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STATIC CONCENTRATOR PEC-44D OPTIMIZED FOR STAND-ALONE SYSTEMS IN BRAZIL

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ABSTRACT: The use of static concentrator modules is an approach to reduce the cost of PV systems. Nevertheless, remarkable cost reductions and good performance of the PV system depend on the optimization of the concentrator. The purpose of this paper is to present the optimization of the static concentrator module PEC-44D for stand-alone systems in Brazil. This device consists of bifacial cells and of a linear asymmetrical optical system, shaped by part of a parabola, circle and ellipse. The tool used to achieve this goal was a computer program to simulate a ten year period of a stand-alone system. The results are the upper and lower acceptance angles as well as the slope of the concentrator that lead to the lowest cost of the PV array. The method was applied to optimize the PEC-44D module for 27 Brazilian cities. We concluded that the upper acceptance angle should be 90^o and the lower acceptance angle decreases with the increase of latitude. Based on these results, three different devices were selected as a function of lower acceptance angle and latitude.The comparison of the selected modules with the optimum design for each location results in an increase of the PV-array cost of only 2%.
Keywords: Concentrators - 1: PV - modules - 2: Stand-alone PV systems - 3

1. INTRODUCTION

An approach to reduce the cost of photovoltaic solar energy is to concentrate solar radiation on solar cells by a low cost static concentration system [1], [2]. This kind of module concentrates solar radiation from a wide angular region of the sky and, consequently, the concentration ratio is low. In this way, the nominal operating cell temperature is similar than that of a standard module [3], [4] and a cooling system assembled to the solar cells is not required. These concentrators do not need any tracking system and they can be installed on façade or rooftop as a standard module. Independently if monofacial [5]-[7] or bifacial [7]-[10] solar cells are used, a remarkable cost reduction can be achieved.

The trade-off between low cost and good performance of the device depends on the optimization of the concentrator for a specific application. Bearing this in mind, the purpose of this paper is to present the optimization of the static concentrator module PEC-44D for stand-alone systems in Brazil.

2. STATIC CONCENTRATOR MODULE PEC-44D

The static concentrator module PEC-44D was proposed by Miñano and Parada [11] and it consists of a linear asymmetrical optical system and bifacial cells. In Figure 1, the prototype of this module is illustrated. The optical system is shaped by part of a parabola, circle and ellipse and it is designed starting from the lower θ_p and upper ξ acceptance angles, as Figure 2 shows. From this figure we can observe that solar radiation is concentrated only on the rear face of the bifacial cells. Miñano and Parada developed this concentrator for Madrid, in such a way that the highest concentration ratio occurs in winter and the lowest in summer, in order to compensate the annual solar radiation behaviour.

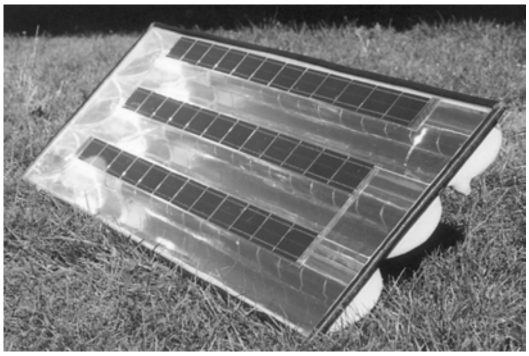

Figure 1: Static concentrator module PEC-44 developed for Madrid.

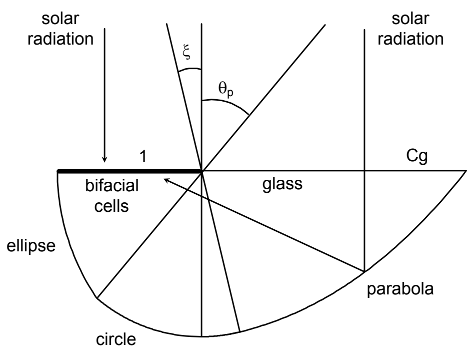

Figure 2: Schematic cross section of the static concentrator module PEC-44D, showing the solar radiation on each face of bifacial cells.

3. OPTIMIZATION METHOD

3.1 Solar radiation on bifacial cells

The PEC-44D module was optimized using a computer program to simulate a stand-alone system with constant demand during the year.

In this simulation, solar radiation has to be hourly data. A sequence of daily clearness indexes is generated by the Aguiar's Method [12] and the monthly average daily irradiation on a horizontal surface. Following this, the daily irradiation is split into its beam and diffuse components. Starting from the daily total and diffuse irradiation, the hourly irradiation data are estimated [13] [14]. The hourly diffuse irradiation on tilted surface is calculated using the Perez's model [15]. In this way, the hourly irradiation on the frontal face of cells is obtained. The irradiance at the middle of the hour is considered equal to hourly values.

The beam irradiance that reaches on the rear face of the bifacial cells [4] is estimated by the geometric concentration Cg and the directional intercept factor. The latter is defined as the ratio of the power that reaches the cells to that reaching the entry aperture of the concentrator at a specific direction [11] and it is obtained from the acceptance angles and the slope of the module. The geometric concentration is the ratio of the entry aperture area to the cell area [16], [17]. Based on a similar procedure, the diffuse irradiance on the rear face of the cells is determined [4]. In this case, the intercept factor for the radiation reflected by ground and for each component of diffuse radiation obtained by Perez's Model is determined.

3.2 Computer simulation

When we deal with concentrator modules, the cost of PV-array varies as a function of the concentrator design. Then, the method used to optimize the PEC-44D module is based on a computer simulation of a stand-alone system in order to minimize the cost of the PV-array for a specific loss of load probability and storage capacity. In other words, the optimization consists of simulating the system during ten years and to find the acceptance angles and the slope of the module that lead to the lowest PV-array cost.

The input data are acceptance angles, slope of the module β, loss of load probability LLP, storage capacity C_S, bifacial cell efficiency and monthly average daily irradiation on a horizontal surface.

The electric energy provided by the PV system relies on the natural behaviour of local solar radiation. Consequently, the system is related to a loss of load probability, defined as the ratio of energy deficit to energy demand.

For a system with PEC-44D modules, the PV-array capacity C_A [18], [19] and the storage capacity C_S [19] are defined related to average daily energy demand L:

$$C_A = \frac{A}{1+Cg}\eta_f\left(1+Cg\frac{\eta_r}{\eta_f}\right)\frac{G_{dm}}{L} \quad (1)$$

and

$$C_S = \frac{C}{L} \quad (2)$$

Where,

A = PV-array area;

η_r = total efficiency of bifacial cell on the rear face, taking into account the optical losses;

η_f = total efficiency of bifacial cells on the frontal face;

G_{dm} = horizontal monthly average daily irradiation for the month that presents the lowest value;

C = maximum energy that can be taken out of the batteries.

Otherwise, if standard modules are used, then Cg = 0, and:

$$C_A = \frac{\eta A G_{dm}}{L} \quad (3)$$

Where η is the PV-array efficiency. Similarly, the cost of PV-array is normalised to the daily energy demand:

$$P_N = \frac{P}{L} = \left[P_{cell} + (1+Cg)P_{con}\right]\frac{C_A}{\left(1+\frac{\eta_r}{\eta_f}Cg\right)\eta_f G_{dm}} \quad (4)$$

and

$$P_N = \frac{P}{L} = \frac{C_A}{\eta G_{dm}}P_{cell} \quad (5)$$

for PEC-44D and standard modules, respectively. P_{con} and P_{cell} are the price per square meter of the optical system and encapsulated cells.

The LLP is obtained from the analysis of the state of charge of the batteries [20] and depends on an initial value of C_A. An interactive method is used to calculate C_A for a determined LLP and C_S.

After analysing some methods to find the minimum of the $P_N(\xi,\theta_p,\beta)$, the following procedure was adopted. The acceptance angles and the slope of the module initially is varied from 0^o to 90^o in increments of five degrees and the set angles that leads to the minimum PV-array cost is found. Then, the procedure is repeated, varying the angles in steps of one degree in the range limited in $\pm 6^o$ around the above encountered angles.

4. RESULTS AND ANALYSIS

This method was applied to optimize the PEC-44D module for 27 Brazilian cities, distributed as Figure 3 shows. In order to analyse the parameters that may influence the design, the computer simulation was carried out for:

- loss of load probability: LLP = 10^{-2};
- storage capacity: C_S = 4, 6 and 8;
- total frontal and rear face efficiency of bifacial cells: 1) $\eta_f = \eta_r = 0.135$; 2) $\eta_f = 0.16$ and $\eta_r = 0.11$; 3) $\eta_f = 0.11$ and $\eta_r = 0.16$;
- price per square metre of the optical system: P_{con1} = US\$130/m^2 and P_{con2} = US\$260/m^2;
- price per square metre of the encapsulated cells: P_{cell} = US\$ 1000/m^2.

This LLP was selected because a previously analysis for Rio Grande do Sul State confirmed similar results for LLP = 10^{-1}.

For each location, eighteen different situations were simulated. This procedure finds the minimum value of P_N as a function of C_S, P_{con} and bifacial solar cell efficiency. The lowest slope β was limited to 10^o, because for low latitudes its optimum value is smaller than 10^o.

Figure 3: Distribution of the 27 Brazilian cities selected to optimize the PEC-44D module.

We observed a slight influence on the acceptance angles due to the price of the optical system. Only for higher latitudes the upper acceptance angles varies as a function of P_{con}. Otherwise, the influence of C_S on angles is negligible.

For locations with latitudes higher than 26°, the lowest PV-array cost occurs when the face of the bifacial cells with higher efficiency is facing the reflector in the module. However, for low latitudes, the opposite result is found. In these cases, the solar radiation does not present a remarkable variation during the year and, therefore, higher concentration ratios are not necessary in a specific season.

Table I presents the minimum value of the PV-array cost for each location and the concerned angles. Values of P_N were calculated taking into account P_{con1} and C_S=6. We found that the upper acceptance angle should be equal to 90° for all locations and the lower acceptance angle decreases with the increase of latitude. On the other hand, the slope β does not present a relation with the latitude.

Based on the analysis of the lower acceptance angle, the country was separated in three regions and the average value of this angle was selected for each region:

- latitude<20°→θ_p=75°, named PEC-BR1 module;
- 20° ≤latitude≤26°→θ_p=31°, named PEC-BR2 module;
- latitude>26°→θ_p=6°, named PEC-BR3 module.

The optimum slope of the modules and the new values of P_G were recalculated for these configurations. When these results were compared to the optimum design for each location, the increasing of the PV-array cost is lower than 2%.

Figure 4 compares the monthly average daily irradiation on both faces of bifacial cells of the three selected PEC-44D modules for Brazil. We note that values are approximately constant during the year, excepting for Fortaleza, where there is a higher irradiation in spring. Nevertheless, this seasonal dependence is not due to the performance of the concentrator, but it is a feature of the local radiation.

Table I: Latitude (ϕ), cost of the PV-array normalised to the daily energy demand (P_N), upper (ξ) and lower (θ_p) acceptance angles as well as slope of the module (β).

ϕ	P_N*	ξ	θ_p	β
3.2°	1.529	90°	79°	10°
2.8°	1.337	90°	79°	10°
0°	1.403	90°	79°	10°
-2.5°	1.385	90°	70°	10°
-3.1°	1.545	90°	79°	10°
-3.7°	1.160	90°	79°	10°
-5.0°	1.168	90°	79°	10°
-5.7°	1.066	90°	75°	13°
-7.1°	1.114	90°	70°	16°
-8.2°	1.245	90°	59°	21°
-8.7°	1.367	90°	79°	10°
-9.6°	1.141	90°	9°	25°
-9.9°	1.396	90°	79°	10°
-10.5°	1.224	90°	79°	10°
-10.9°	1.066	33°	22°	15°
-12.6°	1.297	90°	53°	23°
-15.5°	1.265	90°	79°	10°
-15.7°	1.220	90°	79°	10°
-16.6	1.140	90°	79°	10°
-19.9°	1.347	90°	73°	14°
-20.3°	1.165	90°	45°	24°
-20.4°	1.178	90°	28°	27°
-22.9°	1.243	90°	23°	28°
-23.5°	1.474	90°	43°	27°
-25.3°	1.825	90°	18°	36°
-26.9°	1.595	90°	11°	40°
-30.0°	1.398	90°	2°	52°

* US$/Wh

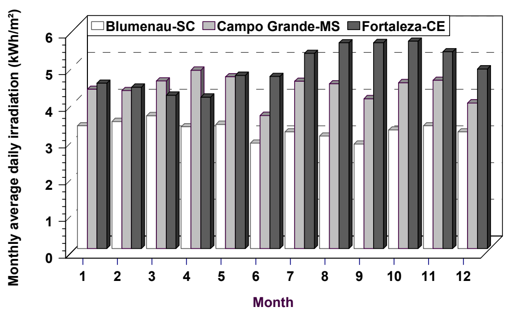

Figure 4: Monthly average daily irradiation on both faces of bifacial cells for selected PEC-44D modules, taking into account the optimized angle β for each location.

5. CONCLUSIONS

In summary, the module PEC-44D was optimised for stand-alone systems in Brazil and we found three different designs. When this device is compared to standard modules, the average cost reduction is 24%, taking into account all locations. This result confirms that the PEC-44D module is also suitable for regions near the Equator.

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