DESIGN METHODOLOGY FOR OPTIMIZATION OF ELECTRICITY GENERATION AND DAYLIGHT UTILIZATION FOR FAÇADE WITH SEMI-TRANSPARENT PHOTOVOLTAICS

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ABSTRACT

Semi-transparent photovoltaics (STPV) have a large potential for integration in fenestration systems, adding the option of solar electricity production while still allowing for satisfaction of daylight needs. This paper studies the potential of using such a technology and examines the impact of changing the photovoltaics (PV) area ratio (ratio of PV coverage to fenestration area) on the STPV façade. It includes a preliminary verification of the workplane illuminance model through comparison with measured data from an experimental office with a specially built full-scale prototype of a window with spaced solar cells in its upper section. The paper will address the issue of optimizing the PV area ratio for a simplified model based on a typical office in Montreal with a 3-section façade. The effect of changing orientation and PV efficiency on the overall net electricity generation (including the lighting load, heat gain from the artificial lighting, and the output of the PV) is presented. The annual simulation results show that a façade with integrated STPV has the potential to improve overall energy performance when compared with opaque PV due to the significant daylighting benefits even at low transparency ratios.

INTRODUCTION

Recent trends in building design over the last two decades include the use of transparent façades in commercial buildings due to an increased appreciation of daylighting. This tendency is likely to continue as more studies link daylight and a view to the outdoors with reduced lighting loads (Lee et al., 1998), and increased worker productivity (Heschong, 2002) as well as a general feeling of well being and reduced absenteeism from work. Currently, façades with large glazing areas often maximize incoming daylight rather than controlling it appropriately, which could lead to increased thermal loads and thermal/visual discomfort in perimeter building zones (Tzempelikos & Athienitis, 2007). However, this trend has the potential to have an important positive impact on building energy performance while concurrently providing a comfortable space for its occupants. To do this, the façades must meet the following requirements:

1. Allow adequate daylighting into the space and a view to the outdoors. With an appropriate lighting and shading strategy, this will provide for both a reduction in lighting energy consumption and improved visual comfort for the occupants (mostly dependant on glare and the quality of the light in a space).
2. Reduce the heat transfer to and from the exterior environment. This will reduce the energy consumption for space heating and cooling, and potentially lead to smaller HVAC equipment (Li, et al., 2005), while providing better thermal comfort for the occupants (dependent on the temperature of the indoor window glass layer and affecting the mean radiant temperature felt by the occupants).

Cooling energy costs are a major concern in most office buildings and for this reason double-glazed façades with an integrated strategy to reduce the transmission of solar radiation is becoming the norm. Instead of using tinted glass or ceramic frits to reduce the solar radiation, semi-transparent photovoltaics (STPV) could be integrated, thus reducing solar heat gains and lighting loads while concurrently producing electricity; providing more energy benefits and possibly turning the façade into a net energy generator. There has been limited research on the combined performance of this technology, examining both ideal daylight use and maximum electricity generation, while taking into consideration the optimal spacing, or transparency, of the cells; and even less work has been done on the development of guidelines for design/construction of glazed building façades with STPV.

By providing an optimal PV area ratio in the STPV façade, or choosing thin film PV with an optimal efficiency/transmittance ratio and thus optimizing the daylight entering in the room, both the lighting loads and cooling loads may be kept to a minimum. There has been work done previously in this area, exploring both ideal daylight use and maximum electricity generation, while taking into consideration the optimal spacing, or transparency, of the cells.

However, there is much variation in the results and no concrete guidelines given for any deviation from the specific situation studies. Fung (2006) has developed a mathematical model which looks at the thermal performance of, and in particular the heat gain through, building-integrated STPV for a base case in Hong Kong. He concluded that the optimal cell-to-glass ratio is 70%-90%, depending on window-to-wall area. Miyazaki, et al. (2005) found that, for a window-to-wall area of 50%, a solar cell transmittance of 40% achieved the minimum electricity consumption in Japan for an office space of 24m x 24m. Vartiainen (2000) explored the effect of optimizing the window area and PV area in a façade for 4 different European cities and found that a 15-20% coverage of opaque PV of the entire façade was optimal for all 4 locations. De Boer, et al. (2001) conducted a comprehensive study of various STPV applications including a vertical 3-section façade in Madrid, looking at the effect of changing orientation, room size, slope, internal heat production, infiltration, and PV transparency. They found that changing the transmittance of the PV module had little effect on the overall energy balance. However only PV electricity generation, heating and cooling loads were taken into account, while the effect of daylighting was not examined.

As can be seen, some work has been done in this area but there is much variation in the results and as far as the authors have found, there has been little in the way of proposing a methodology for designing a façade which incorporates semi-transparent photovoltaics taking into consideration the constraints faced in real situations. How do you integrate the selection of PV and its transparency into the overall design of the façade system taking into account the total energy picture but also the quality of the indoor environment? For Northern hemisphere locations, a southern façade is ideal for maximum PV electricity generation and daylight utilization and a vertical façade is ideal for minimizing cooling loads in the summer and heating loads in the winter. However, in reality, true-South facing façades are not always possible and the importance of understanding the implications of designing for a different orientation, or a different PV efficiency than that given in the previously mentioned studies is important.

SIMULATION OF SEMI-TRANSPARENT PHOTOVOLTAIC FAÇADE

Description of façade and office used in simulation

A simplified model based on a typical small office (3m wide x 4m deep x 4m high) in Montreal has been developed as the base case. The façade is equally divided into three sections: (i) a top section covered by STPV, (ii) a middle section used for view, and (iii) an opaque spandrel section. It has been found that, for south-facing façades, a 30% window-to-wall ratio ensures that daylight provides enough light a similar space for 76% of the working time of the year; and larger window areas do not result in a significant increase in useful daylight in the room (Tzempelikos, & Athienitis, 2007). The effect of changing the PV area ratio (cell spacing or effective transmittance) of STPV is evaluated for different orientations and PV efficiencies. The results allow the selection of PV area ratio based on orientation and PV efficiency based on the following criteria: (i) electric lighting demand, (ii) photovoltaic electricity output, and (iii) heat gain cost to the space from artificial lighting. More detail of the individual calculation steps are in (Robinson, et al., 2008).

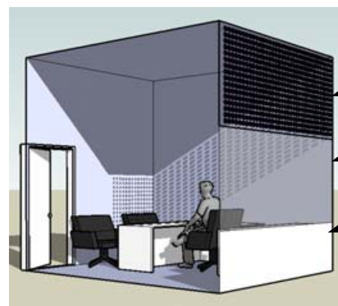

Figure 1: The office space used in the simulation model; the top part of the three-section façade is covered by semi-transparent PV.

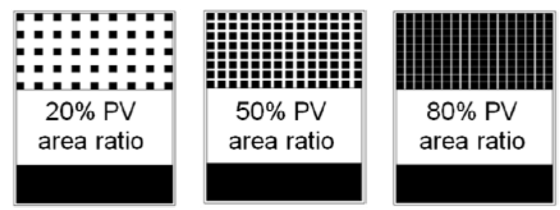

Figure 2: Percentage of PV coverage in the upper section of window; 20%, 50%, 80%.

Daylighting model

A yearly daylighting analysis was performed for typical office working hours (weekdays 8am to 5pm, standard time) in order to determine the electric lighting load required to augment the workplane illuminance to the desired 500 lx. The amount of daylight entering the room is a function of the sky condition, the solar angle of incidence and the characteristics of the window through which it is entering. The Perez irradiance model (Perez, et al., 1990) was used to predict the beam and diffuse solar radiation on the façade from TMY2 data file. The Perez luminous efficacy model was then used to predict the incident beam and diffuse illuminance.

The viewing section effective transmittance depends on the angle of incidence of the solar radiation. A double-glazed window with clear glass was used and a control loop is added to the model to account for activation of an interior roller shade (with 5% transmittance) whenever the incoming direct radiation is higher than 100 W/m^2. In this way, the occupant will be protected from glare when direct (beam) sunlight is present. The upper PV section does not have a shading component in this model. A sensitivity analysis was performed on the effects of changing the blind transparency and coverage of the PV section and is presented in the results section.

The horizontal illuminance on the workplane is calculated using radiosity theory after infinite interreflections, using the configuration factors, relating illuminance to a point on the workplane, and final illuminous exitances (M_i) for all surfaces (i) of the 8-surface room are based on radiosity theory (Athienitis & Tzempelikos, 2002).

$$M_i = [(I - T)^{-1}] M_o \quad (1)$$

where I is an 8x8 identity matrix, M_o is the initial luminous exitances for all surfaces, and matrix T is evaluated by multiplying the reflectance of each surface by the form factors of the room. Note that uniform diffuse isotropic sources are assumed, and diffuse reflection from each surface. To calculate the horizontal illuminance on the workplane ($E_{workplane}$) after infinite interreflections, the configuration factors (f_i), relating illuminance to a point are utilized as follows:

$$E_{workplane} = \sum M_i f_i \quad (2)$$

In this base case, the minimum desired workplane illuminance is 500 lx on the point on the workplane 1.5m from the window. The model predicts 8760 values of the workplane illuminance for each of 5 orientations, PV efficiency, and PV technology. An albedo of 0.7 is assumed for March to November and 0.2 from December to March (snow cover). A complete overview of the daylighting calculations can be found in (Robinson, et al., 2008).

Electric lighting consumption

Continuous dimming electric lighting control was assumed for this study, along with a typical electric lighting system with T8 fluorescent lamps and 12W/m^2 installed power lighting density. For continuous dimming control, the lighting adds only enough output to achieve the desired illuminance on the workplane. The luminaires were selected using the zonal cavity method (Murdoch, 2003) and the lighting loads for one day are calculated by taking the sum of the power required for each hour (based on the use factor) of the working day (8am to 5pm, standard time). A sensitivity analysis was performed on the effect of changing the lighting strategy from continuous dimming to active on/off control (all lights turn on when workplane illuminance less than the desired) to passive control (lights are continuously on during office hours).

Heat gain due to lighting

Artificial lighting produces heat gains which are beneficial if heating is required and detrimental if cooling is required. Based on a similar office with a south facing façade modelled by Tzempelikos & Athienitis (2007) in Montreal, November-February were heating dominant, April- October were cooling dominant, and March was split evenly. Based on ASHRAE (2005), the instantaneous heat gain from lighting is equal to:

$$q_{el} = W F_{ul} F_{sa} \quad (3)$$

Where q_{el}= heat gain, (W); W= total light wattage, (W); F_{ul}= lighting use factor; F_{sa}= lighting special allowance factor. In this study T8 lamps were used with special allowance factor of 1.0. In order to convert the lighting energy gains into an approximate cooling or heating load, a ground source heat pump is assumed. Typical values for the coefficient of performance (COP) were used with $COP_{heating}$=4 (NRCAN, 2008) and $COP_{cooling}$=3 (lower due to detrimental heat produced by GSHP which needs to be removed). The cooling/heating energy consumption due to the lights (Q_{lights}) is calculated by dividing the heat gain (q_{el}) by the appropriate COP (depending on if it is the heating or cooling season).

$$Q_{lights} = \frac{q_{el}}{COP_{cooling/heating}} \quad (4)$$

Electricity generation by PV

The energy generated by the photovoltaic cells depends on the incident radiation on the cells and their electrical efficiency. A simplified efficiency model was used based only on the deviation of the cell temperature from the standard test conditions (STC). According to Messenger, (2000), for variations in ambient temperature and irradiance from the standard test conditions, the cell temperature (T_{cell}) can be estimated quite accurately using the outdoor temperature (T_o), the nominal operating cell temperature (NOCT), the irradiance (I_t) and the reference irradiance (I_o = 800W) using the linear approximation:

$$T_{cell} = T_o + \left(I_t \frac{NOCT - 20}{I_o} \right) \quad (5)$$

In our window prototype, described in the next section, the cell temperature is expected to be higher due to glazing thermal resistance and a more detailed thermal model is under development.

The efficiency of the array due to temperature (η_{temp}) is equal to the manufacturers' stated efficiency at STC (η_{PV}) and the deviation of the cell temperature from the outdoor temperature of the cell for NOCT ($T_{o,NOCT}$) multiplied by the cell temperature efficiency coefficient (η_{cell_temp}).

$$\eta_{temp} = \eta_{PV} [(1 - \eta_{cell\_temp} (T_{cell} - T_{o,NOCT})] \quad (6)$$

The power generated from the PV (P_{PV}) is thus equal to the radiation incident on the cells (I_t) multiplied by the area occupied by the PV (area of window area- A_1 * percentage of PV coverage- A_{PV}) multiplied by the cell efficiency:

$$P_{PV} = I_t \, A_{PV} \, A_1 \, \eta_{temp} \quad (7)$$

The simulations use polycrystalline cells (c-Si) with a base efficiency of 11%, a cell temperature coefficient of 0.4%/°C, and an outdoor temperature is taken from the TMY2 data. The cells are assumed to be on the exterior surface of the window and thus the glazing transmittance does not affect the efficiency of the cells. The total power generated by the PV for one day is calculated by taking the sum of the power generated per hour for the entire 24hour day (midnight to midnight).

Overall energy balance

The overall energy balance of the office (excluding conduction heat losses/gain through the façade) based on changing the PV area ratio of the STPV is given as:

$$NetElecGen_{cooling} = P_{PV} - P_{lights} - Q_{lights} \quad (8A)$$

$$NetElecGen_{heating} = P_{PV} - P_{lights} + Q_{lights} \quad (8B)$$

The net electricity generation (NetElecGen) is equal to the electricity generated from the PV (P_{PV}), less the energy consumption of the lights (P_{lights}) +/- the heating/cooling energy consumption of the lights (Q_{lights}). This model does not consider the solar heat gain effects through the window or the heat produced by the PV. Future work is planned in this area.

EXPERIMENTAL VERIFICATION OF STPV FAÇADE

Experimental set-up

The experimental office is a 3m x 3.3m x 2.3m room with a window to wall ratio of 32%. The window is south-facing and is integrated in the 'Northern Light' solar house which was presented at the 2005 Solar Decathlon, and is now located in Montreal (Figure 3). The window is 2.4m x 0.5m for both the PV section and viewing section.

Figure 3: STPV window used integrated in Montreal

The custom-made window is an evenly divided two-section window with an upper section containing the semi-transparent photovoltaics and an unobstructed bottom section acting as a viewing section (Figure 4).

Figure 4: Office space used in experimental study

The semi-transparent photovoltaics are spaced opaque poly-crystalline cells with an overall coverage of 75%; this is the optimal determined by the mathematical model for this room. The make-up of the window (from outside to inside) is: a) 6mm tempered glass, b) poly-crystalline photovoltaic cells, c) Ethylene vinyl acetate (EVA) encapsulate, d) 2" air gap, e) 6mm glass with low-e coating.

The illuminance on the workplane and the output of the PV will be studied in detail in different locations in the room. Thermocouples on the window are used to measure the temperature distribution in the window, enabling a thermal analysis on the system.

The illuminance on a workplane was measured in 9 locations in the room at a height of 0.8m from the floor. They are placed at 0.5m, 1.5m and 2.5m from the window, and 0.55m from right wall, center of room and 0.55m from left wall. The window is not centered on the façades, being 0.2m from the left wall and 0.65m from the right wall. The reflectances of the room were measured at $\rho_{ceiling}$=0.85, ρ_{walls}=0.86, ρ_{floor}=0.28.

Illuminance on the workplane-preliminary results

Overcast day→Mar 29 @ solar noon

The measured values for Mar 29, 2009 at solar noon are compared with simulated values for the same day. This day was overcast for the entire day. Weather data was taken from a few sources. Irradiance data components were taken from NRCAN's weather station in Varennes QC (loc: 45°37'35"N; 73°22'52''W). Temperatures and total vertical irradiance and illuminance were taken in site. Dew point temperature was taken from Environment Canada's online climate database (Environment Canada, 2009). The visible transmittances of the windows were measured with interior photometers and found to be $\tau_{diffuse}$=0.327*25% for the PV section and $\tau_{diffuse}$=0.62 for the viewing section.

The comparisons were done on an overcast day in order to verify the use of radiosity method to estimate the daylight distribution in the room. It models perfectly diffuse reflections and is generally an adequate model. However, for the beam component of the illuminance, the radiosity model assumes that it is diffuse light and therefore non-directional. We know that this is not true for the beam component. A ray tracing technique would be a more realistic model for the behaviour of the beam component being distributed in the space, as it takes its direction into account.

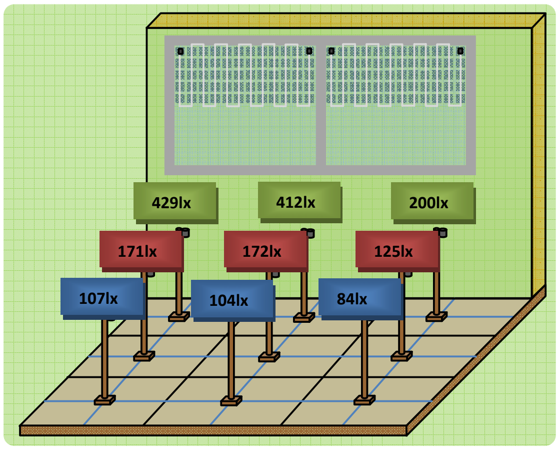

Figure 5: Measured workplane illuminance

Distance from window	0.5m	1.5m	2.5m
Component directly through window	284.3 lx	63.8 lx	20.0 lx
Interreflected component (one-bounce) off walls	36.1 lx	47.1 lx	50.4 lx
Interreflected component (mulitple-bounces)	78.3 lx	107.4lx	119.6lx
Simulated total	363 lx	171 lx	140 lx
% Error with measured	12 %	0 %	25 %

Table 1: Calculated workplane illuminance values, overcast day-center of room (1.625m from each wall)

As is seen above, for the overcast day, the radiosity model gives satisfactory agreement, as the assumption that the light is diffuse is close to reality for our daylighting model. In the simulations for a clear day, there is always a blind on the viewing section if the radiation exceeds 100W/m^2 and all light will be diffuse and our radiosity model should again be sufficient. (IESNA, 2000) warns that generally the differences between detailed analysis methods and field measurements are as high as 20% when dealing with basic lighting from luminaires. Daylighting adds another degree of complexity.

RESULTS AND DISCUSSION

Impact of using STPV at different orientations

The values presented in the following graphs represent the impact of sky conditions and changing PV area ratio on the net electricity generation for different orientations. For the Northern hemisphere, a southern façade receives the most radiation yearly, but this orientation is not always possible. The intent was to show to what extent a change of 45 degrees (SW and SE) and 90 degrees (W and E) has on the net electricity generation. Of the orientations explored, South facing façades receive the most daylight and East facing façades receive the least daylight during working hours (compared with South and West). Figure 6 gives an overall view of the net electricity generation (PV output- lighting load – heat gain penalty due to lighting) for different orientations. A 80-90% coverage is optimal for all orientations studied.

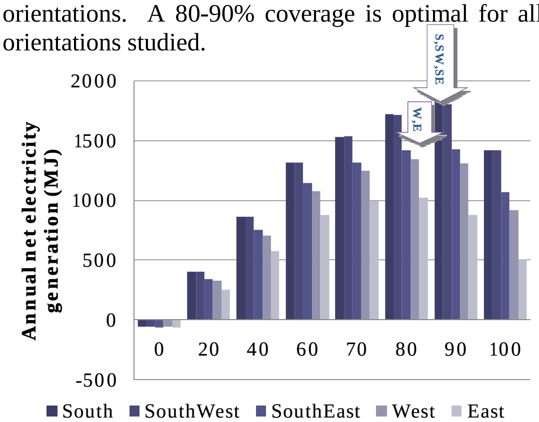

Figure 6: The impact of changing PV area ratio on the net electricity generation of a small office for different façade orientations, PV efficiency= 11%.

South, PV efficiency of 11%

For a South facing façade, it can be seen that a 100% PV coverage of the upper section gives the highest net electricity generation for the months December to March but 90% coverage gives the highest yearly net electricity generation (Figure 7, Table 2).

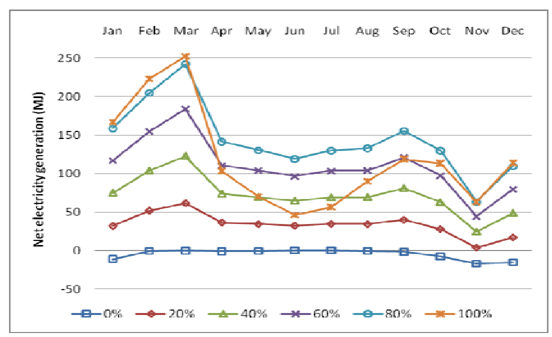

Figure 7: The impact of changing PV area ratio for South facing façade, with PV efficiency of 11%.

	0%	40%	80%	90%	100%
Lighting load	67.3 MJ	79.3 MJ	146 MJ	246 MJ	804 MJ
PV elec. generation	0 MJ	931 MJ	1863 MJ	2095 MJ	2328 MJ
Heat gain cost- lights	-12 MJ	-12 MJ	-3.1 MJ	+19 MJ	+108 MJ
Net elec. generation	-56 MJ	864 MJ	1719 MJ	1829 MJ	1416 MJ

Table 2: Summary of annual simulation for South facing façade, with PV efficiency of 11%.

The lighting loads more than triple from 90 to 100% coverage due to the high lighting loads in the summer as the blind is closed on the viewing section and the upper section allows no daylight to enter. The heat gain cost (penalty) also increases significantly due to their increased use in summer.

45° Southwest, PV efficiency of 11%

For a Southwest facing façade, it can be seen that a 90% PV coverage of the upper section gives the highest net electricity generation for the entire year. (Table 3). The Southwest façade performs similarly to the South façade and only experiences a 1% decrease in overall net electricity generation. There is a decrease in the PV electricity generation but also a similar decrease in the heat gain penalty from the lights. It is also interesting to note that for a 100% PV area ratio, this façade performs similarly to a South facing façade.

	0%	40%	80%	90%	100%
Lighting load	64 MJ	76 MJ	150 MJ	269 MJ	803 MJ
PV elec. generation	0 MJ	926 MJ	1852 MJ	2083 MJ	2315 MJ
Heat gain cost- lights	-12 MJ	-12 MJ	-7.6 MJ	+10 MJ	+91 MJ
Net elec. generation	-52 MJ	864 MJ	1709 MJ	1804 MJ	1421 MJ

Table 3: Summary of annual simulation for Southwest facing façade, with PV efficiency of 11%

West, 45° Southeast, and East, PV efficiency of 11%

For a West facing façade, 100% PV coverage is never optimal and 80% is preferable, giving an overall net electricity generation of 1340 MJ. This is an overall decrease of 27% compared with a South orientation. The impact of changing the orientation 45° from Southwest to West is much greater than from South to Southwest.

A Southeast orientation gives significantly worse results than a Southwest orientation due to the time of day of the office hours. The net electricity generation is 1428MJ, a reduction of 22% when compared with South and 21% when compared with Southwest. This is an important design implication. 100% PV area ratio is never ideal for Southeast. The lighting loads are higher than for a South façade and PV electricity generation lower.

For an East facing façade, a significant reduction in net electricity generation is observed at 1020 MJ. For the month of November, many PV area ratios result in a negative net generation. 100% PV area ratio results in near zero net electricity generation for 5 months of the year.

Semi-transparent PV vs. opaque PV

The use of semi-transparent photovoltaics on the upper section of the façade instead of an opaque PV spandrel presents a significant increase in the overall net electricity generation from a façade, due to an increased workplane illuminance and thus a reduced lighting load. As can be seen in Figures 8 and 9, on clear days the workplane illuminance is much higher for the STPV façade (90% PV area ratio) than the opaque PV (100% PV area ratio). This is true for both cold and warm clear days.

Cold clear day

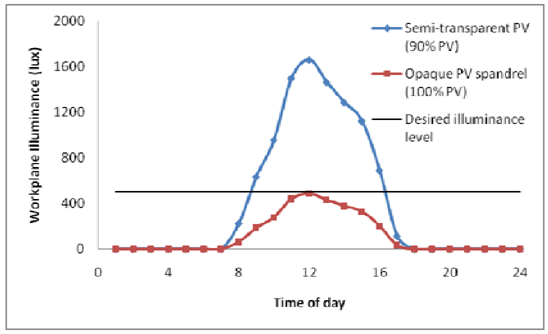

Figure 8: Workplane illuminance for typical clear cold day (Feb 12) for STPV (90% PV area ratio) vs opaque PV spandrel (100% PV area ratio), South.

Warm clear day

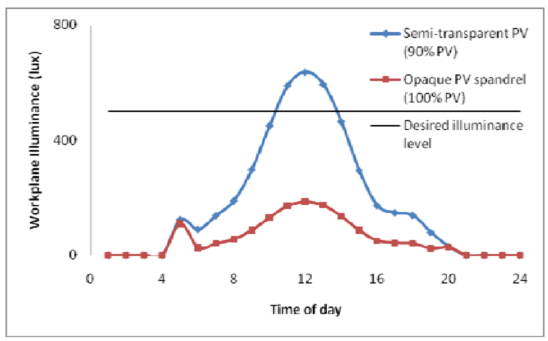

Figure 9: Workplane illuminance for typical clear warm day (Jun 30) for STPV (90% PV area ratio) vs opaque PV spandrel (100% PV area ratio), South.

Impact of changing PV efficiency

By changing the nominal efficiency, our optimal PV area ratio could change as now the PV electricity output changes. Table 4 and Figure 10 demonstrate that for a South facing façade, the optimal stays the same (between 80 and 100%). The lighting loads and heat gain penaltys stay the same for all efficiencies and only the output of the PV differs. The impact from the PV output is greater than the the other loads. There is however a noticeable change in the difference between 80 and 100% PV area ratio for 6%, 11% and 16% efficiency. The decrease from 80 to 100 is 60% for 6% efficiency, 18% for 11% efficiency and only 4% for 16% PV efficiency.

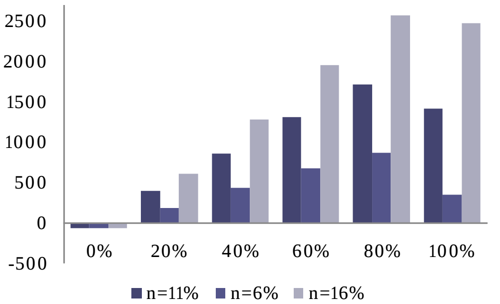

Figure 10: The impact of changing PV cell efficiency for South facing façade

	0%	40%	80%	100%
η=6% net elec. generation	-56 MJ	443 MJ	875 MJ	356 MJ
η=11% net elec. generation	-56 MJ	864 MJ	1719 MJ	1416 MJ
η=16% net elec. generation	-56 MJ	1288 MJ	2566 MJ	2474 MJ

Table 4: Summary of annual net electricity generation for changing PV efficiencies, South

Impact of changing lighting control strategies

The lighting load due to a passive lighting control strategy (lights always on during working hours) does not change for changing PV area ratios. An active on/off control strategy (lights turn on if workplane illuminance is below the desired) and a continuous dimming strategy (lights only add enough to augment to desired workplane illuminance), both change for changing PV area ratios (See Figure 11).

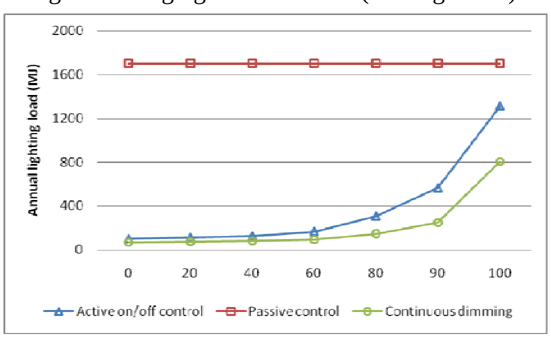

Figure 11: The impact of changing lighting control strategy for South facing façade, PV efficiency=11%

For a 0% PV area ratio, the increase in lighting load from a passive control strategy is 17 and 25 times respectively for active on/off and continuous dimming difference. This decreases to 1.3 and 2 times the load at 100% coverage. The increase between the active on/off and continuous dimming is 40% for 100% coverage. An appropriate lighting control strategy has a significant impact on the lighting loads.

Impact of changing shading model

By changing the transparency of the shade over the viewing section from 5% to 20% transparency, there is little difference in the overall net electricity generation for 0 to 80% PV area ratios (Figure 12).

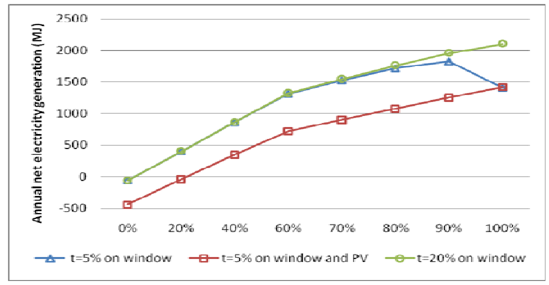

Figure 12: The impact of changing shading model for South facing façade, with PV efficiency of 11%

For 90 and 100% coverage there is an increase of 7% and 48% for changing transparency respectively. This shade has less seasonal impact and results in an optimum of 100% PV area coverage. The shading model which covers both the window and PV area results in a fairly stable decrease in net electricity generation from the case where it is only covering the window for all PV area ratios, except of course 100% where it is the same.

The simulations were run for a shade over the viewing section of the façade only. If a shade is put on the PV section as well as the viewing section, the workplane illuminance decreases significantly and behaves similarly to a façade with 100% PV area ratio in the upper section (Figures 8, 9). For both the warm and cold clear days, the decrease in workplane illuminance is significant and a more detailed analysis of the glare through this section needs to be conducted to choose an appropriate shade.

DISCUSSION AND CONCLUSION

This paper presents the results of a simulation-based daylight and photovoltaic output analysis, based on an integrated semi-transparent photovoltaic façade. The intent of the study was to determine to potential of this technology as well as the influence of the PV area ratio on the net electricity generation (PV electricity output – lighting loads from artificial lighting to supplement daylight +/– loads associated with heat gain from artificial lighting). The study was conducted for different façade orientations and PV manufacturer's efficiencies in order to give relevant guidelines for designers of such façades. It was found that the optimal PV area ratio was 80-90% for all façade orientations studied from East through South through to West as well as for PV efficiencies of 6 to 16%. It was demonstrated that the use of STPV over opaque PV spandrel can significantly increase the overall net electricity generation of the façade. A better option would be that of thin-film photovoltaics as the natural light coming in through this technology would be uniform, allowing for unobstructed view. However the current low-efficiency and high cost of this technology when applied to windows is a major limitation to its widespread application. New solar cell technologies that result in lower cost and higher efficiencies while having adequate daylight transmission characteristics are needed.

The office in the simulations was a small office located in Montreal with a 3-section façade, incorporating an equal height STPV section, viewing section and spandrel section. The effective window to wall ratio of both the STPV and viewing sections were 33%. The difference between a South and Southwest façade, in terms of net electricity generation is minimal while the difference from South to Southeast is much higher. If given the choice, a more western façade should be used rather than an eastern façade, due to the timing of the office hours with respect to solar angles and the increased cooling loads in the afternoon. The workplane illuminance decreases significantly (and thus the lighting loads increase significantly) between 90% PV area ratio and 100%. The experimental set-up has given preliminary results for an overcast day and coincides fairly well but needs to be looked at further in order to determine the appropriate interreflections of light for a clear day.

A sensitivity analysis was performed on the shading model and it was found that if the PV section is shaded (not only the viewing section) there resulted in a 32% decrease in the annual net electricity generation (for 90% PV area ratio). When looking at the workplane illuminance only, the case with a blind covering the PV section has much lower levels and acts similarly to the 100% PV area ratio case. However, there is little difference in the net electricity generation if the transparency of the blind on the viewing section is increased from 5 to 20%. A more detailed analysis of the glare through these sections needs to be conducted in order to maintain the maximum user comfort. Continuous dimming lighting control results in a 85% decrease in energy consumption relative to on/off passive lighting and active on/off control results in a 67% decrease. The use of an appropriate lighting control strategy is imperative.

This model does not consider the solar heat gain effects through the window or the heat produced by the PV. (Fung & Yang, 2008) found that the effect of changing the solar cell area ratio has a significant impact on the total heat gain in Hong Kong. There was an annual heat gain reduction of nearly 70% if the solar cell area ratio is 80%, when compared with clear glass. More research is planned for this area, looking at the optimal PV area ratio for Montreal.

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