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Energy Optimized Envelope for Cold Climate Indoor Agricultural Growing Center

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Abstract: This paper presents a study of the development of building envelope design for improved energy performance of a controlled indoor agricultural growing center in a cold climate zone (Canada, 54° N). A parametric study is applied to analyze the effects of envelope parameters on the building energy loads for heating, cooling and lighting, required for maintaining growing requirement as obtained in the literature. A base case building of rectangular layout, incorporating conventionally applied insulation and glazing components, is initially analyzed, employing the EnergyPlus simulation program. Insulation and glazing parameters are then modified to minimize energy loads under assumed minimal lighting requirement. This enhanced design forms a base case for analyzing effects of additional design parameters—solar radiation control, air infiltration rate, sky-lighting and the addition of phase change materials—to obtain an enhanced design that minimizes energy loads. A second stage of the investigation applies a high lighting level to the enhanced design and modifies the design parameters to improve performance. A final part of the study is an investigation of the mechanical systems and renewable energy generation. Through the enhancement of building envelope components and day-lighting design, combined heating and cooling load of the low level lighting configuration is reduced by 65% and lighting load by 10%, relative to the base case design. Employing building integrated PV (BIPV) system, this optimized model can achieve energy positive status. Solid Oxide Fuel Cells (SOFC), are discussed, as potential means to offset increased energy consumption associated with the high-level lighting model.

Keywords: building envelope design; energy performance; indoor agricultural growing center; building integrated PV

1. Introduction

Controlled Indoor Agriculture presents opportunities to mitigate the environmental impacts of conventional farming, while extending the growing season, especially in cold, high latitude regions. Negative impacts of conventional farming include greenhouse gas emissions [1], high water consumption and employing fertilizers that may infiltrate neighboring ecosystems [2].

Developing a building in cold climate for year-round energy supply for crop cultivation encounters significant challenges. These challenges include ensuring a sufficient level of lighting and carbon dioxide (CO_2) to maintain a healthy photosynthesis for plants' growth, while maintaining optimal climatic conditions [3]. These conditions are not easy to meet in high latitude, cold climate regions. For instance, Edmonton (Alberta, Canada) has few daylight hours and low angle solar radiation for half of the year, both of which restrict receiving sufficient sunlight to support yearlong agriculture. Moreover, outdoor air required for proper ventilation has low temperatures over long time periods, necessitating thus a substantial amount of energy to bring it to an acceptable temperature.

Building envelope design can play an important role in the design of energy efficient controlled agriculture. Greenhouse related research highlights building envelope improvements as crucial to achieve efficient designs, at the levels of both energy efficiency and agricultural productivity. These improvement strategies include: enhancement of solar radiation transmitted though the glazing, increased insulation and reduced glazing (presumably compensated for by artificial lighting) use of thermal mass as a means to regulate diurnal temperature fluctuations, [4–8]. Through efficient design of the building envelope that takes into account the considerations mentioned above, summer vegetables can be grown year-round using significantly reduced energy (approximately 12 kWh per month) [4]. In fact, a carefully designed greenhouse can increase the number of crop yields in a year. For example, under controlled conditions of humidity, temperature, light and water, within the greenhouse, tomato plants experience two crop cycles in a year rather than one, which would be the case in rural settings [1]. Moreover, research indicates that control of heat and air flow through the envelope is crucial to reduce energy consumption while enhancing concentration of greenhouse CO_2 level. CO_2 enrichment is currently attracting attention as a means to increase agriculture productivity [9].

This paper presents a systematic approach to the ad hoc optimization of building envelope design of a growing center. The term Growing Center is employed to describe a building designed for controlled indoor agriculture. The design approach employed for this growing center, contrary to the existing approach, is characterized by an opaque, airtight envelope with restricted amount of glazing. The objective of the proposed design is to achieve a high energy performance building for cold climate, with minimum overall energy consumption for heating, cooling and lighting for indoor growth of crops. While, in principle, the performance of this type of buildings is not primarily measured by its energy performance, as the agriculture productivity remains the ultimate goal, energy efficiency is a primary component of building operations' costs and sustainability of such enterprise.

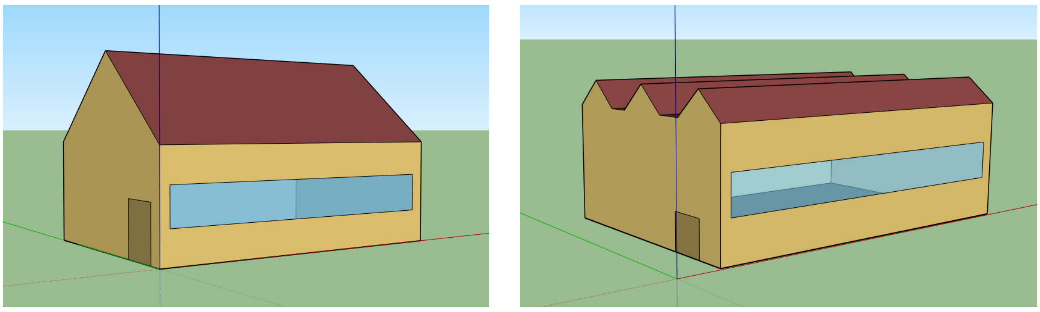
2. Methodology

This study is divided into three main parts, summarized in the following. The first stage aims at addressing the design of the building envelope for improved energy performance of Growing Centers in cold climates, assuming a minimal functional artificial lighting level. A parametric approach is used to determine design criteria for the Growing Center to achieve maximum energy efficiency under the minimum lighting level recommended for healthy plant growth. The second part examines the enhanced model of the first stage under a substantial increase in lighting requirements, with the objective of increased production. It investigates the impact of intensified lighting environment on the design of the building envelope components.

The third part investigates the building potential to generate its own electricity employing various on-site technologies. Two technologies are theoretically explored: the use of photovoltaic panels to generate onsite electricity with changing roof shape [10], and potential electricity generation from Solid Oxide Fuel Cells.

2.1. Growing Center Base Case

A base model growing center, located in Edmonton, Alberta, Canada (54° N), is designed to serve as reference in a comparative study in which specific building envelope parameters are systematically modified to achieve optimal energy performance design for the growing center. The basic geometrical design assumes a rectangular building of 12 m × 18 m plan dimensions and 6 m height, with the long façade facing south (Figure 1). The window constitutes 30% of the south façade. The response variables analyzed to evaluate the design are heating and cooling loads, indoor illuminance level and lighting loads as well as electrical energy produced on-site. The assumptions for the base model are summarized in Table 1.



(**a**) (**b**)

Figure 1. Sketch up Model. Dimensions: 12.2 m (W) × 18.3 m (L) × 6.1 m (H). Height is measured to top of south facade. Glazing is 30% of south facade. (**a**) Base case: Gable roof with 40° tilt angle; and (**b**) Saw-tooth roof with 50° tilt angle.

Table 1. Summary of assumptions of the base case model in EnergyPlus.

Parameter	Explanation	Value
Electrical Load	Office Equipment and water pumps	4500 W [1]
Lighting Load	Optimal Level for single layer growth	25 W/m^2; LED lighting [2]
Light Density	Minimum for Healthy Plant Growth	7000 lux [2]
Humidity Set-Points	Optimal Range for Plant Growth	50–90% [3]
Temperature Set-Points	Optimal Range for Plant Growth	17–27 °C [3]
Insulation	ASHRAE Recommended for Commercial	Wall: 1.74 m^2·K/W; Roof: 2.64 m^2·K/W [4]
People Loads	Specified by Industry Contact	4 People [1]
Building Dimensions	Specified by Industry Contact	12.2 m (W) × 18.3 m (L) × 6.1 m (H) [1]
Roof Design	Optimized for PV Generation in Edmonton	40° slope gable roof
Window Assembly	Commonly Used Windows	Double pane, air filled
Window Size	Needed value for simulation	30% of South Facade
Vegetation	Needed for Accurate Simulation	Single layer; 80% floor space

[1] Calculated using required hydroponic equipment specifications. [2] [11], [3] [3]. [4] [12].

2.2. Simulations

EnergyPlus [13] (Version 8.4.0) is employed to carry out the simulations. The simulations evaluate the effect of various envelope design parameters on heating, cooling and lighting loads, as well as on energy generation potential by means of building integrated photovoltaic (BIPV) system. This energy simulation tool allows control over individual processes and designs within the reference building as well as an extensive array of output options. A number of assumptions are made, including the assumption of "green roof" (at ground level) and irrigation inputs to simulate the area of the floor space devoted to crops (see Table 1). The computational model of the heat transfer processes used by EnergyPlus for this crop cultivation surface accounts for a large number of parameters [13,14]. This includes short and long wave radiation, convective heat transfer, and evapotranspiration from the soil and plants. EnergyPlus allows input related to various aspects of the green area, including the depth of the growing media (i.e., soil), the plant canopy density, soil moisture conditions and others.

Other assumptions and inputs used are presented in Table 2. The weather files of EnergyPlus, for Edmonton (Alberta, Canada) are used for the simulations (EnergyPlus, Weather Data Sources).

Table 2. EnergyPlus Assumptions and Simulation Controls used.

Assumption or Necessary Input	Value
Time Step	10 Minute Intervals
Weather File	Edmonton Region
PV Models	Simple PV Performance
Heat Balance Algorithm	Conduction Finite Difference
Run Period	One year
HVAC System	Electrical with Coefficient Of Performance (COP) = 1
Daylighting Set-Point	7000 Lux. Lights on Dimmer Control [1]
Phase Change Materials (PCMs)	EnergyPlus Example Material. Acts as 30% per volume PCM to gypsum board
Reflective Light Shelf Material	90% reflectivity

[1] [11].

2.3. Studied Parameters

The key parameters whose effects are investigated include: insulation values in the opaque wall assemblies [15], window size and characteristics [16], solar radiation control including light shelves and overhangs [17], air infiltration rate, and the addition of phase change materials (PCMs) to passively regulate heat [18]. The parametric study also focuses on designing building envelope components which maximize interior illumination to reduce the dependency on high consumption growing lamps while still maintaining energy efficiency such as the use of sky-lights or exterior reflective shelves.

2.3.1. Ad hoc stepwise optimization process

The Flowchart presented in Figure 2 shows the sequence of the simulations process for the optimization of the building envelope under low and high lighting levels.

The main envelope parameters that affect energy performance are wall insulation and glazing assemblies. These parameters interact with other building envelope components, so that the effects of other parameters, such as light shelves, infiltration rates, etc., strongly depend on the values of insulation and glazing assemblies. In order to simplify the computational process, the initial base case is optimized sequentially for insulation of the opaque surfaces, then for glazing (with optimal insulation) and finally for window area (with optimal insulation and glazing).

The remaining parameters are then applied individually to the upgraded base case to evaluate their optimal values. The final optimal design is obtained by combining the optimal values of individual parameters, based on the simplifying assumption that they do not interact strongly.

Each step of the optimization process is obtained by performing simulations on incremented values of the studied parameter and selecting the parameter value corresponding to the best performance of the response variables.

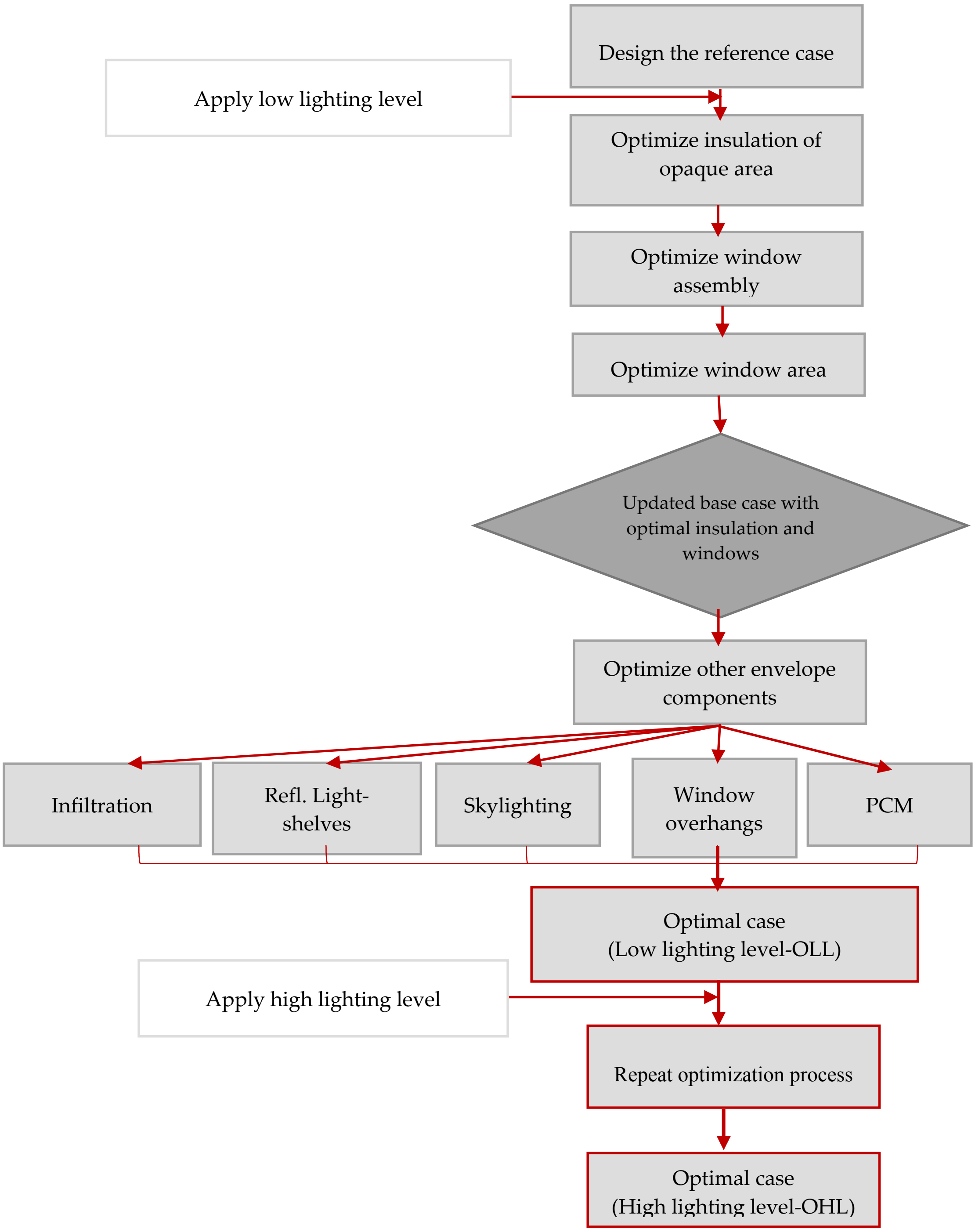


Figure 2. Flowchart of the simulation process.

2.3.2. Scenario with Low Lighting Level

The main parameters studied for the low lighting level scenario are presented below. The minimum lighting requirement for healthy plant growth is about 7000 lux [11], which equates to a load of approximately 16,000 kWh annually.

Insulation

The impact of insulation values of the opaque area of the building envelope is first investigated. The base model insulation values are recommended by ASHRAE for low-rise commercial buildings [12].

The exterior walls have an original value of 1.74 K·m^2/W and the roof has an insulating value of 2.64 K·m^2/W. ASHRAE values are adopted since neither the Alberta building codes nor the Canadian building codes specify values for this type of buildings. The insulation level is stepwise increased from the code, with values ranging from 125% to 400% of the code (at 25% increments). The increase is applied systematically f to the walls and roof, in isolation and in combination.

Window Assemblies and Surface Area

Setting the opaque wall assemblies to optimal thermal resistance values allows accurately determining the optimal assembly of windows. The base case for assessing performance of window assemblies is the base model window setup (double paned, clear glazed and air filled window assembly, constituting 30% of the south facade), with updated wall and roof insulation. The investigated assemblies are presented in Table 3.

Table 3. Window Assemblies and corresponding characteristics used in simulations. [16].

Assembly	Frame	U-Value	SHGC	VT
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

Using an updated envelope that features the optimal insulation level and window assembly, window sizes are increased from 30% to 90% of the total facade area, at 10% increments. This is done for each facade and then for all of them together.

Other Envelope Parameters

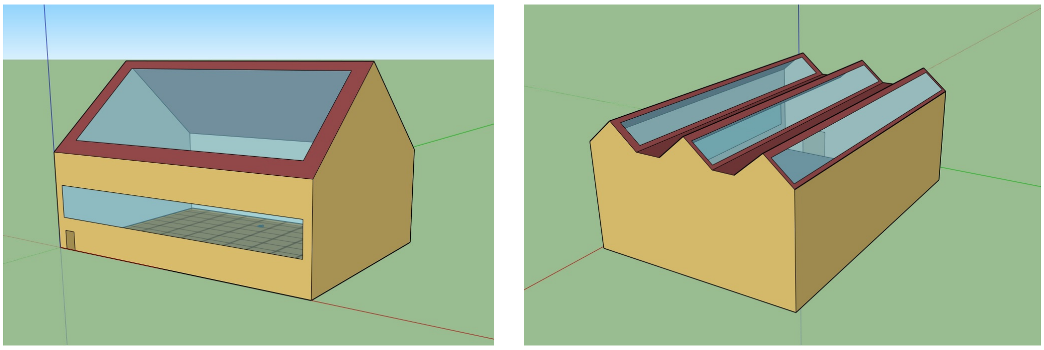
This section employs the building envelope updated with the optimal insulation level, window assembly and size, to explore the impact of other envelope design parameters. The parameters detailed below are applied to the updated envelope separately—one at a time.

Infiltration: Infiltration is the uncontrolled movement of air through the building assembly. The base case uses a very low infiltration rate, conforming to the passive house standards (e.g., 0.6 air changes per hour (ACH)). This is increased systematically and the effect on heating and cooling loads is analyzed.

Reflective Light Shelves: Research indicates that reflective light shelves can reduce the need for artificial lighting by redirecting light deeper into the building [17]. This leads to reduction in the required artificial lighting and consequently to a reduction in cooling load (due to less radiant heat from the lights [17]). Using the updated base model design, an analysis is conducted to determine the effect of reflective light shelves on the availability of light within the building. This light shelf is assumed as a horizontal fixed plan located under the window, and is iterated over widths ranging from 0 m to 2 m.

Sky-Lighting and roof design: As the primary function of this building is the growing of indoor crops, it is necessary to explore additional means to maximize daylight penetration into the building. Effect of integration of sky-lighting within the roof surface on thermal loads and lighting loads is investigated. The skylight impact is analyzed for each of the southern and northern surfaces of the gable roof. The sky-lights are systematically changed from 10% to 90% of the roof surfaces at 10% increments for each surface individually.

An additional saw-tooth roof design is investigated in this part of the study (Figure 3). Two models are created for this roof design, one without sky-lighting and the other with sky-lighting covering 80% of the north side of the saw-tooth. The effects of these designs on thermal loads and lighting loads are compared to those of the improved reference case.



(a) (b)

Figure 3. Sky-lighting SketchUp Models: (**a**) example of the Gable Roof Model with 70% sky-lighting; and (**b**) Saw-Tooth roof design with 80% of the North facing slopes as sky-lighting.

Window Overhangs: Overhang on a south facing window is an efficient method to block the higher incident solar radiation associated with Edmonton summers while still allowing lower angle winter sunlight to access the indoor space. To study the impact of overhang width on heating, cooling and lighting loads, the overhang is placed horizontally directly above the top frame, along the length of the window. The width is changed systematically with 0.25 m increments from 0.2 m to 2 m, representing 10% to 110% of the window height respectively.

Phase Change Materials (PCMs): PCMs can passively control high cooling loads by storing large amounts of heat in the material as it undergoes phase transitions [18]. In fact, studies demonstrate that this building material is an effective way to control excess thermal heat in greenhouses [19]. PCMs are often added to building envelopes as microencapsulated paraffin wax mixed into the drywall components during manufacturing. This study assumes a similar application of PCM (with melting point of PCM is 22 °C), as modified drywall components, to analyze its impact on thermal loads.

2.3.3. Scenario with High Level Lighting

As CO_2 enrichment is starting to be employed as a method to increase agriculture productivity, plants would require more lighting in order to consume this CO_2 through photosynthesis. In this section, an increase of lighting intensity is applied to the optimal low lighting design presented above, and the effect of this change on the building thermal and lighting loads is analyzed. The increase from 7000 lux to 64,000 lux results in lighting load of approximating 240,000 kWh annually.

The increased lighting leads to overheating and consequently to increase in cooling load. The building envelope parameters that might assist in reducing the cooling loads are insulation, window assembly and size, air infiltration rate and the application of PCM. In this section, those parameters are re-simulated and the results are presented below.

2.3.4. Mechanical System and Renewable Energy Generation

This section examines on-site electricity generation through the use of photovoltaic systems to offset some of the electrical requirements of these buildings. The potential use of Solid oxide fuel cells (SOFC) is explored as a supplement to PV systems for electricity generation. The implementation of a more efficient mechanical system is also investigated. The goal of this part is to study the necessary conditions to achieve a net-zero or net-positive energy building.

Roof Slope for Photo-Voltaic (PV)

Indoor agricultural buildings are associated with high electricity demand. The necessity for growing lamps and circulating water as well as climate control equipment (i.e., HVAC, humidifiers, CO_2 replenishment, etc.) drive up the energy consumed. One way to offset some of the energy consumption is to generate on site renewable energy through the integration of photovoltaic panels within south facing surfaces of the roof. This stage of the study determines the amount of electricity that can be generated on-site with different roof designs. The three different roof designs for this section of simulations are a gable roof with two different tilt angles 10° and 40°, and a saw-tooth roof design with a tilt angle of 50° (Figure 2). The 50° tilt angle, which is close to optimal for the studied location, is implemented on the saw-tooth design since this design assists in reducing the overall height of the building associated with higher tilt angles

For this study, the PV array is selected from EnergyPlus database to provide approximately 18% efficiency, under standard conditions. For Edmonton, PV potential/Potentiel PV (kWh/kWp) for South surface tilted at lat-15° is about 1247 kWh per kW peak of installed PV (NRCan, 2017).

Mechanical Systems

The HVAC used for the base case and through the optimization process of the building envelope is an electrical system assuming a coefficient of performance (COP) of 1, which means that one unit of energy regulates one unit of heat. The potential of using a heat pump to reduce the energy consumption for heating and cooling is investigated. COP values ranging from 1 to 5 to represent common performance of various types of heat pumps are adopted and the resulting energy consumption for heating and cooling is analyzed. The balance between energy generation potential and energy consumption is then studied.

Solid Oxide Fuel Cells (SOFC)

Solid oxide fuel cells (SOFC) utilize a chemical process to produce electricity from fuel and oxygen, without combustion. Fuel is fed through the cell anode, and oxygen through the cathode, combining in the electrolyte to produce an electrochemical reaction resulting in electron flow between the two electrodes [20]. Hydrogen is generally considered as the optimal fuel for fuel cells (National research center). While Emissions associated with standard fossil fuel powered plant include Sulfates, Nitrates, Carbon Monoxide, as well as Carbon Dioxide and water vapor [21], SOFC plants are responsible for the emissions of Carbon Dioxide and water (Table 4). In addition to reduced emissions, SOFC can generate above 200 kW draw per cell and have relatively long life cycle (lasting several years before replacement) [22]. These cells are scalable and can be chained in series in order to achieve the required amount of energy [23]. The Growing Center with high lighting level design requires a large amount of CO_2. It is possible to condense the CO_2 out of the high temperature exhaust gas of the SOFCs in order to meet this requirement [24]. To size the fuel cells to achieve net zero energy status, it is important to determine the electrical loads that are still unmet by onsite electricity generation from the photovoltaic systems, described above.

Few assumptions were made in order to include fuel cell materials in the design, such as assuming the fuel cells are isolated from the building to reduce waste heat generated from their operation into the indoor space.

Table 4. Kilograms of Green House Gas (GHG) emissions for one tear of operation at 1650 MWh output [21].

Air Emissions	SO_x	NO_x	CO	Particles	Organic Compounds	CO_2
Coal Fired Fuel Plant	12,740	18,850	12,797	228	213	1,840,020
SOFC System	0	0	32	0	0	846,300

3. Analysis of Results

3.1. Building Envelope Effects at Low Lighting Level

This section presents the main results of the impact of various design parameters on the energy performance of GC at low lighting level. The optimal combination of these parameters is discussed.

3.1.1. Insulation

The analysis of the effect of changing the insulation levels indicates that increasing the insulation value of the walls has a large effect on the thermal load of the GC in general. The results show that increasing the insulation value of the walls has more impact on the overall thermal load than increase of roof insulation values (Figure 4). Increasing the insulation value of both roof and walls leads to significant reduction of thermal load as compared to the base case (by up to 25%). The optimal insulation for the cold climate Growing Center is about 250% of the base case's value (i.e., Wall: 4.23 $m^2 \cdot K/W$; Roof: 6.69 $m^2 \cdot K/W$). Cooling loads are unaffected by changes in wall or roof insulation values and up to a wall insulation of 3.35 $m^2 \cdot K/W$ combined with roof insulation of 5.28 $m^2 \cdot K/W$ beyond which cooling load increases.

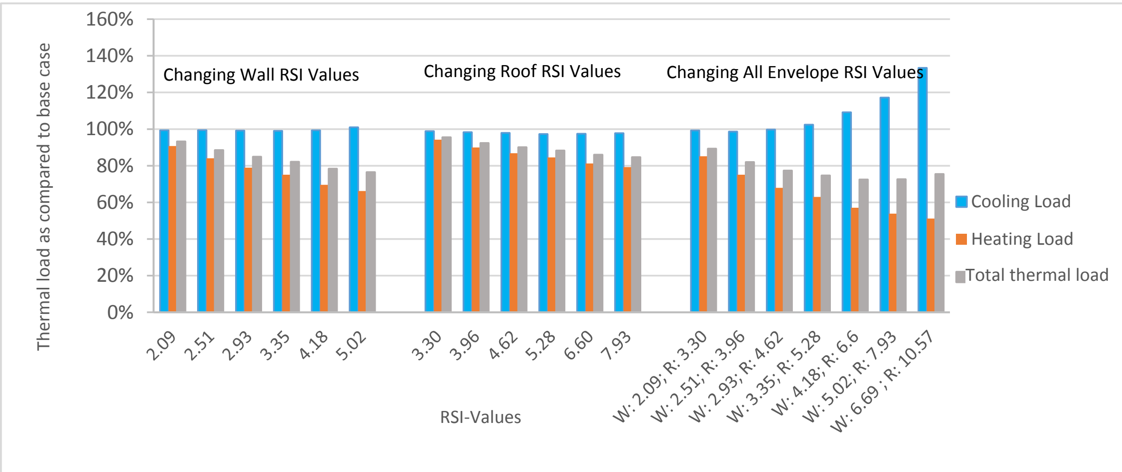


Figure 4. Impact of insulation level in walls and roof on the thermal load of the GC. Data are compared to base case model.

3.1.2. Window Assemblies

The effect of window assembly characteristics on heating and cooling load is analyzed in this section for the insulation levels of the reference case updated to the optimal values (see flowchart in Figure 2). The results indicate that the window assembly with triple glazing, low-e glazed, argon filled and high solar heat gain coefficient (SHGC) represents the optimal solution for the studied case. This assembly reduces the overall thermal load of the building by nearly 50% as compared to the updated reference case (i.e., with optimal insulation levels). The quadruple glazing configuration has a similar overall reduction of the thermal load as the triple glazing configuration but the cooling load is 30% higher. Figure 5 displays the impact of various window assemblies on the thermal load as compared to the updated base case (base case with updated insulation level).

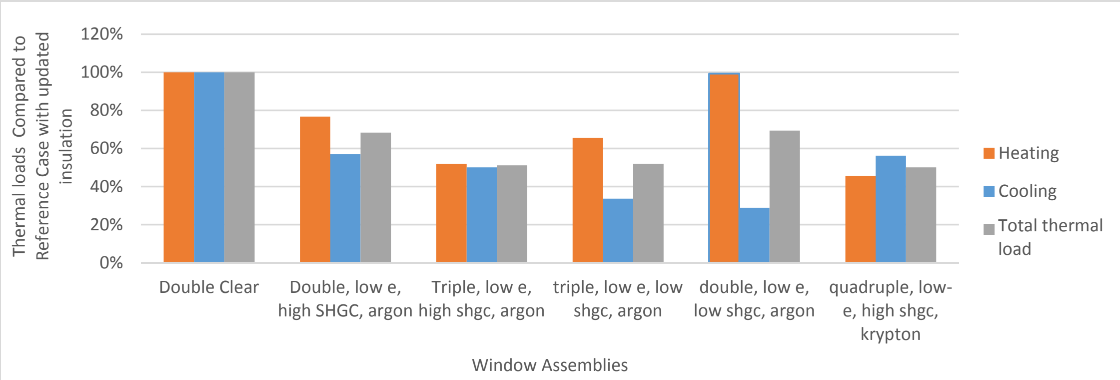


Figure 5. Comparison of various window assemblies. Double Clear is the base model with wall and roof insulation set to 4.18 K·m^2/W and 6.60 K·m^2/W, respectively. Best case is Triple, low-e, high SHGC and argon filled assembly.

3.1.3. Glazing Area and Orientation

Analysis of the impact of glazing size is performed using the configuration with optimal insulation level and window assembly found above to properly determine the optimal glazing area and its orientation for the Growing Center. Figure 6 presents the impact of the orientation and size of glazed area on heating, cooling and lighting loads.

Typically, for all facade configurations, lighting load drops slightly while heating and cooling loads increase substantially. A south window size of 30% is conductive to the best overall performance, in comparison to all other studied configurations (Figure 6). This design option, being the original option adopted in the reference case, is associated with the lowest thermal load. Scenarios in which glazing surfaces are integrated in all facades lead to significant reduction in lighting load but the annual heating and cooling loads drastically increase with the increase in glazing surfaces. The results show that the cooling load associated with the window assemblies being on the north façade is significantly lower than all other cases. This is largely due to the reduced solar heat gain through this façade.

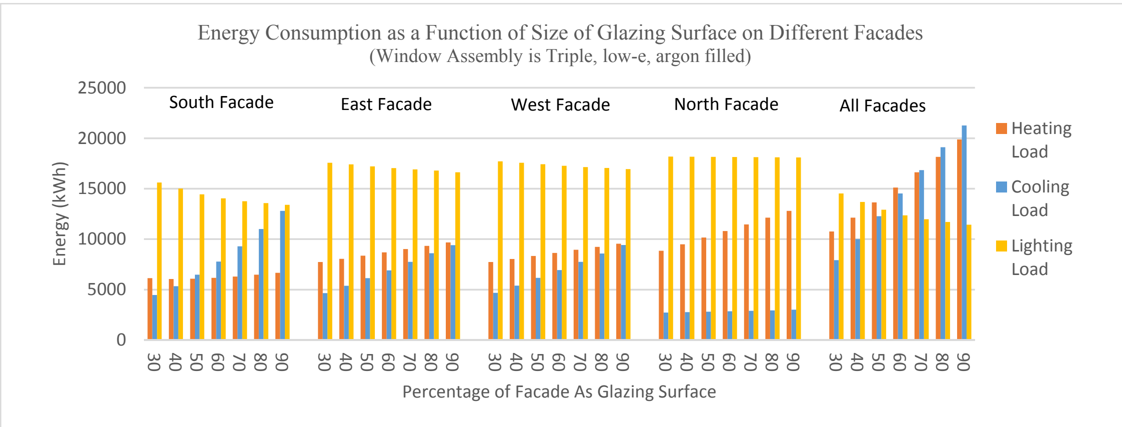


Figure 6. Results of the investigation of window size on each facade, and on all facades combined. North facade windows result in lowest cooling loads.

Additional models were created to combine south facade and north facade window surfaces, aiming at determining the overall impact on the building's thermal load and lighting load, and thus an optimal combination between the two configurations. Both the north and south facing windows were varied over 0–60% of the surface and combinations of the two are compared. The results show that the optimal window configuration is still in agreement with the above results. Including glazing surfaces on the north facade does improve the illumination quality slightly but not enough to balance the increase in thermal load.

3.1.4. Infiltration

Studying the impact of infiltration rates indicates that the building favors a tight construction. The thermal loads sharply increase as the building allows more and more air changes per hour. The cooling load is largely unaffected by such a change but the heating load grows to nearly ten folds the original levels over the range of the study from 0 to 1 ACH. The results of the impact of infiltration on heating and cooling loads are displayed in Figure 7.

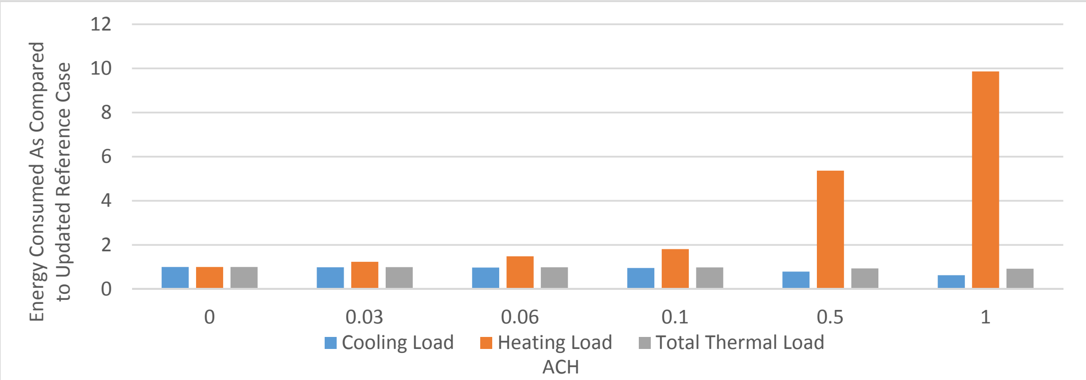


Figure 7. Changing infiltration's effect on HVAC loads as compared to updated reference case. Simulations show that the optimal model favors a tight building construction.

3.1.5. Light Reflectors

The effect of light reflectors on the availability of natural light within the building is analyzed. Results indicate that light reflectors impact mainly the depth of solar radiation penetration inside the building, as opposed to increasing the average indoor illuminance level. The difference in lighting level is most prominent in the corners and back of the growing center. This can reduce the lighting load in areas within the growing center with little access to natural light. The overall reduction of lighting load associated with these areas is about 15% as compared to the base case. Heating and cooling loads are not affected by this parameter.

3.1.6. Sky-Lighting

Gable roof. Simulations are conducted for two different sets of models: one with a north facing skylight and one with a south facing skylight with varying sizes. For the north facing skylight (Figure 8a), heating load increases drastically with increased size of skylight. This increase in heating load can be as high as 260% of that of the improved base case scenario. This is to be expected as there is minimal solar heat gain combined with increase of heat loss to the outdoor environment, due to reduced insulation level. South facing skylight (Figure 8b) significantly affects the cooling load with increasing size. The heating load, by contrast, increases only marginally throughout the iterations. For both skylight orientations, the lighting load is only marginally reduced.

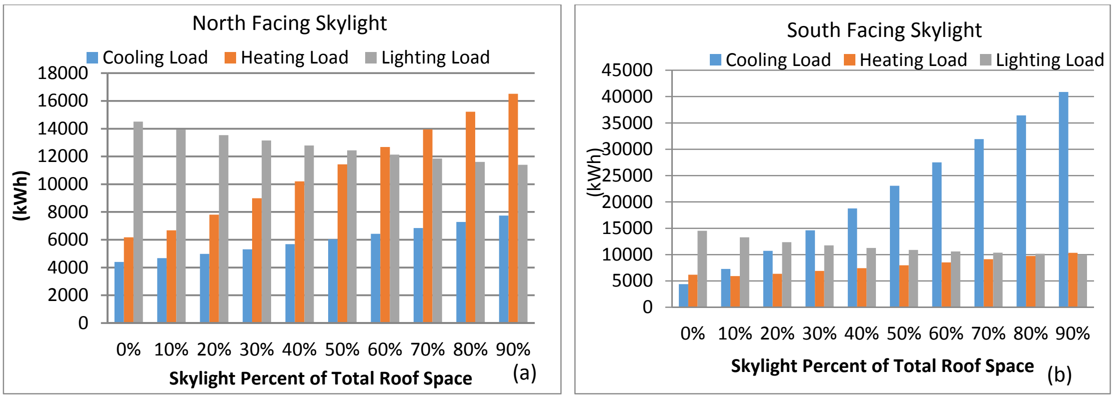


Figure 8. Impact of skylight design on thermal heating cooling and lighting loads: (**a**) north facing skylight; and (**b**) south facing skylight.

Saw-tooth roof. The results of the impact of saw-tooth roof design are shown in Figure 9. Adopting a simple saw-tooth design (without skylight) reduces the heating load by about 50%, as compared to the improved base case scenario. This is mainly due to the reduced volume and reduced height of the inner space. Cooling load is however increased by almost the same value. The combined thermal load of the saw-tooth roof is somewhat higher than the reference case (by about 15%). Adding sky-lights to the saw-tooth roof improves mostly the lighting load, but results in increased heating load as compared to the two other scenarios (reference case and saw-tooth). Figure 9 presents the total energy consumption assuming a low efficiency HVAC system of COP 1. The impact of improving the mechanical system efficiency is presented below.

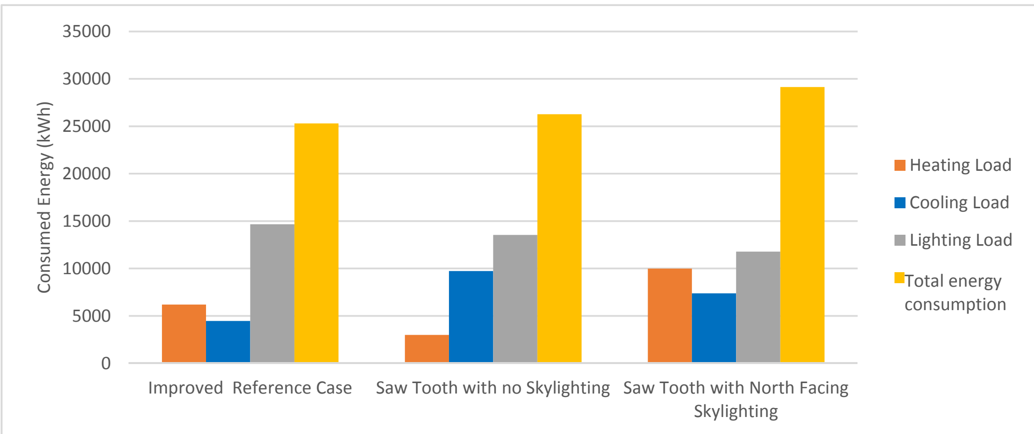


Figure 9. Effects on the energy performance of saw-tooth roof design with and without sky-lighting.

3.1.7. Window Overhang

Changing the width of the window overhang impacts mostly the cooling load. At an overhang width of 1.25 m, representing a ratio of 60% of the window, height cooling load is reduced by 35%. The lighting and heating loads increase at a slower rate than the cooling load is decreasing until the optimal width of 1.25 m. Beyond this value, the increase in heating and lighting load overtake the decrease in cooling load. The total load is however not significantly affected (less than 3%).

3.1.8. PCM in Envelope

Implementing phase change materials to the building envelope design (facades and roof areas) leads to some reduction in the building thermal load. This impact is most prominent on the cooling load, resulting in a reduction of 25% in cooling requirements. The heating load shows change but not as drastic as for the cooling load (about 10%). The total combined thermal load is reduced by about 25%.

3.2. Optimized Design

An optimized model is designed with the best case scenarios for each of the building envelope design parameters investigated in this study. The optimal values of the studied parameters are listed in Table 5.

Table 5. Summary of Optimized Design Parameters.

Parameter	Value
Insulation	Roof: 6.69 m^2·K/W; Wall: 4.23 m^2·K/W
Window Assembly	Triple Glazed, Low-e, High SHGC, Argon Filled
Window Location	Only on South Facade
Window Size	30% of Facade area and centered
Overhang width	1.25 m
Light Shelf width	2 m, located directly under window
Sky-Light Size	No Sky-lights
PCM	Located in Exterior Walls and Roof Design
PV area	Full south facing roof surface
Roof Shape	40° Roof Slope
Infiltration Rate	0.03 ACH

Figure 10 shows the simulated results of the optimized building envelope design, as compared to the base case. The optimized model performs more efficiently at all functions. Heating and cooling loads are significantly reduced. The lighting load is moderately reduced. The combined thermal load can be reduced by up to 65% while the total energy consumption, assuming an HVAC system of COP of 1 is reduced by approximately 40% relative to the base case.

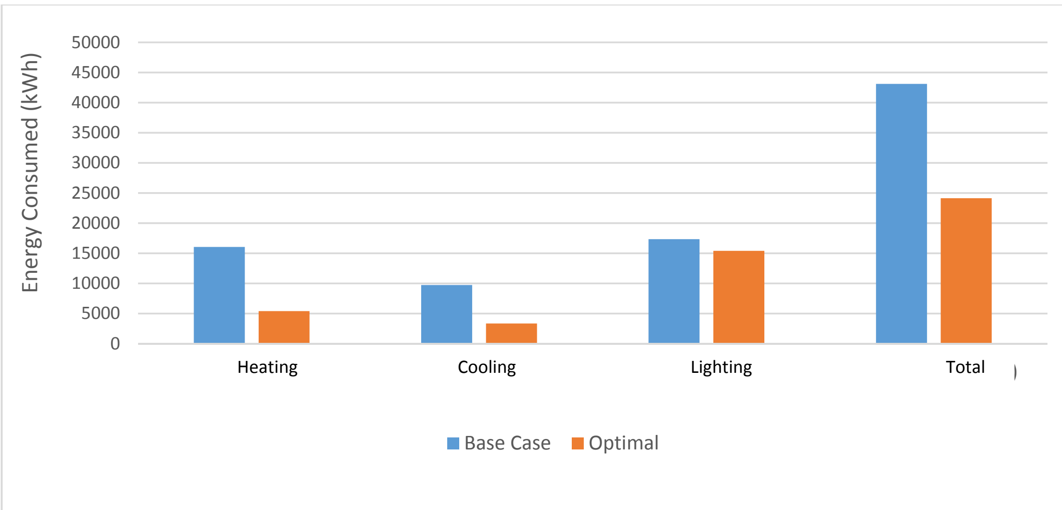


Figure 10. Energy performance of the optimized building envelope model, and its comparison to the base case.

3.3. Building Envelope Effects at High Level Lighting Scenario

In this section, an increase of lighting intensity is applied to the low-lighting optimal design presented above, and the effect of this change on the building thermal loads is analyzed. The results show that, in addition to the increase in the electricity demand for the artificial lighting, cooling load increases substantially. Parameters analyzed for the high level lighting and their impact are presented below.

Insulation. With the increased lighting load, the simulations indicate that substantially reduced insulation can assist in reducing the excess cooling load resulting from lighting equipment. The energy performance of the building increases as the insulation values decrease. In the low level lighting optimized model (OLL), the thermal resistance values are 6.69 $m^2 \cdot K/W$ for the roof and 4.23 $m^2 \cdot K/W$ for the walls. Assuming the same values as the base case (2.64 and 1.74 $m^2 \cdot K/W$, respectively), the overall energy for heating and cooling is reduced by some 17% (cooling can be reduced by 20%), as compared to the OLL case, but with high lighting load.

Glazing assembly and size. The glazing assemblies that reduce the energy consumed within the growing center with high lighting level are the double paned clear and the double paned, low-e, low SHGC and argon filled assemblies. Both assemblies are characterized by higher conductance value which allow for heat exchange between the growing center and the exterior. The low heat gain coefficient (SHGC) further assists in reducing the overheating of the building.

Re-simulation of glazing size on each facade separately and on all facades together indicates that the best configuration combines windows on south and north facades. A configuration that implements 70% glazing on south facade and 80% on north facade allows reducing the cooling energy consumption at high lighting level by 60%, the lighting consumption by 25% and the overall energy consumption by 30%, as compared to the OLL. Heating load, however, increases by about 10%.

Infiltration. Similar to the OLL model, the optimal infiltration rate of the growing center with high level lighting (HL) is kept as tight as possible. This is consistent with CO_2 enrichment strategies, since in order to properly enrich the growing environment, infiltration or natural ventilation should be kept minimal.

Phase Change Material. The use of this smart building material shows promise in passively reducing the thermal load of the building. By including PCMs in the building envelope, an overall reduction of 15% is noticed in the heating and cooling loads. The impact on reduction in load is less significant as compared to the scenario with low lighting level (which is about 25%).

Summary of the optimized high level lighting scenario (OHL). Applying increased lighting requirements to the OLL design introduces a substantial increase in internal heat gain which results in a large increase in cooling load. Reverting to the base case insulation level, in both roof and walls, as well as to the base case glazing assembly (double clear window assemblies) reduces energy consumption for cooling by about 20%, relative to the OLL design. In addition, increasing glazing size (70% on south facade, 80% on north) can further reduce the overall energy consumption by about 30%. The comparison between the optimal high level lighting scenario (OHL) and the OLL, together with their potential of electricity generation (studied below) is presented in Figure 11.

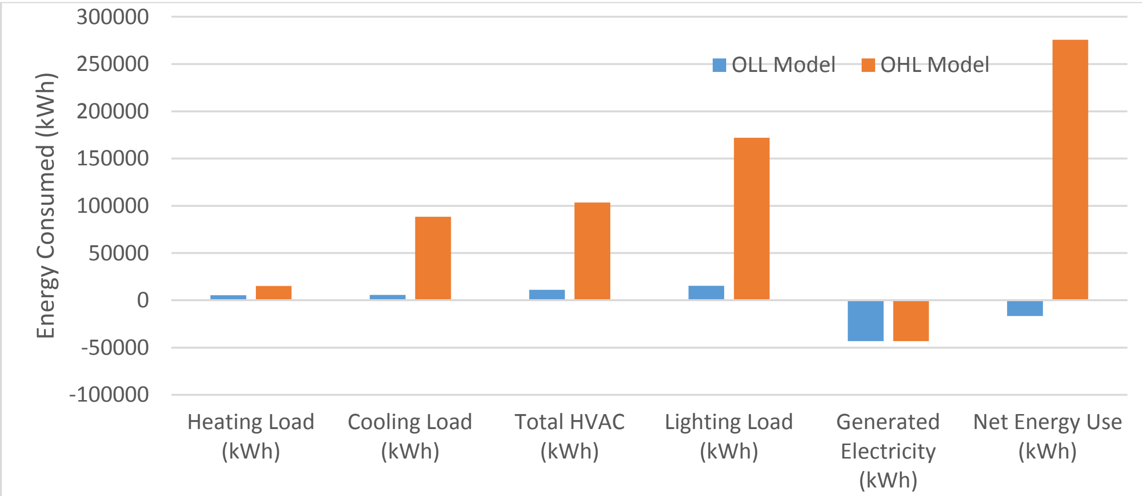


Figure 11. Comparison between the energy performance of the OLL and OHL. The OLL model achieves net-positive energy status with the use of rooftop photovoltaics. The OHL only offsets 16% of its total energy use. HVAC COP of 1.

3.4. Impact of Renewable Energy Generation and Improved Mechanical System

Roof Slope for Photo-Voltaic (PV) Optimization. The three different roofing designs—gable roof with two different tilt angles 10° and 40°, and a saw-tooth roof design with a tilt angle of 50°—described and analyzed above are simulated to determine optimal design scenario to maximize the electricity generation potential form PV integrated systems, for Edmonton region. The case in which photovoltaics are mounted over the south facing slope of the 40° gable roof generates the highest amount of electricity. This is due to the fact that the tilt angle of the roof is within the optimal range for the Edmonton's latitude. This is combined with the largest south facing roof surface area that can accommodate a large PV system. The saw-tooth design produces however the most amount of electricity per square meter, largely due to the increased tilt angle of 50° which is near optimal. The PV roof area in the saw-tooth configuration is reduced due to the distance allowed between each saw-tooth unit, to eliminate shading (see Figure 1).

Using rooftop photovoltaics with efficiency of 18% in each of the optimized models shows that the low level lighting model (OLL) can achieve net-positive energy status. The OHL model, however, can only offset 16% of the energy requirements with the use of rooftop photovoltaics. This is assuming an HVAC with COP of 1. Better performance is demonstrated below, with more efficient HVAC systems.

Mechanical systems. This section presents a rough estimate of the impact of increasing the efficiency of the HVAC system on the energy performance of the OHL (optimized high level lighting) model. Figure 12 presents energy consumption and generation of scenarios of the OHL with HVAC systems of varying COP. With the introduction of more efficient heat pumps, energy consumption for cooling loads can be significantly reduced. For instance, the annual cooling energy use is reduced by 80% with COP of 5. It can be noticed that while the total energy consumption is significantly affected by increasing the COP between 1 and 3 (by up to 30%), the reduction becomes relatively marginal above this value. This is mainly due to energy consumption by lighting system, which is not affected by this change, and is the largest contributor of the building's high energy usage.

Solid Oxide Fuel Cells (SOFC). The OHL growing center requires a large amount of CO_2 in addition to the substantial amount of electricity to meet the lighting and cooling loads. SOFC can therefore offer a promising application to generate both electricity and CO_2 in order to bring this building to an energy positive status, while providing a high level of CO_2 to promote intense growing of crops.

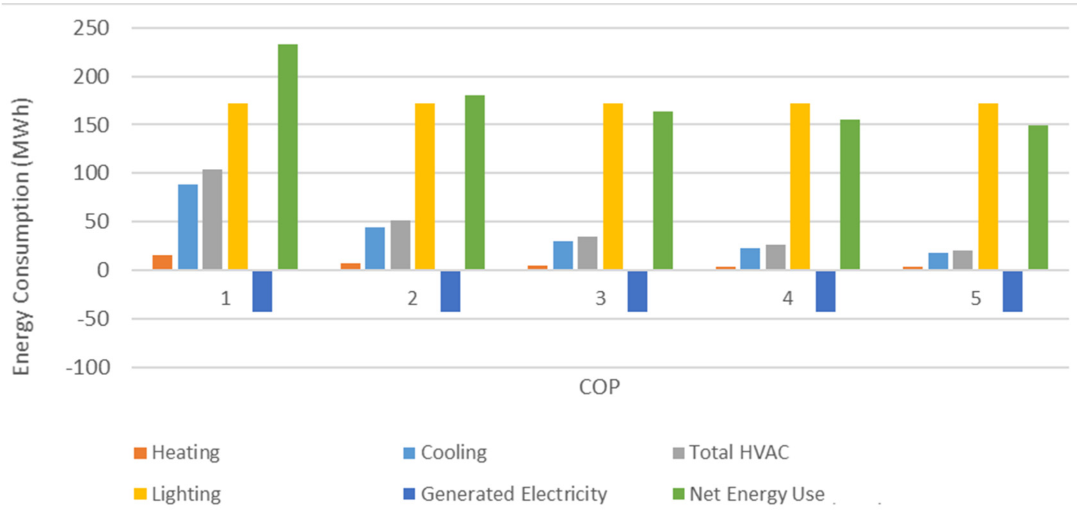


Figure 12. Energy consumption and generation of scenarios of the OHL with various HVAC COP.

To determine the amount of fuel cells necessary to achieve a net-zero energy status in the OHL model, the results of the mechanical system optimization and use of more efficient heat pumps are used. The graph in Figure 12 displays the amount of electricity the SOFC system needs to generate in order to achieve net-zero energy status, taking into account the contribution of PV systems electricity generation. Depending on the heat pump efficiency, the amount needed to be generated by the fuel cells ranges from around 232.5 MWh to 150 MWh annually. These values are in the range of expected output of such a system. This implies that the inclusion of solid oxide fuel cells into the OHL building design allows achieving energy self-sufficiency status. The OLL model, by comparison, has the ability to maintain a net-positive energy scenario without the use of SOFCs.

4. Discussion and Concluding Remarks

This paper presents a parametric investigation to optimize energy performance of a controlled indoor agriculture center, termed Growing Center. The main parameters studied relate to the building envelope components, under two levels of artificial lighting scenarios, a minimal level for normal growth, and high level lighting associated with CO_2 enriched environment. In addition to building envelope design, improvements of mechanical system, roof integrated PV designs and the potential use of fuel cells are explored.

The study indicates that, under minimal lighting level, the increase in energy efficiency of the building envelope can reduce the thermal load by up to 65% as compared to the base model. With the integration of PV systems in the roof, this model (termed OLL) can achieve a net-positive energy status.

The intensification of lighting requirements leads, in addition to increase in energy required for the artificial lighting, to a significant increase in cooling load. This is due to substantial internal heat gain associated with the increase in artificial lighting. The results indicate that reverting to the base case insulation and glazing assembly can reduce the cooling load by about 20% as compared to the case with optimal low level lighting envelope (OLL). Increasing the size of glazing, both on south and north facades (70% of south facade and 80% of north facade), leads to a further reduction of total energy consumption by 30%. The excess internal heat gain can be potentially recovered and utilized in other applications, including regulation of the indoor conditions of adjacent buildings, either through a forced-air system or as a thermal heat storage, or combination of both strategies. It is important to bear in mind, however, that, while lighting level can be controlled by the user, the building structure is unchangeable. Unless lighting level is prescribed, maintaining a high performance building envelope may, therefore, be a preferred option, even under higher lighting level scenarios, particularly when heat recovery is available.

In both optimized high level lighting (OHL) and low level (OLL) scenarios, the use of roof integrated photovoltaic systems for electricity generation is effective in improving the overall energy balance. In the low level lighting model, a net-positive energy scenario can be achieved by the addition of PV panels on the south facing roof. For the OHL, 17% of the energy requirement can be offset through the integration of PV system on the south facing roof. Solid oxide fuel cells are discussed as an alternative method to generate electricity for the OHL model, while providing potential to capture CO_2 required for intensified agriculture production.

Concluding Remarks

The research presented in this paper highlights promising options for the development of low-energy indoor growing environment for more resilient and sustainable community, in extreme cold climate. The optimal low lighting, growing center model achieved in this paper shows that when designing for a single layer of plant growth under normal growth requirement of plants, a net-positive energy scenario is feasible with the addition of roof integrated photovoltaic systems. An optimized building envelope design can considerably improve energy performance by comparison to conventional standard design. In a scenario of high level lighting, the overall thermal resistance of the building envelope has reduced significance, as compared to the magnitude of internal heat gain associated with intensified artificial lighting. In this case, conceiving methods of capture and utilization of this excess heat gain presents numerous benefits. In addition, for the high intensity lighting scenario, fuel cells present promising technology to offset high energy demand while assisting in CO_2 enrichment. This can be a topic for further research in this and other high energy applications.

The future development of indoor controlled agriculture is a promising tool to address anticipated global environmental concerns. It is acknowledged however that energy performance is not the main criterion in evaluating the performance of an indoor agriculture facility. The main concern in the design of these types of buildings is maximizing the quality and quantity of agricultural produce. Energy consumption however can be a substantial cost component, as demonstrated in this study, and attempts at reducing this energy together with increasing agricultural productivity can contribute toward establishing sustainable, resilient communities.

Although the study was done on a specific design in specific locations, the results are generally applicable to other designs in northern climates and the methodology can be applied to envelope optimization under any climatic and design conditions.

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