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ScienceDirect

Energy Procedia 158 (2019) 73–78

Energy Procedia

www.elsevier.com/locate/procedia

10th International Conference on Applied Energy (ICAE2018), 22-25 August 2018, Hong Kong, China

Long Term Electrical Rating of Concentrated Photovoltaic (CPV) Systems in Singapore

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Abstract

Owing to the diverse photovoltaic (PV) systems available commercially, ranging from the stationary silicon-based PV panels to 2-axes tracker concentrated photovoltaic (CPV) systems and dynamic nature of meteorological data, energy planners and PV system designer require a simple but accurate methodology to understand the economic viability of a renewable solar PV plant. An electrical rating methodology is proposed for evaluating the long-term performance for assorted PV systems, providing a common "playing field" to consumers, planners and manufacturers of PV systems. Given a meteorological condition, the output-based approach or electrical rating of renewable energy system is the key for economic and environmental CO_2 emission evaluations. Despite the overwhelming catalog data furnished by PV manufacturers, the long-term electricity rating of a PV system is deemed to be a quick and accurate method for the evaluation of economic viability and the determination of plant sizes and power production from a PV facility. This paper presents and analyses the long term performances, as monthly and overall electrical ratings in kWh/m^2.year of two concentrated photovoltaic (CPV) prototypes, the mini dish Cassegrain-type and the Fresnel lens CPVs with triple-junction solar cells, operating under the meteorological conditions of Singapore and compares performances with the other photovoltaic systems.

Keywords: Electrical Rating; CPV; Concentrated Photovoltaic; Long Term Performance; Solar Tracker.

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1876-6102
10.1016/j.egypro.2019.01.048

1. Introduction

Because of the huge dependency on burning of fossil fuels, CO_2 emissions in atmosphere have increased to alarming level and scientists have predicted a rise of 3.6-5.3°C in global temperature, in current situation [1-3]. In the period from 2000 to 2011, CO_2 emissions have increased from 23.7Gt to 31.2Gt and to 43.1Gt increase is expected in 2035 [4]. One of the possible solution in this situation is the use of renewable energy resources as primary energy supply.

Solar energy has highest energy potential and is feasible to fulfil global energy needs. However, the most simple and elegant method of solar energy utilization is the direct conversion of solar energy into electricity by using solar cell. In the current PV market, crystalline silicone based solar cells have biggest share of 85-90%. However, these single junction conventional solar cells offer very low energy conversion efficiency ranging 7-19% [5,6]. In addition, the maximum thermodynamic efficiency limit for these single junction cells is also limited to 31% [7]. At present, multi-junction solar cells (MJCs) have the highest energy conversion efficiency of 46% [8]. Multi-junction solar cell is a stack of different single junction solar cells, joined together and respond to certain wavelength of solar spectrum [9].

In addition to higher energy conversion efficiency [10-12], MJCs are expensive to fabricate for large scale systems. So as to make them cost effective, concept of concentrated photovoltaic is used in which solar radiations are concentrated onto a small area of solar cell, as a result, reduce the use of expensive solar cell material [13-17]. For CPV systems, concentrating assembly is designed according to the required solar concentration at cell area. However, concentrators only concentrate and respond to beam radiations of solar energy and thereby need to face towards sun all the time. Although there is a big share of solar energy hitting earth surface in form of beam radiations, but diffuse radiations are also always present and their share depend upon weather location and particular location. Moreover, the atmospheric condition of specific location i.e. the amount of pollutants present in the air and clouds also affect the share of diffuse radiations and total solar energy hitting the earth surface.

Unlike conventional photovoltaic (PV) systems, CPV can only respond to beam radiations of solar energy and there is no production from diffuse radiations i.e. cloudy weather conditions [18-20]. However, conventional PV systems, although lower but still have power production in cloudy conditions as they can respond to diffuse part of solar radiations. Moreover, the overwhelming catalogues of PV manufacturers only provide the rated maximum efficiency of the system, which cannot be achieved for the whole day operation due to changing irradiance and ambient temperatures. Therefore, based upon the PV manufacturers' data, the total power output of the PV system cannot be accurately estimated and system will always deliver less than the estimated designed value. Similarly, CPV systems have higher operating efficiency but they can only respond to beam radiations and cannot accept diffuse radiations. However, at some regions, diffuse radiations form a significant part of solar radiations and power output of the CPV system can be affected. Owing to too many different operating parameters and working conditions, designers need a simple but accurate methods to understand the economic viability and plant sizing of PV system or any other renewable energy system. In spite of different operating condition, electrical rating methods provide a common playing field for designers to analyze any PV system in terms of the total power output given in kWh/m2.year.

This paper focuses on the long term performance evaluation of two different concentrated photovoltaic (CPV) systems in tropical weather conditions of Singapore by using electrical rating method. One of the CPV system is based upon the mini dish based Cassegrain-type concentrating assembly and other one uses Fresnel lenses as concentrators. Both of the CPV system are mounted on to developed two axis solar tracking system. Experiment was conducted from September, 2014 to March, 2015 and data regarding power out from CPV systems and direct normal irradiance (DNI) received, was recorded after each second. Overall and monthly electrical rating was then calculated in kWh/m2.year by summing up the total energy delivered by CPV systems each day.

2. Electrical Rating Methodology

Most of the renewable energy sources are intermittent in nature and their availability varies throughout a year, depending upon weather conditions and geographic coordinates of particular location. However, there are various energy conversion technologies available for renewable energy system, which have different operating conditions and working principle. Electrical rating methodology provide a platform to analyze the real potential of any renewable energy system, irrespective of the technology used, by comparing them at same level in terms of total power delivered. Moreover, this methodology provide a simple but accurate common playing field for the economic analysis and feasibility of renewable energy system by knowing a simple costing factor in $/kWh. This method also helps to evaluate and compare the total CO2 emissions that can be saved per kWh of power produced by different systems. However, the main significant of electrical rating method is to help the designers to estimate the accurate power plant size based upon the real production data at specific location, instead of using data from overwhelming catalogue of manufacturers.

In this paper the electrical rating of two developed CPV system is determined to study the long term performance of CPV systems in a tropical environment of Singapore and these electrical rating values are then compared with the conventional PV system installed at different locations of Singapore. The performance of system was evaluated from September, 2014 to March, 2015. The CPV systems were operated for whole day, from sun rise to sunset and the power output from the systems was recorded in terms of current and voltage output of MJC cell at an interval of one second, along with the measurement of direct normal irradiance (DNI) by using pyrheliometer. The power output from the system and solar input received were integrated over period of whole day to obtained total energy input and output from the system. The calculated parameters and their formulations, used to analyze CPV system performance, are discussed below.

In order to ensure the efficient operation of CPV systems, instantaneous efficiency of the system was determined and observed during whole period of operation. Instantaneous efficiency (η_{ins}) of CPV system was determined by using (1).

$$\eta_{ins} = \frac{V_C \cdot I_C}{Ir \cdot A_D} \times 100 \qquad (\%) \tag{1}$$

Where 'Vc', 'Ic', 'Ir' and 'AD' are cell voltage, cell current obtained from multi-junction solar cell, DNI received in W/m2 and total effective area of concentrator, respectively. Trapezoidal rule can also be used to compute CPV power output and DNI integrals to calculate total electrical energy produced, total solar energy received in form of DNI over the whole period of operation. In order to find out the monthly power delivered by the concentrated photovoltaic (CPV) systems, the equation (2) can be used which sums up the daily total energy yields for entire month.

$$E = \sum_{j=1}^{n}[\int_{1}^{t}(V_C \cdot I_C)dt] = \sum_{j=1}^{n}[\sum_{i=1}^{t}(\frac{(V_C \cdot I_C)_i - (V_C \cdot I_C)_{i-1}}{2}) \cdot S] \qquad (\frac{kWh}{m^2}) \tag{2}$$

Where 't', 'j' and 'S' represent seconds, particular day and scanning time interval for logging data. Equation (3) gives the total solar energy received in form of DNI. In addition the overall and monthly average efficiencies if CPV system, as per defined electrical rating, are also given by equations (4) and (5).

$$D_m = \sum_{j=1}^{n}[\int_{1}^{t}(Ir)dt] = \sum_{j=1}^{n}[\sum_{i=1}^{t}(\frac{(Ir)_i - (Ir)_{i-1}}{2}) \cdot S] \qquad (\frac{kWh}{m^2}) \tag{3}$$

$$Overall\ Averge\ Efficiency = \frac{\sum E}{\sum D_m} \times 100 \qquad (\%) \tag{4}$$

$$Monthly\ Averge\ Efficiency = \frac{E}{D_m} \times 100 \qquad (\%) \tag{5}$$

Now, the proposed electrical rating based upon monthly and yearly performance data is given by equation (6) and (7) as overall electrical rating and monthly electrical rating, respectively.

$$Overall\ Electrical\ Rating, R_e = (\sum_{j=1}^{m} E_i).\frac{m}{365} \qquad (\frac{kWh}{m^2.\,year}) \tag{6}$$

$$Monthly\ Electrical\ Rating, R_{e,m} = (\sum_{j=1}^{n} E_i).\frac{n}{365} \qquad (\frac{kWh}{m^2.\,year}) \tag{7}$$

At last, based upon calculated electrical rating and the recorded daily DNI data, the CO_2 emissions saving and the DNI share of beam radiations in global solar energy received, are given by equations (8) and (9).

$$CO_2\ Emissions\ Saving = R_e \times 0.0635 \qquad (\frac{kg}{m^2.\,year}) \tag{8}$$

$$DNI\ Monthly\ Share = \frac{G_m}{D_m} \times 100 \qquad (\%) \tag{9}$$

3. Results and Discussion

Figure 1 shows monthly performance of CPV system in terms of monthly electrical rating and monthly average efficiency in variation with the percentage of total beam radiations received per month. It can be seen that monthly electrical rating is higher for months with higher amount of total DNI received. Highest monthly electrical rating, 275.4 KWh/m^2.year (as per Eq. 7) was recorded for January month as highest total DNI, 106.1 KWh/m^2.month was received for this month. Moreover, for November and December months, lowest electrical rating was recorded as smallest amount of total DNI was received. This observation is in accordance with the previous figure as November and December were month for which lowest average sunshine duration and total DNI received per day was observed. The monthly average efficiency of CPV system is observed to be almost same for every month except for December for which average efficiency was 20.9%. This can be explained as only 28.5% of total solar energy was received in form of beam radiation, which is extremely low as compared with other months. Moreover, the highest average efficiency of CPV system was observed for February month, although total and percentage of DNI received for this month is not highest. This trend can be explained from the efficiency variation of CPV system against DNI. As seen in figure 1 that efficiency of CPV system remain constant for higher value of DNI or solar concentration, which means the possible reason for higher efficiency of CPV system in month of February may be that the most of the portion of DNI received in this most was higher in value.

In Fig. 2, the overall electrical rating of CPV system is given in comparison with published electrical rating of other conventional single junction PV system installed in Singapore [18]. It can be seen from the figure that overall electrical rating recorded for CPV system is 237.56 KWh/m^2.year which is highest among all other photovoltaic technologies. Another important parameter of comparison is the amount of CO2 emission savings per year from CPV system. The highest CO2 emissions, 69.76 kg/m^2.year, can be saved by the use of CPV systems. Moreover, highest electrical rating depicts lesser footprint of solar system which is one of the big issue for solar energy systems because of their lower efficiency. For Singapore, annual average amount of energy solar energy received is

1700KWh/m[2].year [21] and from electrical rating it can be seen that 14% of this energy can be utilized by CPV system, around 86% higher than all other photovoltaic technologies.

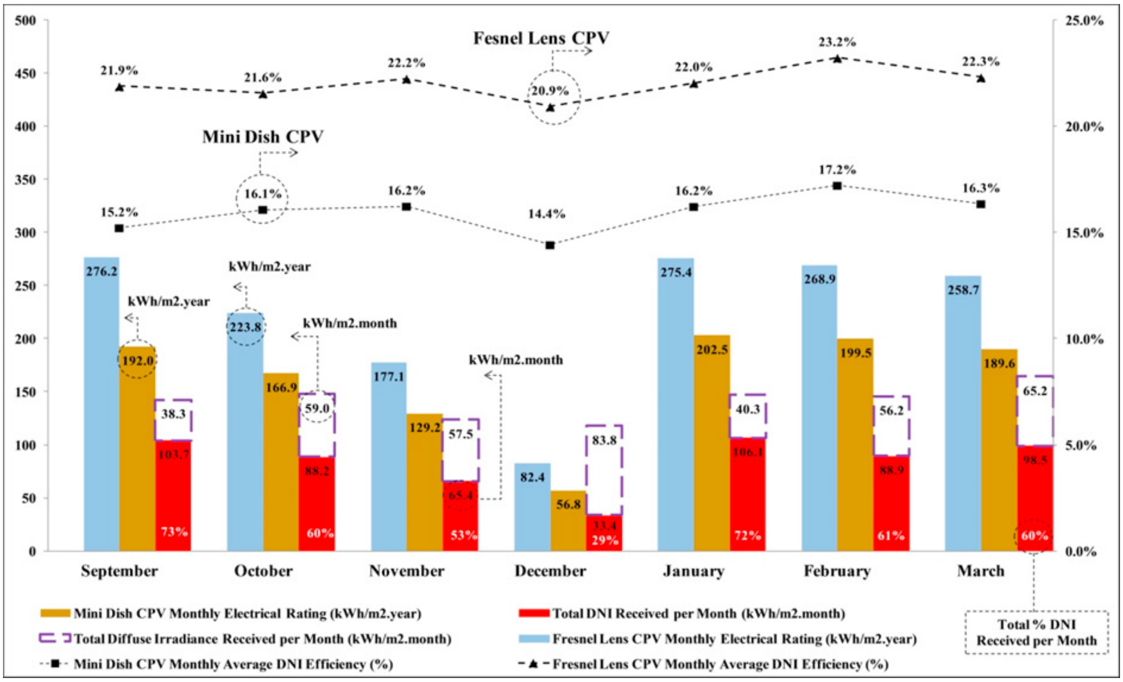
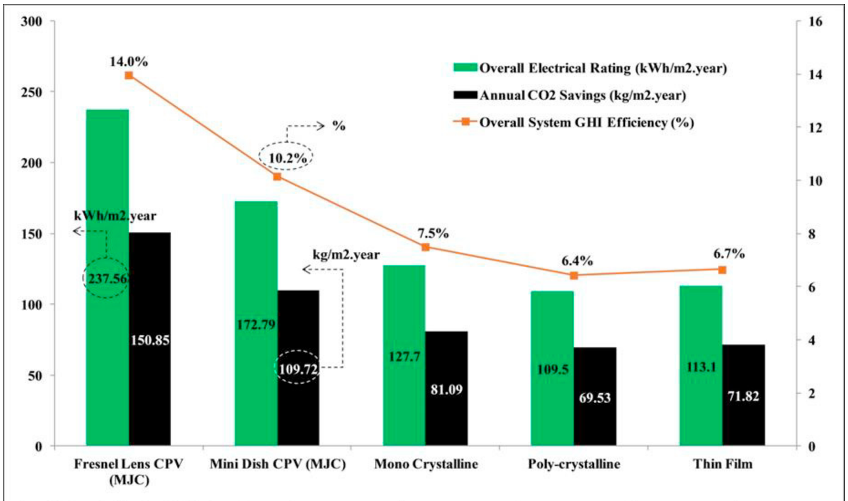


Fig. 1. Monthly Electrical Rating and average Efficiency of CPV with Received DNI



	Fresnel Lens CPV (MJC)	Mini Dish CPV (MJC)	Mono-Crystalline	Poly-Crystalline	Thin Film
Overall Electrical Rating (kWh/m2.year)	237.56	172.79	127.7	109.5	113.1
Annual CO2 Savings (kg/m2.year)	150.85	109.72	81.09	69.53	71.82
Overall System GHI Efficiency (%)	14.0	10.2	7.5	6.4	6.7

Fig. 2. Overall Electrical Rating and CO_2 Savings of CPV System in Comparison with other Photovoltaic Systems

4. Conclusion

The overall electrical rating of CPV system from collected data has been found to be 237.56 kWh/m^2.year, which is 86% higher than the other conventional photovoltaic system, even for a tropical weather of Singapore where diffuse radiations form a significant part of solar energy and %DNI can go to 28%, as recorded in month of December. Moreover, up to 86% higher CO_2 savings can be achieved by CPV system as compared to other photovoltaic systems. Furthermore, the total power delivered by the CPV system is directly depending upon the total amount of solar energy received in form of beam radiations. The quantitative relationship between total power delivered and total DNI received is based upon the overall average efficiency of the CPV system. Thus, if average efficiency of CPV system and total DNI available is known then the total power output or long term performance of CPV system can be correctly approximated irrespective of concentration ratio and cell temperature.

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