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Cold-Climate Supermarket attached Greenhouse: A Case Study

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Abstract

Supermarkets are responsible for large amounts of energy consumption, for building operations (HVAC and refrigeration) as well as for transportation of produce and other goods. This study is based on an on-going research to reduce the energy consumption of this type of buildings by attaching a greenhouse to an energy efficient supermarket for locally grown organic produce. Using a parametric approach, a design model for a supermarket attached greenhouse for improved energy performance is proposed. The analyzed parameters pertain to passive design (building envelope, shape, day-lighting, PCMs, aerogels) and active design (photovoltaic, semi-transparent photovoltaics, supermarket waste heat harnessing), to develop a model for year-round production in Calgary, Canada (51ºN). The results indicate that energy consumption can be reduced by up to 85% as compared to the base case.

Keywords: *Supermarket, Energy efficiency, Parametric study, optimization, building envelope, phase change material, photovoltaics*

1. Introduction

The population of Canada and the world is increasing with higher concentrations of people living in dense urban areas (Ackerman, et al. 2014). With the global risk of climate change, it is pertinent to centralize commodities, mainly food, to restrict GHG emissions and energy consumption associated with rural agriculture (Sanyé-Mengual, et al. 2015). Supermarkets are already a centralization of commercial products, however, energy required to transport these products to the consumer site of purchase, and the associated GHG emissions, can be significant. Coupling energy efficient greenhouse to supermarkets for locally grown organic produce has the potential to achieve two goals: utilization of waste heat from the supermarket in the greenhouse, and reducing the negative impact of food transportation. The supermarket can generate significant amount of heat (MacGregor and Hachem, 2016) that can be used to supply some of the heating requirement of the greenhouse.

Designing a greenhouse to operate year-round is presented with some obvious challenges when the target location is Calgary, Canada (51ºN). The most apparent challenge is harsh winters that embrace the city for nearly half of the year with temperatures often dropping to sub-zero levels. The second is the high-latitude location of this city resulting in low angled sun in the winter and limited day length, increasing thus dependencies on artificial lighting and heating. The summer season can also be relatively warm with higher incident solar radiation and temperatures reaching 30-35ºC (EnergyPlus, Weather Data Sources) for several weeks leading to potential overheating especially when designing an all-glass greenhouse.

This paper investigates the feasibility of implementing an on-site greenhouse, attached to a supermarket, for the year round growth of organic produce in Calgary, Alberta, Canada (51ºN). This in-depth study aims at examining the potential of coupling these two structures (greenhouse and supermarket) in view of exploring methods of energy sharing between these buildings, and consequently the mitigation of the negative environmental impact, of both types of buildings.

2. Methods

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The study employs a model of supermarket that has been previously optimized (MacGregor and Hachem, 2016). and an attached glass greenhouse, built according to standards (see below). This paper presents, in addition to an outline of the optimized supermarket design, the optimization process of the greenhouse, and the potential of energy sharing between the two buildings.

A number of parameters are explored to increase the energy efficiency of the greenhouse including the insulation values in the opaque wall assemblies (Fokaides, et al. 2014), the window assemblies (Carmody and Haglund, 2012) and advanced building materials such as aerogels (Buratti, 2012) and phase change materials (PCM) to passively regulate heat (Tabares-Valasco et al., 2012). The parametric study also focuses on designing building envelope components which maximize the buildings ability to generate on-site electricity through the use of building integrated photovoltaics (BIPV) and semi-transparent photovoltaics (STPV) while still maintaining energy efficiency.

2.1 Supermarket Design

The design of the supermarket is optimized for increased energy performance and to achieve a near net zero energy status (MacGregor and Hachem, 2016). This is reached by using high efficiency LED lighting and a thermally optimized building envelope as well as the use of on-site generation of electricity. The characteristics of this energy efficient supermarket design are summarized in Table 1. The supermarket model accounts for essential electrical and thermal loads associated with this building type, such as refrigeration units, cooking appliances, lighting, occupancy and miscellaneous electrical equipment. This supermarket design consumes 25% less energy (234 kWh/m^2) than a base model (319 kWh/m^2) designed to be representative to those found in the location of study.

The rooftop of the supermarket is designed to maximize the solar capture at Calgary's latitude. A saw-tooth roof configuration is adopted (Fig.1) with 50 ° tilt angle, towards the south. This tilt angle is optimal for year-round solar collection in Calgary (Hachem. *et al* 2011). The south facing surfaces of the saw-tooth structures are covered with BIPV panels of 18% electrical efficiency. Taking into account the BIPV electricity generation, the net energy consumption is about 94 kWh/m^2, representing 70% less than the base model, described above (Macgregor and Hachem, 2016).

Role of the supermarket

The supermarket can benefit the attached greenhouse in two ways. The rooftop space of the supermarket can be utilized for photovoltaic generation to subsidize some of the energy costs of the building complex (i.e. supermarket + greenhouse). The other method of utilization of the supermarket is the use of refrigerator waste heat to reduce the heating load for the entire building complex. These refrigerator compressors are constantly running to maintain safe temperatures for food preservation, releasing thus large amounts of heat. This heat is partially vented to the exterior and partially transferred into the supermarket interior space increasing thus the cooling load of the building. Theoretically, a thermal storage tank and heat pump can be used to capture the heat and utilize it in the adjacent thermal zone- namely the greenhouse. This paper presents an estimation of the amount of waste heat is needed to fully subsidize the complex total heating load.

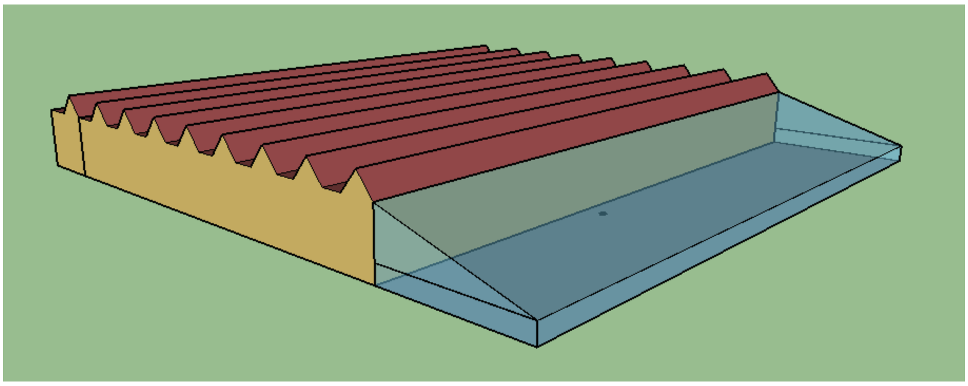

Figure 1: SketchUp model of attached greenhouse on supermarket. Saw-tooth structures on supermarket are sloped at 50° for photovoltaic generation.

Table 1: Supermarket Design Considerations (MacGregor and Hachem, 2016)

Design Parameters and Conditions	Value
Insulation	Wall: 3.3 m^2K/W; Roof: 5 m^2K/W
Windows	No Windows
Lighting	High efficiency LED; 8w/m^2
Phase Change Material	In ceiling and in walls
Building Integrated Photovoltaics	18% efficiency, on south facing side of saw-tooth roofing design
Dimensions	45 m x 35 m x 4.3 m
Annual Electrical Load	474 MWh (includes refrigerators, lighting, electrical HVAC and miscellaneous equipment)
Annual Electricity Generative Capabilities	258 MWh

2.2 Base case design

The base model is used as a reference case for the simulations presented hereafter. This base model is defined as the base level greenhouse attached to the optimized supermarket. Loads analyzed below are those associated with the entire complex.

EnergyPlus (Version 8.4.0, 2016) is employed to carry out the simulations within this parametric study. This energy simulation tool allows control over individual processes and designs within the reference building as well as an extensive array of output options. Assumptions and initial inputs adopted for simulations are shown in Table 2. The heating, cooling and lighting loads are studied to analyze the effect of various parameters on the energy performance of the complex.

Table 2: EnergyPlus initial assumptions or inputs for base model

Assumption/Input	Value
Run Period	1 Year, simulated at 10 m intervals
Weather File and Location	Calgary, Alberta, Canada
Heat Balance Algorithm	Conduction Finite Difference
Base Window Assembly	Single Pane
Ventilation Rate	0.5 ACH, only day-time. Only available above 0°C [(1)]
Infiltration Rate	0.03 ACH
HVAC System	COP 1. (EnergyPlus' Ideal Loads System)
Thermostat Range	20 – 26°C [(2)]
Humidity Range	50-90% [(2)]
Lighting Requirements	25 W/m^2 [(3)]
Daylighting Set-Point	7000 lux, on dimmer control [(3)]

[1](Vadiee, 2013), [2](von Zabeltitz, C. 2010), [3](Jahns, T.R, 2009)

2.3 Parametric investigation

This section presents the studied parameters, in view of optimizing the overall energy performance of the complex of buildings.

Greenhouse Design. The designs used in this study are based on the standard, all-glass greenhouses. Three different shapes of greenhouses are investigated to identify the impact on heating, cooling and lighting loads. All three of the cases are attached to the south facade of the supermarket with the roof sloping downwards until it intersects with the south façade of the greenhouse. This façade is the aspect of the design which is modified to determine the impact on the various loads, while other parameters remain constant (as for the base case design, see above). The south façade is 1.7 m, 2.7 m and 3.7 m high for the cases 1, 2, and 3, respectively (Figure 2). 1.7 m is chosen for the shortest south façade height such that a person can attend easily to the plants against the wall. The north façade, as it is attached to the supermarket at this side, is of an opaque wall assembly.

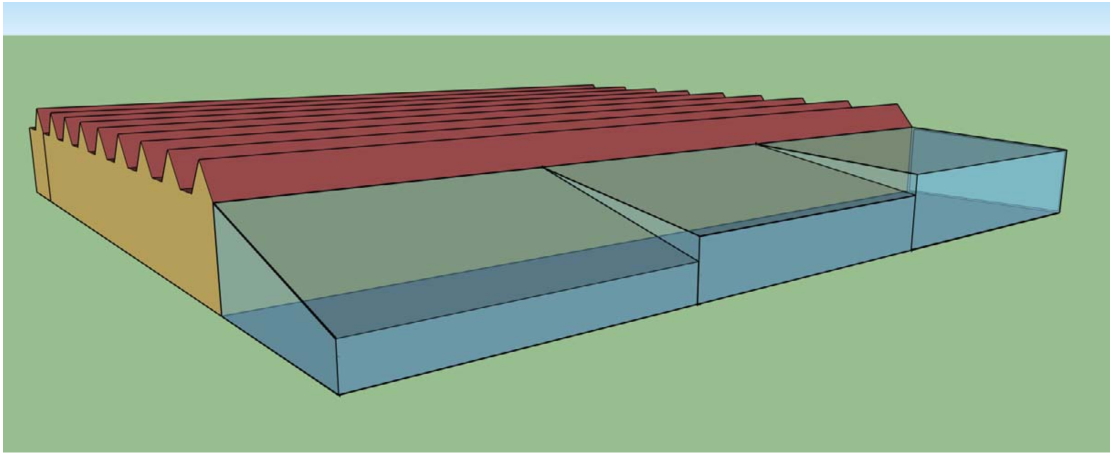

Figure 2: SketchUp design of the three different designs. In the image they have been presented beside each other to better showcase the differences. In the simulations, the designs span the entire length of the supermarket.

Boundary Insulation. The insulation level of the barrier between the two thermal zones (i.e. greenhouse and the supermarket) is systematically changed to determine the insulation level that reduces the HVAC loads of the entire complex. The optimal thermal resistance value for the supermarket's walls are found to be 3.3m^{2}K/W (MacGregor and Hachem, 2016) and the values chosen for the boundary wall's insulation are iterated between 25 – 400 % of this value.

Window Assemblies. The envelope construction of the greenhouse consists of transparent fenestration in nearly 100% of the surfaces. Determining the optimal window assembly to reduce the greenhouse loads is essential to the goal of designing a high energy performing supermarket with attached growing area. Clear, single paned windows are used as the base model to simulate commonly used fenestration surfaces in greenhouses. The different assemblies are as shown in Table 3. The building's heating, cooling and lighting loads are used to determine which assembly is optimal for this design.

Table 3: Window assemblies and corresponding characteristics used in simulations. (Carmody and Haglund, 2012)

Assembly	Frame	U-Value (W/m^{2}K)	SHGC	VT
Single, Clear	Aluminum	5.778	0.82	0.88
Double, Clear	Aluminum	4.71	0.65	0.63
Double, low-e, High SHGC, Argon Filled	Aluminum	3.63	0.38	0.61
Triple, low-e, High SHGC, Argon Filled	Improved non-metal	1.14	0.41	0.5
Triple, low-e, Low SHGC, Argon Filled	Improved non-metal	1.08	0.18	0.37
Double, low-e, Low-SHGC, Argon Filled	Aluminum	3.57	0.26	0.49
Quadruple, low-e, High, SHGC, Krypton Filled	Improved Nonmetal	0.77	0.41	0.36

Infiltration. Airtightness has an important impact on the thermal loads of a building. For the greenhouse the effect of this parameter is studied over a range of 0.03 - 10 air change per hour (ACH) under normal atmospheric pressure. The results are compared to the base model's performance with an infiltration rate of 0.03 ACH. This minimal infiltration rate is selected to control the CO_2 levels for healthy agricultural production. A ventilation rate of 0.5 ACH is adopted during day-light hours which replenishes the carbon dioxide for photosynthesis (Vadiee and Martin, 2013). The effect of increasing the infiltration rate is investigated.

Aerogels. Aerogels are transparent or semi-transparent building materials which offer much higher thermal resistance than the traditional window assemblies. Two different aerogel products are used in the simulations and the characteristics of both are shown in Table 4. Aerogels are employed in two different scenarios: 1) to replace all the glazed areas, 2) to replace all glazed areas except for the roof. The roof in the latter scenario is assumed to take the configuration of the optimal window assembly, determined above.

Table 4: Aerogel characteristics used in simulations (Buratti, 2012)

AeroGel	U-Value (W/m^2K)	SHGC	Visible Transmittance
Monolithic	0.65	0.74	0.8
Granular	0.44	0.31	0.8

Shades and Moveable Insulation. Due to the nature and design of greenhouses, the interior can overheat due to high solar radiation. Two types of moveable fenestration covers are introduced in this study. The first being an inflatable thermal barrier that expands and covers the greenhouse. This thermal barrier is an inflating polyethylene cover which sheathes the greenhouse portion of the building at sunset and then is deflated at sunrise. When inflated, the cover has a thermal resistance value of 1.79 m^2K W-1 (Arinze, et al, 1988). A rollout shading device on the roof of the greenhouse is explored in this study to reduce overheating. The shades are assumed to have no effective thermal resistance but block out a portion of the incoming radiation. Three different transmittance values are investigated; 75%, 50% and 25%. These solar screens are activated when the solar radiation is high during the summer months.

Semi-Transparent Photovoltaics. Semi-transparent photovoltaics is investigated as means to subsidize the electrical loads while providing some shade to the interior due to the inherent design of these panels. The semi-transparent photovoltaics simulated in this study are termed STPVXX, where XX is the percentage of the photovoltaics per area of surface. The remaining surface area is comprised of double paned glass window assemblies. The characteristics of each of the cases and their corresponding thermal and transmittance qualities are shown in Table 5. STPVs are assumed to replace all transparent surfaces. This is to determine the maximum on-site electricity generation that can be produced.

Table 5: Semi-transparent photovoltaics characteristics used in simulations (Kapsis, 2015)

Assembly	U-Value (W/m^2K)	SHGC	Visible Transmittance
STPV90	1.634	0.146	0.061
STPV80	1.634	0.219	0.122
STPV70	1.634	0.292	0.183
STPV60	1.634	0.364	0.244
STPV50	1.634	0.437	0.305

Phase Change Material. Phase change materials can regulate internal climate due to their ability to store thermal energy within the material as they undergo phase transition. When the material then reverts back to its prior state, this thermal energy is released back into the room. This cycle can help reduce cooling loads as the PCM is melting and also reduces heating loads as the PCM freezes. This type of material is shown to be effective in controlling the heat gain within the attached supermarket associated with the refrigeration and lighting (MacGregor and Hachem, 2016). An example of this material exists in the EnergyPlus and has been added to the boundary wall between the supermarket and greenhouse in this study.

3. Analysis of Results

This section presents the results of the optimization of the energy performance of the complex coupling the greenhouse and the supermarket. The supermarket performance is analyzed, both as isolated structure and as a part of the complex. In addition, this section analyses the impact of the building envelope design parameters, and outlines the aspects of the supermarket which can be utilized in developing a more unified and efficient complex.

3.1 Base Case Building Loads

The two components constituting the complex investigated in this study are the supermarket and the greenhouse. Figure 3 compares the building loads of the isolated supermarket, and then as attached to the greenhouse in addition to the entire base case complex's energy consumption, on per unit are basis. The base case-complex combines the optimized supermarket and the standard greenhouse. Coupling the greenhouse to the supermarket, the building loads of the supermarket decreases due to thermal transfer with the inefficient greenhouse as well as the slightly reduced size of the supermarket. The southernmost 10 m of the supermarket is replaced by the greenhouse for this study in order to maintain the same size of complex. In the parametric analysis below, the entire complex will be the object of optimization.

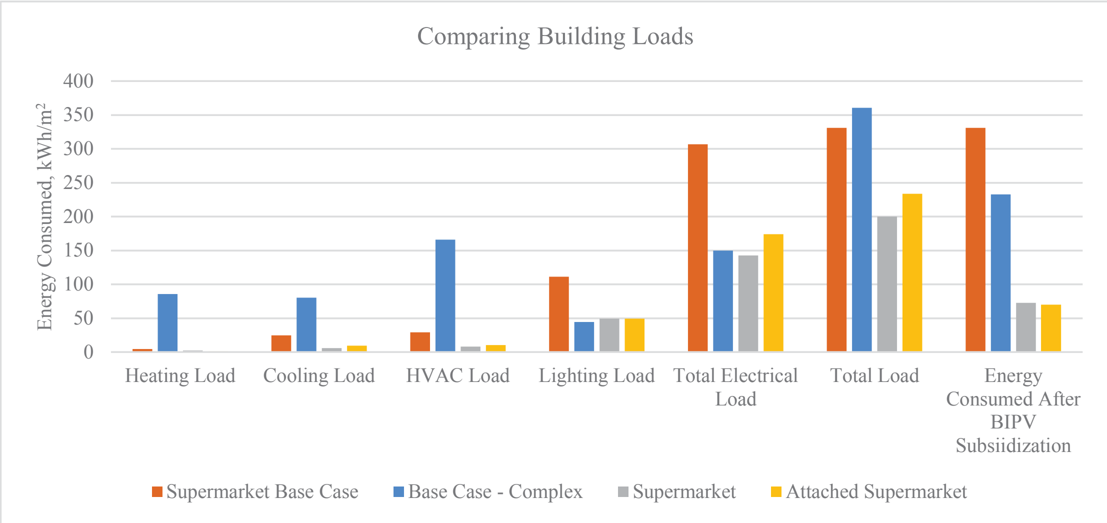

Figure 3: Comparison of the building loads of the supermarket by itself, attached to the greenhouse and then as the entire complex. The base case-complex loads are the target of optimization in this study.

3.2 Effect of greenhouse design parameters

Greenhouse shape. The three different geometrical designs of the greenhouse, perform very similarly. Each design has approximately the same total energy consumption, with case 3 (largest south façade and lowest sloping roof) having marginally more energy consumed annually. The increase in height with the front façade, and the resulting decrease in slope angle for the roof, the heating load increases as cooling load decreases. The lighting load is not affected. The front façade height of 1.7 m is adopted for all following models.

Boundary Insulation. The thermal resistance in the boundary wall between the supermarket and greenhouse does not have significant effect on energy consumption. Since the impact is less than 1%, the optimal insulation of the supermarket is maintained as it is the larger energy consumer of the two zones.

Window Assemblies. Triple paned, low-e, low shgc and argon filled assembly reduces the energy consumed in the design significantly as compared to other assemblies. For instance, this assembly reduces the heating and cooling energy consumption by 80% as compared to the base case. Limiting the solar heat gain in the greenhouse the cooling load is substantially reduced, as displayed in Fig. 4.

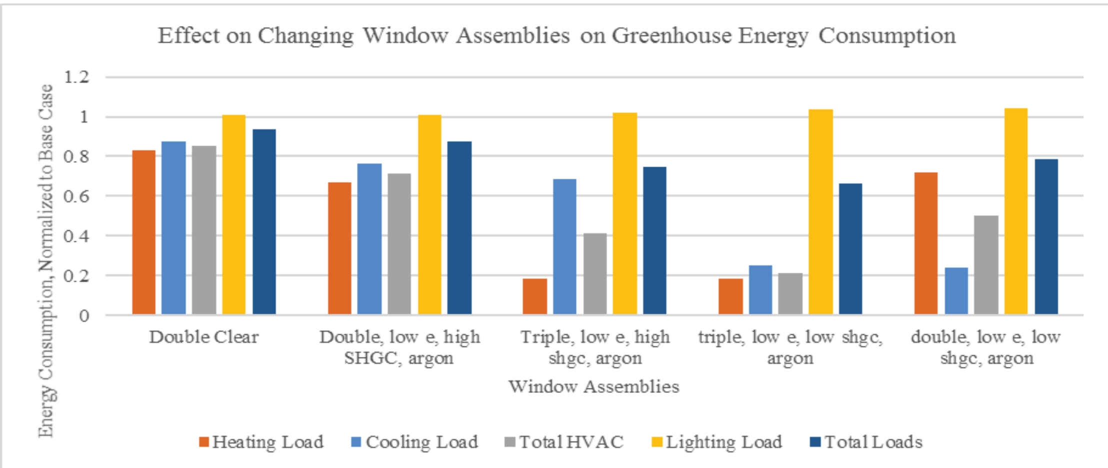

Figure 4: Best case window assemblies are triple, low-e, low shgc and argon filled. Reduces combined heating and cooling load by 80%

Infiltration. These simulations are completed using the optimal window assembly found above as these assemblies allow significant improvements to the interior environment. The results of analyzing the impact of increased infiltration rate indicate that the lowest rate is the most favorable for reducing heating and cooling loads.

Aerogels. Aerogels show promise in reducing HVAC energy loads while allowing light to penetrate the envelope. The insulating qualities of these materials leads to an increase in cooling loads, when used in place of all window (see Figure 5). Replacing all fenestrations but the roof (which maintains the optimal window assembly; triple, low-e, low shgc, argon filled) with aerogel leads to a total reduction in heating and cooling loads of 70%. However, even though these reductions are significant, the scenarios which contain the triple, low-e, low-shgc and argon filled assemblies in all fenestrations perform marginally better (2% difference in total load reduction).

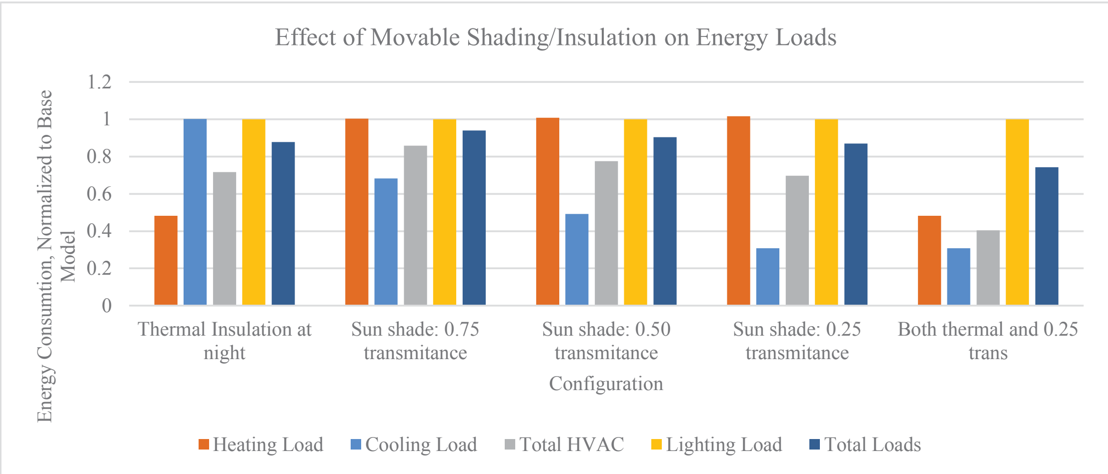

Figure 5: Granular aerogel in all fenestration but the greenhouse roof shows reduction in total energy consumption of 25%

Shades and Movable Insulation. The polyethylene inflatable cover which activates at sunset, reduces the heating load by 52% as compared to the base case, while it does not impact the other loads. The rolling shade with 75% transmittance qualities shows a reduction in the cooling load by 32%. Rolling shade with 25% solar transmittance shows even greater results with a reduction in cooling loads by 70% as compared to the base model. The best case of all these scenarios is the addition of the night time insulation to the 25% transmittance shade with a simulated reduction in heating and cooling loads by 60% (See Fig 6) and an overall reduction in energy consumed by 26%.

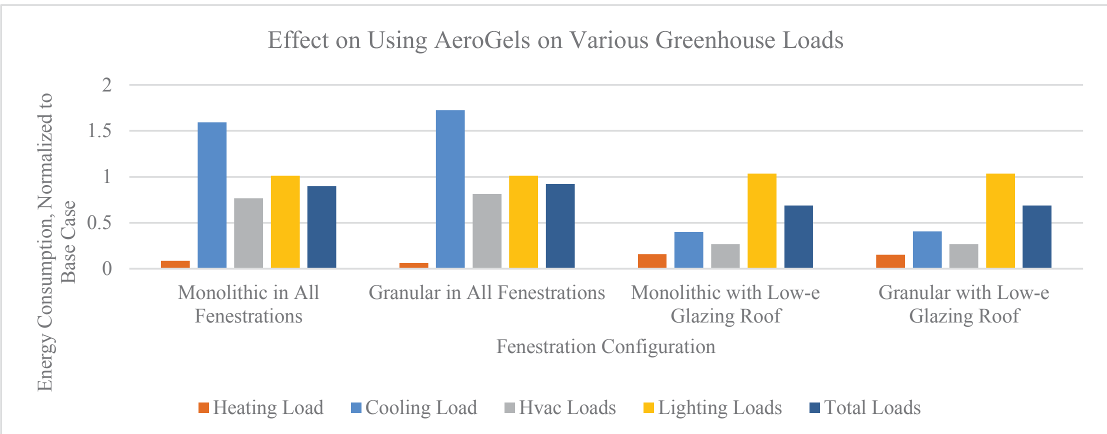

Figure 6: Using night-time thermal covers and 25% transmittance roll-out shade shows reduction in combined heating and cooling loads by 60%.

Semi-Transparent Photovoltaics. The STPV are useful in two aspects. The first is the reduction of the heating and cooling loads by the thermal and optical properties of these assemblies. The STPV assemblies are in part opaque which blocks solar radiation from entering the greenhouse, thus reducing cooling loads. This cooling load increases linearly with the decrease in opaque areas of the different assembly configurations. The thermal properties of the assembly (Low –e, argon fill gap) reduce the heating loads by 70% as compared to the base case across the different configurations (Fig. 7).

The electrical loads are high in the supermarket-greenhouse complex and using semi-transparent photovoltaics help in the reduction of energy consumed from non-renewable sources. There is an obvious increase in the lighting load as the STPV assemblies block incoming radiation, however, this assists in minimizing the cooling loads. The potential electricity generation can reduce the total energy consumption by approximately 20%, in the case of STPV 90. This potential decreases to 10% in the case of STPV 50.

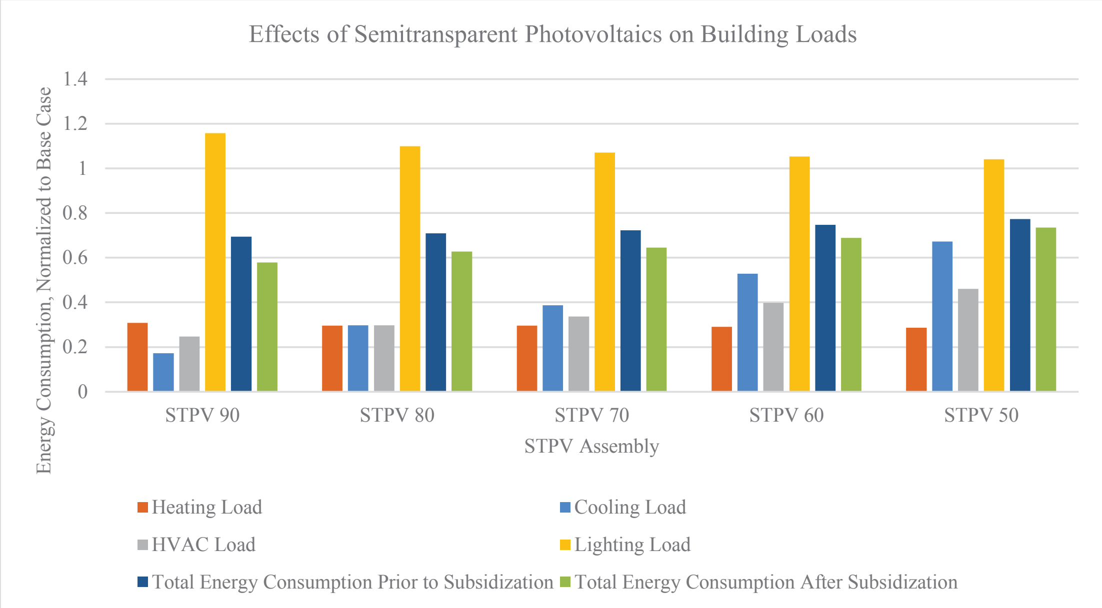

Figure 7: STPV can reduce the total energy consumption by 42% by blocking incoming solar radiation and generating electricity.

Phase Change Materials. Using PCMs in the greenhouse boundary wall shows that some of the heating and cooling loads can be controlled. The simulation*s* are carried out for the base case as well as the optimal window assembly case. In both cases, the combined heating and cooling load reduction is about 10% and 5% for the base case and the low-e glazing case, respectively.

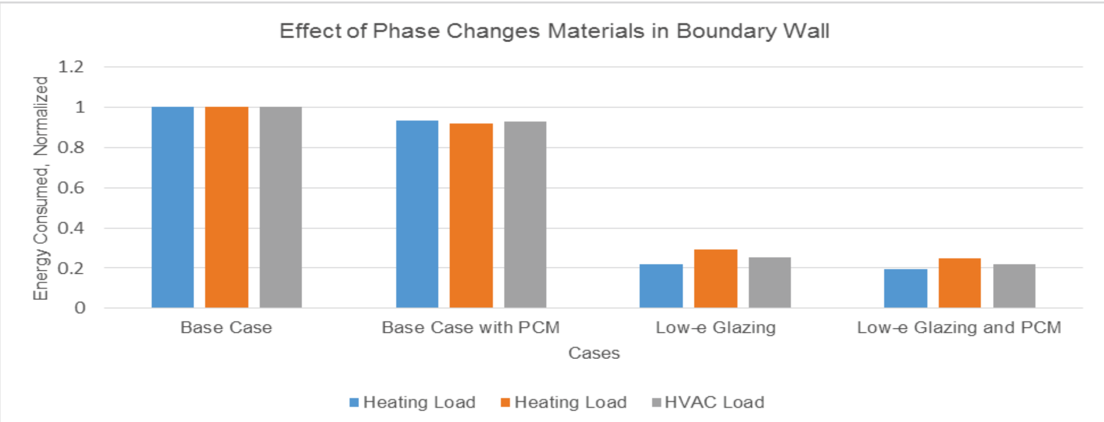

Figure 8: Phase change materials can reduce some of the heating and cooling loads by adding them to the boundary wall construction.

3.2 Utilization of Supermarket

BIPV electricity generation. A BIPV is assumed to cover the south surfaces of the saw-tooth roof structures

This BIPV system generate about 258 MWh annually. This amounts to 35% of the total energy requirements of the base model (base model consumes 360 kWh/m^2 annually) and 53% of the total energy consumption of the optimized model (241 kWh/m^2, annually). If combined with the energy generated from the semi-transparent photovoltaic assemblies, 80% of the energy requirements of the entire complex can be met with on-site generative means.

Heat recovery potential. The supermarket has two sets of refrigerator units with their corresponding compressor racks; the self-contained refrigerators with built in compressors as well as the medium (4°C) and low (-15°C) temperature refrigerators and their back-room standalone compressor rack. The supermarket back-room refrigerator compressor racks generate about 521 MWh of heat. Much of this heat is ejected into the outdoor environment as to have a minimal impact on the building's HVAC system. The heating requirements of the base model is 153 MWh annually, and the case with optimal window assemblies is 34 MWh, annually. Both of these loads are a fraction of the available heat of the compressor racks (30% and 6%, respectively). Especially in the case of the high efficiency windows, it can be assumed that the entirety of the heating load can be accounted for by a mechanism which captures the necessary amount of waste heat from this ejected source. On the other hand, the self-contained refrigerator/compressor units are responsible for a large portion of the internal heat gain, in the supermarket. Implementing a mechanism to capture all or part of this available heat has the potential to significantly reduce the cooling load. For instance, assuming that all heat gain generated by the self-contained refrigerator/compressor is captured, the cooling loads of the whole complex can be reduced by approximately 40%. When 50% of the available heat is captured, reduction of about 25% can be achieved.

3.3 Proposed Models

Table 6 shows the most influential parameters, selected based on the above analyses, to represent an optimized model. Heating and cooling loads are reduced by up to 95% as compared to the base model. The lighting loads are slightly higher than the original base model due to the shading devices and to the properties of the window assemblies. The overall electrical energy consumption, without accounting for the BIPV electricity generation, is reduced by 39% (241 kWh/m^2). With the utilization of the supermarket BIPV system, an overall energy consumption reduction to 62% of the original values is realized. Including STPV assemblies in only the roof portion of the greenhouse, a reduction of 82% in energy consumption is achieved. Finally, when the supermarket is fully utilized with the use of the refrigerator compressor racks to supply the heating requirements, 86% of the base model's energy consumption are reduced to a final value of 54 kWh/m^2.

Table 6: Parameters Chosen for Optimized Model

Parameter	Value
Greenhouse Design	Case 1; 1.7 m south façade
Boundary Insulation	3.3 m^{2}K/W
Window Assembly	Triple, low-e, low shgc, argon filled. On roof only
Aerogels	Granular. All fenestrations but roof
Infiltration	0.03 ACH
Movable shades and insulation	25% transmittance shade and night-time thermal insulation
STPV	STPV90 in roof only (In specified case in Figure 9)
PCM	Located in boundary wall

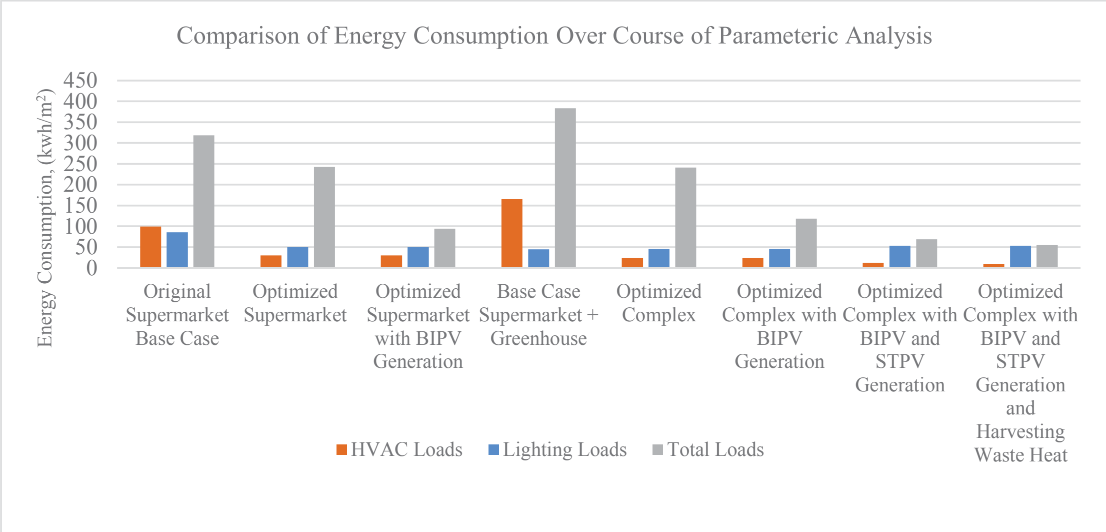

Figure 9: Total energy can be reduced by 86% as compared to the base model with a yearly electrical consumption of 54 kWh/m2. Final model performs 50% more efficiently than optimized supermarket design.

Discussion and Concluding Remarks

This study examines the potential of coupling greenhouse and supermarket in view of reducing energy consumption of the two buildings and exploring methods of energy sharing between them. An 86% reduction in energy requirements is reached through an optimized building envelope and increased potential of on-site electricity generation and heat recovery. However, despite this reduction, the building's energy intensity is 54 kWh/m^2, largely due to the use of inefficient refrigeration/compressor systems. This reduction is the topic of future research as followed:

- *Mechanical Optimization of Refrigeration.* The supermarket still relies on a number of refrigeration units to keep food at safe temperatures. However, these refrigerators often do not utilize the exterior temperatures for the source of the cooling, rather a reliance on compressor racks. Utilizing exterior temperatures in Calgary's cold winters may prove worthwhile in electrical load reduction.
- *Investigating Minimally Glazed Greenhouse Design.* The design adopted in this report adheres to greenhouse standards. A transparent greenhouse, as compared to an opaque building design, requires much less artificial lighting and allows for a higher degree of solar heating. However, an opaque building construction for the greenhouse could perform better in an environment whose temperatures fluctuate so rapidly over the course of the year as is shown in another study where limiting transparent fenestration to only 30% of the south façade and implementing, rooftop photovoltaics, day-lighting devices and increased insulation values produced a net-positive energy scenario of a stand-alone growing facility (Hachem and MacGregor, 2016). Investigation of this opaque design applied to the supermarket-greenhouse complex is an important next step.

This study is a step towards a more sustainable future by increasing the resiliency of communities. Providing the means for communities to centralize their source of food in a low energy consuming manner will further reduce the dependencies of these communities on fossil fuels and associated GHG emissions.

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