Potential Benefits of PV-Shading System in Office Buildings and Semi-Continental Climate Conditions

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Abstract. Solar PV shading devices are good solutions to control daylight and reduce the unwanted solar gains, while generate electricity at the same time. Since thermal, electrical and daylighting performance competing each other, it is imperative to consider specific design criteria to optimize and allow energy efficient level of thermal and visual performance. In this context, the study focus on the optimum design of PV shading devices for typical office building with high fenestration ratio and climate conditions of Prague. TRNSys simulation environment was used for the evaluation of the power and thermal performance of the PV shadings considering various tilt angles, projection depth and orientations. Ecotect/Daysim software tools were used to evaluate the daylighting performance and lighting energy use. Useful Daylight Illuminance (UDI) and Discomfort Glare Probability (DGP) indices were also calculated for indoor visual comfort analysis according to the design configuration. Results were overall evaluated to reveal the potential energy benefits compared to the non-shaded case. The study serves as a guide for the optimum design of PV shading systems.

1. Introduction

Building sector can be classified among the leading energy consumers and carbon emitters, contributing by 40% of the primary energy and 39% of CO₂ emissions within Europe [1]. Currently, there is a major transformation taking place through national building codes, roadmaps and building rating systems. Energy efficiency is becoming an integral part of the building design in order to achieve national targets but also long-term climate change strategies (EPBD recast, EED) [2, 3]. In addition, an emphasis is given on the adoption of renewable energy systems on the building envelope [4]. From that point of view, photovoltaics are expecting to be the main technology to generate on-site electricity in high performance buildings.

Because of the request of modern architecture for transparency, glass has been increasingly used and is today a key material in façade technology. Especially for office buildings, is due to the fact that daylight and view to the outdoors have to some extent a positive effect on occupants’ health, well-being and productivity [5]. Nonetheless, excessive daylight in office rooms can contribute negatively to indoor comfort and increase the energy consumption in summertime. The problem has also been observed for office buildings with high fenestration ratio in the city of Prague.

An effective way to control daylighting, decrease solar gains during summer and generate electricity at the same time, is the use of building-integrated photovoltaics (BIPV) as in façade shading systems. Configurations vary between overhangs, side fins and louvres [6], while different PV materials, opaque or
semi-transparent [7] can be used. Among the influential parameters that affect building’s performance are the WWR, location and geometrical characteristics, but also orientation and tilt angle of shading device.

A significant number of research studies have dealt with active solar systems integrated in building envelopes. However, only few studies deal with the overall energy performance of PV shading devices and visual comfort at the same time. Vassiliades et al. [8] investigated integration of such systems in terms of energy production, shading and insolation of building facades, as well as in terms of visual comfort. Sun et al. [9] examined the effect of orientation and inclination, while Zhang et al. [10] recommended that installation of PV shading on a south façade with 20° slope will maximize the overall electricity benefits in Hong Kong. Finally, Mandalaki et al. [11] evaluated various types of fixed shading systems in terms of daylighting and visual comfort.

These studies usually performed on hot climates where optimal configuration can vary significantly from the one in Prague, where such studies are very limited. In the present work, extensive parametric simulations carried out in Ecotect/Daysim/Radiance software to account for daylighting performance and indoor visual comfort. Additionally, electrical performance of PVs and annual energy demand for heating/cooling were analysed through dynamic simulations in TRNSYS. In the end, results were overall evaluated and recommendation are given for the optimal design configuration and climate conditions of Prague.

Figure 1. Geometrical characteristics of the selected office and orientation used for simulations.

2. Methodology
In current study a typical office room with dimensions 5.9m x 5m x 3.6m was adopted for simulations (Figure 1). It is characterized by only one external façade facing south, while internal walls, floor and ceiling considered adiabatic. Opaque part constitutes the 48% of the façade with U-value estimated about 0.19 W/m²K. The rest part is transparent including four identical triple-glazing insulating units with a U-value of 0.5W/m²K. The characteristics for both opaque and transparent part are presented in Table 1. Overheating is evident in such office rooms without shading, leading to discomfort, especially during the summer period (but even in sunny days of heating period). In this context, static shading device with integrated PVs is analysed for its potential to mitigate solar gains during summer, while not affecting daylighting and passive heating during winter.

Frameless glass-glass poly-Si PV modules with dimensions 1600mm x 990mm each were used as overhangs above the transparent part of the façade. For the simulations stable parameters were the dimensions of the PV modules and variables were orientation (see Figure 1), tilt angle (from 0 to 90°) of the modules and overhang projection (see Figure 2). Weather data of Typical Meteorological Year (TMY) in city of Prague were extracted from METEONORM. Subsequently, a radiation model available in TRNSYS was used for the estimation of radiation on tilted surfaces. It uses Perez sky model and parameters for the location of the building, while it was validated for optimal operation in previous work [12]. Equivalent one-diode model was used to reproduce the real behavior of the system and estimate
the output power generated by the PVs. An appropriate performance ratio (PR) is then considered to take into account the rest system losses (mismatch, inverter, etc.) [13].

Dynamic thermal simulation environment of TRNsys was used to predict the effect of PV shadings on the air temperature of the office and thus the need for heating and cooling over a year period. Construction materials with their thermo-physical properties were imported through the TRNBuild interface, while glass insulated units were developed in WINDOW [14]. The office is occupied from 8AM to 6PM during the weekdays with set point temperatures of 19° for heating and 26° for cooling. For simulations, ideal-heater and cooler with efficiencies of 1 were assumed, while internal heat gains were set to 200W continuous [15] according to occupancy schedule.

**Table 1.** Properties of the opaque and transparent part of curtain wall (mean U-value=0.68) and key parameters for the selected PV module.

| Opaque part |  |
|---|---|
| Thickness (mm) | Area (m²) | U-value (W/m².K) | Layers |
| 8 – 140 | –50 | –140 – 20 | 10.2 | 0.19 | Coloured glass panel – Air cavity – Extruded polystyrene – Mineral wool – Plaster |

| Transparent part |  |
|---|---|
| Structure | Thickness (mm) | T<sub>SOL</sub> | R<sub>SOL</sub> | T<sub>VIS</sub> | U-value | SHGC |
| Triple glazing | 6 – 18 | 6 – 18 – 6 | 0.215 | 0.5 | 0.522 | 0.8 | 0.262 |

**PV shading device (glass-glass PV)**

| Dimensions (mm) | Cell type | I<sub>SC</sub> (A) | V<sub>OC</sub> (V) | I<sub>MP</sub> (A) | V<sub>MP</sub> (V) | Temp I<sub>SC</sub> (%/°C) | Temp V<sub>OC</sub> (%/°C) |
|---|---|---|---|---|---|---|---|
| 1600 x 990 | Poly-Si | 8.74 | 37.1 | 8.19 | 29.9 | 0.04 | -0.30 |

Daylighting analysis was carried out through Daysim software, while Ecotect used for the development of the geometry and visualization of the results. A grid at the height of 0.8m above the floor was selected for the evaluation of indoor illuminance inside the office. Annual amount of daylight and light quality were quantified through the metrics Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) [16]. Finally, glare analysis were performed with vertical eye illuminance values at the height of 1.2m considering a working area at the centre of the room. For electrical lighting consumption, a photosensor
dims the activated lighting until the work plane illuminance reaches the desired value (500lx). In this case, fluorescent tubes with luminous efficacy of 50lm/W and lighting power density of 10 W/m² were assumed.

3. Results and discussion

3.1. Electricity generation

Simulation results regarding annual electricity generation of the installed active solar systems are presented in Figure 3 for varying slope and orientation. Best results obtained for South followed by SE and SW. Regardless orientation, highest amount of electricity (annually) is generated from PVs with 30° slope. In general, PV production increases with the increase of the tilt angle up to this level. Exceeding this point, it decreases sharply till 80° where lowest generation is observed. It is worth to mention that vertical PV claddings would generate less electricity compared to horizontal or tilted PV shading systems. Finally, annual generation for South orientation and 30° slope equals to 726.8 kWh (or 145kWh/m²) which is 5.5% higher compared to South-west.

![Figure 3. Annual electricity generation per unit area of PV for varying tilt angle and orientation.](image)

3.2. Heating/Cooling electricity demand

As a first approximation about the effect of the PV shading on cooling demand of the office, number of hours of overheating were calculated and presented in Figure 4. It is obvious that PV shading can effectively reduce overheating regardless the tilt angle of installation. Further evaluation was made through the calculation of the degree-hours of overheating \((DHO)\), which reflects the time and exceedance of maximum temperature and thermal comfort [17]. It is calculated as follows:

\[
DHO = \sum_{i=1}^{n} (T_i - 26) \times t \quad [\text{degC} \cdot \text{h}]
\]

where \(T_i\) is the instantaneous value of temperature inside the office (°C), \(t\) is the time step considered (h) and \(n\) is the number of time steps used for analysis. Calculated values of \(DHO\) indicated that efficiency of PV shading depends on the tilt angle. As expected the lowest value of \(DHO\) was obtained for the horizontal installation (highest projection), but similar results can be achieved for angles up to 30° (Figure 4). In that case, values for \(DHO\) could be three times lower compared to the reference case.

Afterwards, annual heating and cooling needs were calculated to estimate the thermal demand of the room. Cooling demand reduces as the overhang projection increases (lower tilt angles) up to 74% compared to reference case. Opposite trend is observed for heating demand but the effect is less significant with maximum increase in the range of 20%. Results for thermal energy use including both heating and cooling are presented in Figure 5. An interesting remark is that, regardless the slope and azimuth, thermal energy demand decrease in total by 34%, 28% and 29% for S, SW and SE orientations respectively. Optimal slope of PVs is 10° for South and SW orientations, while best results for SE obtained by horizontal overhang.
3.3. Lighting electricity demand
Besides the reduction of cooling loads integration of PVs as shading devices can also control daylighting. A simulation analysis was carried out which allows the comparison of daylight distribution between reference condition and shading device configurations. Initially, $DA (\%)$ was calculated and used for the estimation of the annual lighting energy use according to the following equation:

$$E_L = P_L h_w (1 - DA) \quad [\text{kWh}]$$

where $P_L$ is the light power installed (W), $h_w$ is the time of occupancy (h) and $DA$ is the average daylight autonomy over a year period ($\%$). Based on the results presented in Figure 6, lighting energy increases as the slope of PVs decreases (higher overhang projection). The average values of $DA$ are consistently high ranging between 71\%–76\%. Maximum difference between reference and PV shading is 5.2\% which leads to extra 45 kWh for lighting annually. In terms of orientation, simulations indicated that lighting energy is not significantly affected.

3.4. Indoor visual comfort
Figure 7 illustrates the distribution of DA and UDI inside the office. It can be observed that DA is not affected significantly from the addition of PVs, while three zones are created based on the performance. Highest values achieved for the façade zone (next to windows) followed by central (working area) and rear zone at the back of the room. Level of illuminance inside the office follow similar trend with the reference case but increase significantly (~15\%) the percentage which falls in the range 100–2000 lux and thus visual comfort. Effect is more significant at the rear and central part of the office and minor close to the façade where working tasks should be avoided.
The effectiveness of PV shading in terms of visual comfort was also demonstrated through glare reduction. The same inputs used for UDI was adopted for the calculation of the Daylight Glare Probability (DGP) and provide the comparison between reference and PV shading scenarios. As shown in Figure 8, glare attenuates significantly, on a year distribution, when passing from reference to PV shading cases. Percentage of working hours, where DGP values exceed the 0.4 limit, decrease from 18% to only 8.9%. Improvement is mainly observed during noon for South oriented facades and the summer period where the sun is at higher position and overhangs block direct solar radiation.

Figure 7. Distributions of Daylight Autonomy (DA) and Useful Daylight Index (UDI) inside the office room for a) reference, b) horizontal and c) optimal tilt angle of PV shading device.

Figure 8. Comparison of Daylight Glare Probability (DGP) as a function of time between reference case and PV shading.

3.5. Overall performance
Individually presented results demonstrated different effect of tilt angle and orientation on the power, thermal and daylighting performance of PV shadings. Therefore, it is imperative to evaluate the overall electricity benefits and provide guideline for the optimal integration of PVs as shading devices. Results from this process are presented in Figure 9 according to PV tilt angle and azimuth of the external façade. Increasing the angle leads to a decrease of energy demand up to a certain level (30° optimal angle) and then increase again till vertical installation (lowest performance). For south facing façade installation with 20°–40° tilt angle and 0.8m–0.9m overhang projection is suggested to achieve maximum energy benefits. This was found to be in the range of 33.5 kWh/m² compared to reference case, in accordance
with the results for max PV generation. In this case it is enough to compensate for increased thermal and lighting loads.

As expected, installation on South façade results in less energy demand for the office, followed by SW and SE orientations. Finally, optimal performance for PV shadings on SW and SE orientations achieved for 20° angle, with additional energy benefits in the range of 31kWh/m². Generally, in such office buildings (with similar WWR and g-value), PV shading devices should be installed with a tilt angle up to 40° and never exceed the 60° regardless the orientation.

4. Conclusions

The analysis presented in this paper highlights the importance of PV shading devices in terms of electricity benefits in office buildings. Impact of tilt angle, orientation and overhang projection has been analyzed in this study. Important conclusions can be summarized as follows:

- Regarding power performance, best results obtained for 30° slope and South orientation. In addition, annual generation equals to 145kWh/m², 5.5% and 4.2% higher compared to SW and SE orientations.
- PV shading devices with small tilt angle can effectively reduce cooling loads, but also increase heating during winter. Maximum benefits are obtained for 10° tilt angle and 1m overhang projection for S and SW orientation. For SE orientation horizontal overhang found to perform best.
- PV shading devices reduce daylight autonomy of the office and thus the energy use for lighting. Reduction is proportional to the length of overhang. Conversely, it increases UDI and reduce glare by 10% of the occupancy hours. This trade-off should be carefully considered by engineers during the design process.
- Best installation scenario for PV shadings facing south is 30° tilt angle and 0.9m overhang projection, while for SE and SW orientations is 20° with 0.98m overhang projection. This is the best balance between PV conversion and solar gain reduction, without increasing significantly the energy use for heating and lighting.

In a future research, other important parameters such as WWR and g-value of selected windows and ventilation strategy should be also examined for their impact on the design of PV shading devices. Results could be further discussed and compared with different PV shading device configurations (e.g. horizontal/vertical PV louvers) under the same conditions. This analysis will provide a good reference for design of such systems.
Acknowledgment
This work has been supported by the Ministry of Education, Youth and Sports within National Sustainability Programme I (NPU I), project No. LO1605 – University Centre for Energy Efficient Buildings – Sustainability Phase and by the Operational Programme Research, Development and Education of the European Structural and Investment Funds, project CZ.02.1.01/0.0/0.0/15_003/0000464 Centre for Advanced Photovoltaics.

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