AN ACCURACY OF THE SV METHOD FOR EVALUATED SHADING LOSSES
~ COMPARED WITH RESULTS USING THE FISH-EYE-PHOTOGRAM METHOD ~

Takashi OOZEKI[1], Kenji OTANI[2], and Kosuke KUROKAWA[1]
1 Kosuke KUROKAWA Lab., Tokyo University of Agriculture and Technology,
2-24-16 Naka-cho, Koganei, Tokyo, 184-8588 Japan Phone/Fax: +81-42-388-7445, E-mail: oozeki@cc.tuat.ac.jp
2 National institute of Advanced Industrial Science and Technology
AIST Tsukuba Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568 Japan

ABSTRACT: A shading loss is one of significant losses in a PV system. The sophisticated verification method (SV method) has been developed as an evaluation method of PV systems. The method can identify system losses by using utilizing hourly monitored data. In the method, the extracting method of maximum data has been proposed to estimate the shading loss. This paper describes the accuracy of the SV method in term of shading losses by comparing with the fish-eye photograph analysis, which is one of the responsible estimation methods for shading losses. Eight PV systems were evaluated by both methods, and errors between two methods were within 1.0% of MBE and RMSE in almost all systems. Moreover, after correlated by the shading losses, array output was proportional to irradiation clearly. Those results suggest that the shading detected in the SV method is useful for the evaluation method of PV systems.
Keywords: Evaluation, PV system, shading

1 Backgrounds and Objective

The rapid growth and expansion of grid-connected photovoltaic (PV) systems utilization is significantly beneficial to the mitigation of environmental issues. Even though they are known as the maintenance free generation, PV systems have to be monitored and evaluated their output energy since certain troubles have been reported. In fact, some PV systems could not generate energy as much as they are expected - shading effect around buildings and trees, the failure of system rating, the repression of output energy by over voltage control, and the failure of construction, and so on. Therefore, an evaluation method for PV systems seems to be necessary. In our laboratory, the sophisticated verification (SV) method [1], which is the evaluation method for PV systems, has been developed. The method can estimate system losses by using a few utilized monitoring data items despite of numerous kinds of losses, which seem not to be measured easily. In particular, it is difficult to identify shading losses. The purpose is to confirm the accuracy of shading losses estimated by the SV method, and the paper describes to compare with the fish-eye photographs analysis.

2 The SV Method

The SV method can estimate system losses between irradiation energy (optical energy) and system electricity output power (AC power). The method needs typical four monitored data such as in-plane irradiation data, cell junction temperature, array output power, and system output power, and allocates system losses to the part of the total system loss. In the latest version of the SV method, classifiable characteristics of PV systems are eight factors: shading losses, optical losses, losses by load mismatching, temperature effect on module efficiency, power conditioner standby losses, power conditioner efficiency, DC circuit losses, and the other losses which reduce the fundamental system performance, for instance; soil on modules, depleted modules, and the erroneous system rate.

2.1 Procedure to estimate the shading effect in the SV method

The SV method assumes that the shading effect is caused by some obstructions, the tree and building, but shading in a short time caused by a cloud and a bird is excluded. In addition, the shadow is classified three types as shown in Fig. 1. One of them is named “partial shading” and means that shadow exists on a part of PV array surface, but not on a radiometer. The second one is named “full shading” means that shadow covers both of PV array surface and a radiometer. Full shading includes the shadow by a hill may be included “full shading”. The other one is that shadow exists on a radiometer, but not on a PV system. That case is named by “faked shading”, and the effect of that should be compensated by a certain method before evaluating. In principle sense, “partial shading” is determined to be the shading loss of PV systems.

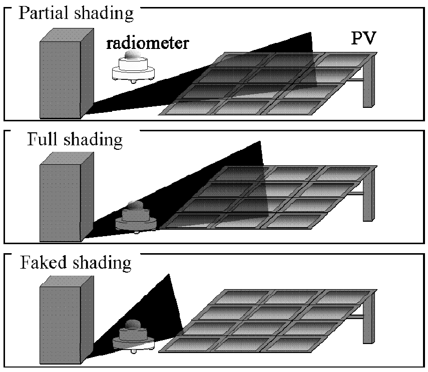

Figure 1: Types of shading

In the SV method, the extracting maximum data was proposed to detecting the shading effect. For example of irradiation, Fig. 2 illustrates all the hourly irradiation data for a specific month and each maximum point, which is taken from each time zone. Note that the average of top three data is defined as maximum point so far. The extracted data indicates to be the profiles of a clear day. Moreover, if shading is assumed to exist every day almost in the same way during the month, maximum values for a specific hour cannot reach the level of theoretical data of a clear day. Therefore, a certain level of dip from the theoretical clear day curve can be easily determined to be the shading effect.

By using the extracted method, procedures of detecting shading effect of the PV system are two step processes as followings;

- A daily irradiance profile on a clear day is formulated for a specific month by utilizing hourly irradiation data for the month.
- Assuming that shading effect does not vary so much during as same month, formulated pattern includes shadows on a clear day apparently.

In first step, the characteristic of irradiation on a clear day was obtained by using the extracted maximum data of irradiation (H_{Agmax}) as shown in Fig. 2. However, it may include the shading effect according to full shading. Therefore, the pattern of theoretical irradiation of clear-day is approximated by using the extracted data in order to remove the full shading effect.

Global irradiation consists of direct irradiation and diffuse irradiation as defined by Equation (1). The model of Burgur [2] was one of common model as the estimation of direct irradiatin, which is difined by Equation (2). In contract, there are some theoritical models of diffuse irradiation.The model of Berlage [3] was developed assuming ideal Rayleigh scattering, and is one of the most famous models in the world. However, Nagata described the model of Berlage which uses the value smaller than the actual data in Japan, and the model of Nagata [4] assumes scattering of the direct irradiance in the air and reflection from the ground, and determined parameters of Equation (3) by using monitored data in Japan. In the SV method, the theoretical model applies to the model of Nagata. Moreover, the convertion model of inclined-irradiance applies the model of Perez, which is one of the most utilization model in the world.

The envelope of theoritical irradiation (H_{Agth}) is approximated in such a way that estimated data through the top second of the extracted maximum data by changing the atmospheric transmittance in the model of theoretical irradiation as shown in Fig. 3. The reason of the top second data is that diffuse irradiation increases extremely rapidly at the edge of cloud and over the level of a clear-day data in some case.

$$h_g = h_b + h_d \quad (1)$$

$$h_b = h_{go} \cdot \tau^m \quad (2)$$

$$h_d = h_{go} \cdot S \frac{D \cdot (1-\tau^m) + \rho \cdot W \cdot \tau^m}{1 - \rho \cdot S \cdot W} \quad (3)$$

$$D = 0.5 + (0.4 - 0.3 \cdot \tau) \cdot \cos\theta_Z \ , \ W = 085 \cdot \tau \cdot (1-\tau) \ ,$$
$$S = 0.6 + 0.4 \cdot \tau$$

Where small latter is hourly data.

h_g	: global irradiaton	[kWh/m^2]
h_b	: direct irrdiaton	[kWh/m^2]
h_d	: diffuse irradation	[kWh/m^2]
h_{go}	: ex-territorial global irradiation	[kWh/m^2]
τ	: atmosphric transmttance	[-]
m	: air mass	[-]
θ_Z	: zenith angle	[deg.]

Coincidentally, the same kind of clear-day curve including shadow an also be formed by using array output power data (E_{Amax}), which are corrected by module temperature. The clear-sky power pattern consists of partial shading and full shading as shown in Fig. 4. The array output data may also be additionally affected by so-called mismatch effect. It is naturally omitted by the extraction of hourly maximum values because the mismatch hardly occurs in a clear day. The array output performance is determined by Equation (4). The Array performance ratio (K_A) includes many kinds of losses, but the extracted maximum data ignore losses exception of shading and losses proportional to irradiation such as soil on modules, depleted modules, and the erroneous system rate. In addition, the theoretical array output (E_{Ath}) can be defined by Equation (5) because it should remove the shading effect, and remaining losses ratio are defined as K_X. E_{Ath} is estimated by changing the value of K_X in such a way as to cover the E_{Amax} as shown in Fig. 4, in similar method to obtain H_{Agth}.

$$E_{Amax} = K_A \cdot P_{AS} \cdot H_{Agmax} / G_S \quad (4)$$

$$E_{Ath} = K_X \cdot P_{AS} \cdot H_{Agth} / G_S \quad (5)$$

P_{AS}:	standard array output rate	[kW]
G_S:	standard irradiance	[kW/m^2]

The shading ratio each hour is calculated by equation (6) as following assumption; the diffused component on a clear-sky is assumed 20 % of global irradiation according to a known model in Japan, and the shading effect mainly influence on direct irradiation (refer to Fig. 5).

$$\Gamma_{HS} = \frac{E_{A\max} - 0.2 \cdot E_{Ath}}{(1-0.2) \cdot E_{Ath}} \quad (6)$$

(1.0 is corresponded to non shading)

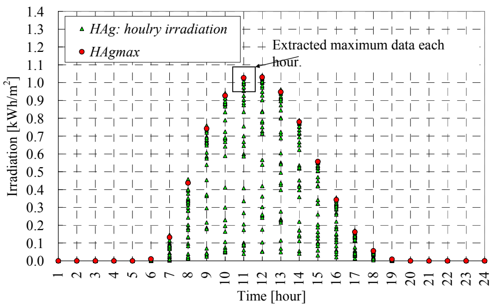

Figure 2: The extracting of maximum data; an example of irradiatin

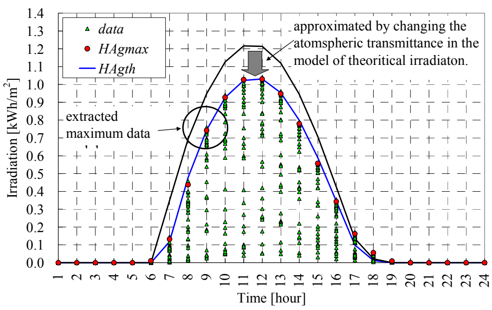

Figure 3: Approximation of the theoritical irradiation

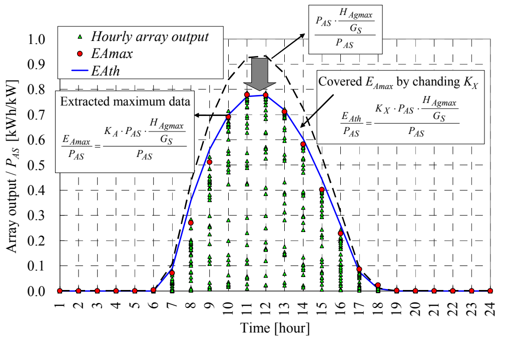

Figure 4: The extracted array output data and Approximation of the theoritical array output data

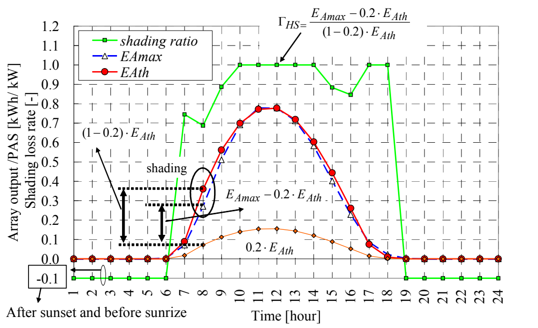

Figure 5: Monthly shading loss rate each hour

Equation (7) indicates to calculate the hourly shading loss (l_{HS}). The direct irradiation is estimated by the conversion model of global to diffuse irradiating such as the model of Erbs.

$$l_{HS} = h_{Ab} \cdot P_{AS} \cdot (1 - \gamma_{HS}) \qquad (7)$$

3 Methodology of estimation shading effect by using the fish-eye photographs analysis.

Shading losses analysis using fish-eye photographs have been also developed by authors' group in order to identify with shading factor [5]. Fish-eye photographs are useful to estimate a shading area and a shape. For example, pictures of Fig 7 are taken on the PV module at the site as shown in Fig. 6. The PV system has the obstacle, the own house, toward the east side. Analyzing the fish-eye photographs with sun tracks, the shading is easily observed for two or three hours from sunrise. The shading rate at any time can be calculated each module. In this paper, the shading ratio was calculated by the average of the ratio at all modules.

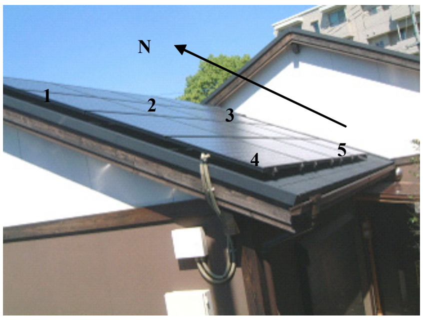

Figure. 6 overview of the PV system with the obstacle

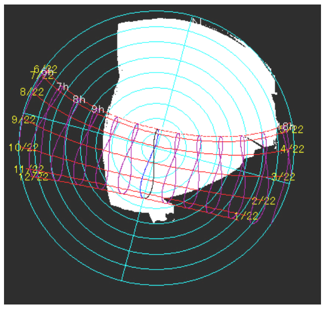

Figure 7: An example of Fish-eye photographs with sun tracks

4 Monitored data and the picture of fish-eye

Monitored data were obtained by 8 residential PV systems in the field. Table I shows site specifications of them. Monitored data were hourly data which averaged 2 sec sampling data. The items of measuring data were inclined plane irradiation, PV array output, PV system output, and module temperature.

Moreover, fish-eye photographs were taken from 1 to 14 pictures in a system. In almost all system, it was taken at four comers of the system, but only one picture can be taken in two systems of all due to the structure of roof.

site	longitude	latitude	P_{AS}	tilt angle	azimuth angle	monitoring term	pictures
	deg.	deg.	kW	deg.	deg.		
A	130.40	33.15	4.03	22	20	2000/10-2003/3	6
B	131.38	33.26	3.34	22	-30	2000/10-2003/3	7
C	131.50	33.29	3.6	20	0	2000/10-2003/3	7
D	130.50	33.01	3	21.5	3	2001/4-2004/3	1
E	129.96	33.26	3.51	25	10	2001/4-2004/3	6
F	130.62	33.31	3	24	13	2001/4-2004/3	6
G	131.40	31.91	5.23	24.22	-50	2001/10-2004/9	14
H	130.84	33.74	4.43	30.96	0	2001/10-2004/9	1

Azimuth: south is 0, east 90, and west -90)

Table I: Site specifications

5 Comparing results between the SV method and the fish-eye photographs analysis.

Equation (8) is determined to be monthly shading loss ratio (λ_{HS}), which are the parentage of monthly shading loss (L_{HS}) accounted for the input energy.

$$\lambda_{HS} = \frac{L_{HS}}{P_{AS} \cdot \frac{H_{Ag}}{G_S}} \qquad (8)$$

Fig. 8 shows the box chart of the error of the shading loss ratio between the SV method and the fish-eye photographs analysis. In the figure, the bottom of box is the first quartile (25 % points), and the top of box is the third quartile (75 %). The line in the box is the middle of data, and a square in the box is the average of data. Lines from the box indicate 5 % data points and 95 % data points respectively. The max and minima data also are potted by multiple marks. In addition, Table II demonstrates results of mean bias error (MBE) and the root mean square error (RMSE).

Almost all errors are with in +-1 % as shown by the result of MBE and RMSE. Fig. 9 demonstrates an example of shading losses at site H. The figure shows the correlation diagram between irradiation and array output. As for the relation of that, plots are dropped from proportional agminated data the line if there is a shadow on PV array as shown in Fig. 9. Additionally, the array output added shading losses estimated by the SV method is drawn in Fig. 9. After corrected data, dropped plots are disappeared, and the plots are included in proportional agminated data. The accuracy of shading losses detection, both of time and level, was evidenced by those results.

However, the result of site A is exception and RMSE are over -2%. Fig. 10 is illustrated an example result of site A as well as Fig. 9. In this figure, shading losses estimated by both of the SV method and fish-eye photograph analysis were drawn. It seems that there is no shading effect by the relation between irradiation and array output, but the fish-eye photograph analysis detected the shading effect and estimated excessive shading losses as shown by Fig. 10. In contrast, the SV method evaluated without shading effects. Fig. 11 is the fish-eye photograph taken in 30th June at Site A. The picture was used to analyze in this case. According to the analysis, the tree may cast a shadow at afternoon in winter, but leaves of the tree would fall in winter. The fish-eye analysis, therefore, is too much to estimate the shading effect in that case. In fact, results of MBE and RMSE from March to September are -0.46 and 0.85 % respectively.

6 Conclusions

To evidence the accuracy of the shading loss by using the SV method, evaluated result was compared with the fish-eye photographs analysis. As a result, MBE and RMSE were within +-1.0%. Moreover, after correlated by the shading losses, array output was proportional to irradiation clearly. Those results suggest that the shading detected in the SV method is useful for the evaluation method of PV system.

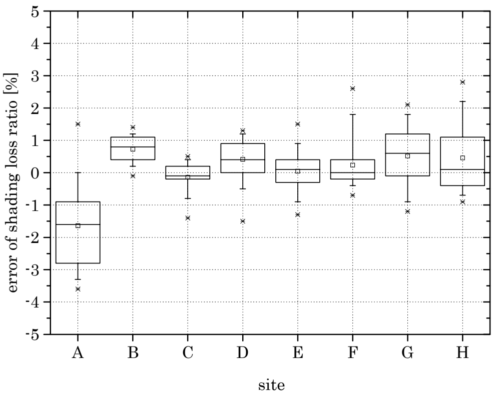

Figure 8: Error of shading loss ratio

Site	Number	MBE	RMSE
A	28	-1.81	2.23
B	20	0.73	0.84
C	23	-0.11	0.47
D	29	0.48	0.83
E	19	-0.25	0.9
F	29	0.16	0.77
G	30	0.39	0.86
H	24	0.39	1.05

Table II: Error of shading loss ratio

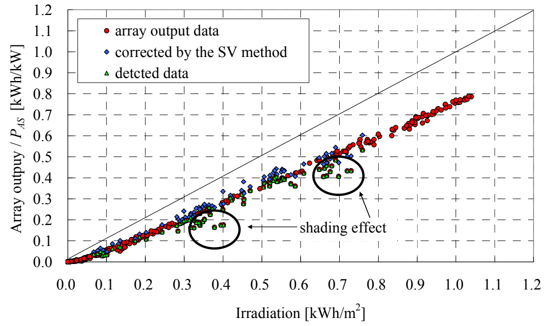

Figure 9: Array output vs irradiation after compasanted shading losses estimated by the SV method at 2004/3 (Site H)

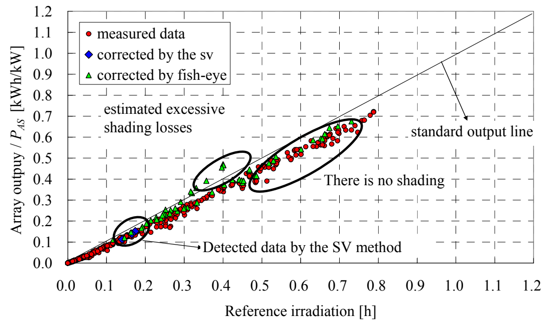

Figure 10: Array output vs irradiation after compasanted shading losses at 2002/12 (Site A)

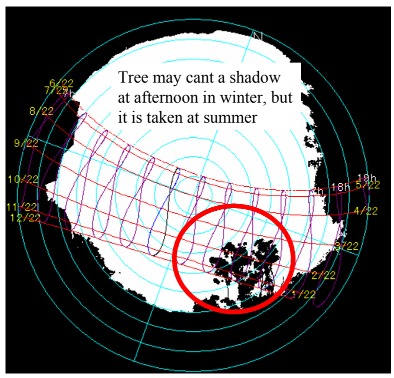

Figure 11: Fish-eye photograph taken in 6/30 at Site A

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