INVESTIGATION OF DESIGN STRATEGIES FOR IMPROVED ENERGY PERFORMANCE IN SUPERMARKETS: A CASE STUDY

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1.0 ABSTRACT

Supermarkets consume large amounts of energy to maintain a comfortable indoor temperature and to preserve merchandise. In an attempt to improve the energy efficiency of this building type, this paper investigates the effect of various design strategies on the energy performance of a hypothetical supermarket. The parameters whose effects are analyzed include: geometry of the envelope, wall and window design, as well as the use of Phase Change Materials (PCMs), photovoltaics and green roofs. EnergyPlus is employed to simulate energy consumption using weather data from Calgary, Alberta (52ºN).

Results indicate that an optimal design can be created for a supermarket that can significantly increase the energy performance of these high-energy intensity buildings by 30%. With the optimization of the building envelope design and the addition of smart materials and renewable energy generation, a near net-zero energy building is feasible.

2.0 INTRODUCTION

In Canada, building sector accounts for 30% of total end use energy consumption (Behidj, 2013). Of that, commercial buildings account for 44% (Behidj, 2013). The Canadian government has committed to reducing the national emission levels by 17%, from 736 Mt of greenhouse gas (GHG) emissions to 611 Mt, in a span of 15 years (Environment Canada, 2014). In order to achieve this goal, all sectors of end-use energy consumers need to commit to better practices in energy conservation and sustainability.

Supermarkets maintain the highest energy intensity value of all types of buildings (Hachem et al, 2015), which is a measurement of energy consumption per unit floor space (Office of Energy Efficiency 2012). This is due to the buildings reliance on inefficient refrigeration units to maintain safe food temperatures, which release large amounts of waste heat, increasing thus the overall cooling load (Fricke, 2013). Other contributing factors also include the use of inefficient equipment and lighting systems.

In recent years, some research and design guidelines have been proposed to help reduce the energy consumption and associated GHG emissions of supermarkets. The Canadian government has compiled resources and tools to help supermarkets benchmark their energy performance (National Resources Canada, 2015). ASHRAE recently published design recommendations for supermarkets to increase energy savings (Torcellini, 2015). The study presented in this paper aims at developing design guidelines of supermarkets for reduced energy consumption and GHG emissions to add to these resources. The key parameters whose effects are investigated consist of: the use of LED lighting, optimizing the building envelope through ideal insulation level, glazing surface and ceiling height, in addition to the utilization of advanced materials and technologies including phase change materials, green roofs and photovoltaic (PV) panels.

These design parameters are systematically iterated and compared to a reference case, which conforms to industry standards and the Canadian building codes for low-rise commercial buildings. The study employs EnergyPlus (EnergyPlus 8.4.0, 2015) to simulate overall energy consumption.

3.0 METHODOLOGY

The first phase of research is to develop a base case model serving as control for the comparative study. This base case is created using the American Society of Heating, Refrigeration and Air-Conditioning Engineer's (ASHRAE, 2011) standards recommended building codes for supermarkets in Calgary's climate zone (Crowther, 2004) and in compliance with the Canadian and Alberta building codes for low-rise commercial buildings (Alberta, 2009). The insulation values for the ceiling, walls and windows are based on ASHRAE's recommendation as well as the design specifications for the ceiling (insulation entirely above deck) and walls (light-weight continuously insulated) to create the base model (Deru, 2011). The next phase investigates various design strategies to determine which scenarios result in a higher energy - performing supermarket. Energy performance refers in this study to the energy consumed versus the energy generated onsite, through the use of photovoltaics.

EnergyPlus is employed to simulate the building's energy requirements and loads through a typical year in Calgary (52 °N) using weather data from this region. A total of 60 cases are designed to simulate the effect of various parameters on energy consumption of the supermarket. These parameters and cases are presented in Table 1.

Parametric Investigation

The parametric investigation focused primary on improving the building envelope design, and verifying whether this improved envelope has a significant impact on the overall energy consumption. Prior to this systematic analysis of the building envelope, the base case energy consumption is analyzed according to the various end uses (see section 4.1 for details). Inspecting the energy consumption of the base case indicates that artificial lighting consumes a significant amount of energy and result in equally significant internal heat gain (Ahn, 2015). Therefore, lighting was the only aspect that was investigated beside the building envelope, in this study. Future research will explore other avenues for reducing energy consumption of refrigeration and mechanical systems.

Building envelope parameters consist of: modification of the insulation level from those recommended by the building code (Fokaides 2014), optimizing the geometry of the building envelope (specifically ceiling height) and window design (Hachem et al, 2011), employing smart material such as phase change material

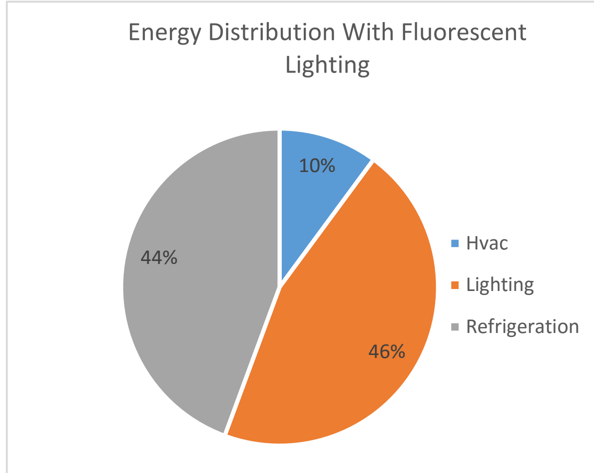

Figure 1: Energy Distribution with Fluorescent Lighting. Total End use is approximately 2150 GJ of Energy Annually. Lighting is 46% of total consumption

(Muruganantham, 2010), and green roof construction, and exploring the potential electricity generation of the building from PV systems. Table 1 summarizes each of those parameters and their ranges.

3.1 Lighting Design

The end-use energy consumption of the base case supermarket shows that lighting accounts for a significant amount of energy consumption. The original model assumes fluorescent light tubes. The energy consumption associated with these types of lights constitutes 46% of the total energy consumed annually (Figure 1). Changing to high efficiency LED bulbs for the lighting requirements is the first parameter explored.

3.2 Envelope design

Parameters	Cases	Cases							
		1	LED	Insulation 1 - 5	Glazing 1 - 5	Ceiling 1 - 2	PCM 1 - 3	Green Roof 1 - 7	PV 1 - 6
Phase Change Material	Three Examples								
Insulation R Values	100%								
	50% - 300%								
Ceiling Height	4.27 m								
	Modifying Ceiling Height (3.27 m - 5.27 m)								
Windows	Double Glazed Argon Filled								
	Triple Glazed Argon Filled								
Glazing Surface	Changing Glazing Surface 0% - 50%								
Interior Lights	Incandescent								
	LED								
Green Roof	Changing Green Roof Composition (Depth and LAI)								
Photovoltaics	Photovoltaic Surfaces and Design								

Table 1: Table of parameters that were simulated in this study. Orange blocks represent parameters investigated in each case. The incremental changes associated with each parameter being investigated will be stated in the graphs presented later in this paper.

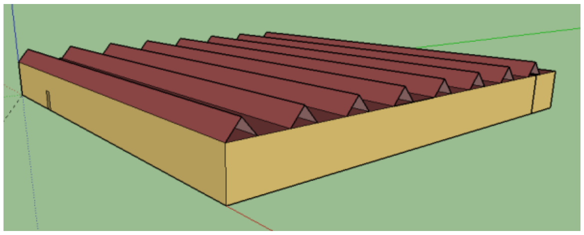

Figure 2: Supermarket design with Saw-Tooth structures for increased solar performance (SketchUp Model)

Finding the optimal insulation levels for the supermarket is the next parameter to be investigated. The insulation (Insl) level are modified from those prescribed by the code (1.7 m^2.K/W for exterior walls and 2.6 m^2.K/W for roof). The explored insulation values range from 50% to 300% of the code value.

The ceiling height (Cg) of the base case is 4.3m. This height is modified to 3.3m and again to 5.3m to investigate the effect of this parameter on energy consumption within the supermarket.

The effect of glazing (Glg) area is also analyzed. Glazing surfaces are assumed on the south façade, for all cases, and are composed of triple clear glazed, argon filled windows. The base case has a window to wall ratio of 20%. The window to wall ratio of the studied cases range from 0% to 50% of the south façade (see Table 1).

3.3 Phase Change Material

Phase change material (PCM) has been shown to be an effective smart material in passive temperature regulation (Tabares-Valasco, 2012). Due to its ability to store and release thermal energy throughout its phase cycle, the study explores the implementation of PCMs in the building envelope. This material is used to help lower cooling costs and to shift the peak interior temperature by a few hours. Three types of PCMs are investigated. The first is a material supplied by EnergyPlus Database. It consists of micro-encapsulated PCM with 30% paraffin wax in gypsum board (PCM 1). The second type of PCM is an organic material called Dodeconal (PCM 2) (Seong, 2013). This type is commercially available, as macro-encapsulated pouches that can be inserted behind or above drywall. The last is a commercially branded micro-encapsulated product similar to PCM 1 provided by Dupont Energain (PCM 3) (Tabares-Velasco, 2012).

3.6 Green Roof

Different compositions of green roofs are investigated for their effects on energy consumption of the supermarket (Sailor, 2012). Varying soil depths and leaf area index (LAI; a variable which represents density of foliage) are investigated in this research. The following parameters are investigated and assigned to cases as followed:

Table 1: Green Roof Scenarios.

Green Roof Scenarios	Soil Depth, m	Leah Area Index
GR 1	0.15	2
GR 2	0.15	0.5
GR 3	0.30	0.5
GR 4	0.30	2
GR 5	0.30	5
GR 6	0.50	0.5

3.7 Building Integrated PV systems

The integration of PV systems is explored to reduce the energy consumed from non-renewable energy sources. Various design considerations are investigated is to explore the potential of developing a model which achieves Net-Zero Energy status. Photovoltaics were assumed to have 18% efficiency for this study. The cases that were studied are as followed:

Table 2: Building Integrated Photovoltaic Scenarios

PV Scenarios	Notes
PV 1	On South Facade
PV 2	On South, East and West (SEW) Facades
PV 3	On SEW Facades and Flat Roof
PV 4	On SEW Facades and Saw-Tooth Roof (See Figure 2)
PV 5	Only on Flat Roof
PV 6	Only on Saw-Tooth Roof

4.0 SIMULATION

This study comprises a series of systematic simulations. The results of each simulation is analyzed and compared to the base case. EnergyPlus is employed to carry out these simulations. This energy simulation tool allows control over individual processes and designs within the reference building as well as an extensive array of output options, making it a good candidate for energy modeling. Below is a summary of the base case scenario.

4.1 Base Case

In order to assess the effects of each design parameter on the overall performance, a control case is created based on the design of typical supermarkets in Calgary's climate zone.

The building area is 45 m x 45 m and 4.3m high. The south façade contains the doorway and a glazing surface of 20% of the wall. The windows are low-e triple glazed argon filled. The building envelope is designed to conform to the Canadian building code for low-rise residential buildings as well as to ASHRAE recommendations for supermarkets. An above deck roof insulation of about 2.6 m^2K/W, is assumed. The exterior walls are designed with continuous insulation of 1.7 m^2K/W. The simulations assume two thermal zones, the sales floor and the back room; both of which have their specific schedules of operation (e.g. occupation, lights, etc.). The supermarket's HVAC system is controlled by DX coils; An electric DX coil for cooling and a natural gas DX coil for heating. In order to maintain safe food temperatures, the heating and cooling setpoints are 20 and 24 °C, respectively.

A number of refrigeration units are assumed to simulate the amount of electrical demand and waste heat associated with this equipment. In total, there are 7 refrigeration units; a self-contained refrigeration display, two open case refrigeration displays for meat, one open multi-deck refrigeration display for dairy, an open well for ice-cream display, a closed door frozen food case and a walk-in freezer.

The lighting system employs fluorescent light tubes and is on a schedule tied to working and store hours.

5.0 ANALYSIS

The various parameters of study are systematically analyzed, to estimate the impact of each component on the building performance.

5.1 Lighting Design

LED lights reduces the total energy consumed by 20% and the energy consumed by the lights had dropped from 46% to 27% (FIGURE 3). Through the systematic analysis of each parameter analyzed in this study, no single change had reduced the energy consumed by as much as this design feature. In the cases in which fluorescent lighting are used, some of the following results are drastically different. For example, while investigating the effects of changing the insulation values from code, the optimal value of insulation is considerably lower. Thus, the control case used to compare the effects of changing the insulation values and glazing surface employs LED lights as the LED lighting contributes significanlty less to the internal heat gain (FIGURE 4). This base case with LED lighting is denoted as Base Case LED in all relevant charts.

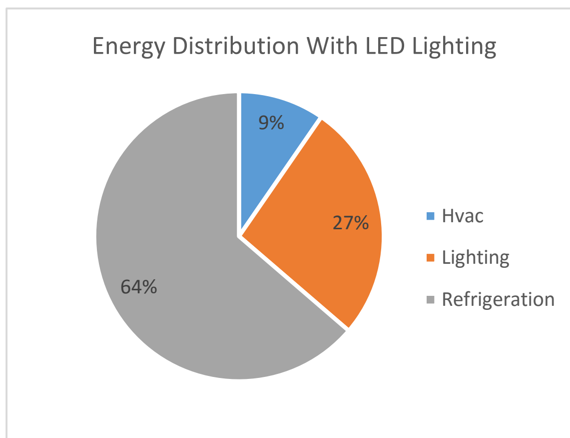

Figure 3: Energy Distribution with LED lighting. Total End Use is approximately 1700 GJ energy annually. Lighting has dropped to 25% of total consumption.

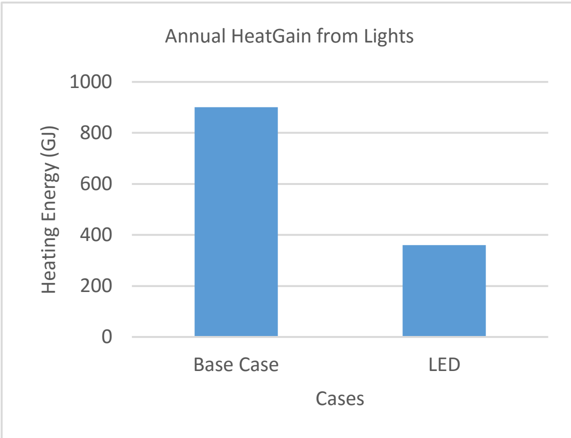

Figure 4: Heat Gain from Lighting Annually. Base case uses fluorescent tubing lights which are associated with higher levels of radiant heat.

5.2 Effect of Insulation

Increasing the insulation value to 200% (3.3 m^2K/W for the exterior walls and 5 m^2K/W for the roof) of the base value (Insl 4, in Figure 5), the total energy used for heating and cooling the building is at its lowest point. Beyond this point, the total energy starts to increase as the HVAC system requires more energy to cool the building (FIGURE 5). As mentioned above, the base case in this comparative study is that which uses LED lights. With less efficient lighting, there exists a large amount of internal heat gain in which the optimal insulation values are of 80%.

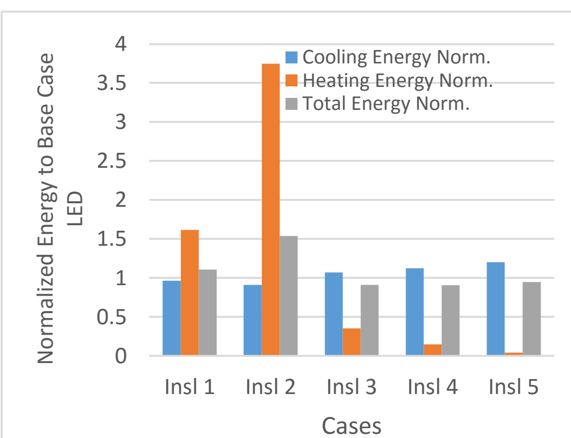

Figure 5*: Effect on Energy Consumption by Modifying the Insulation Values from Code. Insl 1: 80%; Insl 2: 50%; Insl 3: 150%; Insl 4: 200%; Insl 5: 300%*

5.3 Effect of Ceiling Height

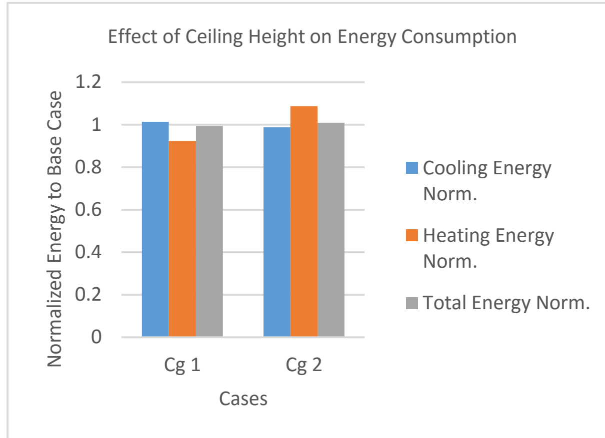

Figure 6: Effect on Energy Consumption by Changing the Ceiling Height. Base Case has ceiling height of 4.27 m; Cg 1 has ceiling height of 5.27 m; Cg 2 has ceiling height of 3.27 m

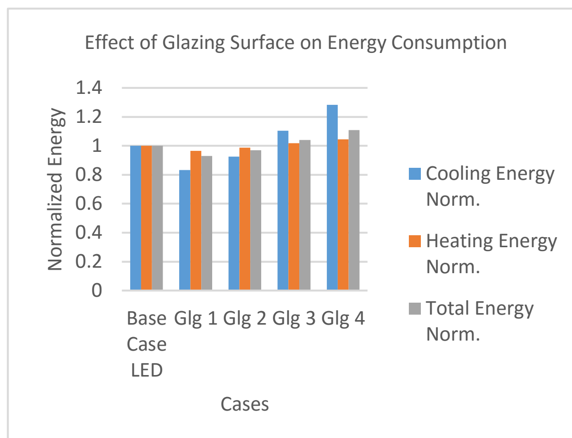

Figure 7: Effect on Energy Consumption by Changing the Size of Glazing Surface on South Facade. All cases use LED lighting. 20%, 0%, 10%, 30% and 50% glazing surfaces in cases, respectively.

Investigation of the ceiling height's effect on energy consumption produced marginal results (FIGURE 6). This parameter was looked at due to the fact that most supermarkets have high ceilings which results in a larger volume of air to be conditioned when it may not be needed. The results show that the case in which the ceiling was raised by a meter (Cg 1) produced slightly better than the two other cases (Base Case and Cg 2). However, this design aspect (the height of the ceiling) can increase the facades area, allowing thus a larger area for the integration of photovoltaics systems.

5.4 Glazing Surface

The best case in the investigation of glazing surface, is the case in which there are no windows in the building design (Glg 1). Compared to the base case, this scenario (Glg 1) reduces the energy consumption by approximately 10% (FIGURE 7). The case in which 50% of the south façade (Glg 4) is used for windows, an increase in 10% of HVAC energy consumption, mainly due to cooling, is recorded. The limits of energy performance through the use of windows is overall not very significant, however, with the lowest energy being consumed in the case with no glazing, it may be useful in using the south façade for electricity generation through utilization of photovoltaics rather than including windows. Further research into using various form of day-lighting techniques will illuminate the full extent of the boundaries of energy performance. Effective use of day-lighting may prove to reduce energy consumption even further.

5.5 Phase Change Material

PCM 1 is found to be the most effective in regulating temperature, in addition to reducing the energy consumption by nearly 25% (FIGURE 8). The way in which this scenario affects the energy consumed within the building matches the results found by PCM 3 (DuPont Energain) with a slight difference of about 4%.

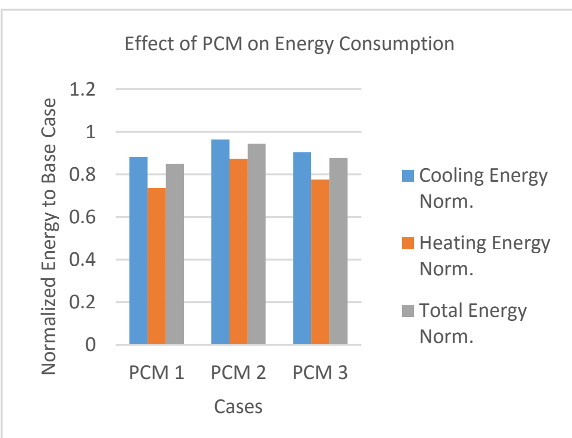

Figure 8: Effect of Energy Consumption by use of Phase Change Material. Comparing EnergyPlus Database Supplied PCM (PCM 1) to Macro-Encapsulated Dodeconal PCM (PCM 2) and Micro-Encapsulated DuPont Energain PCM (PCM 3

5.6 Green Roof

Six scenarios of green roofs are simulated and the results are compared to those of the base case. The green roof

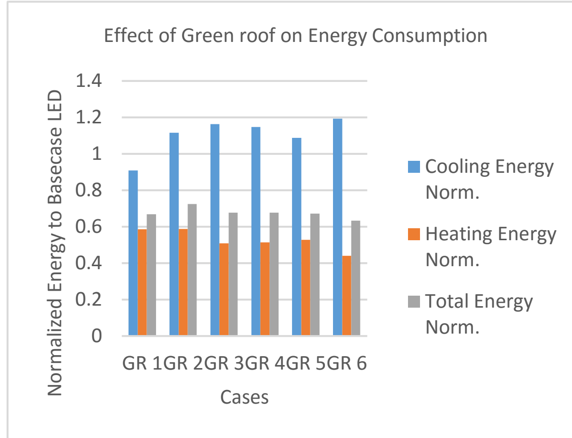

Figure 9: Effect on Energy Consumption with Different Green Roof Compositions. Refer to section 3.6 for green roof compositions being investigated.

was added to 80% of the roof surface area to account for necessary HVAC and refrigeration equipment exposed on the roof. The results indicate that the reduction of HVAC expended energy ranges from 30% to 40% with the best case being GR 6 (Soil Depth: 0.50 m; LAI: 0.5) (FIGURE 9).

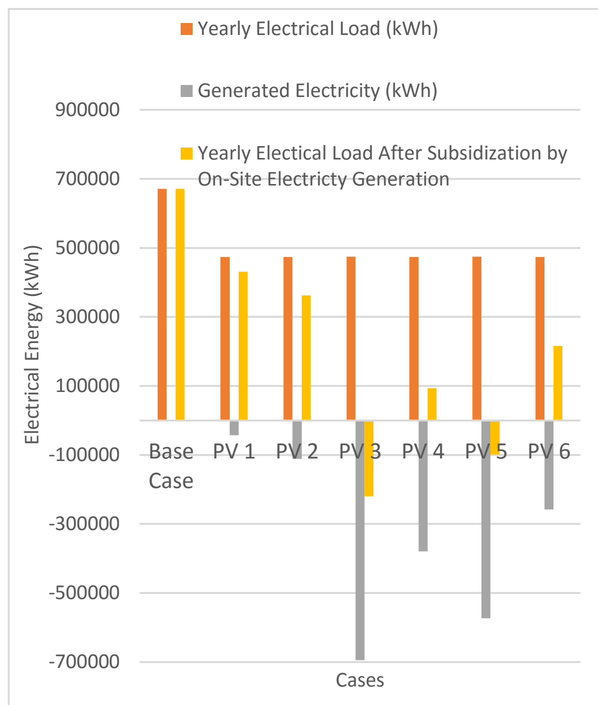

Figure 10: Effect on Energy Consumption by the Utilization of Photovoltaics. Refer to section 3.7 for implementation scenarios of the BIPV systems being investigated.

5.7 BIPV potential

The simulations show that the surface which has the potential to generate the most amount of energy is the flat roof (PV 5: BIPV only on Flat Roof). This roof scenario can generate enough electricity to satisfy all of the electrical needs within the building (FIGURE 10).

The tilted roof (sawtooth design, see Figure 2), with 50° tilt angle has the highest efficiency, on a per unit area basis, allowing an optimal incident surface for the studied location. However, due to the design limitations to minimize shadowing, the angled structure contains approximately 1/3 the amount of photovoltaic cells as the flat roof.

It should be mentioned however, that these structures provide a means to reduce snow accumulation on the panels during the winter months.

6.0 RESULTS

A total of 60 design scenarios are designed and analyzed in this study. These scenarios are meant to investigate the different combinations of all the aforementioned parameters in order to determine the best case design models for energy performance. Eight final models are created that perform significantly better than the base case supermarket.

6.1 Parametric Table of Best Case Models

The best case design models (1-8) are various combinations of the best case models for each of the different parameters analyzed in this study and summarized in Table 4 for reference. This is a simplified table and all zero entry parameters have been removed to save space.

6.2 Performance of Best Case Models

As can be observed from the best case scenarios (FIGURE 11), the total energy drawn from the grid (except for case 7 and 8, which are the best cases of energy performance in this study) is quite constant. This is mainly due to the fact that refrigeration units are running at all hour, in addition to constant light usage during working hours. This seems to be the minimum energy required by these scenarios without an optimization of the refrigeration system and the mechanical system. The effective use of optimization strategies reduce the energy consumption of the studied supermarket by approximately 30% of the original levels. The integration of PV systems, can generate on-site electricity to account for a major portion of the energy requirements within the supermarket. By including these panels on the flat roof, south, east and west façade, the supermarket generates 133% of the required energy usage which could potentially supply a significant amount of electricity to the grid. The panels on the south, east and west facades are not entirely needed to achieve net-zero energy status. The scenario with PV integrated on the complete area of a flat roof can generate 112% of the required electrical demand. The scenario with sawtooth PV panels at 50 ° tilt angle, and PV integrated in the south façade (case 8), a nearly net-zero energy status is achieved, where 85% of the electrical demand is met. This latter scenario is likely the most economical due to the fact that less panels need to be used to achieve net-zero energy goals.

Parameters	Details	Cases								
		Base Case	1	2	3	4	5	6	7	8
Phase Change Material	EnergyPlus		■	■			■		■	■
Insulation R Values	100%	■						■		
	200%		■		■					
	300%			■		■	■		■	■
Ceiling Height	4.27 m	■	■	■	■	■	■	■	■	■
Windows	Triple Glazed Argon Filled	■	■	■	■	■	■	■		
Glazing Surface	0%								■	■
	20%	■	■	■	■	■	■	■		
Interior Lights	Incandescent	■								
	LED		■	■	■	■	■	■	■	■
Green Roof	Soil Depth: 0.50 m; LAI: 0.5						■			
Photovoltaics	BIPV on SEW Facades and Flat Roof								■	
	BIPV on South Facade and Angled Roof									■

Table 4: Parametric table containing the best design cases for the supermarket.

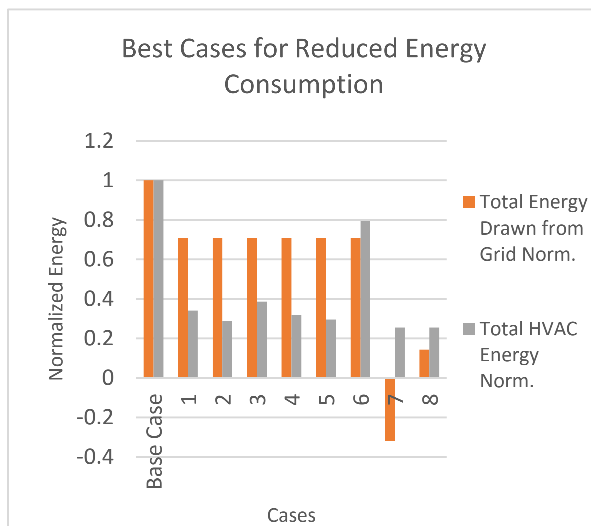

Figure 11: Energy Performance of Best Case Models. See Table 4 for case descriptions. Case 54 has 150% of required energy generated on site. Base Case model shown here for comparison is one with fluorescent lighting.

7.0 CONCLUSIONS

Various design parameters are investigated in this study to determine design strategies that increase the energy performance of a supermarket. These parameters are systematically examined and their effect on the energy performance are compared to a control case. Finally, the best case scenarios are constructed using combinations of these parameters.

A design model has been reached which reduces the overall energy consumption by more than 30%. Achieving a nearly net-zero energy status can be reached by implementing building integrated photovoltaics on the roof and south façade.

This study also points out a few opportunities for future research:

- Life-cost analysis and economic incentive of these different parameters.
- Feasibility of rooftop greenhouse, and their mutual effect on the energy performance of the supermarket and of growing potential of the greenhouse.
- Effect of advanced use of day-lighting on energy consumption (Chen 2014).
- Refrigeration and mechanical systems optimization to further reduce energy consumption.

Although this study raises a few questions for further research, it is deemed successful in determining measures to reduce the impact of these high energy intensity buildings on the environment. Incorporating better passive strategies such as optimal insulation levels and the use of phase change materials as well as changing lighting systems to use more efficient LED lighting can significantly improve the energy performance. The further addition of building integrated photovoltaic systems in the design can change these buildings from high energy consumers to net-positive energy contributors. Determining the extents as to which these parameters influence the energy performance of a supermarket is the first step in reducing the GHG emissions associated with these type of buildings within Canada.

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