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Thermal Characteristics of Flat-Plate Photovoltaic Modules Deployed at Fixed Tilt

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ABSTRACT

The thermal characteristics of flat-plate photovoltaic modules, deployed at fixed tilt, are investigated in order to characterize their behavior against meteorological elements. For all modules above ½-sun irradiance, the difference between module and air temperatures is proportional to the solar irradiance and related by a constant of proportionality, whose specific value appears preordained by module construction—ranging 27°C to 41°C per kW/m^2. At high irradiance, these thermal characteristics are driven by the radiant power. When low irradiance occurs under clear-sky conditions, the average temperature differences per unit irradiance become small and can exhibit negative values. Greater module reflectance, resulting from larger angles of incidence to the sun, coupled with radiant heat loss to the sky determine the thermal properties in this regime. Conversely, when low irradiance conditions arise from the obscuration of the sun by clouds, the thermal characteristics are similar to or larger than those at high irradiance.

1. Introduction

Because operating conditions typically encountered in the field rarely emulate standard reporting conditions, determining realistic energy-production capacities for photovoltaic (PV) modules remains a challenge. Recently, methodologies for deriving energy ratings have been developed at the National Renewable Energy Laboratory (NREL) and at Sandia National Laboratories. Operating module temperature is a critical parameter that enters these energy-ratings methods. Hence, accurate characterization and prediction of the thermal behavior of PV modules from the prevailing meteorological conditions become essential tasks in determining energy production capacities.

2. Experimental

Eleven PV modules, representing all existing flat-plate terrestrial technologies were studied: four crystalline silicon (c-Si) modules; two amorphous silicon (a-Si) modules (one a single-junction and the other a triple-junction); two cadmium telluride (CdTe) modules; one poly-crystalline silicon (poly-Si) module; and two copper indium diselenide (CIS) modules. These modules are deployed on the Performance and Energy Ratings Testbed (PERT) situated on the roof of the Outdoor Test Facility at NREL. PERT modules are mounted on a steel structure at fixed plane-of-array (POA) tilt with respect to the horizontal, set to latitude (40°±1°), facing due south (±2°). The mounting structure resembles one-half side of an A-frame roof, in which the roof angle is 40° and defined by the modules. It allows air to circulate on both sides of the modules, albeit, airflow on the backside is partially obstructed by the building. PERT modules are connected to data acquisition systems that monitor their I-V characteristics, module temperatures and concurrent meteorological conditions including POA irradiance and wind speed. Another meteorological measurement station—located in the array field about 60 m away—was used to augment the PERT data. For this analysis, wind speed and irradiance data were measured about a half-meter or less in elevation above the modules; air temperatures were measured 60 m away.

3. Results

Fig. 1 portrays the difference between module and air temperatures ($\Delta T = T_{MOD} - T_{AIR}$) plotted against wind speed in any direction along the horizontal plane, and for data within two irradiance ranges about 1000 and 500 ±25 W/m^2. The straight-line fits to these data are also depicted as either dashed or solid lines. This figure illustrates two tenets of module thermal characteristics: ΔT is a decreasing function of wind speed and an increasing function of solar irradiance. For all data measured at or above 500 W/m^2, the intercept of ΔT at zero wind speed is very nearly a linear function of irradiance—the intercepts in Fig. 1 are ~18° C and ~39° C at 500 and 1000 W/m^2, respectively. Henceforth, it is useful to characterize thermal characteristics by temperature difference divided by POA solar irradiance (ΔT/Irr) and to analyze its behavior against meteorological conditions.

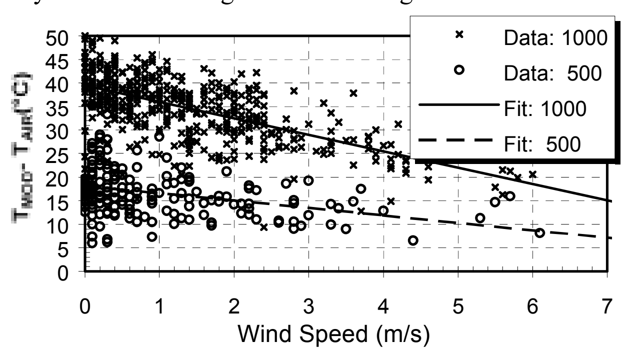

Fig. 1. Difference between module and ambient temperatures versus wind speed, for two data sets within two irradiance windows centered about 500 and 1000 ±25 W/m^2.

The module thermal characteristics (ΔT/Irr) were analyzed by segregating the data into 50 W/m^2-wide irradiance bins and performing least-squares fitting of the data within each bin to a linear function in wind speed. The constant term from this fit represents the intercept of ΔT/Irr with zero wind speed. These data are depicted in Fig. 2 along the abscissa, plotted against irradiance along the ordinate, for seven out of the eleven modules investigated.

Additionally, the data in Fig. 2 have been filtered to reflect largely clear-sky illumination conditions, using a statistical filtering method. Fig. 2 shows that above 500 W/m^2 irradiance for all modules, the intercept values of ΔT/Irr are primarily constant and span 27°–41°C/(kW/m^2) in values. Each module type develops a specific preordained value that is only slightly moderated by radiant thermal emission. Average module (zero wind) temperatures can be obtained from this graph: the product of respective ΔT/Irr values times the irradiance plus the air temperature. For a-Si #4737 for example, at 1000 and 500 W/m^2, the module is ~40°C and ~20°C hotter than the air temperature, respectively, at zero-wind speed. Toward lower irradiance, ΔT/Irr values diminish and can become negative, which can be ascribed to a combination of greater module reflectance at larger angles of incidence—angle between the direction to the sun and the vector normal to module surface—coupled with relatively high (in comparison to incident irradiance) radiant thermal emission from the module under clear-sky conditions.

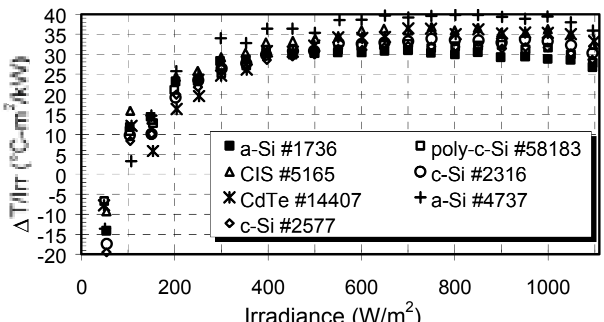

Fig. 2. Intercepts of ΔT/Irr data at zero-wind speed analyzed by irradiance bins, versus average irradiance within each bin, under predominantly clear-sky conditions, for seven PV modules.

The linear slopes of ΔT/Irr with wind speed, computed within 50 W/m^2-wide irradiance bins for the same seven PV modules, are portrayed in Fig. 3, plotted against irradiance. These data were filtered in order to include predominantly clear-sky conditions. Wind data include all directions in the horizontal plane. These data show that above 400 W/m^2, the slopes are negative and range –2.5° to –5 °C per kW/m^2 per m/s. For example, a slope of –3 units indicates that for every 1 m/s increment in wind speed, ΔT/Irr diminishes by 3°C/(kW/m^2)—equivalently, cooling the modules by 3°C and 1.5°C at 1000 and 500 W/m^2, respectively. These slopes represent the low-wind speed, linear approximation to the convection coefficients, since for moderately to very high

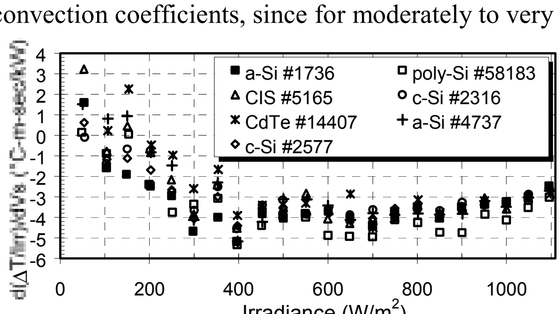

Fig. 3. Slopes of ΔT/Irr with wind speed analyzed by irradiance bins, versus average irradiance in each bin, under predominantly clear-sky conditions, for seven PV modules .

wind speeds (>10 m/s), their application predicts increasingly negative ΔT, contrary to expectation. Negative ΔT does occur as depicted in Fig. 2, but generally only at very low irradiance when under clear skies—corresponding to high angle of incidence between the modules and the sun. Toward lower irradiance in Fig. 3, the slopes appear to increase to positive values—which is likely an artifact of the linear approximation that reflects the decrease and change in sign of ΔT/Irr at low irradiance. Because increasing wind speed must oppose increases in the magnitude of ΔT, the slopes appear to mirror the behavior of ΔT/Irr.

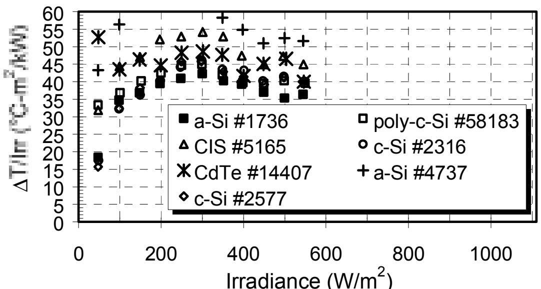

Fig. 4. ΔT/Irr data intercepts at zero-wind speed analyzed by irradiance bins, versus average irradiance in each bin, under predominantly cloudy-sky conditions, for seven PV modules.

Fig. 4 depicts ΔT/Irr intercepts at zero wind speed for the same seven PV modules, when the analysis is carried out for data that portrays predominantly cloudy-sky conditions by using a statistical filtering method. These data are generally limited to low-irradiance values, because cloudy-sky conditions primarily diminish the irradiance. Fig. 4 shows that when low irradiance conditions are produced in this manner, the corresponding values of ΔT/Irr are much larger than those obtained at low irradiance under clear-sky conditions, and similar to or larger than those obtained under clear-sky conditions at high irradiance.

4. Analysis and Conclusions

For modules deployed at fixed tilt, radiant solar power drives their thermal characteristics (ΔT/Irr) above 500 W/m^2 irradiance, forcing average differences between module and air temperatures to be directly proportional to the irradiance and related by constants ranging from 27° to 41°C/(kW/m^2) in values dependant upon module construction. Coefficients were presented that indicate cooling effects spanning 2.5°–5 °C/(kW/m^2) per 1 m/s wind speed for all modules above 400 W/m^2. At lower irradiance, the thermal behavior depends upon the cause of low illumination. If it is due to cloudy versus large angle-of-incidence conditions, the ΔT/Irr values will be 10°–20 °C/(kW/m^2) larger, or 10°–40 °C/(kW/m^2) smaller, respectively, than values at high irradiance. This distinction is likely because of the importance of radiant thermal emission from the modules and ground up to the sky. Under clear skies, a large fraction of radiant heat is lost into space, leading the modules to cool off faster than the ambient air and resulting in negative ΔT/Irr values. When skies are cloudy, more of this thermal emission—long-wavelength IR largely invisible to the pyranometers—is reflected back, resulting in much larger ΔT/Irr values.