DEVELOPMENT OF OPTIMIZATION METHODOLOGY FOR INCREASED ENERGY EFFICIENCY OF PV INTEGRATED CURTAIN WALL SYSTEMS

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ABSTRACT

The study presented in this paper aims at developing a methodology for energy optimization of PV integrated curtain wall systems. This proposed methodology employs a simulation-based iterative model. The space on which the effect of PV curtain wall systems is studied is a south perimeter zone of a multi-story office building. Annual simulations are conducted using EnergyPlus in conjunction with Rhinoceros 3D. The objectives of the optimization are to minimize the overall annual gained/lost heat, while maximizing solar panels' energy production. The first stage optimizes the thermal performance of a standard curtain wall, which serves as reference case. Subsequently a new BIPV/T paneling system is developed and analyzed. This paneling system utilizes the curtain walls as a flexible mounting structure. Preliminary results indicate that the new paneling system can increase the BIPV energy generation by 25% and improve overall envelope energy performance by 50%, while providing a geometrical variety in skin design.

INTRODUCTION

Canada is reshaping its urban centers to accommodate higher density developments, consequently, high-rise buildings are increasing in numbers in many Canadian cities (CTBUH, 2012). High utilization of glazed building envelopes and curtain wall (CW) systems is considered as a main feature of most new office, high-rise buildings. Although they might be aesthetically appealing, curtain wall systems are identified as the main vessel for heat loss due to higher glazing percentages (window to wall ratio) and large thermal bridges (exposed slab edges, steel framing etc.), hence, increased heating and cooling energy consumption (HPO Technical Research, 2012). The need for energy efficient curtain wall solutions – especially for mid/ high-rise buildings – is therefore becoming crucial to address, to reduce the energy consumption of such buildings (NRCan, 2010).

Traditional CW system can be designed to enhance the energy performance of the building, in terms of reducing the associated heating and cooling loads, and increasing their potential to generate electricity, employing building integrated PV systems (BIPV) (Hachem et al, 2014a). Building-Integrated Photovoltaics (BIPV) refers to an architectural approach that combines photovoltaic (PV) panels with the building construction system. This *solar curtain wall* system offers the dual functionality of BIPV, not only as a renewable energy generation function, but also as an aesthetical building envelope upgrade.

Several research has been conducted on curtain wall systems, including study of heat flow, effect of shading devices, effect of tilt and size of the device on the overall energy performance (Hwang et al, 2012), as well as the effect of some geometrical configurations (Hachem et al, 2014b). An increasing number of studies are performed to optimize BIPV integrations within office building enclosures, shading devices and light shelves (Walter K. 2015; Josco K., 2015; Valérick C., 2015), however, most studies consider BIPV as façade additives rather than a standardized layer of curtain wall assemblies. Moreover, these studies aim primarily at optimizing a specific geometry/system of building enclosure (Graham P.C., 2012), and mostly consider one or two optimization objectives rather than produce a multi-objective flexible optimization methodology.

Facade design is an aesthetical architectural task, and therefore requires a visually comprehendible methodology to achieve solar optimization, while allowing flexibility of design. Most existing simulation tools entail extended time and large computing power to reach optimal designs, and often involve manual interference to conduct the desired iterations. Numerous research have discussed the limitations, barriers and solutions of integrating simulation into the design process (Bleil de Souza and Knight, 2007; Rizos, 2007; Y. Elghazi et al, 2014; Macdonald et al, 2005). The process of creating complex geometries through geometrical modeling platforms like Computer Aided Design (CAD), then importing models to other software for energy simulations cause compatibility issues, therefore resulting in simulation errors and inaccurate results (Roudsari et al, 2013). Simulation programs that bring together geometrical modeling, conceptual massing and environmental analysis within the same platform like Vasari and Revit have limitations in modeling complex geometry (Roudsari et al, 2013). Lacking a flexible, parametric and relatively fast optimization methodology/tool lead to limited data about geometrical solar envelopes, hence, uncertainty about those designs as a practical choice. Moreover, the lack in knowledge of the impact of various designs of building envelope/curtain wall systems on building performance, restrict the flexibility in the overall building façade design.

The aim of this paper is to develop the basic stage towards an optimization methodology that explores the effect of building envelope geometries on the energy performance of CW systems. Energy performance refers, in this paper, to heating and cooling load, and PV electricity generation potential. The work presented in this paper is based on a comparative study that compares various geometries of curtain wall systems, to a base case built according to several standards.

METHODOLOGY

The design optimization of solar curtain wall systems employs several iterations of simulations. EnergyPlus (US Department of Energy: EnergyPlus, 2014) is used to run the simulations. Grasshopper3D (grasshopper3d, 2015) in conjunction with Rhinoceros are employed as the parametric platform. Honeybee (Roudsari et al, 2013) acts as a link between the Grasshopper3D/ Rhinoceros interface and the EnergyPlus simulation engine. EnergyPlus determines the amount of heating/ cooling required in the zone to maintain it at the desired conditions (see assumptions in table 2) as well as the potential electricity generation using BIPV systems.

Building façade and zone geometry are controlled within Grasshopper by numeric input data. This allows automated and relatively fast modification of parameters in an iterative process for environmental optimization. There are several space performance criteria that should be considered when designing building enclosures. However, in this study only three performance criteria (heating, cooling loads and PV electricity generation potential) are studied. The input data comprises several design parameters, while the output data consists of heating and cooling loads and electricity generation. Input and output data are outlined in Table 1.

The methodology implemented in this study is divided into two successive stages. The first stage focuses on analyzing the effect of CW geometry on the heating/ cooling loads on the office space test zone. The second stage is conducted using exhaustive parametric optimization for BIPV alternatives to determine the optimal range of configurations for potential electricity production. The two stages use EnergyPlus simulation engine. The iterative methodology is explained in the following workflow of Figure 1.

Definition of the case study

The case study analyzed in this paper on a single office room space in the mid-section of an eleven-storey high-rise office building, with a total cumulative surface area of about (15,000 m²). The study is conducted under the climatic conditions of Calgary (Canada, 52° N), representing a northern cold climate zone (ASHRAE zone 7). The thermal zoning for the office building consists of 5 zones per floor: one main office zone on each of the four major orientations and a core zone that accounts for 57% of the floor space. The studied zone is assumed to be situated on the south perimeter. Settings are described in Table 2 as follows. The base case curtain wall system is designed according to ASHRAE Standards (ASHRAE/IES Standard 90.1-2013). Optimization of the energy performance of this base case in term of, insulation, window to wall ratio (WWR) and glazing types is an ongoing process. This paper focuses on the isolated effect of external envelope geometry on the energy performance of the analyzed zone. The annual heating and cooling loads for the base case are 2923 KWh and 531 KWh respectively.

Table 1 Parametric Input/output for curtain wall systems

Design Variables			Performance Categories
Window and Glazing	Window to wall ratio (WWR), Glazing size Frame and Divider design and thermal properties	Whole Building Simulation	Annual Heating load Annual Cooling load Electricity Generation
Opaque façade parts	Thermal resistance and inertia (Assembly R value) Façade geometry (total surface area)		
Shading and Glare protection	Device geometry (dimensions, position and inclination tilt) Device type and position and configuration (internal, external or integral)		
BIPV	Photovoltaic geometry (Surface area, Inclination tilt and position)		

Table 2 Curtain Wall assumptions

Category		Assumptions		Unit
1- Outdoor environment	Calgary, City context	Incident Solar radiation G and hourly ambient air temperatures determined by EnergyPlus at each time step		
2- Test room	Dimensions	5m deep and 3.3m wide 4m high		m
	Space Area	15		m^2
3- Curtain Wall enclosure	Glazing	ASHRAE 90.1-2010 ext. window metal climate zone 7-8	U-Factor {W/m2-K} = 2.557 SHGC = 0.45 Visible Transmittance = 0.35	R-2.22
	WWR		40%	
	BIPV	Solar cell: Mono-silicone	Cells Efficiency 18%	
	Opaque area and spandrel	ASHRAE 189.1-2009 ext. wall metal climate zone 4-8	Metal Siding Wall Insulation 0.5 Inch Gypsum	R-18.18
	Floor Slabs		50mm Insulation 200mm Heavyweight Concrete Air Space + Tiles	R-17.9
3- Indoor environment	Indoor room air temperature	Heating Set point	18	°C
		Cooling Set point	24	°C
	Occupancy	ASHRAE 90.1, 2010	5	per $100m^2$
	Lighting	ASHRAE 90.1, 2010	0.9	watt/ft^2
	Infiltration		All Rooms' doors are assumed closed and all cracks are neglected	

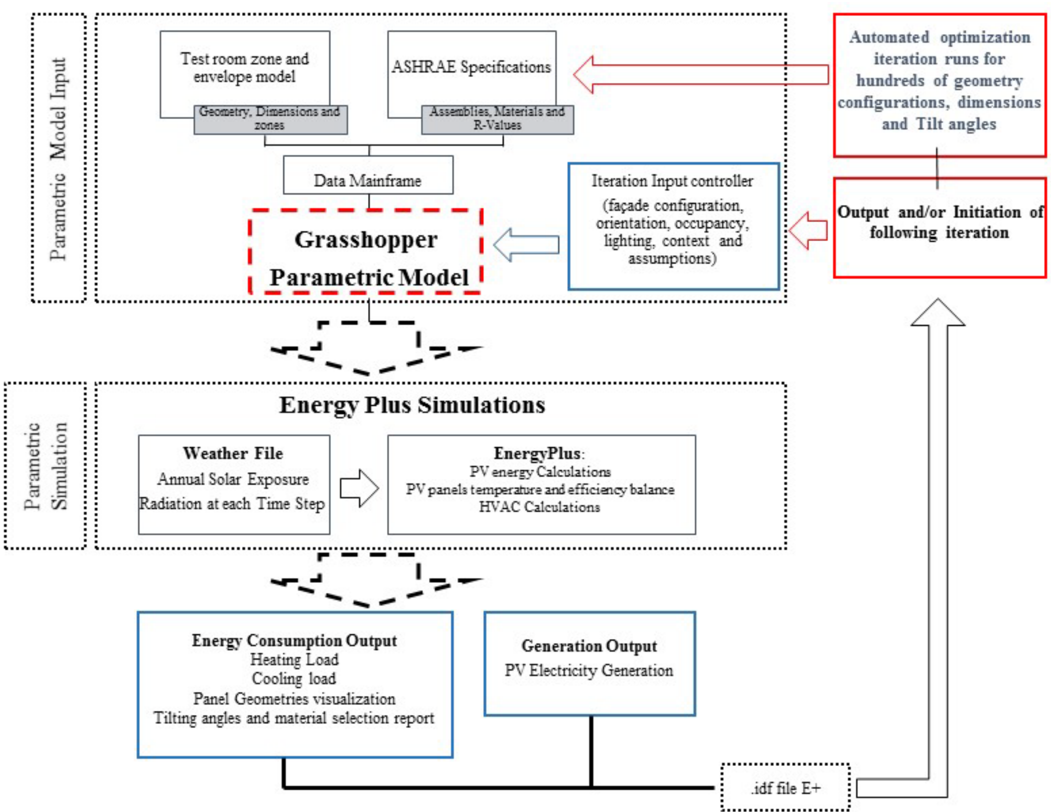


Figure 1 Methodology Parametric Workflow

Parametric Investigation

The impact of CW geometry is determined using a "Layering approach". The first stage of the investigation consists of designing the base case basic curtain wall layers (assembly and Glazing). The study focuses on analyzing the design of the external layer, as an integrated part of the facade or as an attached shading devices. This methodology helps developing new curtain wall BIPV systems that can be modular, versatile, scalable and geometrically diverse through customization. In this study, PV panels are added as a substitute to the metal siding external layer of curtain wall assembly. Thermal performance of base case serves as a reference case, against which the thermal performance of all other designs are compared

In the second stage, two sets of geometrical configurations of the envelope are tested for energy generation optimization. The design of the CW façade is altered by changing/ adding one or more of the curtain wall assembly configurations. The first set (see Table 3), considers PV systems as added shading devices (SDs). The first configuration of this set is a PV integrated horizontal shading device. The second configuration is a PV integrated vertical shading device. The third configuration is a PV integrated, combined vertical and horizontal shading device. The fourth configuration is a PV integrated, L shaped section, combining spandrel and horizontal shading device. Shading devices' depth range from 0.5m to 1.5m, orientations for vertical devices range from east/west facing to 45° SE/SW and tilt angles range from 0°(Horizontal) to 45°.

The second set is composed of three geometric configurations of PV integrated CW paneling systems, as shown in Table 4. The first configuration of this set is based on a commercially available, standard 250 W,

Table 3 PV integrated Shading Device Optimization Iterations

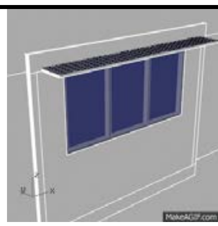
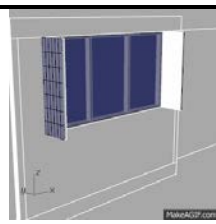
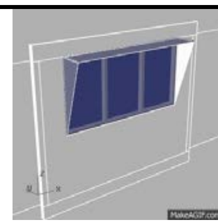
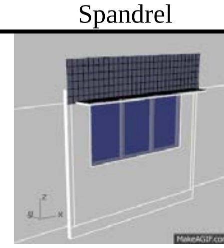
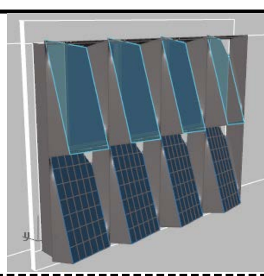
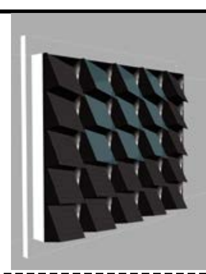
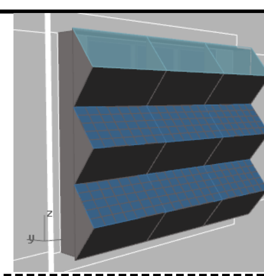
Type Variables	PV Horizontal Overhang	PV Vertical Shading Device	PV Horizontal + Vertical Shading Device	PV Horizontal Overhang + Spandrel
				
Orientation	0°S	45°SE-0°S-45°SW	30°SE-0°S-30°SW	0°S
Tilt angle	0° (Horizontal)- 45°	0°(Horizontal)	0°(Horizontal)- 45°	0°(Horizontal)- 45°
Depth	0.5 m – 1.5 m	0.5 m – 1.5 m	0.5 m – 1.5 m	0.5 m – 1.5 m
PV faces	1	2	3	2

Table 4 Curtain wall PV integrated system Optimization Iterations

Type Variables	Standard PV paneling	Square PV paneling	PV Planar Folded faces paneling
			
WWR	40%	40%	40%
Orientation	45°SE-0°S-45°SW	45°SE-0°S-45°SW	0°S
Vertical Tilt angle	90° (Vertical)- 70°	90° (Vertical)- 70°	85°- 45°
Depth	0.5 m	0.5 m	0.1 m – 0.8 m

1652mm by 994mm panels. The zone height is divided into 8 panels, the bottom four panels are PV and the top four panels are the glazing area. The second configuration integrates square 120 W, 800mm by 800mm PV panels. The zone façade is divided to a matrix of five by five square panels, the mid-upper three by three panels are the glazing area, while the rest of the panels are PV. The third configuration is a PV integrated two-sided folded plates paneling system. The zone façade is divided to three rows of folded panels, the upwards facing plates of the top row are the glazing area, the lower two rows hold the PVs on their upwards facing plates. Each iteration runs simulation based on the input data, iterations run for a pre-set range of configurations. The simulations run according to the parametric iterative method described below. In this study, for each iteration, the geometrical configuration changes based on depth, orientation and/or tilt angle input values. These geometrical changes are explained in Table 5.

SIMULATIONS

The objective of the simulations conducted in this study is to evaluate the effect of geometrical configurations on the energy performance of high-rise office buildings. These simulations employ an exhaustive recursive method as described below. A single platform and file is used for both the design model and the analysis model, allowing a smooth, integrative and efficient workflow. Four main steps take place to run an analysis using the Honeybee link (Roudsari et al, 2013); during this study all steps have been performed for each set of iterations.

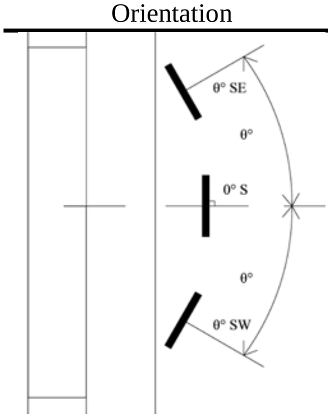
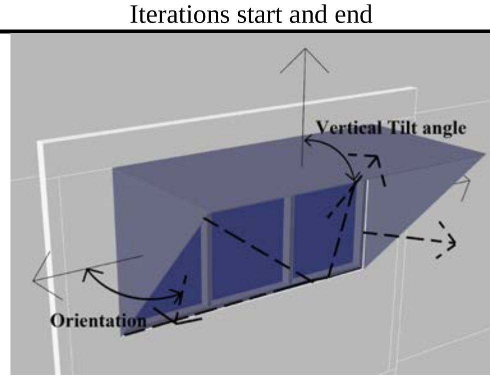
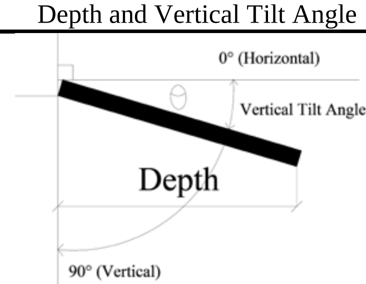
1. Preparing simulation geometry: The geometrical model is formulated in Rhinoceros interface as EnergyPlus (EP) input format by assigning EP materials and construction to surfaces, identifying thermal zones, glazing areas, and assigning test zone functional program, schedule, location, context and weather file.
2. Check the input file: Honeybee provides a dual way link by communicating with EnergyPlus to import back the simulation (as idf file). In addition, the EP files are checked in the EP interface for inputs and outputs while the geometry is visualized in Rhino/Grasshopper environment before running the simulation.
3. Run the simulation(s): Simulations are run in the EnergyPlus interface after confirming the weather file.
4. Visualize the results: Honeybee then re-imports the results of energy simulations to visualize the results with the geometries. Visualizing the results is an essential stage in the study of designing building envelopes.

EnergyPlus output is analyzed for every iteration to develop patterns of energy performance and correlation with changing inputs. Simulations are first run for the base case with defined window-to-wall area ratio of 40%, this WWR is based on ASHRAE manual and the Canadian market facts (ASHRAE 90.1 2010 and NECB 2011).To study the isolated effect of the façade only, all other walls are set as adiabatic, in the EnergyPlus simulations.

RESULTS AND ANALYSIS

Total heating/ cooling load and potential BIPV electricity generation, associated with each curtain wall geometrical configuration are computed at each time step (twice hourly). Each input change is plotted against the total heating/cooling loads for the zone. Annual simulations are run for the two sets of configurations (all seven cases). The simulation analysis shows that the heating/cooling loads of the tested curtain wall façade changes widely from the base case at different geometrical configurations. The optimization results show correlation between different geometrical cases

Table 5 Iterative change of Geometry

<table>
<tr><th>Orientation</th><th>Iterations start and end</th><th>Depth and Vertical Tilt Angle</th></tr>
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Plan View</td><td>3D view</td><td>Section View</td></tr>
</table>

studied as a function of depth, orientation and tilt angle of the curtain wall panels. These geometrical variables change the solar exposure of the façade, hence, effect the heating and cooling loads as well as potential electricity generation of the PV panels.

Analysis of heating and cooling loads

Curtainwall BIPV shading devices (SD)

1- Effect of Depth

For the first set of SDs, the annual heating and cooling loads are plotted in Figures 2, 3 against the change of depth for each of the four shading device configurations.

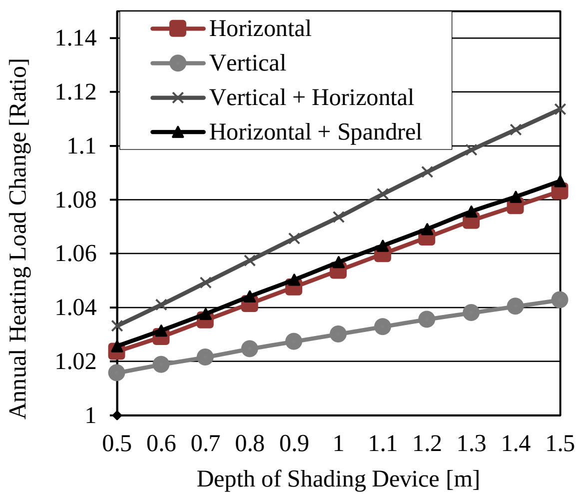


Figure 2 Effect of Device Depth on annual heating loads compared to base case

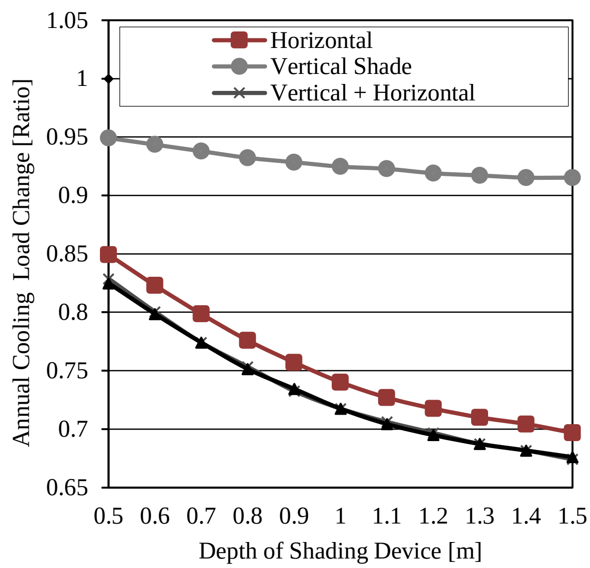


Figure 3 Effect of Device Depth on annual cooling loads compared to base case

For vertical + horizontal SD, heating load increases by up to 12% at device depth of 1.5m, while cooling load decreases by 33%, as compared to the base case.

2- Effect of Tilt

In Figures 4, 5 the tilt angle is studied against the annual heating and cooling loads respectively. For vertical + horizontal SD, heating load increases by up to 28% at SD tilt of 45°, while cooling load decreases by 40%, as compared to the base case.

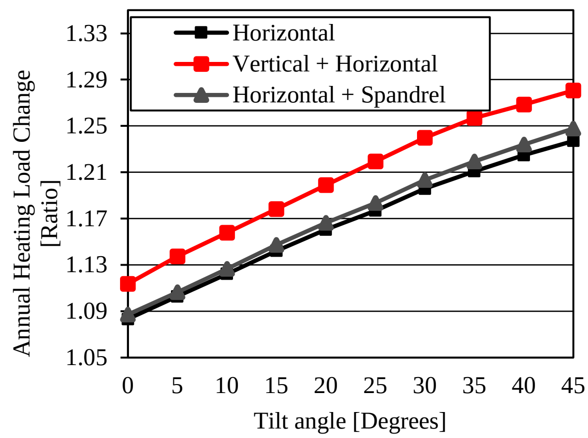


Figure 4 Effect of Device Tilt angle on annual heating loads compared to base case

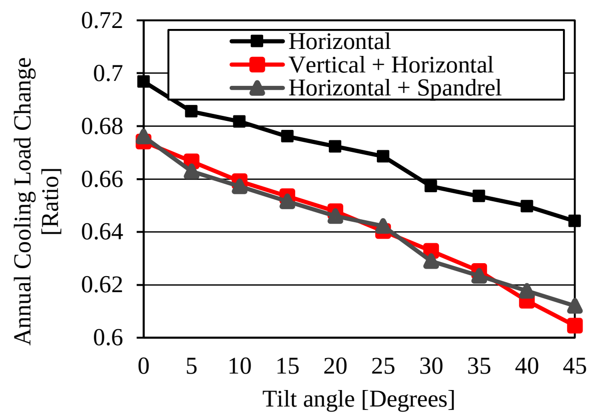


Figure 5 Effect of Device Tilt angle on annual cooling loads compared to base case

3- **Effect of** Orientation

The effect of orientation from due south, for (vertical) and (vertical + horizontal) SDs on heating and cooling loads are plotted in Figures 6, 7. Simulated devices are of a symmetric design, hence, vertical sides are rotated

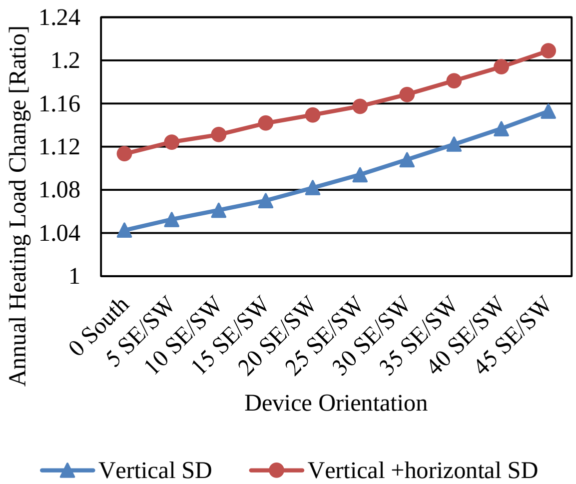


Figure 6 Effect of Device orientation on annual heating loads compared to base case

toward the glazing as illustrated in Table 5. Compared to the base case, the vertical + horizontal SD, heating load increases by up to 21% at SW/SE orientation of 45°,

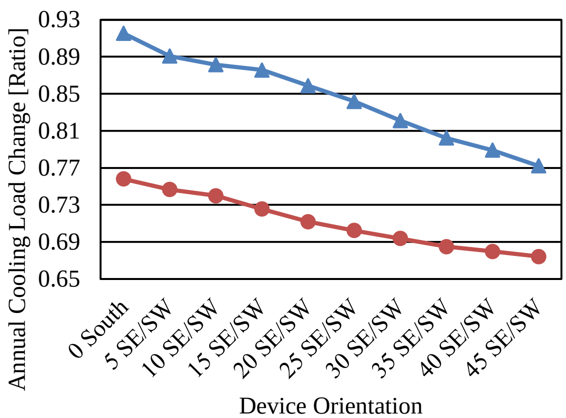


Figure 7 Effect of Device orientation on annual cooling loads compared to base case

while cooling load decreases by 33%.

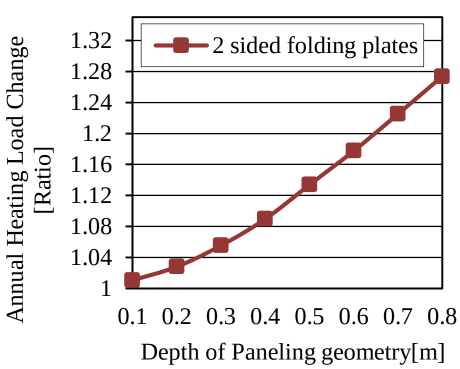
In the first four alternatives of shading devices, the heating load is found to be directly proportional to the size of the shading device. Combined devices such as (vertical + horizontal) and (horizontal + spandrel), have a bigger impact on increasing heating load and decreasing cooling load compared to single vertical or horizontal shading devices Figure 2 and Figure 3, due to the increase of the casted shade on the glazing area. However, as the heating load is initially 4 times the cooling load for Calgary weather, the overall energy performance and electricity production are the determinant for the most energy efficient solutions.

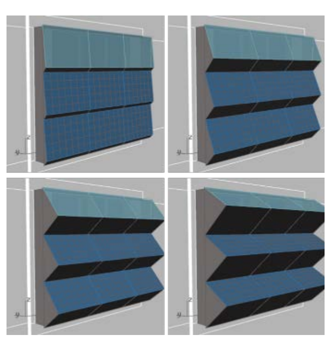
Curtain wall PV Integrated systems

The curtain wall PV integrated analysis conducted in this paper is the first stage towards creating a database of different curtain wall geometries. For each studied configuration, the analysis correlates annual heating and cooling loads to the geometrical configuration change, and compare them to the base case thermal performance.

1- Effect of Depth

For the first alternative, the two sided folded plates, the effect of panels' Depth on the heating and cooling loads is plotted in Figures 8, 9 respectively. The increase of folded panels' depth shows an increase of up to 28% in heating loads for 0.8m depth, as compared to base case, due to the self-shading which decreases the external surface temperature, therefore causing less heat to be transmitted to the conditioned space. Cooling load at a paneling depth of 0.1m is less by 10% compared to the base case, however, the load increases up to 13% at a paneling depth of 0.8m, due to the increase of solar radiation on the glazing area as its tilt angle changes toward almost a horizontal configuration.





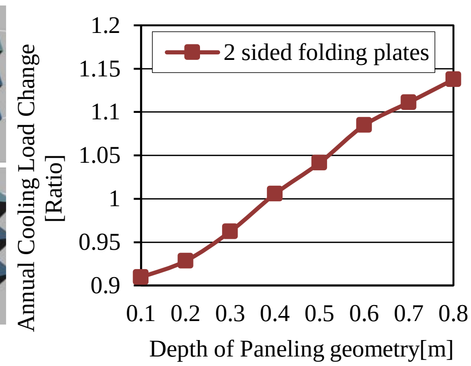


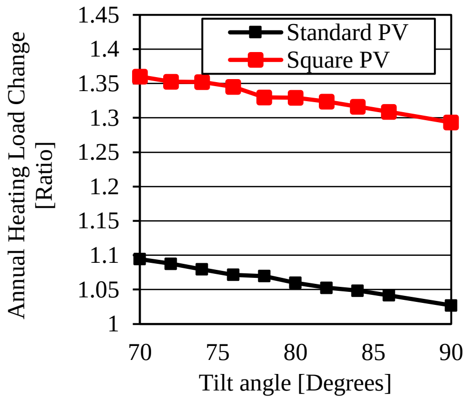
Figure 8 Effect of depth on annual heating load for folded plates PV integrated CW compared to base case

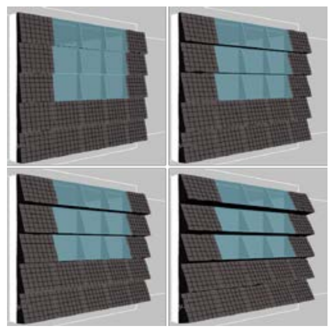
Figure 9 Effect of depth on annual cooling load for folded plates PV integrated CW compared to base case

2- Effect of Tilt

For the second and third alternatives (standard PV CW paneling and square PV CW paneling), the change in annual heating load at different studied tilt angles is plotted in Figure 10, and the change in cooling load against the same variable is plotted in Figure 11.

In case of square PV paneling, the increase in heating load starts from 29% at vertical configuration, reaches 36% at a tilt angle of 70°, in comparison to heating load of the base case. The self-shading increases the heating load and decreases the cooling load by up to 40% at a tilt angle of 70°. For standard PV paneling, tilt angle increases heating load by up to 10% at a tilt angle of 70° due to significantly less self-shading unlike the smaller square PV integrated curtain wall system. Cooling load decreases by up to 7% at a tilt angle of 70°. However, at vertical configuration of standard PV paneling, heating and cooling loads are almost equivalent to the base case with a 3% increase in heating load and 1% decrease in cooling load. All the above analyzed results, are presented in term of comparison to the base case.





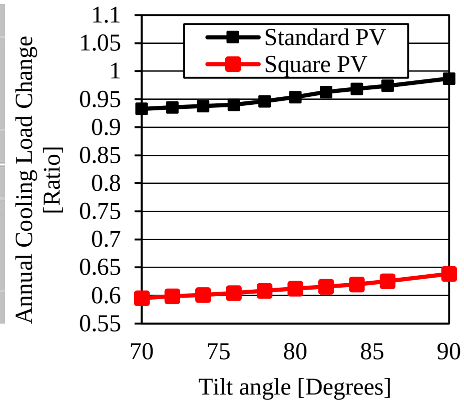


Figure 10 Effect of PV paneling tilt angle on annual heating load compared to base case

Figure 11 Effect of PV paneling tilt angle on annual cooling load compared to base case

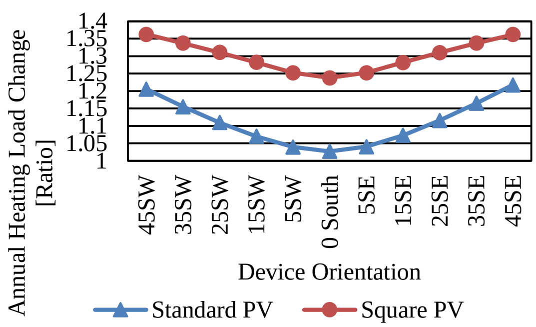


Figure 12 Effect of PV paneling tilt angle on annual heating load compared to base case

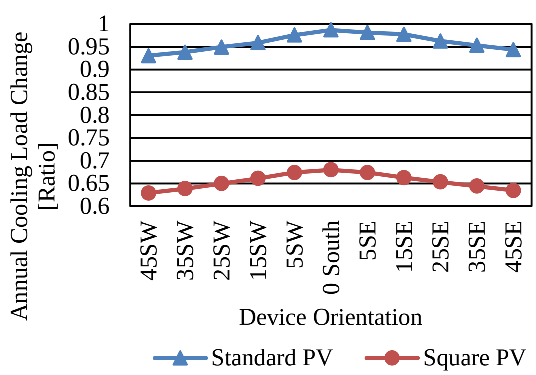


Figure 13 Effect of PV paneling tilt angle on annual cooling load compared to base case

3- Effect of Orientation

The effect of orientation for the second and third alternatives (standard PV CW paneling and square PV CW paneling) on heating and cooling loads is plotted in Figures 12, 13., heating load increases by up to 15% from South to 45° SW/SE, while cooling load decreases by up to 6%.

Analysis of electricity generation

1- Effect of Depth

For the shading device alternatives and folded panels CW BIPV, the effect of depth on the electricity generation potential are plotted in Figures 14, 15 respectively. For horizontal + spandrel SD at a depth of 1.5, annual electricity generation potential reaches 135 Kwh/m^2. For folded panels PV integrated curtain wall system at a paneling depth of 0.8m, annual electricity generation potential reaches 97 Kwh/m^2 representing about 72% of the potential generation per unit area from the case discussed above (horizontal + spandrel SD).

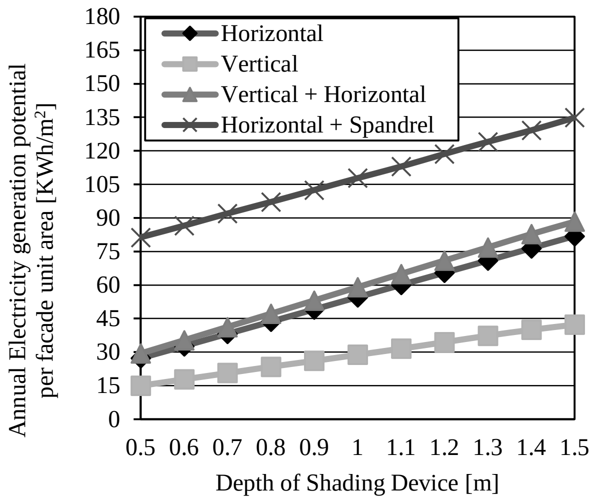


Figure 14 Effect of Depth on annual electricity generation potential per façade unit area

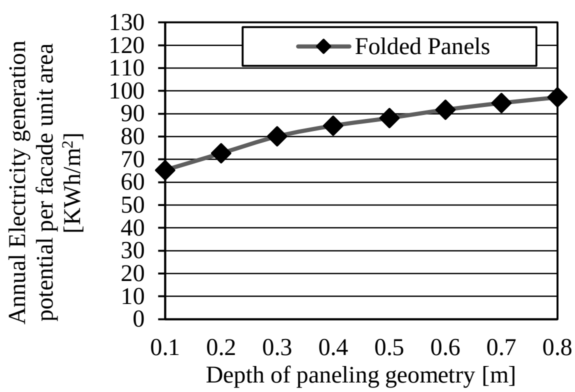


Figure 15 Effect of Depth for folded panels on annual electricity generation potential per façade unit area

2- Effect of Orientation and Tilt

To understand the effect of tilt and orientation on the electricity generation of these design configurations, all alternatives are set at a depth of 0.8m for SD and PV curtain wall systems. Effect of tilt angle for SD and PV integrated curtain wall systems on the annual electricity generation potential is plotted in Figures 16, 17 respectively.

The SD configurations are compared to the horizontal SD, at 0.8m depth. For SD at 40° tilt, generation potential increases to 56 Kwh/m^2 representing 30% increase of the potential generation per unit area compared to horizontal SD, while for vertical + horizontal the generation potential reaches 76 Kwh/m^2 representing 75% increase in potential generation per unit area compared to horizontal SD, due to the added potential of the vertical side panels. For horizontal + spandrel SD at 45° tilt angle, annual generation potential reaches 114 Kwh/m^2 representing 160% increase in potential generation per unit area compared to horizontal SD.

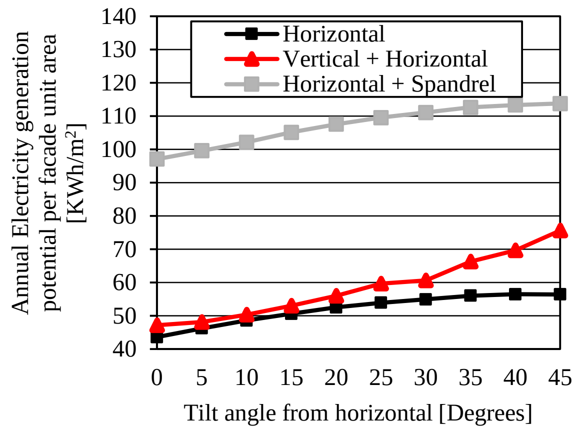


Figure 16 Effect of tilt for SDs on annual electricity generation potential per façade unit area

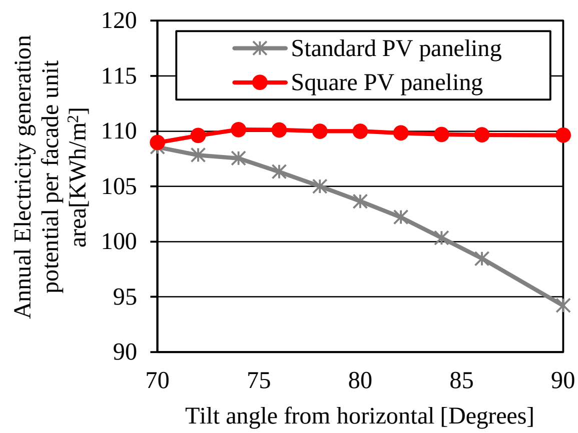


Figure 17 Effect of tilt for PV paneling CW on annual electricity generation potential per façade unit area

For the PV integrated CW, effect of tilt and orientation is studied by comparing all configurations to the configuration with a tilt angle of 90 (vertical panel) and south oriented configuration. For standard PV panels' integrated CW systems at 70° tilt angle, annual generation potential reaches 109 Kwh/m^2 representing 16% increase in potential generation per unit area compared to vertical standard BIPV CW . For square PV curtain wall systems at 76° tilt, generation potential reaches a maximum of 110 Kwh/m^2 representing 17% increase in potential generation per unit area compared to vertical standard BIPV CW, further tilt has no significant effect on generation as all increases of solar insolation on the panels due to tilting is reduced by self-shading. The relatively smaller size of PV panels in case of square panels allows more installed panels in narrower left areas on the sides of glazing area compared to standard PV panels.

Effect of orientation on annual PV electricity generation potential for standard and square PV integrated curtain wall systems is plotted in Figure 18, results show that PV panels' annual generation potential decreases by up to 15% at 45° SE or SW due to less solar insolation on the panels.

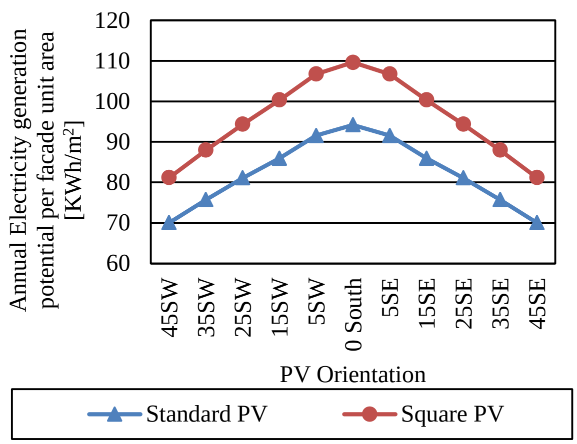


Figure 18 Effect of orientation on annual electricity generation potential per façade unit area

Best case optimization alternatives

For every alternative tested in this study, the total heating load change in most cases is significantly greater than cooling loads. However, as the objective of the optimization methodology is overall energy performance, results are compared for the lowest total annual combined heating and cooling loads and maximum potential electricity generation potential from integrated PV. Configurations with maximum PV panel electricity generation potential that can cover the percentage of the building's electric energy consumption for heating/cooling loads are compared in Figure 19.

CONCLUSION

This study is a first stage towards developing a parametric methodology to compare the effect of varying geometries of PV integrated curtain wall systems on the energy performance for an office space within a high-rise office building. Two sets of curtain wall shading devices and PV integrated curtain wall systems are designed and analyzed, towards developing this methodology. The first set is a variation of shading devices with different orientations and tilt angles. The second set is a variation of PV integrated curtain wall system. The parameters investigated for this set of configurations are: panels' size, orientation, tilt angles.

The developed methodology predicted the annual heating and cooling loads change, and the best potential electricity production for each of the tested alternatives. Out of seven tested design alternatives, the horizontal + spandrel shading device at a 1.5m depth and tilt angle of 15° decreases the annual cooling load by 33%, and decreases the annual heating load by 10%, however, PV produced 135 Kwh/m^2 of the façade area and 60% of the total heating and cooling loads. For the PV integrated curtain wall systems, the folded plates at a depth of 0.1m

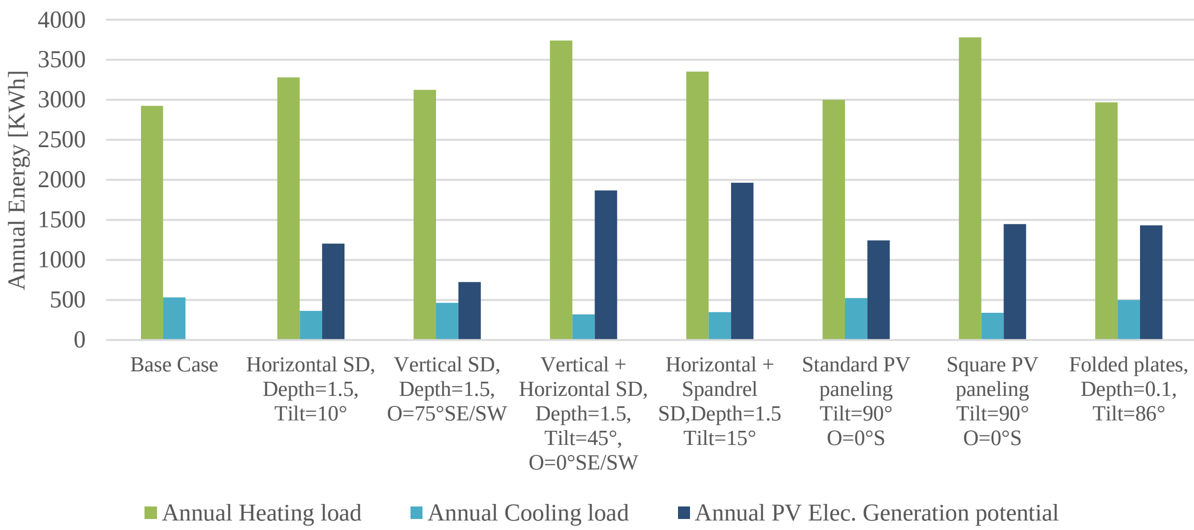


Figure 19 Best case curtain wall configurations optimization

maintained the same heating and cooling loads as the base case, while PV produced 50% of the total heating and cooling loads. For the studied case, the best total saving on energy is for the horizontal + spandrel SD estimated by almost 50% of the base case annual combined heating and cooling load.

The developed optimization methodology successfully coupled geometric modeling and parametric input/output workflow with environmental analysis tools, fostering the advancement of energy optimized solar envelope paneling designs. The proposed design methodology will encourage a diversity of designs, enabling the exploration varieties of curtain wall designs while increasing the energy performance of glazed building enclosures.

Future research includes further development of the parametric methodology Future application of this developed multi-objective optimization methodology can assist in the production of optimized solutions and design guidelines of multi-storey building envelope design.

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