Modelling of a 3D solar module based on flexible photovoltaic panels

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Abstract—This paper presents a new concept of a photovoltaic module. An increase in efficiency is obtained by using a three-dimensional form of flexible photovoltaic panels with an additional reflecting mirror. A flexible panel is distributed over the entire inner surface of the cylinder, while the mirror distributes the flux on its surface. The comparison of selected solutions for a mirror shape is realized with numerical simulations. The irradiance results for absorbed flux are discussed on grounds of possible improvements.

Photovoltaic (PV) has become an attractive electrical power resource enabling solar-energy conversion [1]. New technologies prove more efficient, reliable, and affordable solutions [2]. Besides rigid monocrystalline silicon cells, alternative perovskite, organic or mixed technologies on a flexible substrate are developed [3]. Thin-film flexible solar cells are lightweight, mechanically robust, and may be fabricated at a low cost. The energy gain from a given cell surface is closely related to cell construction technology. For example, the certified efficiency of solar cells on a flexible substrate made with the most promising material - perovskite - achieved 25.2% [3].

Currently, there is a limited number of projects that can provide a step-by-step increase in the efficiency of flat PV cells and thus increase the profit energy from the installation. In the next decade, experts estimate an improvement in the efficiency of a few percent, which will not solve the problem of the necessary space for such installations. The decrease of needed surface or maximization of produced power may be achieved with different types of energy concentrators. High efficiency of concentration systems has been demonstrated for small dimensions of high-efficiency solar cells that can be made of expensive materials [4]. The reflecting concentrators often containing complex cylindrical-parabolic-ellipsoidal surfaces are technologically challenging. Another typical option for concentrating PV systems is a Fresnel lens [5]. However, both Fresnel lenses and reflectors for concentrating PV systems must be installed on a high-accuracy sun-tracking platform.

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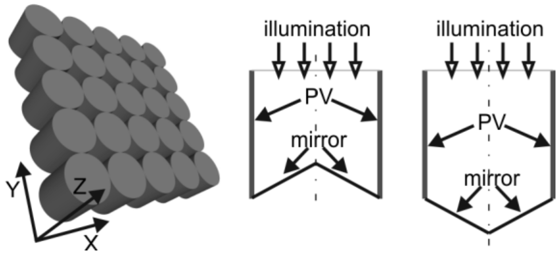
The main goal of this work is the development of a new concept of photovoltaic modules that offers breaking down the limitations of standard modules based on flat panels. An increase in efficiency is obtained through the use of three-dimensional forms of flexible photovoltaic panels with an additional optical element. Here additional optical elements are used for the distribution of energy in a specific way on the panel surface.

The whole module consists of an array of 25 identical cylinders (Fig. 1a) with dimensions of 200 mm (height) × 200 mm (cylinder diameter). The *z*-axis indicates the direction of illumination. A PV cell made on a flexible substrate is distributed over the entire inner surface of the cylinder (Fig. 1b and c). The upper circular cylinder surface defines the amount of light flux available for a single element of an array. At the opposite end of the cylinder, there is a mirror that distributes the flux on the PV surface. This work focuses on comparing selected solutions for the mirror shape. The simulations were performed with Trace Pro (Lambda Research Corporation, USA) [6] – ray-tracing software for the design and analysis of illumination and optical systems.



(a) (b) (c)

Fig. 1. Visualization of 3D solar panel module (a), the cross-section of a single-cylinder with an external (b) and internal mirror surface (c).

For the purpose of numerical simulations and comparison of the proposed solutions, a few simple theoretical parameters of PV material have to be defined:

- the absorption coefficient is assumed constant, corresponding to the 80% absorbance and 20% reflectance;

- power conversion efficiency equals 10%;
- parameters are constant and do not change with the illumination direction or absorbed energy.

For simplicity of the simulations, the upper surface is fully transparent. It does not affect incoming light flux. The mirror at the bottom surface has a 100% reflection, and this value is independent of the wavelength. The irradiance of the light source is equal to 1000 W/m^2 (according to Standard Test Conditions (STC) for photovoltaic devices). With all those parameters, the photovoltaic area of 0.031416 m^2, equal to the circular, upper region of the cylinder, produces 2.5026 W. The irradiance for the absorbed flux is evenly distributed and equals 800 W/m^2.

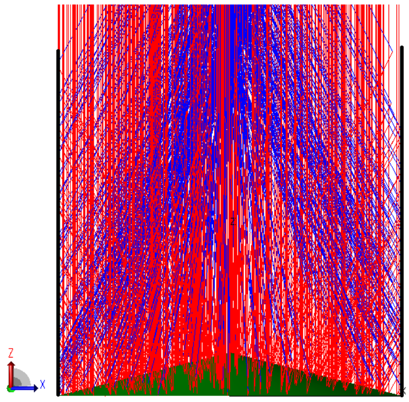


Fig. 2. The view of the ray's path inside the cylinder.

The total area of the PV material placed at the internal surface of the cylinder equals 0.125664 m^2. This area is four times bigger than the upper circular area and, with the normal direction of illumination (uniform irradiation of 1000 W/m^2), produces more than 10 W. However, the flux is limited by the upper area of the cylinder, and the distribution of irradiance at the internal surface of the cylinder depends on the shape of the mirror located at the bottom of the cylinder. With such conditions, only the combination of PV material properties and the unique construction of a whole PV module may be advantageous.

In this paper, two different shapes of mirrors are studied. The first is a simple conical mirror, as shown schematically in Fig. 1b. The mirror with a cone height of 25 mm and angle of 151.92° (the apex directed towards the interior of the cylinder) allows it to reflect the whole entering flux and distribute it on the photovoltaic material. Figure 3 presents a view of the illumination rays (marked in red) and the rays reflected from the conical mirror (marked in blue). Unfortunately, the distribution of irradiance for absorbed flux cannot be uniform, as seen in Fig. 3. The highest irradiance value, equal to 700 W/m^2, is found at the bottom of the cylinder and linearly decreases to 0 (according to the height of the cylinder). Even if the surface is four times larger, this configuration produces 2.282 W.

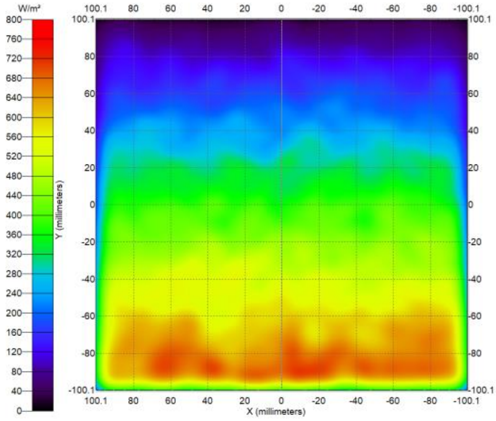


Fig. 3. The distribution of irradiance for absorbed flux at the internal surface of the cylinder after reflection from the conical mirror.

The first important issue of the proposed solution (uneven distribution of flux) can be solved by creating a mirror of unique construction. The second challenge is maximizing the value of irradiance at the internal surface of the cylinder. It can be realized with multiple reflections of non-absorbed energy inside the cylinder. The solution to both problems may be realized by the bottom mirror divided into sections with different angles of cone inclination or by a mirror with a continuous surface but a more complex shape. An example of the mirror geometry that ensures acceptable uniformity of irradiance is shown in Fig. 4. The presented model contains 3 sections: one concave and two others with a convex shape. The mirror reflects an incoming parallel beam by its internal surface (the apex is outside of the cylinder, as shown in Fig. 1c). The light reflected by the mirror is partially absorbed by the PV material, but it does not provide the expected improvement. The radiation that is not absorbed is reflected from the PV surface and absorbed again in other regions of the PV material.

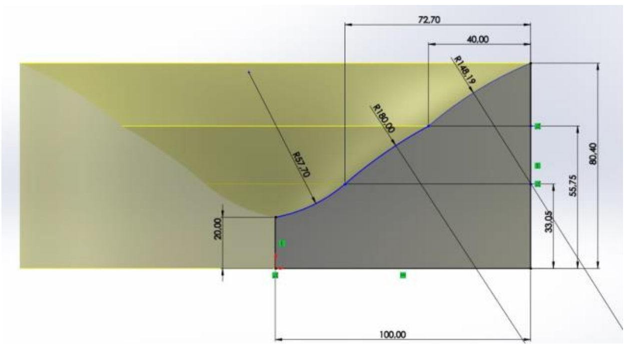


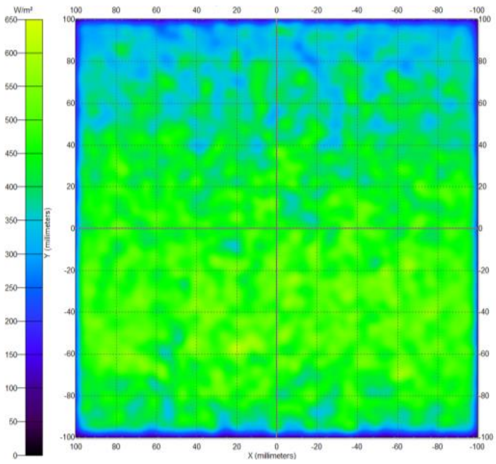
Fig. 4. Model of the mirror with a modified shape.

Table 1 presents the amount of absorbed (A) and reflected (R) energy for 3 consecutive reflections from the PV material of different absorption coefficients. The sum of absorbed radiation A_{sum} is highest for material with an absorption coefficient of 0.8. It is expected that after three internal reflections, 99.2% of the whole energy will be absorbed by the PV material. The drop of A_{sum} is small also for absorption coefficient 0.6 and equals only 6.4%. However, the distribution of absorbed flux will be completely different in both cases. Each of them needs a specially optimized mirror for uniform illumination distribution.

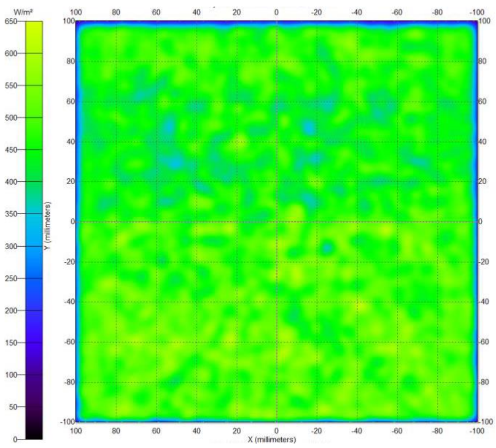
Table 1. The sum of absorbed radiation as the function of the absorption coefficient.

Absorption coefficient	**A_1 [%]**	**R_1 [%]**	**A_2 [%]**	**R_2 [%]**	**A_3 [%]**	**R_3 [%]**	**A_{sum} [%]**
0.8	80	20	16	4	3.2	0.8	99.2
0.6	60	40	24	16	9.6	6.4	93.6
0.4	40	60	24	36	14.4	21.6	78.4
0.2	20	80	16	64	12.8	51.2	48.8

Applying reflections inside the cylinder, we observed an increase in absorbed irradiation and its improved distribution over the internal surface (Fig. 4a).



(a)



(b)

Fig. 4. Distribution of irradiance for absorbed flux in the case of the applied modified mirror surface: (a) for rays reflected by the mirror, (b) for the sum of rays reflected by the mirror and additional rays from environmental scattering.

If, additionally, we will assume the existence of environmental light scattering that enters from the top of the cylinder, the resulting distribution becomes uniform with an average level of 450 W/m^2 represented by the green color. The result of the simulation is presented in Fig. 4b. It also slightly increases the resulting power: from 2.6685 W for distribution (Fig. 4a) to 2.7015W (Fig. 4b), respectively.

The presented results of simulations show limited enthusiasm for the developed solution. On the one hand, it proves the possibility of the power increase with the bottom mirror and the use of multiple reflections inside the cylinder satisfying uniform distribution of absorbed energy. On the other hand, the analyzed solution is much more expensive in practical realization than a flat panel. It requires the creation of additional mechanical and optical components.

The future improvements of the proposed solution are strictly related to the parameters of the flexible PV material, especially with its efficiency of power conversion. In simulations, we assumed only 10% of efficiency. That value was set after consultations with the leading companies working on the development of flexible solar panels. Actually, the highest values are disponible only for areas of single cm^2. The efficiency increase may also be connected with a reduction in the PV area inside the cylinder. In the considered case, the shape of the mirror may be redesigned to increase mean irradiance (the same amount of solar energy is distributed over a smaller area). The area can be reduced until the PV cell is not saturated or the concentration of light is so high that it will introduce undesirable heating of the material.

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