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ELECTRICAL RATING OF CONCENTRATED PHOTOVOLTAIC (CPV) SYSTEMS: LONG-TERM PERFORMANCE ANALYSIS AND COMPARISON TO CONVENTIONAL PV SYSTEMS

Muhammad Burhan[1*], Chua Kian Jon Ernest[1], Ng Kim Choon[2]

[1]*Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore, Block EA, #07-08, 9 Engineering Drive 1, Singapore 117575*
[2]*Water Desalination and Reuse Centre, 4700 King Abdullah University of Science & Technology Thuwal 23955-6900, Kingdom of Saudi Arabia*

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ABSTRACT

The dynamic nature of meteorological data and the commercial availability of diverse photovoltaic systems, ranging from single-junction silicon-based PV panels to concentrated photovoltaic (CPV) systems utilizing multi-junction solar cells and a two-axis solar tracker, demand a simple but accurate methodology for energy planners and PV system designers to understand the economic feasibility of photovoltaic or renewable energy systems. In this paper, an electrical rating methodology is proposed that provides a common playing field for planners, consumers and PV manufacturers to evaluate the long-term performance of photovoltaic systems, as long-term electricity rating is deemed to be a quick and accurate method to evaluate economic viability and determine plant sizes and photovoltaic system power production. A long-term performance analysis based on monthly and electrical ratings (in kWh/m^2/year) of two developed CPV prototypes, the Cassegrain mini dish and Fresnel lens CPVs with triple-junction solar cells operating under the meteorological conditions of Singapore, is presented in this paper. Performances are compared to other conventional photovoltaic systems.

Keywords: CPV; Electrical rating; Long-term performance; MJC; Solar tracker

1. INTRODUCTION

Energy has become a vital need for human survival, and due to population growth and a huge dependency on fossil fuels, CO_2 emissions in the atmosphere have increased to an alarming level. Scientists have predicted a rise of 3.6–5.3^{o}C in global temperature based on the current situation. Using renewable energy as a primary energy supply is one possible solution to this crisis (Ho et al., 2011; BP Energy, 2014; IEA, 2013).

Among all energy resources, solar has the highest energy potential and is a feasible way to fulfill global demand. However, direct conversion of solar energy into electricity via solar cells is the simplest and most elegant method of solar energy utilization.

Moreover, conventional single-junction solar cells offer very low energy conversion efficiency, ranging from 7-19% (Lewis et al., 2007; Fraunhofer, 2015). Presently, multi-junction solar cells (MJCs) have the highest energy conversion efficiency at 46% (García-Domingo et al., 2015). In addition to higher energy conversion efficiency (Chantana et al., 2015; Vossier et al., 2012; Mendelsohn et al., 2012), MJC fabrication is expensive for larger cell area. To make them cost

*Corresponding author’s email: burhan@u.nus.edu Tel. +65-6516-2212, Fax. +65-6779-1459
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effective, a concentrated photovoltaic (CPV) concept in which solar radiations are concentrated onto a small solar cell area is employed. This reduces the use of expensive solar cell material (Mendelsohn et al., 2012; Mathur et al., 1990; Wang et al., 2010; Siaw et al., 2014; Chong et al., 2009).

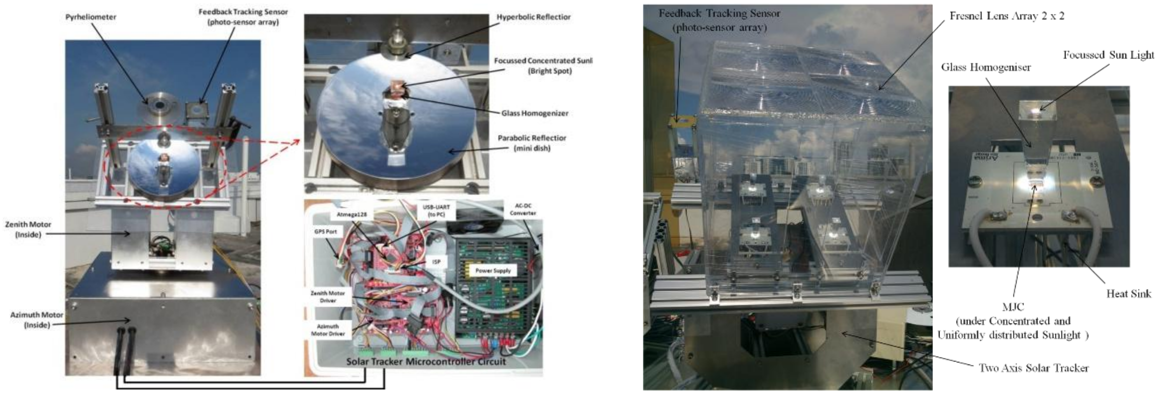
Unlike conventional photovoltaic (PV) systems, CPVs can only respond to beam radiations of solar energy. There is no production from diffuse radiations (i.e., in cloudy weather conditions). In addition to higher efficiency, total annual power is another main evaluating parameter of system performance. This paper focuses on the long-term performance evaluation of two CPV systems in the tropical weather conditions of Singapore using an electrical rating method. The experiment was conducted from September 2014 to March 2015. Data regarding power out output from each CPV system and direct normal irradiance (DNI) was collected, which was recorded per second. Overall and monthly electrical ratings were then calculated in kWh/m^2/year by summing up the total daily energy delivered by CPV systems.

2. DEVELOPMENT OF CPV SYSTEM

Figure 1a shows the developed mini dish CPV system with a two-axis solar tracker and its control box. The concentrating assembly consists of a primary reflector as a parabolic dish and a secondary reflector as a hyperbolic mirror, arranged in a Cassegrain arrangement such that the first focal point of hyperbolic reflector matches focal point f1 of the primary parabolic dish. Solar radiations, after reflecting from primary and secondary reflectors, are concentrated at the second focal point, f2, of the hyperbolic reflector. This is where the glass homogenizer is located, at the end of which an MJC is placed. The homogenizer functions to guide, uniformly distribute and further concentrate sunlight onto MJCs. This unit also increases the concentrating acceptance angle to accommodate tracking errors. An MJC is attached to the head spreader followed by a heat sink to dissipate heat and lower cell temperature, as cell performance decreases at higher temperatures. A mini parabolic dish with a 15 cm diameter, 9.75 cm focal length and rim angle (θ_r) of 42^o was used as a primary reflector. A hyperbolic reflector with a 3 cm diameter was used as a secondary reflector. A tapered light pipe from TECHSPEC was used as a homogenizing rod, with overall length of 50 mm and inlet and outlet size of 4 mm x 4 mm and 12mm×12mm, respectively. The designed concentrating assembly has a maximum geometric acceptance angle of 1^o, for which a concentrated bright spot is set within the homogenizer inlet. It has a working acceptance angle of 0.3^o with zero ray loss. The reflectors were fabricated with aluminum and further covered with aluminum as a reflective coating to enhance surface quality.

Figure 1b shows another CPV system based on Fresnel lenses and a two-axis solar tracking system. A concentrating assembly utilizing a 2×2 array of Fresnel lenses at 12cm×12cm for each lens and a quartz glass homogenizer with an inlet and outlet size of 12mm×12mm and 5.5mm×5.5mm was used to concentrate sunlight onto an MJC. The Fresnel lens, with a focal length of 20 cm, focuses sunlight onto the glass homogenizer, which further guides and uniformly distributes concentrated sunlight onto the MJC. The glass homogenizer also helps to increase the concentrating assembly's acceptance angle to accommodate tracking errors. The MJC is attached to a heat sink to dissipate heat and avoid cell overheating, as it operates under high solar concentration.

The concentrating assemblies were mounted onto the frame of a two-axis solar tracking system for performance analysis. The tracking system consists of a control box and mechanical driving assembly. The two-axis solar tracking system's control box consists of an AVR ATmega128 microcontroller, stepper motor drivers, power supply and GPS module. To receive feedback from the microcontroller, it is attached to a PC through a serial port using a USB-UART module. ISP communication was used to load a tracking program to the microcontroller via PC.



(a) (b)

Figure 1 (a) Developed CPV system; (b) Cassegrain mini dish with fresnel lens

The two-axis tracker's mechanical assembly design is based upon the structural frame and driving assembly. The driving assembly consists of two worm gear assemblies, connected to two stepper motors; one for each axis of movement (i.e., zenith and azimuth). The stepper motors are moved by motor drivers, which are controlled through a tracking program written to the microcontroller. In Figure 1, a perfect bright spot at the middle of the homogenizer validates concentrating assembly designs and tracking system accuracy**.**

3. ELECTRICAL RATING METHODOLOGY

Electrical rating is a method or tool to evaluate the long-term performance of any electrical power producing renewable energy system utilizing an intermittent energy source for power input, such as solar or wind energy. Electrical rating as a value is obtained from the total power delivered by the system and is measured in terms of kWh/m^2/year. The electrical rating method can analyze the real potential of any renewable energy system, irrespective of the technology used, by comparing the total power delivered.

In this paper, the CPV system's electrical rating is determined to study long-term performance in the tropical environment of Singapore. The system was evaluated from September 2014 to March 2015. The calculated parameters and their formulations, used to analyze CPV system performance, are discussed below. Instantaneous efficiency (η_{ins}) of the CPV system was determined using Equation 1, accounting for the ratio of power input into the system in terms of DNI and power output as current and voltage output.

$$\eta_{ins} = \frac{V_c.I_c}{Ir.A_D} \times 100\ (\%) \tag{1}$$

where (V_c) and (I_c) are cell voltage and cell current obtained from the MJC, (Ir) represents the DNI received in W/m^2 and (A_D) is the total effective area of concentration. At the end of the day, total solar energy received and total electrical energy produced by the CPV system were computed by integrating power output and DNI over period of operation, which provides area under power output and DNI plots against time. Software OriginPro was used to calculate the area under the CPV power output and DNI plots. To calculate the monthly power delivered by the CPV system (E), daily total energy yields were summed up for the whole month, as noted by Equation 2.

$$E = \sum_{j=1}^{n}\left[\int_1^t (V_c.I_c)\,dt\right] = \sum_{j=1}^{n}\left[\sum_{i=1}^{t}\left(\frac{(V_c.I_c)_i-(V_c.I_c)_{i-1}}{2}\right).S\right]\left(\frac{kWh}{m^2}\right) \tag{2}$$

Terms in brackets provide daily total power delivered by the CPV system per day, accounting for time (t) in seconds for that particular day (j) of that month. Here, (S) represents the scanning time interval for data logging. Similarly, total DNI received per month (D_m) was computed using Equation 3.

$$D_m = \sum_{j=1}^{n}\left[\int_{1}^{t}(Ir)\,dt\right] = \sum_{j=1}^{n}\left[\sum_{i=1}^{t}\left(\frac{Ir_i - Ir_{i-1}}{2}\right).S\right]\left(\frac{kWh}{m^2}\right) \quad (3)$$

(Ir) represents instantaneous DNI received. The monthly average and overall average efficiency of the CPV system can now be computed using Equations 4 and 5.

$$Monthly\ Average\ Efficiency = \frac{E}{D_m} \times 100\ (\%) \quad (4)$$

$$Overall\ Average\ Efficiency = \frac{\sum E}{\sum D_m} \times 100\ (\%) \quad (5)$$

Electrical rating of CPV system can be calculated by extending the average total energy delivered by CPV system to one year period. To investigate and compare monthly performance and overall CPV system performance, the monthly and overall electrical rating can be determined using Equations 6 and 7.

$$Monthly\ Electrical\ Rating, R_{e,m} = \left(\sum_{j=1}^{n} E_i\right).\frac{n}{365}\left(\frac{kWh}{m^2.year}\right) \quad (6)$$

$$Overall\ Electrical\ Rating, R_e = \left(\sum_{j=1}^{m} E_i\right).\frac{m}{365}\left(\frac{kWh}{m^2.year}\right) \quad (7)$$

(n) represents the maximum day number of that particular month, and (m) represents the total number of days the experiment was performed. However, the CPV system only accepts beam radiations. Thus, the percentage of solar energy received in the form of beam radiation is revealed by Equation 8.

$$DNI\ Monthly\ Share = \frac{G_m}{D_m} \times 10\ (\%) \quad (8)$$

(G_m) represents the total global irradiance received in kWh/m^2. Moreover, CO_2 emissions savings for each kWh$_e$ produced can be computed using the carbon emission factor provided by the International Energy Agency (IEA). This is shown in Equation 9.

$$CO_2\ Emissions\ Saving = R_e \times 0.635\left(\frac{kg}{m^2.year}\right) \quad (9)$$

0.635 CO_2 tonnes/MWh$_e$ is the value for crude oil using the International Energy Agency equation (IEA, 2013). The value of CO_2 emissions savings depends on the carbon emissions factor, which is different for different fuels and depends on their calorific values. In this paper, the calculation is based on the carbon emissions factor for crude oil, which is provided by the International Energy Agency (IEA).

4. RESULTS AND DISCUSSION

Figure 2 depicts the monthly performance of both CPV systems in terms of monthly electrical rating and monthly average efficiency in variation with the percentage of total beam radiations received per month. The monthly electrical rating is higher for months with higher amounts of total DNI received. The electrical rating for the Fresnel lens-based CPV system is higher than the mini dish based CPV system for each month. This is because the average efficiency of the Fresnel lens CPV system is higher than the mini dish CPV system. The three best months recorded with regard to CPV system performance are September, January and February. However, for February, the total DNI received per month was higher than March. On the other hand, the average efficiency of both systems is highest for February, which reveals higher electrical ratings for both systems than for the month of March in spite of a lower DNI than March and other months. This trend can be explained from the efficiency variation of CPV systems against DNI that the CPV system's efficiency remains constant for a higher value of DNI or solar concentration; most of the DNI received in this month was higher value, which may explain the higher CPV system efficiency for February.

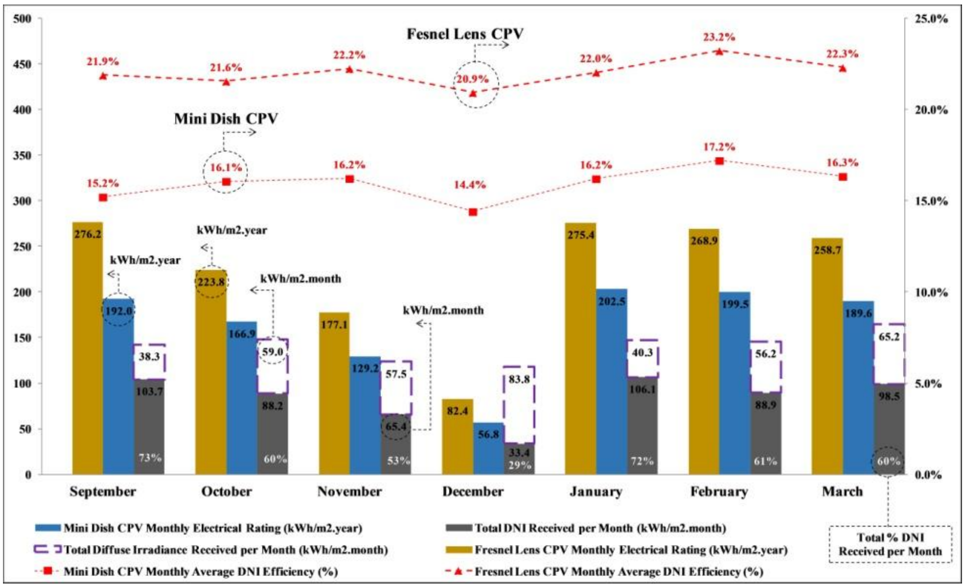
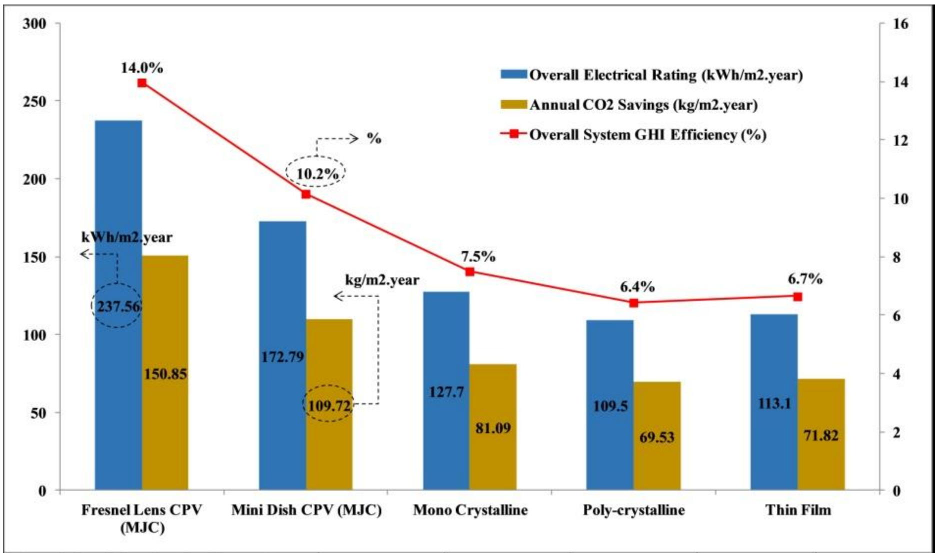


Figure 2 Monthly electrical rating and monthly average efficiency of CPV systems with the DNI received

For November and December, the lowest electrical rating was recorded as the lowest amount of total DNI received with the lowest average sunshine duration per day. In addition, the monthly average efficiency of both CPV systems is almost the same for every month except December, which had the lowest average efficiency. 20.9% and 14.4% were observed for the Fresnel lens and mini dish CPV systems respectively. This is due to extremely low beam radiation i.e. 28.5% of total solar energy, which is extremely low compared to other months.



	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

Figure 3 Overall Electrical Rating of CPV Systems Compared to Other Photovoltaic Systems and CO_2 Savings

In Figure 3, the overall electrical rating of both CPV systems is given in comparison with the electrical rating of other conventional single-junction PV systems installed in Singapore (Shahzad et al., 2013). The highest electrical rating (237.56 kWh/m^2/year) is recorded for the Fresnel lens CPV system, which is 1.86–2.17 times higher than the conventional PV systems. However, for the mini dish based CPV system, an electrical rating of 172.79 kWh/m^2/year was recorded. This is still far higher than the conventional PV systems, but it is lower than the Fresnel CPV due to lower average system efficiency. In addition, the amount of CO_2 emissions savings per year from CPV systems is another important parameter of comparison. Because of higher kWh production, Fresnel lens and mini dish CPV systems have the highest CO_2 emissions savings, at 150.85 kg/m^2/year and 109.72 kg/m^2/year respectively. This is about 1.53–2.1 times higher than a poly-crystalline system. The highest electrical rating also depicts the solar system's smaller footprint, which, because of their lower efficiency, is one of the big issue for solar energy systems. A summary of results is given in Table 1.

Table 1 Mini dish CPV system long-term performance data

Month	GHI per Month [18] G_m kWh/m^2	DNI per Month D_m kWh/m^2	Mini Dish CPV		Fresnel Lens CPV	
			Power Delivered E kWh/m^2/month	Average Efficiency %	Power Delivered E kWh/m$^{2/}$month	Average Efficiency %
September	142.04	103.75	15.78	15.2	22.70	21.9
October	147.20	88.19	14.17	16.1	19.00	21.6
November	122.97	65.44	10.62	16.2	14.55	22.2
December	117.21	33.45	4.82	14.4	7.00	20.9
January	146.37	106.10	17.20	16.2	23.39	22.0
February	145.17	88.83	15.30	17.2	20.63	23.2
March	163.73	98.52	16.10	16.3	21.97	22.3

As explained, the CPV system only accepts beam radiations, but conventional PV systems accept diffuse and beam radiations. Despite different operating conditions, all PV technologies can be analyzed at the same level using electrical rating method. The electrical rating of both CPV systems is higher than conventional PV systems, even in the tropical weather of Singapore. Moreover, from a design point of view, engineers can estimate total plant size and area requirements, as they can make fairly accurate annual power production estimations by looking at the electrical rating value. This is because overall average weather conditions remain the same for certain regions. So far, CPV system efficiency is based on the DNI received, as it can only accept beam radiations as energy input. However, efficiency of conventional single-junction PV systems is based on global irradiance, which can also accept diffuse radiations. For Singapore, the annual average total amount of solar energy received is 1,700 kWh/m^2/year (Shahzad et al., 2013). With a common playing field irrespective of beam and diffuse radiations, from an electrical rating, CPV systems are capable of producing almost double power and are twice as efficient: 14% in capturing the overall annual amount of solar energy (i.e., 1,700 kWh/m^2/year).

5. CONCLUSION

Two CPV systems based on Fresnel lens and Cassegrain mini dish arrangements were developed and analyzed. The overall electrical ratings for the Fresnel lens and mini dish CPV systems were recorded at 237.56 kWh/m^2/year and 172.79 kWh/m^2/year respectively. This electrical rating value reveals the total power output from the system in that particular region and under those weather conditions irrespective of operating conditions. Designers can estimate the CPV system's plant size and overall economic viability as the total output of 237.56 kWh/m^2/year and 172.79 kWh/m^2/year. This can be achieved from Fresnel lens and mini dish CPV systems in the tropical environment of Singapore with an operating average efficiency of 22–23% and 16–17% respectively. Moreover, an electrical rating comparison shows that CPV systems are more feasible than other conventional PV systems, as they can produce almost twice the power output in the tropical environment—although they only respond to beam radiations. The electrical rating also provides an easy solution for calculating CO_2 emissions savings; the carbon emission factor of the Fresnel lens and mini dish CPV systems have CO_2 emissions savings of 150.85 kg/m^2/year and 109.72 kg/m^2/year, respectively, which is approximately 1.5–2 times higher than conventional PV systems.

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