SMART WINDOWS: OPTICAL AND THERMAL PERFORMANCE EVALUATION

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1. Abstract

A new concept for a **Smart Window** system is discussed, which can provide electricity and reduce solar gain by integrating high efficiency third generation photovoltaic cells with Fresnel lens concentrators that replace the active blinds currently employed in some double glazed facades. In the proposed window system, high efficiency concentrating photovoltaic elements (CPVs) are tracked in 2-axes to allow direct solar radiation incident at the glazing surface to be collected. The 2-D tracker is designed to avoid the overlapping and shading effects between adjacent Fresnel lenses. This design could also provide hot water or air obtained by cooling the cells for use within the building. In the optical analysis, beam intensity to the CPVs and room, diffuse intensity to the room through the window system, and radiation absorbed by the window components are analysed. Using the solar radiation fluxes calculated in the optical analysis TRNSYS based simulations of a simple building model located in Madrid and Birmingham were performed for rooms with standard double glazed and smart windows. Predicted zone temperatures and cooling loads resulting from solar gain show reduced peak room temperatures with cooling loads reduced by 40% annually for rooms with the smart window system.

2. Introduction

The development of effective renewable energy systems may be the most important topic in the twenty first century. Solar energy utilization will become one of the main substitutes for fossil fuel use in the future due to its essentially non-polluting, inexhaustible nature. The integration of photovoltaic with solar thermal technologies can provide a significant increase in the overall efficiency of solar energy conversion (Jie et al. 2008). Different types of double glazed facades are being employed in buildings with the aim to provide increased in-house comfort by reducing space heating requirements and energy consumption for cooling (Nassim et al. 2005). Blinds are used within such facades to control the fraction of the incident beam radiation entering the building, which reduces the cooling load for the building; these blinds however do not have any mechanism to use the intercepted energy.

Smart Windows is a new concept for the next generation of windows that provides control of energy flow through a double glazed facade which reduces the energy consumption within a building and improves its energy rating. Many recent window designs incorporate low E-coatings, spectrally selective glazings, and low conductivity gas fills, but they do not utilize the incident solar energy to generate heat or electricity. It is not easy to achieve a good level of natural day lighting within a building without, at some time of the year, suffering from excessive overheating. Smart Windows can mitigate the above problem and also help to reduce the discomfort in indoor living spaces caused by glare from solar radiation incident on windows or rays reflected from indoor surfaces (Piccolo and Simone 2009, Kim et al. 2009). Fresnel lenses coupled with high efficiency solar cells can make solar electricity generation more effective if the cell temperature is controlled in an efficient way. In Smart Windows good electrical conversion efficiency is maintained by controlling the intensity of beam radiation on the solar cells and using active or passive cooling. Integration of Fresnel lenses in double glazed facades enables the separation of beam radiation from diffuse radiation by concentrating direct radiation on the solar cells while the diffuse radiation penetrates into the interior of buildings to provide daylight of suitable intensity without sharp contrast and glare (Tripanagnostopoulos et al. 2007). This new generation of windows with transparent, water or air cooled, two-axes tracking CPVs using high efficiency solar cells will act as an efficient blind for direct sunlight, reduce the air conditioning load, generate electricity and transmit diffuse sunlight into the building to maintain natural day lighting.

This paper presents specifications and comparison of the predictions of Smart Windows performance when mounted at different slopes with different two-axes tracking limits at two different locations in Europe.

2. Methodology

The dimensions of the window control the total number of CPVs installed within the glazing and are related directly to the generation of electricity and system's cost. Fresnel lenses CPVs can only generate electricity if beam radiation is concentrated onto and effectively blocked by the solar cell located at the focus of the lenses. In this design, the CPVs track the sun by moving in two-axes in prescribed ways so that the angle of incidence of beam radiation is zero as illustrated schematically in Figure 1.

For a plane that is continuously tracked about two-axes to minimize the angle of incidence, the slope of the plane should be equal to the zenith angle and the surface azimuth angle should be equal to the solar azimuth angle (Duffie and Beckman 1991). In the proposed design the tracking angle about the first axis will be equal to the difference between the slope of the window and the zenith angle, and for the second axis will remain equal to the solar azimuth angle. For CPVs placed between the glazings of a window, it is not possible practically to track the sun from sunrise to sunset; specification of the tracking limits for each axis is an important part of the design. The CPVs are tracked simultaneously about two-axes to maintain the angle of incidence of beam radiation on the Fresnel lenses at zero, when the required inclination is outside the specified range then the CPVs are tracked back to be parallel to the plane of the window as shown in Fig. 1(c). From the tracking limits and dimension of the window the minimum spacing between the adjacent cells in each axis can be calculated which determines the optical performance of the system.

There is no overlapping and shading by adjacent Fresnel lenses within the tracking limits to prevent power dissipation in shaded cells. The increase in beam intensity when the sun moves toward noon is offset by the effective lens area being reduced as illustrated in Figure 1. In Figure 1(a) θ1 is the minimum solar azimuth angle limit, and d1 is the spacing between adjacent Fresnel lenses. In Figure 1(b) due to the increase in sun elevation, the spacing between Fresnel lenses d2 decreases. In Figure 1(c) the tracking angle at this time is zero and spacing between the lenses d3 is further reduced to its minimum value (d1> d2> d3). Another key factor in a glazing used for a double skin façade is the optical properties of the glass e.g. its transmittance, absorptance and reflectance (Fig. 2) which play an important role in determining the overall efficiency of the system. The experimental evaluation of the proposed Smart Window's design is presented in the following section.

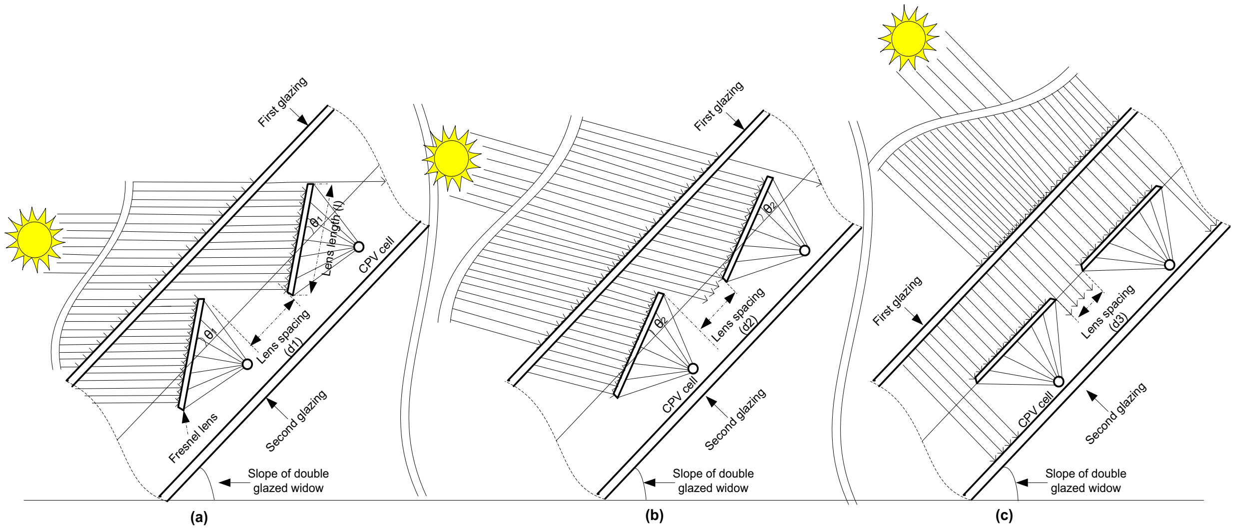


Fig. 1: Illustration of tracking in a Smart Window (in 2-D)

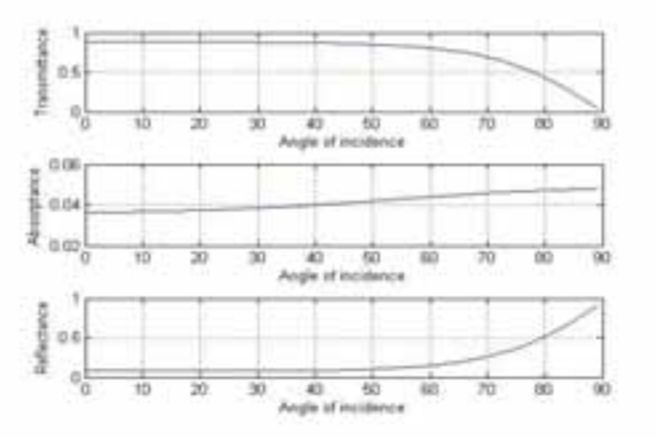


Fig 2: Optical properties of glass.

3. Results

The details of the system designs and the locations of installation are presented in Table 1.

Tab. 1: System Design Parameters

Window and Fresnel Lenses	**Value**
1. Double glazed smart window area	2x2 m^2
2. Fresnel lens area	50x50 mm^2
3. Thickness of glass	2.3 mm
4. Number of glazings	2
5. Extinction coefficient of glass	16
Location 1: Birmingham UK	
1. Latitude	52.3^o N
2. Longitude	2.1^o N
3. Altitude	100 m
4. Slope of the window	90^o
5. Tracking range for first axis	-45^o to +45^o
6. Tracking range for second axis	-60^o to +60^o
7. Total number of CPVs used	560
8. Max. possible lens spacing for beam radiation along first axis	20 mm
9. Max. possible lens spacing for beam radiation along second axis	50 mm
Location 2: Madrid Spain	
1. Latitude	40.5^o N
2. Longitude	30.5^o N
3. Altitude	582 m
4. Slope of the window	60^o
5. Tracking range for first axis	-45^o to +45^o
6. Tracking range for second axis	-45^o to +45^o
7. Total number of CPVs used	780
8. Max. possible lens spacing for beam radiation along first axis	20 mm
9. Max. possible lens spacing for beam radiation along second axis	20 mm

The solar data for the "peak day" of each month (19th Jan., 21st Feb., 20th March, 20th April, 22nd May, 22nd June, 23rd July, 23rd Aug., 23rd Sep., 23rd Oct., 22nd Nov., 22nd Dec.) for two locations Birmingham UK and Madrid Spain was downloaded from PVSYST 5_0. In Figure 3(a) the beam radiation concentrated by the Fresnel lenses and used for electricity generation in Birmingham is shown, collection time depending on date, starts between 8:15 and 9:50 and stops between 14:10 and 15:45. The maximum predicted daily intensity of beam radiation collected at noon is 235W/m^2 on April 20th and August 23rd with a minimum peak daily beam intensity of 140W/m^2 on December 22nd. In June beam radiation is not collected around noon because the required tracking angle in the first-axis is outside the tracker's range, which is determined by the slope of the window and the solar zenith angle. Figure 3(b) shows the beam radiation transmitted to the room which will affect the room temperature. The maximum peak value of 323W/m^2 is transmitted to the room at noon on February 21st and October 23rd. The minimum peak value transmitted to the room at noon on May

22nd and July 23rd is 108W/m^2. Figure 3(c) provides the total (beam and diffuse) intensity transmitted to the room which shows peak values at noon to range from 280 to 430W/m^2. The increase in intensity transmitted to the room at noon in the month of June is due to the tracking limitations discussed above. Figure 3(d) provides the total intensity transmitted to a room with the same size of window and same specifications with no CPV system between the glazings. These results show that a significant amount of radiation is utilized by the CPVs and a significant amount of summer cooling load may be avoided.

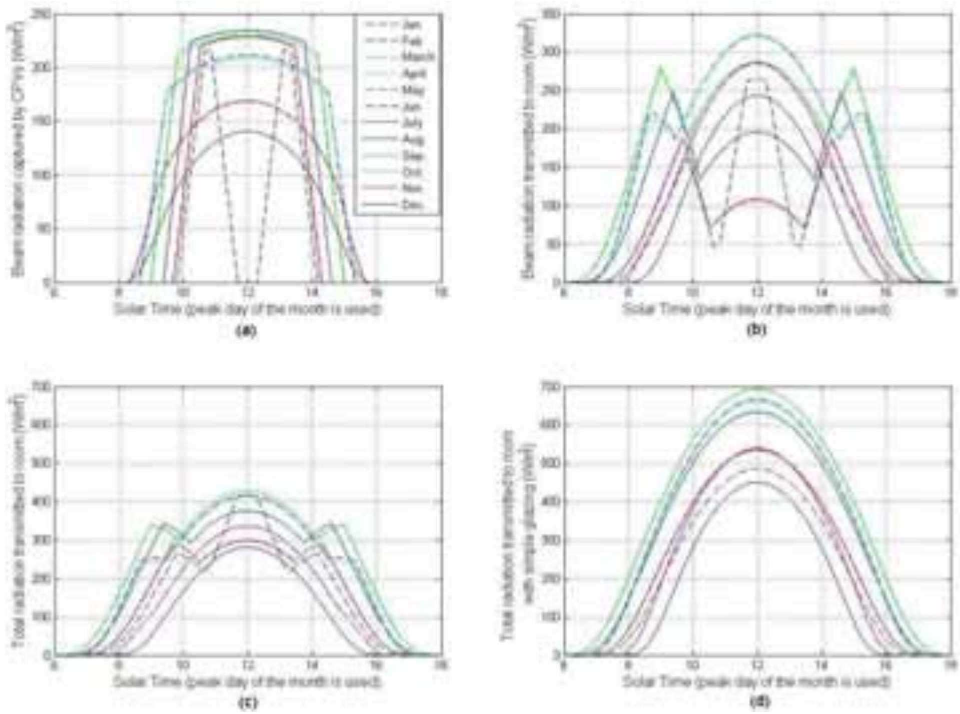


Fig. 3: Predicted beam radiation to CPVs (a), beam radiation transmitted to room (b), and total (beam and diffuse) radiation transmitted to room (c) for the Smart Window system. Total radiation transmitted to room through a simple double glazed window (d) for comparison. Location: Birmingham UK.

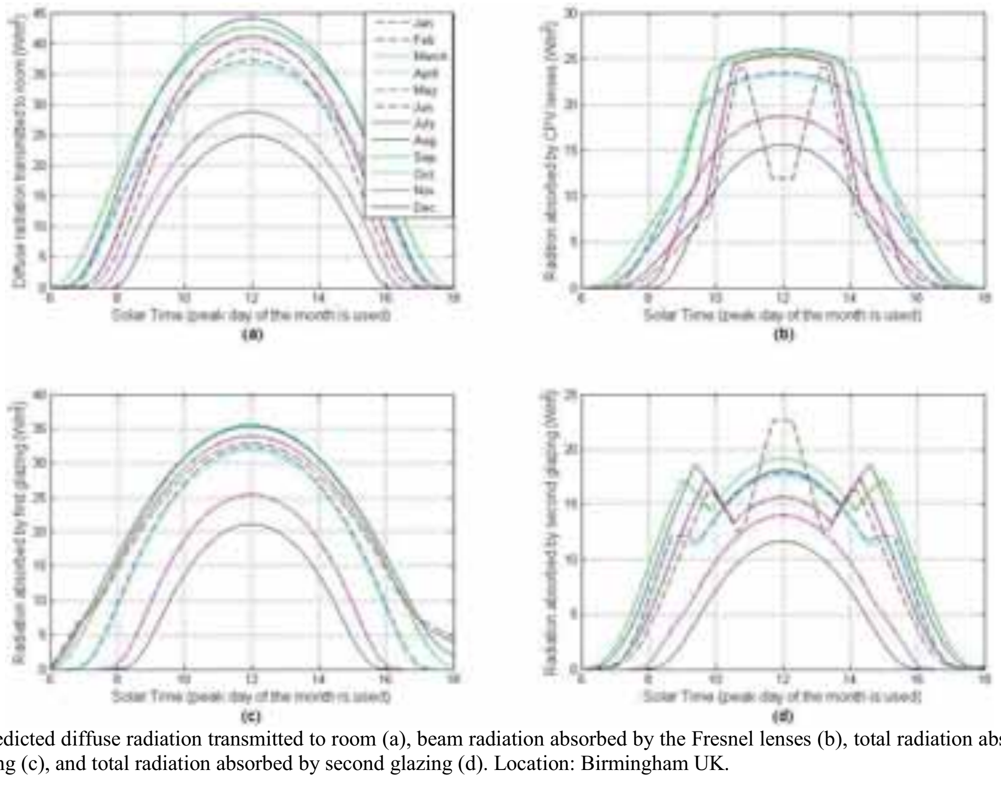


Fig. 4: Predicted diffuse radiation transmitted to room (a), beam radiation absorbed by the Fresnel lenses (b), total radiation absorbed by first glazing (c), and total radiation absorbed by second glazing (d). Location: Birmingham UK.

The diffuse radiation transmitted to the room, Figure 4(a) will provide natural daylight to the room. The energy absorbed by the Fresnel lenses, first glazing and second glazing, have maximum intensities of 25, 35 and 22W/m^2 respectively and provide input parameters for a thermal model of the system. Figure 5(a) illustrates the percentage of the total window area obscured by CPVs during the collection time in Birmingham and Figure 5(b) shows the percentage of area obscured for Madrid.

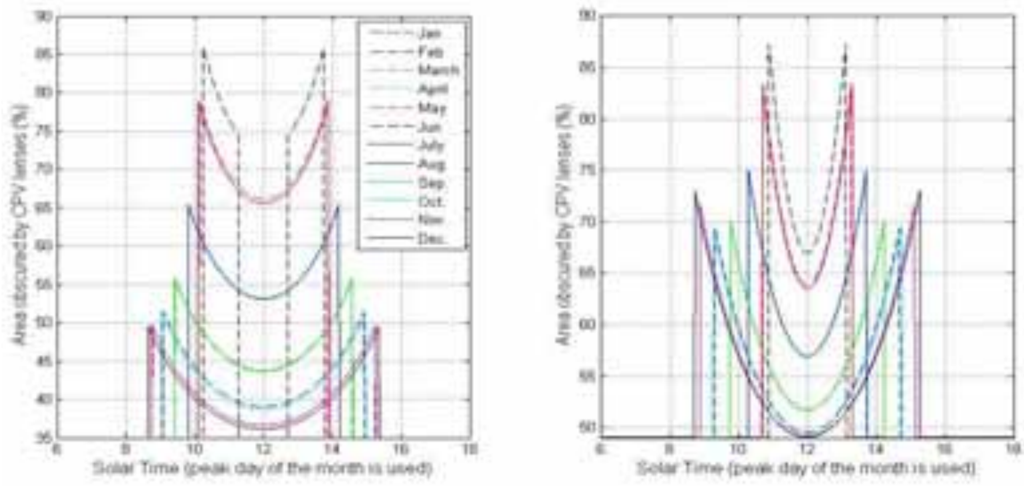


Fig. 5: Area obscured by CPV lenses in the Smart Window, (a) for Birmingham and (b) for Madrid.

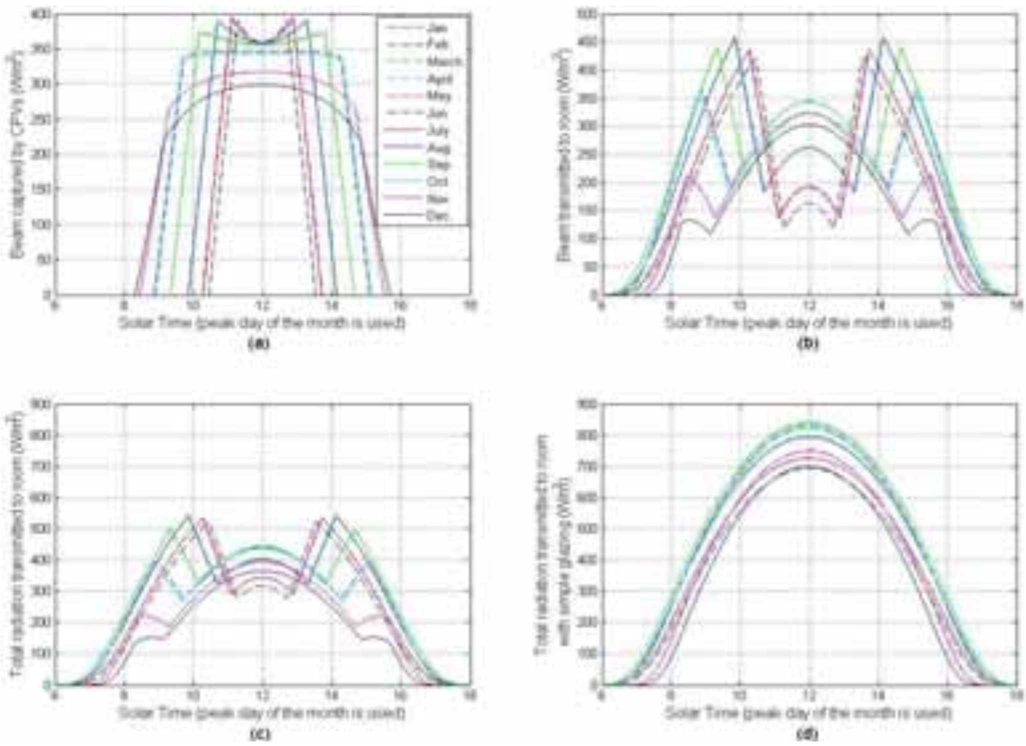


Fig. 6: Predicted beam radiation to CPVs (a), beam radiation transmitted to room (b), and total (beam and diffuse) radiation transmitted to room (c) for the Smart Window system. Total radiation transmitted to room through simple double glazed window (d). Location: Madrid Spain.

The beam intensity concentrated onto the CPVs for Madrid Spain is shown in Figure 6(a). The collection time starts between 8:15 and 10:30 and stops between 13:30 and 15:45 depending on the time of the year. The minimum peak of beam intensity i.e. 300W/m^2 at noon is collected on December 22nd, the maximum peak of beam intensity i.e. 395W/m^2 is collected in May and July at 11:06 and 12:54 hours. The beam radiation collected in the summer time is slightly decreased from the peak values at noon due to the decrease in area obscured by the CPV lenses as shown in Figure 5(b). The maximum beam intensity transmitted to the room 450W/m^2 is in August at 9:55 and 14:05 hours as shown in Figure 6(b). A comparison of total (beam and diffuse) radiation intensity to the room in Figures 6(c & d) indicates that the minimum difference in peak radiation at noon of 385W/m^2 is in June and the maximum difference in peak radiation at noon of 395W/m^2 is in March and September. These results illustrate that a significant amount of radiation is utilized by the CPVs and a significant amount of summer cooling load can be avoided. The diffuse radiation transmitted to the room, Figure 7(a) will provide natural daylight to the room. The energy absorbed by the Fresnel lenses, first glazing and second glazing, have maximum values of 43, 39 and 25W/m^2 respectively in Figures 7(b, c & d) and provide input parameters for a thermal model of the system.

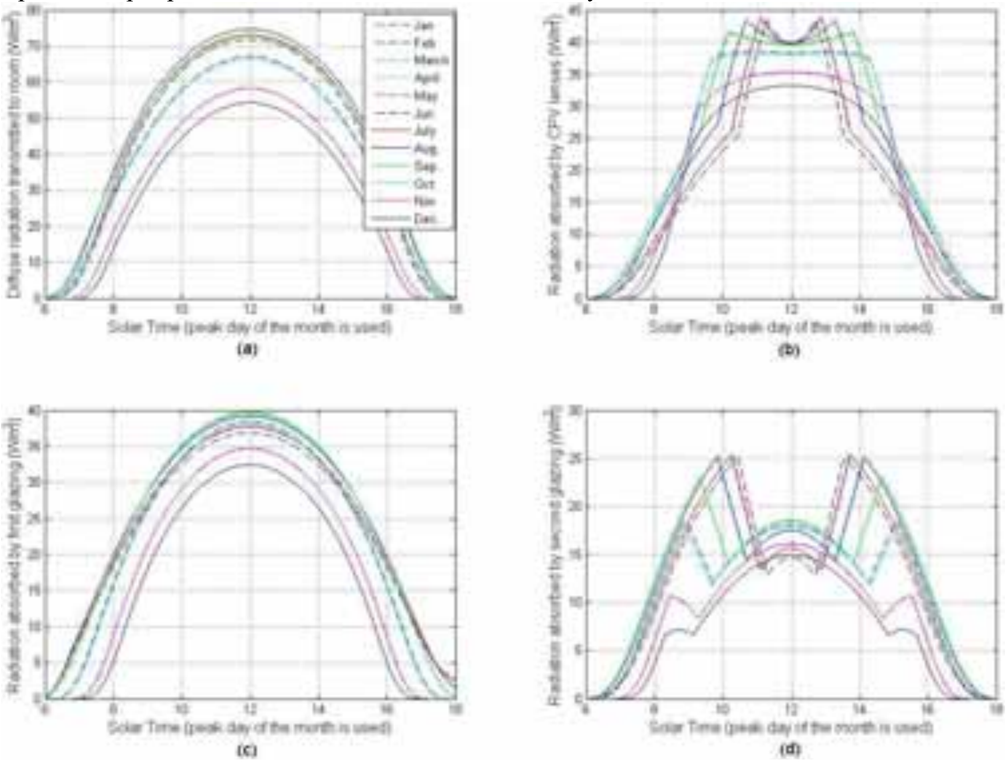


Fig. 7: Predicted diffuse intensity transmitted to room (a), beam intensity absorbed by Fresnel lenses (b), radiation absorbed by first glazing (c), and radiation absorbed by second glazing (d). Location: Madrid Spain.

4. Predictions of cooling demand reduction in a simple building

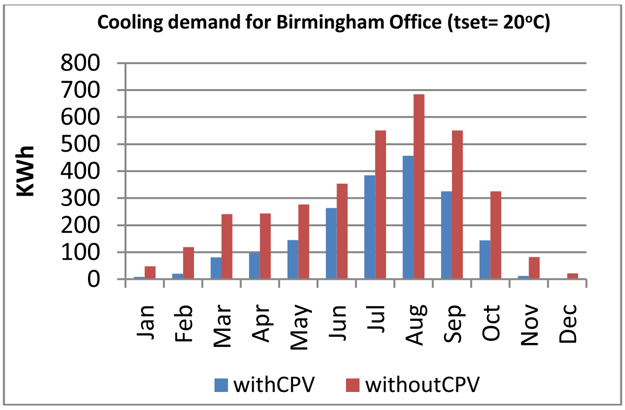
Predictions of cooling demands have been made for an office with either standard double glazing or the smart window installed using the TRNSYS computational simulation software. Simulations were undertaken for offices located in Birmingham and Madrid. The basic format and construction characteristics of the office simulated are provided in Table 2.

In the TRNSYS simulation undertaken the previously predicted daily total and beam radiation intensities with and without CPVs were provided as the inputs for the south facing window. The values for total and beam radiaiton obtained from the Meteonorm Program for the locations of Birmingham and Madrid were used for the solar radiation inputs in the calculation of solar transmission through the office walls facing south, north, west and east. The ambient tmperature and sky temperature for Birmingham and Madrid used were also those from the Meteonorm Program. The predictions of the performance of the specified office were undertaken without any additional heat gains being considered. The calculated room temperatures at 12pm resulting only from incident solar radiaiton for Birmingham and Madrid with and without CPVs indicate that the decrease in room temperature due to the CPVs in the smart window are around 3K and 5K for Birmingham and Madrid, respectively.

Tab. 2: Office dimensions and construction properties

Office size:	**Value**	
1. Height	2.5m	
2. Length	16m	
3. Width	10m	
4. Volume	400m^3	
5. Window area		
• North facing	16m^2	
• South facing	16m^2	
6. CPV shaded area (total)	5.6m^2 for Birmingham 7.8m^2 for Madrid	
Construction characteristics:	**U_value**	
1. Out wall layers: brick (240mm), insulation (100mm), plaster (15mm);	0.339W/m^{2}K	
2. Ground floor layers: floor (5mm), stone (60mm), silence (40mm), concrete (240mm), insulation (80mm);	0.425W/m^{2}K	
3. Flat roof layers: concrete (240mm), insulation (160mm);	0.233W/m^{2}K	
Window characteristics:	**U_value**	**g_value**
1. North facing window: double glazing;	1.4 W/m^{2}K	0.589
2. South facing window: double glazing;	1.4 W/m^{2}K	0.589

For determination of cooling demand, simulations were repeated with the room temperature set to temperatures of 20°C, 22°C and 24°C . The monthly cooling demands with and without smartwindows for the specified office located in Birminham and Madrid are presented in figures 8 and 9.



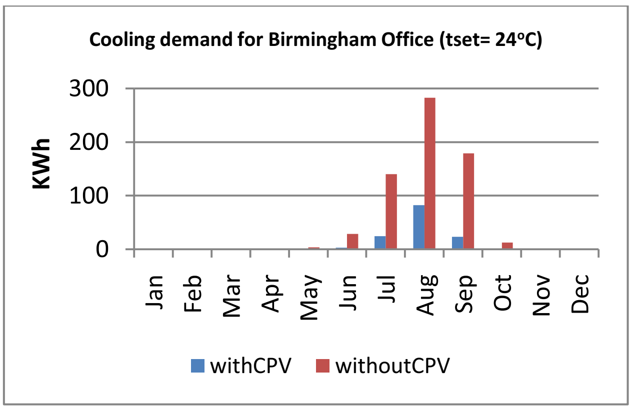
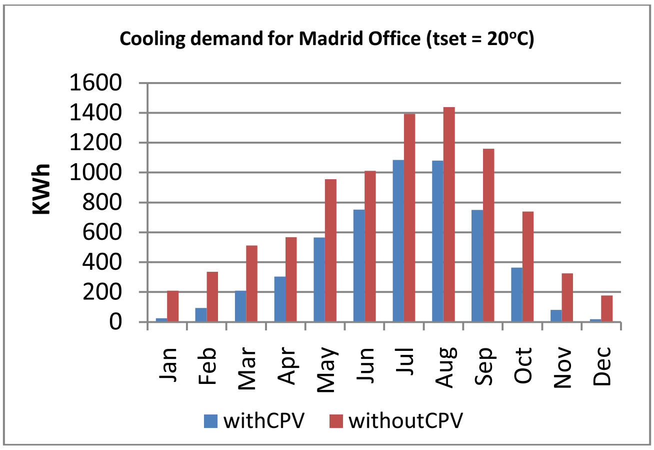


Fig. 8 Calculated cooling demand for the office in Birmingham with internal set point temperatures of 20 and 24°C

From figure 8 it can be seen that with a room set point temperature of 24˚C the cooling load is reduced in magnitude and duration. The smart windows delay the onset of cooling by two months and reduces the time when cooling is required to a period of three months. With the more stringent set point temperature requirement of 20˚C the reduction in cooling load is significant for most of the year.



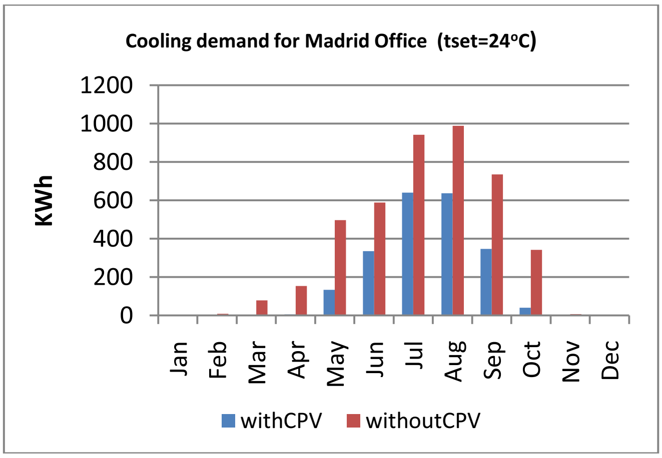


Fig. 9: Calculated cooling demand for the office in Madrid with internal set point temperatures of 20 and 24˚C

From figure 9 it can be seen in a similar way to those for the Birmingham office the predicted cooling demands are reduced significantly by the smart windows installed in the office in Madrid. The reduction in loads will have two important consequences i) the amount of electrical energy required for cooling will be reduced, ii) the cooling plant required to meet the peak loads will be smaller. The consequences of this are that the initial investment in cooling plant will be smaller for buildings employing smart windows and the building running costs will be reduced.

The calculated annual cooling demands for the specified office located in Birmingham and Madrid with and without smart windows are summarized in Table 3. It can be seen that the reductions in cooling load achieved are 40% or greater.

Tab. 3: Predicted annual cooling demand for the specified office with and without smart windows located in Madrid and Birmingham for different room temperature settings

Room Temperature setting	20°C		22°C		24°C	
	With SW	Without SW	With SW	Without SW	With SW	Without SW
Cooling load Madrid (KWh)	5327	8823	3957	7080	2208	4567
Cooling Load Birmingham(KWh)	1943	3498	1178	2431	165	742

5. Conclusions

An optical model to evaluate the performance of a new generation of windows which incorporate transparent two-axes tracking CPVs using high efficiency solar cells is presented. The results indicate that this design can be an effective blind for direct sunlight reduction while transmitting diffuse sunlight to the room for natural day lighting. Simple simulations using TRNSYS indicate that the reduction in beam radiation transmitted to a building could reduce air conditioning loads by 40% or more, in addition the CPVs in the smart window will generate a supply of onsite electricity.

6. References

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