and 4), two distinct cold snaps occurred, resulting in minimum modelled outside temperatures of -25.0°C (-13.0°F) and -16.5°C (2.3°F) on the days of January 8 and 28, respectively. There were 44 days with a mean temperature below 0°C (32°F), 6 days with a mean temperature below -10°C (14.0°F), and 2 days with a mean temperature below -20°C (-4.0°F). Over the entire modelled period, Kamloops received 336655.3 Wh/m2, making it the area that received the least amount of sunshine in all the areas explored.

Within the scope of evaluating greenhouse thermal performance in Kamloops, the TRNSYS output and subsequent analysis reveal insightful distinctions across different greenhouse designs. Despite the lower maximum temperature reached within the PSGH, when compared to the other styles of greenhouses, the PSGH maintained an average temperature of 4.7°C (8.5°F) warmer when compared to its conventional counterpart, and 1.9°C (3.4°F) warmer when compared to the insulated conventional greenhouse. Similarly, the average temperature between the PSGH and the outside ambient temperature during the model period was 14.1°C (25.4°F).

In other words, the thermodynamic modelling suggests that the PSGH displays a higher capacity to modulate temperature extremes by being cooler when it is warmer outside, and warmer when it is colder outside. Of particular note, is that the PSGH accomplishes this by both using significantly less energy and requiring the receipt of less sunlight than its counterparts (see Figure 5). While the receipt of less sunlight in the passive solar greenhouse is less, our prototypes suggest that yields are not considerably affected.

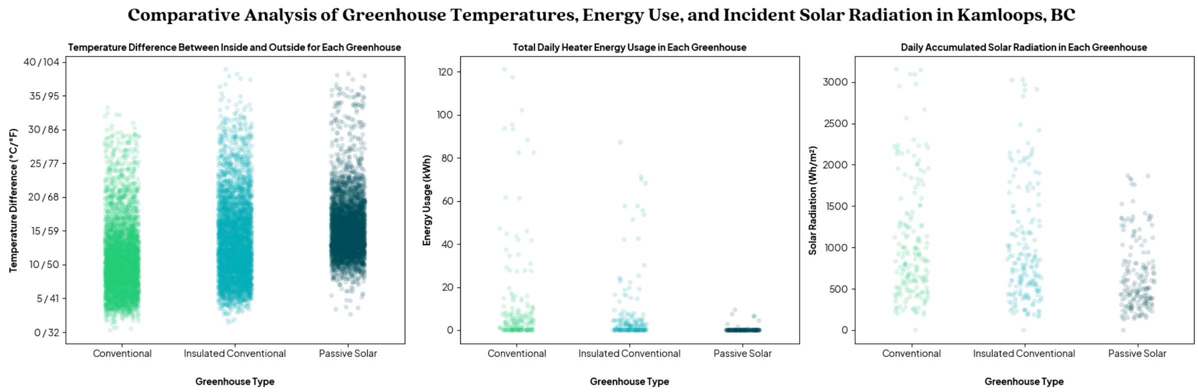

Figure 5. Comparative analysis of Greenhouse Temperatures, Daily Energy Use, and Incident Solar Radiation for Varying Designs in Kamloops, BC

Day 6 represented the coldest day within the TMY file, with a minimum temperature of -25.0°C (-13°F), mean temperature of -22.7°C (-8.9°F), and maximum temperature of -19.0°C (-2.2°F); on this particular day, the conventional greenhouse managed to maintain an average temperature of 6.6°C (43.9°F) (minimum of 5.0°C (41.0°F); maximum of 13.4°C (56.1°F)) with an energy expenditure of 102.1 kWh. While the conventional greenhouse was able to keep temperatures above freezing on this particular day, it did so with roughly the same amount of energy required to keep a modern efficient refrigerator (approximately 300 kWh/year) running for 4 months. In contrast, the conventional insulated greenhouse demonstrated improved thermal regulation over its non-insulated counterpart, utilizing 57.6 kWh to maintain an average temperature of 8.8°C (47.8°F) (minimum of 5.0°C (41.0°F); maximum of 19.1°C (66.4°F)). Most notably, the PSHG with Climate Battery showcased a relatively exceptional efficiency in temperature regulation and energy use, with an average temperature of 12.6°C (54.7°F) (minimum of 9.2°C (48.6°F); maximum of 18.4°C (65.1°F)) and energy expenditure of 9.5 kWh, significantly outperforming the conventional models with regards to both thermal comfort and energy efficiency.

The stark contrast in performance between the PSGH with Climate Battery and conventional counterparts underscores the potential of passive solar designs and climate batteries in achieving sustainable and energy-efficient greenhouse operations in the Kamloops region of British Columbia. Please refer to Table 3 for a relative comparison between the greenhouses on the coldest three days within the TMY file.

Regarding cumulative energy expenditures across the different greenhouse types in Kamloops, BC, Figure 6 reveals distinct thermal performances. The conventional greenhouse experiences significant fluctuations in heater energy usage in response to ambient temperature variations, with a total cumulative energy expenditure of 2126.1 kWh over 160 days for 142 unique days (started on day 294, and stopped on day 89). The insulated conventional greenhouse experiences the same fluctuations but to a lesser extent, and was on for 119 days in total in the modelling period over 157 days (started on day 297, and stopped on day 89), culminating in a total energy consumption of 1228.9 kWh. Finally, the Passive Solar Greenhouse with a Climate Battery used a total of 39.4 kWh over 26 days for 9 days only (started on day 3, and ended on day 29).

The insights drawn from the analysis of the TRNSYS output for Kamloops, BC lead to an inevitable conclusion: the investment in a passive solar greenhouse with a Climate Battery is a path to significant energy savings and regenerative greenhouse operations in the climate of Kamloops, BC. By maintaining stable temperatures without reliance on extensive heating, even in the coldest of days, the PSGH with Climate Battery stands out in spades from its conventional counterparts.

Table 3. Comparative Performance Analysis of Greenhouse Design Strategies on Coldest Days in Kamloops, BC

Day:	Day 6				Day 7				Day 5			
Metric:	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)
Outside/Ambient:	-24.9/-12.8	-22.7/-8.9	-19.0/-2.2	-	-24.6/-12.3	-20.7/-5.3	-16.4/2.5	-	-23.0/-9.4	-20.0/-4.0	-17.0/1.4	-
Conventional Greenhouse:	5.0/41.0	6.6/43.9	13.4/56.1	102.1	5.0/41.0	5.4/41.7	9.3/48.7	117.5	5.0/41.0	7.6/45.7	14.9/58.8	93.6
Conventional Insulated Greenhouse:	5.0/41.0	8.8/47.9	19.1/66.4	57.6	5.0/41	6.4/43.5	13.5/56.3	71.3	5.0/41.0	10.0/50.0	20.4/68.7	55.6
PSGH with Climate Battery	9.2/48.5	12.6/54.7	18.4/65.1	9.5	8.7/47.7	13.2/55.8	19.2/66.6	6.5	9.3/48.7	12.4/54.3	17.2/63.0	4.4

TRNSYS Modelled Energy Expenditure Comparative Analysis Across Greenhouse Types in Kamloops, BC

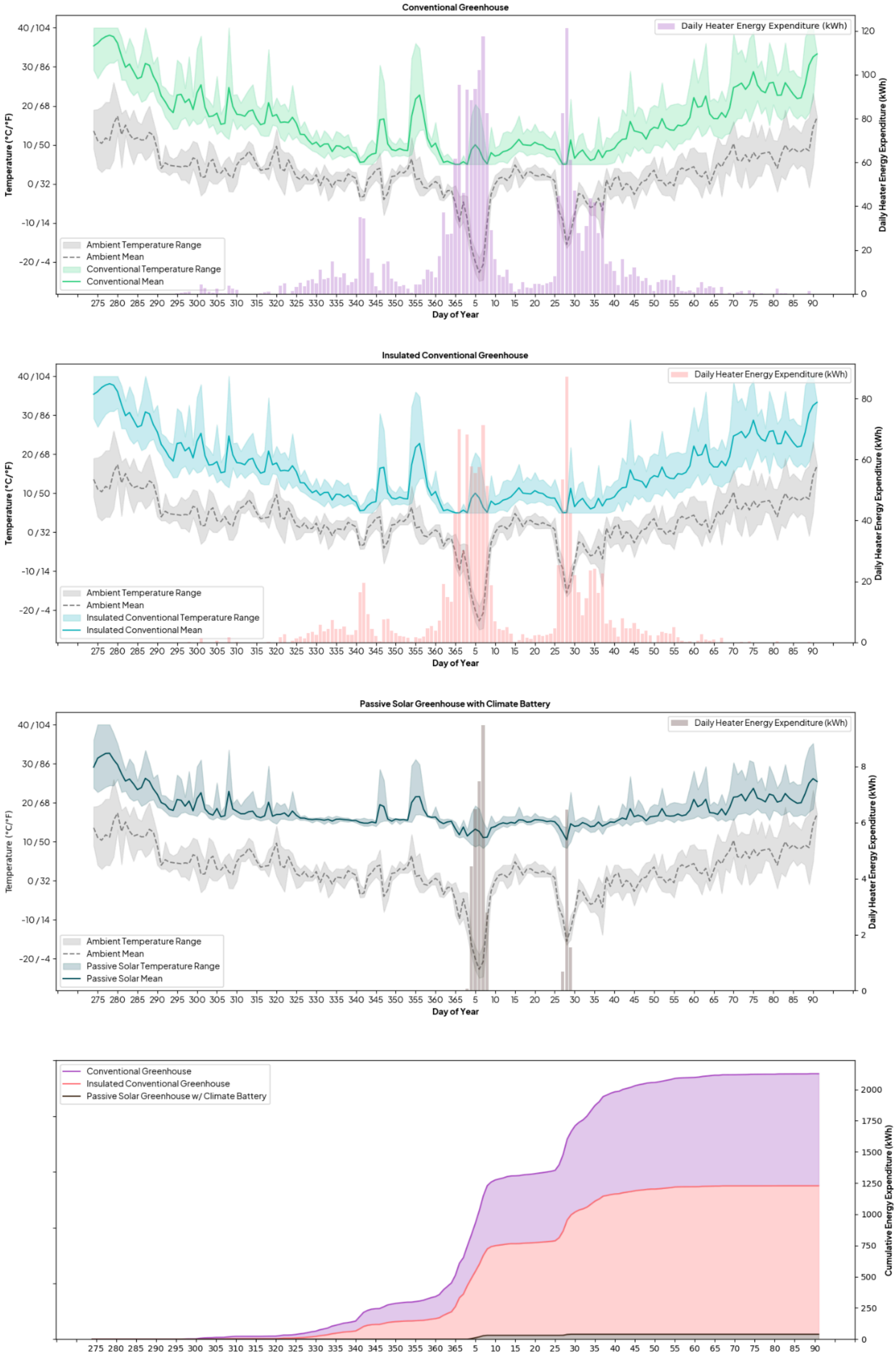

Figure 6. Comparative Analysis of Thermal Performance and Heating Energy Expenditure in Different Greenhouses in Kamloops, BC

Calgary, Alberta

Nestled in the foothills of Canada's Rocky Mountains, Calgary, Alberta has a climate classified as humid continental with warm summers (Koppen Geiger classification of Dfb), characterized by stark temperature contrasts across seasons. Calgary endures long, brisk, snowy winters, with temperatures often plummeting to -40°C (-40°F), whereas summer ushers in the heat with temperatures that can exceed 32°C (89.6°F). The outdoor growing season in Calgary is short—generally starting in week 22 and ending around week 37. With a growing season of only 15 weeks, which is further characterised by having incredibly dynamic weather patterns that can bring temperatures below freezing at any point in the summer, greenhouses are often used as a means to extend the growing season and provide a buffer between the plants and the outside environment.

Relative to the other locations explored in this paper, Calgary experienced the coldest overall temperatures with 35 days having an average temperature below -10°C (14.0°F), and 5 days with an average temperature below -20°C (-4.0°F). Compared to the other locations considered in this paper, Calgary was modelled to have received the second least amount of insolation, with 344517.6 Wh/m2 over the model period. Furthermore, Calgary displayed the highest standard deviation of average daily temperatures at 8.1°C (14.8°F), suggesting that the day-to-day temperatures can vary significantly.

Several key insights emerge upon evaluating the thermal performance of each greenhouse design in Calgary. As per Figure 7, the Passive Solar Greenhouse clearly exhibits a visible concentration towards higher values regarding the temperature difference between the greenhouse and the outside temperature; both conventional counterparts display a higher variability of temperature differences.

The trait of high variability with respect to the conventional greenhouses extends further when considering the total daily heater energy, whereby the range of total daily heater energy expenditure is clearly highest with the conventional, followed by the insulated conventional, and finally the passive solar. Much like the modelled Kamloops example, it appears that the PSGH displays a higher capacity to modulate temperature extremes by being cooler when it is warmer outside, and warmer when it is colder outside, all while using less energy, and with less sunlight. Despite the reduced sunlight exposure in the passive solar greenhouse, our prototype greenhouse suggests that crop yields remain largely unaffected.

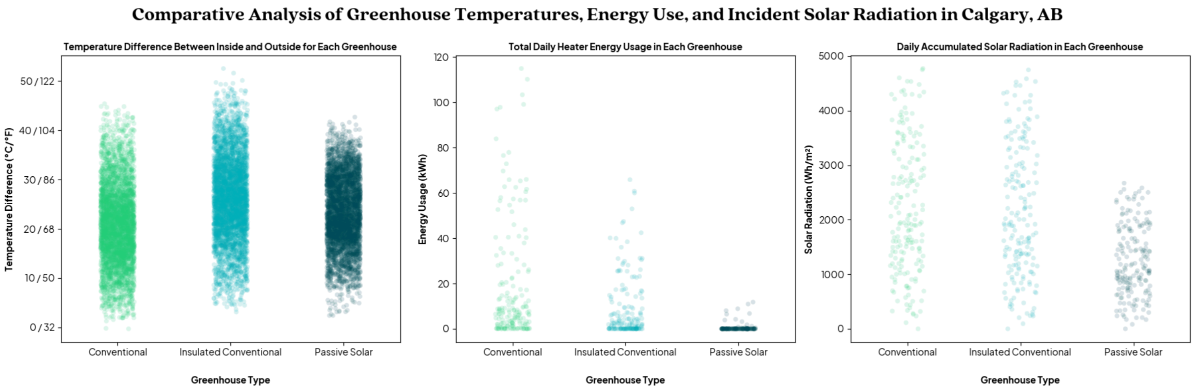

Figure 7. Comparative analysis of Greenhouse Temperatures, Daily Energy Use, and Incident Solar Radiation for Varying Designs in Calgary, AB

The coldest day modelled in Calgary was day 22, when the temperature outside reached a modelled minimum of -26.0°C (-14.8°F) (mean of -22.8°C (-9.0°F), maximum of -20.3°C (-4.5°F)). On this day, the conventional greenhouse reached a modelled minimum temperature of 5.0°C (41.0°F), a mean of 6.8°C (44.2°F), a maximum of 13.3°C (55.9°F), and achieved such a temperature profile with a cumulative daily expenditure of 99.1kWh.

Boasting a slightly better performance on the coldest modelled day, the insulated conventional maintained inside temperatures at an average of 9.4°C (48.9°F) (minimum of 5.0°C (41.0°F), maximum of 19.3°C (66.7°F)), with an energy expenditure of 46.8 kWh.

Lastly, on the coldest modelled day, the Passive Solar Greenhouse had an expenditure of 8.0 kWh which maintained an average daily temperature of 12.6°C (54.7°F), and a minimum of 10.1°C (50.2°F) and a maximum of 16.8°C (62.2°F). This data exemplifies the performance of 5th World's Passive Solar Greenhouse with Climate Battery technology, which, with minimal energy expenditure maintained a stable thermal environment despite harsh external temperatures. Please refer to Table 4 to see the relative performance of each greenhouse on the three coldest days within the TMY file for Calgary.

In examining total energy usage within the three greenhouse models in Calgary, Figure 8 highlights the varying thermal efficiencies compared to ambient temperatures. The standard conventional greenhouse demonstrates notable energy consumption peaks aligned with cold snaps, with a modelled total energy use of 3293.2 kWh over 181 days but being on for 165 days (beginning on day 275 and concluding on day 91). The greenhouse with added insulation shows a similar variation in energy consumption, albeit to a lower amplitude, operating for 131 days within the analysis period over 158 days (between day 297 and day 90), resulting in an overall energy expenditure of 1534.5 kWh. In contrast, the Passive Solar Greenhouse equipped with a Climate Battery demonstrates a minimal energy requirement of 70.0 kWh over 88 days (from day 324 to day 47), whereby the heater was on for 21 of those 88 days.

The evaluation of TRNSYS output data for Calgary, AB undeniably supports the notion that opting for a Passive Solar Greenhouse integrated with a Climate Battery paves the way for substantial energy savings and both a reduction in greenhouse gas reliance and the size of the carbon footprint in this particular climate.

TRNSYS Modelled Energy Expenditure Comparative Analysis Across Greenhouse Types in Calgary, AB

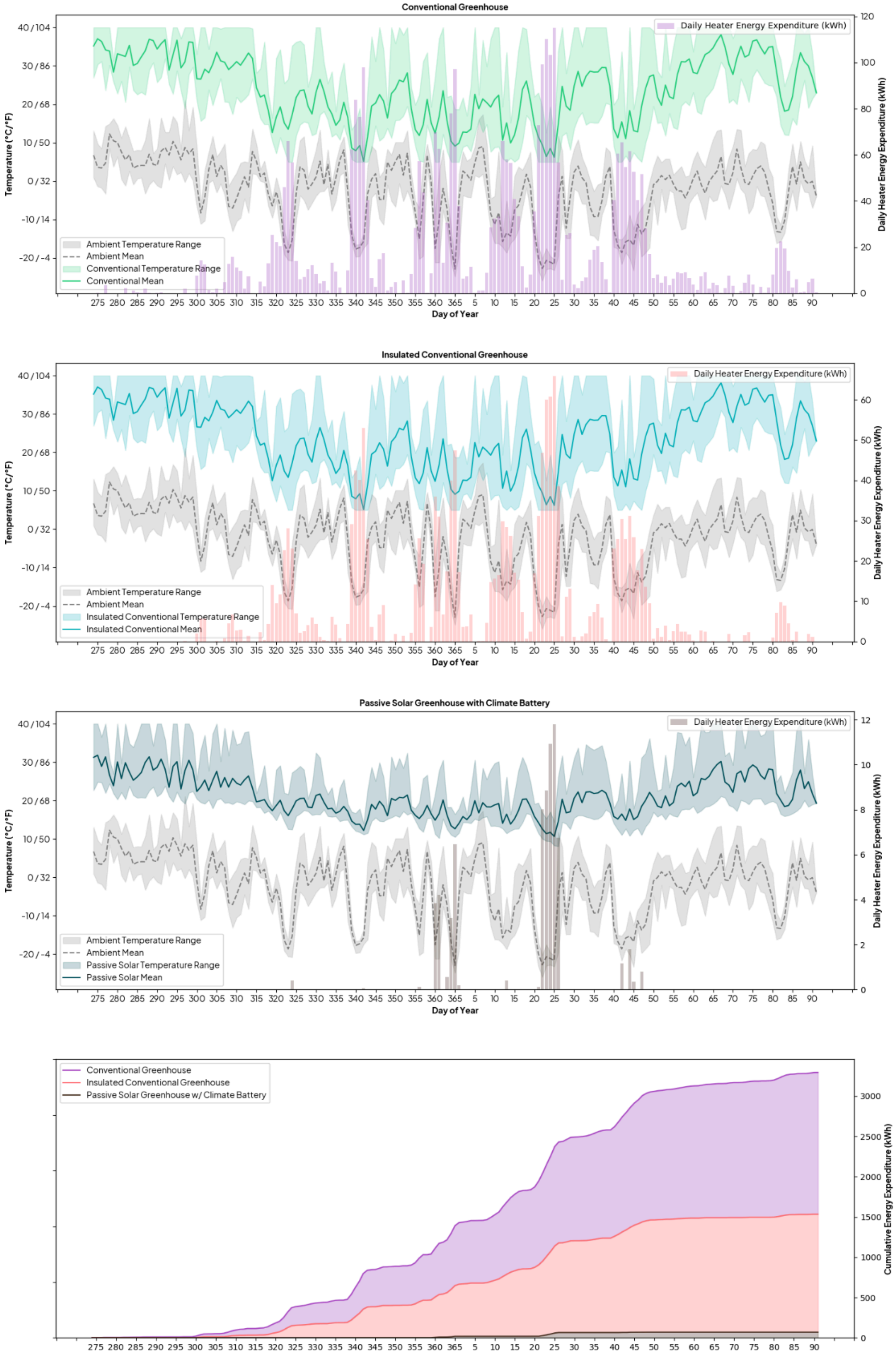

Figure 8. Comparative Analysis of Thermal Performance and Heating Energy Expenditure in Different Greenhouses in Calgary, AB

Table 4. Comparative Performance Analysis of Greenhouse Design Strategies on Coldest Days in Calgary, AB

Day:	Day 22				Day 365				Day 45			
Metric:	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)
Outside/Ambient:	-25.9/-14.6	-22.8/9.0	-20.3–4.5	-	-24.9/-12.8	-22.9/-9.2	-21.2/-6.2	-	-23.3/-9.9	-16.8/1.8	-12.5/9.5	-
Conventional Greenhouse:	5.0/41.0	6.8/44.2	13.3/55.9	99.1	5.0/41.0	6.6/43.9	12.7/54.9	97.0	5.0/41.0	7.6/45.7	12.7/54.9	52.7
Conventional Insulated Greenhouse:	5.0/41.0	9.4/48.9	19.3/66.7	46.8	5.0/41.0	9.1/48.4	18.7/65.7	47.4	7.4/45.3	13.2/55.8	18.7/65.7	25.9
PSGH with Climate Battery	10.0/50.0	12.6/54.7	16.9/62.4	8.0	10.5/50.9	12.7/54.9	16.4/61.5	6.47	12.3/54.1	15.1/59.2	17.8/64.0	0.35

London, Ontario

London, Ontario is situated in the heart of the Great Lakes region, and experiences a humid continental climate (Koppen Geiger Dfb) and four distinct seasons. London is also located about 170km (a 2–hour drive) from Leamington, Ontario, known as the greenhouse capital of North America, which boasts approximately 1500 acres of land beneath glazing. Winters are typically cold and snowy, with the temperatures dipping as low as -28°C/-18.4°F, albeit rarely, and hot and humid summer with highs reaching up towards 32°C/89.6°F, with some exceptional instances of exceeding 35°C/95.0°F. The outdoor growing season in London typically spans from week 20 or 21 to week 41, offering a much more generous 20–week window of growing relative to both Calgary and Kamloops.

The TMY used in the case of London contained 105 days where the average temperature was below 0°C/32°F, including 19 days where the average temperature was below -10°C (14°F), but is the first of the case studies that did not have any days where the average temperature was below -20°C (-4°F). Standard deviations of 2.6°C (4.7°F) and 7.7°C (13.9°F) for the daily temperatures, and average daily temperatures suggest that London exhibits a more stable daily temperature range, albeit with variability in day-to-day temperatures throughout the modelling period. Finally, London experienced the second-highest insolation, with an accumulated value of 403,828.1 Wh/m2.

According to the thermodynamic modelling output of TRYNSYS, as depicted in Figure 9, the Passive Solar Greenhouse once again stands out from its conventional counterparts for maintaining a more moderate internal temperature regime; in the PSGH, there is a visible concentration towards higher values with regards to the temperature difference between the greenhouse and outside as compared to the conventional counterparts, which further display a much greater variability and extremes. Similar to the previously explored case studies of Kamloops and Calgary, the PSGH with Climate Battery located in London achieves very effective climate modulation with less energy inputs, which is exemplified by the mean day-to-day standard deviation of 3.8°C (6.9°F) and overall standard deviation of 7.7°C (13.9°F) in the PSGH, as compared to the conventional and insulated conventional greenhouses with a day-to-day standard deviation of 5.7°C (10.3°F) and 6.4°C (11.5°F), respectively, and an overall standard deviation of 11.6°C (20.9°F) and 13.8°C (24.8°F), respectively. Our prototypes indicate that the Passive Solar Greenhouse maintains consistent crop yields even with lower sunlight reception.

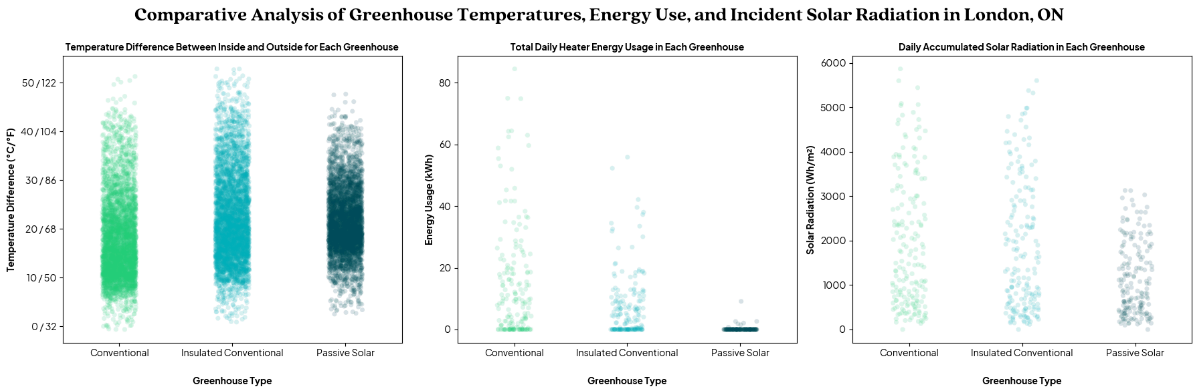

Figure 9. Comparative analysis of Greenhouse Temperatures, Daily Energy Use, and Incident Solar Radiation for Varying Designs in London, ON

Similar to the patterns in the case studies of both Kamloops and Calgary, the TRNSYS output for London suggests that the conventional-style greenhouses have pronounced usage when compared to the Passive Solar Greenhouse, particularly on colder days (Figure 10). That being said, the model output would suggest that with the heater being turned on for only 11 days and using only 20.7 kWh of energy expenditure over the entire modelling period, the Passive Solar Greenhouse uses under 1% of the amount of energy that a conventional style greenhouse uses (2608.3 kWh, switched on for 142 different days), and is 98% more efficient than the conventional style greenhouse equipped with insulation, which used 1305.6 kWh during its operation for 122 days.

When considering the performances of the different greenhouses on the coldest day contained within the TMY file for London, which was characterized by a minimum temperature of -20.5°C (-4.6°F) (mean of -9.7°C(14.5°F), maximum of -3.3°C(26.1°F)), the above efficiencies are further exemplified. A modelled energy expenditure of 32.3 kWh in the conventional greenhouse was able to create a mean temperature over the course of the day of 8.0°C(46.4°F), and a maximum of 12.4°C(54.3°F), but the temperature was modelled to dip to 5.0°C(41.0°F). In the insulated conventional greenhouse, a modelled energy expenditure of 17.0 kWh kept the greenhouse at a mean temperature of 12.4°C (54.3°F) (minimum of 8.1°C (46.6°F), maximum of 16.7°C (62.1°F)). In comparison, the passive solar greenhouse equipped with a Climate Battery, a modelled minimum temperature of 13.4°C (56.1°F), a mean temperature of 15.5°C (59.9°F), and a maximum temperature of 17.5°C (63.5°F) were achieved with 0 kWh. Please note that while this day reached the coldest minimum temperature in the TMY, there was a significant increase in temperatures in the day, which led to the PSGH not needing to turn heaters on, which is not the case for other cold days. Please refer to the detailed comparisons of each model's performance during the three coldest days, available in Table 5.

The above data and subsequent analysis of the modelling output from TRNSYS for London, Ontario (not too distant from the greenhouse capital of North America), reinforces the argument that a shift towards more sustainable and energy-efficient agricultural practices is well within reach.

TRNSYS Modelled Energy Expenditure Comparative Analysis Across Greenhouse Types in London, ON

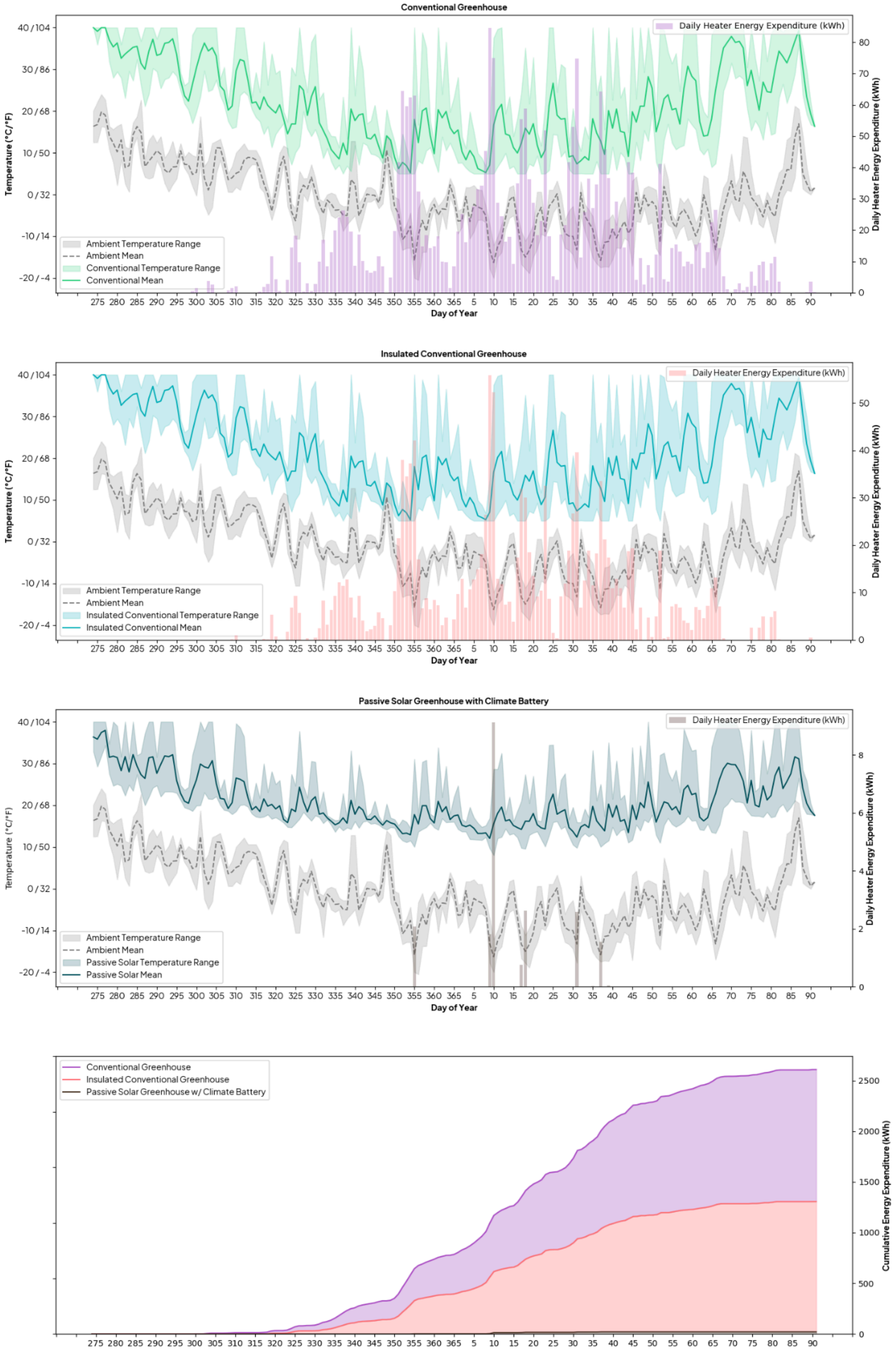

Figure 10. Comparative Analysis of Thermal Performance and Heating Energy Expenditure in Different Greenhouses in London, ON

Table 5. Comparative Performance Analysis of Greenhouse Design Strategies on Coldest Days in London, ON

Day:	Day 356				Day 10				Day 355			
Metric:	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)
Outside/Ambient:	-20.5/-4.9	-9.7/14.5	-3.3/26.1	-	-20.0/-4.0	-16.3/2.7	-12.2/10.0	-	-20.0/-4.0	-15.9/3.4	-12.8/9.0	-
Conventional Greenhouse:	5.0/41.0	8.0/46.4	32.3/90.1	32.3	5.0/41.0	13.4/56.1	30.7/87.3	75.0	5.0/41.0	14.6/58.3	33.9/93.0	63.0
Conventional Insulated Greenhouse:	8.1/46.6	12.0/53.6	16.7/62.1	17.0	5.0/41.0	16.7/62.1	37.5/99.5	52.3	5.0/41.0	18.1/64.6	41.0/105.8	42.1
PSGH with Climate Battery	13.7/56.7	15.5/59.9	17.5/63.5	0.0	8.0/46.4	15.6/60.1	28.7/83.7	9.1	10.0/50.0	17.8/64.0	31.1/88.0	2.1

Boulder, Colorado

Positioned in the shadows of the Rocky Mountains and driving distance from the hub of agricultural innovation and greenhouse design that is Denver, Boulder, Colorado, can be characterized as having a semi-arid climate with clear, defined seasons. According to the Koppen Geiger classification, Boulder is in the BSk zone, which represents cold and semi-arid locations. Boulder experiences a wide range of temperatures in the winter, ranging from minimums of approximately -24°C (-11.2°F) to the odd occasion whereby temperatures exceed 20°C (68°F). In the summertime, the range of variability is dampened, with the rare occurrences of 40°C (104°F) being measured, and minimums generally hovering between the 12°C (53.6°F) and 16°C (60.8°F) mark. The growing season out of doors generally begins around week 20 of the year. It concludes around week 40 or 41, offering a longer cultivation window than both Calgary and Kamloops, but on par with London.

The modelled temperatures within the TMY for Boulder contained 55 days where the mean temperature of the day was less than 0°C (32°F), 12 days where the mean temperature was below -10°C (14°F) and 0 days where the average temperature was below -20°C (-4°F). In terms of temperature variability, a standard deviation of 7.2°C (13.0°F) for the average daily temperatures suggests that there is quite a bit of variability in temperatures from day to day, and even with a standard deviation of 4.5°C (8.1°F) for the daily temperatures suggests a lot of variation in any given day. Lastly, Boulder received the most modelled insolation of any given location in the series of case studies, with a cumulative insolation of 564,248.7Wh/m2.

In Boulder's case, as demonstrated by the TRNSYS thermodynamic simulations in Figure 11, the Passive Solar Greenhouse equipped with a Climate Battery distinctly maintains a steadier internal temperature than traditional greenhouse models. Lower levels of sunlight in the Passive Solar Greenhouse do not significantly impact yields, as evidenced by the immense growth achieved in our prototype greenhouses. The key highlight in the case of Boulder is however the expenditure of energy. As seen in Figure 11, there is a very clear concentration of points centred around 0 kWh for the daily energy expenditure in the Passive Solar Greenhouse, as TRNSYS modelled that with this particular design, the heater would be turned on a total of zero times.

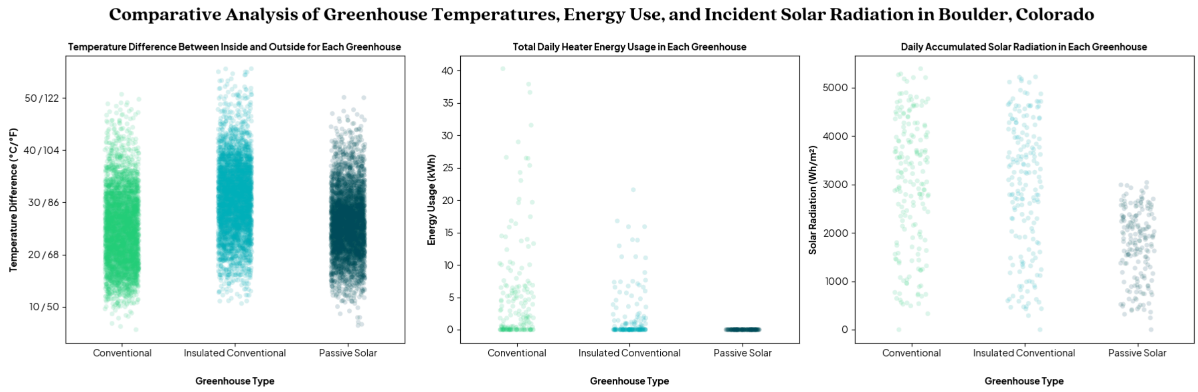

Figure 11. Comparative analysis of Greenhouse Temperatures, Daily Energy Use, and Incident Solar Radiation for Varying Designs in Boulder, CO

Reflecting on Figure 12, a similar trend can be observed in relation to the case studies of Kamloops, Calgary, and London, presented above, but perhaps to a more amplified extent given Boulder's climate. As mentioned earlier, the data indicates that the PSGH's heaters were turned on for zero days, and as a result, used 0 kWh throughout the modelling timeframe. As for the other greenhouse designs, in the conventional style greenhouse, the heater first turned on on day 280, and had its last day running on day 88, representing a span of 173 days (but was only on for 131 days, or 75%), and used 942.2 kWh (the equivalent of running a refrigerator for 2.5 years). Within the insulated conventional greenhouse, heater usage commenced on day 310, and ceased on day 82, representing a span of 137 days, whereby the heater was on 56% of days (77 days), and used a total of 310.6 kWh.

During Boulder's most frigid day on record in the TMY data (day 6), temperatures dipped to -23.3°C (-9.9°F) (with a mean of -15.4°C (4.3°F) and a maximum of -6.2°C (20.8°F)). In the conventional style greenhouse, 29 kWh was required to maintain an average temperature of 19.8°C (67.6°F) (minimum of 5.1°C (41.2°F); maximum of 39.4°C (102.9°F)). Meanwhile, the insulated conventional greenhouse expended 13.89 kWh, which achieved an average temperature of 30.5°C (86.9°F), a minimum of 14.7°C (58.5°F), and a maximum of 51.4°C (124.5°F) (although as mentioned earlier, it is fair to assume that ventilation would have capped this maximum at 40°C). Finally, with no energy expenditure, the passive solar greenhouse with Climate Battery technology achieved an average inside temperature of 22.3°C (72.1°F), a minimum temperature of 19.4°C (66.9°F), and a maximum temperature of 30.2°C (86.4°F). Further details and comparisons for the three coldest days are delineated in Table 6.

The above analysis showcases the clear benefits of adopting a more efficient approach to agriculture through the design and implementation of appropriate technologies, especially in areas near key agricultural hubs. This approach not only enhances the resilience of farming systems, but also contributes to the broader goal of creating a more regenerative and food-secure future.

TRNSYS Modelled Energy Expenditure Comparative Analysis Across Greenhouse Types in Boulder, Colorado

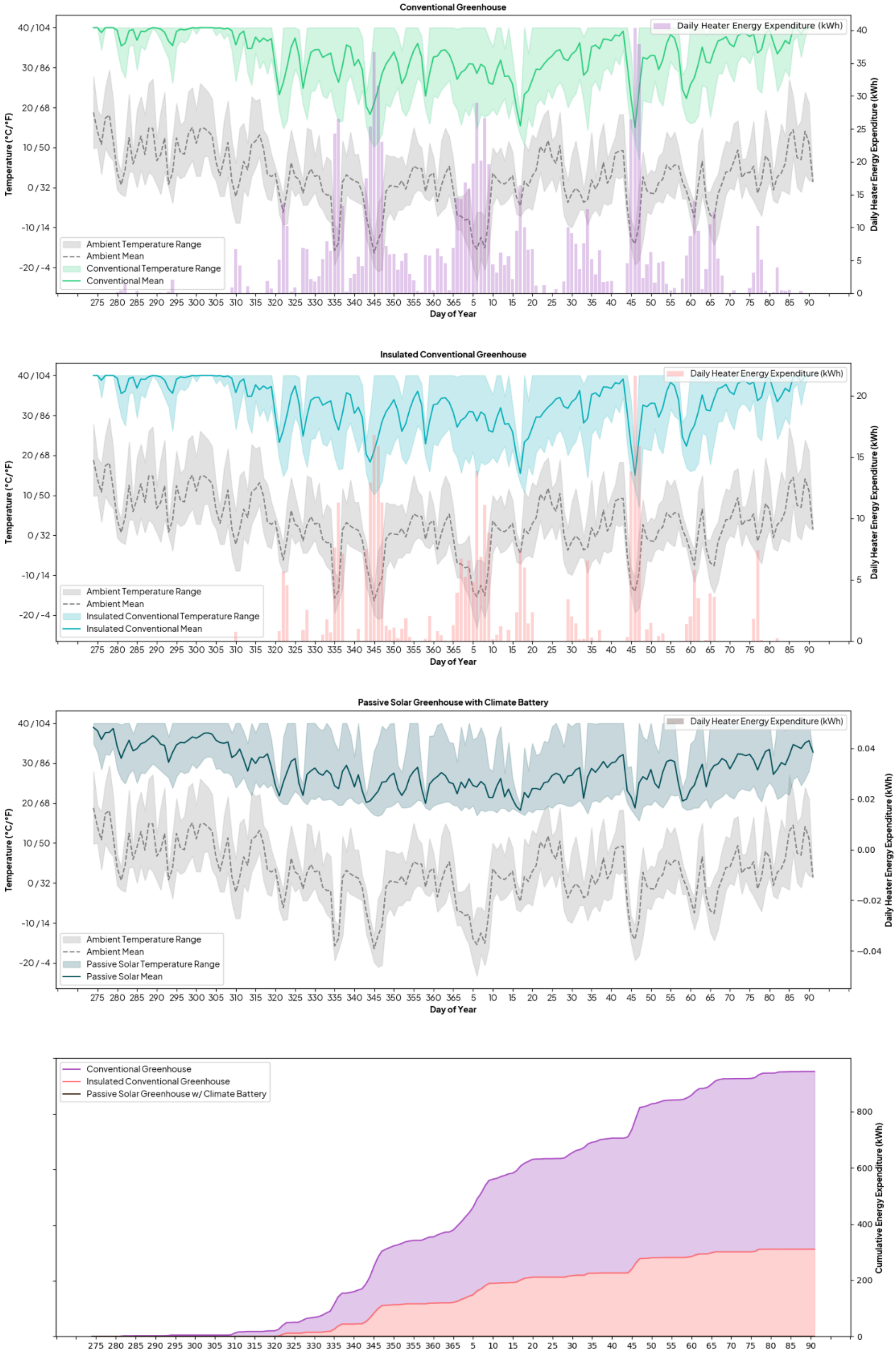

Figure 12. Comparative Analysis of Thermal Performance and Heating Energy Expenditure in Different Greenhouses in Boulder, CO.

Table 6. Comparative Performance Analysis of Greenhouse Design Strategies on Coldest Days in Boulder, CO

Day:	Day 6				Day 346				Day 8			
Metric:	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)	Min Temp (°C/°F)	Mean Temp (°C/°F)	Max Temp (°C/°F)	Energy Expenditure (kWh)
Outside/Ambient:	-23.3/-9.9	-15.4/4.3	-6.2/20.8	-	-21.0/-5.8	-13.1/8.4	-3.9/25.0	-	-20.6/-5.1	-15.1/4.8	-7.3/18.9	-
Conventional Greenhouse:	5.1/41.2	19.8/67.6	39.4/102.9	29.0	5.0/41.0	16.4/61.5	35.7/96.3	31.6	7.7/45.9	21.2/70.2	40.2/104.4	26.6
Conventional Insulated Greenhouse:	14.7/58.5	30.5/86.9	51.4/124.5	13.9	11.5/52.7	25.1/77.2	45.4/113.7	15.9	17.7/63.9	32.1/89.8	52.1/125.8	11.1
PSGH with Climate Battery	16.9/62.4	24.0/75.2	36.4/97.5	0.0	17.9/64.2	24.5/76.1	36.3/97.3	0.0	17.9/64.2	24.5/76.1	36.3/97.3	0.0

Conclusion

In conclusion, our in-depth exploration of the 5W Passive Solar Greenhouses equipped with a Climate Battery across various locations exemplifies their performance in creating a resilient and antifragile space in even some of the harshest environments in the world. The analysis, conducted on the output of TRNSYS, a flexible software environment used to simulate the behaviour of dynamic and transient systems, demonstrates the pivotal role that the Climate Battery system plays in the design of energy-efficient greenhouse design. Three greenhouse designs (conventional style, conventional style with an insulated north wall, and a Passive Solar Greenhouse with Climate Battery) were input into TRNSYS in 4 different locations Kamloops (British Columbia), Calgary (Alberta); London (Ontario), and Boulder (Colorado).

Our findings highlight both the adaptability and effectiveness of Passive Solar Greenhouses equipped with a Climate Battery in varying climatic conditions, revealing significant benefits in terms of energy savings, carbon footprint reduction, and overall thermal comfort. In all locations explored, the model output suggests that the Passive Solar Greenhouse equipped with a Climate Battery presents itself as an energy-efficient alternative when compared to its conventional counterparts. In all areas explored, the Passive Solar Greenhouse was modelled to utilize two orders of magnitude less energy in comparison to both conventional-style greenhouses, and conventional-style greenhouses with an insulated north wall. On average, between all locations considered, the PSGH expended 1.2% of the energy than the conventional style greenhouse, and 2.3% of the energy used by the conventional greenhouse.

Table 7. Comparative Energy Efficiency of PSGH vs. Conventional and Insulated Conventional Greenhouses Across Locations

Location	Energy Expenditure (kWh)		
	Conventional	Insulated Conventional	PSGH
Kamloops	2126.1	1228.9	39.4
Calgary	3293.2	1534.5	70
London	2608.3	1305.6	20.7
Boulder	942	310	0

Table 7 illustrates the significant energy savings and reduced footprint that PSGH with Climate Battery technology offers, even across a range of climatic conditions. The above findings as elucidated by TRNSYS don't just bolster the case for a Passive Solar

Greenhouse as a pivotal solution for societies energy challenges (especially those in colder climates), but also highlights its potential to serve as a regenerative investment.

Next Steps in Research

At 5th World, we are committed to delivering state-of-the-art Passive Solar Greenhouse technologies, continuously enhancing their efficiency, and adaptability to diverse climates. Recognizing the critical role of accurate data and advanced modelling in achieving these goals, we are dedicated to further refining both the TRNSYS model and our designs. This endeavour aims to identify the design principles that are most effective under various environmental conditions, ensuring that we can offer tailored solutions that maximize value for specific locations and climates. To that end, we will be directing our research efforts to further study the following:

- Configuring our greenhouses with sensors: we plan to equip a select few of our greenhouses with sensors to collect real-time observational data on temperature (air and soil), humidity, photosynthetically active radiation, and more. These data will not only validate our TRNSYS simulations but also provide invaluable insights into the behaviour of our greenhouses, allowing for calibration and improvement of our models.
- Understanding ventilation, humidity, and heat stacking effects: in some ways, these are some blind spots within the TRNSYS model. By configuring our greenhouses with sensors, we will be able to receive feedback and optimize our designs for better ventilation, reducing condensation, and ensuring uniform temperature distributions.
- Study under extreme conditions: by creating a new input file for TRNSYS, we aim to conduct thermodynamic modelling under the most extreme conditions.

All of these studies will inform and optimize our future greenhouse designs, ensuring that they are more resilient, efficient, productive, and comfortable. By continuously refining our models and designs based on empirical data and advanced simulations, we are setting new standards for the industry and helping our clients achieve success in their agricultural and resiliency-minded endeavours.

A More Delicious and Nutritious Portfolio: Custom Greenhouses Tailored to Your Vision

In our journey towards bridging ancient wisdom with modern innovation, we've showcased the transformative potential of 5th Worlds Passive Solar Greenhouses equipped with Climate Battery technology. This technology not only aligns with the cooperative nature of our ancestors but also addresses contemporary environmental and energy challenges. That being said, we're not just designing and constructing greenhouses for our clients – we're crafting miniature ecosystems that extend beyond agriculture to enhance your quality of life. Each PSGH, customizable to its environment, can optionally include features such as hot tubs, games rooms, rainwater harvesting systems, and intimate hang-out areas, where you can sit down and enjoy your home-grown figs and bananas while it's freezing just outside.

As we conclude this white paper, we invite you to explore the possibilities that 5th World's Passive Solar Greenhouses provide. If you are interested in learning more about cultivating an opportunity for dialogue, innovation, and collaboration to make your greenhouse dreams come true, then please book a free discovery call with a member of our team. We'd be more than happy to help you create a legacy of resilience, efficiency, and harmony with nature, all bolstered by our commitment to scientific excellence and innovation.

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Appendix 1: Natural Processes

The natural processes that are being utilized in passive solar design are:

- Convection
    - From the Latin word “convehere” meaning “to carry together”, convection refers to the transportation of heat energy and mass via turbulent eddies in liquids and gases. The movement arises due to differences in fluid density, which can be induced either naturally (free convection), or mechanically (forced convection).
        - Free convection is induced when a fluid parcel (air or liquid) is less dense than the surrounding fluid (generally as a result of being heated) and thus rises. One can observe this phenomena on a sunny day, when the sun’s rays heat the ground, and the air directly above it heats up, becomes less dense, and rises, resulting in the establishment of a convection current.
        - Forced convection is mechanically induced, typically by fans or pumps. In the context of greenhouses, fans are often used to drive air from one area to another to create air movement which can reduce the potential for fungal pests to become established.
- Conduction
    - Stemming from the Latin word ‘conducere’ meaning ‘to lead or bring together’, conduction is the process through which heat is transferred from molecule to molecule within a solid material or between solid materials in direct contact. Here are the key aspects of conduction:
        - Material Properties: different materials have varying rates by which they conduct heat, also known as thermal conductivity. For example, metals are excellent conductors of heat, while materials such as wood, straw bales, or rubber resist the movement of heat, effectively classifying them as insulators.
        - Degree of contact: because conduction occurs in solid materials, conduction occurs when materials are in direct contact.
        - Temperature gradient: the rate of conduction is proportional to the temperature difference between two ends of a medium. A greater temperature difference results in a more rapid heat transfer.
        - Cross-sectional area and distance: the total amount of heat transferred is influenced by the size of the conducting medium’s cross sectional area, which is further influenced by the length/thickness of the materials.
- Radiation
    - Coming from the Latin word “radiare”, meaning to “emit rays or waves”, radiation is the emission and propagation of energy through space or a

medium in the form of electromagnetic waves. Here are some key facets of radiation:

- Longwave radiation vs. shortwave radiation: The sun primarily emits shortwave radiation, which includes visible light. When this radiation is absorbed by objects, they re-emit it as long wave or infrared radiation, also known as heat.
- Albedo: the rate at which the amount of sunlight is reflected by a surface is called albedo. Surfaces with a high albedo will reflect most of the incoming shortwave radiation, such as snow or shiny metals, whereas surfaces with low albedo, such as black walls or dark exposed soil will absorb more sunlight, and then convert it to heat.

Appendix 2: Anatomy of a Passive Solar Greenhouse

Expanded explanation of the architectural elements of importance in Passive Solar Greenhouse design:

Architectural Element	Purpose	Mechanism
Aperture	Component through which sunlight enters a structure – essentially the 'window' for the sun.	In Passive Solar Greenhouses, polycarbonate glazing captures and maximizes the inflow of sunlight. In a dwelling, the inflow of sunlight is maximized in the winter months by windows on the south side of the building (northern hemisphere), and minimized in the summer months by an overhang.
Collector	Directly takes in the sunlight streaming through the aperture	A low albedo surface that readily absorbs sunlight and converts it to heat. The positioning and colour of the absorber are crucial for effective heat absorption.
Thermal Mass	Materials that can capture and store heat	Materials with good thermal mass properties store heat for prolonged periods, releasing it slowly and consistently, thus modulating extreme diurnal temperature changes.
Distribution	To distribute the heat generated by the collector	Generally achieved through free convection, where the design of the space allows for warm air to circulate. Fans and vents can be added for added efficiency.

Control	To regulate the amount of sunlight and /or heat that is permitted to stay in the structural system	Achieved by insulation, shading devices, thermostatically controlled vents/windows/doors, or other mechanisms that adjust based on the time of day, season, or interior temperature.