Performance analysis of one-axis tracking photovoltaic system with flat planar reflectors

Ryoma Yoshimori*, **Masayuki Nakayama***, **Atsushi Akisawa***
*Tokyo University Agriculture and Technology, Tokyo (Japan)

Abstract

This study examined the performance of a photovoltaic system with flat planar reflectors and south-to-north direction sun tracking system. In order to enhance sunlight collection with simple mechanism, the flat planar reflectors are connected to the solar cells alternately, which can track the sun by expansion and contraction of the system. The objectives are to find out the optimum operation of the inclination angle of the solar cell and to design the ratio of the length of the flat planar reflector and the solar cell by ray-tracing simulations. According to the simulation results, the larger the reflector is the more sunlight is collected in winter. On the other hand, in summer the shorter reflector is effective. The system with short reflector collects more sunlight and less area for installation than conventional PV system. Simulations show that the system with reflectors, which is 1.5 times longer than solar cell is the best in consideration of both concentration performance and area for installation. Its annual sunlight collection is 41 % higher and area for installation is 19 % smaller than those of conventional PV system. The experiments were conducted outside in August and September. The solar radiation intesity on the solar cell of the system was higher than that of conventional PV system throughout the experiment period by 40 - 50 %. Power output of the system was larger than that of conventional PV system by at most 50 % on August 24th and 20 % on September 14th. Non-uniformity of the reflected sunlight affects the output of the system.

Keywords: Low concentrating PV system, Flat-planar mirrors, One-axis tracking, Ray-tracing simulation

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1. Introduction

Renewable energies are expected to increase the installation to reduce the consumption of fossil fuels. Photovoltaic (PV) system is the most widely spread energy source using renewable energy all over the world. The main problem of the PV system is still more expensive than conventional electricity. This is caused by the cost of semi-conductors which is the most expensive part in the PV system, and low conversion efficiency. Conventional Si-based PV cells convert approximately 20 % of sunlight into electricity [1–3].

One of the effective measures to reduce the cost is concentrating photovoltaic (CPV) system, which enhance the sunlight on the PV cells. The CPV system reduces the use of PV cells for given power demand. Inexpensive optical devices such as lenses and mirrors are used for concentrator of the CPV system. Sunlight hits the earth surface in the forms of direct and diffuse radiations and their share in total received sunlight depends on the local climate, weather and sky conditions such as pollutants in the air and clouds. Sun tracking is required as concentrators only respond to direct radiation [4].

CPV systems are crassified with their concentrating ratio namely high and low concentration PV systems [5, 6].

High concentration PV (HCPV) system concentrates 500 suns or higher and it is usually constituted by multi-junction cells, which efficiency is reported over 40 % [7, 8]. Yuan-Hsiang Zou obtained effciency of 28.6 % with 800 suns concentrator and PV cell with the effciency of 35.5 % [10]. One of the disadvantages of this technology is the system needs highly accurate tracking system. The optical efficiency of HCPV system using Fresnel lenses, which concentrate approximately 150 suns, is about 20 % lower than its peak when the incident angle is 0.5 degree, reported by Dianhong Li [11]. The other disadvantage is that concentrators only respond to the direct sunlight. When the weather conditon changes from sunny to cloudy, the energy yield significantly decreases. HCPV system is suitable for the places like desert area, where almost all the days are sunny for whole year.

On the other hand, low concentration PV (LCPV) system concentrates up to 40 suns. The concentrating ratio is lower than HCPV system, however conventional silicon solar cells, which made for 1 sun, can be used for LCPV systems. The sollar cells are used under the concentration of 10 suns or below [5, 7, 12]. LCPV systems have less demand on tracking accuracy than HCPV systems. In the Giorgio Grasso's report [13], the prism-coupled compound parabola system is designed with 5 suns concentration. The optical efficiency

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does not decrease until incident angle is changed 15 degree in north and south direction. Consequently, LCPV system can be a low-cost solution to increase the density of the sunlight and to reduce the use of solar cells. For LCPV systems, compound parabolic reflectors, V-trough reflectors or flat planar reflectors are used [14–16]. In particular, the flat planar reflectors have the advantage of being inexpensive compared with both V-trough and parabolic reflectors [17].

The sun always changes its position in the sky. The location depends on the longtitude and the latitude, the date and the time. To harvest energy effectively PV modules and mirrors should be placed on the solar tracker. However this two-axis tracking system could be complicated in terms of structure and causes to be expensive. One-axis tracking systems, which moves north-south direction or west-east direction, can have more simple structure.

In this paper, a one-axis tracking LCPV system with flat planar reflectors is proposed. The flat planar reflectors are connected to solar cells alternately. This system enhances the sunlight to the solar cells by the reflectors and tracking when the system expands or contracts to control the inclination angles. Two main activities were conducted in this study. One is ray-tracing simulation described in section 3 which predicts the energy yield and evaluates the performance of the systems with different length of reflectors. It is one of the objectives to find out the optimum operation of the inclination angles of the solar cells and the flat planar reflectors. The other objective is the experiment investigation for confirming the performance under the real sunlight which is described in section 4. The optimum system model and the operation derived in section 3 was used in the experiments.

2. One-axis tracking LCPV system with flat planar reflectors

The one-axis tracking LCPV system with flat planar reflectors is represented by Fig.1 where solar cells are inclined at angle θ and the flat planar reflectors are declined at angle ϕ. The solar cells and the flat planar reflectors are connected each other in north and south direction. The inclination angle of the flat planar reflectors move in response to that of the solar cells. The equation of the relation of both angles is defined by Eq.(1). In this study, the inclination angle of the solar cells is controlled. This structure allows one driving source to controll multiple units. A unit means a combination of one solar cell and one flat planar reflector. There is a design parameter R which is the ratio of the length of the solar cell L_{PV} and the flat planar reflector L_m as defined by Eq.(2).

$$L_{PV} \cdot sin\theta = L_m \cdot sin\phi \tag{1}$$

$$R = L_m / L_{PV} \tag{2}$$

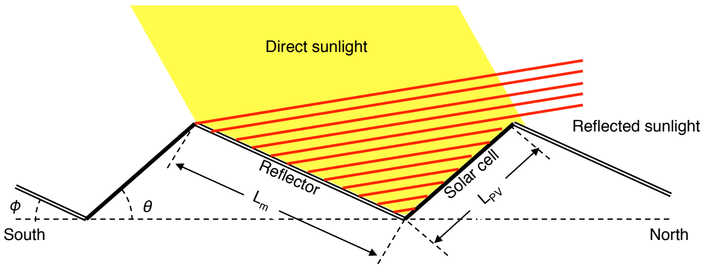


Fig. 1: Geometric scheme of the one-axis tracking LCPV system with flat planar reflectors

3. Ray-tracing simulaion for estimating sunlight intake

3. 1. Simulation conditions

Ray-tracing simulation was conducted as Fig.2 using *Solar Emulator* of *Tracepro* [18]. The sun positions were calculated automatically from the latitude and the longtitude of the system placed, date and time. To model the sunlight parallel light source is assumed. The power flux is set to 1067 W/m^2 considering atmospheric transmittance of whole year average. The weather in the simulation is all cloudlessness and direct radiation was considered while scattered radiation was neglected. The wavelength of sunlight spectrum was set to 550 nm since the software does not provide a continuous sunlight spectrum. The hourly data of solar radiation from 6:00 to 18:00 in Tokyo were used in the simulations.

The solar cell was set to perfect absorber to evaluate the sunlight intake of the system that is the amount of the solar radiation collected on the solar cell. The reflection ratio of flat planar reflector was set to 0.95. The resolution of inclination angle was set to 10 degree from 10 degree to 80 degree and it was adjusted to optimum angle every one hour. The parameter *R* was selected from 1.0 to 3.5.

The concentration performances were calculated in the simulations. The monthly and annual concentration are expressed by the ratio of the proposed system to the conventional PV system of which PV system cells are fixed with the inclination angle of 35 degree. The seasonal, monthly annual concentration performances are reported in the following subsections. Moreover the areas of solar cells, mirrors and the land for the installation are also discussed to compare the performances.

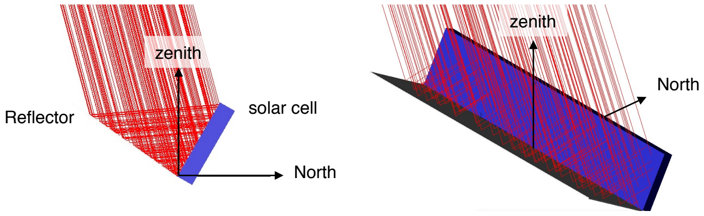


Fig. 2: Example of the ray-tracing simulation of the one-axis tracking LCPV system with the R = 1.5, θ = 60 degree on June 20th

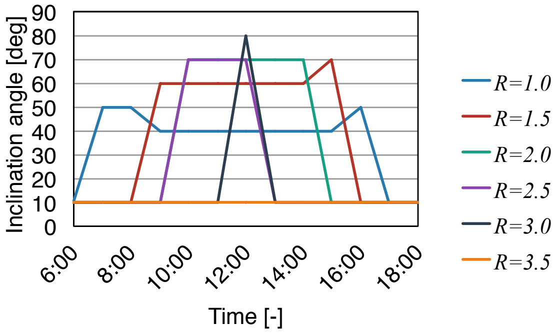
3. 2. Seasonal concentration performance

The seasonal optimum inclination angle θ and concetration performances are represented in Fig.3. The representative dates of the seasons were selected as June 20th for summer, September 20th for fall and December 20th for winter. The optimum inclination angles and concentration performance of March 20th are similar to those of September 20th therefore they are left out on this paper.

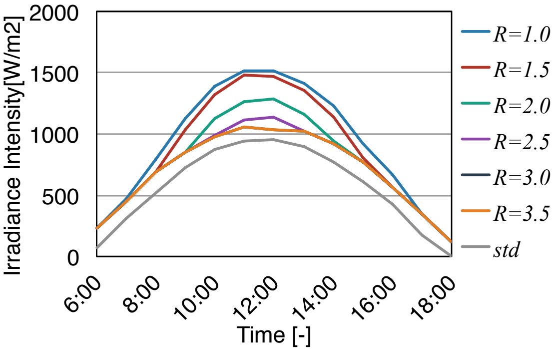
In summer when the sun height is high, the systems with smaller *R* obtained high concentration performance ratios as Fig.4(a) shows. The system with R = 1.0 has the highest concentration performance. It is about 60 % higher than that of conventional system named as *std* in the graphs. The angles of the PV cells and the reflectors are relatively large. The more reflected sunlight hits the solar cells. On the other hand, The systems with large *R* such as R =3.0 and 3.5 give low concentration performance. The angles of the PV cells and the reflectors are small. Since most of reflected sunlight goes to the sky, the concentration performance of the systems with large *R* are low.

In middle season such as spring and fall show similar results. The results of fall are shown in Fig.3(b) and Fig.4(b). The concentration performance of each system is higher than the conventional system by 40 % to 60 %. All systems obtained reflected sunlight compared with the case of summer.

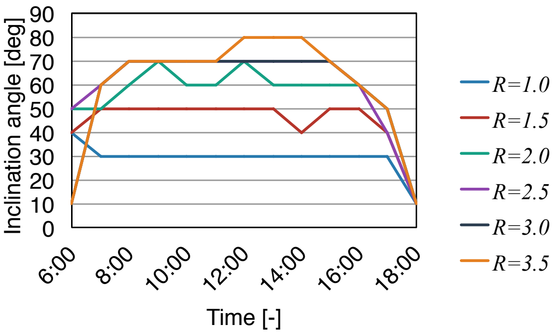
In winter when the sun height is low, the systems with larger *R* obtain high concentration performance as Fig.4(c) shows. The system with R = 3.5 has the highest concentration performance. It was twice as high as that of the conventional system. The larger area of the reflectors is advantageous to collect sunlight with low incident angle in winter. On the other hand, inclination angle of the PV cells with smaller *R* can not be large because there is a risk that the system makes the shade on the solar cells. Since the system with R = 1.0 makes shade on the solar cells, the concentration performance is lower than that of the conventional system.



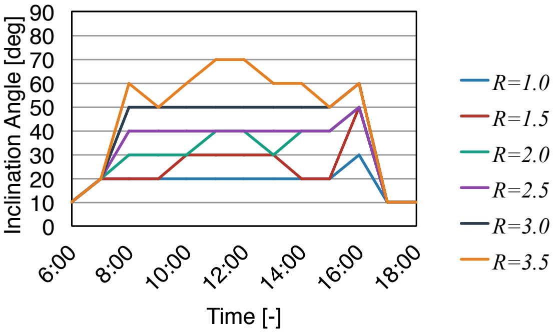
(a) June 20th



(a) June 20th

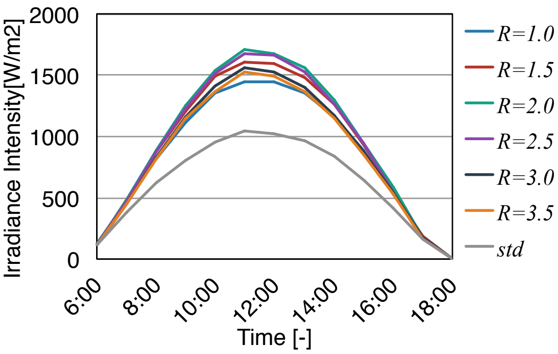


(b) September 20th

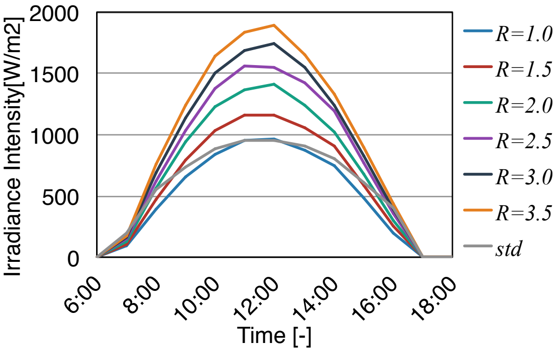


(c) December 20th

Fig. 3: Optimum angle of PV cells



(b) September 20th



(c) December 20th

Fig. 4: Concentration performance

3. 3. Monthly and annual concentration performance

Monthly concentration performances of the proposed system with various *R* are represented in Fig.5. Here the improvement ratio is defined so that the performance of the proposed system is normalized with that of the conventional system. When the ratio is higher than 1.0, the proposed system works better. The ratios were calculated using total collected sunlight when the hourly inclination angle of the solar cells was operated optimally. In summer season, the concentration performance ratios of the systems with smaller *R* are higher. The system with R = 1.0 is the highest in June by 60 % higher than the conventional system. The system with R = 1.5 shows good performance from April to September by 50 % or higher than the conventional system. In winter season, the systems with larger *R* work effectively. The system with R = 3.5 shows relatively high performance from November to January by about 70 % as high as the conventional system. In December, the concentration performance ratio of the system with R = 1.0 is lower than that of the conventional PV system. As already mentioned in the previous subsection, the system makes shade on the solar cells.

Annual concentration performance ratios of the proposed system are represented in Fig.6. The system with R = 2.5 shows the highest performance by 44 % higher than the conventional PV system. When *R* is above 1.5, the system has stably high performance than the conventional PV system by 40 to 44 %. The system with R = 1.0 decreases the improvement. The result implies that the system should be designed with *R* more than 1.5.

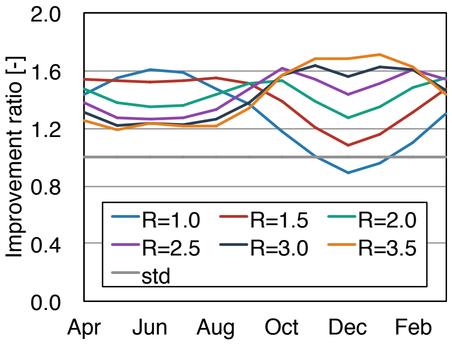


Fig. 5: Monthly concentration performance of the proposed system with various R normalized with the performance of the conventional PV system

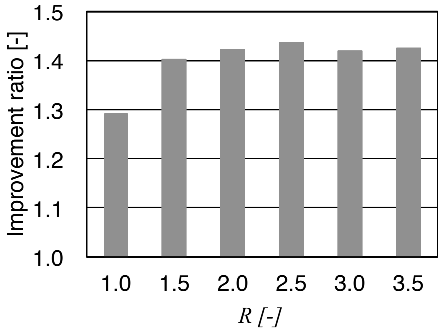


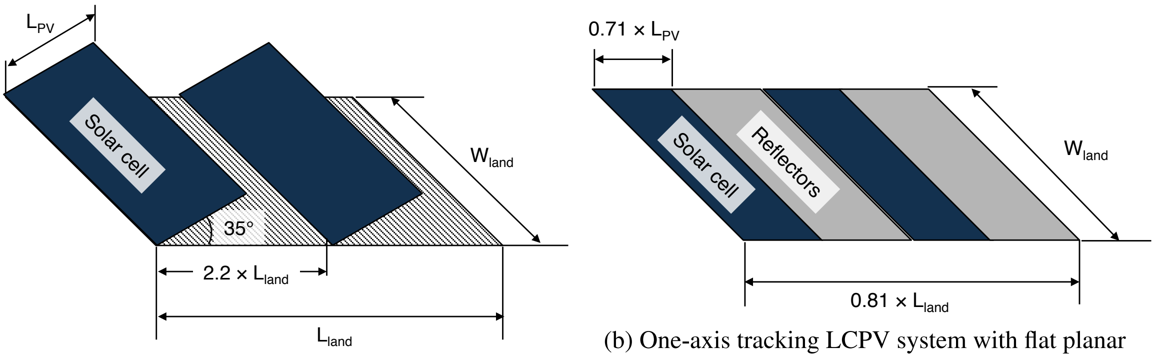
Fig. 6: Effect of R on the annual concentration performance of the proposed system compared with the conventional PV system

3. 4. Efficiency of land use of the installation

The comparison of land use for the systems is disscussed in this subsection. The size of the proposed system can be bigger than the conventional PV system because of additional reflectors. The conventional PV system is installed with a rule that is avoiding the PV array making shade on the other PV array behind [19]. It means avoiding shade when between 9 a.m. and 15 p.m. in Japan. For example, PV array with 1 m in length at 35 degree of inclination angle needs 2.2 m of distance including the gap between 2 arrays. On the other hand, the length of the land use for installation the proposed system is simply the sum of PV cell and the reflector, where the system is flat. For example, one unit of the system with $R = 1.5$ needs 2.5 m, where 1.0 m is for solar cell and 1.5 m for the reflector.

Here the efficiency of land use was defined as the land area needed to capture a given amount of solar irradiation for one year. The comaprison index was made so that the land area for the proposed system was divided by that of the conventional system. The conventional system uses 45 % of the land area for the solar cells. The system with $R = 1.0$ needs the smallest land area. It is 30 % smaller than that of the conventional PV system. The area of solar cells is 23 % as small as that of the conventional system. The system with $R = 1.5$ can make the land area smaller than conventional PV system by 20 %. Moreover the area of solar cells is smaller than that of conventional system by 30 % as shown in Fig.8. It is obvious that the wider the reflectors are the larger becomes the land area for the proposed systems. The systems with R over 1.5 use almost the same area of the solar cells while the area of the reflctors increases gradually.

In regard to the area of land, the systems with $R = 1.0$ and 1.5 have advantage. However, it should be noted that the performance of the system with $R = 1.0$ in winter is less than that of the conventional system due to the shade. From the viewpoints of monthly and annual performance, the system with $R = 1.5$ will be the best choice. As Fig.8 the area for system installation was 20 % smaller than the conventional PV system and cell area was 30 % smaller.



(a) Conventional system

(b) One-axis tracking LCPV system with flat planar reflectors $R = 1.5$

Fig. 7: View of the land area

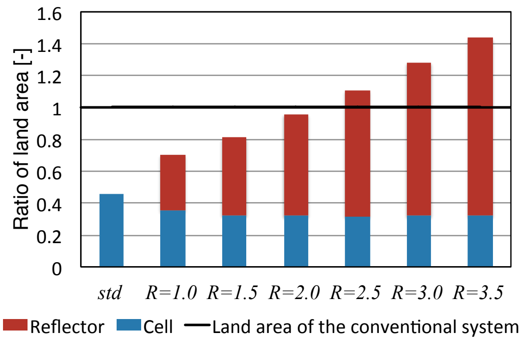


Fig. 8: The areas of solar cells, reflectors and land use for system instllation with a given intake of solar irradiation

4. Experiments for evaluating system performance

4. 1. Experimental setup

Based on simulation analysis, the system with R = 1.5 was selected to be build for the actual measurement of the perfromance by experiments. Figure 9 shows the experimental setup of the system with R = 1.5 which connects 2 solar panels and 2 reflectors. These solar panels and the reflectors can change their inclination angles at the same time by linear guide. The solar panels consist of single crystalline silicon. The single panel has the nominal maximun output of 5.5 W. The length of the solar panel is 100 mm and the width is 500 mm. The length of the mirror is 150 mm and the width is 500 mm. Cell A in Fig.9 measures the output of the conventional PV system by setting the inclination angle of Cell A to 35 degree while Cell B measures the output of the system with R = 1.5 by operating optimum angles calculated by the simulations. The solar radiation intensity on the solar panels was measured by a pyranometer. The pyranometer changed its position depending on the measurement. When measuring the solar radiation intensity of the conventional PV system, the pyranometer is set in front of the Cell A. On the other hand, when measuring the system with R = 1.5, the pyranometer is set behind the rear reflector as shown Fig.9. The output of the solar panels are measured by an I-V checker (EKO INSTRUMENTS CO., LTD, MP-170).

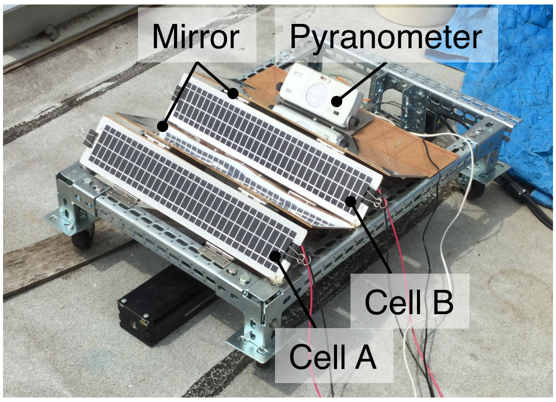


Fig. 9: The experimental setup of the system with R = 1.5

4. 2. Methods of experiment

Experiments were held with the following procedure. The weather conditions were sunny or partly cloudy.

Measurement of conventional PV system

1) Setting the inclination angle of Cell A to 35 degree and locating the pyranometer in front of the Cell A.
2) Measuring the solar radiation intensity by the pyranometer and the output by the I-V checker.

Measurement of the proposed system

3) Setting the inclination angle of Cell B to a specified degree and locating the pyranometer behind the rear reflector.

4) Measuring the radiation intensity by the pyranometer and the output by the I-V checker. The pyranometer detects the direct sunlight from the sun and reflected sunlight from the reflector.

This procedure was repeated every 20 minutes during the measurement period. Time lags occurred the measurements of Cell A and Cell B. The solar radiation intensity sometimes changes suddenly during the time lag.

The performances of partly cloudy day and sunny day were observed. The optimum angle of the system on these dates are shown in Table.1.

Table. 1: Operation of the inclination angles of the system with R =1.5

Weather	Time	9:00	10:00	11:00	12:00	13:00	14:00	15:00
Partly cloudy	Aug 24th	60 °	60 °	50 °	50 °	50 °	60 °	60 °
Sunny	Sep 14th	50 °	50 °	50 °	50 °	50 °	50 °	50 °

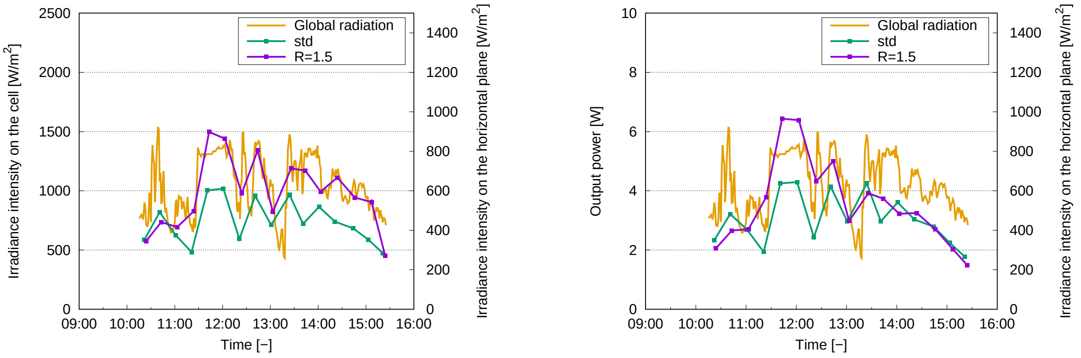
4. 3. Results of the experiments

The experiments were conducted outside in August and September. The results of August 24th, which was partly cloudy and September 14th, which was sunny, are reported in this paper.

Figure 10 (a) represents the solar radiation intensity on each of the solar panels on the 24th of August. The weather condition was partly cloudy therefore global solar radiation intensity was up and down with short steps. The solar radiation intensity on the solar cell of the system with R = 1.5 was higher than that of the conventional PV system almost every time, especially it was about 50 % higher around noon. As seen in Fig.10 (b), the output of the solar panels were in accordance with the solar radiation intensity from 11:00 until 13:00. In contrast the effect was not significant after 13:00.

Figure 11 represents the measurement results on the 14th of September which was sunny day. The solar radiation intensity on the solar panel of the system with R = 1.5 was about 50 % higher than that of the conventional PV system every time. However the output of the system with R = 1.5 was higher than that of conventional PV system only by 10 to 20 % around noon. It was found that the solar concentration did not enhance the power generation significantly.

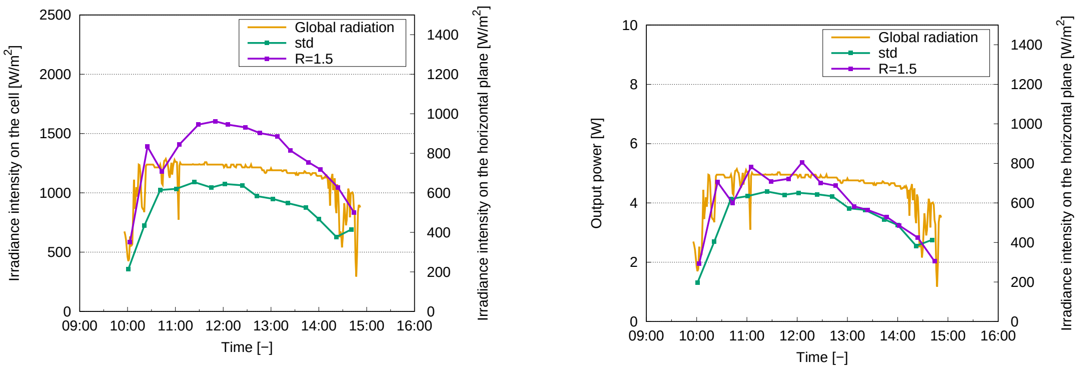
In order to understand what caused the insufficient performance of the proposed system, it was observed how the mirror concentrated the irradiation on the solar panel. Fig.12 (a) to (e) show the reflected sunlight distribution on the solar panel of the system with R = 1.5. As can be seen in the graphs, there existed non-uniform distribution which changed time to time. Fig.12 (c) shows that the illuminated area was largest among the samples. The non-uniformity is considered to degrade the power generation as discussed by Hasan et al. [20]. The results suggest that the proposed system needs to employ suitable PV panels which can work even with non-uniform irradiation on it. The pyranometer measures the solar radiation intensity of the area the reflected sunlight hit.



(a) Solar radiation intensity of two PV panels

(b) Output of two PV panels

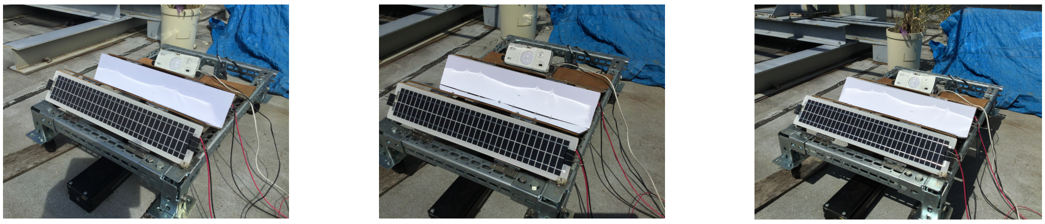
Fig. 10: Measurements on August 24th



(a) Solar radiation intensity of two PV panels

(b) Output of two PV panels

Fig. 11: Measurements on September 14th



(a) 10:00

(b) 11:00

(c) 12:00

(d) 13:00

(e) 14:00

Fig. 12: Sunlight distribution on the solar panel of the system with $R = 1.5$ on September 14th

5. Conclusion

The one-axis tracking LCPV system with flat planar reflectors was examined in this study. The performance was analysed by ray-tracing simulations and also investigated by experiments.

It was found from the simulations that the length of the reflector would affect the seasonal concentration performance of the proposed systems. The system with small reflectors shows high concentration performance in summer while the system with large reflectors gives high concentration performance in winter. The system with $R = 2.5$ showed the heighest annual concentraion performance, which is 44 % higher than that of the conventional PV system. The system with $R = 1.5$ gives similar performance of 41 % even though the area of the reflectors are three-fifth of the system with $R = 2.5$.

Regarding the area for system installation, the systems with $R = 1.0$, 1.5 or 2.0 need smaller area than the conventional PV system. Although the system with $R = 1.0$ shows the best result, its concentration performance is lower than the conventional PV system in winter. Consequently the system with $R = 1.5$ is considered the best design under the assumed operating conditions. The area of the installation and the solar panels of the system are 20 % and 30 % smaller than the conventional PV system respectively.

The system with $R = 1.5$ was built as an experiment setup. Experiments were conducted under the weather of partly cloudy and sunny in August and September. The solar radiation intesity on the solar panel of the system with $R = 1.5$ was successfully enhanced by the reflector up to 50 % at the maximum. In contrast, the output power was not improved so much as the concentration. It was considered to be caused by the non-uniform distribution of the solar illumination on the solar panel. The results suggest that suitable PV panels are necessary to boost the output even with non-uniform illumination.

Nomenclature

L_m	The length of the flat planar reflrctor
L_{land}	The length of the land for installation of the conventional PV system
L_{PV}	The length of the solar cell
R	The ratio of the length of the solar cell and flat planar
W_{land}	The width of the land for installation of the conventional PV system
θ	The inclination angle of the solar cell
ϕ	The inclination angle of the flat planar reflector reflector

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