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Numerical Investigation on the Performance of Solar Photovoltaic Shading Above Building Window

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ABSTRACT

Energy consumption in Bangladeshi buildings is rapidly increasing due to growing demand and urbanization. Energy-efficient designs can significantly reduce this consumption while improving thermal comfort. This study investigates the performance of solar photovoltaic (PV) modules used as external shading devices above building windows under Bangladesh's climatic conditions. EnergyPlus simulation software was employed to analyze a single-room model with two PV modules (1001 mm × 734 mm each) installed as shading. The analysis focused on solar heat gain, daylighting performance, and electricity generation. Results show that PV shading effectively reduces solar heat gain through windows and generates substantial electricity. For a south-facing window at a 30° tilt, solar heat gain decreased by about 20.82% compared to an unshaded window, while annual electricity generation reached approximately 283.86 kWh/m² - over 20% higher than east or west-facing configurations. However, increasing the tilt angle reduced daylighting levels, potentially increasing the need for artificial lighting. The findings highlight that south-oriented PV shading with a 30° tilt provides the optimal balance between thermal comfort and energy generation for energy-efficient buildings in Bangladesh.

Keywords: Photovoltaic Shading, Building-Integrated Pv, Energyplus, Thermal Comfort, Daylighting.

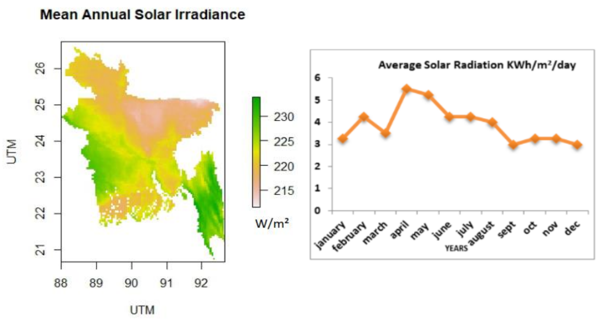
1. Introduction

In Bangladesh, energy consumption is rising rapidly due to population growth and higher living standards. To meet this demand, it is crucial to promote energy efficiency and renewable generation [1]. Energy-efficient buildings can significantly help reduce the growing energy crisis [2]. Building Integrated Photovoltaic (BIPV) systems offer a sustainable solution by generating electricity through the building envelope. PV modules mounted on roofs or façades can produce power and improve thermal performance [3]. In Bangladesh, using PV modules as window shading can provide dual benefits, such as lower cooling loads and added power generation, although limited studies have explored this under local climatic conditions.

External shading improves thermal comfort and efficiency, and integrating PV modules as shading further enables renewable energy use while maintaining visual comfort. This study investigates PV window shading performance in Bangladesh to evaluate its potential for energy savings and electricity generation. In the country's warm climate, reducing solar heat gain is essential to minimize cooling demand, especially as shading use in modern buildings continues to decline due to design preferences.

Fig 1 shows the mean solar irradiance in Bangladesh on monthly basis which represents how much solar irradiance is incident in different areas of Bangladesh and the solar irradiation on monthly basis. It represents how solar irradiation varies every month in Bangladesh.

Several studies have explored PV integration as shading or façade elements. Yun et al. [6] and Kim et al. [7] analyzed shading control strategies in Korea, reporting improvedenergy performance. Palmero et al. [8] and Manzan et al. [9] demonstrated that external fixed shading effectively reduces sunlight and enhances daylighting balance. Yang et al. [10] [12], Peng et al. [11], and Dominguez et al. [13] found that PV integration on façades and rooftops can reduce cooling loads by 33–65%. Yoo et al. [14], [15] evaluated rooftop and sunshade PV modules for south-facing buildings, while Sun et al. [16], [17] optimized PV shading geometry for Hong Kong. Rababah et al. [18] discussed challenges of BIPV adoption in South Asia, where costs are higher but solar potential is strong. Mesloub et al. [19], Lin et al. [20], and Frasca et al. [21] examined visual and thermal performance improvements using PV façades. Abdelsalam et al. [22] reported that external shading offers better lighting and thermal benefits than internal systems



(a) (b)

Fig. 1 (a)Mean Annual Solar Irradiance in Bangladesh from 2001-2017 [4] and (b) A profile of average solar radiation throughout the year in Bangladesh [5].

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Solar PV modules used as shading can reduce solar heat gain but may also lower indoor daylight, increasing artificial lighting demand. This study aims to determine the optimal PV window shading setup in Bangladesh that balances daylighting, thermal comfort, and power generation. Different orientations and tilt angles were analyzed to evaluate their energy performance and potential design improvements.

Solar heat gain is the amount of solar radiation entering a building, and lower values reduce cooling loads in hot climates. The declination angle, between the Earth–Sun line and the equatorial plane, explains why north façades receive less sunlight. The daylighting factor (DF), the ratio of indoor to outdoor illumination, was assessed for different PV tilts to find the best daylight–shading balance.

This work investigates PV modules as shading devices in Bangladeshi buildings, focusing on annual electricity generation and thermal performance. Due to limited local data, this study serves as an initial feasibility analysis emphasizing energy and comfort benefits.

2. Methodology

Since this is a numerical analysis, the first step is to select a building and conduct performance simulations based on its characteristics, such as location and photovoltaic (PV) features. To do this, software is needed that allows for 3D modeling as well as performance simulation.

2.1 Climate Condition

The investigated building is a residential building and it is located in the city of Dhaka. It is a district in the geographical center of Bangladesh, with a Latitude of 27.77°N, a Longitude of 90.38°E, an Elevation of 2.7m, and a Time zone of GMT+06.00. The hottest summer month is May.

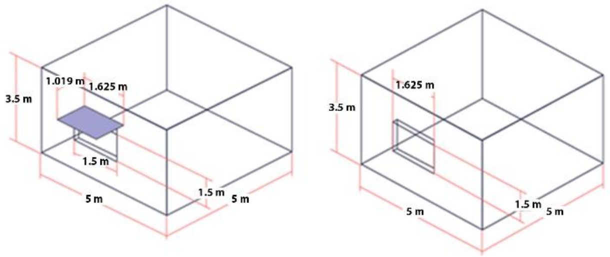
2.2 Software Selection

To investigate the overall performance of the building and PV module when the PV module is used as a shading device over the window, a building energy simulation program, EnergyPlus, which is widely accepted, was used [24]. For this purpose, a 3D building modeling software, DesignBuilder, which has engines such as EnergyPlus, CFD, Radiance, etc., to analyze different indoor and outdoor energy conditions of a building.

2.3 Description of Model

In this study, a generic residential building (single room) was used. The size of the room (W × D × H) was (5m × 5m × 3.5m). Only a single window was exposed to the outside environment. The entire wall was assumed adiabatic, so that no heat transfer could affect the results. The single window dimension was 1.524m × 1.524m. There was a PV shading over the window which had a dimension of 1.625m × 1.019m ×0.046m.

Fig. 2 shows the isometric view of the building before and after installing PV panel over the window. It shows the building with the PV shading with the dimensions.



(a) without shading (b) with shading

Fig. 2 Perspective view of the building.

<u>Description of the PV Module</u>

For this study, a PV from Sun module (SW 100W POLY RGP) was chosen because it has proper manufacture data and because of its dimensions, if two modules are installed side by side in series, they cover the window best.

2.4 Simulation Procedure

To investigate the building's performance for different tilt angles of the PV panel above the window, different performance was analyzed on hourly, monthly and annual basis. The tilt angle has been taken with a 10-degree increment from the 0-degree tilt angle in every geometrical direction: South, East, West, and North. For different tilt angles, electricity generation, solar gain data through the window, and daylighting performance were analyzed in every direction.

To investigate the effects of PV shading sizes on thermal and electricity generation performance, three different PV modules were taken as shown in Fig. 3.

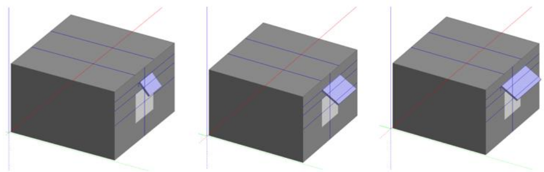


Fig. 3 Perspective view of the PV shading over the window

Table 1 Different PV module sizes

Name in this study	Dimensions
PV Shading 1	1.625m × 1.019m
PV Shading 2	1.001m × 0.734m
PV Shading 3	2.202m × 0.734m

3. Results and discussions

3.1 Solar Heat Gain Through Window

(a) <u>Without PV Shading</u>

Fig. 4 shows the solar heat gain data through the window in May, without PV shading. It is showing the solar heat gain data for the first 10 days of the month. Peak heat gain occurs at the east side window before noon and at the west side in the afternoon. Heat gain through the south and north side windows shows a peak gain at midday; however, peak values are lower than those of the east and west side windows.

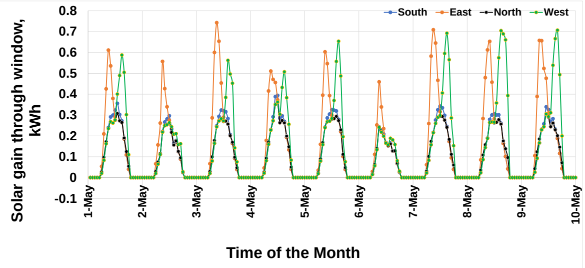


Fig. 4 Solar heat gain through the window in different directions in May.

(b) With PV Shading

Fig. 5 shows the solar heat gain from the east-facing window with PV shading at different PV shading tile angles. It shows the hourly data of a typical day in May. The blue line illustrates the data without PV shading, as shown in Fig. 4, differentiating between solar heat gain data with and without PV shading. The figure illustrates that the use of shading decreases solar heat gain. As the tilt angle of the PV shading increases, the solar heat gain further decreases. It is important to note that tilt angles are considered up to 60 degrees; beyond this angle, the PV or any shading device may block sunlight from entering the space. Focusing only on the east direction, employing shading results in enhanced comfort by significantly reducing solar heat gain inside the interior.

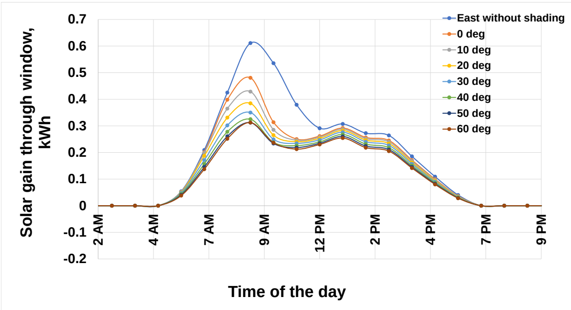


Fig. 5 Daily average solar heat gain from the east-facing window at different tilt angles of the PV shading.

Fig. 6 shows the solar heat gain through the west-facing window for various tilt angles of PV shading. The maximum value of the solar heat gain is 0.58 kWh when there is no shading and if shading is used, then it comes to 0.45 kWh in maximum at 0 deg tilt angle of the shading. It also decreases as the tilt angle increases. So, if only the west direction is considered, then it will give better comfort if shading is used, as solar heat gain at the interior decreases a greater amount.

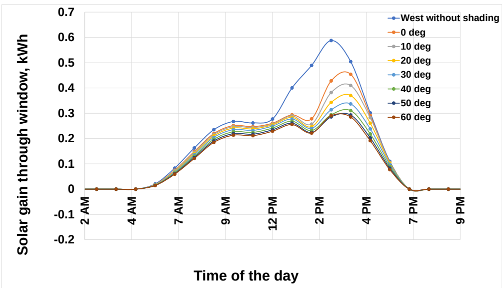


Fig. 6 Daily average solar heat gain from the west-facing window at different tilt angles of the PV shading

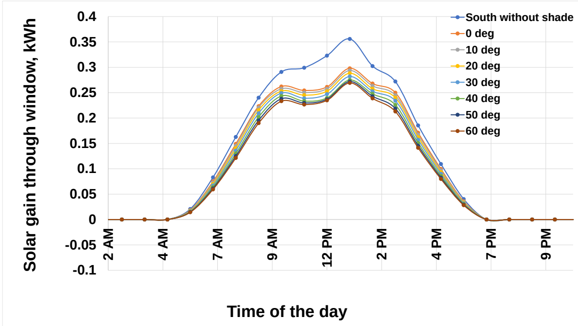


Fig. 7 Daily average solar heat gain from the south-facing window at different tilt angles of the PV shading.

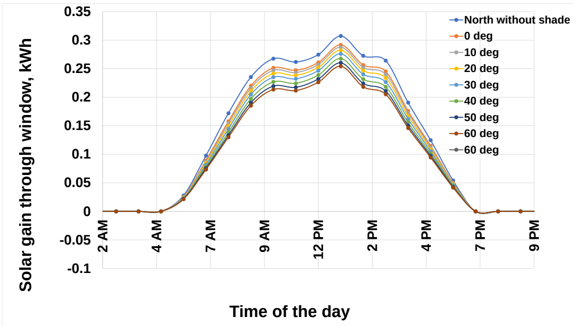


Fig. 8 Daily average solar heat gain from the north-facing window at different tile angles of the PV shading

From Fig. 7, it can be observed that the maximum solar heat gain is decreased from 0.35 kWh to 0.29 kWh when a PV shading is used over the south-facing window. Fig. 8 shows the solar heat through the north-facing window. The maximum value of the solar heat gain is 0.31 kWh when there is no shading and if shading is used, then it comes to 0.29 kWh in maximum at 0 deg tilt angle of the shading. It also decreases as the tilt angle increases.

So, if only the west direction is considered, then it will give better comfort if shading is used as solar heat gain at the interior decreases.

So, from the above analysis, it can be seen that it's better to have shading over window. And if we do some further analysis then south and north face window gives better results.

3.2 Annual Electricity Generation

Fig 9 represents the annual electricity generation from solar PV shading at different tilt angle of the PV shading and at different orientation of the building in Bangladesh. The vertical axis represents the annual electricity generation from per unit area of the PV shading above the window and horizontal axis represents the tilt angle of the PV shading.

The graph shows that the optimum location for the installation of the solar PV shading is on the south side window, and for all tilt angles, generation is maximum. And the worst orientation is in the north. It's because the sun's movement is not directly from east to west. It creates a declination angle. For this reason, the north façade window doesn't get that much solar radiation compared to the other directions. The east and west oriented building window give a very close value, but they are less than the south façade window generation value.

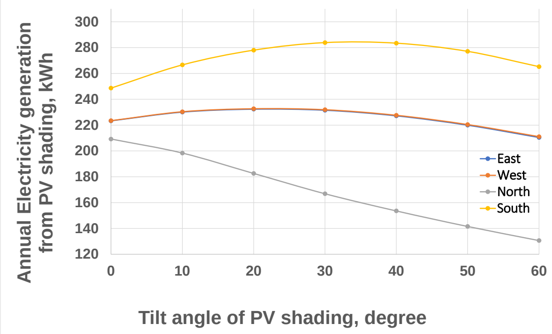


Fig. 9 Annual electricity generation from the solar PV shading.

The maximum annual electricity generation in the south-facing window of a building is at 30 30-degree tilt angle, and the value is 283 kWh/m^2 of the PV shading. At the west and east directions, the maximum value is between 20 and 30 degrees of tilt angle.

3.3 Comparison of Thermal and Electricity Generation for Optimum Output

Now, an optimum result has to be taken from the above analysis. In order to get the maximum annual electricity generation from the PV shading, the optimum installation of the solar PV shading has to be in the south direction and the tilt angle should be 30 degrees. In the south façade, it gives more electricity generation, and at 30 30-degree tilt angle, it gives 283.86 kWh, which is 20% more than the corresponding east and west-facing window solar PV shading. So, someone wants to install in only one direction of the building, then the south direction will give the most optimum results.

Table 2 Different PV shading scenarios

Scenarios	Shading design for optimum results
East	Solar PV shading with 20 deg tilt angle
West	Solar PV shading with 20 deg tilt angle
North	Solar PV shading with 0 deg tilt angle
South	Solar PV shading with 30 deg tilt angle
Overall optimum	Solar PV shading with 30 deg tilt angle in the south direction

In this study, the electricity generation is shown in terms of per unit area of the PV shading, and it will be used over only one window of a prototype building. So, if it can be implemented over every window, then it will give some power output, which will not contribute a huge amount, but a significant amount of power in terms of demand. This system has another advantage that it will not occupy any extra area of a building envelope, so, if it is possible to manufacture different designs of the PV modules in the near future, then people will also be motivated to use PV as a shading device over the building window in Bangladesh.

3.4 Effect of PV Shading Sizing

(a) Solar heat gain

PV shading 2

Fig. 10 shows hourly solar heat gain data from the PV module for the south-facing window on a daily basis. It's seen that all the solar heat gain is more than 0.3 kWh, whereas in the previous case, it was a maximum of 0.29 kWh in the south-facing window shading.

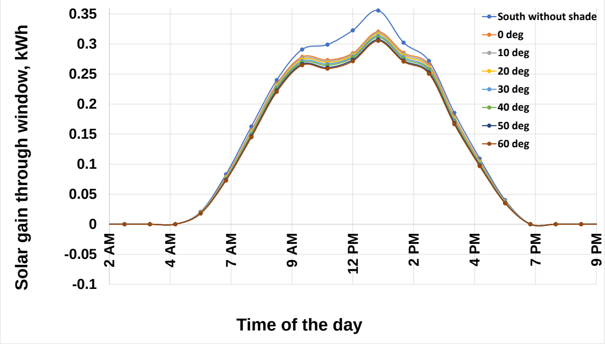


Fig. 10 Hourly solar heat gain from a south-facing window at different tilt angles of the PV shading 2.

PV shading 3

Fig 11 shows the hourly solar heat gain data from the PV module of a daily basis in the south faced window for increasing the size of the PV shading. It's seen that all the solar heat gain is less than 0.28 kWh where in the PV shading 1, it was maximum 0.29 kWh in the south faced window shading and for a smaller size of the PV shading PV shading 2, it was more than 0.3 kWh.

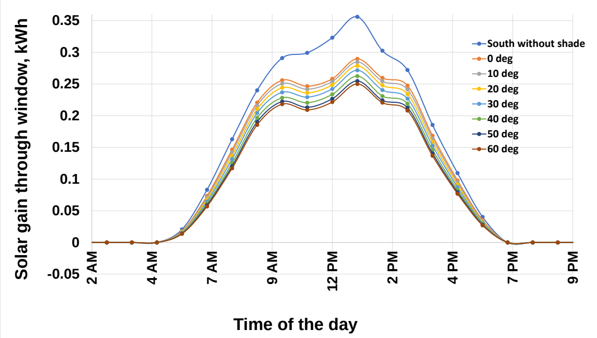


Fig. 11 Hourly solar heat gain from a south-facing window at different tile angles of the PV shading 3.

(b) Electricity generation

Fig. 12 shows the annual electricity generation from the PV shading for different sizes of the PV shading over the window. It only shows annual electricity generation from the south direction.

Here, only the south direction is shown because in the previous analysis, it was seen that in the south direction, the generation is noticed to be maximum, and also it gave the minimum solar heat gain. The other direction will act as the same.

(c) Daylighting Analysis

Comparing the daylighting for different sizes

Fig. 13 shows the daylighting factors for different tilt angles of the PV shading for the main size PV shading, bigger size, and smaller size PV shading in the south-facing window.

For the bigger size PV shading the daylighting factor is the lowest among the three. It's because when the size is big, then less natural light will be able to penetrate into the zone. The line for the bigger size PV shading is very close to the main size PV shading, it's because the main PV shading was modeled according to the window size. So, it blocked a larger portion of the solar rays. And when the size is increasing, then it just increases the side area of shading and blocks some more, but not a large portion of solar rays. For the smaller size of the PV shading, it is smaller than the window size, so a large portion of solar rays are penetrating into the zone. That's why the value is much greater than the other two sizes of the PV shading.

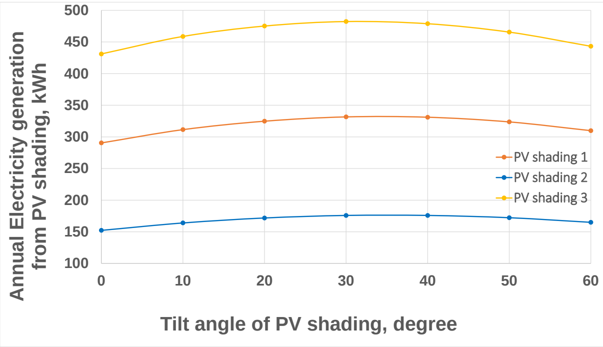


Fig. 12 Annual electricity generation from different sizes of solar PV shading over the south-facing window.

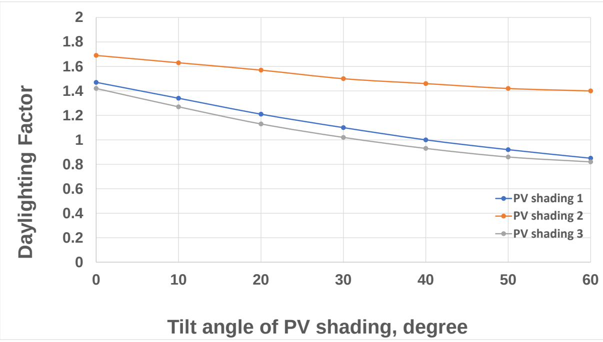


Fig. 13 Comparison of the Daylighting factor for different tilt angles of the south-facing PV shading.

So, there is an effect of changing the size of the PV shading over the window. With increasing size, the electricity generation increases as more cells are added. And at the same time, solar heat gain and daylighting factors are also decreased. But overall, it increases the initial cost of the PV shading installation. So, it's better to use the optimum size of the PV shading as it will give the optimum output in the thermal and generation sector.

4. Conclusion

In this study, the performance of the PV shading above a building window in Bangladesh has been observed where it is found that the solar PV shading has an impact on the solar heat gain through the window, daylighting performance, as well as generating electricity.

The location was taken in a city of Bangladesh. It can be any city in Bangladesh as it doesn't change the results that much, as within Bangladesh the latitude, longitude and elevation don't change significantly. The main conclusions of this study are given below:

i. The optimum annual electricity generation from the PV shading is in the south-facing window at 30 30-degree tilt angle of the PV shading. The annual electricity generation is around 283.86 kWh/m^2 from south PV shading, which is more than 20% higher than from west- and east-facing window PV shading.

ii. Solar PV shading reduces the solar heat gain through the window when it is used as window shading. From the south-facing window, PV shading at a 30-degree tilt angle can reduce solar heat gain by around 20.82% compared to a similar window without shading.

iii. The daylighting performance is affected with increasing the tilt angle of the PV shading, which will have an effect on artificial lighting inside the building. Daylighting factor decreases with increasing tilt angle of the PV shading and with increasing the size of the PV shading.

The annual power generation is a maximum of 283.86 kWh from south-facing PV shading, which is not a significant amount from one window PV shading. But a building has many windows. Consequently, if it can be used across multiple windows and on a large scale, significant benefits will be gained.

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