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Field Performance of Thin-Film Photovoltaics

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Abstract:

Fluctuating irradiance, spectral, and temperature characteristics causes a wide sweep in the outdoor performance of thin-film photovoltaics (TFPVs). In order to forecast the outdoor behavior of such TFPV modules it is customary to develop empirical models augmented from measured datasheets, which in-turn leads to key performance insights of these modules. The impending discourse is dictated by this motive at the first place, followed by an analysis of real-time results comprising of data procured from various locations by dint of standard approaches. Analysis of spectral behavior based on measured and simulated spectra are also discussed in this context.

Keywords **—Air mass, FOF, PV, Spectral irradiance, Temperature, Thin-film.**

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I. INTRODUCTION

According to Ossenbrink et al. [1], the habitual testing procedures of solar panels prescribe that solar panel outputs are estimated under standard test conditions (STC). STC for solar panels cites to an irradiance value of 1000 W/m2 and an airmass (AM) measuring 1.5, operating at a temperature of 25°C. However, these specifications are rarely obliged under real-time conditions, which leads many researchers to adopt to actual values in consonance with the respective outdoor conditions. Nevertheless, procurement of case specific data requires outdoor measurements over longer periods of time.

II. SPECTRAL EFFECTS

Generally, solar panels are provided with manufacturer ratings based on spectral data. But incident spectrum and AM varies under real world scenario due to seasonal changes and intra-day fluctuations in solar altitude. The consequences of such fluctuations on the performance of crystalline silicon (c-Si) devices is paltry. However, the spectral response of TFPV, especially in case of amorphous silicon is far more evident. Collation of spectral responses of TFPVs and other c-Si PV modules is illustrated in Fig. 1.

Effect of spectral variations on PV performance can be measured using a multitude of approaches. However, one of the widely exercised figure-of merit used in performance measurement is short-circuit current Isc, aka field output factor (FOF), which relates the actual performance PV with the expected performance under STC in terms of its irradiance intensity, and temperature.

Whereas, some performance measures are based on a factor known as the useful fraction (UF) [2]. It is the ratio of observed irradiance and global irradiance in the useful spectra. Some of the other ways of expressing spectral variations are in terms of AM or average photon energy (APE). Obtained data from a testing facility in Utrecht, Utrecht Photovoltaic Outdoor Test (UPOT), by Van Sark et al. [3] has shown the inversely proportional relation between AM and APE.

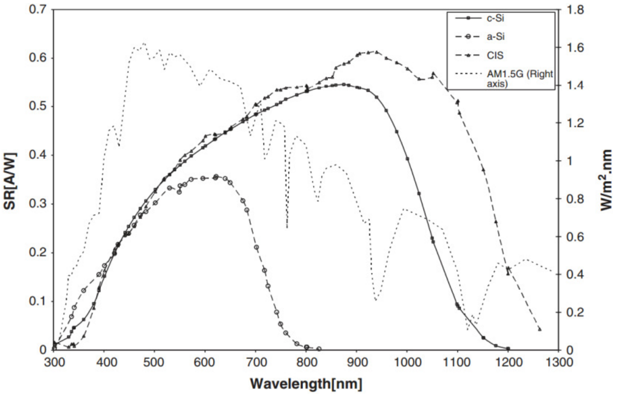

Fig. 1Spectral response ledger of a-Si, c-Si, and CIS PV modules [4]

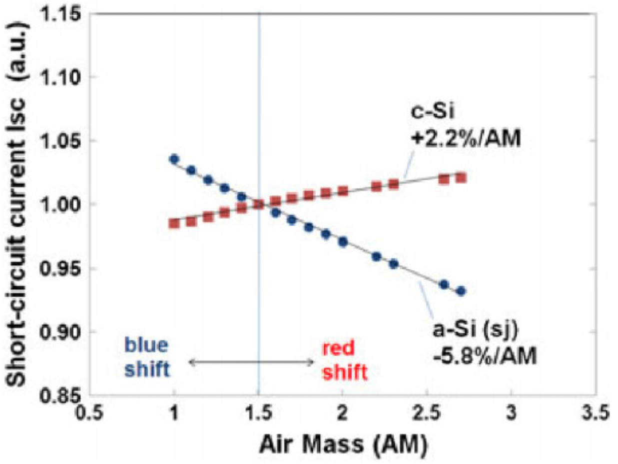

Fig. 2Dependence of Isc on incident AM, for a-Si and c-Si (dark lines are linear fits to the modeled data points) [6]

Different approaches exercised by researchers show that amongst the various TFPV technologies studied so far, the effect of spectral variations on PV performance is most evident in case of amorphous silicon (a-Si). As illustrated in Fig. 2, some authors observed the inverse effects of AM on a-Si performance when measured in terms of Isc [4–6], and identified the constricted spectral response of a-Si being the reason behind such detriment [7].

Current mismatch in triple-junction a-Si causes larger variations in spectral response, compared to its uni-junction variant [5], [8]. Furthermore, analysis from subsequent efforts demonstrate the proportional relationship between Isc and APE [9–11]. Minemoto et al. [10] regarded APE as a suitable performance measure to analyze the spectral variations. Moreover, a linear trait of FOF with respect to changes in APE or AM is reported in many literatures.

A similar trend can be expected from c-Si, i.e., improved performance with increment in APE up to a threshold limit, beyond which the performance starts to deteriorate. Research findings corresponding to APE and Isc exhibit maximum performance at an APE of approximately 2 eV. This value of APE correlates with that of an a-Si for an apex spectral response at 600 nm. In order to suppress the effects of low irradiance under normal conditions, APE values beyond the stipulated 2 eV point are not taken into consideration for performance assessment measures.

Spectral responses of Cadmium telluride (CdTe) modules are less constricted than that of a-Si modules, but it is still marginally more constricted than that of c-Si. Gottschalg et al. [2] have established that the efficiency of CdTe modules varies proportionately with UF and its annual average varies from +4% to –6% [12].

Copper indium gallium selenide (CIGS) or simply CIS modules exhibit broader spectral response compared to that of conventional c-Si modules. Such response profile, however, has paltry effects on the performance of TFPV technologies addressed here. Gottschalg et al. found that in case of CIGS modules, the UF of incident light-fringes sweeps between 6% to 10% during the daytime [2]. Other studies show that the consequences of spectral variations on the performance of CIGS modules is minor [4], [13]. However, interdependence between spectral parameters needs a thorough redressal.

III. TEMPERATURE EFFECTS

The STC for PV modules, as stated earlier, refers to a solar spectrum with the following specifications: AM 1.5, 1000 W/m2 at an operating temperature of 25°C. As specified by manufacturers, normal operating cell temperature (NOCT) for majority of PV modules is 20°C at 800 W/m2, which is a technology independent parameter. However, higher module temperature ranging between 40° to 50°C, at wind speeds of 1 m/s can be easily achieved. Nevertheless, according to the fundamental laws of material physics, higher operating temperature leads to performance degradation. This factor is experimentally tested for crucial operating parameters such as Voc, Vmp, Isc, Imp, and Pmax by means of laboratory tests. Rigorous research has also been carried out under practical operational scenario to affirm this temperature dependence of PV module performance.

According to Makrides et al. [14], non-STC operation of TFPVs cause a performance degradation of about 5.5% on an average. It is noted that the degradation in performance caused by temperature dependence is less for a-Si modules compared to that of the c-Si variants. To quantify this effect, independent research endeavors establish that the temperature coefficient of power is in the order of –0.25% per Kelvin [5], [15–17].

Performance of a-Si modules may encounter favorable effects of higher temperature due to thermal annealing. Observed value of temperature coefficient for CdTe solar modules are usually –0.28% per Kelvin, which is remarkably smaller than that of c-Si modules [15], [18]. It is also observed that CIGS modules exhibit temperature coefficients in the range of –0.36% per Kelvin to –0.42% per Kelvin, which is similar to that of c-Si modules [15].

IV. SEASONAL AND TRANSIENT VARIATIONS

Interplay between various performance metrics transpiring within the same timeframe over distinct phases dictate the seasonal variations in TFPV performance. Occurrence of spectrum-loss and reflection-loss occur are homogeneous due to the relation between angle-of-incidence and AM; as shown in Fig. 3. When the effects of thermal annealing are not taken into consideration, due to their inherent inverse relationship, increased temperature effects lead to deteriorated spectral performance.

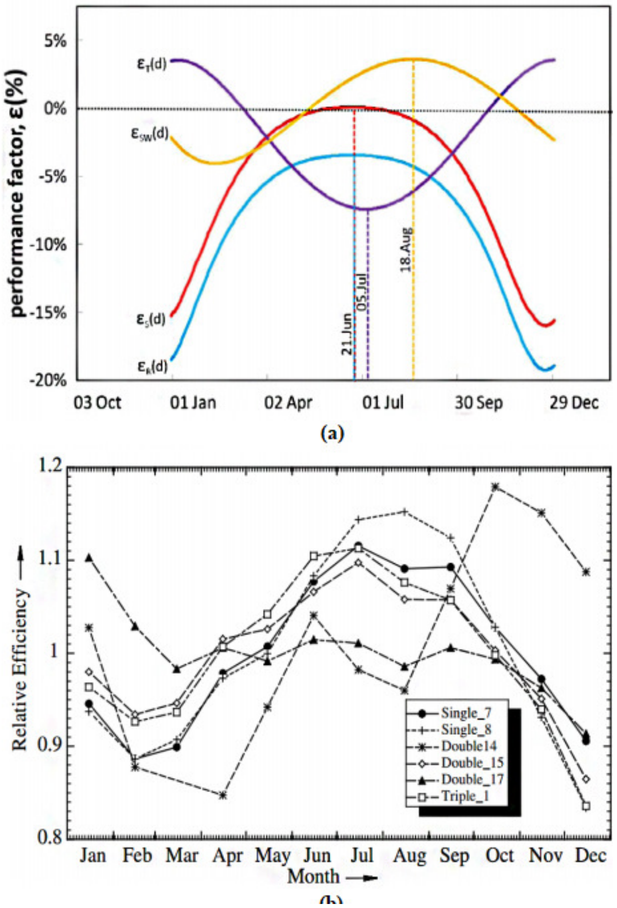

Fig. 3 (a) Effects of seasonal variationsin reflection, spectrum, SWE,temperatureon a-Si performance [5],(**b**) Seasonal variationsin a-Si [19]

A. *Amorphous Silicon*

For a-Si modules, seasonal variations are mainly caused by two parameters: temperature and spectrum. Fluctuations in temperature lead to variation in the performance of a-Si modules due to two primary effects: decrease of performance due to the negative temperature coefficient and increase of performance due to thermal annealing. As shown in Fig. 3, during the colder periods of the year; temperature effects act favorably to PV performance and conversely during the warmer periods. The marginally out-of-phase behavior of thermal annealing restores the temperature led deterioration of a-Si modules up to a certain extent, which is also featured in Fig. 3. By the dint of considering different environmental parameters individually; several independent research efforts have successfully established that increased recombination during the summer exhibits a negative effect on module performance, while performance improvement is observed due to thermal annealing [5], [6], [14], [19].

Performance summits caused due to spectral variations are observed during summer months, because spectra are more favorable (blue-shift) during summer compared to winter (red-shift); as shown in Fig. 2. Various researchers have confirmed these prominent seasonal spectral effects of a-Si modules [5], [12], [15]. Another seasonal effect is the reduced disinclination during summer; originating from the low angle of incidence of solar fringes [5], however, Fanni et al. [5] analyzed in their study that a PV module placed horizontally during the winter would cause increased disinclination when collated to a tilted installation.

The total seasonal performance results from the interplay of the four metrics described in Fig. 3, namely, reflection, spectrum, SWE, temperature. Influence of these seasonal parameters on the overall seasonal variations is somewhat related to location of the installed PV module. Virtuani et al. [6] stated that spectral variations are the main reason behind the occurrence of summits in module performance during summer months. Whereas, other researcher endeavors report the spectral variations influence the seasonal performance of TFPV, and also consider the favorable effect of thermal annealing on module performance during summer months [14]. As it can be seen from Fig. 3, the effects of spectral variations and thermal annealing are mostly overlapping with just a marginal out-of-phase behavior. This leads to the occurrence of maxima and minima in the performance during summer and winter months respectively.

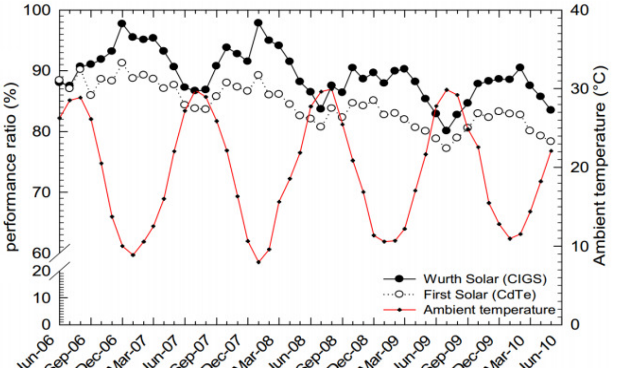

Fig. 4Performance ratio of CdTe and CIS modules (expressed in terms of monthly average); recorded between June'06 – June'10 [14]

B. CdTe and CIS

Compared to a-Si technology, the effects of seasonal variations on the behavior of CdTe or CIS modules are almost intangible. However, the seasonal effects on these modules are discernable enough in comparison with c-Si modules. The prime concern associated with CIS modules is that their output deteriorates drastically during the summer months due to the excessive dependence of these technologies on operating temperature [14].

A homogeneous seasonal variation profile is recorded for the CdTe technology as well, although due to their lower temperature coefficient the fluctuations are not so huge [14]. Performance ratio of CdTe and CIS modules (expressed in terms of monthly average); recorded between June'06 – June'10 are illustrated in Fig. 4.

V. CONCLUSION

As reported by various authors across different literatures, it is observed that the outdoor performance of TFPV modules depends upon spectral, transient, and temperature conditions. Such dependencies are summarized in this discourse in order to provide a comprehensive understanding of the related effects which in-turn facilitates the researchers and engineers with performance prediction. Based on the stochastic data obtained from such behavioral patterns due to seasonal and intra-day variations; fluctuations are observed in airmass and incident spectrum.

Laboratory tests are designed to establish temperature coefficient for important operating parameters such as Voc, Vmp, Isc, Imp. It is observed that spectral variations are less in c-Si, but not in a-Si. Also, variations in UF is more in c-Si due to broad response. Some authors observed that performance of a-Si devices decrease with increasing air mass and the seasonal variations of a-Si are caused due to temperature and spectrum. Other literatures show relatively high dependency on temperature is the main factor for decreasing performance in CIGS during summer. This insight would lead to the development of empirical models augmented from measured data using a combined strategy to better understand the technological traits

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