Influence of PV facade configuration on the energy demand and visual comfort in office buildings

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\textbf{Abstract.} On the road towards Low or Zero Energy Buildings (ZEB), both a reduction of energy demand and on-site electricity generation from renewable energy systems becomes necessary. Recently, Photovoltaics (PVs) have been widely used in modern buildings as part of the façade, mounted on the envelope or integrated as construction elements. This work investigates the effect of the PV facade configuration on the energy demand and visual comfort of an office building under the semi-continental climate conditions of Prague. Different BIPV systems are compared, focusing on the competing functions associated with the PV system in terms of electrical, thermal and daylighting performance.

1. Introduction

The building sector is classified among the leading energy consumers and carbon emitters, causing 40\% of the primary energy demand and 36\% of CO\textsubscript{2} emissions in Europe [1]. Although the majority of buildings are energy inefficient, only 1.2\% of the building stock is renovated each year [2]. With regards to energy Directives (EPBD recast, EED), each European Union country must set minimum energy requirements for new buildings and for those that undergo major retrofitting. In addition, an emphasis is given on the adoption of renewable energy systems on the building envelope.

Rooftop PVs are so far considered to be the most common application, since it provides the best annual energy harvesting. However, vertical integration of PV modules into building facades is gaining wide attention and support, especially in high-rise, institutional and commercial buildings where the façade area is much larger compared to rooftop space. Building-integrated Photovoltaics (BIPV) brings attractive solutions for effectively and sustainably retrofitting building envelopes, providing an efficient way to reduce the building energy consumption. Current research is moving in the direction of using PV façades as a dynamic building envelope and a climate-adaptive building shell.

A significant number of experimental and theoretical research studies have dealt with the performance of BIPV systems. Solutions proposed by researchers vary between ventilated PV facades [2], PV curtain walls [3], PV glazing [4] and PV shading devices [5]. Apart from generating electricity, they are linked with the thermal and daylighting performance of the building, providing energy savings and increased indoor comfort [4, 5]. So far, most of the studies have focused on the implementation of such systems in geographical locations close to the equator, where cooling demand is dominating. For the Czech environment, this was not the case over the last decades, where experts had focused on reducing the energy demand for space heating. With regard to climate change, it appears that this approach is unlikely to be sufficient, if the criteria for indoor comfort are to be maintained.
The current work presents a method that will help designers and engineers to investigate and quantify the influence of the PV façade configuration on the energy demand and visual comfort in office buildings under semi-continental climate conditions. BIPV systems applied as opaque, transparent and additional façade elements are compared in terms of electrical, thermal and daylighting performance. The dynamic simulation environment of TRNSYS is used for the estimation of the PV generation and the building energy demand, while simulations are carried out in Ecotect/Daysim/Radiance software to account for the daylighting performance and indoor visual comfort. In the end, results are evaluated overall and discussed indicating the potential of each design configuration.

2. PV façade configurations

The integration of photovoltaics in buildings is of high importance for decreasing the building energy demand. Further to electricity generation, additional benefits can be achieved by taking into account the thermal behavior of the system and the effect on the building itself. Added functions include façade protection, thermal/acoustic insulation, sun shading and aesthetic quality. In this respect, four types of BIPV systems (Figure 1), mostly used in office buildings with curtain-wall design, were considered as follows:

I. **Vertical PV façade**: Opaque thin film PV modules (Table 1) vertically attached to the building façade as an alternative to conventional envelope material.

II. **Tilted PV façade**: Similar PV modules are attached considering ZigZag geometry [6], as a balanced solution between solar gain mitigation (summer period) and passive heating (winter period).

III. **Semi-transparent PV façade (STPV)**: Photovoltaic windows with the addition of mono-Si solar cells, on the top part of the glazing units (40% of transparency), for solar gain mitigation.

IV. **PV shading device (PVSD)**: External louver blade system, with integrated solar cells (Table 1) at fixed angle, for daylighting control.

The BIPV systems were analyzed for their energy behavior and compared with the reference case. In this context, a typical office room with dimensions 5.9m x 5m x 3.6m, was adopted and used for simulations. It is characterized by a well-insulated external façade with large south-facing windows, the details of which are presented in Table 1.

![Figure 1](image.png)

**Figure 1.** Typical office room of a multi-storey office building and the configuration of the PV curtain wall systems.

3. Methodology

Initially, a prototype building model, with a curtain wall design, was constructed in TRNSYS software and used for the assessment of the energy saving potential of each configuration, compared to the reference. More specifically, dynamic thermal simulations were performed to predict the effect of BIPV systems on the air temperature inside the office and thus the need for heating and cooling. Construction materials, with their thermo-physical properties, were imported through the TRNBuild interface, while glass insulated units were developed in WINDOW. To take into account the effect of the designed configurations, all surfaces other than the studied PV facade, were modelled as adiabatic. Heating and cooling demands were calculated in a simplified way as the amount of energy required to meet the set-point temperatures - 19°C and 26°C for heating and cooling respectively - provided by the relevant
operation schedule. It is assumed that this demand is provided by electrical energy using a mixed air-conditioning system with a 95% efficiency rate [5]. Heating and cooling are activated, considering an occupancy schedule from 8AM to 6PM during the weekdays and internal gains according to SIA 2024 [7]. Simulations were performed in 1h time-steps using typical meteorological data extracted from METEONORM for the city of Prague.

Subsequently, a radiation model available in TRNSYS was used for the estimation of radiation on tilted surfaces. It uses the Perez sky model and parameters for the location of the building, and has been validated for its optimal operation [8]. Different configurations were investigated for self-shading effects and results were obtained regarding the optimal tilt angle (case II) and number of louvers (case IV) for minimizing shading factors. Results were then passed to the PV model (validated previously [4, 8]) to reproduce the real behavior of the PV systems and estimate the output power. In case of BIPV, the connection between building envelope and PV array was realized by a two-sided temperature transfer using Type-567 from TESS library. In the case of STPV modules, simulations were performed according to the thermal model described in [9].

As a tool for parametric design and indoor visual comfort, the DAYSIM software was used to obtain the daylight autonomy (DA) and Useful Daylight Illuminance (UDI) metrics, according to the design configuration. For electrical lighting consumption, a photosensor dims the activated lighting until the work plane illuminance reaches the desired value (500lx). Finally, glare analyses were performed through the calculation of vertical eye illuminance values at the height of 1.2m, considering a working area close to the centre of the room.


| Table 1. Properties of the opaque/transparent parts of curtain wall and PV technologies used. |
|-----------------------------------------|-----------------|-----------------|-----------------|-----------------|
| **Opaque part**                         | **Area (m²)**   | **U-value (W/m².K)** | **Layers**                  |
| Thickness (mm)                          |                 |                 |                               |
| 8−140 –50 –140 - 20                     | 10.2            | 0.19            | Coloured glass panel – Air cavity – Extruded polystyrene – Mineral wool |
| **Transparent part**                    | **Structure**   | **Thickness (mm)** | **T_SOL** | **R_SOL** | **T_VIS** | **U-value** | **SHGC** |
| Triple glazing                          |                 |                 | 0.215         | 0.5      | 0.522     | 0.8         | 0.262    |
| **Photovoltaic system**                 | **Technology**  | **Active area**  | **I_SC** | **V_OC** | **P_MAX** | **η**       | **Temp P_MPP** |
| CdTe PV module                          |                 | 0.72 m²         | 2.01A       | 62.8V   | 80W       | 11%         | -0.25 (%/K) |
| Mono-Si cells                           | 156 cm²         | 4.9A            | 0.49V       | 2.4W    | 15.4%     | -19 (mW/²K) |

4. Results and discussion

4.1. Electricity generation

Results obtained for the annual generation per unit area (Wh/m²) of the installed PV systems are presented in Figure 2. In case I, annual PV generation corresponds to 56.3 kWh/m² with an average simulated efficiency of 7.7%. Despite the same tilt angle (vertical integration), the STPV façade (case III) achieved better results (64 kWh/m²) due to the increased efficiency, compared to the thin film PVs. The annual generation for the tilted PV façade (case II) is even higher (87kWh/m²) as a direct consequence of the tilt angle (30deg). Even with a similar efficiency to case I (8.2%), increased generation is explained by the improved insolation. Finally, the best results correspond to SDPV (case IV) with a 12.6% simulated efficiency and an annual generation of 110kWh/m². This is mainly due to the high efficiency solar cells and the optimal tilt angle (32deg) of the PV louvers.

For tilted PVs (cases II, IV), peak power and a broader daily generation profile are observed during the period from April to September. Conversely, in cases I and III, peak power occurs during the winter period (February) in accordance with the solar radiation on a vertical façade. Obviously, PV technology
plays the most important role in the efficiency of the PV system, followed by the operating temperature and non-proper ventilation of the modules. However, for the comparison of the PV configurations, the total annual electricity generation is also important. From that point of view, the external view and self-shading effect is limiting the potential of STPV (only on the top part of glazing surface) and SDPV up to certain extent (six rows of PV blades) with additional impact on the maximum annual generation. Considering the available surface in each PV façade configuration, results for annual generation are presented in Table 2.

![Figure 2. Heat maps of the annual power generation per unit area for each PV façade configuration.](image)

4.2. Annual energy demand

Simulation results for the annual energy demand including heating, cooling and artificial lighting are presented against the PV generation in Table 2. For the reference case the annual energy demand is 1091 kWh, with the highest contribution due to cooling. Overheating is evident in such office rooms without shading, leading to discomfort, especially during the summer period (but even on sunny days of the heating period). As expected, similar results are obtained for the vertical integration of PV modules (case I), reducing just slightly the energy demand of the office (-1.3%). The PV modules act as a protection layer in terms of low ambient temperatures, reducing effectively the heating demand by 4%. Furthermore, PV generation is enough to contribute 50% on this demand.

The cooling effect is evident (up to 56%) for the remaining three cases, with an additional small increase on the heating demand, compared to the reference case. Significant savings are observed for the inclined PV façade (case II) and SDPV (case IV). The total energy demand was found to be reduced by 24% and 17.8% respectively, due to the shading effect. Passive heating of the office is enhanced for the inclined façade during the winter period (sun in low position), compared to the SDPV configuration. Finally, the STPV façade (case III) achieved a decrease of 20% on the cooling demand compared to the reference case. This is explained by the lower SHGC of the PV glazing, which also affects the heating demand (+12.8%).

Besides the reduction of cooling loads, integration of PVs can also control daylighting. According to the results presented in Table 2, the energy demand for lighting increases slightly compared to the reference case. The maximum increase was found for the STPV façade (+17%) due to the lower visible transmittance. However, the DA (%) inside the room was consistently high, above 65%, during occupancy hours (Figure 3). In general, the energy demand decreased regardless the PV façade configuration. The annual PV generation and the reduction of the cooling loads is enough to compensate for increased heating and lighting loads, approaching the zero-energy standard in most of the cases.
Table 2: Annual energy demand of the office room with respect to PV facade configuration.

| PV configuration   | Lighting (kWh/m²) | Heating (kWh/m²) | Cooling (kWh/m²) | Total (kWh) | PV output (kWh) |
|--------------------|-------------------|------------------|------------------|-------------|-----------------|
| Reference          | 8.57              | 9.37             | 19.68            | 1091        | -               |
| I. Vertical Façade | 8.57              | 9                | 19.57            | 1077        | 564             |
| II. Inclined Façade| 8.94              | 10.97            | 8.65             | 828         | 798             |
| III. STPV Façade   | 10.01             | 10.57            | 15.76            | 1053        | 266             |
| IV. SDPV Façade    | 9.85              | 12.5             | 8.61             | 897         | 568             |

4.3. Indoor visual comfort

Distributions of DA and UDI metrics inside the office room, for all the PV façade configurations, are presented in Figure 3. It can be observed that DA is not affected significantly by the addition of PVs, while three zones are created in the interior. Highest values are achieved for the zone close to façade, followed by the one in the middle and finally the one at the back of the room. This does not apply for the SDPV configuration where a more uniform distribution of daylight is observed. Cases II, III and IV increase significantly (from 12% up to 16%) the percentage of illuminance in the range 100-2000 lux and thus the visual comfort inside the room. The effect is more significant at the back and in the middle of the office and minor close to the façade, where working tasks should be avoided. Considering both DA and UDI metrics best results were obtained for case IV, followed by case II and then case III.

Figure 3. Distributions of Daylight Autonomy (DA) and Useful Daylight Illuminance (UDI) inside the office room for a) vertical PV, b) tilted PV, c) STPV and d) SDPV façade configurations.

The effectiveness of a PV facade in terms of visual comfort was also demonstrated through glare reduction. At times, glare in the space is significantly reduced when passing from case I (similar to reference) to the rest configurations with increased solar protection. The percentage of working hours where DGP values exceed the 0.4 limit, decreases by up to 12% over a one-year period. Best results were obtained for the STPV façade, followed by the PV louvers and then the inclined canopy. It is obvious that integration of PVs could eliminate disturbing glare during the summer period (Figure 4). However, when the sun is aligned through a gap in the PV cells or louvers with the observer’s viewpoint, glare is inevitable.
5. Conclusions
The large surfaces in the facades of office buildings offer unique opportunities to integrate photovoltaic modules on opaque or transparent parts. Typical and emerging PV curtain wall systems simulated in this study, not only generate power, but also effectively contribute to the reduction of the energy demand and improve visual comfort. Results indicated that the variation in PV configuration has generally a greater impact on the PV generation and cooling followed by heating and lighting. DA is not significantly compromised, while complex façade geometries can significantly increase UDI and mitigate glare. This analysis will provide a good reference for the selection of suitable PV configuration.

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