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Passive Redirection of Solar Radiation by Micro Optics to Increase the Bifacial Gain of Photovoltaics

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Abstract

Bifacial solar cells allow radiation to reach the cell from the rear side, which is transparent. To increase the bifacial gain, which can be 5% to 15 % under normal conditions, micro-optical systems were developed, which redirect the solar radiation to the rear side. They are rigid and do not require any sun tracking. A variation of principle solutions is discussed, including existing and innovative micro-optics. The efficiency of redirection is defined by optical measurements and simulations, achieving values between 30% and 50%. Exemplary calculations for middle Europe show photovoltaic annual gains up to 33%. The location at other latitudes is feasible and the application includes open spaces, agrivoltaic and building integrations like roofs or facades.

Keywords: Bifacial photovoltaics, redirection of solar radiation, micro-optical structures, efficiency of redirection, bifaciality, annual gain of global insolation, climate zone, variety of applications.

1 Introduction

Bifacial solar cells, which are also transparent to solar radiation on the rear side, enable an increase in efficiency that can amount to 5% to 15% under normal boundary conditions [1], depending on factors such as albedo), orientation, transparency and bifaciality of the modules [2, 3, 4]. The global market for bifacial photovoltaics (BPV) reached US$ 8.7 billion in 2021 and its share of total photovoltaics (PV) is expected to rise to 50% in 2025 and 70% in 2027 [5]. The additional costs of BPV of 5-7 cent/W make it economically viable [5, 6].

Possibilities for increasing the efficiency of BPV by optical systems were demonstrated in a feasibility study [7]. They are based on the principle of passive redirection of direct solar radiation without tracking, as shown in Figure 1. The range of angles of incidence for efficient redirection of this type is limited. For this reason, the redirecting elements are oriented to the vertical angle of the sun, which varies significantly less over the course of the day and year than the horizontal angle (azimuth).

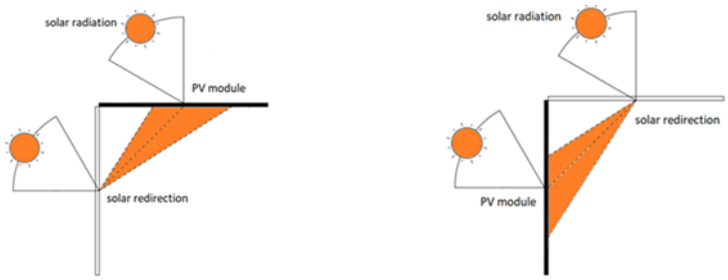


Figure 1: Principle of the arrangement of the bifacial module and radiation redirection [7]; left: horizontal module, right: vertical module.

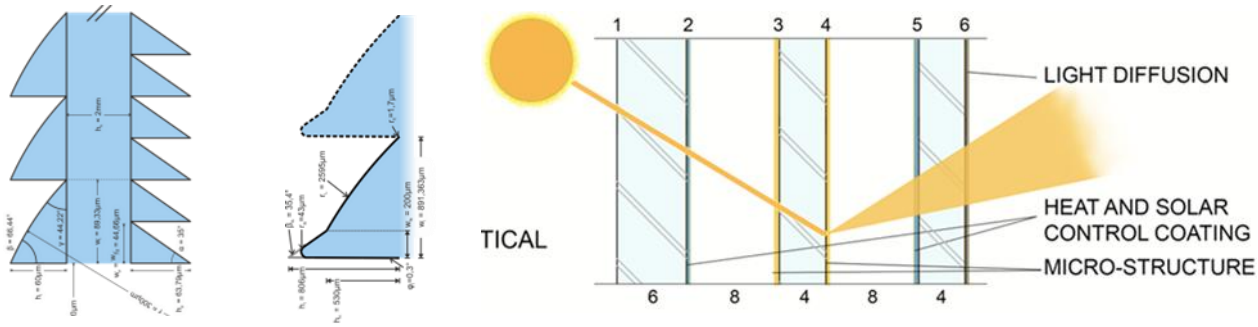
2 Solution principles of solar deflection on BPVs

In order to find a large variety of solutions for the task of radiation redirection on BPV, Table 1 shows a systematic overview with solution variants for four parameters, which can be combined. The most efficient solution principles can be selected by the following explanation and evaluation of redirection efficiency and photovoltaic gain.

Table 1: Solution principles for BPV with sunlight redirection

parameter	**variation**					
A optics for redirection of radiation	A1 double sided micooptics between two panes, 2012	A2 double sided microoptics between two panes, 2019	A3 microoptics on interfaces of double glazing	A4 additional optics (mirror)		
B angle of incidence and redirection; orientation BPV	B1 0° - 60° horizontal	B2 0° - 60° inclined	B3 15° - 75° inclined	B4 15° - 75° horizontal	B5 circ., 0° - 75° inclined	B6 15° & 75° vertical
C ratio of area redirection / BPV-panel	C1 redir. = BPV		C2 redir. < BPV		C3 redir. > BPV	
D arrangement of redirection and BPV	D1 separate		D2 integrated in double glazing, tilted		D3 integrated in glass tube	

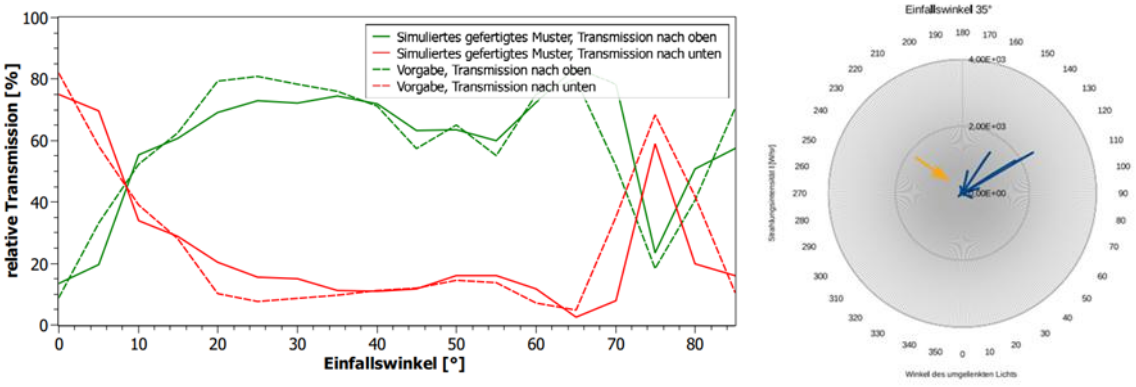
Parameter A shows micro-optical systems that are suitable for redirecting solar radiation. Variants A1 and A2 were developed for illuminating rooms with sunlight [8] using glass or PMMA panes structured on both sides. Integrated in the centre of a triple-glazed unit, they are installed in the upper window area and deflect the sunlight upwards to the ceiling and into the depth of the room. The part of the sunlight transmitted horizontally and downwards is so small that no glare occurs. The first solutions implemented and measured in 2012 were optimised in 2019 in joint research projects with industrial partners [9, 10] and tested under realistic conditions. Figure 2 shows two variants of the micro-optics, which are industrially produced in 50 cm wide tracks by UV embossing (structure sizes approx. 50 µm) or by hot embossing (structure sizes approx. 500 µm). As the sharp edges of the outer structure of solution a) could not be realised in terms of production technology, geometry b) was developed.



a) b) c)

Figure 2: Microstructures for sunlight redirection, which were developed in the TaLED research project for room illumination [9];
a) variant from 2012, b) Variant of the outer structure from 2019,
c) vertical section of triple glazing with microstructure in the centre.

Measurements of the micro-optics show good agreement with calculated specifications: For angles of incidence of 15° to 65°, the desired redirection upwards is 60% to 80% and only 5% to 20% of the incident light is redirected downwards (Fig. 3a). The measured redirection angle upwards varies between 100° and 160° depending on the angle of incidence (example see Fig. 3b).



a) b)

Figure 3: Exemplary simulation and measurement results of the redirection over the angle of incidence for micro-optics from 2019 [9, 10];
a) relative transmission upwards and downwards depending on the angle of incidence.
b) redirection angle as a function of the angle of incidence.

The triple glazing used in variants A1 and A2 is suitable for the building sector because of thermal insulation, but for the BPV application the material costs should be reduced as far as possible. For this reason, a double-pane glass with micro-optics on both inner surfaces was developed (variant A3). Optical simulations [11] were used to create the structures shown in Figure 4, which enable efficient redirection for angles of incidence of 5° to 75°.

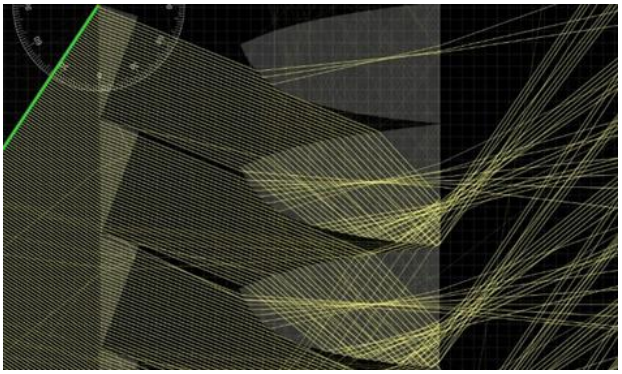


Figure 4: Micro-optics for the boundary surfaces of an air gap. Exemplary simulation radiation transmission for an angle of incidence of 30°.

A comparison of the radiation redirection over the angle of incidence (Fig. 5) shows the best overall result for micro-optics A3. The curves of micro-optics A1 and A2 are similar, with A2 performing slightly better than A1. For small angles of incidence from 0° to 15°, optic A3 shows clear advantages. For large angles of incidence between 60° and 75°, there is still room for optimisation for all three solutions.

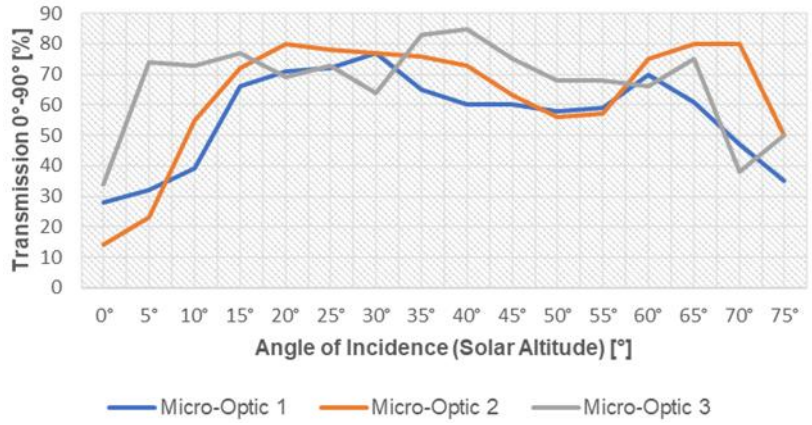


Figure 5: Efficiency of radiation redirection over the angle of incidence (0° horizontal, 90° vertical).

Parameter B shows the geometric arrangement of the redirector and BPV element with regard to the angles between them and the angle of solar incidence. The efficiency of the redirection increases if the angle between redirection element and module is reduced (Figure 6).
In addition, the angle of solar incidence on the BPV front surface influences the photovoltaic gain: the orientation of the solar cells to the sun is decisive for the overall gain. The orientation of the redirection surface, on the other hand, is influencing the bifacial gain by the back of the module.

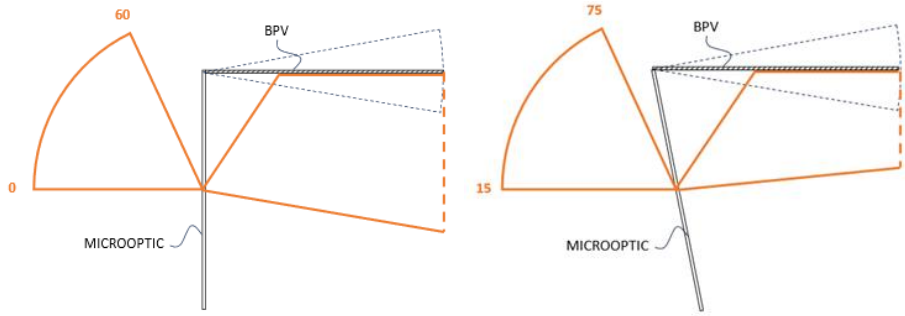


Figure 6: Range of radiation redirected to the BPV module, depending on the angle of incidence of the sun and the angle between redirector and module; left: angle of incidence 0° - 60°, right: angle of incidence 15° - 75°.

As an example, solutions for the Central Europe with solar incidence on the redirector element from 0° to 60° are selected (variant B1, B2). By rotating the redirector by 15° (variant B3, B4), the angle of incidence of the sun changes to 15° - 75°. For this angle range, the redirection efficiency of the optical systems is greater than for the range from 0° to 60° (see Fig. 5), but the radiation incident on the redirector element is smaller.

For special applications, curved or circular redirection surfaces can be useful (variant B5), which are used under parameter D. Theoretically, it is also possible to exchange the position of the deflection element and module (B6), but for the selected geographical area of application, the gain is smaller than for variant B2.

Parameter C varies the area ratios of module and deflector element. Larger BPV areas (C2) increase the direct irradiation, but reduce the proportion of deflected radiation. Furthermore, the uniformity of the module irradiation from the rear decreases. By increasing the deflection area (C3), the bifacial gain can be increased as far as the deflected radiation hits the module. For high magnification, e.g. doubling the area, supplementary optical systems such as mirrors (variant A4) are helpful.

Parameter D shows application-orientated and constructive arrangement options for redirection and BPV elements. A separate arrangement (variant 1) can be useful in many cases, as already described in [7]. These include free-standing installations, agrivoltaics or building integrations. Figure 7 shows an example of integration in skylights in commercial and industrial buildings. The redirector, integrated into the vertical south-facing glazing, provides solar control and glare protection as well as

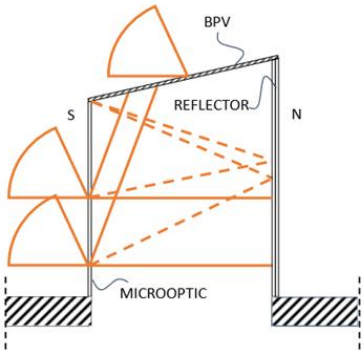


Figure 7: Separate arrangement of reflecting south-facing glazing and BPV module in skylight; reflector optional.

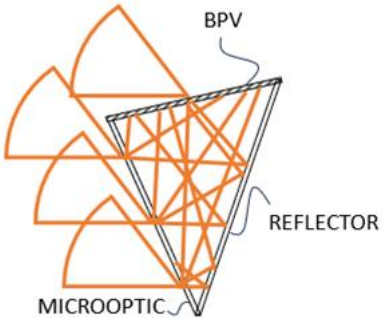


Figure 8: Integrated system with triangular arrangement of BPV, micro-optic and reflector.

bifacial energy gains on the one hand and transmits diffuse light from the zenith for room lighting on the other. The north-facing glazing can be used for room lighting as well, provided it is not mirrored to increase the efficiency of the redirection. The mirror can, alternatively, be integrated between BPV and micro-optic as shown in Figure 8, forming a highly effective triangle.

Other forms of integrating redirection, bifacial solar cells and reflector in one module are shown in variants D2 and D3. These solutions are based on small-format solar cells that are integrated together with micro-optical elements in flat double glazing or in glass tubes. In the protected glass cavity, micro-optics and solar cells can be used without additional protective glazing, reducing reflection losses.

Variant D2 shows double glazing, which enables optimum orientation and size of BPV and redirector elements and, if necessary, the use of mirrors (Figure 8). However, the albedo radiation from outside is no longer transmitted when the glass is mirrored at the rear. As an alternative to an inclined module arrangement, a vertical arrangement is possible as well, which can be interesting for integration into buildings.

Glass tubes (D3) enable circularly curved redirection surfaces, which can be laminated onto the glass surface as a film if necessary (Figure 9). Compared to a flat redirector, the receiving surface is larger and the angle of incidence varies. Alternatively, flat elements can also be integrated into the glass tube. The installation of additional mirrors is possible, but their orientation differs from the tube surface. They can follow the circular shape, as shown in Figure 10, or be installed in a triangular arrangement as shown in Figure 8.

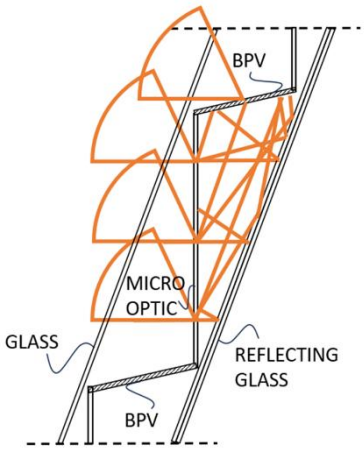


Figure 9: Double glazing with integrated BPV and redirection

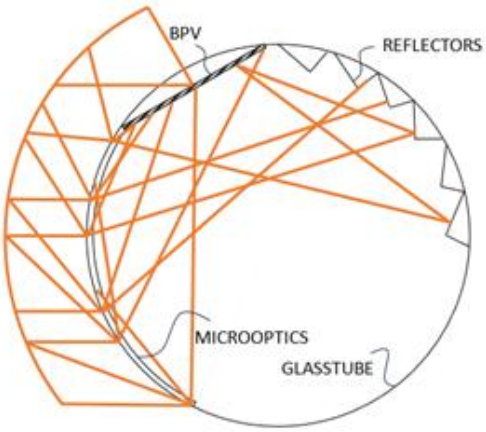


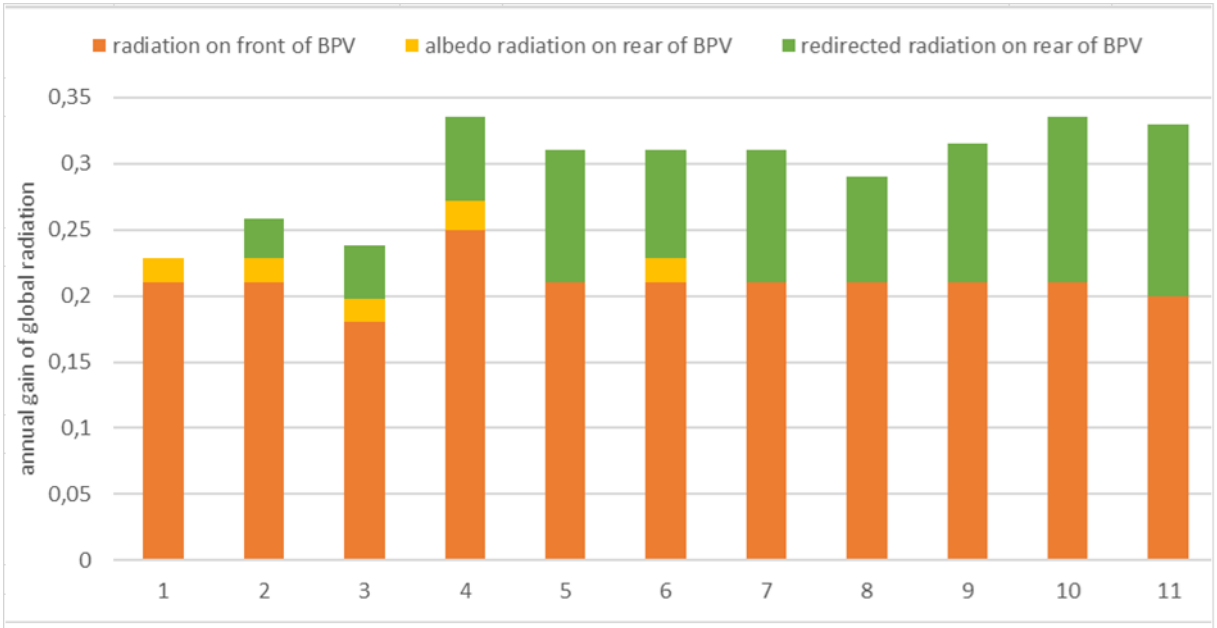
Figure 10: Glass tube with integrated BPV and redirection

3. Evaluation of solution principles

The individual parameter variants are evaluated in combination of complete solution principles as to redirection efficiency and photovoltaic gain. For the photovoltaic gain, the annual yield of the BPV system is shown with special consideration of radiation redirection. As an example for Central Europe, the variation of the annual global radiation for Germany is used. It is 100% for south orientation and an inclination of 35° [12]. Depending on the region, the maximum global radiation is 930 - 1010 kWh/(m²a).

Based on the simulation results for the micro-optical systems and the transmission losses of protective glazing, the efficiency of the redirection is calculated, which varies from 29% to 52% for systems without additional optics and up to 57% for systems with additional reflective glazing. It represents the proportion of incident radiation that is redirected onto the back of the BPV.
In addition, the orientation to the sun and the area ratios of BPV and redirector influence the photovoltaic gain. Table 2 provides a comparative overview of selected solution principles based on bifacial solar cells with a front side efficiency of 21% and a bifaciality of 95%, i.e. a back side efficiency of 20%. In Table 2, the following proportions distinguished: gain by irradiation on the front side of the solar cell, by albedo irradiation on the rear side and by redirected irradiation on the rear side.

Table 2: Photovoltaic gain of solution principles according to Table 1



A	Ref.											
B	Ref.	35°	0°	0°	35°	35°	35°	35°	35°	35°	15°	
C	Ref.											
D	Ref.											

Reference solution no. 1 shows a bifacial module without radiation redirection, optimally orientated for Central Europe to the south with an inclination of 35°. The albedo irradiation on the rear side of the modules was assumed to be 8% for all solutions. Solutions no. 2 to 11 represent different principles of radiation redirection according to the overview in Table 1. The optimal BPV orientation of 35° was selected for all solutions except no. 3 and 4 with horizontal inclination of the solar cells.

Solutions 2 and 3 differ with regard to parameter 2, the angles of BPV and redirection element. Although the redirection efficiency is slightly higher in solution 3 (36% compared to 30%), solution 2 achieves a higher photovoltaic yield due to the optimal orientation of the solar cells towards the sun.
Solution 4 shows the highest yield due to the direct irradiation on the module, as its area was increased by a factor of 1.38 compared to the redirection area.
Solution 5 represents a possible application for rooflights with BPV in the roof surface and redirection arranged vertically in the south-facing glazing. For the north glazing a reflective coating was assumed. Accordingly, the proportion of redirected radiation in the gain is relatively high.
Solutions 6 and 7 show glass tubes as modules with integrated redirection, without and with mirroring. The yields and the proportion due to redirection are relatively high.
Solutions 8 to 11 are integrated modules in double glazing with mirroring on the back. They differ in terms of parameter B with an inclination of the BPV of 35° and 15° and achieve the highest total yields (33%) and the highest bifacial gain due to redirection (max. 50%).

4 Conclusions

Solution principles for the optimisation of bifacial photovoltaics by redirection of radiation were developed, based on industrially manufactured and measured micro-optics. A large number of solutions was generated by varying parameters of optics, geometry, application and design. The evaluation based on approximate calculations shows that significant increases in photovoltaic gains of up to 50% can be achieved by redirection of radiation. Innovative micro-optics and system integration offer a further potential for optimisation. The application in other geographical latitudes is possible by appropriate orientation to the sun. The decisive factor for realisation is the economic viability of the system with costs for the redirection significantly lower than for the BPV.

References

[1] Dullweber, T.; Schmidt, J. Industrial Silicon Solar Cells Applying the Passivated Emitter and Rear Cell (PERC) Concept—A Review. IEEE J. Photovolt. 2016, 6, 1366–1381. https://doi.org/10.1109/JPHOTOV.2016.2571627.

[2] Muehleisen, W.; Loeschnig, J.; Feichtner, M.; Burgers, A.R.R.; Bende, E.E.E.; Zamini, S.; Yerasimou, Y.; Kosel, J.; Hirschl, C.; Georghiou, G.E.E. Energy Yield Measurement of an Elevated PV System on a White Flat Roof and a Performance Comparison of Monofacial and Bifacial Modules. Renew. Energy 2021, 170, 613–619. https://doi.org/10.1016/j.renene.2021.02.015.

[3] IEA Task 13, Performance, Operation and Reliability of Photovoltaic Systems - Bifacial PV Modules and Systems. Report IEA-PVPS T13-14:2021.

[4] Wikipedia: Bifacial solar cells. https://en.wikipedia.org/wiki/Bifacial_solar_cells.

[5] Elmehdi Mouhib, Leonardo Micheli, Florencia M. Almonacid and Eduardo F. Fernández: Overview of the Fundamentals and Applications of Bifacial Photovoltaic Technology: Agrivoltaics and Aquavoltaics. Energies. MDPI.

[6] Deline, C.A.; Ayala Pelaez, S.; Marion, W.F.; Sekulic, W.R.; Woodhouse, M.A.; Stein, J. Bifacial PV System Performance: Separating Fact from Fiction; National Renewable Energy Lab.(NREL): Golden, CO, USA, 2019.

[7] Helmut F.O. Mueller: Optimization of Bifacial Photovoltaics by Optical Systems - Feasibility Study. ICOEO-2022 Journal of Physics: Conference Series 2548 (2023) 012015 IOP Publishing doi:10.1088/1742-6596/2548/1/012015.
[8] Klammt, S, Müller, H.F.O., Neyer, A. Microoptics for Efficient Redirection of Sunlight. Applied Optics Vol. 51 Issue 12, pp.2051-2056 (2012).
[9] Research Reports of Project TaLED (Energy- and cost efficient, façade integrated Day- and LED lighting based on mico-optical components), 2016 - 2019. Partners: RIF e.V., Karl Jungbecker GmbH, Temicon GmbH, Durlum GmbH, Saint-Gobain Securit GmbH, Green Building R&D GmbH, ai3, SSP AG. Funding: German Federal Ministry for Economic Affairs and Energy. Co-ordination: Fraunhofer Institute Building Physics, Stuttgart, Germany.
[10] Research Reports of Project TaHo (Energie- und kosteneffiziente Tageslichtbeleuchtung mittels mikrooptischer Baukomponenten: Demonstration Struktur für Vertikalfassaden. Neue Struktur für Horizontalfassaden und Dachoberlichter), 2021 – 2025. Partners: RIF e.V., Karl Jungbecker GmbH, Temicon GmbH, Durlum GmbH, Okalux Glastechnik GmbH, Green Building R&D GmbH, SSP AG, Kassenärztliche Vereinigung Westfalen-Lippe, Stadt Krefeld. Funding: German Federal Ministry for Economic Affairs and Climate Protection.
Co-ordination: Fraunhofer Institute Building Physics, Stuttgart, Germany.
[11] Ray Optics Simulation. https://phydemo.app/ray-optics/
[12] Energieagentur NRW: Solaratlas für Nordrhein-Westfalen. www.ea-nrw.de

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