STATIC CONCENTRATOR PV MODULE OPTIMIZED FOR FAÇADES

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ABSTRACT: In the last decade the market of building integrated PV systems has increased, mainly due to the promotion and dissemination of programmes. A barrier for larger scale penetration is the initial cost of energy delivered by PV system when compared to that from conventional power plants. A way to overcome this disadvantage is the use of linear static concentration modules. In this paper, the optimization and analysis of the static concentrator PV module PEC-44D for façade is presented. The linear optical system of the module was designed for bifacial cells. The acceptance angles θp and ξ were optimized, considering a façade sloped 90° toward the Equator. To find the values of angles, the simulation of the PV-system was carried out for 10 years irradiation data. The method was applied to 34 Brazilian cities. The acceptance angles found were the same for all cases: θp=0º and ξ=90°. We also verified that the side of the bifacial cells with lower efficiency must be faced the optical system. The module is cost effective only for optical system priced lower than U$100.00 per square meter. However, for the cost of the optical system per square meter of U$50.00, the reduction is as a function of latitude and it varies from 15% to 41%, when compared to standard modules. In order to achieve higher cost reduction of the optical system, we proposed an alternative device with cross-section of the optical system equal to a semicircle. For this concentrator module, the cost reduction varies from 12% to 36%. A prototype was constructed and installed at Porto Alegre – RS – Brazil (latitude = - 30º). Irradiance on each face of the cells has been measured and the analysis of experimental results confirms the simulated ones.
Keywords: Static Concentrators, PV module, Façade

1 INTRODUCTION

In 2002, the PV power installed mainly in industrialized countries was of 1300 Wp [1], as a result of worldwide government programs [2]-[9]. Nowadays, for instance, a capacity of 4820 MWp is expected in Japan in 2010 [1]. At the same time, in Germany, building integrated PV systems has been increased rapidly [2]. In all cases, the architects play an important role to develop aesthetically attractive elements, increasing the building's value [3], [9]. However, a barrier that impedes a rapid expansion of this photovoltaic application is the expensive investment. In this scenario, new designs of PV modules have been developed based on concentration of solar energy to solar cells [10]-[15]. Solar radiation is concentrated on solar cells by a low cost optical system, without the need of a tracking system. Consequently, they can be installed on façades.

The goal of this paper is to present the optimization of the static concentrator module PEC-44D for façades and the analysis of its performance.

2 STATIC CONCENTRATOR MODULE PEC-44D

The static PEC-44D module consists of a linear optical system and bifacial cells. The cells are installed in the plane of the entry aperture, with concentration of solar radiation only on the rear face. The cross-section of the optical system is asymmetrical, formed by part of a parabola, a circle and an ellipse. The optical system is designed starting from the lower (θ_p) and upper (ξ) acceptance angles [16]. The concentration ratio is higher in winter than in summer, in order to compensate the solar radiation behavior at medium and high latitudes. Therefore, the electrical output is similar in both seasons and it fits in well with constant energy demand of stand-alone PV systems. As previously mentioned, this module was initially designed for stand-alone PV systems and in this paper we present the optimization and analysis of the module for grid-connected façades.

3 SIMULATED RESULTS

3.1 Hourly solar irradiation

The method used is based on simulation of the PV system during 10 years [17] taking into account that the façade is sloped 90º toward the Equator. When the performance of static concentrator modules is analyzed, we have to use hourly irradiation data. Thus, a sequence of daily clearness indexes was generated [18] to estimate the monthly average daily irradiation on a horizontal surface. Following this, the daily irradiation data were split into its beam and diffuse components. Starting from the daily total and diffuse irradiation, the hourly irradiation data are estimated [19],[20]. The hourly diffuse irradiation on tilted surface was calculated using the Perez's model [21]. In this way, the hourly irradiation on the front face of cells was obtained.

The beam irradiance that reaches the rear face of the bifacial cells was estimated by the geometric concentration (Cg) and the directional intercept factor [17]. Both parameters were obtained from the acceptance angles and the slope of the module. Based on a similar procedure, the diffuse irradiance on the rear face of the cells is determined [17]. In this case, the intercept factor for the radiation reflected by ground and for each component of diffuse radiation obtained by Perez's Model was determined.

3.2 Optimal design

The simulation of system was carried out in order to find out the cost of the PV-array normalized to the annual energy produced by system as follows:

$$P_{GN} = \frac{P_{cell} + P_{con}(1+Cg)}{\left(G_{df} + \frac{\eta_r}{\eta_f} G_{dr}\right)(1+Cg)\eta_f} \quad (1)$$

where P_{cell} and P_{con} are the price per square meter of the encapsulated cells and optical system, respectively; $G_{df}(\beta)$ and $G_{dr}(\beta)$ are the annual average daily irradiation on frontal face and on rear face of the bifacial cells, respectively; η_f is total efficiency of the bifacial cells on the frontal face and η_r is total efficiency of the bifacial cell on the rear face, taking into account the optical losses.

The approach was applied to 26 Brazilian cities in order to find the acceptance angles of the module that leads to the lowest cost of the PV array, as defined in Eq. 1. As result, we found that the acceptance angles are the same for all locations: $\theta p=0^o$ and $\xi= 90^o$. In this case, the cross-section of the optical system is formed by part of ellipse and circle. The module was denominated of PEC-FAC. We also concluded that the best performance of the PEC-FAC module occurs when the face of the bifacial cells with lower efficiency is facing the optical system. Two prices per square meter of the optical system was explored: P_{con1}=US\$50.00 and P_{con2}= US\$100.00.

The simulation was also carried out to standard modules in order to compare the performance of both modules. For this kind of modules, P_{GN} is obtained from Eq. 1:

$$P_{GN} = \frac{P_{cell}}{G_{df}\eta_f} \quad (2)$$

We obtained that cost of the concentrator module, using P_{con2}, is similar to that of standard modules. However, results for P_{con1} lead to reduction costs as a function of latitude. The values obtained varies from 15% for low latitudes up to 41% for medium latitude (ϕ = - 30^o).

A concentrator module with both acceptance angles equal to 90^o was also explored in order to reduce the cost of the optical system construction. In this device, named PEC-FAL, the cross-section of the optical system is a semicircle, as shown in Fig. 1. The comparison of the PEC-FAL module with a standard module leads to cost reductions from 12% to 36%, approximately 4% lower than the results for PEC-FAC. We observed that both concentrator modules present better performance for higher latitudes.

In order to compare the concentrator to a standard module with same area, the irradiance related to concentrator modules is calculated by:

$$I_T = \left(\frac{1}{1+Cg}\right) I_F + \left(\frac{Cg}{1+Cg}\right) I_R \quad (3)$$

Losses due to optical systems were taking into account.

3.3 Simulated results

Fig. 2 compares the simulated results of the monthly average daily irradiation on both faces of bifacial cells for PEC-FAL, PEC-FAC and a standard module installed at Porto Alegre (latitude = -30^o), Brazil. We note that the behavior during the year of daily irradiation is similar for the three modules. This means that output energy produced by each module may also be similar. Nevertheless, the irradiation corresponding to the standard module is higher, because losses occur in concentrator devices, such as reflectance of the glass and of the internal surface of the optical system.

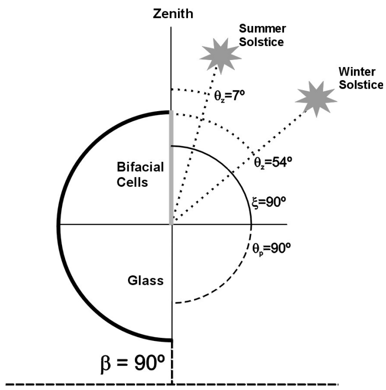


Figure 1: Cross-section of the PEC-FAL module, upper (ξ) and lower (θ_p) acceptance angles, slope of the module (β), zenith angle (θ_z) and position of the sun at noon in the solstices, at Porto Alegre – RS – Brazil.

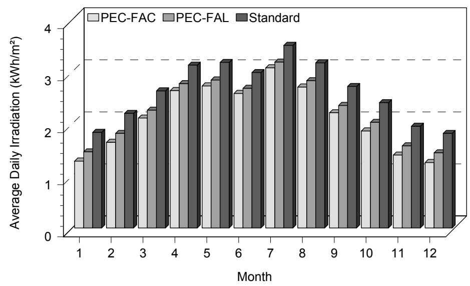


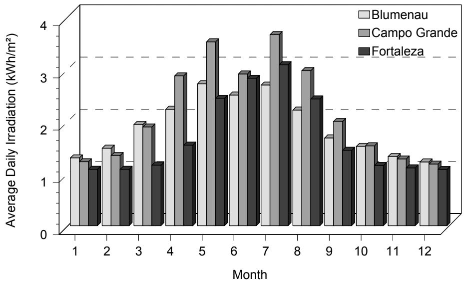
Figure 2: Monthly average daily irradiation simulated for PEC-FAL, PEC-FAC and standard module installed at Porto Alegre (latitude = -30^o), Brazil.

The above comparison was also carried out for Blumenau (ϕ = - 26.9^o), Campo Grande (ϕ = - 20.4^o) and Fortaleza (ϕ = - 3.7^o) to analyze the performance of different modules. The results are illustrated in Fig. 3. We observe the same behavior of irradiation during the year for PEC-FAL and standard module when Fig. 3-a is compared to Fig. 3-b. As expected, in Campo Grande the irradiation is higher in both cases.

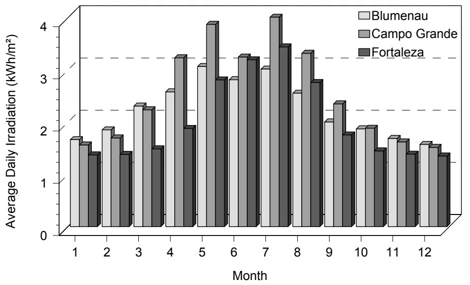
4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Construction of the prototype

A prototype of the PEC-FAL was built and installed on a surface sloped 90^o to the north, at Porto Alegre. Two monofacial cells were encapsulated and connected to a resistive load. The cells were calibrated to measure independently the irradiance on each face of bifacial cells. The internal surface of the optical system was covered with a silver film that presents an average reflectance of 0.96. Then, the cells were assembled with the optical system. The prototype is shown in Fig. 4.



(a)



(b)

Figure 3: Monthly average daily irradiation simulated for (a) PEC-FAL and (b) standard module, installed at Blumenau (latitude = -26.9°), Campo Grande (latitude = -20.4°) and Fortaleza (latitude = -3.7°).

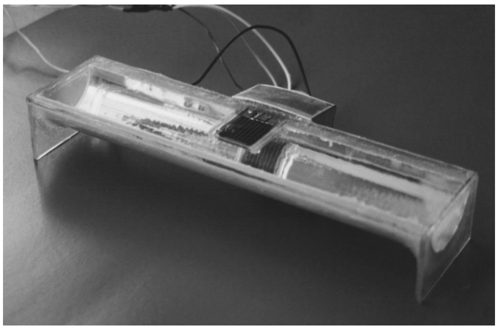


Figure 4: Prototype of the PEC-FAL module.

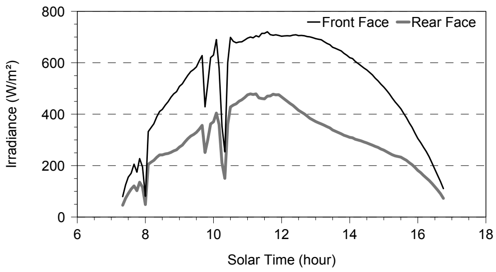
4.2 Irradiance on bifacial cells

A data acquisition system was developed to monitor and record experimental data. The irradiance on each face of the bifacial cells and the irradiance on the module have been measured every five minutes. The irradiance on the vertical surface is been measured with a PV pyranometer. In this paper, we are presenting the analysis of experimental results obtained in 2004.

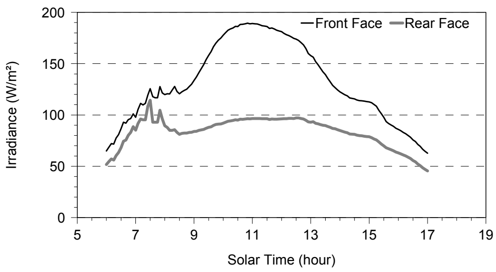
Fig. 5 a and b give the irradiance on each face of the bifacial cells, in a day with cloudless sky near winter and summer solstice, respectively. The comparison of Fig. 5-a with Fig. 5-b shows that in winter higher irradiance reaches on the rear face of the cells due to the values of the irradiance on the front face. Nevertheless, in both cases, the ratio of irradiance on the rear to front face is similar.

4.3 Daily irradiation

To confirm the simulated results, the irradiance measured was integrated to determine the daily irradiation. The values of the irradiation on the faces of the bifacial cells are compared in Fig. 6. As expected, we note that on the rear face the irradiation is lower during the year than that on the front face.



(a)



(b)

Figure 5: Irradiance on each face of the bifacial cells, in a day near (a) winter and (b) summer solstice.

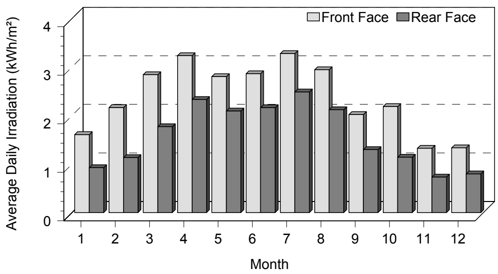


Figure 6: Monthly average daily irradiation measured on the front and rear face of bifacial cells assembled to PEC-FAL. The prototype was installed at Porto Alegre, Brazil.

Fig. 7 presents the experimental results of daily irradiation corresponding to the PEC-FAL and a standard module. The comparison of the irradiation presented in Fig. 7 and Fig. 2 allows one to verify that simulated and experimental results correlate well. In this way, the analysis of the experimental data confirms the simulated results.

5 CONCLUSIONS

The static concentrator module PEC-44D was optimized for façades. The cross-section of the optimum concentrator module is formed by part of a circle and an ellipse. An alternative module, named PEC-FAL, was also proposed with the cross-section of the optical system equal to a semicircle. Both modules were compared and we verified that the annual performance is similar. Nevertheless, the cost reduction obtained with PEC-FAL module is only 4% lower. Comparisons of the PEC-FAL with a standard module lead to cost reduction of 12% for low latitudes up to 36% for medium latitudes. A prototype was built and measurements confirm the performance simulated. We conclude that PEC-FAL module may be an approach to reduce the cost of the PV system.

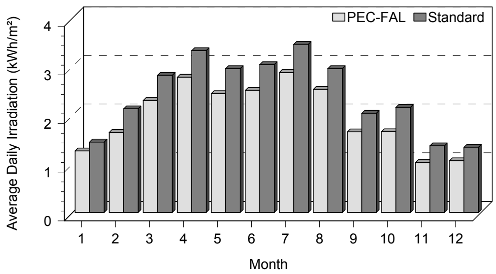


Figure 7: Monthly average daily irradiation measured for PEC-FAL and standard module, installed at Porto Alegre, Brazil.

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