Improved thermal modelling of the 5B MAVERICK system: impact of sky temperature

Phillip Hamer[1], Shaozhou Wang[2], Mattias Juhl[3], Moonyong Kim[1], Jack Fletcher[3], Keith R. McIntosh[4] and Bram Hoex[1]

[1]School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney, Sydney, NSW, Australia
[2]GreenDynamics, Sydney, NSW, Australia
[3]5B, Mascot, NSW, Australia
[4]PV Lighthouse, Coledale, NSW, Australia
p.hamer@unsw.edu.au

This study reports on the application of improved thermal models to the 5B MAVERICK mounting system, including consideration of radiative exchange with the sky and transient effects. The use of these models reduces errors by approximately 1ºC.

1. Introduction

The standard models used to predict module temperatures are typically simple linear relationships with plane-of-array irradiance and ambient temperature [1], [2]. These simplifications result in significant uncertainty in simulated module temperature, particularly when default coefficients are applied across different sites. Given that the module temperature is the second-most important factor (after irradiance) affecting PV system output, this uncertainty has implications for system simulation.

Two recent studies have investigated more complex models for the case of single-axis trackers, taking into account non-linear radiative heat exchange with the sky dome, as well as the use of transient models[3], [4]. These models substantially increase modelling accuracy. In this paper, we will apply these approaches to the 5B MAVERICK (MAV) mounting system.

The 5B MAVERICK is a prefabricated mounting system designed for rapid deployment. It consists of “waves” of modules with opposing 10º tilts. Due to its unique design, the MAV can allow almost little or no shading loss from other modules, despite having a high ground cover ratio. This leads to lower land use and it can be deployed at a very low costs due to a high degree of factory integration. However, as the MAV mounting system is relatively new and quite distinct from standard fixed-tilt or tracking systems, it is imperative to improve models for this technology to accurately simulate system output.

2. Methodology

Data for this study was obtained from a 5B test site located near Bungendore in NSW (35.175ºS, 149.522ºE) from September 2022 to February 2023, shown in Figure 1. While the MAV is nominally deployed with module tilts along the E-W axis in this case the modules were aligned NE-SW. This has a negligible impact on the system output. The modules are JKM315PP-72, with an efficiency under standard testing conditions of 16.23%, a thermal coefficient of -0.40%/K, and a nominal operating temperature (NOCT) of 45 ± 2 °C.

Local weather data was obtained from a weather station located ~50 m from the main site. This data includes global horizontal irradiance, POA irradiance for the two module orientations, ambient temperature, wind speed and direction (measured at 1.8m). The data is recorded at 5-minute intervals. The temperature of modules was monitored using four thermocouples attached to their rear, along with a fifth sensor located in the air space underneath. These sensors provide data at slightly irregular intervals, typically 3 minutes. System output data was monitored at the inverter level, with DC current, voltage and power monitored at 5-minute intervals.

Figure 1: Birds-eye view of the site

Downwelling data on a horizontal plane was obtained from the ERA5 reanalysis dataset, accessed from the climate data store[5]. This data is relatively low resolution (approx. 8km pixel size) and on an hourly basis. Simulations were performed on a 5-minute basis, with linear interpolation used for data using differing timesteps.

Data cleaning was performed using the pvanalytics package in pvlib-python[6] to detect sensor faults as well as data outside physical limits. Custom routines were also developed to detect and remove data associated with hardware faults. Figure 2 illustrates some of the data excluded through this process. In this case data was excluded where the sensor gave lower readings throughout the middle of the day than the measured ambient temperature. Site inspection revealed that the sensor had detached.

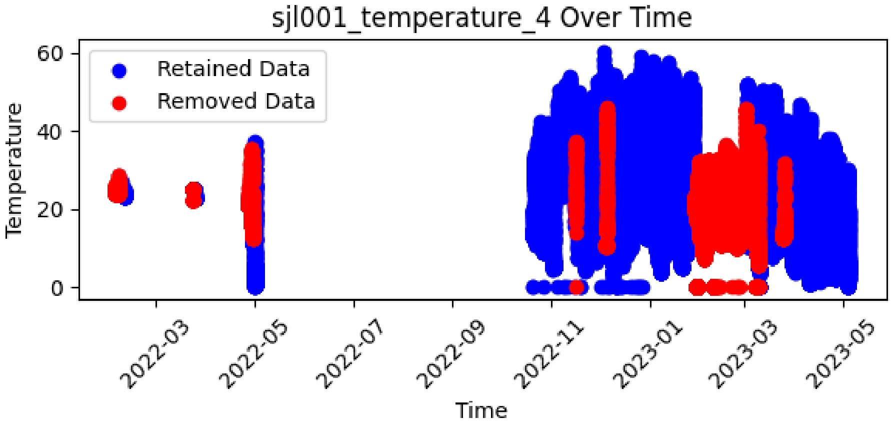

Figure 2: Temperature data cleaned for hardware error

The total heat into the modules is described by the following equation:

$$Q_{in} = \Phi_m(\alpha - \eta) \qquad (1)$$

Where Φ_m is the plane-or-array irradiance on the front of the modules, α is the absorption coefficient of the modules, assumed to be 0.9 and η is the module efficiency. For this site the inverters were undersized, resulting in clipping throughout the middle of the day. Therefore, the equation was modified as follows:

$$Q_{in} = \Phi_m \alpha - \frac{P_{electrical}}{A_{module}} \quad (2)$$

$$P_{electrical} = \frac{P_{inv.dc}}{N_{modules}} \cdot \frac{2\Phi_m}{\Phi_m + \Phi_{opposite}} \quad (3)$$

Where A_{module} is the module area, $P_{inv.dc}$ is the DC power measured at the inverter, $N_{modules}$ is the number of modules connected to the inverter and $\Phi_{opposite}$ is the POA measured irradiance for the modules of opposing alignment. This is required as modules facing both directions were connected to the same inverter. This allows the use of data during periods of inverter clipping, while introducing additional errors.

Thermal energy emitted by the modules was modelled according to the following equations:

$$Q_{out.Faiman} = (T_{module} - T_{ambient}) \cdot (U_C + U_V \cdot ws) \quad (4)$$

$$Q_{out.sky} = vf \cdot \varepsilon \cdot \left(\sigma T_{module}{}^4 - q_{dr}\right) \quad (5)$$

Where T_{module} is the simulated module temperature, $T_{ambient}$ is the ambient temperature and ws is wind speed. vf is the effective view factor (approximated after Dreisse et al.[4] as 0.989), ε is emissivity, assumed to be 0.88, σ is the Stefan-Boltzmann constant and q_{dr} is long wavelength downwards radiation on a horizontal plane from ERA5 data. U_C and U_V are the fitting parameters. For the Faiman models $Q_{out.sky}$ was neglected. Fitting was performed based on least squares minimization in Python. Transient calculations were performed considering a module mass of 26.5 kg and a specific heat of 833 $J.kg^{-1}.K^{-1}$ as used by McIntosh et al.[3].

3. Results and discussion

Table 1 presents the fitted coefficients, U_C and U_V, as well as the mean bias error (MBE) and corrected root mean square error (CRMSE) for each model. The simplest model used was the PVSyst default setting for an open rack which neglects the effects of wind speed. This method is intended to simulate cell temperature and so the Sandia cell to module conversion was used. The Faiman module, using either default or fitted coefficients, includes U_V to account for the effects of wind speed. Finally radiative transfer according to eq. 5 was used for both the steady state and transient sky simulations without introducing any additional fitting variables. The mean-bias errors present for the fitted models is a result of including overnight data.

Table 1 Coefficients and error metrics for thermal models applied to measured data

Model	**U_C**	**U_V**	**MBE**	**CRMSE**
PVSyst Default	29	0	+1.56	2.63
U_C Fit	30.2	0	+1.27	2.73
Faiman Default	25	1.2	+2.45	2.46
Faiman Fit	25.7	3.4	+1.29	2.5
Faiman Transient	24.7	3.6	+1.37	2.26

Faiman + Sky	15.9	2.8	-1.07	2.14
F+S Transient	14.8	3.0	-1.08	1.73

Figure 3 below presents scatter plots for models based on the basic Faiman model, and those that include radiative heat transfer. The primary impact of including sky transfer is more accurate simulation during periods of low module temperature, particularly overnight. Considering transient effects greatly reduces the scatter in the results.

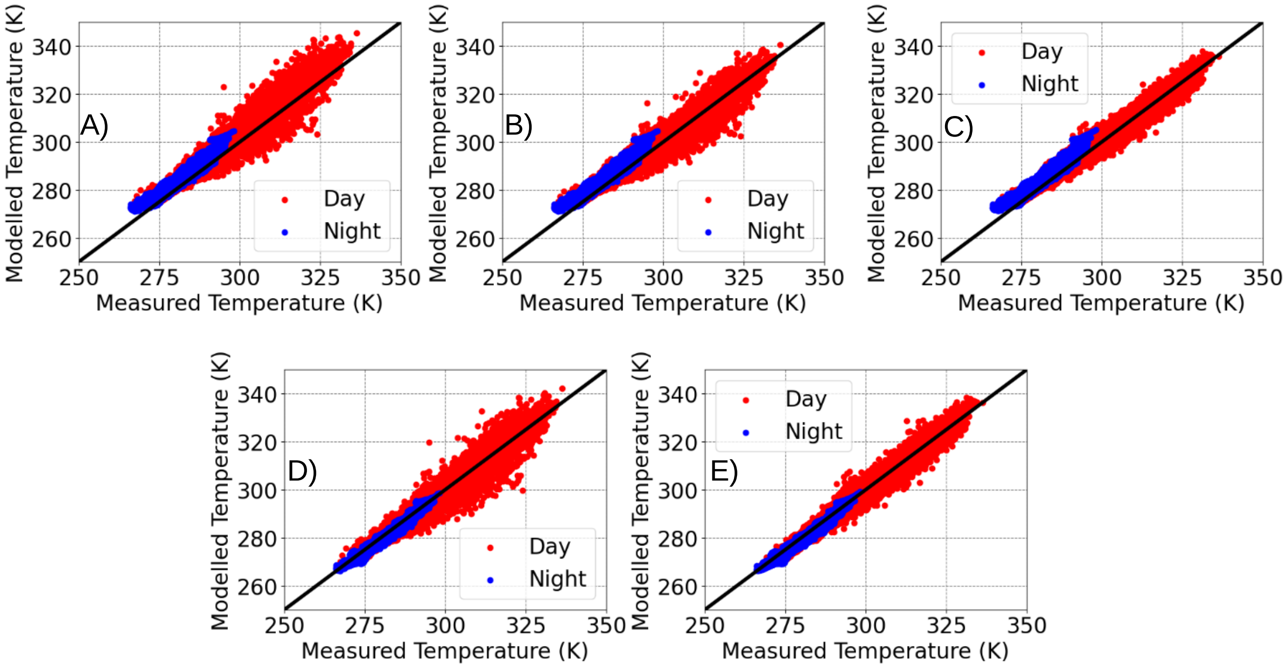

Figure 3. Predicted vs measured Tm for various thermal models. A) Faiman Default, B) Faiman Fit, C) Faiman Transient, D) Faiman + Sky, E) F+S Transient

Conclusion and Future Work

It is instructive to compare the coefficients obtained in this work with those for a SAT system reported by McIntosh[3], despite the fits being performed for different locations. The U_C (14.8 c.f. 15.0) and U_V (3.0 c.f. 3.4) values are only slightly higher. This means that modules mounted on MAV's will generally have lower operating temperatures, due to reduced plane-of-array irradiance.

It is possible that these models might be improved with more detailed fitting, while further data will also improve the process. Fitting will also be carried out for MAV's installed at this site and others to investigate if the model can be broadly applied. Finally, assumptions around sky temperature, and their impact on results will be explored.

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