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On PV module temperatures in tropical regions

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Abstract

Influencing factors, including rooftop material, ventilation, module framing and other environmental conditions on module temperature of selected photovoltaic (PV) systems in Singapore have been analyzed in detail. The variance of module temperature has turned out to be much larger than the variance of ambient temperature on the different project sites. From the analysis of the influencing factors, guidelines for PV system installations are derived in order to achieve lower module temperatures, eventually leading to an optimized system performance in tropical regions.

Keywords: Photovoltaic modules; Module temperature; Tropical regions

1. Introduction

The efficiency of photovoltaic (PV) modules is strongly affected by their operating temperature. Typically for every 1 °C increase of module temperature, there is a ~0.45% drop of module efficiency for crystalline silicon modules (Mau and Jahn, 2006; Skoplaki and Palyvos, 2009a). For thin-film modules, this efficiency loss is only about half of that of crystalline silicon technology.

There are several models that describe the correlation between module temperature and weather variables such as ambient temperature, irradiance and wind speed, with a good summary given by Skoplaki and Palyvos (2009b). The simplest and the most widely used model is given by:

$$T_{mod} = T_{amb} + kG_{mod}, \quad (1)$$

where T_{mod} and T_{amb} are module and ambient temperatures, respectively; the slope k is called the Ross coefficient which expresses the temperature rise above ambient with increasing irradiance (Ross, 1976). Earlier values of k were reported in the range of 0.02–0.04 °C m^2/W (Buresch, 1983), with $k = 0.025$ °C m^2/W being the most broadly accepted value (Sauer and Kaiser, 1994). This range was extended upwards to 0.02–0.055 °C m^2/W by a more recent IEA study (Nordmann and Clavadetscher, 2003), categorizing the results qualitatively according to level of integration and size of air cushion (if any) behind the modules.

The above models with constant k hold for no wind and no electric load. Griffith et al. (1981) pointed out that with regard to the relevant weather variables, the k value is extremely sensitive to wind speed, less so to wind direction, and practically insensitive to the ambient temperature level. If wind effects cannot be neglected, an additional relation to wind speed or even a thermal model based on heat transfer and balance equations has to be applied to achieve a more accurate result. Two such models have been verified by Koehl et al. (2011) through experimental analysis to give relatively good predictions of module temperatures, if long-term time series of the following three climatic parameters are available: ambient temperature, irradiance and wind speed. Generally, there are two kinds of thermal models:

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Nomenclature

G_{mod}	in-plane irradiance on modules (W/m^2)	ΔT	$T_{mod} - T_{amb}$ (°C)
k	Ross coefficient (°C m^2/W)	ΔT_{mod}	T_{mod} changes with irradiance (°C)
T_{mod}	module temperature (°C)	ΔT_{amb}	T_{amb} changes with irradiance (°C)
T_{amb}	ambient temperature (°C)		

the static and the dynamic. The static models assume the holding of a steady-state heat balance at any moment, from which many correlations between module temperature and weather variables are derived (Mattei et al., 2006; Skoplaki et al., 2008). Following the basic laws of thermodynamics, Kurnik et al. (2011) proposed a set of nonlinear equations to describe four different energy flows: solar energy that enters the PV module, electrical energy produced by the module, infrared radiation exchange and the energy flow due to conduction and convection between the module and the ambient. They build the framework to solve for the module temperature. The dynamic models also take into account the transition phase between two steady-state heat balances. With differential equations, it gives much more accurate results (40% improvement in RMSE) than static models (Amy de la Breteque, 2009), although it is not trivial to derive the necessary model parameters.

It should be noted that all studies mentioned before were conducted in higher latitudes. Trinuruk et al. (2009) investigated the suitability of some models under the tropical climate in Thailand, but their work is for building integrated photovoltaics (BIPV) only. Not much work has been reported for tropical regions especially with respect to the influencing factors on module temperatures. Such research becomes even more important as many countries in and near the tropics have started support schemes with hundreds of megawatts of PV installations expected over the next few years (e.g. India, Thailand, Malaysia, Philippines). So for tropical regions, it is therefore increasingly important to understand what will affect the module temperature and how to best control it. This paper gives the results of an analysis of module temperatures of 16 different PV systems in tropical Singapore (also comparing them to systems in Europe), and eventually suggests some guidelines for the installation of PV systems aiming for lower module temperatures.

The paper is organized as follows: Section 2 introduces the 16 PV systems across Singapore, which are under constant monitoring by the Solar Energy Research Institute of Singapore (SERIS). Based on these measurements, Section 3 analyzes the module temperatures in various PV systems in Singapore with a comparison with non-tropical systems given in Section 4. Section 5 discusses the reasons for the differences in module temperatures. Section 6 gives some guidelines for system design and installation in how to achieve reduced module temperatures in tropical climates for an optimized system performance. Conclusions are drawn in Section 7.

2. Measurement setup

The PV systems under SERIS' monitoring are all mounted on rooftops. A broad variety of locations around the island (see Fig. 1) with different system sizes and module technologies has been selected, with the aim of making sample as representative as possible. Further information about these systems can be found in Table 1, with the "roof distance index" explained in Table 2. There are two types of roof – PV array relationships for the monitored systems: (1) inclined roof with PV array mounted in parallel; (2) flat roof with tilted PV array on top. In case (1), the "roof distance" reflects the actual distance between the roof and the inclined PV array. In case (2), the "roof distance" equals the averaged distance between the roof and the PV array. Besides measuring the in-plane irradiance with silicon sensors calibrated at Fraunhofer ISE's CalLab and electrical variables on both DC and AC sides, module temperature and ambient temperature are recorded with PT-100 temperature sensors. For module temperature measurements, the PT-100 is attached to the back side of the module at its center with further protection cover using thermal tapes; while for ambient temperature measurement, the PT-100 is put close to the modules with a weather shield protecting the sensor against direct sunlight and rain. Wind speed is not measured in the monitoring setup since the mean daily wind speed in Singapore is relatively small, ranging from 1.3 to 2.5 m/s only, according to 69 years of data recording (NEA, 2010). As wind effect is negligible in Singapore, a constant parameter k in Eq. (1) is suitable to describe the

Fig. 1. Distribution and location around the island of the 12 sites (with a total of 16 PV systems) in Singapore being monitored by SERIS. Some sites have two or more subsystems.