A NEW ANGLE-SELECTIVE, SEE-THROUGH BIPV FAÇADE FOR SOLAR CONTROL

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Synopsis

Buildings account for almost 40% of the overall energy consumption both in Europe and the USA. Most of this demand is due to the energy needed to provide sufficient indoor comfort. In addition, electricity is required for artificial lighting and equipment. Fortunately, various projects have demonstrated that especially new buildings are able to achieve a neutral energy balance on an annual basis ("net-zero-energy buildings (ZEB)). To produce the same amount of energy, using renewable energy sources, as a building consumes during the entire year, significant reduction in the energy consumption and the use of renewable or non-finite energy sources are required. The main approach to producing usable energy for the buildings, using renewable sources, is the conversion of solar radiation into electricity, heat or cooling energy. As a result, the building envelope, especially the façades due to their large total area, becomes really important as it provides the necessary area for the installation of PV modules or solar collectors if we focus on high-rise buildings or multi family buildings. An example of a new multifunctional glazing PV façade for this application is presented here.

The new angle-selective see through BIPV façade combines four important tasks in one element: solar control (g value less than 10%), glare protection, visual contact and an integrated PV system for electricity generation. These four elements, as they are completely integrated into the system, do not affect the architectural goal of a glazed façade and the view from the interior to the exterior is guaranteed. The paper presents the potential of this new system, using the results of dynamic building simulations to compare the system with traditional shading devices, aspects of the building integration and highly promising predictions for the integrated PV.

1 Description of the new angle-selective, see-through BIPV façade

In a world which is increasingly concerned about carbon emissions, global warming and sustainable design, the planned use of natural light in non-residential buildings and the design of good solar-control façades have become important tasks.

The new angle-selective façade system (Figure 1) is a static, transparent solar-control façade, which can be produced using the usual production technologies for windows and glazing units. It consists of at least two laminated glass panes with two series of opaque stripes, one is sandwiched between the two panes of the laminate and the other is on the inward-facing surface of the laminate. Due to the different refractive indices of air and glass, that are respectively 1 and around 1.52, together with the specific position of the ceramic frit stripes on the glass, the new façade offers high solar control and can protect the occupants against glare. The visual contact to the outside is also guaranteed and varies with the viewing direction.

The opaque stripes can be produced in different materials or colours, depending on the architectural concept and on the shading requirements: dark colours are favoured to maximize the shading and anti-glare performance.

The invention (patent application n° *DE 10 2007 013 331* A1, submitted by T. E. Kuhn - Fraunhofer-ISE) can be implemented with photovoltaic stripes on either the outer and/or the inner layer. The efficiency of the system strictly depends on the design and on the technology adopted in the construction.

Figure 1: On the left: schematic view of the new see-through, angle-selective façade. The stripes (represented in blue) can be produced with photovoltaic technology. On the right: a detailed view of the first prototype with black ceramic frit stripes is shown.

2 Visual contact and solar control performance of the system

A mathematical analysis and Radiance [7] simulations were carried out to optimize the geometry and to assess the visual transmittance and the optical properties of the new window (see [4] for further details): the stripe dimensions and the glass thickness were varied to maximize visual contact from the inside to the outside [6]. The main viewing angles are considered to be in the range of $20° \leq \phi \leq -35°$, where negative angles represent the downward viewing direction and positive angles the upward one (see Figure 2). A detailed description of this analysis can be found in [4] and [6]. Only the final structure is presented here together with the Radiance simulation (Figure 3).

The new façade was modelled in Radiance as a *dielectric* box (see [7] for a further description of the *dielectric* material in Radiance) with opaque stripes. The stripes were described as a *plastic* material.

The description of the daylight source is generated with the *gensky* command (source [7]), the *rpict* program is used to render images. The *ximage* command is used to visualize the simulations.

To asses the visual contact, a cellular office space (based on a reference office segment which is defined for simulation of lighting and energy by a group of researchers active in several international projects such as IEA task 27 and IEA task 31) was considered. External volumes are considered to assess the visual contact (see Figure 3)

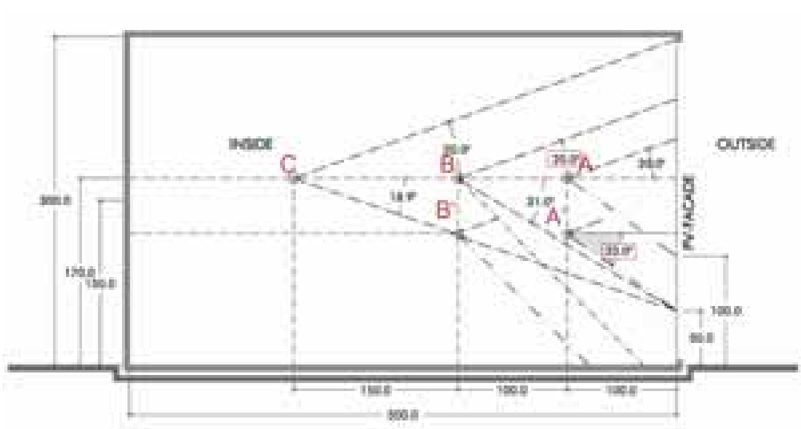


Figure 2: The image illustrates the internal viewing angles for an occupant sitting or standing (Point A, B, C) at 1m, 2m and 3.5m from the window. The angular range is 20° (upward view) to -35° (downward view).

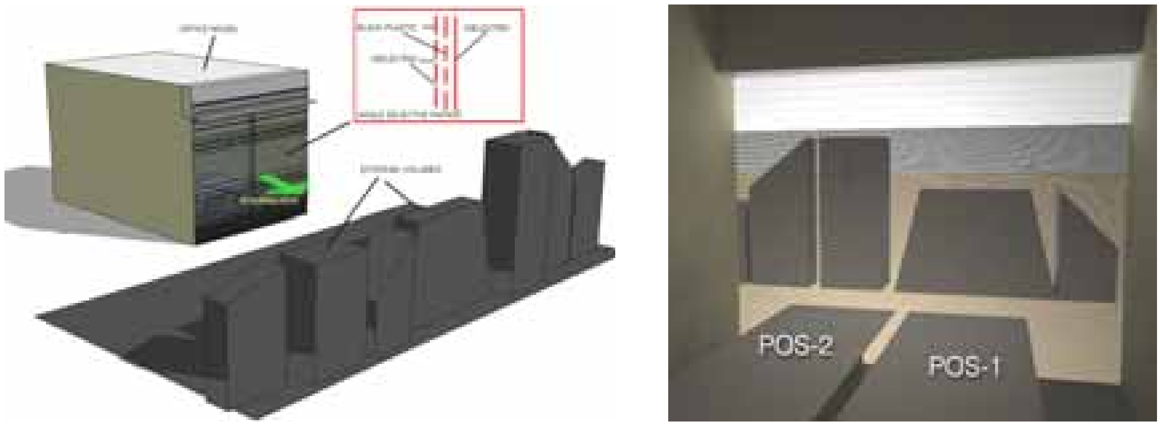


Figure 3: Configuration to investigate user response and visual contact from the inside to the outside. Simple volumes are placed outside the office space. POS-1 and POS-2 are the two working areas investigated during the glare analysis. The image on the right shows the good transparency of the system and also demonstrates that the transparency depends on the view angle (ϕ). The moiré effect that is visible here is an artefact of the digitized image.

The façade is considered to be fully glazed. The upper part is completely transparent to increase the daylight penetration (simulation with Daysim reveals the importance of having a completely transparent area to reach a daylight autonomy of about 70%, source Frontini [4] and [6]) and is equipped with external, light-redirecting shading devices; the remaining area is covered by the new system. Figure 3 shows the good transparency of the system in particular in the lower area of the façade. Due to the moiré effect, which could disturb an occupant sitting in the office space, it is suggested to leave part of the glazing façade fully transparent. Different solutions are possible, as presented in Figure 4, depending on the required façade design.

The angle-dependent transmittance (τ_{ang}) was determined from laboratory measurements and Radiance simulations (Table 1). The angle-dependent total solar energy transmittance (g-value, [2]) of the new façade was simulated with the GWERT program developed by S. Kühn [7] (Table 1). To allow the measurements and to validate the simulations, a prototype was produced in collaboration with a German partner from the glazing industry.

The simulations reveal the good performance of the new façade concerning visual contact to the outside (more than 30% transparency for downward viewing) and solar control (the effective g-value of the new façade can be less then 10%).

Table 1: The table reports the angle-dependent direct transmittance of the system and the angle-dependent total solar energy transmittance (for a solar azimuth of 0° with respect to the normal to the vertical façade). The solar altitude and positive viewing angles are identical by definition. A double glazing unit with Argon gap is considered.

	Viewing angles (positive upward, negative downward) and solar altitude							
	60°	45°	30°	15°	0°	-15°	-30°	-45°
τ_{ang}	< 0.01	< 0.01	< 0.01	0.05	0.12	0.19	0.24	0.22
g-value	< 0.05	0.06	0.06	0.07	0.14	0.20	0.25	0.23

3 Glare protection

The program "*Evalglare*" (implementing a new method for the Daylight Glare Probability, DGP, which is described in [10]) is used to evaluate the glare protection of the system. The new DGP index is considered. DGP is a function of the vertical eye illuminance as well as the glare source luminance, its solid angle and its position index.

Based on user assessment results, which were conducted during a Fraunhofer ISE project, daylight glare comfort classes are suggested to be defined according to the glare rating scale. The classes use the upper level of the 95% confidence intervals of the rating scales as DGP limits (see Table 2) in order to have generous tolerances. These DGP limits may not be exceeded for more than 5% of office time. In addition to this, it is proposed that the integral DGP values be restricted within this 5% interval. The criterion for this is that the average DGP within the 5% interval should not exceed the mean DGP value of the next higher glare category (see Table 2)

Table 2: Proposed definition of daylight glare comfort classes. (Sources J. Wienold [6][10])

	A: best class 95% of office-time glare weaker than "imperceptible"	B: good class 95% of office-time glare weaker than "perceptible "	C: reasonable class 95% of office-time glare weaker than "disturbing"
DGP limit	≤0.35	≤0.40	≤0.45

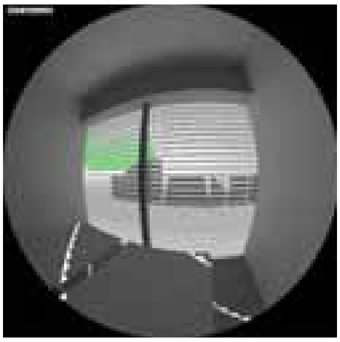
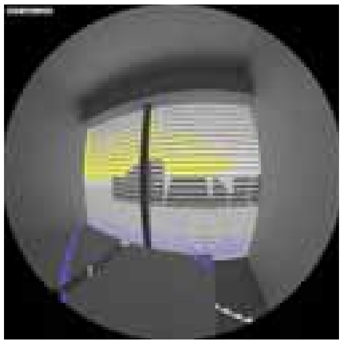
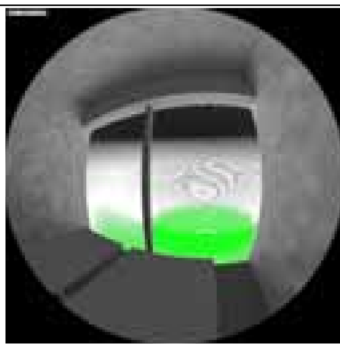
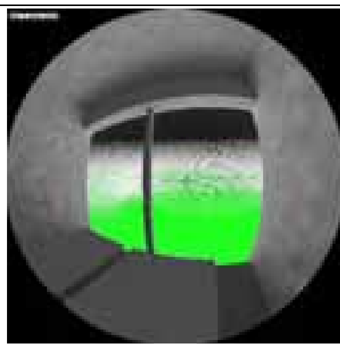
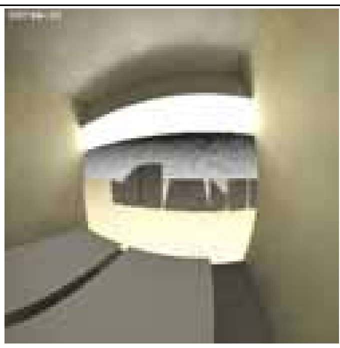
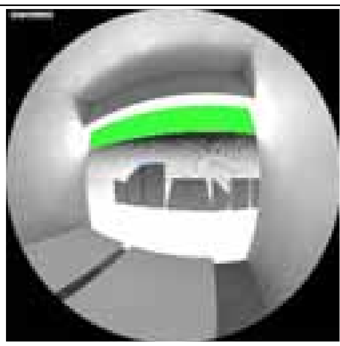
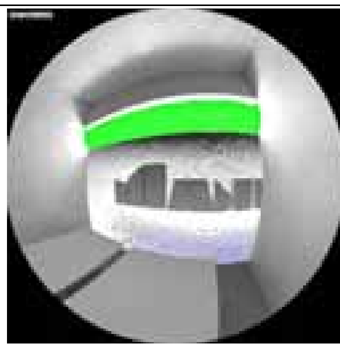
Three different simulations were carried out by the authors for different solar positions (different hours are taken into account):

- fully glazed façade with external venetian blind (Design1);
- fully glazed façade with the new angle-selective façade (Design 2);
- 70% of the external façade is covered by the new system and the upper part is transparent with horizontal slats to redirect the light (Design-3).

Two different working areas are considered, position one on the desk to the right and position two on the desk to the left of the picture (see Figure 3). The possible glare source areas are indicated with different colours.

While Design 1 reveals different glare sources due to the blind position (the slat angle of the blinds is considered to be fixed at 35°) with a critical DGP value (more than 40%), the other two systems provide good glare protection. Especially for the design 2, with a DGP_1=0.22 for Pos. 1 (Table 3) and DGP_2=0.24 for Pos. 2, the probable glare source is located in the lower part of the façade (because of the reflection of the external ground) and does not disturb the users. Design 3, with a higher mean luminance than the Design 2, also has an acceptable DGP value (DGP_3<0.3).

Table 3: Three different façades design were simulated. With the evalglare tool, it is possible to evaluate the area of the picture which could be a glare source for the user sitting in Position 1 or Position 2. It is important to remember that the colour areas are not 100% glare sources; they indicate the possible glare areas.

Design 1: DGP_{med}=0.40		
Reference	Pos 1	Pos 2
		
Design 2: DGP_{med}=0.22		
		
Design-3: DGP_{med}=0.28		
		

4 Building energy simulations

Thermal simulations with ESP-r [1], modified to allow the modelling of such complex glazing systems ([1], [5]), were performed to evaluate the effect of the proposed design on the thermal behaviour of a simple office building. Different sizes of openings (Figure 4) were simulated but only the case of a fully glazed area is here presented. The overall performance of the proposal proved to be promising. The new system is compared with a glazed façade with external venetian blinds or internal Genius ™ shading devices.

The blind slats are tilted depending on the incident solar radiation on the external façade. Occupants, light and equipment are taken as internal loads. The internal loads during weekdays were calculated to be $20W/m^2$ peak load from 8.00 to 18.00. The internal loads at weekends are the same as during the night. The simulations are carried out during a winter period to assess the energy demand for the heating system and during a summer period to check the cooling energy demand and the internal comfort.

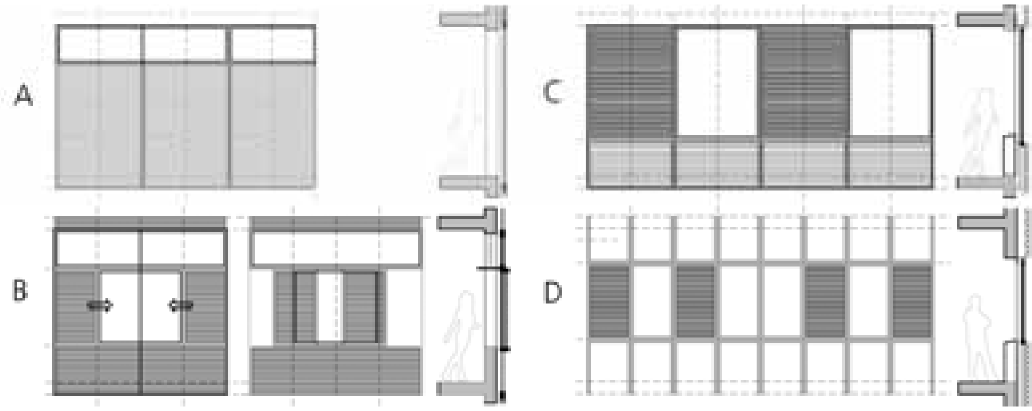


Figure 4: Different façade designs. Only solution A is presented here.

As expected, the solution with the internal Genius blind has a higher temperature for all of the summer period (see Figure 5. The solution with the new angle-selective façade is similar to the situation of the fully glazed façade with a double glazed unit and an external shading device (silver Venetian blind).

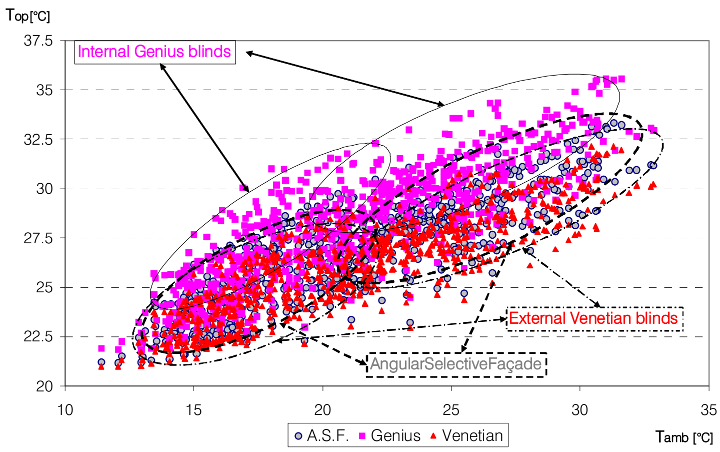


Figure 5: The graph represents the internal operative temperature as a function of the external ambient temperature for the three different façades. The simulations were performed without a cooling system.

5 Building integration

The new angle-selective façade can be used either as a stand-alone system for a glazed façade (as described in the previous chapters) or as an extra shading device layer. The following pictures shows designs to integrate the system either into existing building, where the new glass elements could be installed outside the existing windows, or into new buildings.

Figure 6: The pictures present three ideas for façade integration of the angle-selective glazing as external shading or as tilted windows.

Figure 7: the new façade can be easily installed in airport spaces or large open spaces. (ϕ). The moiré effect that is visible here is an artefact of the digitized image.

6 Outlook: Modelling of PV functionality and optimisation of electricity gains.

The solar façades group at Fraunhofer ISE is currently optimizing the geometry of the stripes in order to maximize the electricity gains and at the same time ensure good visual comfort and solar control performance. This optimization is part of the European FP7-research project cost-effective (see also http://www.cost-effective-renewables.eu).

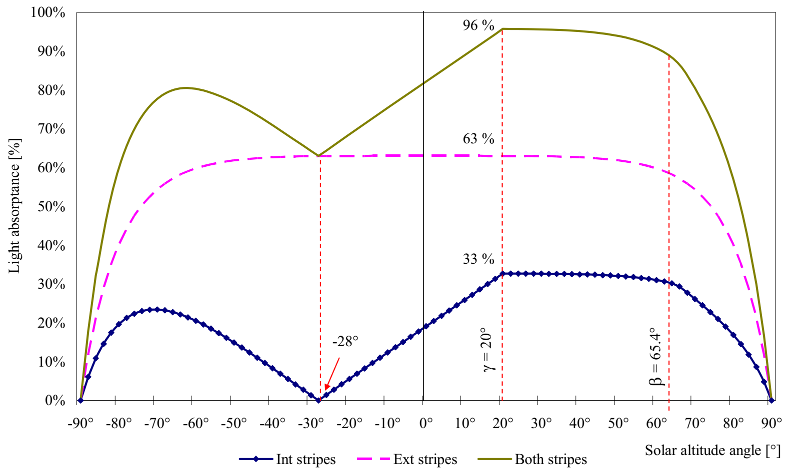


Figure 8: Light absorptance of the two different stripes layer and of the complete system.

Both of the striped layers can be produced with photovoltaic materials (see Figure 1).

The efficiency of the system strictly depends on the design and on the technology adopted in the construction. The efficiency can be very high if both of the striped layers are produced with PV technology.

To keep the study independent of the adopted PV technology, only the geometry is taken into account and the glass absorption is not considered. For this study, the absorptance of the stripes is assumed to be 100 %.

Figure 8 shows the light absorption of the different layers (without considering inter-reflection). The highest theoretical efficiency is reached for the third solution where both striped layers are with PV technologies.

7 Conclusion

The new angle-selective PV façade, proposed here by the authors, is a static shading device. It combines four important tasks in one element: solar control, glare protection, visual contact and an integrated PV system for electricity generation. These four functions, as they are completely integrated into the façade, do not reduce the architectural impact of the glazed façade, and the view from the interior to the exterior is guaranteed.

The system can be easily integrated into façade design as a glazed façade, as windows or as movable shading devices to protect the occupants against glare and to reduce the solar gains.

Building simulation with a new model, implemented in ESP-r, has demonstrated the good solar control provided by the system and the benefit for thermal comfort, especially in summer.

Radiance simulations were carried out to assess the daylight contribution and the optical characteristics of the new product, showing the good performance of the system if it is installed in an office space or in large glazed buildings.

The opaque stripes of the façade can be produced with photovoltaic technology. The authors show the potential of the systems if either two layers of stripes are made by PV technology or only one of them. Research on several ideas is still being conducted in this field by the group of Solar Façade of Fraunhofer ISE and will be published in future.

8 References

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