Development of a practical method of estimating electric power from various photovoltaic technologies with high precision

Tetsuyuki Ishi1,2*, Ritsuko Sato2, Sungwoo Choi2, Yasuo Chiba2, and Atsushi Masuda2

1 Central Research Institute of Electric Power Industry, Yokosuka, Kanagawa 240-0196, Japan
2 National Institute of Advanced Industrial Science and Technology, Tosu, Saga 841-0052, Japan

E-mail: tetsu@criepi.denken.or.jp

Received January 20, 2017; accepted May 16, 2017; published online July 19, 2017

The purpose of this study is to develop a method of estimating the electric power from various photovoltaic technologies with high precision. The actual outdoor performance of eight kinds (12 types) of photovoltaic (PV) modules has been measured since January 2012 in order to verify the precision of the method. Using ambient climatic datasets including solar irradiance, module temperature, and solar spectrum, the performance of these PV modules is corrected to the performance under standard test conditions (STC), which should be constant ideally. The results indicate that the performance of bulk crystalline silicon (c-Si) and copper indium gallium diselenide (CIGS) PV modules can be estimated with high precision (approximately less than ±2%). However, the estimation precision of thin-film Si and cadmium telluride (CdTe) PV modules is low because of the initial light-induced degradation and seasonal variation due to metastability.

1. Introduction

The total cumulative photovoltaic (PV) installations in Japan were more than 30 GW in the beginning of 2016.1,1 The large market indicates that PV systems are recognized as certain power generation systems. To control the electricity provided by PV systems installed in an electric power grid, we need to nowcast2 and forecast3–11 the power supply from the PV systems. To characterize the performance of one PV module under a variety of ambient conditions is the most basic and a fundamental technique because the precision of the power estimation of one PV module limits the precision of the nowcasting and forecasting of the PV systems installed in the electric power grid.

The main factors affecting the performance of PV modules are solar irradiance, module temperature, solar spectrum, and angle of incidence (AOI), according to the international standard of IEC 61853-2.12 In particular, solar irradiance and module temperature markedly affect the performance of PV modules. Therefore, PV performance is usually represented as a function of solar irradiance and module temperature. For example, the matrix of PV power with respect to solar irradiance and module temperature is used in IEC 61853-1.13,14 If a linear relationship is assumed between PV power and solar irradiance, performance ratio (PR) is considered an appropriate index of outdoor PV performance.15–28 In addition, we can estimate PV performance under various module temperatures by assuming a linear relationship between PV performance and module temperature. The impact of the solar spectrum on PV performance has been vigorously investigated in recent years.23–28 These investigations indicate that the solar spectrum slightly affects (within ±1%) the PV performance with broader spectral responses such as those of bulk crystalline silicon (c-Si) including Si heterojunction (SHJ), interdigitated back contact (IBC), single-crystalline Si (sc-Si) and multi-crystalline Si (mc-Si), and copper indium gallium diselenide (CIGS) technologies, although the solar spectrum does not negligibly affect PV performance with narrow spectral responses such as those of amorphous Si (a-Si), amorphous Si and micro-crystalline Si tandem structure (a-Si/µc-Si) and cadmium telluride (CdTe) technologies. Furthermore, PV performance is also affected by the impact of AOI. The impacts of AOI on PV performance depend on the kinds of structured glass and antireflective coating.29–31

The purpose of this study is to develop a practical method of estimating the electric power from various kinds of PV modules with high precision using the initial power and ambient climatic parameters. Here, we use PR as an indicator of PV performance. Moreover, the impact of the solar spectrum is evaluated using the spectral mismatch factor.

2. Experimental methods

The National Institute of Advanced Industrial Science and Technology (AIST) has measured the performance of eight kinds (12 types) of PV modules since January 2012 (Fig. 1), which cover almost all kinds of commercially available PV modules. The surroundings are paved by a soil-based pavement material in order to prevent weeds from growing. The PV modules were under open circuit conditions other than I–V measurement periods.

Fig. 1. (Color online) Investigated eight kinds (12 types) of PV modules, which cover almost all kinds of commercially available PV modules. The surroundings are paved by a soil-based pavement material in order to prevent weeds from growing. The PV modules were under open circuit conditions other than I–V measurement periods.
before the installation. In addition, the relative spectral response of each module was measured in AIST.

Firstly, PR is used as an index of PV module performance in this study. The equation is given by

\[
PR = \frac{P_{\text{MAX}}}{P_{\text{MAX(STC)}}} \times \frac{G}{G_{\text{STC}}},
\]

where \( P_{\text{MAX}} \) is the maximum power point (MPP) calculated from the current–voltage \((I-V)\) curve measured using an \(I-V\) curve tracer (EKO MP-160), \( P_{\text{MAX(STC)}} \) is the measured initial power output of each PV module under the standard test conditions (STC) shown in Table I, \( G \) is the in-plane global solar irradiance measured using a secondary standard pyranometer (EKO MS-802), and \( G_{\text{STC}} \) is the solar irradiance of 1000 W/m\(^2\) defined by STC.

Secondly, temperature correction is conducted for PR using the back surface temperature of each PV module measured using t-type thermocouples fixed by polyimide tape, which is calculated as

\[
PR_{T=25} = PR \times \frac{1}{1 + \gamma(T - T_{\text{STC}})},
\]

where \( PR_{T=25} \) is the PR corrected to 25°C defined by STC, \( \gamma \) is the estimated temperature coefficient of PR for each PV module shown in Table I, \( T \) is the measured temperature of the back surface of each PV module, and \( T_{\text{STC}} \) is 25 °C. The estimated temperature coefficients were determined by a least-squares method based on the relationship between module temperature and PR in 2014, which was filtered by the two conditions described below. Two examples of the estimated temperature coefficients are shown in Fig. 2.

Finally, \( PR_{T=25} \) is corrected to STC by the spectral mismatch factor,

\[
PR_{\text{STC}} = PR_{T=25} \times \frac{\int_{\lambda=350 \text{nm}}^{\lambda=1700 \text{nm}} E_{\text{STC}}(\lambda)SR(\lambda) \, d\lambda}{\int_{\lambda=350 \text{nm}}^{\lambda=1700 \text{nm}} E(\lambda)SR(\lambda) \, d\lambda},
\]

Table I. Specifications of the investigated PV modules. Nominal \( P_{\text{MAX}} \) and initial \( P_{\text{MAX}} \) indicate the nameplate power given by the manufacturer and the initial power measured using a pulse-type solar simulator, respectively. In addition, the nominal temperature coefficient of \( P_{\text{MAX}} \) given by the manufacturer and the estimated temperature coefficient of PR for each kind of PV module are shown.

| Kinds       | \( P_{\text{MAX}} \) (W) | Nominal | Initial | \( \text{Nominal temperature coefficient of } P_{\text{MAX}} \) (W/°C) | Estimated temperature coefficient of PR (\( \gamma \)) (%) |
|-------------|--------------------------|---------|---------|-------------------------------------------------|------------------|
| PV01 SHJ    | 215                      | 210.9   | -0.30   | -0.31                                           |
| PV02 IBC    | 210                      | 209.8   | -0.38   | -0.37                                           |
| PV03 sc-Si  | 209                      | 205.8   | -0.45   | -0.45                                           |
| PV04 mc-Si (a) | 208.4              | 206.9   | -0.45   | -0.43                                           |
| PV05 mc-Si (b) | 190                | 187.1   | -0.45   | -0.42                                           |
| PV06 mc-Si (c) | 190                | 186.2   | -0.45   | -0.46                                           |
| PV07 CIGS (a) | 130               | 134.3   | -0.31   | -0.43                                           |
| PV08 CIGS (b) | 130               | 123.8   | -0.35   | -0.37                                           |
| PV09 CIGS (c) | 75                | 79.9    | -0.38   | -0.33                                           |
| PV10 a-Si/µc-Si | 130             | 145.3   | -0.28   | 0.02                                            |
| PV11 a-Si    | 75                      | 92.0    | -0.23   | 0.05                                            |
| PV12 CdTe   | 65                      | 62.4    | -0.25   | -0.10                                           |

Fig. 2. (Color online) Relationship between the module temperature and PR in the (a) SHJ (PV01) and (b) sc-Si (PV03) modules in addition to the least-squares regression lines. The estimated temperature coefficients (\( \gamma \)) were determined from the slopes of the least-squares regression lines.
where $E_{STC}$ is the reference solar spectrum based on the air mass 1.5 global (AM1.5G), $\lambda$ is the wavelength of the solar spectrum between 350 and 1700 nm, SR is the relative spectral response measured by AIST, and $E$ is the in-plane global solar spectrum measured using spectroradiometers (EKO MS-710 and MS-712).

All the data have been measured every five min since January 2012. The PV modules were under open circuit conditions other than $I$–$V$ measurement periods. The analyzed data in this study are filtered by two conditions, in order to analyze only the data measured under stable and high solar irradiance conditions. One is solar irradiance that is stable for 30 min or more (six or more successive time intervals). Solar irradiance was measured twice (before and after $I$–$V$ curve measurements), each for five min intervals. The difference ($\Delta G$) between the solar irradiances obtained before and after $I$–$V$ curve measurements is given by

$$\Delta G = \frac{2 \times (G_{\text{Start}} - G_{\text{End}})}{G_{\text{Start}} + G_{\text{End}}}, \quad (4)$$

where $G_{\text{Start}}$ and $G_{\text{End}}$ are the solar irradiances obtained before and after $I$–$V$ curve measurements, respectively. When $\Delta G$ is small, there is a high possibility that solar irradiance is stable. However, there are occasional cases in which $\Delta G$ is small, even if the weather is cloudy. To remove such cases, we select only periods when $\Delta G$ is 0.01 or less six times or more consecutively. The possibility that the solar irradiance is stable during the periods is high. The other is that the solar irradiance is 700 W/m$^2$ or more. If we perfectly evaluate all the possible effects on the power output and precisely and accurately measure the initial power output of a PV module, $PR_{STC}$ should be one always.

3. Results and discussion

The PR values calculated using Eq. (1) are averaged over each month, the results of which are shown in Fig. 3. The PR values of all the c-Si modules show the same seasonal variation, which is low in summer and high in winter [Fig. 3(a)]. In the case of thin-film PV modules, the seasonal variation in PR differs among the kinds of PV modules [Fig. 3(b)]. The seasonal variation in the PR of the CIGS (a) and CIGS (b) modules is in good agreement with that of the c-Si modules. However, the PR of the CIGS (c) module increased in the first year and then decreased year after year. A different seasonal variation is displayed by the PR of the a-Si module, which is high in summer and low in winter. A curious pattern is shown by the PR of the a-Si/μc-Si module, which seems to peak slightly in autumn. Strangely, the seasonal variation in the PR of the CdTe module is small.

The results of temperature correction using Eq. (2) are shown in Fig. 4. The $PR_{T=25}$ values of the c-Si [Fig. 4(a)], CIGS (a), and CIGS (b) [Fig. 4(b)] modules are almost constant, suggesting that the seasonal variation in the PR of these PV modules mostly originates from the seasonal variation in module temperature. The amplitude of the seasonal variation in the $PR_{T=25}$ of the a-Si module is slightly lower than that in the PR of the a-Si module.

Figure 5 displays the monthly average $PR_{STC}$ calculated using Eq. (3). The seasonal patterns of the $PR_{STC}$ values of the c-Si [Fig. 5(a)] and CIGS (a) and CIGS (b) [Fig. 5(b)] modules are approximately constant and similar to that of $PR_{T=25}$ except in the period from February to September 2015. The spectroradiometer for low wavelengths (MS-710) was out of order during this period. We examined the shapes of the solar spectra measured during this period and the other period. An example of the comparison between fine days is shown in Fig. 6. The spectral irradiance between 330 and 900 nm for the solar spectrum measured on 5 May 2015 is much lower than those for the AM1.5G standard spectrum and the solar spectrum measured on 16 May 2014, even though both the solar spectra were measured under approximately 1000 W/m$^2$ solar irradiance conditions. Except in the period from February to September 2015, the spectral mismatch factor of these PV modules is approximately one always. Therefore, these PV modules are slightly affected by the effect of the solar spectrum. As shown in Fig. 5(b), the amplitude of the seasonal variation in the $PR_{STC}$ of the a-Si module is further lower than that in the $PR_{T=25}$ of the a-Si module shown in Fig. 4(b). However, the spectral mismatch correction enhances the amplitude of the variation in the $PR_{STC}$ of the a-Si/μc-Si module.
seasonal variation in the PRSTC of the CdTe module seems to be smaller than those in PR and PR$_{T=25}$. All the PR, PR$_{T=25}$, and PRSTC values of the SHJ module are higher than those of the other c-Si modules [Figs. 3(a), 4(a), and 5(a)]. This is mostly due to the underestimation of the initial $P_{\text{MAX}}$ of the high-efficiency modules composed of solar cells with high capacitance. The initial $P_{\text{MAX}}$ shown in Table I is measured using a pulse-type solar simulator. The sweep time is 100 ms. The PRSTC values of the sc-Si and mc-Si modules consisting of ordinary p-type cells overlap each other approximately [Fig. 5(a)]. Therefore, we could measure the initial $P_{\text{MAX}}$ values of these PV modules appropriately. The PRSTC of every c-Si module shows little performance degradation over the measurement period and a small seasonal variation less than ±2%, as shown in Fig. 5(a). The PRSTC values of the CIGS (a) and CIGS (b) modules seem to be constant always [Fig. 5(b)]. In detail, the PRSTC of the CIGS (a) module increased by about 5% for the first half of the initial year because of the effect of light soaking.32) These results suggest that we can evaluate the electric power from c-Si and CIGS technologies with high precision using the initial power and ambient climatic parameters.

Fig. 4. (Color online) Monthly PR$_{T=25}$ averages of the (a) c-Si and (b) thin-film PV modules.

Fig. 5. (Color online) Monthly PRSTC averages of the (a) c-Si and (b) thin-film PV modules. The spectroradiometer for low wavelengths (MS-710) was out of order from February to September 2015 as suggested in gray. Bars indicate that the difference between the maximum and minimum PRSTC values in every c-Si module is less than ±2%.

Fig. 6. (Color online) AM1.5G standard spectrum defined in IEC 60904-3 and solar spectra measured on 16 May 2014 (blue) and 5 May 2015 (red). Both solar spectra were measured under approximately 1000 W/m$^2$ solar irradiance conditions. However, the red spectral irradiance is considerably lower than the blue spectral irradiance between 330 and 900 nm, as suggested by the red arrow.
However, the estimation accuracy must be improved in one way or another. For example, we can estimate the electric power with high accuracy and precision, if we adopt the values of PR_{STC} in July 2012 as the initial power outputs.

The initial degradation of the thin-film Si PV modules (a-Si and the top cells of a-Si/µc-Si) originates from the well-known initial light-induced degradation. The PR_{STC} values of the a-Si and a-Si/µc-Si modules seem to stabilize after outdoor exposure approximately for two years [Fig. 5(b)]. When the spectral mismatch correction is conducted, we use the relative spectral response of the bottom layer of the a-Si/µc-Si cells because a high solar irradiance includes high spectral irradiance at short wavelengths. Therefore, we suppose that the current flowing in a-Si/µc-Si cells is limited by the bottom cells, which have a relative spectral response at middle wavelengths. However, there is still left several percent of the seasonal variation in the PR_{STC} of both the a-Si and a-Si/µc-Si modules [Fig. 5(b)]. This seasonal variation may be due to the effects of thermal annealing and light soaking on the a-Si module and the top cells of the a-Si/µc-Si module.

The PR_{STC} of the CdTe module shows a high degradation rate from October 2012 to August 2013. The degradation rate is low after that period. There is a marked difficulty in evaluating the electric power from such PV modules with a large degradation or failure.

As described in Introduction, the solar spectrum slightly affects the performance of bulk c-Si PV modules, which could be confirmed by the similar monthly PR_{T=25} and PR_{STC} averages shown in Figs. 4(a) and 5(a). This suggests that the power of c-Si PV technologies could be estimated with high precision only from solar irradiance and module temperature, in addition to nominal power, which is expressed as

\[ P_{\text{MAX}} = P_{\text{MAX\_\text{STC}}} \times \frac{G}{G_{\text{STC}}} \times [1 + \gamma(T - T_{\text{STC}})] \]  (5)

By the proposed method in this study, we could nowcast and forecast the electricity provided by PV systems in the electric power grid using nowcasted and forecasted solar irradiances and module temperatures estimated with environmental parameters such as solar irradiance and air temperature, in addition to the total nominal power of the installed PV systems.

4. Conclusions

In this study, we investigated a practical method of estimating the electric power from various photovoltaic technologies with high precision. The actual outdoor performance of 12 types (eight kinds) of PV modules was compared with the performance estimated using ambient climatic parameters such as solar irradiance, module temperature, and solar spectrum, in addition to the initial power outputs and relative spectral responses. The results indicate that the estimation method can be applicable to c-Si and CIGS PV technologies. However, additional further improvements are required to apply the method to thin-film Si and CdTe PV technologies. Specific examples include the development of methods of evaluating the effects of the thermal annealing and light soaking of a-Si and a-Si/µc-Si modules. Furthermore, we revealed that the determination of the initial performance is important to improve the accuracy of performance estimation.

Acknowledgment

This study is supported by the New Energy and Industrial Technology Development Organization (NEDO) under the Ministry of Economy, Trade and Industry (METI).

---

1) Annual Report 2015 — The International Energy Agency Photovoltaic Power Systems Programme (IEA PVPs), 2016.
2) M. Liperotte, J. L. Bosch, and J. Kleo, Sol. Energy 112, 232 (2015).
3) A. Sanlilloppo, L. Martin-Pomares, N. Mohandes, D. Perez-Astudillo, and D. Bouchar, Sol. Energy 125, 77 (2016).
4) H.-Y. Cheng, Renewable Energy 91, 434 (2016).
5) H. Ohtake, K. Shimose, J. G. da Silva Fonseca, Jr., T. Takashima, T. Oozeki, and Y. Yamada, Sol. Energy 98, 138 (2013).
6) J. S. Bejanowski, A. Vrieling, and A. K. Skidmore, Sol. Energy 99, 152 (2014).
7) B. Pillot, M. Muselli, P. Poggii, and J. B. Dias, Sol. Energy 120, 603 (2015).
8) L. Mazorza Aguiar, B. Pereira, M. David, F. Diaz, and P. Lauret, Sol. Energy 122, 1309 (2015).
9) J. G. da Silva Fonseca, Jr., T. Oozeki, H. Ohtake, T. Takashima, and K. Ogimoto, Prog. Photovoltaics 23, 1203 (2015).
10) J. Antonanzas, N. Osorio, R. Escobar, R. Urraca, F. J. Martinez-de-Pison, and F. Antonanzas-Torres, Sol. Energy 136, 78 (2016).
11) Y. Liu, S. Shimada, J. Yoshino, T. Kobayashi, Y. Miwa, and K. Furuta, Sol. Energy 136, 597 (2016).
12) IEC 61585-2 Ed. 1.0 (2016).
13) IEC 61585-1 Ed. 1.0 (2011).
14) R. P. Kenny, E. D. Dunlop, H. A. Ossenbrink, and H. Müllejans, Prog. Photovoltaics 14, 155 (2006).
15) T. Ishii, K. Otani, and T. Takashima, Prog. Photovoltaics 19, 141 (2011).
16) T. Ishii, T. Takashima, and K. Otani, Prog. Photovoltaics 19, 170 (2011).
17) U. Jahn, M. Schweiger, and W. Herrmann, Proc. 27th European Photovoltaic Solar Energy Conf., 2012, p. 3233.
18) C. Cornaro and A. Andreotti, Prog. Photovoltaics 21, 996 (2013).
19) R. Gottschalg, T. R. Betts, A. Eleles, S. R. Williams, and J. Zhu, Sol. Energy Mater. Sol. Cells 119, 169 (2013).
20) T. Huld, E. Dunlop, H. G. Beyer, and R. Gottschalg, Sol. Energy 93, 267 (2013).
21) B. Müller, L. Hardt, A. Armbruster, K. Kiefer, and C. Reise, Prog. Photovoltaics 24, 570 (2016).
22) D. Dirnberger, B. Müller, and C. Reise, Prog. Photovoltaics 23, 1754 (2015).
23) J. J. Pérez-López, F. Fabero, and F. Chenlo, Prog. Photovoltaics 15, 303 (2007).
24) C. Monokroussos, M. Bliss, Y. N. Qiu, C. J. Hibberd, T. R. Betts, A. N. Tiwari, and R. Gottschalg, Prog. Photovoltaics 19, 640 (2011).
25) T. Ishii, K. Otani, A. Itagaki, and K. Utsunomiya, Jpn. J. Appl. Phys. 51, 10NF05 (2012).
26) T. Ishii, K. Otani, A. Itagaki, and K. Utsunomiya, Jpn. J. Appl. Phys. SC. 13, 15 (2013).
27) A. Virtani and L. Fanni, Prog. Photovoltaics 22, 208 (2014).
28) D. Dirnberger, G. Blackburn, B. Müller, and C. Reise, Sol. Energy Mater. Sol. Cells 132, 431 (2015).
29) W. Herrmann, L. Rimmelspacher, and M. Reuter, Proc. 28th European Photovoltaic Solar Energy Conf., 2013, p. 2882.
30) D. L. King, W. E. Boyom, and J. A. Kratochvil, Proc. 29th IEEE Photovoltaic Specialists Conf., 2002, p. 1356.
31) N. Martin and J. M. Ruiz, Sol. Energy Mater. Sol. Cells 70, 25 (2001).
32) T. Ishii, K. Otani, T. Takashima, and K. Ikeda, Prog. Photovoltaics 22, 949 (2014).
33) D. L. Staebler and C. R. Wronski, Appl. Phys. Lett. 31, 292 (1977).
34) T. Ishii, K. Otani, T. Takashima, and S. Kawai, Sol. Energy Mater. Sol. Cells 95, 386 (2011).