Outdoor Performance Analysis of Semitransparent Photovoltaic Windows with Bifacial Cells and Integrated Blinds

Simona Villa, David Out, Nicolas Guillevin, Martin Hurtado Ellmann, Marcel Ribberink, and Roland Valckenborg*

The stricter requirements for the energy performance of buildings are creating a market for several building-integrated photovoltaic (BIPV) technologies, including photovoltaic (PV) windows. Herein, an innovative multifunctional PV window concept designed to enhance energy generation while providing overheating protection for better indoor thermal and visual comfort is presented. This concept utilizes bifacial c-Si solar cell strips combined with venetian blinds, all embedded in a unique insulating glazing unit. The bifacial technology increases the energy yield by using the blinds as reflectors, directing more irradiance to the cells' rear side. The goal of this study is to analyze the outdoor performance of this concept under real operating conditions. Twelve demonstrators are installed and monitored. Various measurement campaigns are conducted, examining the impact of different blind types, tilt angles, sun positions and sky conditions. The highest energy boosts occur when the blinds are fully closed at a 75° angle with their convex side facing outward. Blinds with the highest specular reflectance achieve a maximum performance increase of 25% on sunny days and a daily average increase of 12% compared to the case of no blinds.

1. Introduction

Energy consumption in the building sector, which accounts for 40% of the total energy demand in Europe, is a serious concern due to continuous population growth in urban areas.[1] Consequently, there are stricter requirements for the energy performance of buildings, which are creating markets for building-integrated photovoltaic (BIPV) solutions, including photovoltaic (PV) windows. Especially for buildings with a high window to wall ratio, such as modern high-rise residential buildings or offices, semitransparent PV solutions will become essential to meet the energy targets. While in recent years significant progress has been made to increase the variety and the aesthetic value of opaque PV modules, such as coloring PV solutions,[2] semitransparent PV windows have not yet been extensively researched and commercialized.

The development of (semi-)transparent PV windows focuses on two main requirements: sufficient transparency, to ensure enough visual transmission, and the ability to deliver a significant amount of electricity.[3] Additionally, an ideal PV window should be aesthetically pleasing, meaning color-neutral and visually homogeneous.

Several approaches to achieve (semi-)transparent PV are being investigated. The most straightforward and commercially widespread approach involves segmenting opaque solar cells, reducing the active material area to create semitransparent modules with evenly spaced solar cells shaped as strips or squares on the glass substrate. Research and development efforts are also directed toward other innovative solutions aimed at achieving intrinsically transparent solar cells and modules. These approaches include, for example, reducing the thickness of otherwise opaque PV thin-films or using ultraviolet/near-infrared (NIR) wavelength-selective PV materials.[3–5] Based on these concepts, several emerging solar cell technologies are being investigated, such as, screen-printing dye-sensitized solar cells, NIR organic photovoltaics, polymer solar cells, transparent luminescent solar concentrators, perovskite, tandem perovskite, electrophoretic techniques, and quantum dot solar cells.[5–8] Although promising, most of these technologies are not yet close to commercialization due to serious technological challenges, including durability, stability, scalability, degradation and, most of all, low efficiency.[5,9]

Without sufficient electrical power production, PV windows can hardly compete with alternative types of smart and advanced window technologies, that aim to reduce the building's energy consumption in alternative ways, for instance, with low-emission

S. Villa, D. Out, N. Guillevin, M. Hurtado Ellmann, R. Valckenborg
TNO Energy and Materials Transition
High Tech Campus 21, 5656 AE Eindhoven, The Netherlands
E-mail: simona.villa@tno.nl

M. Hurtado Ellmann
Photovoltaic Materials and Devices group
Delft University of Technology
2628CD Delft, The Netherlands

M. Ribberink
Pilkington Nederland B.V.
De Hoeveler 25, 7547 SB Enschede, The Netherlands

The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/solr.202400515.

DOI: 10.1002/solr.202400515

coatings or vacuum double glazing.[10,11] It is commonly recognized that, to be competitive and achieve a reasonable levelized cost of energy, semitransparent PV windows for BIPV applications should have a minimum efficiency of at least 7–10%.[4] Therefore, efforts should be directed toward enhancing the electricity output of such semitransparent PV products. On top of that, it is essential not to overlook the fact that windows are crucial elements in the building, providing occupants with adequate daylight and ensuring visual and thermal comfort.

In this context, we have developed an innovative and multifunctional PV window concept which aims to boost the energy generation of semitransparent windows while, at the same time, providing overheating protection and visual comfort.[12] The concept that we propose is based on the combination of bifacial striped c-Si solar cells and venetian blinds. The use of the bifacial technology allows to boost the energy yield, thanks to the embedded blinds (also enclosed within the window double-glazing) which act as reflectors, increasing the amount of irradiance reaching the rear side of the cells. The concept has been patented by the glass company Pilkington, which intends to bring the product to the market.[13] This product represents a next-generation advancement compared to the already commercialized window solutions: Pilkington Insulight with Screenline,[14] which integrates blinds into the insulating glazing unit (IGU) but has no solar cells, and Pilkington Sunplus BIPV (PV Vision),[15] a BIPV IGU with monofacial cells and no blinds. Therefore, the innovation of our newly developed window lies in the use of bifacial cell technology combined with reflective venetian blinds. To the best of our knowledge, no bifacial PV window for building-integration exists on the market yet. Although several studies investigate the integration of PV cells into the shading systems themselves, there is very little literature on products using the blinds only as reflectors, as we do in the present work.[10,16] Additionally, most of the literature focuses on simulations with only limited experimental data available.[10,17,18]

The goal of this work is to analyze the outdoor performance of this multifunctional PV window concept. We aim to show how the combination of bifacial cells and venetian blinds can boost the energy yield of this semitransparent BIPV product, thus making it a real competitive BIPV solution. We manufactured 12 small-scale PV window demonstrators, representing different design choices, and tested the influence of different coverage ratios, venetian blinds' colors and PV technologies. Additionally, we conducted several measurement campaigns to study the impact of specific parameters, in particular the effect of the blinds' tilt angle on the performance. We should point out that, due to the intrinsically multifunctional nature of the product, the optimization can prioritize different aspects, such as energy yield, thermal or visual indoor comfort. In this study, the focus is on the electrical output maximization.

The rest of the article is organized as follows. Section 2 presents the investigated PV window concept and explains its operating principle. Section 3 describes the experimental setup, including the prototypes description and the outdoor testing setup, while Section 4 details the approach used for the analysis. Section 5 presents the results of the outdoor performance analysis and, finally, the main conclusions are highlighted and discussed in Section 6.

2. Description of the PV Window Concept

The proposed PV window concept consists of a unique IGU with laminated bifacial c-Si solar cells strips and venetian blinds embedded in the spacer between the two glass panes. As shown in **Figure 1**a, the solar cells are laminated on the outer side of the window, so that the front side of the bifacial cells directly faces the sky, while the rear side of the cells faces the venetian blinds, located toward the internal part of the window. When deployed, typically in moments of high irradiation, the blinds will act as reflectors, sending back part of the sunlight to the rear side of the bifacial cells, thus boosting the energy yield.

Figure 1b illustrates the operating principle of the multifunctional PV window: in the "no boost" mode, we have an ordinary solar window (with c-Si cell strips) because the blinds are out of sight, stored in the top storage box; in the "partial boost" mode, the blinds are deployed but kept open (i.e., horizontal), they will block the heat to some extent, but there is still normal visibility; in the "maximum boost" position, the blinds are completely closed (i.e., vertical), the output from the PV cell strips is maximized and the sunlight toward the inside of the room is blocked. The blinds' tilt can be controlled automatically or manually by the users to achieve the desired output (optimized PV yield, thermal, or visual comfort).

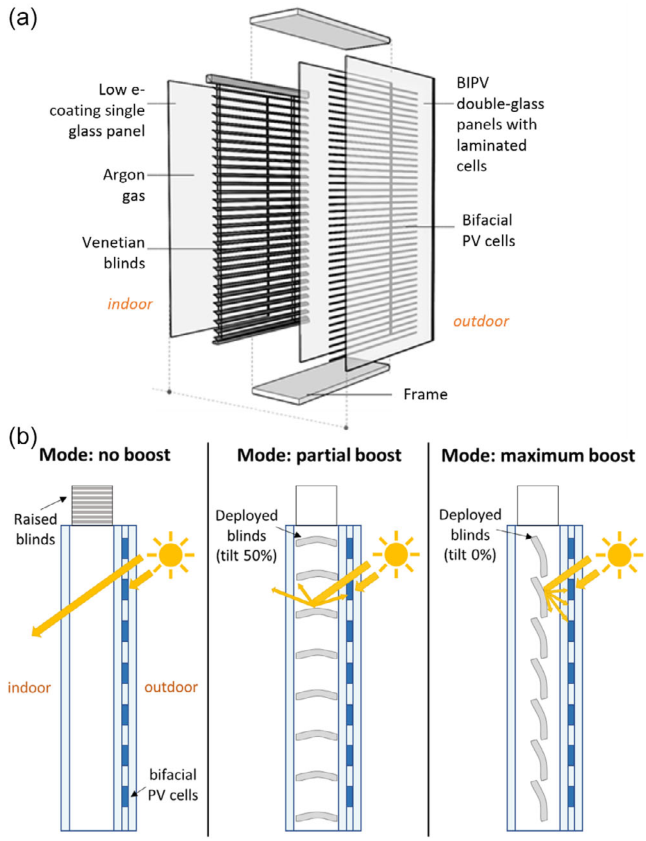


Figure 1. a) Exploded view of the PV window. b) Schematic representation of its operating principle. Three modes are shown: raised blinds (left), partial boost mode with open blinds (middle), and boosted reflection mode with closed blinds (right).

3. Experimental Section

To evaluate the performance of such a product, 12 small-scale PV windows have been manufactured and installed at the outdoor research facility SolarBEAT,[19] in Eindhoven, the Netherlands. The PV windows demonstrators have been integrated in the south-facing façade of a dummy building, as shown in **Figure 2**, and are operational since September 2023. The size of the windows, accounting only for the exposed glass area (thus excluding the frame and the venetian blinds storage box) is 455×333 mm.

With these 12 demonstrators, we are investigating several different aspects, namely, different PV cell technologies, the influence of different coverage ratios, and the effect of different types of venetian blinds. More precisely, we have the following variations: 2x bifacial PV technologies: a) c-Si interdigited back contact (IBC) cells and b) c-Si passivated emitter and rear contact (PERC) cells; 2x coverage ratios (CR): a) CR = 50% and b) CR = 60%; 3x types of venetian blinds (by Pellini):[20] a) S157 (gray, most sold commercially); b) S102 (white, high diffuse reflection); and c) V95 (gray, high specular reflection).

3.1. Description of the PV Windows Variations

The PV windows have been labeled as shown in **Figure 3**. On the first column, from row 1 to 6, the windows with c-Si IBC cells are installed, while the second column, from position 7 to 12,

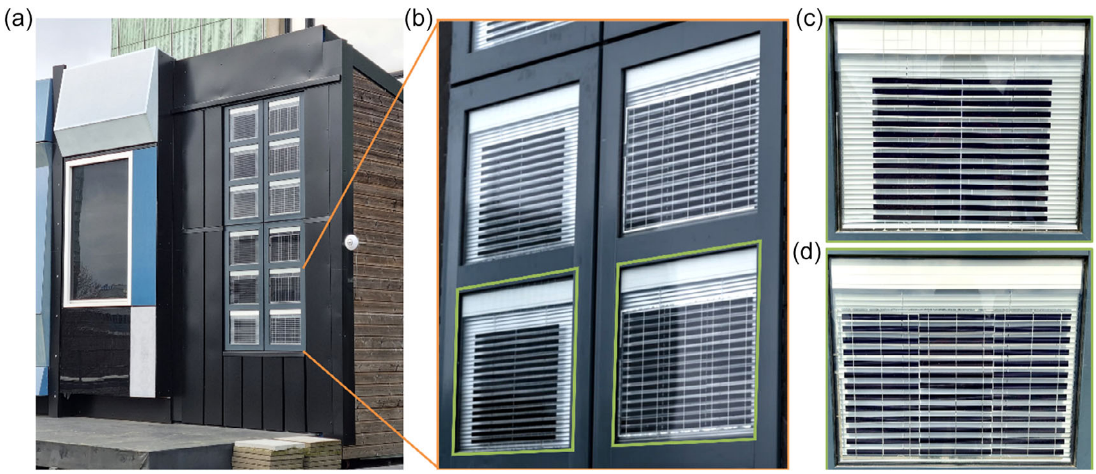


Figure 2. a,b) Photographs of the 12 PV windows installed at the SolarBEAT facility. Zoomed-in pictures of the c) IBC and d) PERC windows.

#	PV cell technology	Coverage Ratio (%)	Venetian blind type
T01	IBC	60	S102
T02	IBC	60	V95
T03	IBC	50	V95
T04	IBC	50	S157
T05	IBC	60	S157
T06	IBC	50	S102
S07	PERC	60	S102
S08	PERC	60	V95
S09	PERC	50	V95
S10	PERC	50	S157
S11	PERC	60	S157
S12	PERC	50	S102

Figure 3. PV windows labeling and characteristics. In the labels, the letter "T" or "S" before the number indicates the initial of the manufacturer (TNO or S'Tile).

contains the windows with c-Si PERC cells. While the PERC cells windows have been manufactured by a commercial company, S'Tile,[21] the 6 windows with bifacial IBC cells have been manufactured in-house at TNO.

The back-contact technology was chosen for the integration of bifacial c-Si strips because it allows maximum performance and flexibility of design and processing for cell interconnection. However, the integration of back-contactable c-Si strips posed several technical challenges. A series of experiments have been conducted to optimize the cell design, cutting and interconnection strategies, choice of materials, etc., but they are out of the scope of this publication and therefore not reported here.

Eventually, the process was optimized and laminates with 50% and 60% coverage ratio were produced. The coverage ratio is defined as the ratio between PV active area (blocking the light) and nonactive area (letting the light through the window). For the IBC windows, the 50% and 60% CR windows consist of, respectively, 28 and 32 strip cells connected in series in two adjacent columns of 14 and 16 cells each. The windows with the PERC cells consist of 3 strings of 13 and 15 series-connected cells (i.e., arranged in 3 columns), respectively, for the 50% and 60% coverage ratios. The three strings are here connected in parallel and the total number of cells is 39 and 45 for the two different CRs. For both window types, CR = 50% means that the vertical spacing between the cells is equal to 10 mm, while at CR = 60%, the vertical spacing is 7 mm, thus more cells can be accommodated. The electrical specifications at standard test conditions (STC) and the technical drawings of the 12 windows are reported in the Supporting Information (Table S1 and Figure S1), along with a more detailed explanation of how the coverage ratios are calculated (Figure S2 and Table S2, Supporting Information).

Once the 12 PV laminates were manufactured and characterized, they were sent to Pilkington for integration in the double-glazing IGU, together with the venetian blinds. The total thickness of the IGUs, comprising the PV laminate, the air cavity (air 10%, argon 90%) in which the blinds are located, and the toughened low-e-coating glass pane, is ≈38 mm for all windows.

The venetian blinds were manufactured by Pellini.[20] They are aluminum-based slats which are not completely flat, but have a slightly curved C-shape. The slats are evenly spaced at a distance that is smaller than their width so that the they can overlap when they are fully closed. In our case, the slats width is 12.5 mm and their distance 10 mm.

The three variations tested in this work are: the S157, which has a silver coating and is the most commercially sold blind type, thus considered our "reference"; the S102, which has a white coating and is highly diffusive; and the V95, which has a special low emissivity and highly reflective coating with silver color appearance. **Figure 4** shows the comparison of the total reflectance spectra of the three different venetian blinds, as well as their decomposition in diffuse and specular components (throughout the visible spectrum range). The V95 slat clearly shows the highest specular reflection, while the white-coated S102 slat is highly diffusive.

3.2. Measurement Equipment

The PV windows were all connected individually to an EKO MP-160 IV tracer, which allowed to measure at every timestamp all the electrical parameters and the complete current–voltage (IV) curves. For in-plane irradiance measurements, an EKO MS-802 pyranometer was installed on the side of the façade. NTC Theben temperature sensors were placed in the airgap inside the window (in the box that hosts the venetian blinds when they are not deployed); these temperature measurements were the most accurate approximation of the module's temperature that our test setup could achieve. The venetian blinds could be regulated in terms of height and tilt; they were controlled remotely thanks to the KNX communication protocol via the ThinkKNX application.

Finally, from a LufftWS600-UMB Weather Station, located at the SolarBEAT site, all weather data could be retrieved (e.g., global horizontal irradiance (GHI), diffuse horizontal irradiance (DHI), T_{amb}, wind speed, etc.), and a webcam placed in front of the setup allowed to visually monitor the system and detect possible shading situations.

4. Approach

4.1. Measurement Campaigns

The main research question we are trying to answer is: "To what extent can the blinds boost the performance of the PV

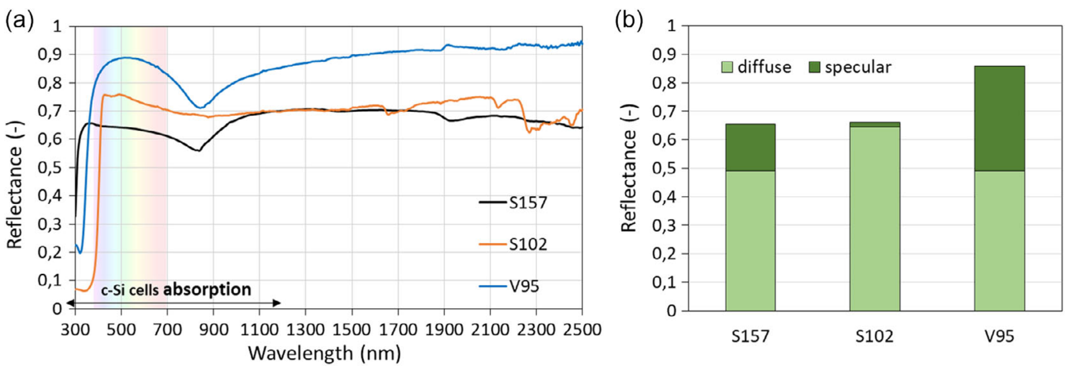


Figure 4. a) Total reflectance spectra of the three different venetian blind types: S157, S102, and V95. b) Diffuse and specular reflectance components of the three blinds in the visible spectrum range.

windows?". The answer is not trivial, as it depends on several aspects, such as the optical properties of the blinds themselves, their tilt angle, the sun position, the sky conditions, etc.

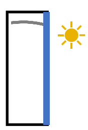
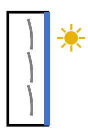
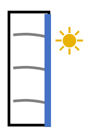
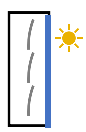
Several measurement campaigns have been conducted in the 9 months of operation. In each measurement campaign, we varied the position of the blinds in terms of height (h) and tilt (t). Both height and tilt can be tuned from 0% to 100%. Height value of $h = 0\%$ means that the blinds are not deployed at all (raised up), while $h = 100\%$ means that the blinds are completely deployed down. When the blinds are deployed, their tilt angle can be set and varied from 0% to 100%. As mentioned, the slats are slightly curved. The situation in which the tilt is set to $t = 0\%$ means that the blinds are fully closed with convex rounded side facing outside; while $t = 100\%$ means fully closed but with concave side facing outside. It is also relevant to mention that, in both cases $t = 0\%$ and 100%, the slats cannot go fully vertical, but only reach a maximum angle of ±75° (with reference to the horizontal axis).

Various intermediate blinds' tilt positions, e.g., $t = 25/50/75\%$, have been tested too. Typically, for each measurement campaign, i.e., for a specific configuration of blind's tilt and height, we measured the performance of the windows for a least one full week, to gather a sufficient amount of datapoints. The configurations that were found most relevant are shown in **Table 1**.

4.2. Performance Analysis Metrics

The main metrics used to assess the outdoor performance of the PV windows are the specific energy yield and the performance ratio (PR). The specific yield allows us to easily compare the different PV windows, in spite of their different rated power.

Table 1. Main tested configurations, in terms of blinds' height and tilt, during the measurement campaigns.

Blinds' height [%]	Blinds' tilt [%]	Blinds' tilt in degrees [°][a)]	Description	Schematics
$h = 0\%$	$t =$ n.a.	n.a.	Blinds are not deployed (reference case)	
$h = 100\%$	$t = 0\%$	75	Blinds are completely deployed and closed (vertical orientation), with convex side facing outside and upward	
$h = 100\%$	$t = 50\%$	0	Blinds are completely deployed and open (horizontal orientation)	
$h = 100\%$	$t = 100\%$	−75	Blinds are completely deployed and closed (vertical orientation), with concave side facing outside and downward	

[a)]With reference to the horizontal plane (normal to the window plane).

Indeed, it is defined as the ratio between the measured yield and the nominal power of the module at STC, expressed in $kWh\,kW_p^{-1}$. The PR is a quality metric, expressed in %, which describes the relationship between incoming irradiation and produced power; it is defined as the ratio of the actual and expected energy output and allows to compare modules and systems independently of their PV technology, orientation and incident irradiation. It allows for a fair comparison, regardless of the specific conditions.

In this study, we deal with bifacial PV modules, but we do not have the possibility of measuring irradiance on the rear side because the cells are embedded in the IGU together with the venetian blinds. Consequently, we cannot use the bifacial-PR equation, as specified in the IEC 61 724 standard.[22] Instead, we calculate PR using the following monofacial equation:

$$\mathrm{PR} = \frac{P_{\mathrm{meas}}}{P_{\mathrm{STC,\ front}}} \frac{G_{\mathrm{STC}}}{G_{\mathrm{meas,\ front}}}\ (\%) \tag{1}$$

where P_{meas} is the total power measured by the bifacial PV window, $P_{\mathrm{STC,\ front}}$ is the front side rated power measured at STC, G_{meas} is the plane-of-array irradiance measured at the front side of the façade and G_{STC} is $1000\ \mathrm{W\,m^{-2}}$. The standard PR metric as defined above neglects the temperature effect, resulting in strong seasonal variations. Since in our study we performed several measurement campaigns, varying the position of the venetian blinds, and we want to compare these different situations measured at different times of the year, we need to remove the impact of seasonal variation on the PR. To do so, we use the temperature-corrected PR metric, defined as:

$$\mathrm{PR}_{\mathrm{T-corr}} = \frac{P_{\mathrm{meas}}}{P_{\mathrm{STC,\ front}}\left(1 - \frac{\delta}{100}\left(T_{\mathrm{ref}} - T_{\mathrm{mod}}\right)\right)} \frac{G_{\mathrm{STC}}}{G_{\mathrm{meas,\ front}}}\ (\%) \tag{2}$$

where δ is the module's P_{mpp} temperature coefficient, T_{mod} is the measured module temperature at each timestamp, and T_{ref} is the STC temperature, i.e., 25 °C. The power temperature coefficient of the IBC cells is $-0.29\%\ \mathrm{P_{mpp}}\ °\mathrm{C}^{-1}$, while for the PERC cells, it is $-0.35\%\ \mathrm{P_{mpp}}\ °\mathrm{C}^{-1}$. For the module temperature T_{mod}, we use the readings from the temperature sensor placed in the airgap inside the window, which is the closest approximation to cell/module temperature that is available.

Using the T-corrected PR instead of the standard PR formula allows us to eliminate (or at least significantly reduce) the influence of temperature, to more clearly identify the differences in performance attributed to the use of the venetian blinds.

4.3. Data Filtering

The data have been recorded with a timestamp of 2 min. Some filters have been applied to disregard the datapoints affected by unwanted mechanisms, such as shading, or characterized by conditions inducing higher uncertainties, such as too low irradiance levels. The applied filters are reported in **Table 2**.

The lower limit for the irradiance filter has been set to $50\ \mathrm{W\,m^{-2}}$. Although this threshold is not excessively strict, it can be observed that this filter already removes more than 40% of the datapoints. This is due to the fact that on vertical

Table 2. Filters applied to the dataset and related datapoints statistics.

Filter description	Filter condition	Aggregation and iteration	Datapoints removed at each step [%]	Datapoints left [%]
Original dataset [day-time]	$G_{poa} > 5\ W\ m^{-2}$	Whole dataset	0	100
Remove low irradiance	$G_{poa} > 50\ W\ m^{-2}$	Whole dataset	−42	58
Remove nongeneration time	$P_{mpp} > 0$	Per window – whole dataset	−16[a)]	49[a)]
Remove outliers [1st step]	$1.5 \times$ IQR on $PR_{T\text{-}corr}$	Per window – daily iteration	−14[a)]	42[a)]
Remove outliers [2nd step]	$1.5 \times$ IQR on $PR_{T\text{-}corr}$	Per window – on whole period	−7[a)]	39[a)]

[a)]With reference to the horizontal plane (normal to the window plane).

façades, the irradiance is typically lower than on other installation types, but also because our 9 month measurement period does not include the sunnier summer months. The G_{poa} filter already excludes night times, but with the additional filter on the maximum power point power we aim to exclude those times in which system outages or any other issue causing no power generation took place. Additionally, since power and irradiance are directly proportional, their relationship (i.e., the PR metric) can be used to detect and remove nonrealistic power–irradiance pairs and outliers representing other potential issues like shading. To do so, we used the interquartile range (IQR) method. With this method, we define the outliers as any point in which $PR_{Tcorr} > Q_3 + 1.5 \times IQR$ or $PR_{Tcorr} < Q_1 - 1.5 \times IQR$, where Q_1 and Q_3 are the first and third quartiles and IQR is the interquartile range (i.e., Q_3–Q_1). This filtering rule is applied in two steps, first on a daily basis and with a daily iteration routine, and second, on the whole dataset. **Figure 5** shows the correlation power-irradiance for a reference window, in which the datasets at each filtering step are shown. At the end of the filtering procedure, a clean dataset is obtained and can be further used for the analysis.

5. Results

In this section, we present and analyze the results, starting with an overview of the daily performance of all windows. We then

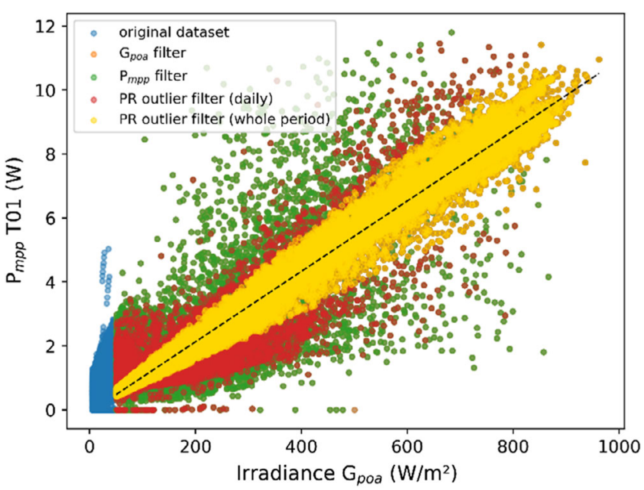


Figure 5. Scatter plot power (T01) versus irradiance showing the effect of the filters on the dataset.

delve into a detailed comparison of the various window types and the impact of venetian blinds on their energy efficiency. Additionally, we examine how different weather conditions influence their performance, also depending on the specific blinds' configuration.

5.1. Overview Daily Performance

Figure 6 shows an overview of the daily temperature-corrected PR for the 12 windows. For clarity, the 6 windows with PERC cell technology are plotted in the top graph, while the 6 windows with IBC cells are in the bottom graph. As a guide for the eye, the windows with blind type V95 are shown in blue color tones, blind S102 in green tones, and S157 in orange tones; additionally, the darker color indicates a coverage ratio of 60%, the lighter color a CR of 50%. In the plots, the different measurement campaigns are indicated by the vertical lines and the schematics on top of the graphs.

The first aspect we can point out is the high recorded absolute PR values: in fact, the daily T-corrected PRs of all windows range approximately between 95% and 130%. We must again point out that this is partially because the PR calculation only includes the contribution of the front-side irradiance, while the bifacial cells are also able to capture reflected light on the rear side. This is why, also in the reference situation where we do not use the blinds to enhance the back-side reflection (so at $h = 0\%$ and $t =$ n.a), the PR value is around or above 100%.

Additionally, we notice differences in performance both between the various measurement campaigns and between the different blinds' types. One obvious feature is the jumps in PR when the blinds changed from "completely raised up" ($h = 0\%$, $t =$ n.a.) to "completely closed" ($h = 100\%$ and $t = 0\%$ or 100%), and vice versa, irrespective of their color and optical properties. If we take a closer look and observe the differences between the blinds' types, we can notice that their behavior changes depending on the specific measurement campaign, i.e., on their tilt position. When the blinds are closed with convex side facing outside ($t = 0\%$), the V95 blind seems to be the best performing, while the windows with blind S102 and V95 become comparable when they are closed with the opposite orientation ($t = 100\%$). In almost all cases where the blinds are deployed, the windows with blind type S157 tend to report the lowest PR values. In contrast, when the blinds are fully raised, the 12 windows exhibit more similar and comparable energy yield and PR values. Part of the reason for these performance

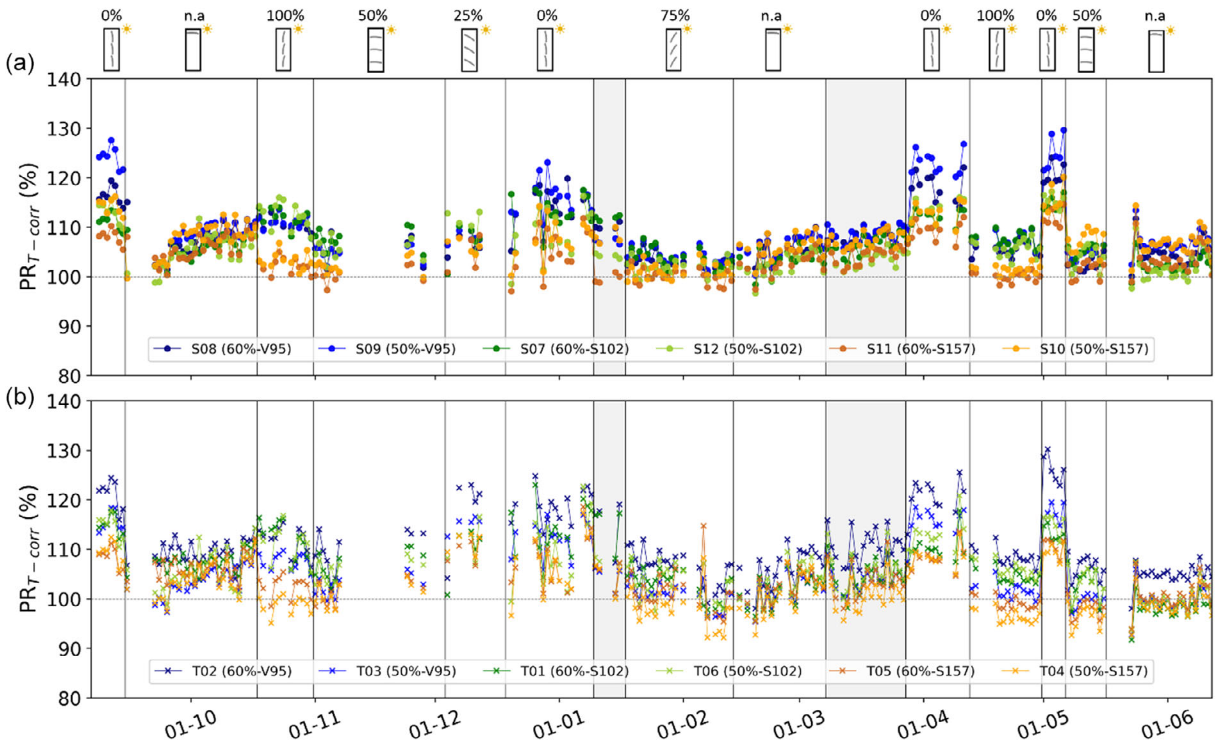


Figure 6. a) Daily T-corrected PR of the 6 PERC windows and b) the 6 IBC windows. The vertical lines mark the different measurement campaigns with the different blinds positions, which are indicated in the schematics on the top, together with the tilt angle percentage. The shaded areas should be disregarded in this analysis.

deviations can be either the different coverage ratios and cell technologies, or in general the uncertainty margin in the flash data of the PV windows. A discussion related to this aspect can be found in the Supporting Information. In general, the differences in performance due to coverage ratio or cell technology are found to be significantly less relevant than those related to the types of blinds. Therefore, for the remainder of the study, we will focus on the effects given by the various venetian blinds types.

5.2. Effect of Blinds' Type and Tilt Angle on Performance

5.2.1. Reference Sunny Days

Although with daily aggregations we can easily compare the different measurement campaigns and analyze long measurement periods, a more in-depth analysis requires focusing on specific days to analyze instantaneous yield and performance. In particular, we selected a (mostly) sunny day for each of the most relevant tested configurations: no blinds ($t = $ n.a), blinds deployed and open in horizontal position ($t = 50\%$), blinds deployed and fully closed with concave side facing out ($t = 100\%$), and blinds deployed and fully closed with convex side facing out ($t = 0\%$). **Figure 7** shows both the specific energy yield and T-corrected PR for four reference days, each representing one of those blinds configurations. Ideally, fully sunny days would be used to better discern performance differences; however, in some cases, such days were not available during the measurement campaigns for a particular configuration. In these cases, we selected days that were at least partially sunny.

For better visual clarity, Figure 7 displays data for only one window per blinds type, specifically the windows with PERC cells and a coverage ratio of 60%; however, the behavior is consistent for the other windows with coverage ratios of 50% and IBC cells. As expected, in the reference case with no blinds (Figure 7a), the yield and PR of the windows are nearly identical. When the blinds are in use, however, more significant deviations are observed. It is interesting to note that for the configurations with tilts 50% and 100% (Figure 7b,c), the average PR is comparable to the case with no blinds, and it is also more challenging to determine which blind type performs best. Generally, it appears that the most common blind type, S157, performs slightly worse than the others. In contrast, it is evident that, when the blinds are tilted at $t = 0\%$, the performance of all windows increases significantly, with the V95 blind clearly outperforming the others.

So far, we have evaluated the impact of adjusting the blinds' position on the windows' performance by comparing data from various days across different seasons. However, this approach has some limitations, as the PR is also affected by environmental and seasonal factors, such as temperature (partially accounted for by using the $PR_{T\text{-corr}}$ formula), position of the sun in the sky, wind cooling effects, and other possible variables.

Therefore, an experiment was conducted in which, for a few days, the blinds of all windows were kept in "raised up" position with the exception of only one window, S09, which blinds (V95 type) were completely deployed and tilted at $t = 0\%$, as shown in **Figure 8**a. Figure 8b,c displays the energy yield and PR of the 6 PERC-cells windows during a sunny day in that period. We can now clearly observe the PR boost given by the use of the V95

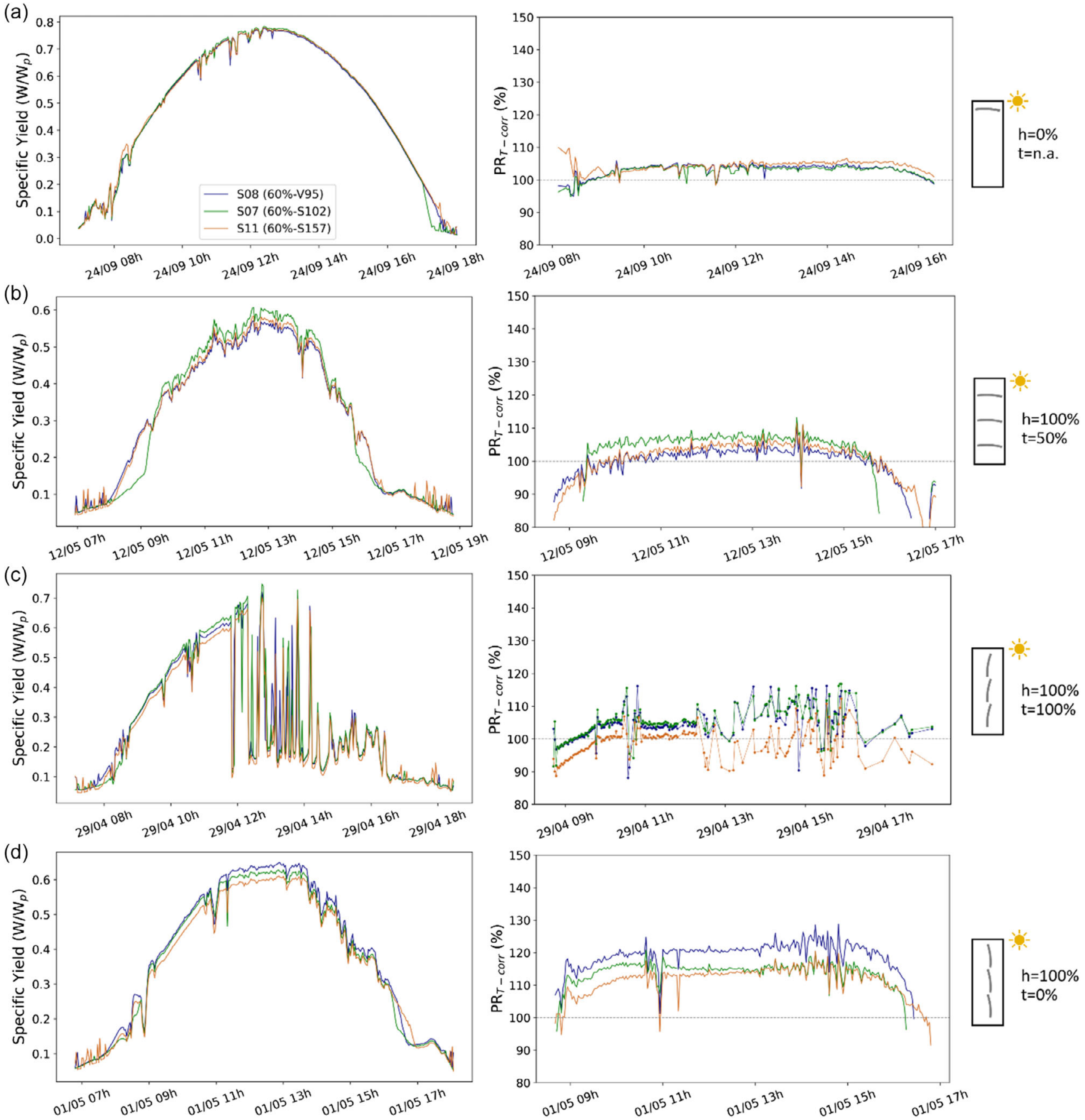


Figure 7. Specific yield and PR plots for four reference sunny days during the various measurement campaigns: a) blinds up, b) blinds down tilt = 50%, c) tilt = 100%, and d) tilt = 0%. Only one window per blind type is shown (PERC cells, CR = 60%).

blinds when fully closed with $t = 0\%$. The performance boost is significant and amounts to more than 25%.

5.2.2. Correlation with Sky Conditions and Sun Position

Understanding the performance of this PV window concept is not trivial because of the several parameters that simultaneously come into play and affect the internal reflections within the IGU unit. In particular, we are interested in investigating how the electrical performance is affected by the sky condition, i.e., if the blinds behave differently under diffuse and direct irradiance, and in the correlations between the sun position in the sky, the plane of the PV cells and the tilt angle of the venetian blinds' slats.

For this purpose, we plot the data shown in **Figure 9**. First, Figure 9a shows the correlation between the PR and the plane-of-array irradiance accounting for the complete period, but distinguishing between the various blind configurations.

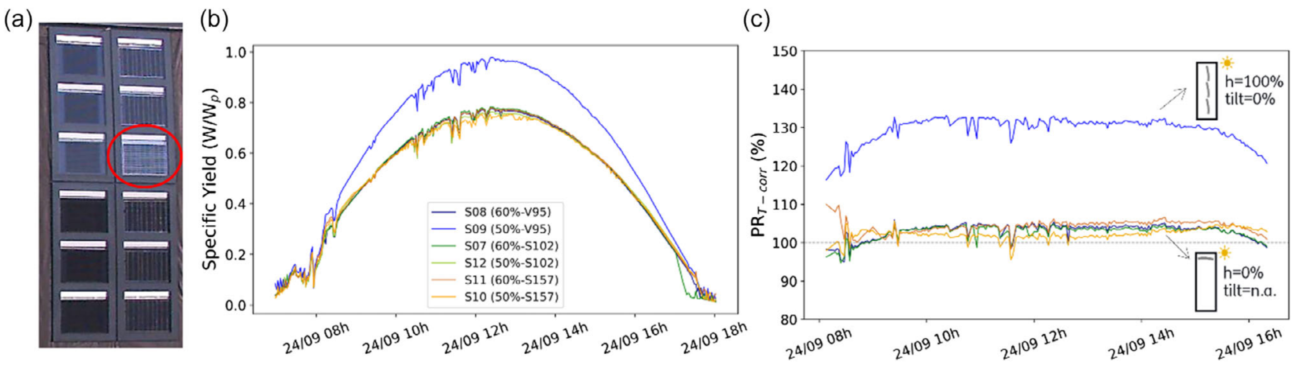


Figure 8. a) Photograph of the setup during the experiment in which the blinds of only one window (S09) were in use. b) Specific yield and c) T-corrected PR on one sunny day (24/09/2023) of the PERC-cells windows (S07 to S12), showing the performance boost given by the blinds' deployment.

One reference window for each blind type is shown, and the data has a 10 min resampling. The highest performance is clearly achieved at blind's tilt of 0%. In general, we can also observe how at low irradiance levels, i.e., below 200 W m^{-2}, the performance starts to drop.

After having verified and discussed in the previous sections that the specular reflective blind V95 leads to the highest energy boost, we dive deeper into the analysis of this particular window type. In Figure 9b–d, we show scatter plots of PR versus irradiance at the various blind configurations, as a function of several parameters, namely, diffuse fraction, angle of incidence (AOI) between the sun and PV plane, and angle of incidence between the sun and the venetian blinds' slats.

The diffuse fraction is defined as the ratio between the DHI and GHI; typically, diffuse fraction values below 30% represent sunny moments. Expectedly, we observe that high diffuse fraction values corresponds to moments in which G_{poa} is lower, however, this does not correlate to lower PR. This means that also when there is no or little direct irradiance, the blinds still induce the boosting effect, by reflecting part of the irradiance to the rear side of the cells.

In contrast, the performance ratio is significantly affected by the AOI (Figure 9c), i.e., the angle between the incident beam of the sunlight and the perpendicular to the plane of the PV window. In general, lower PR values correspond to higher AOI; this is expected as, at high AOI, the reflection from the outer glass increases significantly, thus reducing the transmitted irradiance. What is more interesting to observe is that the high PR values, between 120% and 130%, recorded when the blinds are closed at $t = 0\%$ (75° tilt), seem to be correlated to angle of incidence in the range 50–65°. It is likely that the general PR decrease due to the glass' reflection at high AOI is compensated by the boost given by the reflection of the blinds when they are closed at their maximum tilt angle of 75°. The same does not hold true for the other blinds positions ($t =$ n.a./50%/100%), where the PR is not boosted at this range of angles of incidence; instead, in these cases, the lower the AOI, the higher the performance.

Finally, Figure 9d highlights more explicitly the correlation between the angle of the sunbeams and the venetian blinds ($\mathrm{AOI_{blinds}}$). We would expect that, for the specular reflective blind V95, the lower the $\mathrm{AOI_{blinds}}$, the higher the reflection, thus the energy boost. This is in fact what happens when the blinds are in close position, both at $t = 0\%$ and $t = 100\%$. However, at tilt of 100%, the blinds have a real angle of −75°, meaning they face downward instead of upward to the sky. Therefore, the angle of incidence with the sunbeams rarely approaches the optimal low values. This is also the reason why the boost in this blinds configuration is significantly lower than when the blinds face the sky with an angle of 75° ($t = 0\%$). Finally, we observe that at $t = 50\%$, there are no clear correlations between the window performance and the relative angle between the sun and the blinds. In this configuration, the blinds are placed horizontally, i.e., perpendicular to the plane of the PV cells, therefore the specular reflection from the blinds is directed toward the inside of the room, rather than on the rear side of the PV cells. Only part of the light that is reflected diffusively can reach the cells, but this contribution is found to be insignificant.

5.2.3. Overall Period

For a comprehensive evaluation of the behavior of the windows, we aggregated all data points from various measurement campaigns, regardless of the season in which they were conducted, based on the same blinds configurations. The boxplots in **Figure 10** show the daily temperature-corrected PR of each window for each blind configuration throughout the entire measurement period. It should be noted that the four blind configurations were tested for varying numbers of days (N): $N = 61$ for the configuration with blinds raised up, $N = 20$ for blinds at tilt 50%, $N = 26$ for tilt 100%, and $N = 37$ for tilt 0%. In the boxplot, the median is represented by the middle horizontal black line, while the mean is indicated by the red pointer. It can be observed that windows with the same blind type (aligned on the same columns in Figure 10) show equal or very similar trends. This proves again that the coverage ratio and the cell technology do not significantly impact the general performance of the PV windows. This overview also confirms that the highest performance is achieved, in all cases, when the blinds are closed with the convex side facing outside, i.e., with tilt = 0%. In this situation, the energy boost is maximized, and it is particularly high for the V95 blind, which is the most highly reflective one. When the blinds are tilted at 100%, the performance varies depending on the blind's type: for S102 and V95 we achieve a slight performance boost, while for S157 the performance is even

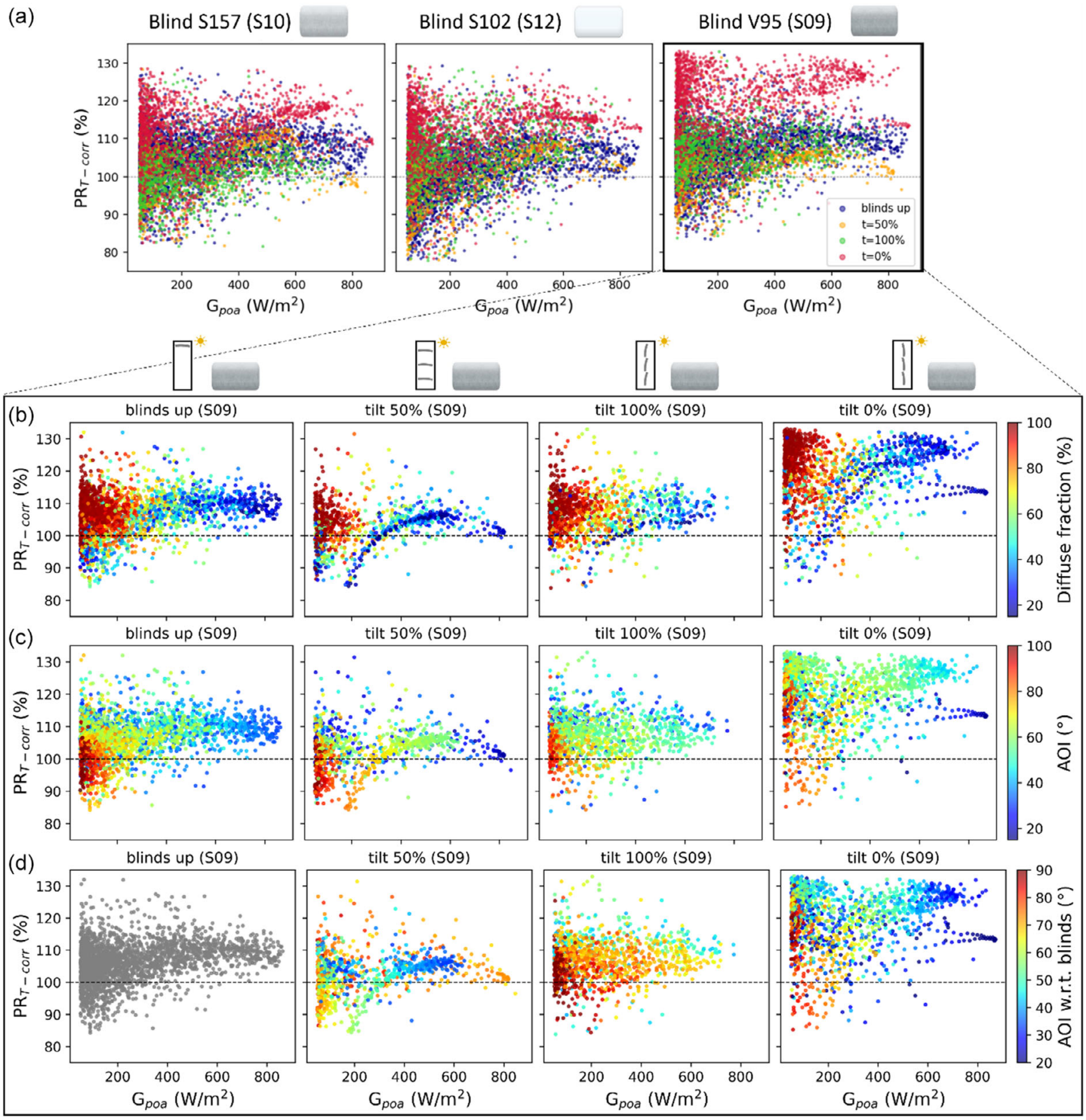


Figure 9. a) PR as a function of irradiance for each blind type (one representative window each) for the whole period. The results for blind V95 (window S09) are further analyzed showing how the performance of each blind configuration correlates with: b) diffuse fraction, c) AOI, and d) angle of incidence between the sun and the venetian blinds.

lower than the case of no blinds. Similarly, at blind position $t = 50\%$, i.e., when the slats are placed horizontally, there is a minor boost for the S102 type, but a slight decrease in PR for the S157 and V95.

All in all, if we take an average of the performance of the various windows with the same blind type, we obtain the results as shown in **Table 3**. The table presents the average relative performance increase, or decrease, of the various configurations relative to the reference case, where the blinds are fully raised. It can be concluded that the optimal blind configuration (achieving the highest energy boost) is the tilt of 0%, corresponding to the slats being fully closed (at a real angle of about 75°) with their convex side facing outward and upward. The most reflective blind V95 led to the highest performance boost of 12%. For the white-coated blind with high diffuse reflection properties, S102, a significant boost of 9% is also recorded, and even the most common gray-painted blind, S157, showed a PR increase of 5%. It should be pointed out that these values are based on daily averages; on sunny days, we saw that the instantaneous energy boost given by the use of the blinds can reach significantly higher values, up to +25%. In addition, the monitored period excludes the main summer months, where the highest amount of sunny instances

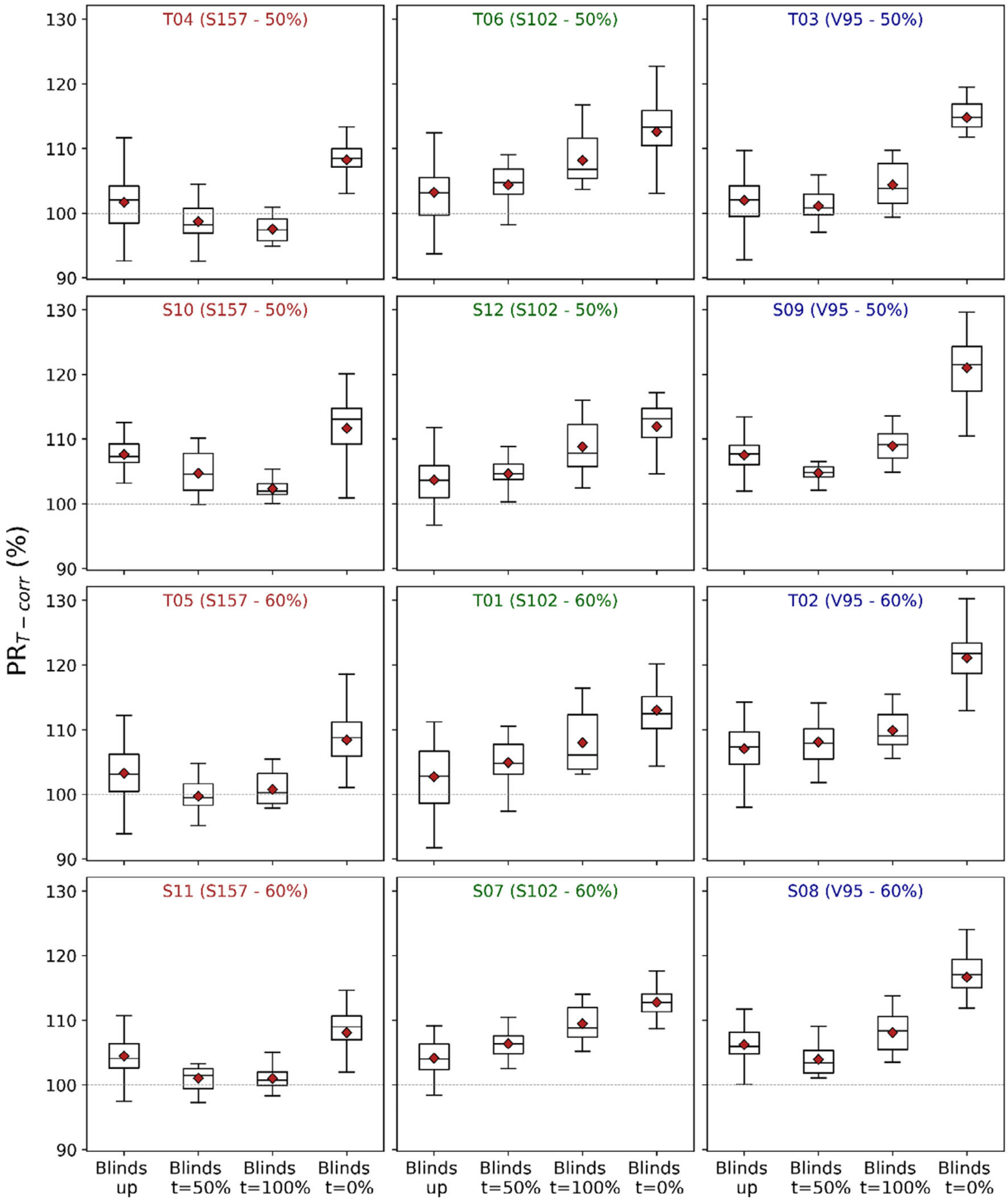


Figure 10. Boxplot showing daily temperature-corrected PR of each window for each blind configuration: blinds up, $t = 50\%$, $t = 100\%$, and $t = 0\%$.

are typically recorded; especially the most specular reflective blind V95 is expected to perform at its best in moments of high direct irradiation.

Another interesting observation is the significant difference in the results when the blinds are tilted in the opposite direction, i.e., when the convex side of the slats faces inside and the concave side faces toward the cells and the sky (i.e., $t = 100\%$ and corresponding angle of $-75°$). In this case, only the diffusively reflective blind S102 still records a PR boost of +5%. This is likely due to the optical properties of this blind: being more diffusively reflective, it is less affected by the exact angle at which the slats are tilted and by the direction of the incoming sunrays. In contrast, for those blinds with lower diffuse reflection component, we achieve a PR increase of just 2% for the V95 blinds and a PR drop of 4% for the S157 blinds. These lower or even negative values seem to indicate that in this position the blinds are not fully shut but still allow some light transmission inside the room, thus less reflection toward the cells. A negative value, as reported

Table 3. Effect on the PR of the various blinds types at the different tilt configurations (calculated with respect to case of blinds raised up). The percentage values shown are the average between all windows with the same blind type.

	Blinds $t = 50\%$	Blinds $t = 100\%$	Blinds $t = 0\%$
S157	−3%	−4%	+5%
S102	+2%	+5%	+9%
V95	−1%	+2%	+12%

for the S157 blind, means that the performance is lower when the blinds are used, than when they are not deployed at all. This result, which is not straightforward, might be due to the fact that the sunrays hitting on the blinds (and after possible reflections between adjacent slats) are mostly redirected toward the inside of the room, rather than toward the solar cells; at the same time, the blinds in this position would block the possible light coming from the inside of the room, thus reducing the overall irradiance seen by the rear-side of the solar cells.

Finally, when the blinds are kept with a tilt of 50%, i.e., horizontally, their effect of the PR is rather low, ranging from −3% for S157 to +2% for S102. As previously discussed, this is likely due to the fact that the specular component of the reflection is directed toward the inside of the room, rather than toward the cells; in fact, this negative effect is mostly present for the more specular reflective blinds, S157 and most of all V95, which recorded the negative ΔPR.

As a final remark, we can argue that small PR differences, in the order of ±2%, could fall within the error and uncertainty margins of the experimental setup. Therefore, the only conclusion that can be drawn when such small PR differences are recorded, is that in those cases the blinds do not significantly affect the performance and the energy yield of the PV windows.

6. Conclusion and Outlook

In this work, we conceptualized, developed, and analyzed the outdoor performance of an innovative PV window solution in which bifacial PV cells are integrated together with venetian blinds in a unique IGU. The use of the bifacial technology allows to boost the energy yield, thanks to the embedded blinds which, when deployed, can act as reflectors, increasing the amount of irradiance reaching the rear side of the cells.

Twelve prototypes were manufactured and monitored for 9 months in real outdoor conditions at the SolarBEAT research facility in the Netherlands. The tested prototype variations included three different venetian blind types, with specific optical properties, two different coverage ratios, and two solar cell bifacial technologies. Several measurement campaigns were conducted to understand which position (tilt angle) of the venetian blinds slats would lead to the highest energy boost. Significantly different energy yields were recorded depending on the blind type and the slats position, while the effects of the coverage ratio and cell technology were found to be less relevant.

It was concluded that the most optimal blind configuration is the fully closed position in which the convex side of the slats faces outside and upward, which corresponds to a real angle of 75° (or tilt $t = 0\%$). At this position, all blind types record an energy boost, with the V95 type showing the highest daily average increase of +12% relative to the case of no blinds. The V95 is the blind having the highest total reflectance and the highest portion of specular component. During sunny days, the maximum yield boost given by the V95 slats reached up to 25%. The performance increase for this blind type is lower during cloudy days, where less direct solar irradiance can hit the blinds and be specular reflected back to the cells. It is also found that, when the slats are tilted at other intermediate angles, the energy boost is more limited, since less sun rays are reflected from the blinds back to the solar cells. At those other angles, e.g., horizontal ($t = 50\%$) or closed with concave side facing outside and downward ($t = 100\%$), the most diffusively reflective blind, i.e., the white-coated S102, provides the highest boost, 5% on average on a daily basis.

Fully understanding the behavior of the blinds at the different configurations was not trivial, due to the interplay of several optical, geometrical, and electrical mechanisms. In general, it was found that the highest energy boost was achieved when the relative angle between the sunbeams and the slats was the smallest, i.e., as close as possible to perpendicular orientations. In this way, the rear side of the cells would receive a higher portion of specular reflection from the blinds. However, this optimal condition was only or mostly met when the blinds were positioned in close position ($t = 0\%$).

To further investigate those correlations and the exact interactions between the internal reflections within the IGU, it would be beneficial to perform modeling work. For this, we plan to publish a separate contribution, that will include simulations of the investigated PV window concept, as well as a sensitivity analysis to study how such concept could behave in different climates and locations.[23]

Finally, it is important to emphasize the multifunctional nature of this building-integrated product, which simultaneously serves as an electricity generator, glazing, and shading device. This means the product can be optimized not only to maximize electricity output, as demonstrated in this work, but also in terms of visual and thermal comfort. In real-life applications, users will likely consider the interaction between these aspects and seek a compromise based on their specific needs.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements

This work is supported by "Netherlands Enterprise Agency" (RVO) via the project: "ZIEZO" with grant number RVO: HER+21-01740618. The authors are grateful to the other project partners, Eindhoven University of Technology and W/E Adviseurs, for the technical discussions. The authors thank S'Tile (A. Straboni) for manufacturing part of the PV windows and Pellini (L. Papaiz) for providing data regarding the venetian blinds. Finally, the authors thank M. Ishac for Figure 1a and for the helpful discussions and C. de Keizer for reviewing the manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Simona Villa: Formal analysis (lead); Investigation (lead); Methodology (equal); Validation (lead); Visualization (lead); Writing—original draft (lead). **David Out**: Data curation (supporting); Methodology (supporting). **Nicolas Guillevin**: Conceptualization (equal); Methodology (equal); Writing—review & editing (equal). **Martin Hurtado Ellmann**: Formal analysis (supporting); Methodology (supporting); Visualization (supporting); Writing—review & editing (supporting). **Marcel Ribberink**: Conceptualization (equal); Investigation (supporting); Methodology (equal); Writing—review & editing (supporting). **Roland Valckenborg**: Conceptualization (equal); Funding acquisition (lead); Project administration (lead); Supervision (supporting); Writing—review & editing (equal).

Data Availability Statement

Research data are not shared.

Keywords

bifacial, building-integrated photovoltaics, performance, photovoltaic windows, semitransparent photovoltaics, venetian blinds

Received: July 12, 2024
Revised: September 6, 2024
Published online: September 18, 2024

[1] European Commission, Energy Performance of Buildings Directive, https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en (accessed: June 2024).
[2] A. Borja Block, J. Escarre Palou, M. Courtant, A. Virtuani, G. Cattaneo, M. Roten, H.-Y. Li, M. Despeisse, A. Hessler-Wyser, U. Desai, A. Faes, C. Ballif, *Energy Build.* **2024**, *314*, 114253.
[3] E. Pulli, E. Rozzi, F. Bella, *Energy Convers. Manage.* **2020**, *219*, 112982.
[4] C. J. Traverse, R. Pandey, M. C. Barr, R. R. Lunt, *Nat. Energy* **2017**, *2*, 849.
[5] A. A. F. Husain, W. Z. W. Hasan, S. Shafie, M. N. Hamidon, S. S. Pandey, *Renewable Sustainable Energy Rev.* **2018**, *94*, 779.
[6] A. Cannavale, U. Ayr, F. Martellotta, *Energy Procedia* **2017**, *126*, 636.
[7] P. Bernardoni, G. Mangherini, A. Andreoli, V. Diolaiti, R. Marrazzo, F. Melchiorre, S. Zanardi, D. Vincenzi, *Sol. RRL* **2024**, *8*, 2400195.
[8] A. S. R. Bati, Y. L. Zhong, P. L. Burn, M. K. Nazeeruddin, P. E. Shaw, M. Batmunkh, *Commun. Mater.* **2023**, *4*, 2.
[9] S. Shi, N. Zhu, *Sustainability* **2023**, *15*, 15876.
[10] G. Yu, H. Yang, D. Luo, X. Cheng, M. K. Ansah, *Renewable Sustainable Energy Rev.* **2021**, *149*, 111355.
[11] K. Khaled, U. Berardi, *Energy Build.* **2021**, *244*, 111022.
[12] TopSector Energie, ZIEZO Public Summary, https://projecten.topsectorenergie.nl/projecten/ziezo-36497 (accessed: May 2024).
[13] M. Ribberink (Pilkington Group Ltd.), US2020332593A1, **2020**.
[14] Pilkington, Pilkington InsulightTM with ScreenLine, https://www.pilkington.com/en/global/products/product-categories/special-applications/pilkington-insulight-with-screenline#overview (accessed: June 2024).
[15] Pilkington, Pilkington Sunplus BIPV, https://www.pilkington.com/en/global/products/product-categories/solar-energy/pilkington-sunplus-bipv (accessed: June 2024).
[16] N. Biloria, M. Makki, N. Abdollahzadeh, *Front. Built Environ.* **2023**, *9*, 1119696.
[17] X. Su, L. Zhang, Y. Luo, Z. Liu, *Build. Environ.* **2022**, *213*, 108861.
[18] A. K. Mohammad, A. Garrod, A. Ghosh, *J. Build. Eng.* **2023**, *79*, 107950.
[19] TNO, SolarBEAT, the Outdoor Test Facility for BIPV, www.tno.nl/solarbeat (accessed: May 2024).
[20] Pellini, Venetian Blind, https://www.pellini.net/en/tipologie/venetian-blind (accessed: May 2024).
[21] S'Tile, https://silicontile.fr/en/ (accessed: May 2024).
[22] IEC 61724-1:2017, *Photovoltaic System Performance, Part 1: Monitoring*, International Electrotechnical Comission, Geneva, CH, **2021**.
[23] S. Villa, M. H. Ellmann, R. Valckenborg, Conf. Proc. EUPVSEC **2024**.