# COMFORT AND BUILDING PERFORMANCE ANALYSIS OF TRANSPARENT BUILDING INTEGRATED SILICON PHOTOVOLTAICS

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## ABSTRACT

Within this paper an annual performance and daylight comfort analysis of building integrated photovoltaic (BIPV) is discussed, evaluated and compared to a common façade solution. The daylight comfort analysis includes annual illuminance, glare evaluations, and further daylight factor calculation. Secondly, dynamic thermal simulations are performed. The energy consumption of the luminaries is considered as part of the thermal internal gains. Both, the heating and the cooling energy demands are investigated.

Different solar cell types (such as multicrystalline cells and monocrystalline cells), integrated in a sandwich-glazing substrate, already existing on the market, are investigated. They are categorized as shading systems differentiating only in their shape, size and therefore transparency ratio. The efficiency per cell as well as their visual comfort performance is exemplarily evaluated for a typical office located in Freiburg, Germany. The impact of the PV area ratio (ratio of PV coverage to fenestration area) on the façade both on the thermal and on the visual comfort are investigated in this paper.

The annual simulation results show that a façade with integrated photovoltaics has the potential to improve overall energy performance of buildings when com-pared with the reference system Venetian blind due to the significant electric yield benefits. The shape and the adopted technologies have also an impact on the visual contact to the ambient and on the energy generation. Nevertheless, none of the investigated systems with the given conditions complies with the criteria for glare protection - therefore an additional (internal) glare protection is needed.

## INTRODUCTION

On 19 May 2010, a recast of the Energy Performance of Buildings Directive (European Parliament 2010) was adopted by the European Parliament and the Council of the European Union. As of 31 December 2020 new buildings in the EU will have to ensure a “nearly net-zero” energy balance and the energy will be “to a very large extent” from renewable sources. Therefore not only the roof but also the façade has to be used for generating renewable energy. Additionally, new building concepts and constructions are even using building integrated photovoltaics in the transparent part of the façade to reach this ambitious objective (e.g., the Yingli Solar Hotel, the Aachen municipal utility, etc.).

But the application of BIPV especially in transparent parts of façades (e.g., as a static shading device) rises more questions than only the energy performance of the PV-system itself. It influences the energy demand for heating, cooling and electric lighting as well as the thermal and visual comfort in the building. Therefore, an integral investigation is needed to analyse the impact of BIPV in a building context. The application of BIPV is also linked to the question of user comfort like the provision of sufficient levels of daylight, ambient view contact, the prevention of glare or protection of massive solar gains in summer.

Up to now, there exist only few investigations (Robinson 2009) on the influence of the amount and shape of the PV opaque areas of the BIPV on visual comfort as well as their relationship on efficiency of modules not investigating the influence of BIPV on the whole transparent facade.

## SIMULATION METHOD

In a first step, the climate based dynamic daylight simulations are performed for each possible position of the shading. The daylight results will be generated by applying the control strategy of the shading device. The hourly energy demand for the lighting and the configuration of the shading device are input for the second step – the thermal simulation with the software ESP-r version 11.10 (Clarke 2001).

**Model set up**
Definition of system, facade, building, climate, orientation, control strategy
↓
**Simulation with RADIANCE/DAYSIM**
Hourly illuminance, glare, electrical lighting energy demand
↓
**Simulation with ESP-r**
Energy demand for heating, cooling, thermal comfort

*Figure 1: Simulation method*

For the daylight simulations RADIANCE is used, which is capable of simulating complex specular materials and combined materials as BIPV (opaque and transparent). For the climate based daylight simulations, the RADIANCE-based tool DAYSIM (Reinhart 2001) is used. The results of the daylight calculations are hourly glare values calculated with evalglare (Wienold 2004) using the ‘Daylight glare probability’ DGP (Wienold 2009), horizontal illuminance, daylight autonomy and energy demand for the electric lighting. Based on manufacturer's specifications, annual electric yield of the BIPV cells is evaluated with Zenit (Müller et.al. 2010, Heydenreich et.al. 2008).

## MODEL SET UP

Simulations are carried out for a typical single rectangular office with a southern partly glazed façade (sill height: 0.85 m, glazed area: 6.34 m², see fig. 2). Two different shading systems are investigated and compared - BIPV-modules and for comparison reason a standard Venetian blind façade. For the Venetian blind, a dynamic control algorithm is applied. Therefore, it is used in cut-off mode throughout the year. In contrast, the shading status of the BIPV is always the same. The net floor area of the office is about 16.7 m².

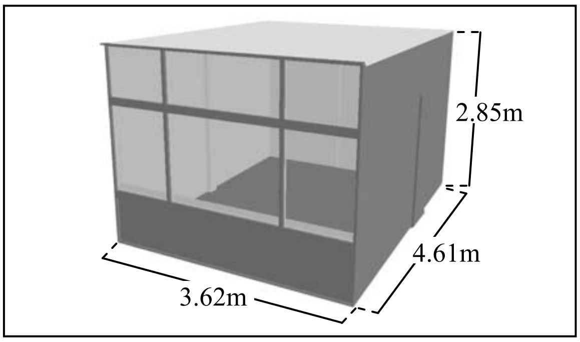


Figure 2: 3D view of the office geometry

The construction of the office is assumed to be medium-heavy, with concrete slabs for the floor and the ceiling, an insulated concrete external wall and plasterboard with insulation for the partition between adjacent zones.

Venetian blind

The Venetian blind (silver raff store with flat lamellae) has a lamella width of 80 mm, a lamella spacing of 72 mm and covers the whole façade at the outside.

Solar cells

Four different quadratic cell types are selected for the simulation: A monocrystalline (length: 156 mm), a monocrystalline perforated (length: 125 mm), a monocrystalline high efficient (length: 125 mm) and a multicrystalline PV cell (length: 156 mm). The monocrystalline perforated cell has an additional square recesses with a size of 5 mm and a recess spacing of 11 mm (fig. 3).

Photovoltaic modules

For the visual comfort evaluations, the cells are classified in on two groups - PV cells and perforated PV cells - arranged over the entire façade for three different cell spacings: 25 mm, 75 mm and 125 mm (fig. 3). Therefore, the BIPV modules have a percentage of the total transparent area: 29.0 % (25 mm), 61.8 % (75 mm) and 73.8 % (125 mm).

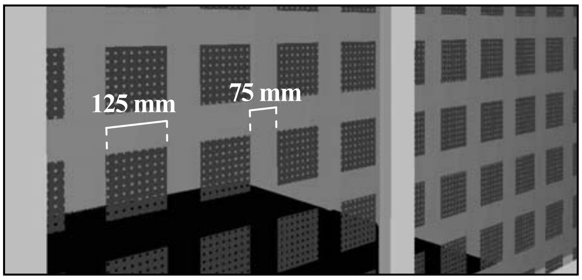


*Figure 3: Perforated PV-cells in the façade*

## BOUNDARY CONDITIONS

For the simulations, the occupation schedule of the office is defined from Monday until Friday with hours of work from 8 am - 18 pm neglecting holidays. For all simulations, hourly weather data from Freiburg, Germany are used, generated by the program Meteonorm 6.1 (Meteonorm 2011).

The Venetian blind is controlled compared to the control strategy 'Automatic: cut-off with fixed height' (Wienold 2009). The cut-off position is defined as the maximum open position of the shading device, when the direct radiation from the sun is entirely blocked. Based on market standards, e.g., Warema, for this control strategy, the blinds are lowered completely (cover the total window area) if the irradiation on the outside of the vertical façade exceeds the threshold of 150 W/m² (activation threshold). The slat angle of the blinds remains in the cut-off position. If the outside vertical irradiation falls below the second threshold of 50 W/m² (retraction threshold), the blinds are retracted.

For the dynamic thermal simulations, the same U-value is considered for the transparent glazing and the PV glazing. The BIPV is modelled as two parts – the PV cells as an opaque layer $(\tau_{bipv\perp} = 0)$ and the transparent layer between the cells with a solar transmission according to the glazing characteristics $(\tau_{glass\perp} = 0.49)$.

Although the dynamic thermal simulations do not consider the effect of the PV efficiency on the total solar energy transmittance (the electric yield is considered as absorption), this influence should be minor, because it causes only 4-6% of the relative value.

The specifications of the other materials can be found in tab. 1. The air change rate per hour (ach) during occupation of office is 1.3 ach, during absence of users 0.3 ach. The offices have a heating set point of 21 °C and a cooling set point of 26 °C. The cooling system is activated between April and October.

Occupants, light and equipment are taken as internal loads. The internal loads for two occupants and equipment are calculated as 72 Wh/m²d load, during absence of users 0.1 Wh/m²d.

*Table 1: Material specifications*

| MATERIAL | REFLECTION/ TRANSMISSION (-) | U-VALUE (W/m²K) | BOUND. CONDITION |
|---|---|---|---|
| external wall | 0.50 | 0.20 | exterior |
| internal wall | 0.50 | 1.30 | adiabatic |
| ceiling | 0.80 | 2.00 | adiabatic |
| floor | 0.20 | 2.00 | adiabatic |
| glass | 0.78 | 1.10 | exterior |
| Venetian blind | 0.61 | | |

The electric lighting is switched on (on/off control) when the internal illuminance on the work plane is less than 300 lux (the calculation of the illuminance level on work level is conducted within the DAYSIM / RADIANCE simulation).

## CALCULATION POINTS

The workstation (white point fig. 4) is placed 2 m away from the facade level in the middle of the room. The viewing direction is perpendicular towards the façade. According to the DIN EN 12464-1 (DIN EN 12464 2003), the calculation of illuminance will be done 0.75 m above floor level. The calculation points for the daylight factor (black marks fig. 4) lay 0.85 m above floor level based on DIN 5034 (DIN 5034 1999). For the investigation of the DGP at the workstation, the vertical illuminance at eye level is defined at 1.2 m height above floor level.

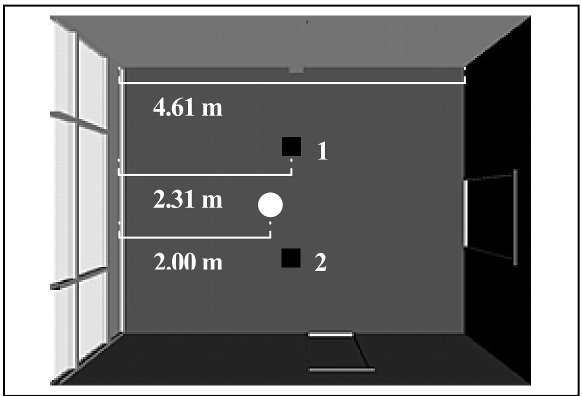


*Figure 4: Ground plan of the single office*

## DAYLIGHT PROVISION

Up to now, no standardization exists which defines threshold values on rating illuminance distributions for daylight in rooms. An exception is the standard DIN EN 12464-1 (DIN EN 12464 2003) which indicates a classification for artificial illumination, where the minimum threshold at work level (500 lux) has to be guaranteed. However, the daylight distribution in rooms varies widely and dynamically with the weather conditions and seasonal differences of the sun position. Therefore, it is impossible to equate either both lighting conditions, but the threshold could be possibly considered as a reference value. For the simulations irradiance data from hourly mean values throughout a year are used (Reinhart, Walkenhorst 2001) evaluated with DAYSIM.

The presented illuminances in fig. 5 are sorted ascending with cumulated office occupation hours.

An office without any shading system exceeds the minimum threshold at work level of DIN EN 12464 about 81 % throughout the year (tab. 2). In contrast, an office with a PV module with a cell spacing of 25 mm achieves the threshold only about 51 % of the year. Therefore, the amount of occupation time exceeding the threshold of 500 lux increases significantly with an increase of spacing of the PV cells (fig. 5).

*Table 2: Minimum illuminance*

| SYSTEM | HOURS <500 lux (H) | DA 500 lux (%) | HOURS <300 lux (H) | DA 300 lux (%) |
|---|---|---|---|---|
| No shading | 540 | 81.2 | 407 | 85.8 |
| Venetian blind | 934 | 67.5 | 652 | 77.3 |
| PV perf 125mm | 622 | 78.3 | 449 | 84.4 |
| PV cell 125mm | 650 | 77.4 | 471 | 83.6 |
| PV perf. 75mm | 675 | 76.5 | 498 | 82.7 |
| PV cell 75mm | 734 | 74.4 | 550 | 80.8 |
| PV perf 25mm | 1216 | 57.6 | 804 | 72.0 |
| PV cell 25mm | 1393 | 51.5 | 953 | 66.8 |

The daylight autonomy (DA) is the percentage of the annual occupation time when no artificial lighting is needed for a room exceeding a specific threshold. Therefore, it can be derived from the simulated illuminance data. Daylight autonomy considers real daylight conditions, i.e. direct and diffuse radiation and control strategies of shading systems.

Contrary to the minimum threshold of DIN EN 12464, user assessments indicated in real situations that probands turn on artificial illumination only at an illuminance of 300 lux on work level especially using manual controlled systems (Reinhart, Voss 2003). Therefore, in tab. 2, both thresholds are presented.

Thus, looking at the threshold of 300 lux the difference between the PV modules with a cell spacing of 125 mm, 75 mm and no shading is negligible. Nevertheless, there is a major difference to the PV modules with a cell spacing of 25 mm (fig. 5).

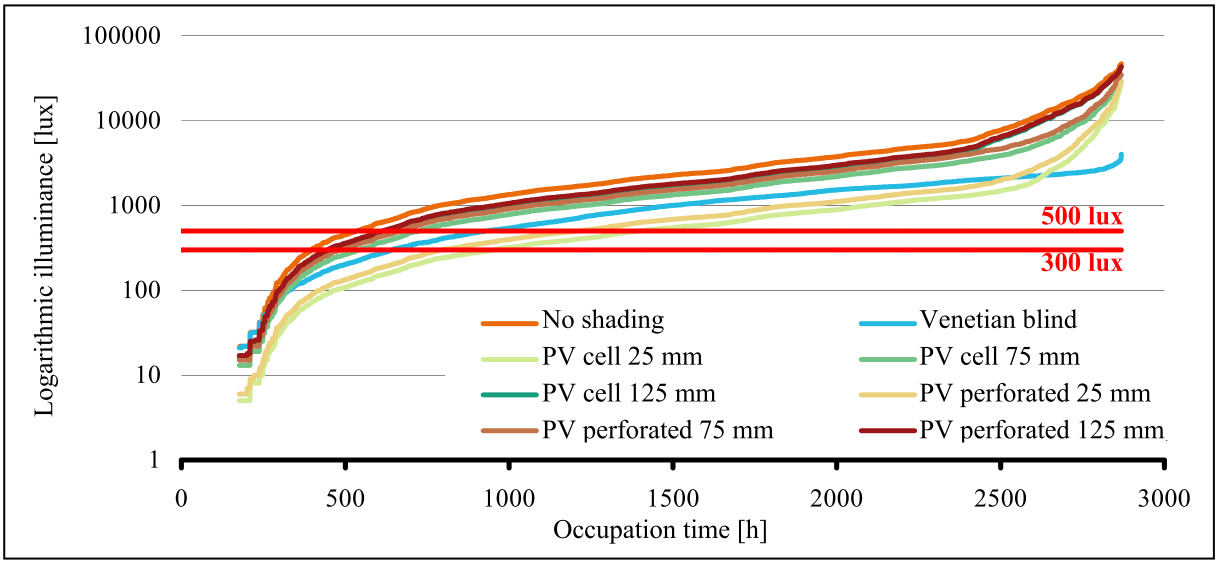


*Figure 5: Annual characteristic curves of the systems during occupation*

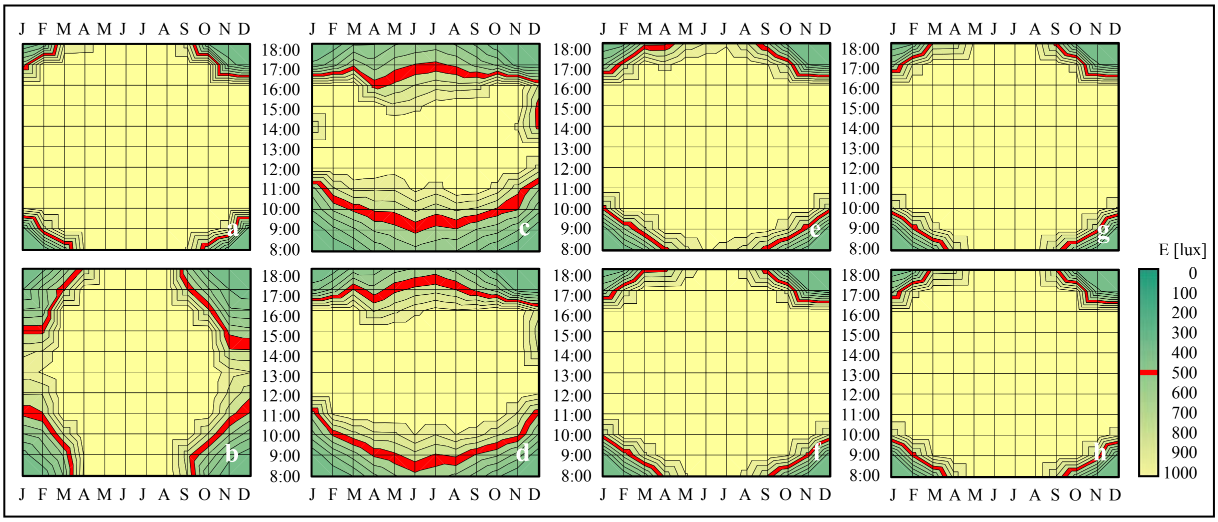


*Figure 6: Illuminance during occupation over the year (a: No shading, b: Venetian blind, c: PV cell 25 mm, d: PV perf. 25 mm, e: PV cell 75 mm, f: PV perf. 75 mm, g: PV cell 125 mm, h: PV perf. 125 mm)*

The fig. 6 shows the illuminances on work level monthly sorted for each hour during occupation. The Venetian blind provides a uniform distribution of daylight over the year. Where the PV modules produce a daylight distribution similar to a room without shading, they provide too high illuminances depending on the cell spacing of the PV modules.

## DAYLIGHT FACTOR

The daylight factor (DF) is defined as the ratio between illuminance due to daylight at a point on the indoor working plane and the simultaneous outdoor illuminance under diffuse radiation. According to the standard DIN 5034-1 (DIN 5034 1999) it should not be lower in the middle of room depth than the minimum threshold of 0.9. The daylight factor only considers daylight conditions under overcast sky, but in reality only some hours over a year fulfil this requirement.

Additionally, the daylight factor method assumes no active controlled shading system.

The results of the daylight factor analysis indicate, that none of the investigated systems falls below the threshold defined by the standard DIN 5034-1 (DIN 5034 1999) in the middle of the room. Only in the last third of the room the case with photovoltaic modules with a cell spacing of 25 mm lead a lower threshold than 0.9 (fig. 7).

*Table 3: Daylight factor at workstation*

| SYSTEM | VIEW OUT (%) | DF (%) |
|---|---|---|
| No shading | 100.0 | 7.8 |
| Venetian blind | 76.5 | 6.1 |
| PV perf 125mm | 73.8 | 5.8 |
| PV cell 125mm | 65.6 | 5.2 |
| PV perf. 75mm | 63.2 | 4.6 |
| PV cell 75mm | 61.8 | 3.6 |
| PV perf 25mm | 36.2 | 2.7 |
| PV cell 25mm | 29.0 | 2.0 |

## VIEW CONTACT TO THE AMBIENT

Wienold (Wienold 2009) stated that it is very probable that people also accept self-rated uncomfortable situations in order to gain from other factors like view contact.

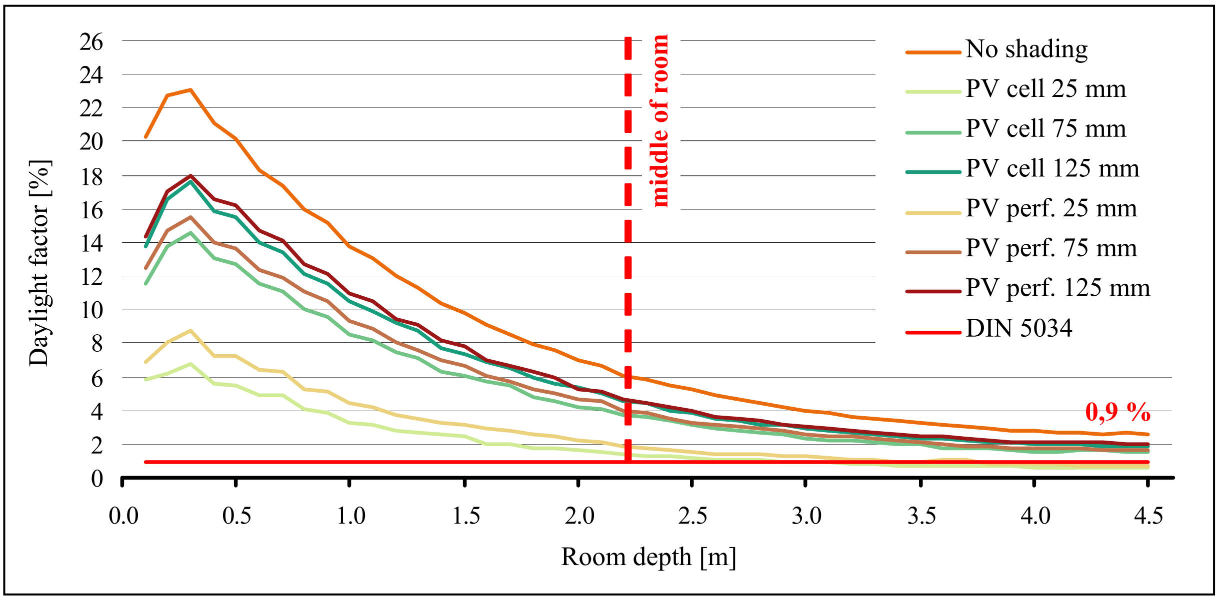


*Figure 7: Daylight factor of the systems*

The view factor can be just one of the triggers for blind setting and acceptance of non-optimal visual environments (Tuaycharoen 2006), but it seems to have the strongest correlations. Therefore, the rating criteria of the view contact for the visual comfort of PV systems in the façade is chosen to be investigated, too (tab. 3).

Although the psychological relevance of the topic view out and visual contact has been examined several times, a quantification method of this factor, i.e. a definition of limit values like how much view out has to be ensured or an investigation of the interaction with other interference factors and their influence is missing so far.

Therefore, a simple ratio between the quantity of view out without shading systems and the quantity of view out with shading systems is evaluated as first step investigation rating the quantity of view out (fig. 8).

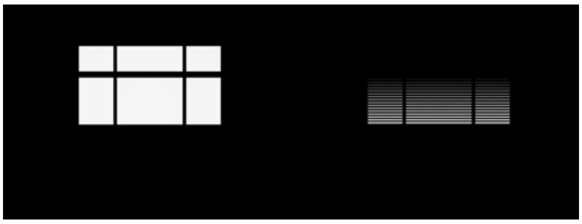

*Figure 8: Exemplary pictures of the evaluation method for the ratio of the quantity of view out (a: No shading, b: Venetian blind with slat angle of 35°)*

In order to evaluate the ratio of the quantity of view out throughout a year for each system, luminance pictures of every possible geometrical position of the shading system (e.g., different slat angle positions of the Venetian blind) are generated. Throughout a year, the pictures are simulated with diffuse modelled materials from the viewpoint of the user and a light source without interreflections with RADIANCE (fig. 8). Afterwards the amount of pixels with a higher luminance than zero is taken as an input for the ratio.

A good view out is attributed to the reference system Venetian blind and provides therefore a basis for the assessment of the ratio.

## GLARE CAUSED BY DAYLIGHT

In order to rate the daylight glare probability (DGP) for a whole year, calculated luminance pictures without diffuse interreflections and calculated vertical illuminances at the work station are investigated with evalglare and DAYSIM (Wienold 2009). The DGP value indicates the probability when a person feels disturbed by glare under the given daylight conditions.

The comfort classes of daylight glare are defined by Wienold (Wienold 2009). 'The classes use the upper level of the 95 % confidence intervals of the rating scales as DGP limits'. For class A (best) 95 % of office time, glare has to be rated weaker than 'imperceptible', class B (good) weaker than 'perceptible' and for class C (reasonable) weaker than 'disturbing'.

*Table 4: Minimum illuminances*

| SYSTEM | ANN. OFFICE OCCUPANCY (%) | | |
|---|---|---|---|
| | CLASS A (DGP ≤ 0.35) | CLASS B (DGP ≤ 0.40) | CLASS C (DGP ≤ 0.45) |
| PV cell 25mm | 82.7 | 88.9 | 91.0 |
| Venetian blind | 65.9 | 78.8 | 89.8 |
| PV perf 25mm | 74.8 | 83.1 | 87.1 |
| PV cell 75mm | 56.7 | 65.0 | 72.7 |
| PV perf 75mm | 53.4 | 61.6 | 69.6 |
| PV cell 125mm | 48.0 | 58.4 | 65.7 |
| PV perf 125mm | 46.0 | 57.1 | 63.8 |
| No shading | 39.2 | 46.4 | 55.7 |

Comparing the systems, the PV module with a cell spacing of 25 mm seems to be the best glare protection system: 83 % of office time glare appears weaker than 'imperceptible' for a typical user (class A). Looking at a room without shading, glare is perceivable weaker than 'imperceptible' for a user in 56 % of office time.

## ENERGY DEMAND FOR ART. LIGHTING

The annual demand for artificial lighting is calculated from the hourly illuminance data during occupation time. The electrical light output is set to 14 W/m² with a switch on threshold of 300 lux of daylight.

*Table 5: Sorted daylight autonomy*

| SYSTEM | ENERGY DEMAND FOR ART. LIGHTING (kWh/m²a) | DA (%) |
|---|---|---|
| No shading | 5.5 | 85.8 |
| Venetian blind | 6.2 | 84.4 |
| PV perf 125mm | 6.4 | 83.6 |
| PV cell 125mm | 6.8 | 82.7 |
| PV perf. 75mm | 9.0 | 77.3 |
| PV cell 75mm | 7.6 | 80.8 |
| PV perf 25mm | 11.1 | 72.0 |
| PV cell 25mm | 13.3 | 66.8 |

In summary, the results indicate that the energy demand for artificial lighting increases linear with the declining daylight autonomy for PV systems. One exception is the Venetian blind, which has a higher energy demand in relation to the daylight autonomy due to the consideration of the dynamic slat angle position resulting by the cut-off control strategy.

*Table 6: Annual electric yield [kWh/m²a] for four cell types per façade area*

| CELL SPACING [MM] | MONOCRYSTALLINE PV CELL (LENGTH: 156 mm) | MULTICRYSTALLINE PV CELL (LENGTH: 156 mm) | MONOCRYSTALLINE PERF. PV CELL (LENGTH: 125 mm) | MONOCRYSTALLINE HIGH EFF. PV CELL (LENGTH: 125 mm) |
|---|---|---|---|---|
| 0 | 123.4 | 105.4 | 98.0 | 147.2 |
| 25 | 87.6 | 74.8 | 69.6 | 104.5 |
| 75 | 47.2 | 40.3 | 37.5 | 56.2 |
| 125 | 32.3 | 27.6 | 25.7 | 38.6 |

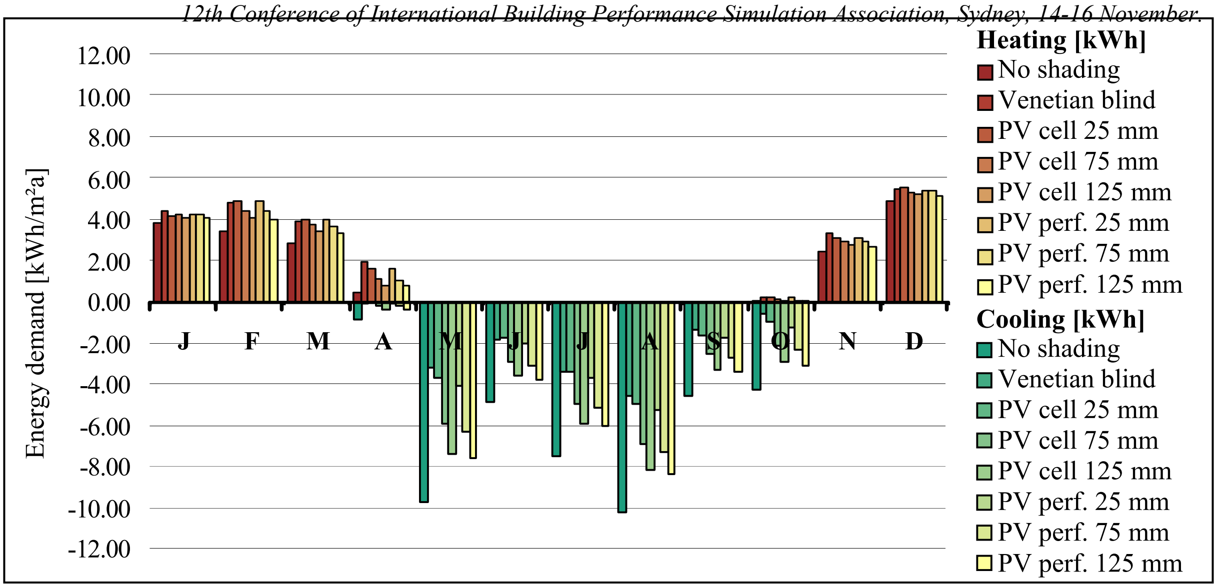


*Figure 9: Monthly energy demand for the eight configurations*

## ANNUAL ELECTRIC YIELDS

The annual electric yield of the photovoltaic is evaluated with Zenit (Müller et.al. 2010, Heydenreich et.al. 2008) without internal or external shading. Based on hourly solar radiation values and temperatures it calculates the sum of the annual yield. The electrical yield is calculated for a vertical south oriented 1kWp solar system. The cell type is characterized with the three parameters of the Heydenreich model (Heydenreich et.al. 2008) and the temperature coefficient.

In tab. 6 is shown that reducing the cell spacing the electrical yield increases depending on the cell's efficiency.

## DYNAMIC THERMAL SIMULATION

Dynamic thermal simulations with ESP-r 11.10 are performed to evaluate the effect of the different proposed facades design on the energy demand of the proposed office building. The reference case with Venetian blinds considers the angle dependent solar transmission of the system that changes also according to the blind position (Frontini 2009). Angle dependent values for the direct transmission, the g-value and the external reflectance are considered as input data for the facade with Venetian blinds. The so-called Black Box Model is used for the simulation within ESP-r (Kuhn et.al. 2011).

*Table 7: Annual useful energy demand*

| SYSTEM | HEATING (kWh) | COOLING (kWh) |
|---|---|---|
| No shading | 295.3 | 703.4 |
| Venetian blind | 400.5 | 251.1 |
| PV cell 25mm | 391.7 | 276.0 |
| PV cell 75mm | 364.3 | 428.7 |
| PV cell. 125mm | 337.5 | 531.1 |
| PV perf 25mm | 387.9 | 301.9 |
| PV perf 75mm | 361.5 | 453.8 |
| PV perf 125mm | 333.5 | 548.5 |

The BIPV facades are modelled in ESP-r separating the transparent area of the windows to the area covered by the c-Si cells. Both surfaces are modelled using the Transparent Material Construction (TMC) definition (Clarke 2001), which is a special ESP-r file type that holds the optical properties and operational characteristics of transparent surfaces (as distinct to default windows).

The useful annual energy demand simulated for each case (Tab. 7) shows that the useful energy demand for heating and cooling is direct proportional to the transparent ratio of the façade. Comparing the different PV module settings with the reference case Venetian blind it is clear that the useful annual energy demand for heating of the all of the PV settings (e.g., a PV cell with a cell spacing of 75 mm 364.3 kWh) is lower than the case with a Venetian blind (400.5 kWh). In contrast, the Venetian blind has the lowest useful annual energy demand for cooling (251.1 kWh) compared to the investigated PV systems (e.g., a PV cell with a cell spacing of 75 mm 428.7 kWh), internal venetian blind, like the one presented by Kuhn (Kuhn 2006) can be used to reduce the total solar heat gain of BIPV glazing. The case without any shading system, as expected, has the lowest useful annual energy demand for heating (295.3 kWh) and the highest useful annual energy demand for cooling (703.4 kWh) than for example, the reference case with a Venetian blind (heating: 400.5 kWh, cooling: 251.1 kWh). Additionally, the results show that the larger the distance between the cells, the higher is the energy for cooling during summer (fig. 9) due to the higher g-value of the BIPV window.

Comparing the relevant components for the useful energy demand in tab. 8 with the produced electrical yield of the PV cells, the investigated office room with PV systems with cell spacing of 25 mm and 75 mm produce more electrical power throughout a year than they need for artificial lighting per net floor area.

Due to higher amount of shaded area, they are not able to compensate the energy demand for cooling and heating, too. Therefore, for example, the monocrystalline high efficient PV system with cell spacing of 25 mm produces 3-times as much energy as needed for artificial lighting per net floor area. In contrast analysing the useful energy demand for artificial lighting, heating and cooling per net floor area, the monocrystalline high efficient PV system results 1.3-times more energy than only for artificial lighting.

*Table 8: Comparison of the four cell types and three cell spacing*

| SYSTEM | DF [%] | DA [%] | DGP [-] | VIEW [%] | ELECTR. YIELD [kWh/m²a] | USEFUL ENERGY DEMAND ART. LIGHTING [kWh/m²a] | HEATING [kWh/m²a] | COOLING [kWh/m²a] |
|---|---|---|---|---|---|---|---|---|
| No shading | 7.8 | 85.8 | 1.0 | 100.0 | 0.0 | 5.5 | 17.7 | 42.1 |
| Venetian blind | 3.6 | 77.3 | 0.5 | 63.2 | 0.0 | 9.0 | 24.0 | 15.0 |
| Mono PV cell 25mm | 2.0 | 66.8 | 0.8 | 29.0 | 33.3 | 13.3 | 23.5 | 16.5 |
| Mono PV cell 75mm | 4.6 | 80.8 | 1.0 | 61.8 | 17.9 | 7.6 | 21.8 | 25.7 |
| Mono PV cell 125mm | 5.8 | 83.6 | 1.0 | 73.8 | 12.3 | 6.4 | 20.2 | 31.8 |
| Mono perf. PV cell 25mm | 2.7 | 72.0 | 0.9 | 36.2 | 26.5 | 11.1 | 23.2 | 18.1 |
| Mono perf. PV cell 75mm | 5.2 | 82.7 | 1.0 | 65.6 | 14.2 | 6.8 | 21.7 | 27.2 |
| Mono perf. PV cell 125mm | 6.1 | 84.4 | 1.0 | 76.5 | 9.8 | 6.2 | 20.0 | 32.8 |
| Mono high eff. PV cell 25mm | 2.0 | 66.8 | 0.8 | 29.0 | 39.7 | 13.3 | 23.5 | 16.5 |
| Mono high eff. PV cell 75mm | 4.6 | 80.8 | 1.0 | 61.8 | 21.4 | 7.6 | 21.8 | 25.7 |
| Mono high eff. PV cell 125mm | 5.8 | 83.6 | 1.0 | 73.8 | 14.7 | 6.4 | 20.2 | 31.8 |
| Multi PV cell 25mm | 2.0 | 66.8 | 0.8 | 29.0 | 28.5 | 13.3 | 23.5 | 16.5 |
| Multi PV cell 75mm | 4.6 | 80.8 | 1.0 | 61.8 | 15.3 | 7.6 | 21.8 | 25.67 |
| Multi PV cell 125mm | 5.8 | 83.6 | 1.0 | 73.8 | 10.5 | 6.4 | 20.2 | 31.8 |

Having a cell spacing of 125 mm for a monocrystalline high efficient PV module, it produces still 2.3-times as much energy as needed for artificial lighting per net floor area, but needs 4-times more energy for artificial lighting, heating and cooling per net floor area (tab. 8).

Additionally, all investigated PV systems have their own characteristics, but the main differences are mainly identifiable for the electrical yield investigating the useful energy demand. In contrast, the comparison of the reference case with the PV systems indicates that for example, the monocrystalline PV cell with a cell spacing of 25 mm has a quite similar useful energy demand for artificial lighting, cooling and heating compared to the Venetian blind. In contrast, it benefits from its electric yield production covering 3-times more than the energy demand for artificial lighting.

In summary, all of the PV systems have a better useful energy demand balance than the reference case Venetian blind except the monocrystalline perforated PV system with cell spacing of 125 mm.

## SIMULATION RESULTS

The balance of primary energy demand is investigated in order to rate the energy contribution of the systems to reduce the overall energy demand of a building without considering for example, the energy demand for air conditioning. Therefore, two different cases are analysed (tab. 9). Case A for the cooling system a compression-cooling machine and for the heating system a gas-condensing boiler are chosen. For case B a ground source heat pump with heating and cooling capability using low-temperature heat are investigated. Based on DIN V 18599-1 (DIN V 18599 2007), the primary energy factors are set as following (Kempkes 2009): gas condensing boiler 1.1, compression cooling machine 2.6, heat pump with heating and cooling capability 2.6, artificial lighting 2.6 and electrical yield of the PV as 2.6. The gas-condensing boiler has a seasonal boiler efficiency of 1.05. The compression-cooling machine has a seasonal efficiency factor of 3.0 and the heat pump has as a heating system a seasonal performance factor of 4.0 (as a cooling system 3.0).

All of the systems for both cases improve the primary energy balance compared to the reference system Venetian blind (tab. 9). Except the PV system with cell spacing of 125 mm, its total primary energy demand is close to the results of the reference system.

Analysing the visual comfort criteria, between one and two criteria are met, but e.g., the rating results of the DGP are inadequate. In contrast, the results of the daylight factor, the daylight autonomy and the view out for the PV depending on the cell spacing are close to the results of the Venetian blind und therefore interpretable as comfortable. None of the investigated systems with the given conditions complies with the criteria for glare protection - therefore an additional (internal) glare protection is needed. The Venetian blind is the only system that could easily meet the requirements with, for example, a cut-off control strategy, when closing the lamella additionally by 10 ° (Wienold 2009). Therefore, the investigated PV systems are not suitable to be used over a completely glazed façade. Having only a static layer on the window with opaque elements the PV systems are not able to respond dynamically to the changing lighting conditions over the course of a year. However, there is a high potential in partial arranged static PV systems on facades especially because of their higher specific electrical yield compared to the energy demand for artificial lighting per net floor area and a better view contact to the outside compared to fully opaque elements.

All simulations are done without any external and internal shading from obstructions. The effects of shading from obstructions can be very significant especially for building integrated photovoltaics and their electric yield results. Investigating only a south oriented façade, another potential study could be to simulate the effect of building integrated photovoltaics and different façade orientations on the energy demand and energy yield as well as the visual comfort over a whole course of a year.

## CONCLUSIONS

The annual simulation results show that a façade with integrated photovoltaics has the potential to improve

*Table 9: Primary energy demand of the four cell types and three cell spacing*

| SYSTEM | ELECTR YIELD [kWh/m²a] | ENERGY DEMAND | | | | | CASE A | CASE B |
|---|---|---|---|---|---|---|---|---|
| | | LIGHT [kWh/m²a] | CASE A | | CASE B | | TOTAL [kWh/m²a] | TOTAL [kWh/m²a] |
| | | | HEATING [kWh/m²a] | COOLING [kWh/m²a] | HEATING [kWh/m²a] | COOLING [kWh/m²a] | | |
| No shading | 0.0 | 14.3 | 43.6 | 77.6 | 24.5 | 77.6 | -135.5 | -116.4 |
| Venetian blind | 0.0 | 23.4 | 59.1 | 27.6 | 33.2 | 27.6 | -110.1 | -84.2 |
| Mono PV cell 25mm | 86.5 | 34.6 | 57.9 | 30.4 | 32.5 | 30.4 | -36.3 | -10.9 |
| Mono PV cell 75mm | 46.5 | 19.8 | 53.7 | 47.4 | 30.1 | 47.4 | -74.3 | -50.7 |
| Mono PV cell 125mm | 32.0 | 16.6 | 49.7 | 58.6 | 27.9 | 58.6 | -93.0 | -71.2 |
| Mono perf cell 25mm | 68.9 | 28.9 | 57.1 | 33.4 | 32.1 | 33.4 | -50.4 | -25.4 |
| Mono perf cell 75mm | 36.9 | 17.7 | 53.4 | 50.1 | 30.0 | 50.1 | -84.3 | -60.9 |
| Mono perf cell 125mm | 25.5 | 16.1 | 49.2 | 60.5 | 27.6 | 60.5 | -100.3 | -78.8 |
| Mono high eff cell 25mm | 103.2 | 34.6 | 57.9 | 30.4 | 32.5 | 30.4 | -19.6 | 5.7 |
| Mono high eff cell 75mm | 55.6 | 19.8 | 53.7 | 47.4 | 30.1 | 47.4 | -65.2 | -41.6 |
| Mono high eff cell 125mm | 38.2 | 16.6 | 49.7 | 58.6 | 27.9 | 58.6 | -86.8 | -64.9 |
| Multi PV cell 25mm | 74.1 | 34.6 | 57.9 | 30.4 | 32.5 | 30.4 | -48.8 | -23.4 |
| Multi PV cell 75mm | 39.8 | 19.8 | 53.7 | 47.4 | 30.1 | 47.4 | -81.0 | -57.4 |
| Multi PV cell 125mm | 27.3 | 16.6 | 49.7 | 58.6 | 27.9 | 58.6 | -97.7 | -75.9 |

overall energy performance of buildings when compared with the reference system Venetian blind due to the significant electric yield benefits. Although the energy demand for artificial lighting increases (having less light penetrating the room), the energy yield of the PV decreases the total primary energy demand. Therefore, the objective of the EPBD Recast (European Parliament 2010), having "nearly net zero-energy" buildings as of 31 December 2020, can be supported by using building integrated PV in the façade.

The shape and the adopted technologies have also an impact on the visual contact to the ambient and on the energy generation. Nevertheless, none of the investigated systems with the given conditions complies with the criteria for glare protection - therefore an additional (internal) glare protection is required.

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