Thermal Uniformity Mapping of PV Modules and Plants

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***Abstract* — The conventional assumption of all the cells in a module and all the modules in a plant is operating at a single temperature. This work indicates that it is not the case. The behavior of temperature distribution of PV cells within a module and of PV modules within a plant is presented. ANOVA, a statistical tool, was used to study the influence of various ambient and design factors on temperature variation. In this study, the effect of thermal non-uniformity on I-V parameters of three different PV technologies (crystalline silicon, CdTe, CIGS) is investigated. The temperature mapping data for two power plants (fixed horizontal-tilt and one-axis) located in a desert climate of Arizona showed that the modules placed in the center of one-axis power plant had higher temperatures, whereas in the fixed-tilt power plant, the modules located in the north-west direction had higher operating temperatures. Higher average operating temperature of modules was observed for the one-axis tracker based plant as compared to the fixed-tilt based plant, thereby a higher degradation rate and a lower lifetime are expected for the 1-axis tracker based modules as compared to the fixed-tilt based modules.**

***Index Terms* — temperature variation, thermal uniformity, thermal mapping, performance.**

I. Introduction

The maintenance of temperature uniformity in a photovoltaic (PV) module is critical to accurately measure the performance parameters and temperature coefficients of the module. In the indoor solar simulator based test setups, these parameters and coefficients are obtained by maintaining all the cells within a module at a single uniform temperature. However, in the outdoor test setups, the module experiences varying ambient conditions and hence the cells within a module may encounter non-uniform temperatures; for example, the edge cells may be cooler than the center cells due to cooler frame temperature. This thermal non-uniformity issue is further complicated due to variations in the module technology, module size, module design, materials and mounting methods. This module-level study is a continuation of our previous study performed on the crystalline silicon modules [1]. In the current module-level study, the test results and analysis obtained on the thin-film technologies (CIGS, CdTe and a-Si) are also included and presented along with the c-Si technology. The module-level thermal uniformity study with c-Si and thin-film technologies was performed at the outdoor site of ASU-PRL, Mesa, Arizona.

Traditionally, it is assumed that all the modules in a PV plant are operating at a single temperature. In our previous short-term investigation, we briefly indicated that the modules placed at various locations in a PV plant tend to experience different temperatures [2]. In the current long-term investigation, the dependence of module temperature on the module location of the plant and on the type of module mounting (1-axis vs. fixed-tilt) is extensively analyzed and presented. The plant-level thermal uniformity study was performed at two power plants (1-axis and fixed horizontal-tilt) located in Tempe/Phoenix, Arizona.

II. Experimental Methods

2.1 Module-level thermal investigation

The test setup used for the module-level thermal uniformity investigation is shown in Fig. 1. The modules were mounted in two rows on the fixed tilt rack at 33°N. The module technology and thermal configuration of each module (corresponding to the code shown in Fig.1) are provided in Table I. The a-Si module and all the c-Si modules are glass/polymer modules whereas the CdTe and CIGS are glass/glass modules.

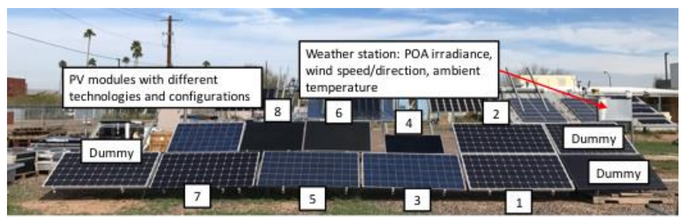


Fig. 1. Module-level thermal mapping setup, Mesa, Arizona

TABLE I

Module-Level Thermal Mapping for Different Thin-film and c-Si Modules with Different Insulation Configurations

Code	Insulation Type	Technology
1	Non-insulated	Mono-Si
2	Aluminum tape covered backsheet	Mono-Si
3	Frame insulated	Poly-Si
4	Non-insulated (frameless)	CdTe
5	Frame and backsheet insulated	Poly-Si
6	Non-insulated	a-Si
7	Non-insulated (black frame)	Mono-Si
8	Non-insulated	CIGS

The module temperatures were measured using multiple T-type thermocouples attached to the backsheet at locations defined in the IEC 61853-2 standard [3]. To collect module

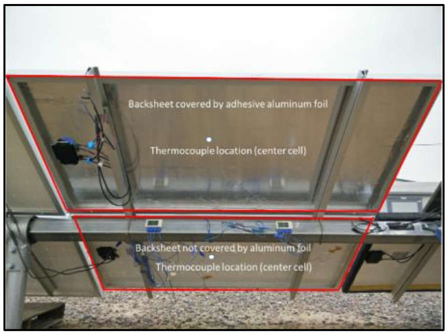


Fig. 2. Two identical modules: Top– Covered by aluminum foil; Bottom–Not covered by aluminum foil

temperature and the module voltage data, HOBO 4-channel data loggers were used. For the module performance monitoring, the performance and temperatures of four cells of each module under maximum power point tracking (MPPT) condition was continuously monitored for several clear sunny days.

The multi-curve tracer was programmed to periodically sweep the I-V curves of all the modules shown in Fig. 1 for 2 consecutive clear sunny days (during the solar window from 10am to 2pm) and the performance parameters were correlated with the module temperatures at four locations. These I-V curves were then translated to STC based on the measured module temperature at each of four locations on the module and the technology-specific temperature coefficients. The technology-specific temperature coefficient measurements were carried out for all the modules at around noon when the angle of incidence was close to zero. To perform these measurements, the modules were first placed in the cold chamber, to bring operating temperatures for modules around 10°C. The IV parameters were recorded for temperature coefficient measurements on each module at four locations on a manual dual-axis tracker on a clear sunny day for a specific range of module operating temperatures (20-30°C). As the modules warm up, multiple curves were taken for the individual modules at different operating temperatures with the thermocouples placed at four locations in each module.

To investigate if the thermal uniformity of the module can be improved by attaching a thermally conductive sheet on the backside of the back sheet, the modules shown by codes 1 and 2 in Fig. 1 were investigated and a photograph of back sides of these two modules is shown in Fig. 2. The back sheet (TPT) of the top module (code 2) was covered with a highly reflective conductive aluminum cover and the bottom module was a control module (code 1) without any aluminum foil.

2.2 Plant-level thermal investigation

Two PV plants with mono-Si modules were investigated in this study. One plant (AZ3) is based on fixed horizontal-tilt arrays and the other plant (AZ5) is based on 1-axis arrays. The fixed-tilt plant has no wind barriers around it. But on the other hand, 1-axis plant located south of the fixed-tilt plant is about 4 feet lower ground level having some wind obstruction. There is also a 15-foot-high wall on the south side of the 1-axis plant and this wall is about 30 feet away from the array leading to some wind obstructions as well. For the thermal uniformity mapping of power plant, five data loggers were installed at the northwest (NW), northeast (NE), southwest (SW), southeast (SE) and center locations for each of the two power plants to record the temperatures of five modules located in these five locations as shown in Fig. 3.

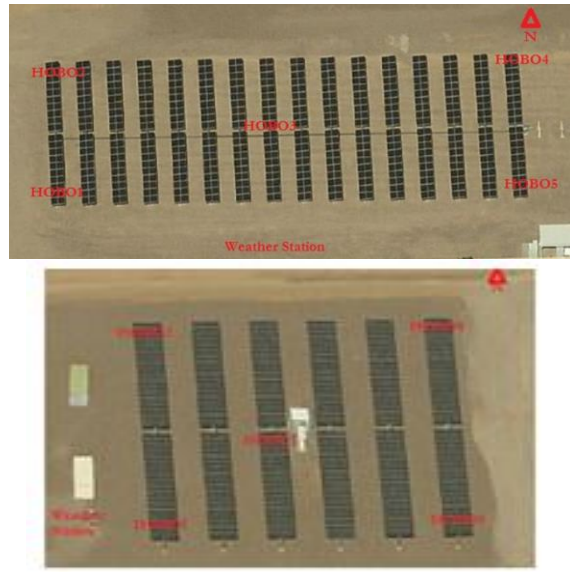


Fig. 3. Thermal mapping at five locations (AZ3 and AZ5 power plant)

Each data logger was recording four temperatures per IEC 61853-2 standard [3] for each of the five modules in the plant. The temperature data recorded by HOBO data loggers was retrieved by using HOBO software and converted into an Excel file type. MATLAB was used to interpolate and map the data values on a grid representative of PV module and a power plant.

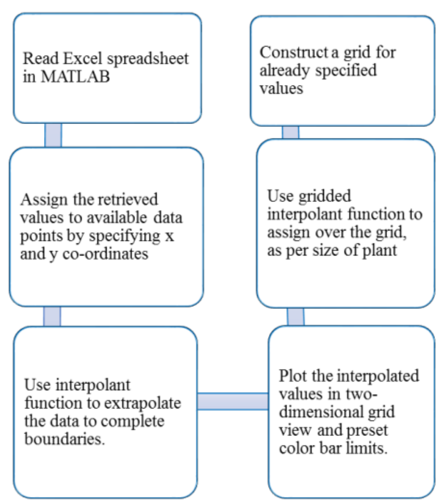


Fig. 4. MATLAB program flowchart

The flowchart representing various steps involved in MATLAB program code is as shown in Fig. 4.

For the analysis of variance (ANOVA) of the five individual modules in each plant, a fixed effect model was performed to study the significance of various factors and their interactions on the module temperature. The three factors (PV technology, electrical condition and thermocouple locations) with different levels were studied through ANOVA design. For the ANOVA of the two individual power plants, the three factors (power plant type, module and thermocouple locations) with different levels were studied on a clear sunny and a cloudy day. The average irradiance recorded from 9 am to 5 pm on a clear sunny day was 940 W/m^2 and that on the cloudy day was 329 W/m^2. The average wind speed recorded on clear sunny day was 2 m/s while that on a cloudy day was 4 m/s.

III. Results and Discussion

3.1. Module-level thermal uniformity

3.1.1 Temperature uniformity: Dependence on thermocouple location and thermal insulation type

Fig. 5 shows the maximum, minimum and median temperature difference between the four thermocouple locations for each insulation type of c-Si modules. This figure also shows the dependence of temperature difference on the operating condition of the module. During these measurements, the average irradiance was in the range of 1007-1015 W/m^2, the average wind speed was in the range of 0.7-0.8 m/s and the ambient temperature was in the range of 22-24°C. The module was initially maintained at P_{max}, V_{oc} and I_{sc} conditions (for a 30-minute duration each) on a clear sunny day around noon time.

Fig. 5 indicates that there is a least variability in median temperatures, for the four thermocouples, in the black framed module, followed by the frame insulated module for both P_{max} and V_{oc} operating conditions. In addition, the least variability in maximum temperatures values within a module is observed at maximum power condition as compared to V_{oc} and I_{sc} conditions. At P_{max}, the general operating conditions of PV modules in the field, the maximum variability was observed in the non-insulated PV modules. Even though the ΔT values and operating temperatures are higher for the module with aluminum cover on back sheet, the standard deviation is found to be lower. Aluminum cover could be a good solution to improve thermal uniformity but the operating temperature shoots up very high due to blockage of the cell radiation through the backsheet. The module with aluminum cover on back sheet was exclusively compared with the conventional white back sheet module in Section 3.1.2.

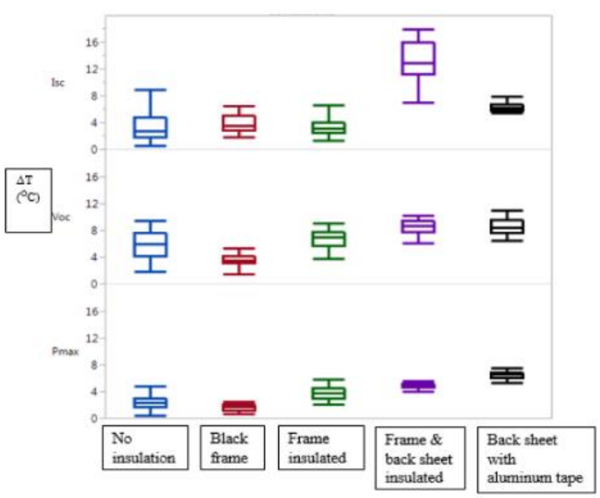


Fig. 5. Temperature difference between four thermocouples for each insulation configuration and each operating condition

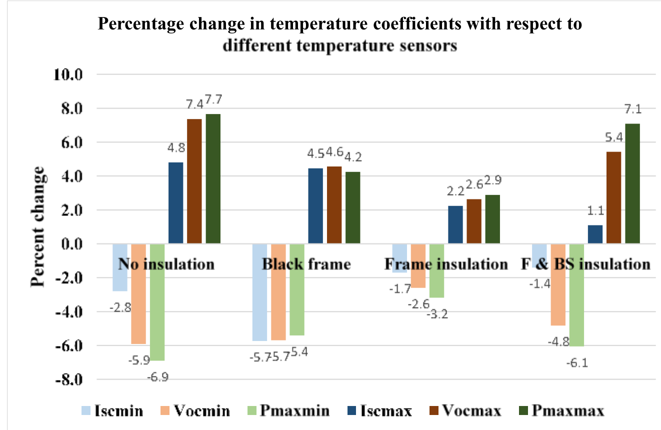


Fig. 6. Percentage change in temperature coefficients with respect to different temperature sensors

Fig. 6 represents the percentage change in temperature coefficients with respect to different thermocouples. The least deviation of about ±3 percent is observed in frame insulated modules and the maximum deviation of about ±8 percent is observed in non-insulated modules. When the frame is insulated, no longer are the edge and corner cells exposed to wind directly. This leads to less variation in the temperature across the modules, thereby resulting to least variation in temperature coefficients.

3.1.2 Effect of aluminum cover: Aluminum cover back sheet versus white back sheet module

A temperature difference as high as 15°C was observed on a clear sunny day around solar noon as shown in Fig. 7. This temperature difference was inversely proportional to the open-circuit voltage value. A temperature difference as high as 15°C was observed on a clear sunny day around solar noon as shown in Fig. 7. This temperature difference was inversely proportional to the open-circuit voltage value. The IR images were taken on a clear sunny day with irradiance= 1019 W/m^2, wind speed= 1.213 m/s and ambient temperature= 24.9°C.

In Fig. 8, the module in the bottom row is the conventional polymer white back sheet PV module and in the top row has aluminum cover on its back sheet. Analyzing the temperature

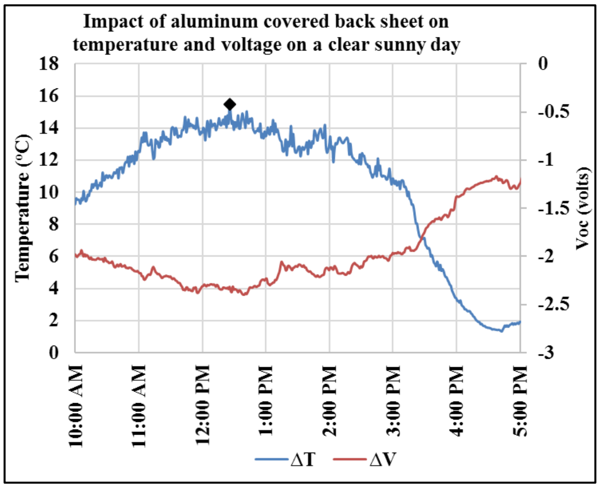


Fig. 7. Impact of aluminum covered back sheet on temperature and voltage on a clear sunny day 10am to 5pm

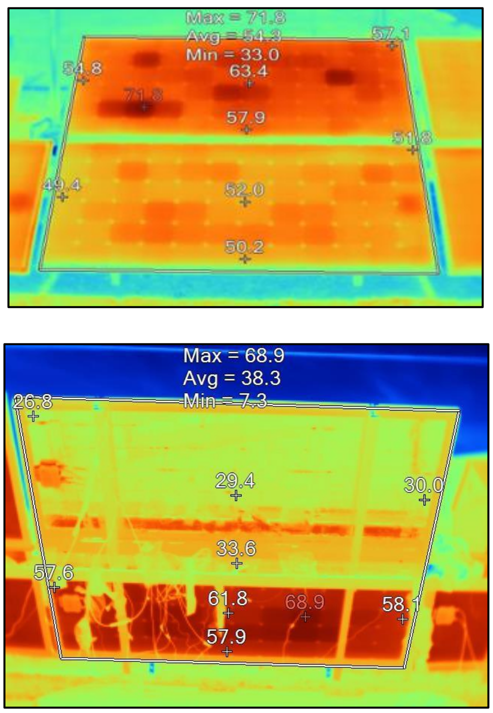


Fig. 8. Front and back side of aluminum cover back sheet and conventional polymer white back sheet PV module

values recorded and IR images, it can be said that the temperature corresponding to the blockage of radiative loss is = 61.9 - 29.4 = 32.5°C. This blocking of radiative loss causes higher operating temperatures. Since IR imaging captures only the surface radiation (not the cell temperature) of the substrate, IR image shows that the white back sheet with aluminum cover is about 32°C cooler but the cell is in fact hotter as can be seen by the attached thermocouples. Therefore, it is cautioned that the temperature determination of the aluminum covered backsheet using IR images would be misleading and cannot be correlated to the measured values.

3.1.3 Temperature coefficients: Dependence on thermocouple location

As shown in Fig. 9, there is a significant dependence of P_{max} temperature coefficient on the location of module back surface thermocouple. The temperature coefficients shown in this figure were obtained on the as-received modules before the installation of thermal insulation or adhesion of aluminum. As noted earlier, the a-Si (double junction) framed and c-Si framed modules are glass/polymer modules whereas the CdTe frameless and CIGS framed modules are glass/glass modules. It is observed that the temperature coefficient of frameless module (CdTe) experiences the least dependence on the thermocouple location of the module.

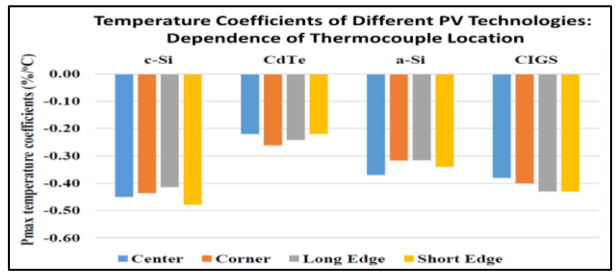


Fig. 9. Dependence of P_{max} temperature coefficient on the thermocouple location of the module

3.1.4 Performance parameters: Dependence on thermocouple location

Temperature variation within a module can have significant impact on the accuracy of module performance parameters' data. For this study, the performance parameters and temperatures of all the modules (while maintaining under MPPT thermal condition at the times when I-V curves are not taken) were continuously monitored for minimum two clear sunny days using the multi-curve tracer. As shown in Fig. 10, about 8% temperature variation between the thermocouples in c-Si and CIGS modules has respectively caused about 2% and 1.5% variations in P_{max}. On the other hand, about 14% variations in temperature in CdTe module seem to cause about 4% variation in P_{max} values.

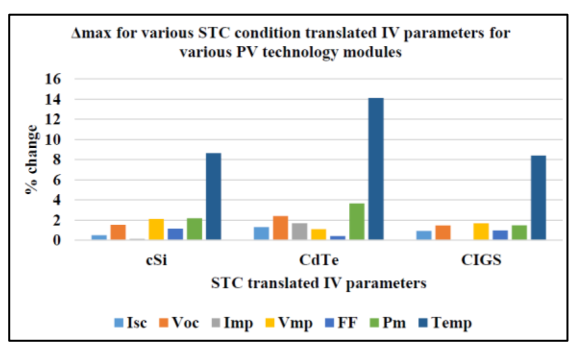


Fig. 10. Dependence of performance parameters (% change) on the thermocouple temperature (% change)

3.2. Plant-level thermal uniformity

3.2.1. The plant and module level temperature distribution

The data for AZ3 and AZ5 PV power plants, which was recorded at five-minute interval, was averaged and analyzed from 9am to 5pm daily from 04/17/2015 to 09/30/2015. Based on the temperature data obtained between 04/17/2015 to 09/30/2015, the following analysis is presented. As shown in Fig. 11, the 1-axis plant experienced higher temperature than the fixed-tilt plant.

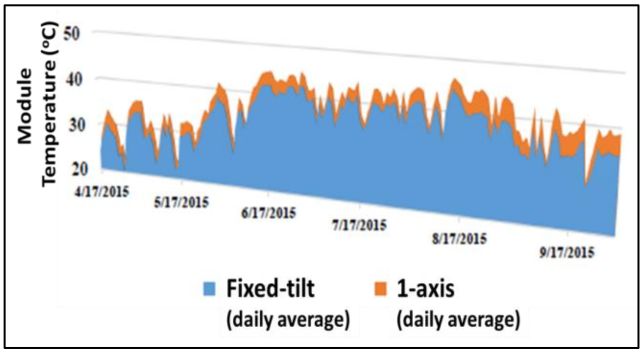
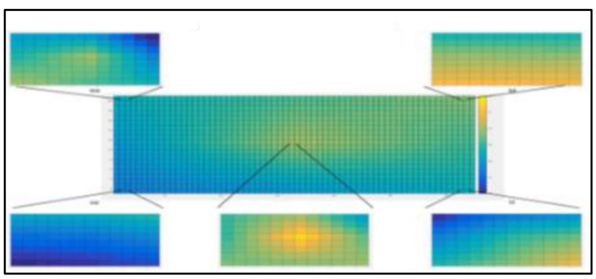


Fig. 11. Average of all five modules in two power plants

In order to study the trend further, thermal mapping was also performed on the individual PV modules (4 thermocouples per module) as well as the complete power plants (5 modules per plant) on a clear sunny day around solar noon time period from 12 to 1 pm. This is shown in Fig. 12.

In the fixed-tilt plant, it is typically observed that the modules



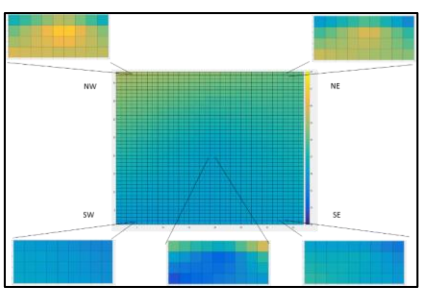


Fig. 12. Thermal mapping of AZ3 (fixed-tilt) and AZ5 (1-axis) PV plant at around noon on a clear sunny day of July 15, 2015.

in NW direction are the hottest while the module in SW direction are the coolest. In the 1-axis plant, it is typically observed that the modules in the center are the hottest, while

TABLE II

ANALYSIS OF VARIANCE (ANOVA) DESIGN SUMMARY FOR AZ3 AND AZ5 PV PLANTS ON A CLEAR SUNNY DAY

Factor	Type	Levels	Values
Plant	fixed	2	1, 3
Module locations	random	5	1, 2, 3, 4, 5
Thermocouple	fixed	4	1, 2, 3, 4

Source	DF	SS	MS	F	P
Plant type	1	0.7317	0.7317	3.67	0.073
Module locations	4	2.7835	0.6959	3.49	0.031
Thermocouple	3	0.8957	0.2986	1.38	0.296
Plant*Thermocouple	3	0.6015	0.2005	1.01	0.416
Module locations*Thermocouple	12	2.5975	0.2165	1.09	0.43
Error	16	3.1907	0.1994		
Total	39	10.8007			

TABLE III

ANALYSIS OF VARIANCE (ANOVA) DESIGN SUMMARY FOR AZ3 AND AZ5 PV PLANTS ON A CLOUDY DAY

Factor	Type	Levels	Values
Plant	Fixed	2	1, 3
Module locations	Random	5	1, 2, 3, 4, 5
Thermocouple	Fixed	4	1, 2, 3, 4

Source	DF	SS	MS	F	P
Plant type	1	8.29	8.29	5.37	0.034
Module locations	4	18.216	4.554	2.95	0.05
Thermocouple	3	17.629	5.876	3.09	0.068
Plant*Thermocouple	3	1.686	0.562	0.36	0.78
Module locations*Thermocouple	12	22.827	1.902	1.23	0.342
Error	16	24.708	1.544		
Total	39	93.358			

the modules in SW direction are the coolest. This trend appears to be mainly dominated by the wind direction.

3.2.2 ANOVA design for AZ3 and AZ5 PV plants

The ANOVA of effect model is performed further to study the effect of various factors on the temperature of AZ3 and AZ5 power plants. The three factors (power plant type, module and thermocouple locations) with different levels are studied on a clear sunny and cloudy day through ANOVA. The average irradiance recorded from 9am-5pm on a clear sunny day was 940 W/m^2 and that on the cloudy day was 329 W/m^2. The average wind speed recorded on clear sunny day was 2 m/s while that on a cloudy day was 4 m/s.

The response values are normally distributed and residual values fitted had satisfactory pattern. Table II and III represent the ANOVA design summary for AZ3 and AZ5 power plants on clear sunny and cloudy days respectively. The p value for plant type and module locations is less than 0.05 on a clear sunny day but on a cloudy day p-value only for module locations is less than 0.05. Therefore, plant type and module location has a significant effect on temperature variation on a sunny day. On the other hand, only module location has a significant effect on temperature variation on a cloudy day.

IV. Conclusions

Thermal uniformity mapping of both modules and plants have been performed through long-term monitoring studies. At the module level, center cells tend to operate at the highest temperatures and the frame-insulated modules tend to experience more uniform temperatures than the framed modules. The temperature coefficients are significantly dependent on the location of the thermocouple on the module. This dependence can be decreased by the use of black frame or insulating the frame. Based on this study, it is determined that all the cells in a module can be assumed to be operating at a single temperature if a single thermocouple is used after thermally insulating the conventional gray frame (best thermal uniformity) or if a single thermocouple is used with black frame (second best thermal uniformity) or if the average temperature of four thermocouples is used with the conventional gray frame without any thermal insulation (third best thermal uniformity). At the plant level, the center modules of the 1-axis plant and the NW modules of the fixed-horizontal plant tend to operate at the highest temperatures. Overall, the 1-axis modules experience higher operating temperatures than the fixed-tilt modules. Therefore, the degradation rate for the 1-axis modules is expected to be higher than the fixed-tilt modules. For the thermal uniformity mapping study of PV modules in powerplants, we can conclude that position (four corners or center) of the hottest modules depends on the time of the day, wind speed, wind direction and height of array. A detailed analysis of this work is presented elsewhere [4].

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