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Daylight performance of perimeter office façades utilizing semi-transparent photovoltaic windows: a simulation study

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Abstract

This paper presents the potential impact of semi-transparent photovoltaic windows on the daylighting performance of commercial building façades. The performance of three façade configurations is examined, integrating Si-based, opaque spaced cells and transparent thin film technologies. Simulation results suggest that a semi-transparent photovoltaic module with visible effective transmittance of 30%, integrated as the outer glass layer of a double-glazed window, provides sufficient daylight within the perimeter zone throughout the year, with $sDA_{300lx/50\%}$=1 and DGI=5%. Moreover, a three-section façade configuration integrating Si-based spaced PV cells on the upper section and thin film PV on the middle section of the façade has the potential to maximize daylight utilization and the view to the outdoors.

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Keywords: Semi-transparent photovoltaic; Dynamic daylight simulations;Commercial buildings

1. Introduction

When considering commercial and institutional buildings completed or under construction during the last several years, one shared characteristic becomes apparent: nearly all of the buildings have enclosures comprised primarily of glass. Older buildings requiring retrofits are being re-skinned with large amounts of glass added to their exteriors. The use of highly-glazed building envelopes has opened the door to innovative technologies such as semi-transparent photovoltaic windows that can incorporate some of the positive attributes of traditional glazing and

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reduce or even neutralize its negative impacts [1,2]. The term semi-transparent photovoltaic (STPV) is used here to cover a broad range of PV technologies, from modules incorporating Si-based (mono-Si and poly-Si), opaque spaced cells to “see-through” thin films such as a-Si/μc-Si [3], organic PV [4] and perovskites [5]. In terms of transparency, Si-based, opaque spaced STPV windows partly obstruct view to the outdoors and provide a non-uniform luminance distribution caused by the opaque PV cells and the light passing through the resulting space between them [6]. In contrast, “see-through” thin films create uniform luminance distributions with monomial or no obstruction to the outdoor view but affects the color rendering properties of the window [7].

A well-designed façade incorporating STPV can enhance the insulating properties of the building envelope, improve its thermal [8] and daylighting [9] performance by regulating solar gains, while generating solar electricity. Such an effective façade design is the three-section façade concept that allows fenestration system properties to be tailored to the particular function of the façade at different heights above the floor [10]. The three-section façade concept (Fig. 1) consists of: i) a bottom (spandrel) section that extends up to workplane height (0.8 m above the floor) and it should be opaque as it contributes little to daylight [11], ii) a middle (view) section which normally extends from the workplane to about 2.0 m above the floor and it allows view to the outdoors [12], and iii) a top (daylight) section that admits daylight deep into the room and it should be designed to protect occupants from direct solar radiation and glare [13].

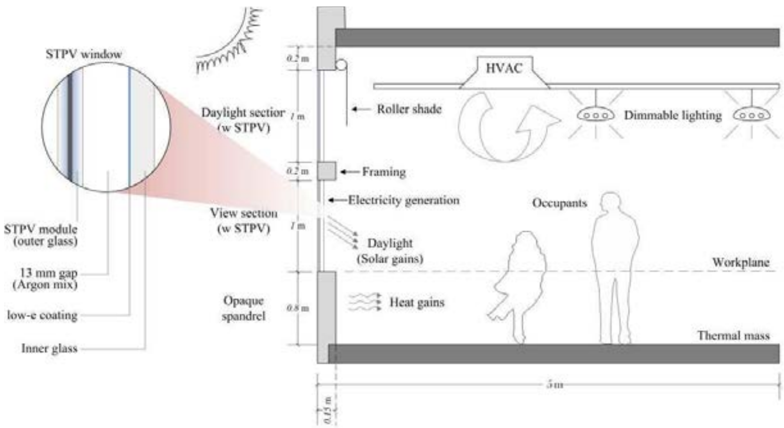

Fig. 1. The three-section façade concept in perimeter office, utilizing semi-transparent photovoltaic windows.

The objective of this study is to investigate the potential impact of STPV windows on the daylighting performance of building façades through the selection of the STPV optical properties. The study focuses on perimeter offices in a continental climate region (Northeastern United States and Southeastern Canada). The end goal of this work is to provide input to the design of cost effective, high performance STPV windows with optical, electrical, and thermal properties suited to commercial building façade applications.

2. Daylight simulation study of a perimeter office utilizing STPV windows

The room modelled in Daysim [14] is a typical, south-facing perimeter office located in Toronto, ON, Canada (latitude 43.7°N). The three-section façade concept was applied with Window-to-Wall ratio of 60%. The office dimensions are 4 m (width) x 5 m (depth) x 3.2 m (height) x 0.15 m (thickness of spandrel and mullion) (Fig. 1). The office surfaces were treated as perfectly diffuse with visible reflectance of 20% (floor), 60% (walls) and 80% (ceiling). A translucent roller shade was used with direct hemispherical transmittance of 5% and diffuse reflectance of 80%. Daysim is an experimentally-validated Radiance-based simulation tool for dynamic daylight and lighting analysis [15,16]. The Radiance simulation parameters used for the analysis are summarized in Table 1.

An absence sensor was utilized to automatically switch electric lighting off when the occupants leave the office (with a 5-min delay) and it was coupled with a continuous dimming sensor (using an ideally commissioned photocell) to maintain minimum workplane illuminance levels. In addition, probability functions were adopted to emulate occupants manually switching lights on and off based on workplane illuminance levels [17], and manually adjusting the height of the roller shade based on solar penetration depth into the room [18].

Table 1. Radiance simulation model parameters

Ambient bounces	Ambient division	Ambient sampling	Ambient resolution	Ambient accuracy	Direct threshold
7	1500	20	300	0.1	0

An EnergyPlus Weather (EPW) file was used as an input to the Perez "all-weather" sky model [19] embedded in Daysim, while a 5-min simulation time-step was selected as a means to capture the short-term dynamics of daylight [20] and manual control of the roller shade and electric lighting [21].

2.1. Parametric study

The STPV window assumed for the parametric study consists of (outer-to-inner layers): i) 10.9 mm STPV module, which optical and electrical properties varied, ii) 12.7 mm sealed cavity filled with Argon mix (10% Air/90% Argon) and iii) 5.9 mm low-e coated glass. Five effective visible transmittance values of the STPV module were simulated: 10%, 20%, 30%, 40% and 50%. The minimum value of 10% was selected in order to ensure a minimum view to the outdoors. The electrical performance of the STPV façade was simulated based on the equivalent one-diode model [22]. As the STPV power output depends on the transmittance of the module [23] (which in returns affects the daylight availability) and the PV cell operating temperatures [24] (STPV windows tend to operate in higher temperatures than free-standing systems), a detailed thermal/electrical model of the office utilizing STPV windows was built in EnergyPlus [25] to predict and quantify such interactions. Detailed information on the electrical performance of the STPV window, the EnergyPlus model and its integration with Daysim model can be found on [26]. Table 2 summarizes the optical properties of the STPV module (outermost glass of the STPV window) and the STPV window (Insulated double-Glazed window Unit, abbreviated as IGU).

Table 2. Optical properties of the STPV module and the corresponding window

Name	STPV10%	STPV20%	STPV30%	STPV40%	STPV50%
STPV module (outer glass layer only) Visible effective transmittance	10.0%	20.0%	30.0%	40.0%	50.0%
STPV window (IGU) Visible effective transmittance	6.1%	12.2%	18.3%	24.4%	30.5%

The performance of three STPV façade configurations were also studied (Fig. 2): i) a three-section façade that utilizes transparent thin film PV, ii) a three-section façade with Si-based spaced PV cells at the view section and thin film PV at the daylight section, and iii) a three-section façade with Si-based spaced PV cells.

Fig. 2. Photorealistic renderings of the view-field of the occupant for the three STPV façade configurations, utilizing transparent thin film PV (left), Si-based spaced PV cells on the view section and thin film on the daylight section (middle), and Si-based spaced PV cells (right).

3. Simulation results and discussion

For this study, the Continuous Daylight Autonomy (cDA) [27], the spatial Daylight Autonomy (sDA) [28] and the Daylight Glare Probability (DGP) [29] metrics are used to evaluate the annual daylighting/lighting performance during the 1827 occupied hours (8:00 to 18:00). Annual and seasonal cDA are presented, for the center line of the office, as the percentage of occupied hours where the minimum workplane illuminance levels of 300 lx (cDA_{300lx}) and 500 lx (cDA_{500lx}) are met. Annual sDA are presented as a percentage of the entire office workplane where the minimum workplane illuminance levels of 300 lx ($sDA_{300lx/50\%}$) and 500 lx ($sDA_{500lx/50\%}$) are met for 50% of the occupied hours. As the DGP is a directional view-dependent metric, it is assumed that the occupant is seated at the center of the room with the view-direction shown on Fig. 2 (45° relative to the STPV façade). For ease of understanding, all of the simulation results are presented as a function of the visible effective transmittance of the STPV module, which is to say the outer glass of the double-glazed STPV window.

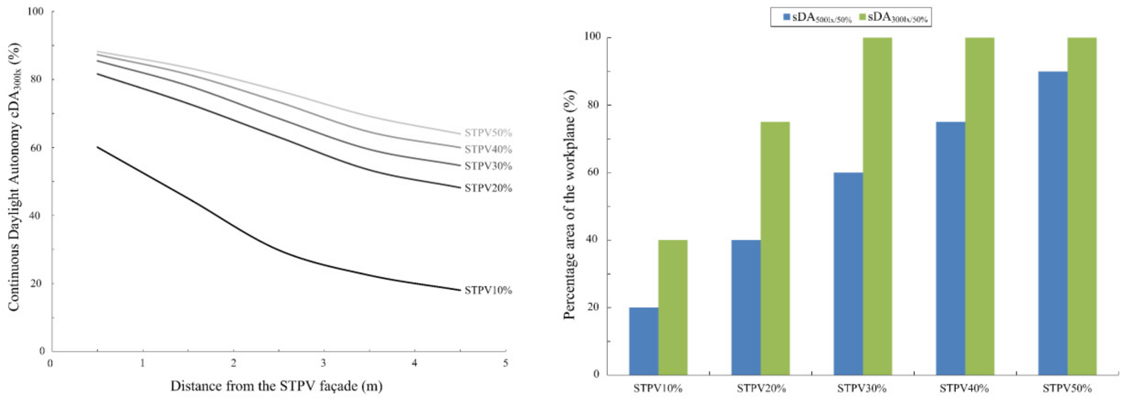

Fig. 3. Annual cDA_{300lx} (left) and corresponding $sDA_{300lx/50\%}$ and $sDA_{500lx/50\%}$ (right) for a façade using STPV modules with various visible effective transmittance (STPV10% to STPV50%). Both figures refer to a façade configuration utilizing transparent thin film PV.

The analysis reveals that the integration of a STPV thin film module with effective visible transmittance of 30% (STPV30%), as the outer glass layer of an IGU, provides sufficient daylight within the perimeter office throughout the year, with $sDA_{300lx/50\%}$=1 and $sDA_{500lx/50\%}$=0.6 (Fig. 3). STPV modules with lower visible transmittance will result to higher annual PV electricity yield and reduced cooling loads [26] (STPV module efficiency and solar gains are inversely proportional to the visible transmittance of the module) but providing inadequate daylight throughout the year. On the other hand, STPV module visible transmittance higher than 30% is not recommended as it will result to reduced annual PV electricity yield and undesirable solar gains that will lead to increased cooling costs [30].

The performance of three STPV façade configurations (Fig. 2), using STPV modules with effective visible transmittance of 30% (STPV30%), is also examined. One would think that the use of different STPV technologies might not affect annual and seasonal cDA, as in all cases the STPV modules used have the same effective visible transmittance of 30%. However, the analysis show that when the thin film STPV module on the daylight section of a three-section façade is replaced with a STPV module utilizing Si-based spaced cells, then the annual cDA could increase by up to 7 to 16 percentage units (0.5 m and 4.5 m away from the façade, respectively) while seasonal cDA could increase by up to 11 to 22 percentage units (Fig. 4). This increase is caused by the interchange of shadows and bright spots on the workplane resulted by the opaque Si-based spaced cells integrated on the STPV window. If the thin film STPV module on the view section is replaced with a STPV module utilizing Si-based spaced cells as well (Fig. 5), then the increase on the annual and seasonal cDA is marginal (up to 3 percentage units). In addition, the use of STPV module utilizing Si-based spaced cells on the view section will partly obstruct the view to the outdoors. Thus, the STPV façade configuration with Si-based spaced PV cells on the daylight section and thin film on the view section is preferred as it has the potential to maximize daylight utilization and the view to the outdoors.

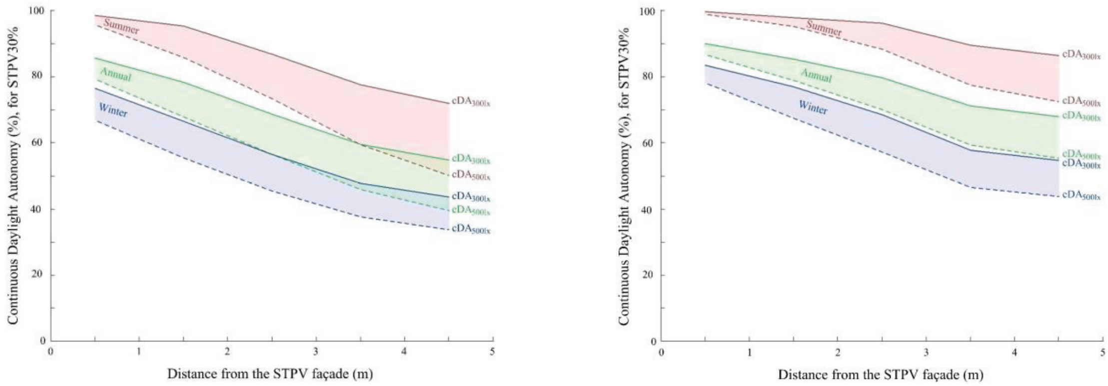

Fig. 4. Annual and seasonal cDA_{300lx} and cDA_{500lx} for a STPV façade integrating STPV modules with 30% visible effective transmittance (STPV30%) utilizing thin film PV (left), and Si-based spaced PV cells at the view section and thin film at the daylight section (right).

For all the three façade configurations, the DGI metric indicates that the glare is intolerable ($DGP \geq 0.45$) for less than 5% of the year (Fig. 5). Despite the use of a roller shade, glare occurs during the fall/winter seasons (October to March, between 11:00-14:00) when the solar altitude is low and solar penetration depth is high. Moreover, for both the façade configurations that integrate Si-based spaced cells STPV module on the daylight section, the glare is perceptible ($0.35 \leq DGP < 0.40$) less than 6.5% and disturbing ($0.40 \leq DGP < 0.45$) less than 3.5% of the year, caused by the non-uniform luminance distribution between opaque PV cells and the light passing through the resulting space between the cells [31].

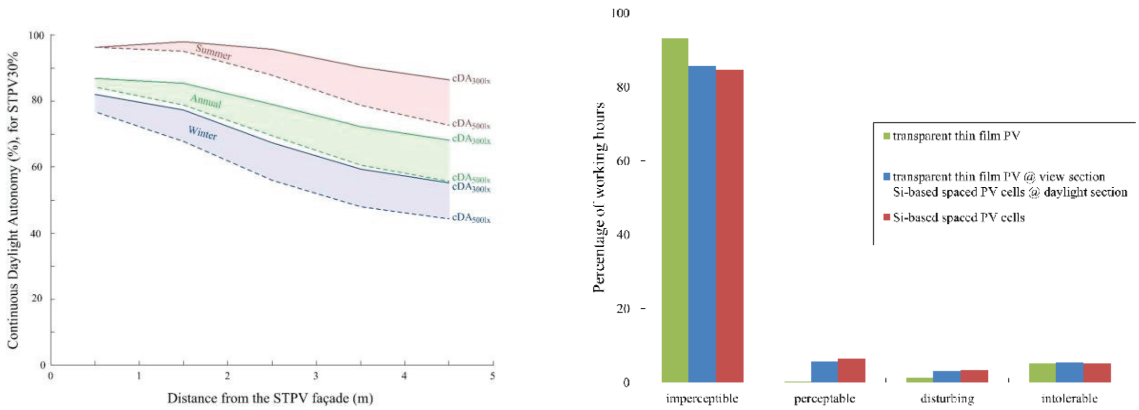

Fig. 5. Annual and seasonal cDA_{300lx} and cDA_{500lx} for a STPV façade integrating STPV modules with 30% visible effective transmittance (STPV30%) utilizing Si-based spaced PV cells (left), and Daylight Glare Probability (DGP) for the three façade configurations studied (right).

4. Conclusions

This study examined the daylight performance of perimeter office façades utilizing semi-transparent Photovoltaic windows. A south-facing perimeter office implementing the three-section façade concept was simulated using Daysim. The daylighting performance of three STPV façade configurations was also examined, utilizing Si-based, opaque spaced cell modules and transparent thin-film technologies. The simulation results revealed that a semi-transparent photovoltaic module with visible effective transmittance of 30% (STPV30%), integrated as the outer glass layer of a double-glazed low-e window, provides sufficient daylight within the perimeter office throughout the year, resulting to $sDA_{300lx/50\%}=1$. STPV visible transmittance higher than 30% should be avoided as it will result in reduced annual PV electricity yield and undesirable solar gains. Moreover, a three-section façade configuration integrating Si-based spaced PV cells on the daylight section and thin film PV on the view section of the façade has the potential to maximize daylight utilization and the view to the outdoors.

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