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# Energy Analysis of Semi-transparent Building Integrated Photovoltaic Window in Hyderabad, India Using Automated Parametric Simulations

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**Abstract.** In recent years, semi-transparent building-integrated photovoltaics (BIPV) technology has attracted attention for its renewable energy utilization. This research aims to develop a methodology for assessing the energy-saving potential of semi-transparent photovoltaic (STPV) window, which has a complex relationship with daylighting and air conditioning (AC) electricity consumption. A case study has been developed for the composite climate of Hyderabad, India. The study examines four commercially available single and double pane STPV windows and similar non-photovoltaic windows. For evaluation, an automated parametric simulation tool was developed to compute the net electricity consumption (NEC) for a representative model building with different window systems, and several window-to-wall ratios (WWR) and orientations. The result shows benefit in adopting the STPV window system across all directions and higher optimal WWR in STPV window as compared to normal window with the same opto-thermal characteristics.

## 1. Introduction

Energy is crucial for human survival and development. Over the last few decades, energy demand has consistently surged across multiple sectors and continues to increase [1]. The building sector is responsible for around 33% of the total energy consumption [2]. With the growing urbanization and economy, the demand for energy in the building sector is rising rapidly. Some of the ways to improve the building energy efficiency is by increasing the reliance on renewable energy and improving the overall building efficiency. Window regulates a significant percentage of total energy consumption of the building and hence, plays a vital role in deciding the energy efficiency of the building [3, 4]. A larger window-to-wall ratio (WWR) provides a better view of the outdoor environment and increases the daylight availability in building. However, this increases the exposure to outdoor weather conditions and may increase/decrease the electricity consumption [5].

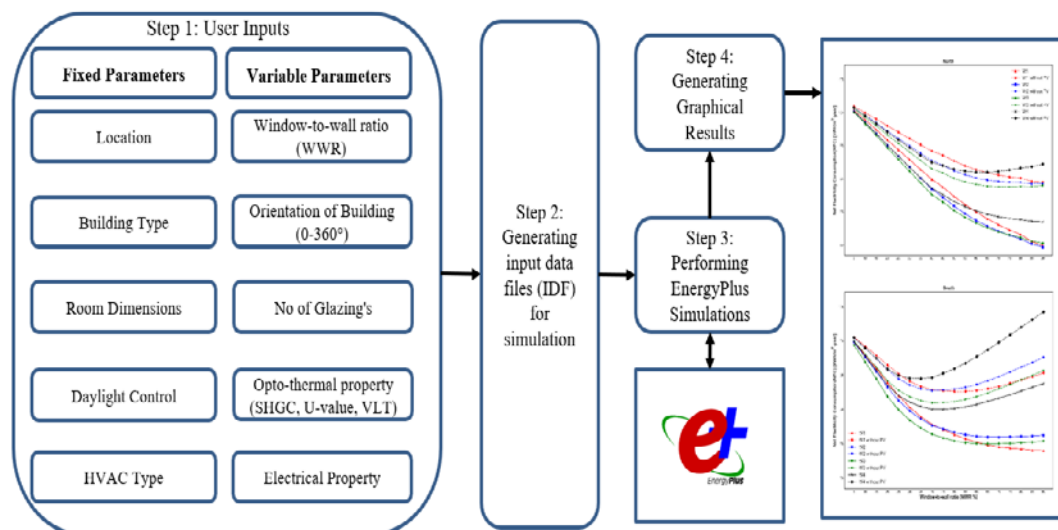
Moreover, new technologies such as building-integrated photovoltaics (BIPV) have been deployed in building façades or windows to generate power and increase overall resource efficiency. BIPV windows have been intensively researched due to their several advantages, including power production, thermal performance and energy saving potential, daylight performance and visual comfort [6-9]. This work aims to investigate the energy-saving potential of building-integrated semi-transparent photovoltaic (STPV) windows in the composite climate zone of India. The study employs



an approach where WWR and orientations are changed simultaneously to get the optimal working condition of STPV window systems under varying weather conditions.

## 2. Methodology

A parametric simulation-based method is developed to evaluate the energy performance of a STPV window. The impact of STPV window systems must be assessed from three different perspectives: optical, thermal, and electrical performance. The optical performance of the model depends on the visible light transmittance (VLT), which is the proportion of light passing through the glass, thereby affecting the artificial lighting usage. Thermal performance depends on the solar heat gain coefficient (SHGC) and thermal transmittance (U-value), which affects air condition electricity use by impacting the heat gain of the room. Electrical performance depends on the electrical parameters of the photovoltaic, which impacts the electricity generation. To analyse the STPV window incorporating all the different perspectives, EnergyPlus is used [10]. EnergyPlus is a building simulation software which complies with ANSI/ASHRAE standard 140-2017 validation test and hence it is employed in this study.



**Figure 1.** Methodology for automated simulations.

The window system with the optical, electrical, and thermal parameters is modelled in EnergyPlus v9.2. The details about the building parameters and modelling are discussed in section 3. The annual energy simulation of various WWR and orientation for a modelled room is performed automatically using a tool developed as a part of this research. Performing parametric simulation to compute the energy performance of four STPV window systems in four orientations and more than fifteen WWR points results in more than three hundred annual energy simulations. This whole process is monotonous and error-prone if not performed carefully. Also, there is a need for platforms that provides the user with more freedom to perform parametric simulation of different parameters. Hence, a web-based, easy-to-use tool has been developed on Flask [11] framework, which gives an interface to the users to perform automated parametric simulation of STPV glazing and standard glazing systems depending on the user requirements. Figure 1 shows the methodology for automated parametric simulations.

The power consumption of air conditioning, artificial lighting, equipment, and power generation from the room's STPV window has been used to assess the room's overall energy performance. The overall energy performance is determined in terms of net electricity consumption (NEC). The formula for NEC is given by equation (1). The simulation calculates the NEC of the room having a window system (PV/non-PV) with a given configuration (WWR, U-value, SHGC, VLT, Electrical Property)

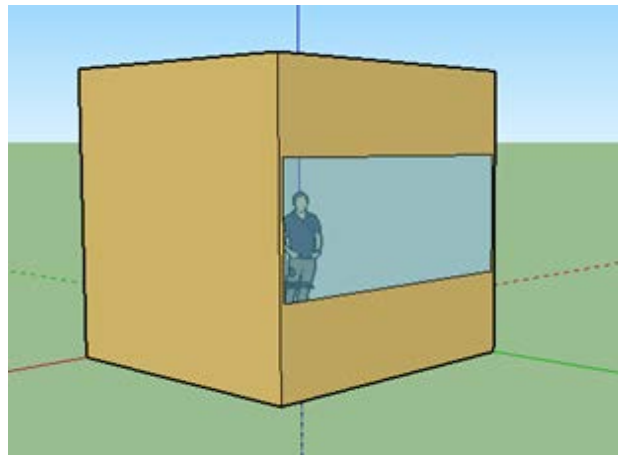
and orientation. Moreover, the optimum direction, WWR, and window system were recommended for a city based on the lowest NEC.

$$NEC = AEC + LEC + EEC - PEG \quad (1)$$

where AEC: AC Electricity Consumption, LEC: Lighting Electricity Consumption, EEC: Equipment Electricity Consumption, PEG: Photovoltaic Electricity Generation

### 3. Simulation model

A single zone room with a dimension of L-10 m x B-10 m x H-3 m was modelled in EnergyPlus as shown in figure 2. The building parameters used for the simulation are shown in table 1. The façade WWR is varied from 5% to 90% in an increment of 5%. The variation of WWR is done in the four major orientations (North, East, West, and South) to identify the best possible orientation for the STPV window. Figure 3 (a)(b) shows an image of installation of STPV window in IIIT Hyderabad campus. The study was carried out in the Indian city of Hyderabad (17.38° N, 78.48° E). The weather of Hyderabad remains warm throughout the year, with little rain in the monsoon. During the summer season, the temperature can go as high as 45° C, while in winters, the temperature may come down to 12° C. The daylighting illuminance reference point was set 0.8 m above the floor in the middle of the room, and 300 lx was fixed as the illuminance set point. "Continuous dimming control" was used as a control strategy to save electricity. The window integrated semi-transparent CdTe photovoltaic (PV) glazing was electrically modelled by using the sandia array performance model (SAPM), which uses experimentally determined coefficients of a PV panel to calculate its electrical production.



**Figure 2.** Single zone simulation model in EnergyPlus.

The application of SAPM to describe the semi-transparent thin-film photovoltaic module in building energy modelling has been validated by Peng et al. [12]. The window configuration and electrical properties of the glazing are listed in table 2 and table 3 [13]. Low-e glazing with transmittance at normal incidence solar (0.295) and visible (0.902) has been used as a second glazing layer for double pane STPV window systems. The same glass opto-thermal properties are chosen without the PV electrical properties to compare and analyse the impact of STPV with non-PV window.



**Figure 3 (a).** STPV window from outside.



**Figure 3 (b).** STPV window from inside.

**Table 1.** Building parameters.

Parameter	Value
Illuminance setpoint	300 lux
HVAC	
• Type	IdealLoadAirSystem
• Cooling setpoint	24°C
• Heating setpoint	20°C
Occupancy	6.5 m <sup>2</sup> /person
Lighting Power Density	8 W/m <sup>2</sup>
Equipment Power Density	10 W/m <sup>2</sup>
Operational hours	0900 – 1800 h
Daylight controls	On
Window-to-wall ratio (WWR)	5 – 90 %
Building Orientation	North-East-South-West

**Table 2.** Window properties.

Window System	Configuration	U-factor W/(m <sup>2</sup> K)	SHGC	VLT
W1	G1/ air gap/ low e glass	1.812	0.228	0.229
W2	G1	5.678	0.210	0.252
W3	G2/ air gap/ low e glass	1.812	0.271	0.297
W4	G2	5.678	0.275	0.327

**Table 3.** Electrical properties of semi-transparent photovoltaic glass.

Glass Id	Nominal Power [P <sub>m</sub> ] (W)	Short circuit current [I <sub>sc</sub> ] (A)	Open circuit voltage [V <sub>oc</sub> ] (V)	Current at maximum power point [I <sub>mp</sub> ] (A)	Voltage at maximum power point [V <sub>mp</sub> ] (V)
G1	47.85	0.59	116	0.55	87.0
G2	43.50	0.54	116	0.50	87.0

#### 4. Results and discussion

This section discusses the preliminary results to understand the impact of WWR and orientations on NEC for the four STPV window systems and non-PV window systems. With the increase in WWR,

artificial lighting energy consumption reduces until certain WWR, whereas the cooling load and PV generation increases. The NEC starts increasing after a certain WWR for the non-PV window because the cooling load keeps on increasing with WWR however reduction in lighting load becomes zero. In the STPV window, NEC decreases for a much larger WWR due to an increase in PV generation with increase in WWR. There is a point of inflection for both the window systems depending on the opto-thermal and electrical properties of the glazing. Figure 4 shows the NEC of the window system in the selected orientations, with different configurations. The dotted and solid line shows the performance of the non-PV and PV window system respectively.

In the North orientation, the NEC of the STPV window systems decreases continuously with the increase in WWR. North receives the lowest solar radiation, as shown in table 4. Therefore, the cooling load of a room with a window in the North direction is much less than in other orientations. The overall energy generation by the STPV and saving from artificial lighting is greater than the increase in cooling load, thereby decreasing the NEC.

Moreover, the result suggests that installing STPV in the West and South results in similar NEC and is the next optimal orientation. Finally, both double-pane STPV systems (W1 and W3) perform better than the single-pane STPV window system (W2 and W4). For low to moderate WWR up to 60-70%, W3 performed better than all other window systems, whereas, for WWR above 70%, W1 is the best.

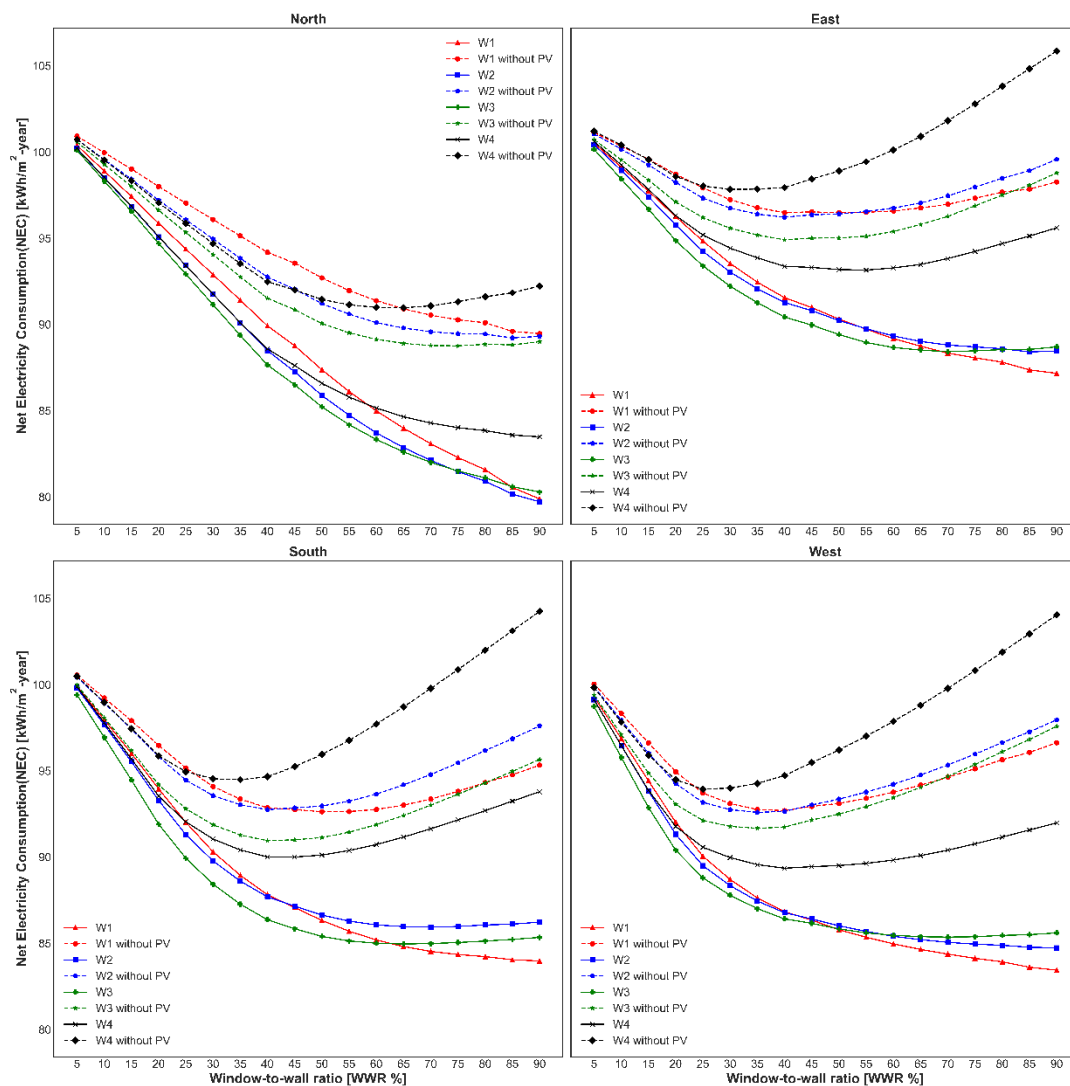


Figure 4. NEC of window systems in different configurations.

**Table 4.** Annual average incident solar radiation.

Orientation	Annual Average Incident Solar Radiation (W/m <sup>2</sup> )
North	65.2
East	120.2
South	118.2
West	118.5

## 5. Conclusion

This study observed that the relationship between windows and energy consumption in the building is a complex problem. The addition of PV as a glazing component in the window further increases the complexity. A parametric simulation-based methodology is proposed to evaluate the energy performance of the four commercially available STPV window systems and assess the relationship between glazing and energy consumption. The study's primary finding is that both the PV and non-PV window system NEC curves have a point of inflection. The inflection point for the PV window system is at a higher WWR than regular glass; hence, more PV can be installed in the building façade. Also, the STPV window system installed in the North has the lowest NEC compared to other orientations. Further, this study also suggests a need for a tool to perform automated parametric simulations and provide accurate results to perform similar analyses for different window configurations and locations.

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