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Modeling reflection by structured building-integrated photovoltaics

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Modeling reflection by structured building-integrated photovoltaics

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Abstract. Evaluating the reflection of solar radiation by Building Integrated Photovoltaics (BIPV) with structured front-glass is challenging for two reasons. First, the resulting irregular scattering of light cannot be accounted for by simple reflection models. Second, the locations where the evaluation needs to take place cannot be predicted by simple geometric considerations, as in the case of mirror-like reflection. The detailed modelling of a BIPV module featuring a periodical, linear structure based on the scanning of its surface is described. The application of the model is demonstrated in the assessment of solar reflection by a concave array of the modules. The stochastic sampling of the BIPV modules from each location in a dense sensor grid, that is required to ensure that no local concentration of reflected solar radiation is missed, is supported by re-orienting the sensors. Rather than relying on a data-driven Bidirectional Reflectance Distribution Function (BRDF) model of limited directional resolution, the geometric structure of the front-glass is modelled by modulating the normal of a mirror-like surface. The method allows an accurate and dense simulation with moderate computational demand.

1. Introduction

BIPV introduce extended glass surfaces into the built environment, that reflect parts of the incident radiation to the surroundings. This reflection can be evaluated e. g. in terms of its effects on thermal and visual comfort [1, 2, 3, 4]. In the case of BIPV modules with flat, clear front-glass, the positions where these effects potentially occur can be easily found by following the path of light along the mirrored incident direction [5].

The development of architectural BIPV solutions has educed not only modules of different colours, but also a variety of light scattering properties. These are typically achieved by the application of structures to the front-glass. Besides increasing the yield of the modules, e.g. due to light-trapping by inverted pyramidical textures, such structures affect the appearance of BIPV, and can be tuned even to mimic conventional building materials. The irregular reflection properties resulting from structured front-glass however complicates the prediction of reflection by BIPV, since each incident direction produces a distribution of scattered light. In ray-tracing based methods, the challenge is two-fold. First, the anisotropic light scattering properties of the module have to be accurately modelled, since they define the local intensity and the spatial distribution of irradiance received by the surroundings [6]. Second, other than the deterministic

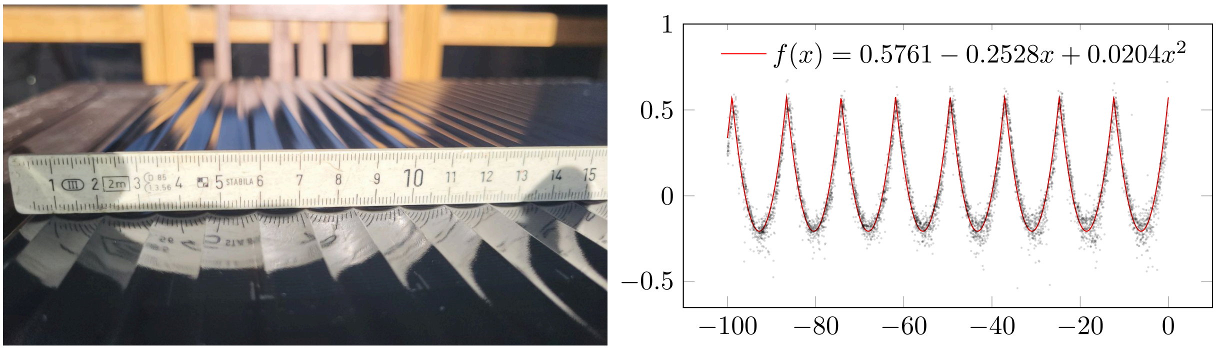


Figure 1. Left: Photograph of the BIPV module's structured front-glass. Right: 3D-scan of the surface and fitted polynomal. Note that the scaled dimensions (in mm) exaggerate the profile.

testing for mirror-like reflection, a solid angle that encompasses the (extended) areas on the BIPV has to be sampled and integrated to solve its contribution to the local irradiance.

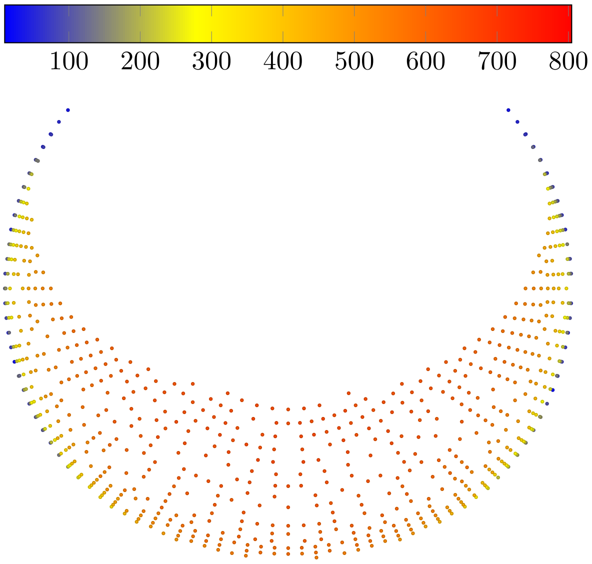
This research presents the detailed modelling of an architectural BIPV module that features a structured front glass (Figure 1, left). The light scattering properties of the models are compared to gonio-photometric measurements, and applied in light simulation to assess the combined irradiance by direct sun-light and concentrated reflection by a concave arrangement of BIPV modules.

2. Method

2.1. Modelling the PV module

Its anisotropic reflection properties were measured gonio-photometrically for few incident directions. The integration of the resulting distributions produces the direct-hemispherical reflectance as a function of the incident direction, accounting for reflection on the outer surface of the front-glass, absorption in its volume, and the reflection on the backside that is reduced due to the lamination of solar cells. The structure of the front-glass was acquired employing a 3D-scanner and used to fit a polynomial $f(x)$ to its profile (Figure 1, right; note that the profile is defined for $x = 0\,\text{mm}$ to $12.37\,\text{mm}$ and periodically repeated). This was then translated into a functional description of the modulation of the surface normal of the front-glass due to its structure. Applied to a flat surface featuring the measured reflectance, this produced a model of the BIPV module with a minimum of geometric complexity. The computation of the average BRDF of this model allows to model the anisotropic reflection as a uniform property.

The BRDF was applied to the geometric model of a planned BIPV installation to evaluate effects on the irradiance in the surroundings of the building. The modules segment four tilted, concave canopies attached to a pavilion. The method relies on backward ray-tracing and employs the light simulation RADIANCE [7]. Irradiance at three measurement planes was computed on a dense grid of positions. To sample the modules' BRDF at sufficient directional resolution, a high number of random rays were integrated. To guide this stochastic sampling, the irradiance at each position was computed for an orientation normal to the centre of the building. Since no diffuse inter-reflection had to be accounted for, the computational effort for the simulations could be kept moderate. The resulting irradiance could then be converted to horizontal irradiance by applying the cosine of the respective orientation. The method was validated by comparison with the results of an image-based calculation of the irradiance, that avoids the stochastic sampling, at few positions.



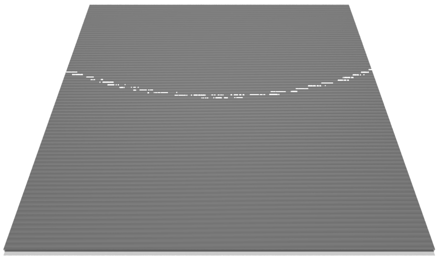


Figure 2. Left: Grid of sun positions by 2305 subdivisions of the hemisphere according to Reinhart, as employed in the simulation, and corresponding direct irradiance [$\mathrm{W\,m^{-2}}$] Top: BIPV module modelled by a flat polygon with modulated surface deflected mirror-image of the sun.

2.2. Simulating reflection of direct sunlight

The primary concern in evaluating the reflections from the planned BIPV installation are the acute effects of the reflected radiation. Namely, whether anywhere on the surrounding site experiences radiation that could cause harm to people, vegetation, or property due to overlapping reflections from the sun off of multiple BIPV panels. This convergence of multiple reflections can, even with a direct reflectance of much less than 1.0, exceed the radiation received directly from the sun. These converging reflections are, above all else, sensitive to the incident angle of the sun, and the orientation of the receiving surfaces. To properly account for the potential radiation on the site, special care needs to be taken in selecting the reference conditions (determined by sun position and intensity) and spatial resolution used for the analysis.

Because the concern is predominantly the worst case or frequency of possible adverse conditions, the conventional approach in daylight availability studies to use typical meteorological year weather data, which constructs a plausible set of sky conditions over the course of a year, is not suitable. At any moment during daytime throughout the year, with varying probability, there is always a chance that the sun could be clearly shining. For this reason, the reference conditions were generated using the ASHRAE fundamentals clear sky formula as implemented in the python package PYCLEARSKY [1]. Based on local climatic conditions, but excluding weather variability, this creates a series of sun positions for every day of the year assuming plausible clear sky direct normal radiation for the given site. To cover a broad range of incident solar angles, simulations were performed with a grid of suns according to the Reinhart patch subdivision with MF parameter of four, yielding 2305 sun positions, an approximate grid resolution of three degrees Figure 2. The evaluated sky conditions are generated for two days per month at 20 min intervals, which fills most of the grid cells within the solar transit.

Given the properties of the measured parabolic shape and scale of the textured BIPV glass, each period of the glass texture converges at around 10 mm. At distances relevant for evaluating site impacts, this means that overall the texture will only scatter the light from individual panels. Therefore, to determine the critical resolution that will not miss any possible convergence across the site, it is appropriate to conduct a sensitivity analysis using flat surfaces, which can be solved deterministically. The resulting convergence from flat surfaces will always be smaller than that

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[1] `https://github.com/santoshphilip/pyclearsky`

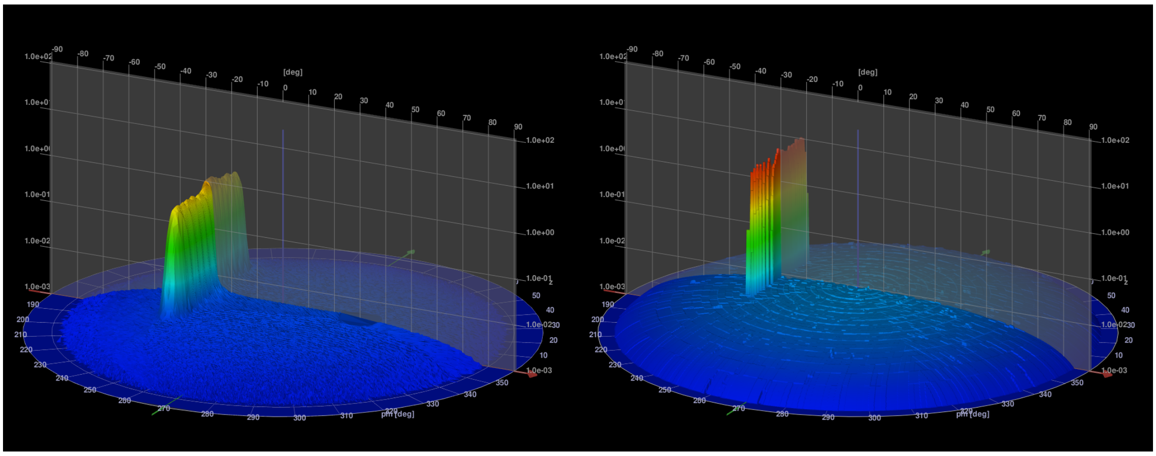

Figure 3. Measured (left) and computed (right) scattering of reflected light for one incident directions $\theta_i, \phi_i = 30°, 0°$ (top). Plotted is the BRDF× $\cos\theta_s$.

from the effectively diffusing textured glass. Testing sensor spacing from 1.0 m to 0.125 mshowed that the peak value for eight sun positions stabilises at a resolution of 0.5 m×0.5 m. The extent of area affected by the peak values was also determined not to exceed a $100\,\mathrm{m}^2$ region of the site, resulting in a final pixel resolution of 200 × 200 pixels. This resolution effectively matches the resolution of the BRDF (≈ 1.5°, which corresponds to 0.5 m at 19.0 m from facade) and the sun grid (Reinhart patch subdivision MF:4, approximately ≈ 3°).

3. Results and discussion

By comparison of the gonio-photometric measurements on the module with the model featuring the normal map, it can be shown that – if the distance of the receiving surface is large compared to the periodical features of the structure – the BRDF as a uniform property is an equivalent representation of the BIPV modules optical characteristics Figure 3. Note that, due to the size of the light source, the specular BRDF is distributed over a slightly larger solid angle and therefore lower in the measurements.

Modelling the structured glass by modulating the normal of a perfectly specular surface rather than relying on a data-driven BRDF model as implemented in RADIANCE preserves the sharp reflection of the sun-disk. This is illustrated by Figure 4. The perfectly specular reflection by a flat front-glass would produce one mirror-image of the sun per module (top). The data-driven BRDF model accounts for deflection by the structured glass, but distributes reflected light over a wider solid angle (middle). This may lead to the underestimation of the concentration effect by the modules' arrangement. Modelling the front-glass by modulation of a specular reflector's surface normals avoids this loss of accuracy (bottom).

Figure 5 (left) shows the annual maximum horizontal irradiance by sunlight directly reflected from the modules for each location in the environment of the planned installation. Adding the direct solar irradiance produced the distribution of maximum direct and reflected sunlight Figure 5 (right). On the evaluated ground plane, the effect of the BIPV installation under the worst condition of a clear, sunny sky produced concentrated irradiance in particular in the North-East and North-West of the planned installation. An annual analysis of the location exposed to the maximum direct and reflected irradiance however shows the moderate extent of this effect over the course of the year (Figure 6).

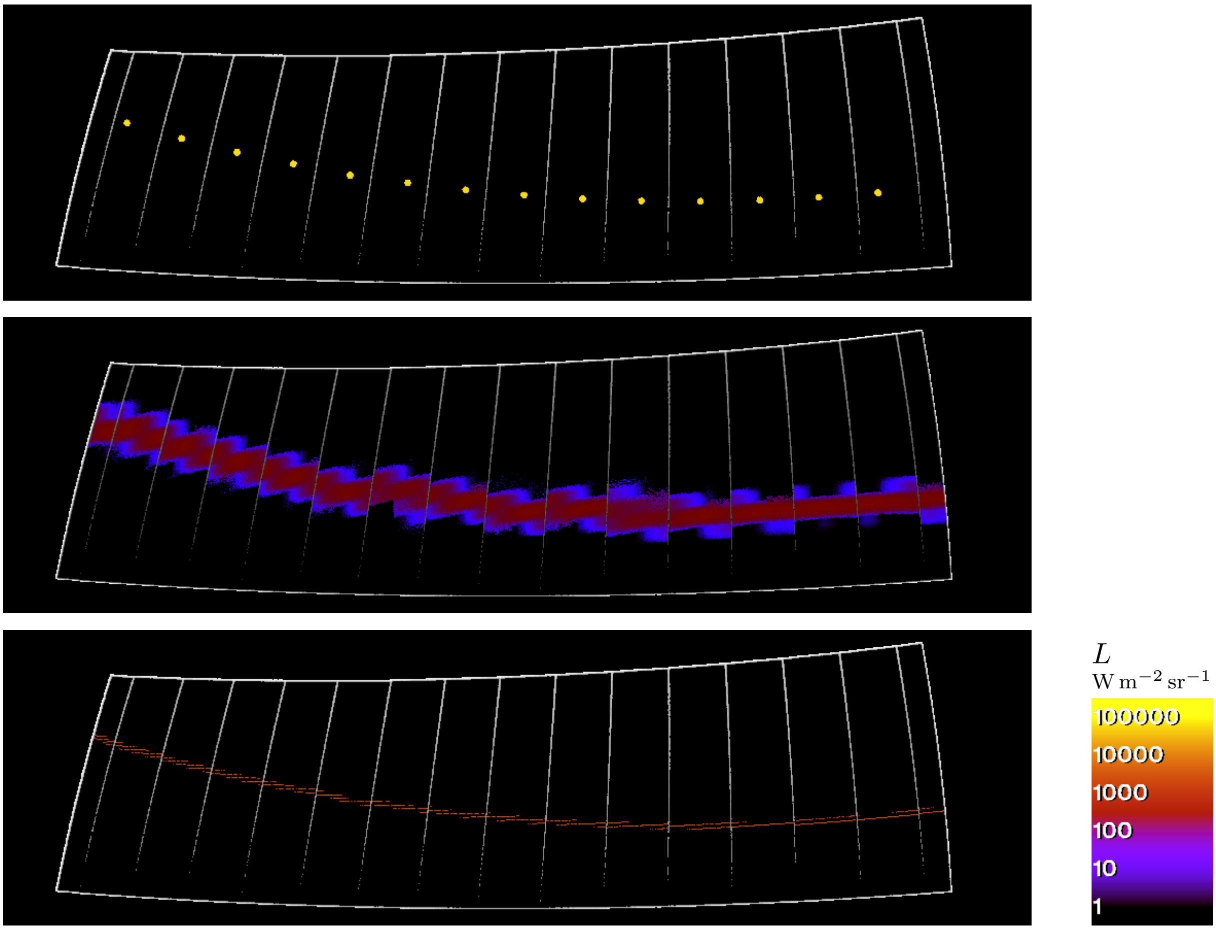

Figure 4. Top: Mirror-like reflection of the sun by a concave array of 14 modules featuring flat surfaces (overlaid white contours). Middle: Reflection by the same array, but with structured front-glass modelled by RADIANCE's data-driven BRDF model. Bottom: Reflection of the sun by the same array, modelled by modulating the surface normal of a specular glass surface.

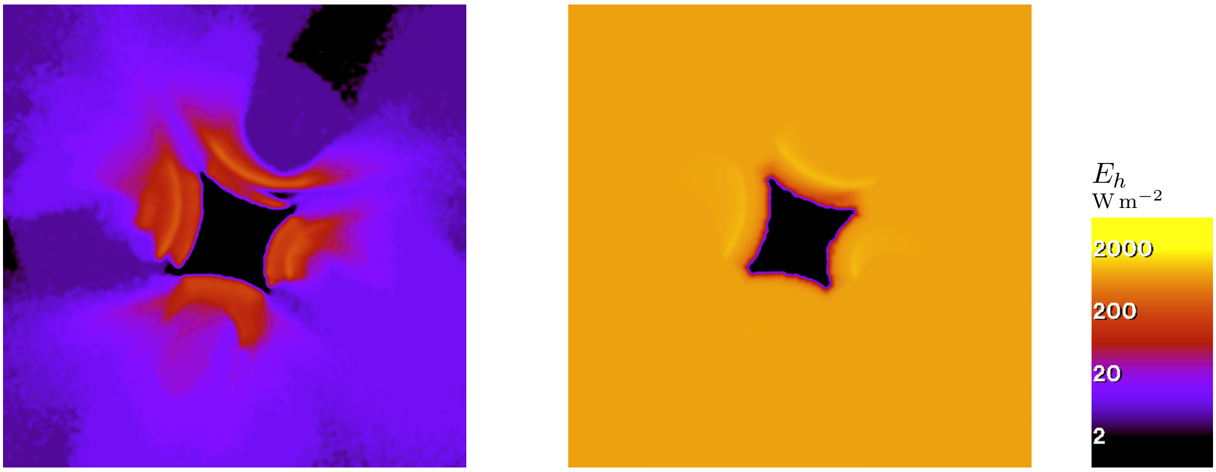

Figure 5. Left: Annual local maximum reflection of sunlight by the surfaces of four concave arrangements of BIPV modules. Right: Annual local maximum of direct and reflected sunlight.

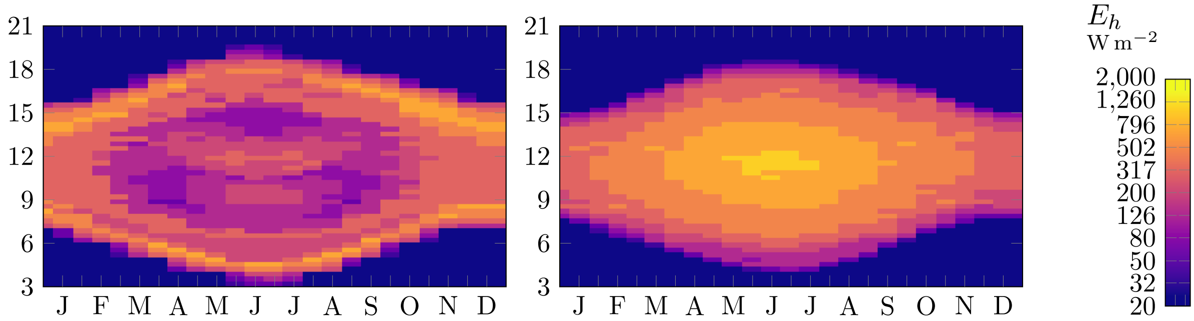

Figure 6. Left: Temporal distribution of the reflection of solar radiation as in Figure 5, but at the location with the highest annual maximum. Right: Temporal distribution of the sum of direct and reflected solar radiation at the same location.

4. Conclusions

The presented method illustrates the complexity of the modelling of BIPV featuring irregular light scattering properties. However, it could be demonstrated that such simulations can produce reliable results given sufficient diligence in the modelling, including thorough testing of models and methods. The reduction of geometric complexity of the structured front-glass into an average BRDF, and the guided sampling in the backward ray-tracing, further reduce the computational effort and thereby make the method applicable.

While for the assessed case, the concentration of reflected solar radiation was mitigated by the glass texture and a given threshold not exceeded, this depends on the size, curvature, and texture of the studied BIPV. Only the increase of reflected irradiance was assessed. Assessing visual discomfort and glare would require a modification of the method.

Acknowledgments

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