The Impact of Haze on Performance Ratio and Short-Circuit Current of PV Systems in Singapore

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***Abstract*—The spectral content of sunlight directly affects the power output of solar photovoltaic (PV) devices. The extent of the effect of seasonal and weather-related spectral variations on the power output will depend largely on the semiconductor bandgap. In this study, haze, which is a common weather condition in many parts of the world, is found to affect the power output of PV systems. An analysis of a recent haze event in Singapore in mid-June 2013 reveals that haze has an impact on the performance ratios and short-circuit currents of PV systems. The performance ratio of amorphous silicon thin-film PV systems dropped during the haze event, while that of crystalline silicon wafer-based systems exhibited a slight increase. A detailed analysis showed that the main cause of the observed performance ratio variations was changes in the generated short-circuit currents, which were due to a red shift of the solar spectrum arriving in the module plane during the haze period. Therefore, PV systems with different semiconductor bandgaps were affected differently.**

***Index Terms*—Average photon energy (APE), haze, performance ratio (PR), photovoltaic (PV) module, spectral analysis.**

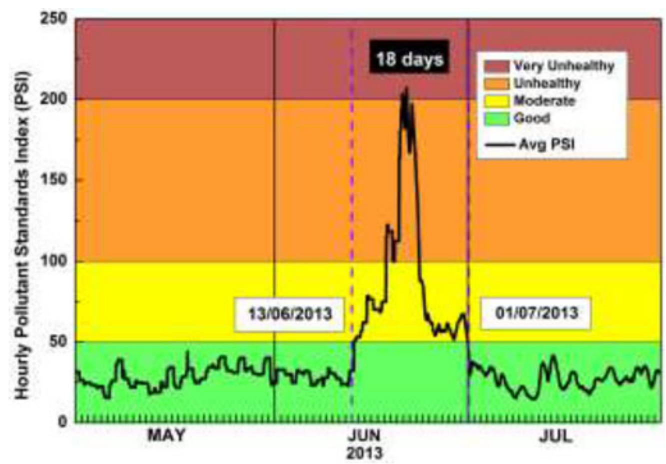

Fig. 1. Average PSI of Singapore during May 2013 to July 2013, encompassing the period from June 13 to 30, 2013 (marked by vertical dashed lines), when the air quality in Singapore was outside the "Good" region. The data were obtained from Singapore's NEA [7] and the graph adapted by SERIS.

I. Introduction

THE Spectral content of sunlight directly affects the efficiency of solar photovoltaic (PV) devices. Commercially available PV technologies present a variety of spectral response (SR) characteristics [1], which stem from the various bandgap values that correspond to the different semiconductor materials. Even the most commonly used semiconductor material—silicon—will result in PV devices with different bandgaps, and thus different SRs, depending on whether the structural arrangement of the atoms is crystalline or amorphous [2]–[4].

Hazy weather can be seen in many places around the world. Common reasons for haze are related to human activities such as man-made forest fires, industrial emissions, and vehicle smog. In particular, smoke haze has become an annual event in Southeast Asia because of the prevalence of slash and burn agriculture [5], [6]. Similar hazy conditions in other parts of Asia are a result of industrial smog and other forms of air pollution. Haze affects the passage of light through the atmosphere, which has a direct impact on visibility. Therefore, it is interesting to investigate how haze affects PV systems that are exposed to it.

For instance, in mid-June 2013, there was a heavy smoke haze in Singapore, caused by forest fires in Indonesia, more than 100 km away. The smoke was transported by winds to Singapore and Malaysia. Gauging from the Pollutant Standards Index (PSI) value and air quality descriptor provided by Singapore's National Environment Agency (NEA) [7], strong haze occurred in Singapore between June 13 to June 30, 2013 (see Fig. 1).

We closely examined PV system performance data in Singapore in the period of May 2013 to July 2013 (see Fig. 2). Looking at the energy output, nothing extraordinary was

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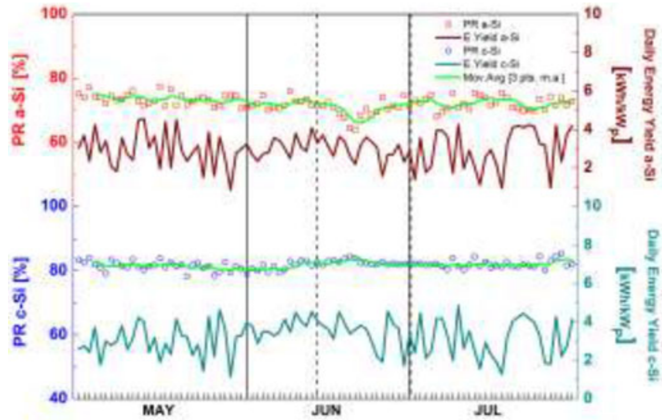

Fig. 2. Daily PRs and daily energy yields of an amorphous silicon thin-film system (red squares) and a silicon wafer-based system (blue circles) during May 2013 to July 2013. A three-day moving average line is added to facilitate observation of the haze effect in the two PV technologies during the period of this study. Graphs are offset to facilitate viewing, and the haze period is marked by vertical dashed lines. Impact of haze is visible from daily PR but not from daily energy yield.

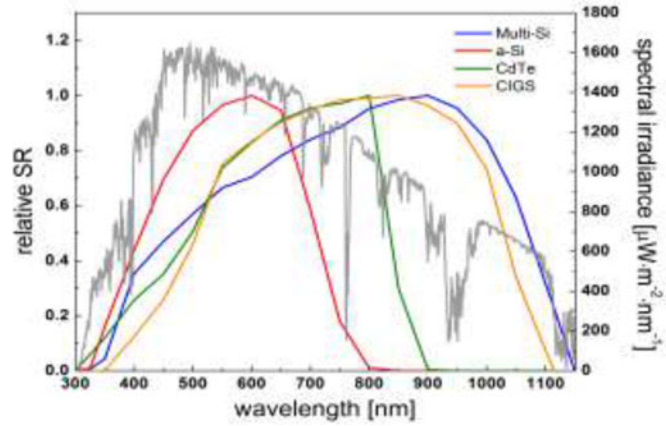

Fig. 3. Relative SR of various PV technologies (multicrystalline Si, amorphous Si, CdTe, and CIGS) measured under STC temperature (25 °C). Data are adopted from measurements done in SERIS [8]. The AM1.5G spectrum (gray) is also shown for reference.

detectable in the haze period. However, when looking at the performance ratio (PR) (defined in the next section) of amorphous silicon-based (a-Si) systems, a clear drop is noticeable for this period. In contrast with this, the PR for silicon wafer-based (c-Si) systems remained relatively constant, and even showed a slight increase in that period. To find the reason behind the observed changes, we investigated in detail the impact of haze on solar irradiance, spectrum, temperature, PV system voltages, and currents, as well as humidity. We found no discernable irregularity in any of these parameters, except in spectrum and current. After careful analysis, we conclude that the change in PR was mainly due to an alteration in the spectrum reaching the PV systems. The measured spectrum during haze is significantly less blue-rich compared with that of a normal day in Singapore. This is discovered in a previous work done in our institute, which studied the effect of the solar spectrum at the single-module level, showing that the effective irradiance ratio changed significantly during the haze period [8]. Aerosols that arise from burning are usually smaller than other particles typically present in the atmosphere, such as water droplets, desert dust, or sea salt. These particles cause additional scattering and absorption, predominantly in the shorter wavelengths of solar radiation. The resulting changes in the blue part of the spectrum adversely affected the current generated by a-Si systems, but had little impact on c-Si systems. In fact, the spectrum became closer to the ASTM standard AM1.5G spectrum [9], under which c-Si systems perform better. We believe this to be the reason behind the slight increase of the PR of the c-Si-based systems.

In this study, we used statistical analysis and theoretical calculation to assess the effect of haze on spectrum change, and subsequently on the current generation of solar cells. Through this exercise, we verified that the main impact of haze on PV systems in Singapore is due to change in spectral composition of solar radiation arriving at the module surfaces. The implication on power output depends on the specific technology employed.

II. Theory

A. Spectral Response

SR is the ratio between generated current of the solar cell and the incident power. Fig. 3 shows the relative SRs (obtained by scaling of the measured SRs so that the maximum SR value is unity) of different PV modules (multicrystalline Si, amorphous Si, CdTe, and CIGS) [1], [8]. The single-junction a-Si module has its peak response at around 600 nm and is able to convert light into electricity from around 320 to 800 nm. For the CdTe module, the corresponding range is 300–900 nm. The SR range for the CIGS module is around 350–1150 nm: similar to that of the crystalline Si module.

B. Average Photon Energy

Average photon energy (APE) is the average energy that a photon in a given spectrum carries [10]. It is a convenient indicator of how blue-rich or red-rich the given spectrum is and is calculated by

$$\text{APE} = \frac{\text{Integrated irradiance}}{\text{Total photon number}} = \frac{\int_{\lambda_1}^{\lambda_2} E(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} \phi(\lambda)d\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} E(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{E(\lambda)}{hc/\lambda}d\lambda} \tag{1}$$

where $E(\lambda)$ is the wavelength resolved intensity distribution of a spectrum, and $\phi(\lambda)$ is the wavelength resolved photon flux density. h and c are the Planck's constant and the speed of light in vacuum, respectively. The APE value of the AM1.5G spectrum in the wavelength range of 305–1150 nm is calculated to be 1.83 eV [8].

C. Performance Ratio

In assessing the quality of PV systems, yield and PR are commonly used as figures of merit in industry and in research

[11], [12]. The PR is an internationally recognized assessment parameter for verification of system design and operational quality [13]. The PR is defined as the ratio of the final PV system yield (Y_f) over the reference yield (Y_r)

$$\mathrm{PR} = \frac{Y_f}{Y_r}. \tag{2}$$

The final PV system yield (Y_f) is the net ac energy output, E_{AC}, divided by the nameplate dc power (P_0) of the installed PV array, i.e.,

$$Y_f = \frac{E_{\mathrm{AC}}}{P_0} \tag{3}$$

with the units of hours or kWh/kW$_\mathrm{p}$, representing the number of hours that the PV array would need to operate at its rated power to provide the same energy. The reference yield (Y_r) is the total in-plane irradiance G_{mod} divided by the PV reference irradiance, $G_0 = 1,000$ W/m^2, i.e.,

$$Y_r = \frac{\sum^t G_{\mathrm{mod}}}{G_0} \tag{4}$$

which represents an equivalent number of hours at the reference irradiance. Thus, PR can be expanded by substituting Y_f and Y_r into PR as

$$\mathrm{PR} = \frac{E_{\mathrm{AC}}/P_0}{\sum^t G_{\mathrm{mod}}/G_0} = \frac{G_0}{P_0} \times \frac{\sum^t P_{\mathrm{AC}}}{\sum^t G_{\mathrm{mod}}} \tag{5}$$

where P_{AC} is the ac power of the PV system. G_{mod} should be measured by a sensor or irradiance measurement device with the same inclination and orientation as the PV array.

III. Methodology

The spectral data used in this study were measured on the rooftop of the Solar Energy Research Institute of Singapore using a 10° tilted EKO MS-700 spectroradiometer. The sensor was tilted to match the typical tilt of systems in the country. The recording frequency was one spectrum measured every minute. Although the reported measurement range from datasheet is 350–1050 nm, the spectroradiometer actually measures from 305 to 1150 nm, with a measurement interval of 3.3 nm. An intercomparison of several spectroradiometers of this type was performed by Krawczynski *et al.* [14]. Their results showed that the repeatability for this type of sensor is good between 303 and 1050 nm (with the mean absolute deviation less than 0.5%). Above 1050 nm, the reproducibility is within 2% of the mean absolute deviation, which is within the measurement uncertainty of the system monitoring. Thus, we report the results with 305 to 1150 nm to give a full spectrum profile. APE was calculated for every recorded spectrum. Frequency count was performed for APE of the whole year period, as well as during the haze period, to assess the change in the shape (spectral content) of the spectrum. Statistical analysis using a nonparametric method and linear regression was performed.

To assess the impact of spectrum variation on the current generation of the different PV systems, we performed theoretical calculations, as well as examined the actual recorded current output. In the theoretical calculation, the short-circuit current produced under illumination by the measured real spectrum during operation ($I_{\mathrm{sc}}^{\mathrm{real\ spectrum}}$) was calculated from the module's measured SR. Additionally, the hypothetical short-circuit current that a module would generate under AM1.5G spectrum illumination with the same intensity as the measured spectrum ($I_{\mathrm{sc}}^{\mathrm{AM1.5G}}$) was also calculated. The ratio r_1 between these two values was taken as a metric for system performance

$$r_1 = \frac{I_{\mathrm{sc}}^{\mathrm{real\ spectrum}}}{I_{\mathrm{sc}}^{\mathrm{AM1.5G}}}. \tag{6}$$

A similar current ratio was calculated using the measured dc output currents of the PV systems ($I_{\mathrm{mpp}}^{\mathrm{measured}}$) and the irradiance falling on the module planes. The hypothetical short-circuit current under AM1.5G ($I_{\mathrm{sc}}^{\mathrm{AM1.5G}}$) was calculated by scaling the nominal short-circuit current provided in the module specification sheet with the measured irradiance (G_{measured})

$$I_{\mathrm{sc}}^{\mathrm{AM1.5G}} = \frac{I_{\mathrm{sc}}^{\mathrm{nominal}}}{1000} \times G_{\mathrm{measured}}. \tag{7}$$

The resulting ratio is

$$r_2 = \frac{I_{\mathrm{mpp}}^{\mathrm{measured}}}{I_{\mathrm{sc}}^{\mathrm{AM1.5G}}}. \tag{8}$$

We obtained r_1 and r_2 for the same set of time points. Subsequently, statistical analysis was performed to assess the correlation between these two sets of ratios.

PV system PR was also examined. It is measured using utility-grade energy meters ($\pm$ 0.5% uncertainty) to verify the daily energy output of the PV systems. The irradiance was measured in the module planes using calibrated c-Si sensors with $\pm$2.0% uncertainty, with calibration performed at Fraunhofer ISE CalLab, Germany.

IV. Results and Discussion

A. *Effect of Haze on Solar Spectrum*

The probability distribution of APE values is plotted in Fig. 4. It is visually obvious that the frequency distribution during haze period shifts to the smaller energies compared with that of the whole year. Rigorous statistical analysis (see Appendix A) shows a positive difference in the means of the two distributions. This implies that red-shifted spectra occurred much more frequently than normal during the haze period. Daily average APE values in June were plotted against the daily average PSI reading, and a roughly linear relationship between these two parameters (with a slope of -5×10^{-4} and *r* value of -0.87) was found.

The APE value for the AM1.5G spectrum is also shown for reference. It was found that the typical spectrum in Singapore is much bluer than the AM1.5G spectrum. A plot of the normalized average spectrum received in May 2013 is shown in Fig. 5. Compared with AM1.5G, the main difference is in the blue and green regions, in which Singapore's spectrum has much higher intensities. Interestingly, haze reduced the intensities in this region and resulted in a spectrum that is closer to AM1.5G. Fume particles that constituted haze have a wide range of sizes, with

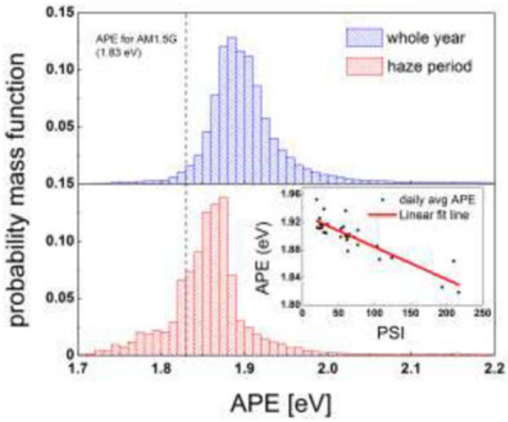

Fig. 4. APE frequency distribution for the whole year (blue) and that for the haze period (red) are shown for comparison. The shift of the distribution implies that the spectrum during the haze period is significantly red shifted. Daily average APE value (inset) in June exhibits a roughly linear relationship with PSI reading (r value $= -0.87$), indicating increased scattering of blue light due to pollutant particles.

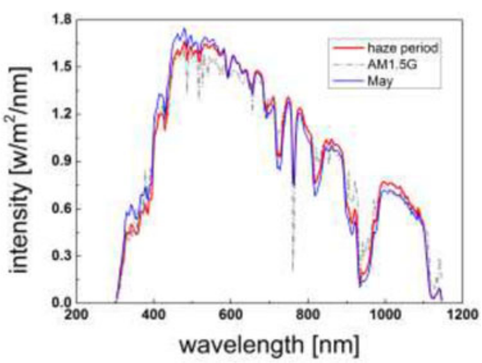

Fig. 5. Average spectrum (normalized to the same intensity as AM1.5G) of May (blue) and the haze period (red). The latter was less blue-rich than the former, due to a significant reduction of intensity in the blue and green regions and a slight increase in the red part. The AM1.5G spectrum (gray) is also shown for reference. A similar comparison can also be found in [8].

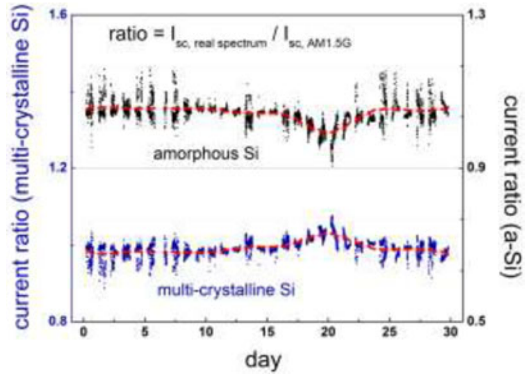

Fig. 6. Ratio between theoretically calculated short-circuit current ($J_{\rm sc}$) under the recorded spectrum and that under the standard AM1.5G spectrum during June 2013. There was a dip for the a-Si module and a slight hump for the multi-Si module during the haze period, which is consistent with the PR results of Fig. 2.

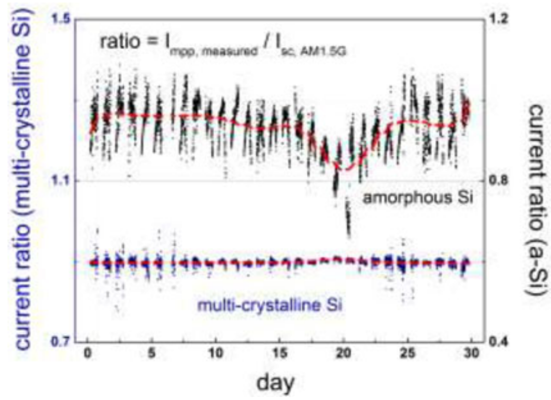

Fig. 7. Ratio between measured maximum power point current of PV systems and nominal short-circuit current scaled with measured irradiance (r_2). The smoothed trend correlates well with that of the theoretically calculated results. Obvious outliers (mainly in the morning and evening) were removed from the measured dataset. The measured values are lower than theoretically calculated, as the maximum power point current instead of the short-circuit current was used as the numerator.

the smallest down to below 10 nm [15]. Additional scattering and absorption by these particles are causes for the observed spectrum change. We believe that the increase in the red part is likely to be an artifact of scaling to the same total intensity. We assume that haze does not change the spectral composition in the atmosphere significantly but only adds scattering effect. This should lead to a reduction in intensity across the whole wavelength range. We found that the spectral composition in Singapore is virtually invariant throughout the year; thus, the red light became relatively rich only because it is scattered or absorbed less than the blue light.

B. Effect of Spectrum Change on Current

As described in the methodology section, calculations were performed to obtain the current ratio $r_1 = I_{\rm sc}^{\rm real\ spectrum}/I_{\rm sc}^{\rm AM1.5G}$ corresponding to the recorded spectra in June 2013. The current ratio r_1 for an amorphous silicon system and a multicrystalline silicon (multi-Si) system is shown in Fig. 6. From the smoothed curves, a dip for the a-Si PV system and a slight hump for the multi-Si PV system is visible around June 21, which coincides with the period of the most severe haze. The ratio drops by as much as 7% for the a-Si system and increases by as much as 6% for the multi-Si system. The drop for the a-Si system is straightforward to understand. The reason is that a-Si PV systems rely primarily on shorter wavelength light (<650 nm), which was less abundant during the haze period. In contrast, due to the red-shifted spectrum during the haze period, the current of the multi-Si PV system improved because such modules have their highest SR at near-infrared wavelengths (see Fig. 3). Therefore, it is expected that the spectrum change observed during the haze period will have a noticeable impact on the short-circuit current of the modules. Indeed, we find that measured data corroborate the theoretical calculations. The current ratio r_2, computed using measured data, is shown in Fig. 7. Outliers (mainly in the morning and evening when azimuth angles are large) were removed, as those

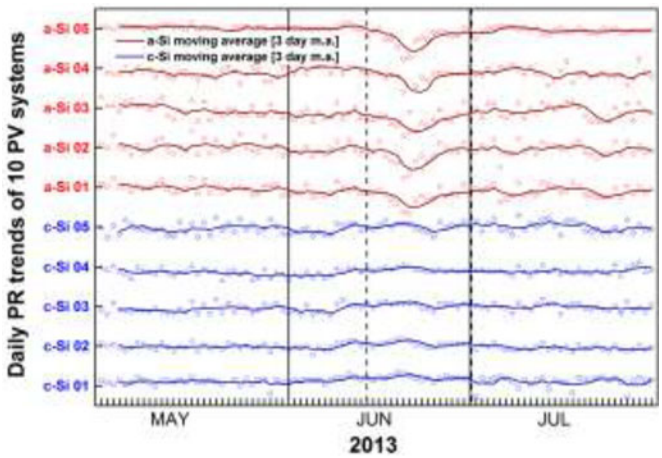

Fig. 8. Measured daily PRs (symbols) of ten PV systems in Singapore for the period of May 2013 to July 2013—five amorphous silicon thin-film systems (top five curves) and five multicrystalline silicon wafer-based systems (bottom five curves). The lines are the three-day moving averages. The haze period is marked by vertical dashed lines.

readings are unreliable due to low insolation, large incidence angle, as well as sensor shading (while the modules are not completely shaded). It should be noted that as the dc output current ($I_{\mathrm{mpp}}^{\mathrm{measured}}$) is the current at the maximum power point instead of the short-circuit current, the ratio is expected to be lower than the previous values in the theoretical calculation. For both amorphous and multicrystalline systems, the smoothed trends show a high correlation with the theoretical calculations, with correlation coefficients higher than 0.9 (see Appendix B). This implies that the actual generated current was indeed influenced by the change in spectrum, as predicted by theoretical calculations. As can be seen in the next section, this effect was also reflected in the PRs of the a-Si and multi-Si systems. The extent of increase in r_2 for the multi-Si system is much smaller than theoretically predicted (r_1). This is because the silicon sensor used to measure the irradiance was influenced by haze in a similar manner and outputted a larger signal. For the same reason, the decrease in r_2 for a-Si system is more pronounced than the decrease in r_1.

C. Measured Performance Ratio of Photovoltaic Systems

The measured daily average PR of ten PV systems deployed in Singapore is shown in Fig. 8. To facilitate viewing of trends, the three-day moving averages are shown as lines. For all a-Si systems, there was a drop in the PR during the haze period. In comparison, the PR for crystalline systems remained relatively constant, arguably with a slight improvement. Throughout this period, the temperature and voltage remained largely constant; thus, the change in PR can be attributed mainly to the output current.

Interestingly, there was less water precipitation during the haze period, partly because most fires in equatorial Southeast Asia happen between June and November, which is typically the driest period of the year [16]. Thus, the total daily energy yield of the PV systems did not seem to be adversely affected by the haze. However, the analysis presented in this study suggests that additional power could have been generated if the haze had not occurred, and the PRs had remained constant. Apart from altering the solar spectrum, the haze might also have influenced the amount of energy reaching the modules, due to additional reflection and absorption in the atmosphere. In future haze events, it would be interesting to determine how much PV energy is lost as a result of the haze.

V. Conclusion

PRs of a-Si based and c-Si based PV systems operating in Singapore were found to behave differently during the haze event in June 2013. We showed that this effect can be attributed to a change in the generated short-circuit current resulting from a change in the spectral composition of the incident sunlight. During the haze period, a red shift of the spectrum reaching the module planes was observed. This shift can be attributed to scattering of light at airborne haze particles. This change in the spectral composition negatively impacted a-Si systems, which mostly rely on short wavelengths (<650 nm), but had a slight positive effect on c-Si systems, which have the best SR at near-infrared wavelengths (800 to 900 nm). A clear correlation exists between the spectral changes and the PRs, as was validated by measurements as well as statistical analysis. As a rule of thumb, it can be concluded that the impact of haze on the PV power output is most severe for PV systems employing high-bandgap solar cells (such as a-Si solar cells), whereas crystalline silicon modules continue to perform well (efficiency-wise) under such conditions.

While this analysis was performed for Singaporean conditions, we believe that it can also provide useful insight into PV systems deployed at other locations, where the spectrum seen by the modules is affected by haze. For instance, industrial smog in China and forest fire smog in Brazil may affect the PV system performance in a similar way. Quantification of the impact of haze on the solar irradiance could be the subject of future works.

Appendix A

Nonparametric Estimation of Mean Difference in Fig. 4

We claim that the test and analysis shown in this appendix follow rigorous statistical procedures; the significant numbers used in the results are, thus, sustained given the sample size. Due to lack of knowledge of the true distribution, we use the nonparametric method instead of the maximum likelihood estimation.

If we suppose that the APE calculations (from measurements) $X_1, \ldots, X_n$ are from an unknown distribution F, the empirical distribution function $\hat{F}_n$ is defined as

$$\hat{F}_n(x) = \frac{\sum_{i=1}^{n} I(X_i \leq x)}{n} \quad \text{(A.1)}$$

where

$$I(X_i \leq x) = \begin{cases} 1, & \text{if} \quad X_i \leq x \\ 0, & \text{if} \quad X_i > x. \end{cases} \quad \text{(A.2)}$$

If we regard the APE calculations displayed in Fig. 4 as samples from two distribution F_1 and F_2, where F_1 is the APE distribution for the whole year, while F_2 is the APE distribution for the haze period. The goal is to determine whether the mean APE is different under these two conditions. The mean and variance can be considered as *statistical functionals* of F. In other words, we can say that the mean $\mu = \int x dF(x)$ and $\sigma^2 = \int (x-\mu)^2 dF(x)$ are two functions of the distribution F. When μ and σ^2 are replaced by a more general representation of the parameter, namely, θ, we can define the *plug-in estimator* of $\theta = T(F)$

$$\hat{\theta}_n = T(\hat{F}_n) \tag{A.3}$$

which is obtained by simply plug-in the empirical distribution function for the unknown distribution F, and T is a statistical functional.

From the APE data shown earlier, the plug-in estimates for μ_1 (whole year) and μ_2 (haze period) are

$$\begin{cases} \hat{\mu}_1 = \int x d\hat{F}_{n,1}(x) = 1.9030 \\ \hat{\mu}_2 = \int x d\hat{F}_{n,2}(x) = 1.8610. \end{cases} \tag{A.4}$$

In addition, the *standard error* $se(\hat{\mu})$ is given by

$$se(\hat{\mu}) = \frac{\sigma}{\sqrt{n}} \tag{A.5}$$

and the estimator is

$$\widehat{se}(\hat{\mu}) = \frac{\hat{\sigma}}{\sqrt{n}} \tag{A.6}$$

where the plug-in estimator for σ is

$$\hat{\sigma} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X_i - \bar{X})^2}. \tag{A.7}$$

We can, thus, obtain

$$\begin{cases} \widehat{se}(\hat{\mu}_1) = 1.0355 \times 10^{-4} \\ \widehat{se}(\hat{\mu}_2) = 5.3179 \times 10^{-4}. \end{cases} \tag{A.8}$$

We can further define a *normal-based interval*, e.g., the $1-\alpha$ confidence interval is given by

$$T(\hat{F}_n) \pm z_{\alpha/2}\widehat{se} \tag{A.9}$$

When $\alpha = 0.05$, the 95% confidence interval of the above mean estimates is

$$\begin{cases} \hat{\mu}_1 \pm z_{0.025}\widehat{se}\,(\hat{\mu}_1) = 1.903 \pm 1.96 \times 1.0355 \times 10^{-4} \\ \qquad\qquad\qquad\qquad = (1.9028, 1.9032) \\ \hat{\mu}_2 \pm z_{0.025}\widehat{se}\,(\hat{\mu}_2) = 1.861 \pm 1.96 \times 5.3179 \times 10^{-4} \\ \qquad\qquad\qquad\qquad = (1.8599, 1.8620). \end{cases} \tag{A.10}$$

This suggests that APE on the whole year average is higher than those from the haze period. We further test the mean difference, i.e., consider$\hat{\theta} = \hat{\mu}_1 - \hat{\mu}_2$, the nonparametric estimation of the 95% confidence interval is

$$\hat{\theta} \pm z_{0.025}\widehat{se}(\hat{\theta}) = (0.04097, 0.04309) \tag{A.11}$$

which is strictly above zero (suggesting a positive difference).

Appendix B

Data Analysis on the Theoretically Calculated and Measured Current Ratios

Visual examination of the current ratios plotted in Figs. 6 and 7 reveals that both the theoretically calculated and the measured current ratios exhibit the same trend during the haze period. We statistically quantify the correlation between the two sets of current ratios in this Appendix.

The current ratios calculated from measured maximum power point current and measure irradiance fluctuate throughout the day. Some values are found to be unreasonable. These values (mainly in the morning and evening) are unreliable due to low insolation, large incidence angle, as well as sensor shading (while the modules are not completely shaded). Therefore, we filtered the data by selecting the data at times when the zenith angle of the sun is smaller than 55°. Several other obvious outliers were removed as well. The corresponding theoretically calculated current ratios at the same time points were then taken out to obtain a same dataset as the measured one.

The theoretically calculated and the measured current ratios have different degree of variance. To smooth and normalize the variance, we fit a trend line to each dataset. We use two distinct curve fitting techniques here [17]: locally weighted scatterplot smoothing (LOESS) and cubic smoothing spline with ten knots. The Pearson correlation coefficients between the theoretically calculated and the measured current ratio for a-Si modules are calculated to be 0.996 for LOESS fit curve and 0.984 for spline fit curve. We perform the same analysis for the current ratios of multi-Si modules. Correlation coefficients of 0.961 for LOESS and 0.947 for spline are found. These high correlation coefficients indicate a high level of agreement between the calculated and the measured current ratio. Therefore, a high level of confidence can be placed on the causal relationship between the change in spectrum and the change in actual generated current.

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