

Analysis of the Performance of an On-Axis Mirror Module Design Compared to a FLATCON[®] Module

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Abstract. In this paper, the development of a HCPV mirror module design with passive heat dissipation and a geometrical concentration of 1000x is discussed. To benchmark the mirror module, the expected performance is compared to the well-known lens based FLATCON[®] module. Therefore, the electrical performance and acceptance angle are evaluated. Moreover, a detailed benefit analysis for both module designs is conducted. The calculation of the values of benefit is based on the evaluation of technical criteria weighted for their importance in a defined space of multi-dimensional criteria.

INTRODUCTION

Concentrator mirror modules have the potential of high optical efficiencies. Compared to lens based modules, they have the advantage that no chromatic aberration occurs. Additionally, the dependency of the optical efficiency on the temperature is expected to be less significant. In this paper, the design of a HCPV mirror module design with passive heat dissipation and a high geometrical concentration of 1000x without using a secondary optics is discussed. An on-axis assembly with the solar cell placed in the focal point of the primary mirror optics is investigated. A challenge for this module design is the heat distribution as the heat distributor is located in the optical path and therefore introduces shading losses. The conceptual design is described in detail in [1], see also Figure 1. In this work, we introduce a figure of merit to evaluate the optimum performance determined through the solar cell operating temperature and shading by the heat distributor (in this case a circuit board on the front glass).

Then, to benchmark the new mirror module design, the expected performance is compared to the experimentally well investigated lens based FLATCON[®] module [2]. As in [1], a detailed benefit analysis based on [3], [4] is conducted for both module designs. The calculation of the values of benefit is based on the evaluation of technical criteria weighted for their importance in a defined space of multi-dimensional criteria. In this way the potential for the proposed mirror module concept can be evaluated.

MIRROR MODULE DESIGN

The mirror based HCPV module design uses paraboloidal mirror optics with an aperture area of 12.84 x 12.84 mm² and a solar cell size of 0.16 mm², resulting in the geometrical concentration of 1030x. The solar cell is placed in the focus of the primary optics and is mounted to an electrical conductor (with a small pad to enhance heat distribution) on a cover glass (see Fig. 1 (a)). The maximum temperature of the solar cell is calculated by finite element method (FEM) simulations using the assumptions described in [1]. Simulations were conducted varying the size of the heat distributor which changes the operating temperature but also the shading area. The simulated maximum operating solar cell temperatures T_{\max} in dependence of the shading area are shown in Fig. 1 (b). It was assumed that solar cell is homogeneously irradiated with 900 W/m² times the concentration factor (no optical losses, open circuit condition when no electricity is extracted). Then the maximum temperature is in the

center of the solar cell. To analyze the simulated variations on the overall module performance a figure of merit for temperature dependent module performance P_{temp} is introduced. The figure describes the reduction of efficiency due to temperature in the solar cell assuming a temperature coefficient of $0.07\%_{rel./K}$ [5]. Combining the figure of merit for temperature and losses due to shading with the optical efficiency η_{opt} , a combined figure of merit $P_{combined}$ is introduced (Equation 1). It is calculated by:

$$P_{combined} = \eta_{opt} * P_{temp} \quad (1)$$

In Figure 1, the dependency versus the shading of the aperture is shown for T_{max} , P_{temp} , η_{opt} and, $P_{combined}$ for the investigated mirror module. The simulations resulted in the optimum figure of merit $P_{combined}$ when 2 % shading through the heat distributor is allowed. Hence, for the comparison in this work a solar cell size of 0.4 mm and 2 % shading is set. With an edge length of a squared solar cell L_{SC} of 0.4 mm and 2 % shading, the maximum temperature of the solar cell is 126 °C. However, other simulations like in [1] showed that the solar cell temperature could be reduced to 115 °C when reducing the aperture of the optics while keeping the geometrical concentration constant, hence reducing cell sizes to L_{SC} 0.3 mm. This could be beneficial in terms of reliability. On the other hand, the number of solar cells per area would be increased and module assembly would be more complex.

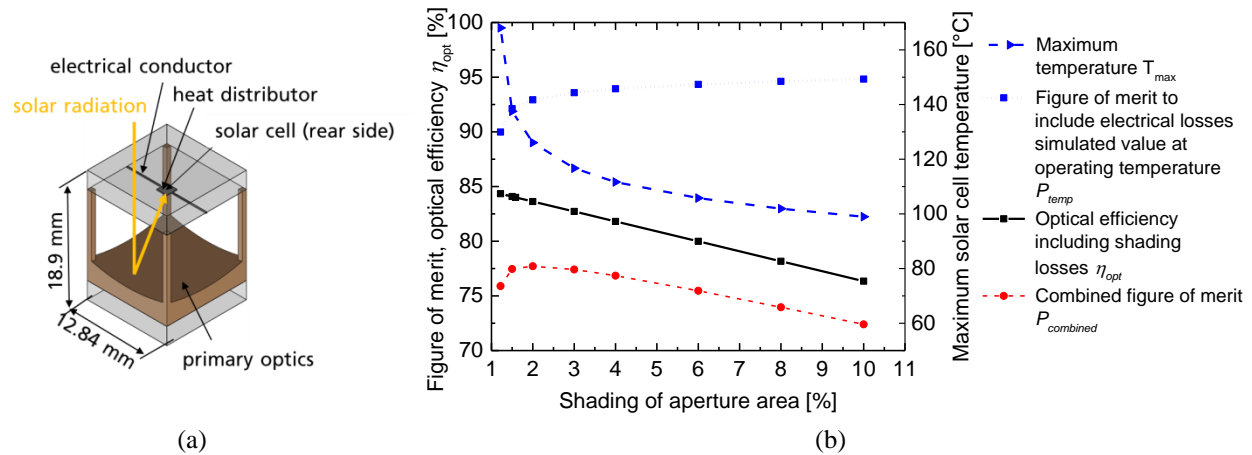


FIGURE 1. (a): HCPV On-Axis mirror module. The solar cell is placed in the focus of the primary optics and the thermal energy is dissipated passively. The edge length of the primary optics is set to 12.84 mm, the half-opening angle is 45° (angle of incidence for radiation on solar cell) and the solar cell has an edge length L_{SC} of 0.4 mm resulting in a geometrical concentration of 1000x. The primary optics is shaded by an electrical conductor inside on the front glass cover. (b): Diagram of the figure of merit to include reduction of efficiency due to temperature in the solar cell P_{temp} , optical efficiency including optical losses by shading η_{opt} and combined figure of merit when cell temperature and optical effects are included $P_{combined}$ versus shading of the aperture optical area. In the simulation the solar has an edge length L_{SC} of 0.4 mm. The shading of aperture area is caused by the electrical conductor and heat distributor at the back of the solar cell. The figure of merit including losses due to cell temperature P_{temp} increases with higher shading (i.e. lower cell temperatures) but the optical efficiency decreases with increasing shading. Thus, the combined figure of merit $P_{combined}$ shows a maximum at 2 % shading.

In this diagram electrical losses for current distribution due to the irradiation profile are not included. The losses caused by the flux profile further reduce the combined figure of merit. In the simulations the loss is constant as the flux profile on the fixed solar cell size is assumed to remain constant for the different heat distributor sizes. In addition, in [1] it was already shown that the electrical losses for current distribution are low as the solar cell is small and thus, the electrical current generated in one solar cell is low.

COMPARISON OF HCPV MIRROR MODULE AND FLATCON® MODULE IN A SYSTEMATIC BENEFIT ANALYSIS

Evaluating new module concepts is complex as there are different criteria that need to be considered. The most important targets are that the electrical performance is high and at the same time the cost for the CPV module are

low. In [1] both objectives are investigated. In this work, only the module performance is analyzed as two module designs on a very different development level are compared. In this work we want to determine the potential of the novel design for the On-Axis mirror mode. For this purpose, it is compared to the well-known experimentally well investigated lens based FLATCON[®] module.

The design and performance for the FLATCON[®] module is based on published data. As described in [6] the module has a silicone-on-glass Fresnel lens, the aperture area of one lens is 40x40 mm², the solar cell has a diameter of 2.3 mm for the designated area and is mounted to a metal heat distributor that is attached to the rear plate also made of glass. The geometrical concentration is 385x and no secondary optics is implemented.

The systematic method for the comparison is a benefit analysis. The analysis approach is adapted to the methodology described in [1] and has the advantage that different, independent criteria can be considered. In the benefit analysis, values for the benefit are determined by quantifying technical criteria with a utility value and weigh them according to their importance. Here, the weighting factors are set with 25 % for the acceptance angle and the rest in the same share as established in [1] where it is defined with the fraction of performance losses. We investigate the criteria “high optical efficiency”, “low operating temperature”, “low losses due to flux non-uniformity” and “high acceptance angle”.

For the mirror module the properties are defined for the design with 2 % shading by the circuit board and the values for optical efficiency and operating temperature introduced in the chapter above. The losses due to flux non-uniformity and the acceptance angle were determined in [1]. For the FLATCON[®] module the properties are specified based on published data and based on measurements or validated simulations. The weighting factors and the properties are summarized in Table 1. Please note that the conditions for the performance values can be different as the technologies are different and therefore the specific arrangement vary.

TABLE 1. List of criteria and corresponding weighting factor and the performance values for the mirror module On-Axis and the FLATCON[®] module.

Criterion	Weighting factor	On-Axis	FLATCON [®]
High optical efficiency [%]	0.4729	83.6 %	87 % [7]
Low losses due to flux non-uniformity [%]	0.2358	5.1 %	10 % [8]
Low solar cell operating temperature [°C]	0.0413	126 °C at V _{OC} and 900 W/m ² , homogenous irradiated	87 °C V _{OC} and 800 W/m ² η _{opt} 0.8, inhomogeneous irradiated [6]
High acceptance angle [°]	0.2500	0.83° at 1000x	0.5° [9] at 385x

All criteria are quantified and summarized in the value of benefit. The properties are evaluated with a utility value in scale of 0 to 10 with 10 for the best score as in [1]. In the reference paper four different mirror module designs are compared. Here, the range for the utility values is extended to include the On-Axis mirror design with 2 % shading and also the properties of the FLATCON[®] module. The approach is that the range for the utility values is defined by allocating the highest property value to a utility value of 9 and the lowest value to a utility value of 3. The scores for the utility values are given in Table 2.

TABLE 2. New scoring range for the utility values including all mirror designs from [1] as well as FLATCON[®] module (achieved score marked in blue) and On-Axis module with 2 % shading (highlighted in red) as investigated here.

Criterion	Score for utility value										
	10	9	8	7	6	5	4	3	2	1	0
High optical efficiency [%]	89.4	87.0	84.6	82.2	79.8	77.4	75.0	72.6	70.2	67.8	65.4
Low losses due to irradiation profile [%]	1.60	2.80	4.00	5.19	6.39	7.59	8.78	9.98	11.18	12.37	13.57
Low solar cell operating temperature [°C]	80	87	94	100	107	113	120	126	133	139	146
High acceptance angle [°]	0.92	0.83	0.74	0.66	0.57	0.48	0.40	0.31	0.22	0.14	0.05

The total, weighted benefits derived in this work are 7.81 for the mirror module and 6.84 for the FLATCON[®] module. The total benefit including the share by the different criteria is shown in Figure 2. This shows the high potential for the novel mirror concept even when compared to an established technology. However, for the new concept the analysis is based on simulated data. This means that the high performance has to be proven experimentally.

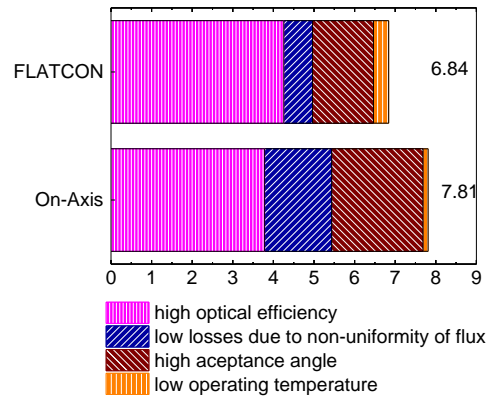


FIGURE 2. Total value of benefit for the investigated module designs. The contribution to the benefit is shown for the four technical criteria.

For a deeper analysis the results are visualized in and adapted spider chart as shown in Fig. 3. The adapted spider diagrams show the benefit for the module designs. The criteria “high optical efficiency”, “low operating temperature”, “low losses due to flux non-uniformity”, “high acceptance angle” are used. The value along the radius gives the score for each criterion and the angle of a pie is defined by the weighting factor. The score is determined via the performance regarding the respective criterion. Comparing the performance criteria (excluding the “high acceptance angle”), through the large area of the pie, the diagrams show that “high optical efficiency” is the most important design criterion. It can be seen that the performance of the FLATCON[®] module in regard of operating temperature with a score of 9 outperforms the mirror module with a score of 3. However, the share for the complete module performance is lower compared to for example the losses due to non-uniformity where the mirror module has a higher score with 7 compared to 3 for the FLATCON[®] module. For the lower losses due to non-uniformity, the reason is that in the lens-based module chromatic aberration occurs. In addition the total current to be conducted in one solar cell is lower in a small area solar cell as used in the mirror design and therefore resistive losses reduced. The diagram also shows that for both module designs a reduction of those losses would increase the complete module performance. This could be achieved for example by introducing a secondary optics.

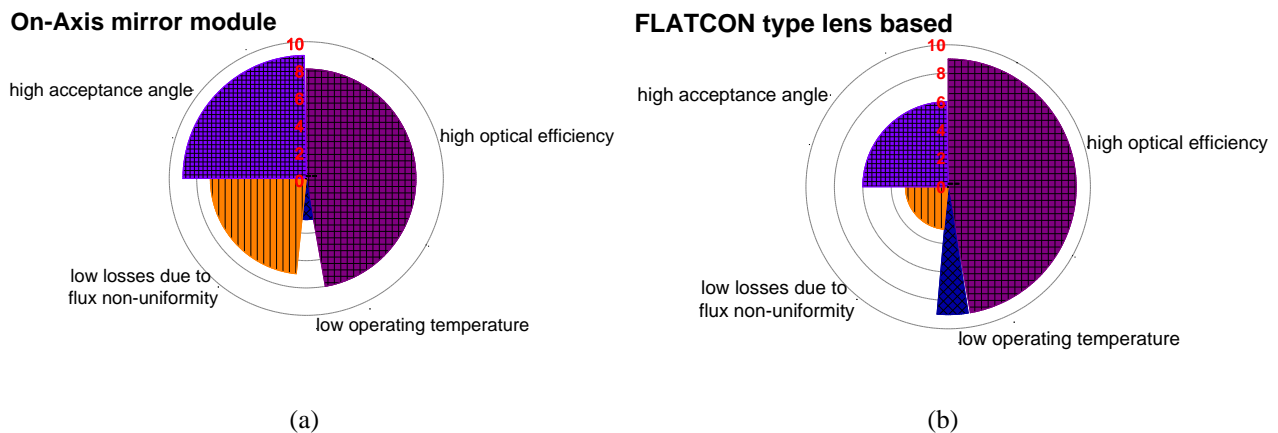


FIGURE 3. Comparison of module performance of the mirror module (a) to the reference lens based FLATCON[®] module (b). The adapted spider diagrams show the benefit for the module designs.

CONCLUSION

The HCPV On-Axis mirror module was optimized for best performance of the complete module. The benefit analysis shows the high potential for the mirror module concept when comparing to the well-known FLATCON[®] module design. The strength of the mirror module is the high optical efficiency, high acceptance angle even at high concentration of 1000x and low losses due to flux non-uniformity as no chromatic aberration occurs and the current in a solar cell is low. The strength of the FLATCON[®] module is that the thermal management is easier and therefore the temperatures in the solar cells are lower in. In the FLATCON[®] module optical efficiency is even higher than in the mirror module. However, considering also the criteria acceptance angle and the losses due to non-uniformity the total value of benefit calculated in this work is higher for the mirror module (7.80) than for the FLATCON[®] (6.84). Although, both values are high. Next, the On-Axis needs to be investigated in a real prototype.

Furthermore, in the benefit analysis, for the modules investigated here, it can be seen that it is important to design them for high optical efficiency while performance losses due to high operating temperature in the solar cell are not as significant. The reason is that the performance losses in the temperature range due to cell operating temperature are lower compared to possibilities of improving the optical efficiency.

For a successful product development besides of module performance also the costs for the product and reliability are important. This is not investigated here. It could be analyzed by comparing the manufacturability. Long-term stability needs to be proven through accelerated aging tests and outdoor measurements.

ACKNOWLEDGMENTS

The authors would like to thank all other colleagues of the department “III-V Photovoltaics and Concentrator Technology” and of the group “Concentrating Collectors and Optics” for their contributions to this paper.

This work was partially funded by the Federal Ministry for Economic Affairs and Energy (BMWi) under the HeKMod4 project, contract number 0325750. The authors are responsible for the content of this work.

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