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Semi-transparent photovoltaic façade: optimization and overall energy performance for commercial buildings in Brazil

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Abstract

By 2022 electricity consumption in commercial buildings in Brazil might represent 20.7% of national electricity demand. Semi-Transparent Building-Integrated Photovoltaics (STBIPV) can generate renewable energy, reduce building cooling loads and permit natural light into the space; therefore, reducing daytime peak loads from urban feeders. This study aims to investigate the overall energy performance (in terms of energy demand, daylight, visual comfort, and PV power generation) of STBIPV for an office in São Paulo, Brazil, through quantitative and comparative analyses against conventional strategies. STBIPV with selected transparencies according to window-to-wall ratios for different façade orientations were examined. Saving up to 17% of total annual electricity consumption was achieved for a fully-glazed office floor with STBIPV windows 16% transparent, in comparison to the base case. Overall electricity benefits in this case accounted for 11.42MWh/year. However, economic evaluation showed that the studied integration is not yet feasible.

Keywords: semi-transparent photovoltaic, building-integrated photovoltaic, overall energy performance, energy consumption, daylighting

1. Introduction

As a developing country, the energy consumption in Brazil is expected to rise significantly, especially for the commercial sector. This sector accounted for 17.6% of national electricity consumption in 2012 and by 2022 the consumption might rise to 20.7% (EPE, 2012). The country is well provided by natural resources and solar energy could be a promising alternative to diversify the national energy mix, considering that daily solar radiation ranges between 4.25-6.5kWh/m^2.day.

Solar energy technologies, as semi-transparent building-integrated photovoltaic (STBIPV), can assist in building energy supply and can be easily integrated into large glazed areas, very common in office buildings. This integration is often justified by STBIPV multi-functionality: thermal isolation, solar control and electricity generation.

Previous researches have shown the benefits of STBIPV in reducing cooling demand in office buildings and argued about the importance of optimizing the solar cell transmittance according to façade orientation and window-to-wall ratio (WWR), in respect to daylight provision (Miyazaki, et al., 2005; Li, et al., 2009). However, there is still a niche for studies investigating the overall energy performance of STBIPV, in terms of energy demand, electrical performance and access to daylight; as well as analysing the economic feasibility of this system.

Moreover, few authors have focused on the performance of this technology in the Brazilian context, where STBIPV could be an option to increase energy efficiency of

commercial buildings and reduce their electricity consumption. This study aims to investigate the overall energy performance of semi-transparent building-integrated photovoltaics (STBIPV) into the glazing façades of an office in Brazil compared to a conventional double-glazed strategy. STBIPV economic feasibility and potential optimization measures to improve the overall performance have also been analysed. The detailed objectives are as follows: to seek the optimum correlation between solar cell transmittances and window-to-wall ratios (WWR) and to investigate the contribution of STBIPV to office energy demand, daylight and glare, and PV power generation

2. Methodology

São Paulo city is located 23.6°S and 46.7°W and was selected for this study because it is one of the most developed cities in the country with significant amount of electricity consumption. The city is situated in a highland tropical climate, where mean temperatures range from 18°C to 22°C. In summer, temperatures can reach up to 33°C, while in winter the minimum temperature reaches 7-8°C, influenced by the cold Atlantic polar masses. Cooling is widely needed throughout the year, whereas heating demand is very low, especially in offices where internal heat gains are usually high. This indicates a major concern for cooling strategies instead of heating.

A hypothetical squared standard office floor of 35mx35m, 3.0m high and oriented 20° east of north was designed as the building geometry (Figure 1). It could fit approximately 20 offices with floor areas between 42m² and 47m², to fulfil the need for small offices with floor areas around 45m² in the city, but this study considers the floor as an open plan. In order to reduce computational loads from a high-rise office building, only the standard office floor was modelled in Design Builder (version 3.0), which prepared the input data to be latter processed by Energy Plus (version 7.0) simulation engine.

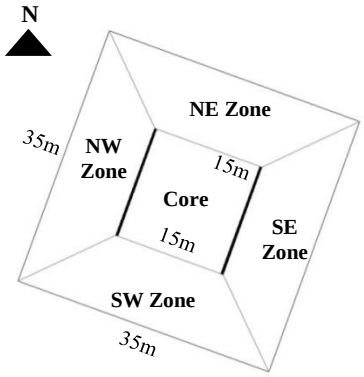

Figure 1: Standard office floor plan oriented 20° east of North.

Table 1: Electrical data for ASI® THRU modules

STBIPV Electrical data	
Nominal power (Wp) - STC	78
ISC (A) - STC	1.11
VOC (V) - STC	111
Temp. Coefficient	-
PV Glass Module Area (m²)	1.50
PV Active Area (m²)	1.372
Efficiency - STC	6%

Operation hours were set from 8:00 to 18:00 during weekdays and from 8:00 to 12:00 on Saturdays. Operational schedules were presented elsewhere (Costa, 2013). In the figure, the two walls of the core (vertical circulation) in thick lines represent an internal thermal mass, simulating the core structure of the building, with an overall thermal transmittance (U-value) of 2.39 W/m².K. The external walls consist of 150mm cast concrete with external stainless steel cladding and internal gypsum insulated plaster (U-value: 1.31 W/m².K) in the opaque part and 6mm double glazing (DG) panes for the base window type (U-value 3.16 W/m².K).

The floor and ceiling were set as adiabatic surfaces to prevent heat transfer to the outdoor environment and assuming that the internal conditions on the floor below and above are the same as the standard floor. Window-to-wall ratios (WWR) of 33% (one third of glazing on the façade), 50%, 75% and 100% were selected to analyse the outcomes for different façade configurations usually common in office buildings.

Thin-film amorphous (a-Si) technology has been presenting excellent performance and good suitability for applications in warm and sunny locations, such as Brazil (Rüther, et al., 2004). For this reason, and due to the homogenous light transmission, the a-Si see through STBIPV module was selected with two light transmittances: 10% and 16%. Both modules have U-value of 1.1 W/m².K and solar heat gain coefficient (SHGC) equal to the transmittance. Solar and visible transmittances were assumed to be the same as the solar cell transmittance (Miyazaki, et al., 2005).

Table 1 shows the electrical data of the STBIPV under standard test conditions (STC: radiation of 1000W/m^2, AM 1.5 and cell temperature 25°C). The temperature coefficient of a-Si can be neglected after the stabilization of the Staebler-Wroski effect (Rüther, et al., 2004). The transparency of the STBIPV module affects the electrical production, where losses are usually equal to the transparency degree. So losses of 10% and 16% were considered for the final PV energy generation.

Continuous/off dimming control was considered for the four zones of the standard office floor that can benefit from daylighting. The required illuminance at work plane height (0.75m) was set to 500lux and an internal blind was active when glare index exceeded 22 at the reference points: centred 1.5m and 6.5m away from the façades.

The average daylight factor (DF) was calculated for an overcast CIE sky with Design Builder, using Radiance simulation engine. This factor indicates how well lit a room is perceived to be, DFs between 2-5% gives the room an adequate lit appearance. Average DF is calculated by the formula below (Eq.1), where T is the diffuse transmittance of the glass, Aw is the window area (m^2), α is the vertical angle of sky seen by the window (degrees), M is the maintenance factor, A is the total area (m^2) of internal surfaces (walls, ceiling, floor and windows) and Ra is the average reflectance of the interior room surfaces.

$$Average\ daylight\ factor\ (DF,\%) = \frac{(T\ Aw\ \alpha\ M)}{A\ (1 - Ra^2)} \qquad (Eq.1)$$

Finally, the overall energy performance was calculated in terms of electricity benefits, which consists of subtracting the electricity consumption from heating and artificial lighting by the electricity generated from the PV modules plus electricity saved from air-conditioning (Li, et al., 2009a).

3. Results and Discussion

This section presents and analyses the results of the computer simulations for the floors with different façade configurations. Later, it focuses on the outputs for a floor with WWR 100% to discuss daylighting and overall energy performance.

3.1 Energy Demand and PV production

Figure 2 illustrates the annual grid electricity consumption for the standard office floor with different WWR and glazing structure, considering the demand without and with PV electricity generation (demand – PV).

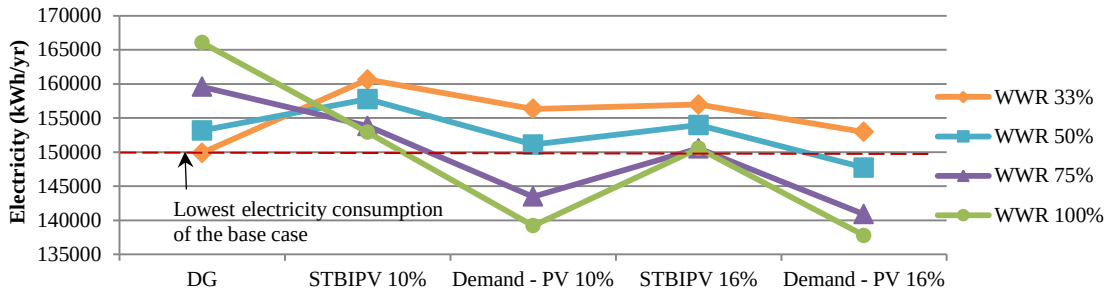

Figure 2: Annual electricity consumption from the grid of floors with different WWR and glazing.

For the base case office with double glazed (DG) windows the energy consumption raises sharply as window area on the façade increases, while for semi-transparent PVs this effect is reversed. The major contribution for such reductions is from air-conditioning savings. STBIPV acts as a solar control device, reducing the amount of solar gains within the interior environment, thus reducing the demand for cooling.

Compared to DG, energy consumption increases approximately 7% and 5% for WWR 33% and in 3% and 0.5% for WWR 50%, for STBIPV 10% and 16% respectively. In contrast, energy savings for WWR 75% was around 3.5% and 5.5% for STBIPV 10% and 16%, respectively, and for WWR 100% it reached 7.8% and 9% in the same order. The difference between STBIPV 16% and STBIPV 10% can be mainly attributed to the lower impact of STBIPV 16% on artificial lighting demand.

For WWR 33% the integration of STBIPV in windows was not beneficial, because none of the configurations achieved lower electricity consumption than the base case (DG). For WWR 50% PV integration was also not justifiable without considering the decrease on grid energy demand due to PV electricity generation. If this reduction is considered, energy savings of approximately 1.35% and 3.55 could be achieved for STBIPV 10% and 16% respectively, compared to the demand for the base case (DG).

On the other hand, the benefits for WWR 75% and 100% were further increased after subtracting PV output from the total energy demand of floors with STBIPV 10% and 16%. Compared to DG energy demand, WWR 75% achieved 10.1% and 11.72% savings after accounting for PV electricity generation from STBIPV 10% and 16% respectively, while WWR 100% achieved savings of 16.2% and 17% for STBIPV 10% and STBIPV 16%, respectively.

Considering the reduction of PV electricity generation for offices with WWR 75% and 100%, the energy consumption was respectively 4-6% and 7-8% smaller than the lowest electricity consumption from the base case (WWR 33%). This indicates that STBIPV is more advantageous for façades with larger window areas due to higher electricity production and lower overall U-value of the wall, since the U-value of the STBIPV glazing is smaller than the opaque wall's.

3.2 Daylighting

Table 2 presents the annual average glare index and daylight illuminance (DI) at the two reference points in each zone for a floor with WWR 100%, as well as the average daylight factor (DF) of each glazing type under an overcast sky condition with 1000 lux. Windows with semi-transparent PV were able to reduce average glare indexes significantly in comparison to the base case without exceeding the limit, which can be attributed to lower light transmission of these windows. For floors with DG windows,

the annual averaged DI exceeded the threshold of 500 lux in all four zones at the two reference points.

Table 2: Glare, daylight illuminance (DI) and average daylight factor (DF) for a floor with WWR 100% with different glazing types.

		Reference Point 1 (1.5m)			Reference Point 2 (6.5m)		
Zone		**DG**	**STBIPV 10%**	**STBIPV 16%**	**DG**	**STBIPV 10%**	**STBIPV 16%**
NE	Glare index	24.32	15.74	18.14	25.94	17.78	20.08
	DI (lux)	5061.17	585.93	994.05	2091.95	235.24	378.88
SE	Glare index	20.5	9.99	12.98	21.84	11.12	14.41
	DI (lux)	4560.48	557.58	984.65	1731.62	197.72	346.81
SW	Glare index	-	-	-	-	-	-
	DI (lux)	2449.88	425.96	753.51	982.64	159.57	279.92
NW	Glare index	20.42	10.12	13.16	21.08	10.58	14.02
	DI (lux)	5775.57	687.47	1215.9	2027.66	231.74	411.69
Average DF (%)		2.978	0.025	0.089			

On the other hand, when STBIPV was integrated into the windows, annual average DI levels at reference point 2 were below the 500 lux limit. Under an overcast sky, the space was only perceived well lit for a floor with clear double glazed windows, where average DF was above 2%. However, for a floor with STBIPVs, DFs were extremely low, with a maximum of 0.09% for STBIPV 16%. The results show that a whole floor with STBIPV with the two selected transparencies may appear very dark and not visually comfortable for its occupants when sky is overcast.

3.3 Overall energy performance

The floor with WWR 100% showed significant benefits from STBIPV integration and its overall electricity benefits are highlighted in Figure 3. It can be seen that the electricity savings from air-conditioning are very similar for both STBIPVs, however, the demand for heating and lighting is approximately 5MWh/year lower for STBIPV 16%. This is a result of the higher degree of transparency of this glazing type that permits more light through, compared to STBIPV 10%. Nevertheless, the electricity generation from STBIPV 10% is slightly higher than from STBIPV 16%: 13.7MWh against 12.8MWh, respectively.

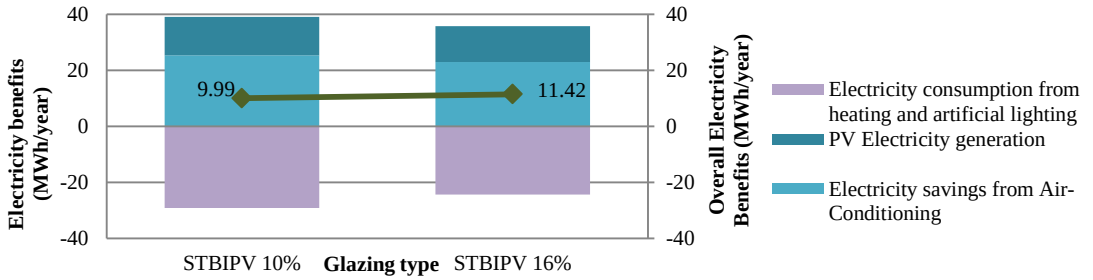

Figure 3: Overall electricity benefits for a floor with WWR 100% with semi-transparent PV.

By subtracting the electricity consumption of heating and artificial lighting from the electricity savings from air-conditioning and PV electricity generation, the overall electricity benefits were obtained. STBIPV 16% grants higher benefits (11.42MWh/year) than STBIPV 10% (10MWh/year), mainly because of the lower demand for heating and lighting. This indicates that thermal performance (energy demand) of the system excels the electrical performance (PV energy conversion) on the overall energy performance in this case.

3.4 Economic evaluation

The payback period was calculated by subtracting the price of conventional glazing from the total investment of STBIPV and then dividing this by the first year's revenues of electricity savings from the grid. It can be expected an additional 25% of national taxes for PV importation.

Table 3: Preliminary economic analysis of a floor with WWR 100% and STBIPV 16%.

	MWh/yr	**R$/MWh**	**Cost (R$/yr)**	**Cost (£/yr, £1=R$3.28)**	
Energy imported from grid	137.76	278.31	38,339.85	11,689.00	
Energy exported to grid	1.33	278.31	369.06	112.51	
	System Cost	**Electricity expense**		**Savings**	**Payback period**
	R$	with PV (R$/yr)	no PV (R$/yr)	R$/yr	years
Taxes included (+25%)	548,183.04	37,970.79	46,214.77	8,243.98	66
No taxes included	413,970.432	37,970.79	46,214.77	8,243.98	50

The results are presented in Table 3, where it is visible the unviability of the system for a floor configuration with WWR 100% and STBIPV 16% for two scenarios: with and without importation taxes. Here, the electricity savings and PV production from STBIPV start paying the investment cost after 50 (no taxes) or 66 years (with taxes). By this time the lifetime of the system of around 20 years has already been expired.

4. Conclusions

In summary, compared to DG windows, both STBIPVs were able to reduce cooling loads significantly. On the other hand, lighting requirements were substantially increased because STBIPV has poorer daylight performance than a clear double glazing structure, especially under overcast skies. This could be further optimized by studying the impact of other solar cell transmittances on overall energy performance. Saving up to 17% of total annual electricity consumption was achieved for a fully-glazed office floor with STBIPV windows 16% transparent and with an overall electricity benefit of 11.42MWh/year, in comparison to the base case.

However, a preliminary economic evaluation showed that the studied integration is not yet feasible for the Brazilian scenario. The payback period of the best case (WWR 100% with STBIPV 16% in all façades) was too long with and without importation taxes. Increasing the electrical conversion efficiency of the solar cell and encouraging more competition in the PV market, especially for semi-transparent PVs, could reduce the payback period and possibly make the system feasible. In addition, future research can investigate the feasibility of the system when integrated only into the façades with higher solar gains, such as the north, east and west.

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