Energy performance and occupancy-based analysis of visual and thermal comfort for transmittance level and layout variations of semi-transparent photovoltaics

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Abstract

This paper investigates the impact of transmittance level and layout variations of semi-transparent photovoltaics (STPV) on both energy performance and occupancy-based visual and thermal comfort, simulating a reference office with a fully south-oriented glazed surface. Four transmittance levels (20, 30, 40 and 50%) were investigated, first uniformly distributed on the full glazing (i.e., one specific transmittance for the entire glazing) and then considered in combination (i.e., with the glazing divided in equal-height bands with different transmittance levels). Simulations were conducted in three climatic conditions: temperate (Geneva), hot-arid (Casablanca) and cold (Helsinki). Following the proposed energy and occupancy-based visual and thermal comfort analysis, the best design option for both Geneva and Helsinki climate resulted the 2-level STPV design variation with 50% visible transmittance on top of the glazing. In Casablanca, the 1-level design variation with the lowest visible transmittance (20%) uniformly distributed resulted as the best choice. This work, besides offering a first exploration of the relationships between climatic context and STPV design variations, describes a spatial multi-criteria analysis method that could be applied for the evaluation of other glazing technologies.

Introduction

An increasing interest in semi-transparent building integrated photovoltaics (STPV) has been observed worldwide due to the system's ability to provide daylight access and produce electricity at the same time (Bahaj, James, and Jentsch, 2008; Rezaei, Shannigrahi, and Ramakrishna, 2017). This window technology seems particularly relevant for fully glazed buildings, that only offer very limited opaque surfaces to apply conventional building integrated photovoltaics (BIPV), or for high-rise buildings with a limited roof area. STPV systems are composed typically of thin-film solar cells that are quite small to minimize disturbing contrast but sufficiently spaced to offer view out and light transmittance. The electricity production of the system, linked to an efficiency ranging from 5 to 10%, is inversely correlated to the degree of transparency of the glazing, meaning that the highest efficiency corresponds to the lowest glazing transmittance. The degree of transparency, besides affecting the energy production, has a direct impact on indoor visual and thermal conditions as it influences the visual transmittance and the g-value of the glazing and therefore also the daylight provision and the solar heat gains. As a consequence, variations of STPV transmittance affect simultaneously occupants' visual and thermal comfort.

An increasing number of studies have focused on STPV benefits and performance in the past years, due to an increasing use of the system in buildings. However, despite the combined influence on energy performance and visual and thermal comfort, past studies never investigated these three factors in combination. Studies, in fact, either focused on the influence of STPV on energy performance only (Do, Shin, Baltazar, and Kim, 2017; Peng et al., 2016; Tian et al., 2018), on visual comfort only (Kapsis, Dermardiros, and Athienitis, 2015; Schmid and Uehara, 2017), or on the combination of energy and visual comfort (Mende, Frontini, and Wienold, 2011; Olivieri, Caamaño-Martin, Olivieri, and Neila, 2014; Wong, Shimoda, Nonaka, Inoue, and Mizuno, 2008; Zhang, 2018). Whenever thermal aspects were considered, analyses were related to the thermal properties of the STPV system (e.g., overheating of the glazing unit - Wong et al., 2008) or to the heat gains due to the system (Fung and Yang, 2008; Karthick, Kalidasa Murugavel, and Kalaivani, 2018; Zhang, 2018). To our knowledge, implications on the thermal comfort of building occupants have never been investigated. As a consequence, no studies exist on the impact of STPV on a combination of energy and comfort requirements, that would look at the thermal *and* visual environment of the room equipped with STPV technologies. In addition, studies have always focused on a uniform distribution of the STPV transmittance on the glazing, and have never considered non-uniform layouts (such as tested for other types of smart windows, i.e., electrochromic - Mardaljevic, Kelly Waskett, and Painter, 2016). This might be interesting from a design point of view due to the effect of different layouts on the spatial distribution of visual and thermal comfort of occupants.

To fill in this gap, the goal of this study is to investigate the impact of different STPV design variations (in terms of transmittance level and spatial layouts) on energy performance, and occupancy-based visual and thermal comfort. The aim is to determine the best design option, among those investigated, considering energy and discomfort indicators, in three different climates: temperate (Geneva), hot-arid (Casablanca) and cold (Helsinki). Another goal of the paper is to describe an evaluation method for a multi-criteria analysis (considering energy and both visual and thermal comfort) applicable for different glazing technologies. The most relevant part of this evaluation is the calculation of the discomfort indicator with a comfort evaluation matrix, examining at the same time different aspects of thermal and visual comfort rather than considering them as separate indicators, on the basis of the work proposed by Ko et al. (2018).

Method

The different STPV design variations were investigated by means of building simulations of a reference office room with a south-oriented fully-glazed façade. Simulations of the same design options were performed in three different climates: for the temperate climate, the IWEC weather file (source: U.S Department of Energy's website) corresponding to Geneva was used, whereas for the cold and hot-dry climatic conditions, the IWEC wather files of Helsinki and Casablanca were selected. A base case model of the same room with a window with solar control and external blinds was also investigated, but only in the temperate climate of Geneva, to compare its results with those of the best design option in the same climate.

Simulations were conducted with the Ladybug/Honeybee (Roudsari and Pak, 2013) interface to EnergyPlus (building energy and thermal performance) and Radiance/Daysim (building daylight performance). The Microclimate Map component was used to calculate the mean radiant temperature (considering also the shortwave radiation directly incident on occupants) and the air temperature, for the consequent calculation of the predicted mean vote (PMV) for the determination of the thermal comfort of each occupant. Radiance and Daysim simulations were run to evaluate the visual comfort of occupants. The outputs were then analysed with a custom script in MATLAB programming language to calculate the energy and discomfort indicators, which were then used to select the best design variation.

In the following subsections, simulation model, investigated design variations, and energy and comfort indicators used for the analysis are described in detail.

Model description

Simulations were conducted for a shoebox model based on the reference office described by Reinhart et al. (2013), representing a deep-floor office layout for six occupants with a south-oriented opening (Figure 1). The model represents a single zone within a larger building, as all the walls except the south-oriented one are considered adiabatic. The WWR chosen for the simulations was equal to 80%, corresponding to a window height of 2.5 m, and a window width of 3.25 m (total glazed area of 8.1 m^2). The internal room dimensions (3.6 m x 8.2 m x 2.8 m), the material properties (Table 1), and the occupancy schedule (from 8 AM to 6PM, from Monday to Friday) were maintained as in Reinhart et al. (2013) to ensure comparability.

The heating and cooling set points temperatures were equal to 20 °C and 24 °C, respectively. The heating set point temperature was chosen at the lower end of the temperature range reported in EN 15251 (EN ISO, 2008) for category II due to the presence of high internal loads and the risk of overheating. The cooling set point falls in the comfort range of the same category (EN ISO, 2008). Setback temperatures were set to 17 °C and 28 °C. An individual electric light (conventional desk lamp of 13 W) was supposed for each occupant, switching on whenever the work plane illuminance was below 300 lux. This type of operation was chosen instead of a conventional control based on a single zone to emphasize the occupancy-based analysis of this study and to be able to calculate the electric consumption due to lighting under different STPV design variations. Six computers were supposed to operate continuously during the occupation hours.

No shading system was considered in the simulations, except for the base case, which presented external venetian blinds with movable slats of 10 cm width and a between-slat distance of 8 cm. The reflectance factor of the blinds was 0.65. The blinds operated on a two-mode slat angle (30 and 45 degrees), based on a glare control operation to maximise the view out. The glazing of the base case was selected as a solar control glazing with a U-value of 1.0 W/(m^2K), a g-factor of 0.28, and a visual transmittance of 0.52.

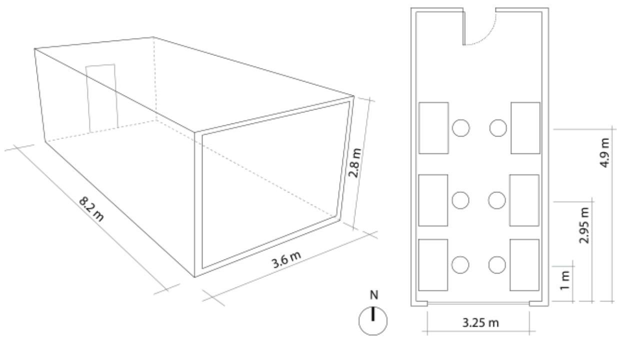

Figure 1: Schematic representation of the shoebox model and seating positions used in the simulations (adapted from Reinhart et al., 2013).

Table 1: Material properties of the model (as in Reinhart et al., 2013).

Component	Properties
External wall (south)	U-value= 0.365 W/m^2 K
Internal walls	Lambertian diffuser with a 50% reflectance; adiabatic surface
Ceiling	Lambertian diffuser with an 80% reflectance; adiabatic surface (office not under a roof)
Floor	Lambertian diffuser with a 20% reflectance; adiabatic surface

STPV design variations

A total of 14 STPV design variations were considered in this study, referring to changes of visible transmittance levels (20, 30, 40 and 50%) and to their spatial combination on the surface (i.e., the glazing was divided in equal-height bands with different transmittance levels). Figure 2 illustrates the 14 STPV design variations, grouping them according to the number of transmittance levels considered in each case (i.e., 1-level, 2-level or 3-level). The first four design variations refer to the visible transmittance levels uniformly distributed on the full glazing (i.e., the entire glazing has one specific transmittance). Six additional design variations consider the glazing divided into two equal-height stripes, considering therefore two levels of transmittance. The combination of two "consecutive" transmittance levels was not investigated (e.g., 20/30% or 40/50%) to reduce the number of design variables that would result too close to each other. As a consequence, the considered 2-level design variations were: 20/50%, 50/20%, 20/40%, 40/20%, 30/50% and 50/30%. Finally, the last four design variations consider the combination of three "consecutive" transmittance levels in a decreasing or increasing order. Random combinations of transmittance levels (e.g., 20/50/40% or 50/20/30%) were not considered in the analysis. The resulting 3-level design variations were: 40/30/20%, 20/30/40%, 30/40/50% and 50/40/30%.

The chosen type of thin film module had a range of visible transmittance going from 10% to 50%, corresponding to a linear decrease of the module efficiency (from 10% to 5.6%). As no detailed manufacturer information were available, we adopted a simplified approach for the consideration of the solar transmittance and the g-value of each STPV level, with the two parameters considered linearly correlated to the visible transmittance. The power output of the module was calculated according to the efficiency, and the temperature behaviour of the module was not considered in the analysis for simplification. Table 2 describes the properties of each STPV visible transmittance level used in the analysis.

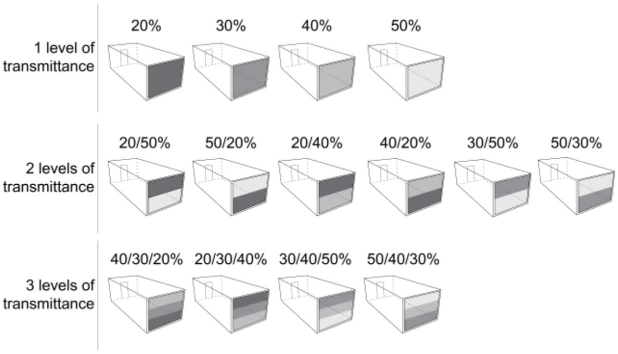

Figure 2: STPV design variations considered in this study, according to the number of transmittance levels.

Table 2: STPV transmittance level properties (the solar transmittance equals the g-value).

STPV level	Visible transmittance	g-value	Efficiency
STPV 20%	20%	0.2	8.9%
STPV 30%	30%	0.3	7.8%
STPV 40%	40%	0.4	6.7%
STPV 50%	50%	0.5	5.6%

Energy and discomfort indicators

The 14 STPV design variations were evaluated in terms of energy performance and occupancy-based visual and thermal comfort (i.e., a combined indicator considered for each of the six occupants). The two indicators (from now on referred to as energy and discomfort indicators) used to summarize these evaluations are defined as follows:

Energy indicator: we used the electric energy per m^2 floor area, calculated on the output from the STPV system subtracted to the energy use due to heating, cooling, lighting, and appliances. The energy use for heating and cooling was computed by converting the calculated energy demand, assuming that the heating and cooling were provided by systems with an average seasonal COP of 3, which also includes distribution losses and needed pumps and controls.

Discomfort indicator: for its calculation we propose a comfort evaluation matrix based on the combination of visual and thermal comfort scores. These scores were derived using pre-defined visual and thermal thresholds, calculated for each of the six occupants of the room (*Figure 3*). The method is adapted from Ko et al. (2018), who combined multiple environmental metrics together using the concepts of luminous, thermal and ventilation autonomy (i.e., with the use of fully-passive heating and cooling) to define the comfort thresholds, and conducted a spatial analysis rather than a conventional single-node evaluation. However, in the present study, the calculation of the visual and thermal comfort scores differed from that presented by Ko et al. (2018).

The "thermal comfort score" (TC_{score}) for each design variation was calculated on the basis of the PVM results for each hour and each occupant. For its calculation, a mechanical system for heating and cooling was modelled to maintain temperature within a comfort range in the room, considered as a single thermal zone (according to the heating and cooling set points defined in the section "Model description"). Hourly PMV values were computed according to the spatial variation in operative temperature due to shortwave irradiation on the body and the asymmetric surface temperatures due to the glazing technology (other PMV inputs: 1.2 met, 1 clo, 0.05 m/s). The TC_{score} was considered equal to 0 whenever the PMV was between -0.5 and +0.5 (so as to consider a Predicted Percentage of Dissatisfied equal to 10% - Fanger, 1970), or to 1 whenever the calculated value was outside the aforementioned comfort limits. With this type of scoring system, the "directionality" of discomfort was not considered, meaning that the same score was assigned to a cold or to a warm environment. Following the same methodology, different scores could be assigned according to the preference of occupants.

For the calculation of the "visual comfort score" (VC_{score}), only daylight was taken into account. Two criteria were used: i) daylight availability, and ii) glare. For the daylight availability a minimum horizontal illuminance of 300 lux must be reached to be considered as comfortable, measured on each workplace position (desk height = 0.8

m). For glare criterion, discomfort and veiling glare values were considered: discomfort glare was detected if the simplified Daylight Glare Probability was larger than 0.4 (simplified DGP- Wienold, 2007). The value was calculated at the eye level (1.1 m above floor) with a viewing direction towards the computer screen (parallel to the facade). The simplified DGP can be applied for this specific facade since the glazing transmission is rather high and the saturation effect is dominating (Jan Wienold et al., 2019). As veiling glare threshold, a vertical illuminance on the computer screen of 2000 lux was used (Schierz, Vandahl, and Schmits, 2012). Like for the TC_{score}, the VC_{score} had a value of 0 whenever the results fell within the minimum and maximum visual comfort thresholds, or equal to 1 whenever the values were outside of the thresholds. Also in this case, the weighting system was not "directional", as it assumed the same value whenever the environment was too dim or glary. This point is further discussed in the limitations of this study.

The combined visual and thermal comfort score (i.e., *discomfort score*) summed up the aforementioned visual and thermal comfort scores (Fig. 3). As a result, the discomfort score was equal to 2 whenever both visual and thermal comfort scores were outside of comfort thresholds, to 1 when one of the two was outside of comfort thresholds, and to 0 when they both were within comfortable ranges. *Figure 3* also illustrates the colour code that is used in the temporal representation of the results for each occupant of the best STPV design variation. In particular, red is used to indicate a too warm environment, blue too cold, grey thermally comfortable, while the brightness is used to illustrate the visual comfort results (i.e., too dim, comfortable or too bright = glare).

The two indicators were calculated for each hour and each of the six occupants in the room. To summarize the results and to be able to compare the different STPV design options, three average values of the discomfort indicator calculated over the year (excluding weekends and holidays) are reported in the following analysis, referring to the "front", "middle", and "back" of the office (averaging the results of the two occupants in the same part of the room). The three average values illustrate quantitatively the potential inequalities of comfort between the six office occupants. To further summarize this inequality, a standard deviation of the discomfort score is also reported for each design variation.

In addition, to illustrate the contribution of thermal and visual comfort to the discomfort indicator, the Thermal Discomfort Fraction ($TD_{fraction}$) is also calculated as:

$$TD_{fraction} = \frac{\sum_{i=1}^{N} TC_{score,i}}{\sum_{i=1}^{N} TC_{score,i} + VC_{score,i}} \cdot 100 \ \ [\%] \quad (1)$$

The complementary value (100-$TD_{fraction}$) indicates the visual discomfort fraction ($VD_{fraction}$) of the discomfort indicator.

After the calculation of the energy and discomfort indicators, the best design option for the selected climate was chosen according to the following method:

1. The design variations with the lowest discomfort score values are retained as they indicate the most comfortable options;
2. Of the design variations with the lowest discomfort score, the one with the smallest standard deviation is considered as the best design option, as it indicates a smaller spatial comfort inequality;
3. In case of very similar values, the design option with the lowest energy indicator is chosen.

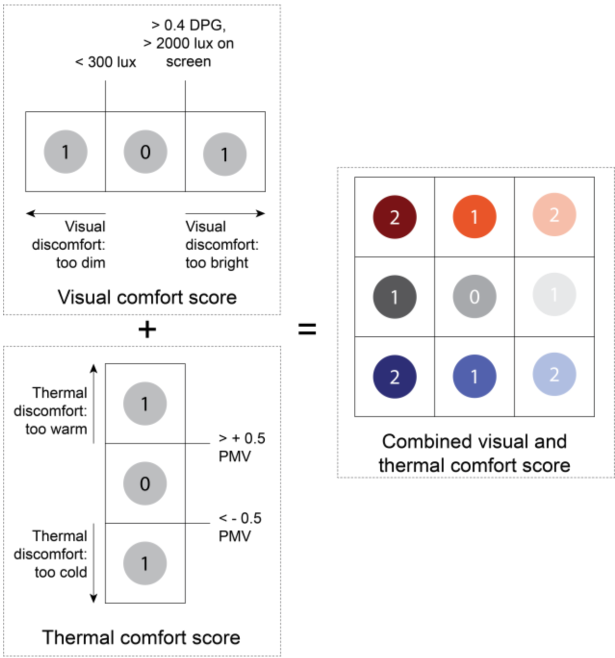

Figure 3: Visual, thermal and combined comfort score (i.e., discomfort score) based on predefined comfort thresholds.

Results and discussion

Results are divided and discussed into three sections. The first two refer to the simulations performed in the temperate climate of Geneva: a general evaluation of the results of the STPV design variations and the selection of the best design option are presented in the first section. Then, in the second section, a comparison of the results of the best design option for the Geneva climate with those of the base case is reported. Finally, the last section describes the evaluation of the STPV design variations in the other two climates, hot-arid and cold, for the identification of the best STPV design variation.

STPV design variations for the Geneva climate

Table 3 illustrates the discomfort indicator values for the 14 STPV design variations for the front, middle and back positions. It also reports the electricity use and production, and the resulting energy indicator.

Transmittance level	Design variation	*Discomfort indicator*					$TD_{fraction}$			Energy use (kWh/m²)			Electricity prod. (kWh/m²)	*Energy indicator* (kWh/m²)
		Front	Mid	Back	**Avg**	**SD**	Front	Mid	Back	Heat.	Cool.	Light.		
1-level	*20%*	0.91	1.44	1.55	1.30	0.28	69%	40%	36%	15.2	4.0	11.3	17.1	46.6
	30%	0.86	1.08	1.40	1.11	0.22	69%	46%	33%	14.9	7.4	9.1	14.9	49.5
	40%	1.00	0.97	1.42	1.13	0.20	64%	58%	37%	13.8	7.2	7.7	12.8	49.0
	50%	1.16	0.85	1.21	1.07	0.16	56%	66%	43%	13.2	9.3	5.8	10.7	50.8
2-level	*20/50%*	0.89	1.18	1.48	1.18	0.24	69%	47%	35%	14.2	6.7	9.6	13.9	49.8
	50/20%	0.97	0.88	1.31	1.06	0.19	63%	63%	40%	14.2	6.7	6.7	13.9	46.9
	20/40%	0.89	1.32	1.52	1.24	0.26	70%	43%	36%	14.6	5.6	10.5	14.9	48.9
	40/20%	0.91	1.02	1.45	1.13	0.23	68%	57%	38%	14.6	5.6	8.1	14.9	46.4
	30/50%	0.95	0.97	1.37	1.10	0.19	63%	55%	36%	14.0	8.3	8.0	12.8	50.6
	50/30%	**1.04**	**0.84**	**1.27**	**1.05**	**0.18**	**58%**	**64%**	**40%**	**14.0**	**8.4**	**6.5**	**12.8**	**49.2**
3-level	*20/30/40%*	0.86	1.22	1.46	1.18	0.25	69%	42%	33%	15.1	6.3	10.2	14.9	49.7
	30/40/50%	0.96	1.00	1.40	1.12	0.20	65%	54%	36%	14.1	7.2	8.1	12.8	49.8
	40/30/20%	0.89	0.99	1.41	1.10	0.23	69%	53%	35%	14.5	7.3	8.2	14.9	48.3
	50/40/30%	1.04	0.88	1.34	1.09	0.19	62%	64%	39%	13.6	7.9	6.8	12.8	48.6
Base case Geneva		0.64	0.79	1.31	0.91	0.29	85%	51%	26%	14.8	5.2	7.9	0.0	61.1
50/20% Helsinki		1.02	0.77	1.00	0.93	0.12	44%	48%	32%	29.7	4.9	7.4	13.6	61.5
20% Casablanca		0.74	1.00	1.14	0.96	0.16	73%	22%	12%	3.1	20.7	10.2	23.1	44.1

Table 3: Discomfort and energy indicators for the 14 STPV design variations and the base case window simulated with the Geneva weather file. The last two lines indicate the best design options for Casablanca and Helsinki. The bold results indicate the best design option for the Geneva climate. Please note that the m^2 used as reference is for all columns the floor area of the investigated space.

In terms of discomfort indicator, it can be observed a spatial inequality in the room: occupants sitting in the front were generally the most comfortable as their discomfort indicator was always the lowest one, except for the 40%, 50%, 50/20%, 50/30%, and 50/40/30% cases, for which occupants in the middle of the room resulted to be in the most comfortable situation. For these STPV design variations levels, in fact, the high visible transmittance led to a higher visual discomfort of the occupants sitting in the front, as it can be seen from the decreased importance of the thermal fraction ($TD_{fraction}$) and the consequent increase of the visual one. Occupants sitting in the back were always the most uncomfortable, due to visual comfort reasons as $TD_{fraction}$ is lower compared to that of other occupants.

When two scenarios with similar transmittance levels but in a reversed order are compared (e.g., 20/50% and 50/20%), it can be seen that the biggest changes occurred in terms of visual comfort and, consequently, in terms of lighting energy use, affecting the energy indicator. Due to the configuration of the room (i.e., deep floor plan with one window only), STPV design variations with lower transmittance levels on the top resulted in a better comfort and in a lower electricity consumption from the grid than the design variations with the same transmittance levels positioned in a reversed order.

From results of Table 3, it is possible to find the best design options among those investigated, for the temperate climate of Geneva. By looking at the lowest discomfort indicator in terms of both average and standard deviation, the design variations with at least one level of the high visible transmittance (50%) result as the best options. Among those, the design variations with the visible transmittance at the top have a lower discomfort indicator. Moreover, the 1-level and the 2-level options result better than the 3-level one. The final comparison results therefore between the 50%, 50/20% and the 50/30% design variations. The 50/20% led to the lowest energy consumption from the grid but it resulted in the highest spatial comfort inequality, with the highest standard deviation of discomfort indicator. The 50% had the lowest standard deviation but not the lowest average comfort indicator in comparison to the 50/30%, as a higher increase of the comfort in the back of the room (due to more light) did not compensate for the decrease of comfort in the front (due to too much light). Moreover, the energy from the grid was lower for the 50/30% case as, even though the energy use was higher in comparison to that for the 50% case, the production resulted larger. In conclusion, for the temperate climate of Geneva, the 50/30% design variation resulted as the best design option in terms of both energy and discomfort indicators.

Comparison with the base case

Figure 4 and 5 illustrate the temporal map of the occupied hours (excluding weekends and holidays) of the combined visual and thermal comfort scores for the six occupants for the best design option (i.e., 50/30%) and the base case, respectively. From the temporal map, the best design option seems to lead to too bright visual conditions for the occupants sitting in the front of the room, in comparison with the base case. On the other hand, the base case appears too dim in the back of the room, leading to visual discomfort of the occupants. Results for the base case are also indicated in Table 3. As it is possible to see, the average discomfort indicator is lower for the base case, indicating an overall higher comfort in comparison to the STPV best design option (i.e., 50/30%). This occurs as visual comfort above thresholds (i.e., glare) was usually controlled by the use of blinds, unlikely for the STPV case. On the other hand, the comfort inequality is higher for the base case than for the STPV design option, as people in the back were much more in discomfort compared to the occupants in the front. In addition, the energy indicator is higher for the base case due to a higher lighting consumption and to a lack of electricity production. The reduction of electricity consumption from the grid with the choice of the design option 50/30% in comparison to the base case is equal to 11.9 kWh/m^2 (-19.5%).

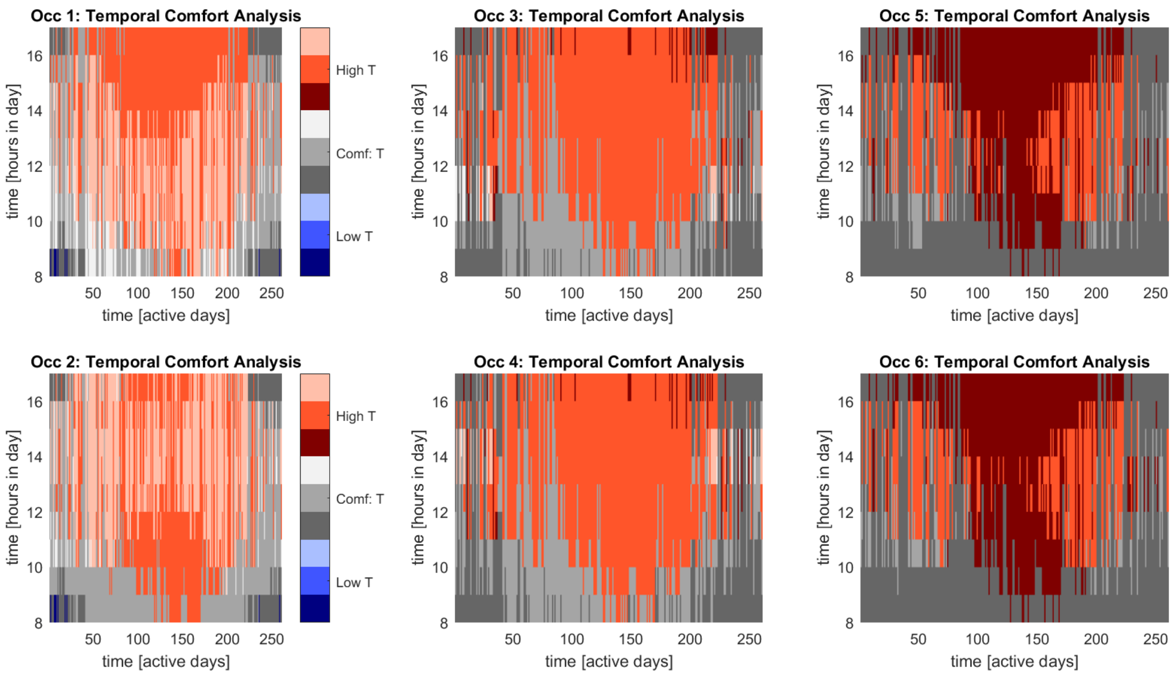

Figure 4: Temporal comfort analysis for the six occupants for the 50/30% case (best design option for Geneva).

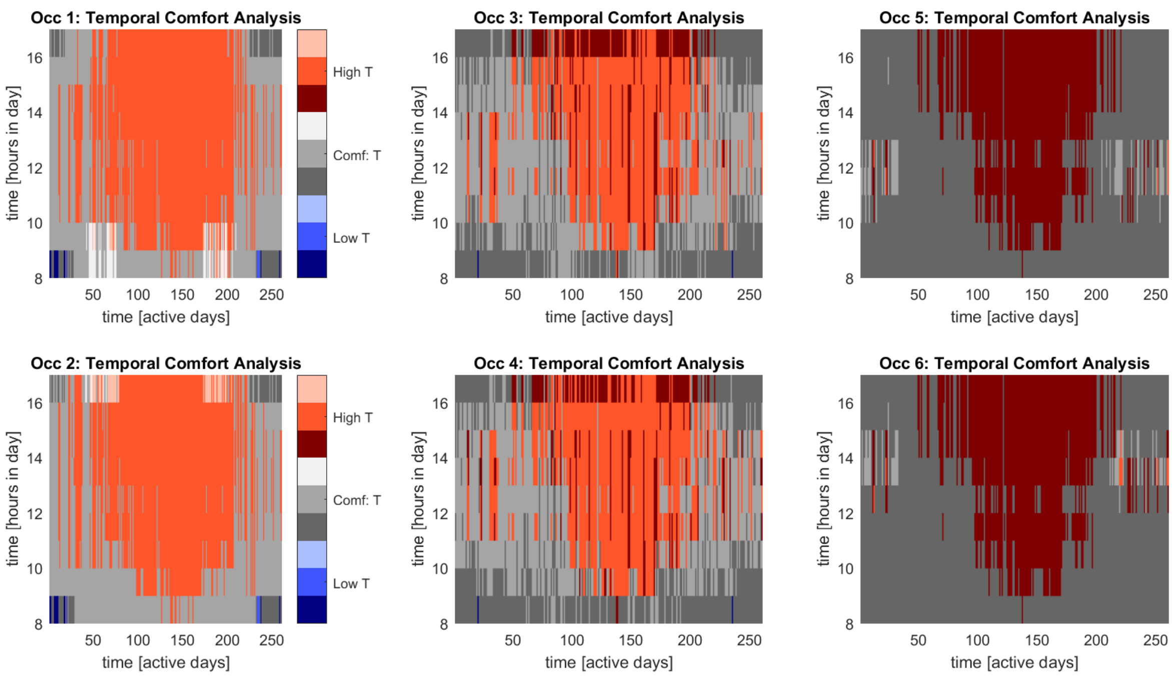

Figure 5: Temporal comfort analysis for the six occupants (Base case Geneva).

Evaluation of STPV design variations in different climates

Table 3 indicates the results for the best case options for both Helsinki and Casablanca. In the cold climate, the 50/20% case resulted as the best one as it provided light in the back of the room but, at the same time, it prevented a too glary environment for the front occupants (in comparison, for example, to the 50% case). In terms of comfort, the 50/30% design variation resulted comparable to the 50/20% one. However, the electricity production was higher for the 50/20% case, which makes it the best design option in both terms of comfort and energy. It must be noted that results in Helsinki were generally more uniform in terms of comfort (manly linked to the visual component), due to the low sun angle at higher latitudes. Moreover, the energy indicator for Helsinki was higher in comparison to that of Geneva as more energy was consumed for heating.

Results for Casablanca were different in comparison with those of Geneva and Helsinki as the best design option corresponded to a 1-level transmittance distribution. In particular, the 20% resulted the best choice in both terms of comfort and energy as it provided less overheated hours and the maximum energy production.

Limitations

The findings of this study are based on simulations performed in a reference office, which presents a deep floorplan in comparison to the glazed surface. Simulations on other types of space (e.g., less deep space) and with different window configurations are necessary to illustrate STPV design variations effects in different layouts. Moreover, as the power output of the STPV module was calculated in a simplified way by using a constant energy conversion efficiency, further investigations could refine the energy indicator to take into account variations of the efficiency of the PV module according to additional factors, such as, for example, the cell temperature and light spectrum. Similarly, future investigations should consider a different weighting approach for the calculation of the discomfort indicator according to the features of the project investigated. More specifically, uncomfortable conditions that could not be corrected by users with an immediate action (e.g., turning on the light is case of too dim visual environment), should have a larger impact for the determination of the discomfort score compared to uncomfortable conditions easier to address. For example, whenever a glare protection is not present in the space, the discomfort indicator should be modified to take into consideration that a too dim environment is not as uncomfortable as a glary one, considering that a personal lamp could always be turned on. Finally, for comparisons between locations, the envelope characteristics should be adapted to each climate.

Conclusions

This study compared 14 STPV design variations in terms of energy and occupancy-based comfort evaluations, investigated in a deep-floor reference room with a fully glazed south oriented facade. Different transmittance levels were tested, as well as their distribution on the glazing (one, two and three equal-height levels). The main investigation was conducted for the temperate climate of Geneva, for which the entire evaluation method and the resulting outcomes were reported. The goal, other than generally evaluate the comfort and energy results for the STPV designs, was to find the best design option as well as to compare its results with those of a base case with a conventional shading system. The best design option was also investigated for two additional climates, a cold and a dry-hot.

For all the climates, dividing the glazing in three parts did not result in a better comfort or in a decreased energy consumption from the grid. On the other hand, the 2-level design option with the higher visible transmittance (50%) on the top of the glazing was the best one for both Geneva and Helsinki climate, whereas for the dry-hot climate of Casablanca the 1-level design option with the lowest visible transmittance (20%) uniformly distributed on the entire glazed surface resulted as the best choice. These outcomes are due to the sun angle as, when it is not too high, the 2-level transmittance variation results in the best design option as it gives the possibility to let more light in the back of the room and to block too much light for the occupants in the front. This design also allows for a higher electricity production due to the presence of a lower visible transmittance of at least one part of the glazing which corresponds to a higher efficiency. In comparison with the base case window, the best STPV design for Geneva (50/30%) allowed for energy savings (19.5%) and resulted in a better distribution of comfort evaluation in the room, but it led to a decreased overall comfort, especially for the occupants in the front of the room.

The presented results provide the first insights on the relationship between energy and comfort related to selected STPV design variations in different climates, which can be helpful for the installation of this technology in practice. Moreover, other than describing specific results for the case study investigated, this paper provides a methodology for a multi-criteria analysis, studying different indicators simultaneously. The same methodology could be useful for the evaluation of other façade technologies, especially when innovative glazing systems are foreseen in a project.

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Nomenclature

STPV = Semi-Transparent photovoltaics

PMV = Predicted Mean Vote

DGP = Daylight Glare Probability

References

Bahaj, A. S., James, P. A. B., and Jentsch, M. F. (2008). Potential of emerging glazing technologies for highly glazed buildings in hot arid climates. *Energy and Buildings*, *40*(5), 720–731.

Do, S. L., Shin, M., Baltazar, J.-C., and Kim, J. (2017). Energy benefits from semi-transparent BIPV window and daylight-dimming systems for IECC code-compliance residential buildings in hot and humid climates. *Solar Energy*, *155*, 291–303.

EN ISO. (2008). *15251-2008: Indoor environmental input parameters for design and assessment of energy performance of buildings- addressing indoor air quality, thermal environment, lighting and acoustics*. Brussels: CEN.

Fanger, P. O. (1970). *Thermal comfort: Analysis and applications in environmental engineering*.

Fung, T. Y. Y., and Yang, H. (2008). Study on thermal performance of semi-transparent building-integrated photovoltaic glazings. *Energy and Buildings*, *40*(3), 341–350.

Kapsis, K., Dermardiros, V., and Athienitis, A. K. (2015). Daylight Performance of Perimeter Office Façades utilizing Semi-transparent Photovoltaic Windows: A Simulation Study. *Energy Procedia*, *78*, 334–339.

Karthick, A., Kalidasa Murugavel, K., and Kalaivani, L. (2018). Performance analysis of semitransparent photovoltaic module for skylights. *Energy*, *162*, 798–812.

Ko, W. H., Schiavon, S., Brager, G., and Levitt, B. (2018). Ventilation, thermal and luminous autonomy metrics for an integrated design process. *Building and Environment*, 145, 153-165.

Mardaljevic, J., Kelly Waskett, R., and Painter, B. (2016). Neutral daylight illumination with variable transmission glass: Theory and validation. *Lighting Research and Technology*, *48*(3), 267–285.

Mende, S., Frontini, F., and Wienold, J. (2011). Comfort and building performance analysis of transparent building integrated silicon photovoltaics. *Building Simulation 2011. Online Proceedings*, 2080–2087.

Olivieri, L., Caamaño-Martin, E., Olivieri, F., and Neila, J. (2014). Integral energy performance characterization of semi-transparent photovoltaic elements for building integration under real operation conditions. *Energy and Buildings*, *68*, 280–291.

Peng, J., Curcija, D. C., Lu, L., Selkowitz, S. E., Yang, H., and Zhang, W. (2016). Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer Mediterranean climate. *Applied Energy*, *165*, 345–356.

Reinhart, C. F., Jakubiec, J. A., and Ibarra, D. (2013). Definition of a reference office for standardized evaluations of dynamic façade and lighting technologies. *Proceedings of BS2013: 13th Conference of International Building Performance Simulation Association*, Chambéry, France, August 26-28, 3645–3652.

Rezaei, S. D., Shannigrahi, S., and Ramakrishna, S. (2017). A review of conventional, advanced, and smart glazing technologies and materials for improving indoor environment. *Solar Energy Materials and Solar Cells*, *159*, 26–51.

Roudsari, M. S., and Pak, M. (2013). Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. *Proceedings of the 13th International IBPSA Conference*. Presented at the BS2013.

Schierz, C., Vandahl, C., and Schmits, P. W. (2012). Evaluation zur Störung der Anzeigen von LCD-Bildschirmen durch die Beleuchtung. *Tech. Rep. Gesetzliche Unfallver-Sich. VBG*.

Schmid, A. L., and Uehara, L. K. S. (2017). Lighting performance of multifunctional PV windows: A numeric simulation to explain illuminance distribution and glare control in offices. *Energy and Buildings*, *154*, 590–605.

Tian, H., Zhang, W., Xie, L., Wu, Y., Sun, Y., Chen, M., … Wu, X. (2018). Study on the Energy Saving Potential for Semi-Transparent PV Window in Southwest China. *Energies*, *11*(11), 3239.

Wienold, J. (2007). Dynamic simulation of blind control strategies for visual comfort and energy balance analysis. *Proceedings of Building Simulation*, 1197–1204.

Wienold, Jan, Iwata, T., Khanie, M. S., Erell, E., Kaftan, E., Rodriguez, R. G., … Andersen, M. (2019). Cross-validation and robustness of daylight glare metrics. *Lighting Research and Technology (in Press)*.

Wong, P. W., Shimoda, Y., Nonaka, M., Inoue, M., and Mizuno, M. (2008). Semi-transparent PV: Thermal performance, power generation, daylight modelling and energy saving potential in a residential application. *Renewable Energy*, *33*(5), 1024–1036.

Zhang, W. (2018). *Study on the overall energy performance of building window integrated photovoltaics systems* (Thesis, The Hong Kong Polytechnic University).