Annual Energy Output Simulation of an Optical Concentrator Based PV System for Energy Security

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Annual Energy Output Simulation of an Optical Concentrator Based PV System for Energy Security

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Abstract. Concentrating photovoltaic (CPV) system is an application of PV devices introduced with the aim of reducing the cost of BIPV systems through the use of an optical element to concentrate or focus the solar radiation from a large area, into a smaller area to which the solar cell is attached, thus reducing the overall cost by saving expensive PV material. This paper aims at presenting the simulation results of an annual prediction for a system comprising of CPV based on the Rotationally Asymmetrical Compound Parabolic Concentrator (RACPC) and compared it with a non-concentrated PV module installed in Bogota, Colombia under different weather conditions. The yearly energy yield of the CPV module was calculated to be 480 kWh whereas the non-concentrating PV module had a drop in the output - almost half of the CPV module output, having a final value of 231 kWh. This indicates that the RACPC can increase the output by a factor of 2.08. This study demonstrates that a CPV system can be used as an alternative to a conventional PV system; as it offers a lower cost without compromising its performance.

1. Introduction

After the latest global warming meeting in Paris the 12th of December 2015, 195 countries agreed with the United Nations (UN) to work with the aim to keep the global temperature increase below 2 ^{o}C and to join efforts to try to keep the temperature increase below 1.5 ^{o}C [1]. According to the National Aeronautics and Space Administration (NASA) [2], 2016 was ranked as the warmest year making the countries to take renewable energies into account as a primary energy source with cost competitive technologies, which should pave the way to a safer climate. In order to achieve this it is required to improve energy efficiency and use renewable energies. By definition, energy efficiency implies delivering the same amount of services for less energy input or more services for the same energy input. Therefore, this is important to reduce CO_2 emissions and brings multiple economic benefits such as reducing fuel poverty, enhancing energy security and improving public health [3]. Currently, around 146 countries have developed and implemented some kind of energy efficiency policy such as policies for electricity, policies for cooling, renewable energy transport, heating; and city and local government

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renewable energy policies; and near to 173 countries had one or even more renewable energy targets by the end of 2015 [3].

The concentrating photovoltaic (CPV) system is a PV based system that reduces the cost through the use of optical elements that concentrate or focus the solar radiation impinging on a large area, into a smaller area to which the solar cell is attached. This reduces the overall cost by saving expensive PV material as optical concentrators can be fabricated using cheaper materials such as glass or plastic [4]; in addition, a higher electrical output is achieved [5]. However, one of the principal disadvantages of these systems is the requirement of a cooling system due to high temperatures that can lead to the faster degradation of the PV material [6].

The rotationally asymmetrical compound parabolic concentrator (RACPC) design was proposed by Abu-Bakar et al. [7]. From the various software options available, MATLAB® was the one used to design the RACPC through a mathematical algorithm that requires various inputs parameters. These include half- acceptance angle (θ_a), the index of refraction of the material (n), the total height of the concentrator (H_{tot}), the trial width of the entrance aperture (d_1), the the length of the PV cell (L_{PV}), the width of the PV cell (W_{PV}); and the number of extreme rays (N) [7]. A prototype was then produced for testing purposes and this is presented in Figure 1. With a geometrical concentration ratio of 3.67, a total height of 3 cm, an entrance aperture of 2.06 x 2.06 cm and an exit aperture of 1 cm x 1 cm, this design greatly reduces the material utilised and increases the electricity output by 3.01 times [8].

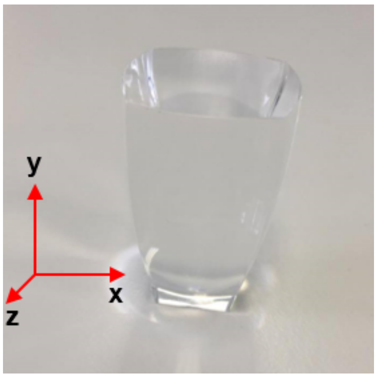

Figure 1. Prototype of an RACPC.

This paper presents the simulation results for the annual prediction of a system comprising of RACPC-PV and compared it with a non-concentrated PV module installed in Bogota, Colombia under different weather conditions. This study demonstrates that a CPV system can be used as an alternative to a conventional PV system; and offers a lower cost without compromising its performance.

2. Methodology

One of the fundamental consideration when installing a PV module is its orientation and angle of installation. The RACPC is static in order to reduce costs and the high risk of operational problems, thus having a limited acceptance angle for the sun variations during the year. March and September are the months with the optimum angle of the equinox and although there are different ways to capture the sunlight throughout the year for this prediction, the mounting of the panels with the optimum tilt angle for March or September will be used. In this paper, the RACPC was used in a skylight (see Figure 2) as an example; and an annual prediction for Bogota, Colombia has been made.

The size of a PV module on a skylight is normally larger than a conventional PV module because of the gaps between the concentrators for natural illumination. The PV material used for a CPV and a PV module in this prediction is based on the same area. Subtracting the frame of the module the active area of the PV module is around 0.58 m^2 and the area of the PV material used on the typical manufactured window sample is about 7.1 times, thus, leading to a CPV module size of 4.1 m^2. The module was installed in Bogota (4° 37' 27.6060" N, 74° 3' 49.1184" W) [9], on a south facing rooftop at an angle of 5° from the horizontal to match the equinox angle during March/September and the latitude of the site for Bogota during the same months [10]. In addition, a tracking system is not used for the predictions.

Figure 2. Skylight with monocrystalline PV modules [11].

In order to calculate the ideal energy yield of the PV module, the following Equation (1) is used [12]:

$$E_{ideal} = A_{PV} * \eta_{PV} * H_{Solar} * C_{opt} \tag{1}$$

where:

A_{PV} is the area of the PV material
η_{PV} is the solar cell efficiency
H_{Solar} is the solar irradiation
C_{opt} is the optical concentration gain

The optical concentration gain value for diffuse irradiance is C_{opt}= 2.12, the PV area is 0.58m^2 and the cell efficiency is taken as 14.9%. The optical concentration gain for direct irradiance depends on the solar azimuth position of the sun on a particular day.

2.1. Tilt angle of RACPC module

The optimum tilt angle for PV modules in Bogota during March/September as already mentioned is 5° from horizontal facing south and using this angle the angles of incidence for each month were calculated using the method presented in [12]. The results for each month are presented in Table 1 where the maximum solar altitude angle data are specifically from Bogota. This information is important to demonstrate if the RACPC module is capable of collecting the irradiation throughout the year. In order to prove the above, the deviation of the angle of incidence with respect to the module must be within the half acceptance angle of the RACPC of ±42.96° [7].

Table 1. Optimum tilt angles and angles of incidence at a tilted plane in Bogota.

Month	Maximum solar altitude angle (^{o})	Maximum angle of incidence at a 5^o tilted plane from horizontal (^{o})
June	108	23
May/July	101	16
April/August	93	8
March/September	85	0
February/October	77	8
January/November	69	16
December	62	23

2.2. Concentration gain of RACPC on a tilted surface

The optical concentration gain was calculated and considering the performance of the RACPC with angles of incidence at 8^o, 16^o, and 23^o along the z-plane of the concentrator and the light source path during the day is tilted from – 90^o to + 90^o along the x-axis (refer Figure 1 for the directions of each axis). Figure 3 was created by Abu-Bakar [13]. This information will be used for the predictions.

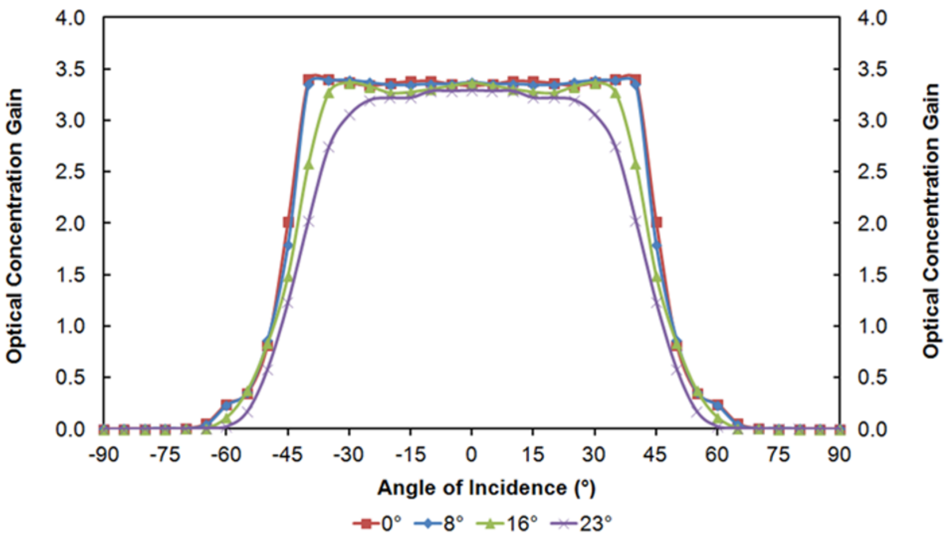

Figure 3. Optical concentration gain for various solar altitude and solar azimuth angles [13].

The optical concentration gain as it can be observed reduced significantly when the angle of incidence along both the x-plane and z-plane increased beyond a certain point. Specifically at angles of incidence of 23^o along the x-plane, the graph shows a significant drop after ±30^o. In all cases, the angle of incidence has a concentration gain more than 1 between ±50^o. This means that during June and December the acceptance angle during the day is ideal to capture direct light.

2.3. Irradiation data

The annual irradiance data for Bogota, Colombia is required in order to predict the annual output. Using the online tool [14], the global irradiance per month is obtained, thus, direct and diffuse irradiance can be known. Using this monthly data over a 22-years period (Jul 1983- Jun 2005) of direct and diffuse radiation the energy yield per month can be predicted. It was found that the diffuse irradiation makes up 72.5% of the global irradiation when summed over the year.

2.4. Irradiance and tilted surface

The RACPC module, as it is above-mentioned, needs to be installed at a certain tilt angle. Thus, direct and diffuse irradiance on a tilted surface must be calculated. According to Quaschning [12], the global irradiance, E_(G,tilt), on a tilted surface has three components, the diffuse irradiance, E_(diff,tilt), the direct irradiance, E_(dir,tilt) and the reflected irradiance, E_(refl,tilt). The diffuse irradiance on tilted surface can be estimated by the isotropic approach and the anisotropic approach. However, the isotropic approach is only applicable for rough estimations or very overcast skies which is not the case; the anisotropic is more precise and it can be calculated using the Klucher´s model [12]. Both the direct and diffuse radiations are calculated using the method presented in [12]

The reflected irradiance was determined with the global irradiance, E_(G,hor) and the Albedo A which value, which depends on the type of surface and influences the accuracy of the results noticeably. For this work, the coefficient recommended for unknown surfaces is 0.2 [12]. E_(G,hor) is the global irradiance on a horizontal plane and γ_t is the angle of the side profile. Figure 4 shows the monthly irradiance of Bogota.

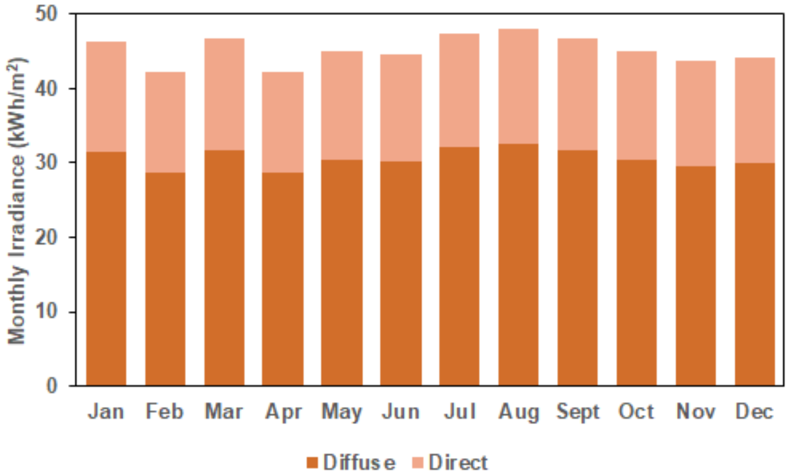

Figure 4. Monthly irradiance in Bogota.

3. Results and Discussion

The yearly energy yield of the CPV module was calculated to be 480 kWh whereas the non-concentrating PV module had a drop in the output of almost half of the CPV module output having a final value of 231 kWh. This means a factor of 2.08 (see Figure 5). The designed concentration gain of the concentrator is 3.34 which is higher than the factor by which the output is increased; however, this can be justified with the values for the monthly irradiation in Bogota where diffuse irradiation makes up to 72.5% of the global irradiation when summed over a year.

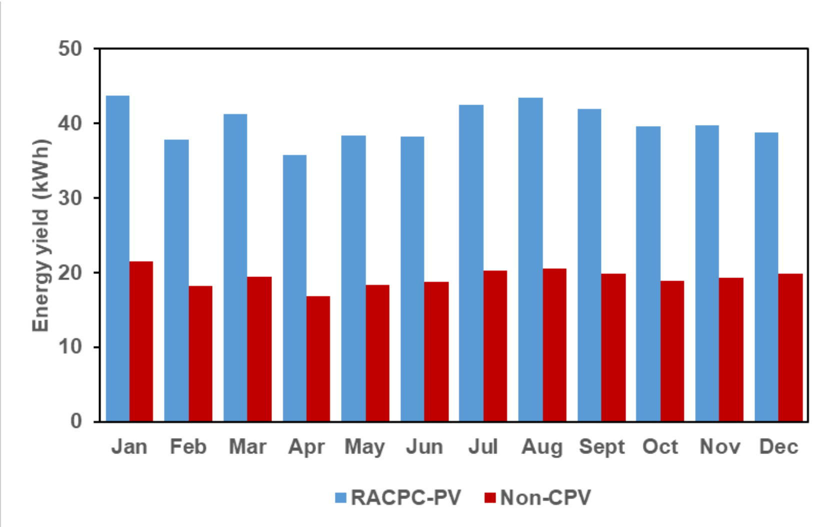

Figure 5. Monthly energy yield for a CPV module and a PV module in Bogota.

As it can be seen most of the months achieved a larger energy yield with the CPV system, particularly for the months of January, July, August, and September. This is due to the fact that in those months the irradiance and the optical concentration gain are higher. In order to have a better evaluation of the concentrator performance during the year under direct and diffuse irradiance the graphs of Figures 6 and 7 were created.

The calculated energy yield output for both systems in January and August are high due to the fact that these are the months with the highest amount of irradiation in comparison with the rest months of the year (see Figure 6). However results of the CPV system achieves quite high energy yield even though direct irradiance in months like February and April are amongst the lowest. These occurred when the angle of incidence is small. This shows the significant influence of the angle of incidence on the electrical output with regards to the solar altitude angle.

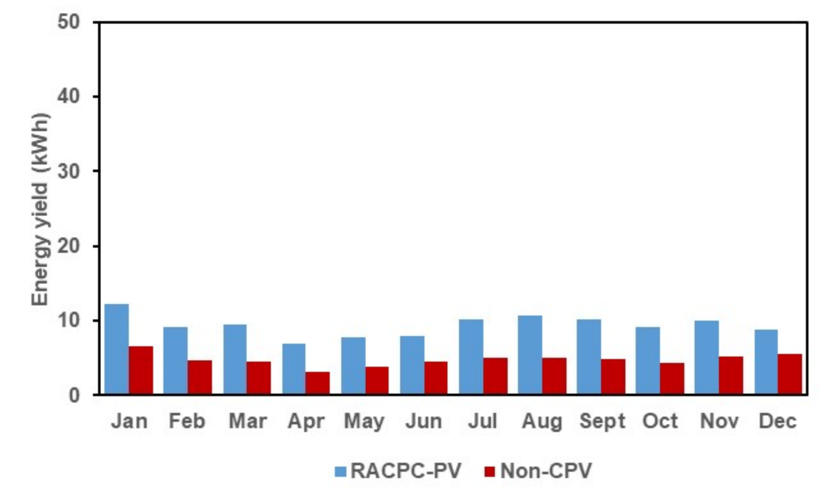

Figure 6. Comparison of the monthly energy yield for a CPV module and a PV module in Bogota under direct irradiation

The performance of the concentrated PV system under diffuse radiation is shown in Figure 7. As it can be seen here, it is much better than under direct irradiance. The results of the energy yield for the CPV module during the year shows that although the angle of incidence is important, the performance under diffuse is giving a higher output - nearly doubled the performance under the direct irradiance throughout the year. The total energy yield from direct irradiation is 113 kWh and from diffuse irradiation is 368 kWh per year.

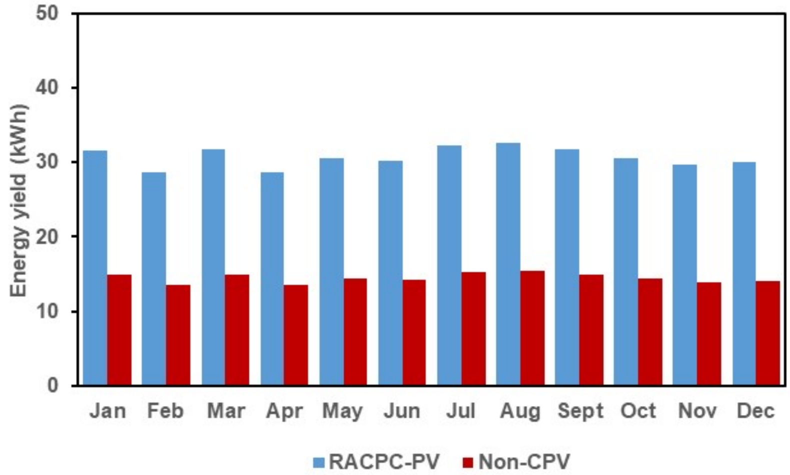

Figure 7. Comparison of the monthly energy yield for a CPV module and a PV module in Bogota under diffuse irradiation

4. Conclusions

The paper presents the simulation of annual performance of an RACPC-PV panel installed in Bogota, Colombia. The yearly energy yield for Bogota increases by a factor of 2.08 when the system includes the RACPC module, especially under diffuse radiation. This highlights the improvement in performance when using the concentrator under overcast conditions. Some suggestions for future work include: (i) to have a reliable source that provides hourly data throughout a day; (ii) placing the CPV system in location at higher ground to reduce reflected irradiance of the buildings and houses near the location, and (iii) to use a pyranometer with better accuracy to accurately measure the percentage of diffuse and direct irradiance because the use of empirical formulas increase the uncertainty in the results.

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