CFD modelling of the 5B MAVERICK system and temperature variations across PV modules

Svetlana Tkachenko[1], Phillip Hamer[2], Tingyi Zhang[1], Ruby Klisser[1], Zibo Zhou[2], Charitha de Silva[1], Victoria Timchenko[1], Bram Hoex[2]

[1]*School of Mechanical and Manufacturing Engineering, UNSW, Kensington, NSW, 2052*
[2]*School of Photovoltaic and Renewable Energy Engineering, UNSW, Kensington, NSW, 2052*
svetlana.tkachenko@unsw.edu.au

The operating temperature of photovoltaic modules is the second most important (after plane-of-array irradiance) parameter affecting their output, for every degree increase in temperature, the module efficiency decreases by 0.3-0.4%. Despite the importance of this parameter, temperature models in solar plant yield calculations are imprecise, with typical uncertainties over 5^{o}C. Computational fluid dynamics numerical studies are presented for the 5B MAVERICK system, showing excellent agreement with field measurements. Such calculations, while intensive, can provide more accurate inputs for simplified thermal models that are used in yield simulation software. Furthermore, temperature variations within a single module can be simulated. While it is well known that such variations exist, they are usually ignored from a modelling perspective. We present simulations quantifying the potential error this simplification may introduce, while future work will also consider the effect on module degradation. The present study calls for further investigations to increase the precision of the thermal modelling of PV modules in large-scale deployments.

Background

Photovoltaic (PV) currently has the largest share in new electricity generation globally, with 295 GW of module sales in 2022 (Jutta Trube, 2022). High operating temperatures result in reductions to the PV module's electric efficiency, driven largely by a reduction in open-circuit voltage. These reductions may be up to 0.3-0.5% of the nominal maximum power value of the module per Kelvin degree of temperature rise (Brinkworth *et al.*, 1997). Furthermore, higher operating temperatures can accelerate the degradation rates of crystalline silicon PV modules (Park *et al.*, 2013), (Ascencio-Vásquez *et al.*, 2019).

There are two common approaches in PV simulation tools for modelling device temperature. The most straightforward is Nominal Operating Cell Temperature (NOCT) method which assumes that device temperature is a linear combination of ambient temperature and irradiance. The Faiman model is slightly more detailed, taking into account device efficiency and using both constant and convective heat transfer coefficients (Faiman, 2008). However, in practice, the convective heat transfer coefficient (U_c) is often ignored. In both cases, errors frequently exceed 5°C (McIntosh *et al.*, 2022) significantly overestimating the yield and the life span.

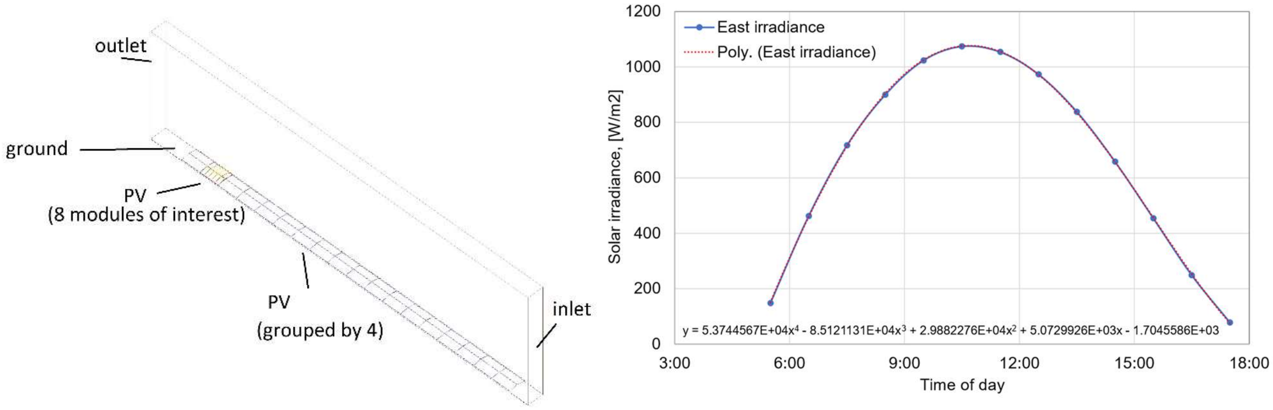
Alternatively, computational fluid dynamics (CFD) modelling, while more computationally intensive, may provide an explanation of the underlying physics (Roache, 1976). Parametric studies include scenarios not available in the field ((Jubayer *et al.*, 2016) and (Dabaghzadeh and Eslami, 2019)); ground temperature (Deardorff, 1978) and sky temperature (Notton *et al.*, 2005) can be modelled. (Zhou *et al.*, 2018) showed temperature variations of 5°C on PV surface in a standalone PV/T system. CFD allows estimating performance of PV at a new site, without requiring extensive field data collection or tuning parameters.

The temperature variations on the surface of PV modules were studied for limited cases, for instance, over 5°C variations for a single module via CFD (Dabaghzadeh and Eslami, 2019), and up to 6°C variations with a single stand-alone module in the field (McIntosh *et al.*, 2022). These variations are ignored in existing yield models, such as pvlib (Holmgren *et al.*, 2018), pvsyst, SAM, which can result in mismatch loss in voltage and degradation rates.

The present study includes field observations and numerical studies of the spatial variations of the PV module temperature, and an assessment of the resulting effects on the module yield and degradation.

Methodology

Computational fluid dynamics model of a 5B MAVERICK site in Western Australia (WA) has been developed with modules stacked in continuous rows with low module slope, making the modules easier to transport and install. Two adjacent rows of PV modules, with symmetry on boundaries, have been modelled (Figure 1 (a)). The wind magnitude, ambient temperature, and irradiance are modelled as a polynomial fit to field data, as shown in Figure 1 (b). Power law wind profile is imposed at the inlet. For radiative heat transfer modeling, the sky and ground temperature from (Hersbach *et al.*, 2020) are assumed.



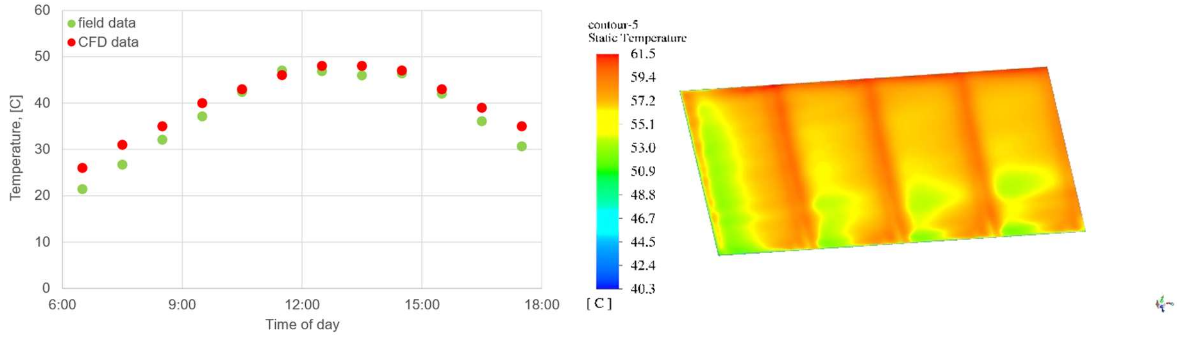
(a) (b)

Figure 1. (a) CFD computational domain and boundary conditions; (b) Field data and polynomial fit for solar irradiance on a clear day, December 4, 2021.

In order to simulate the effect of non-uniform temperature across a PV module, a Python model has been developed using the PySpice package (Salvaire, 2023). Each cell was described using the single diode model, with the current source and diode saturation current adjusted based on cell irradiance and temperature.

Results

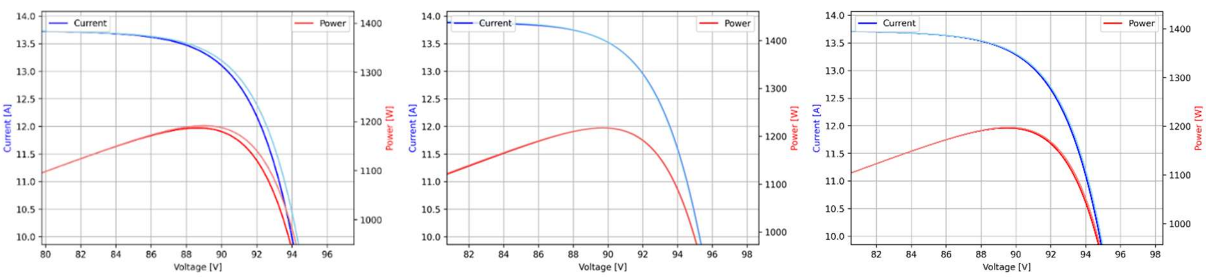
The CFD model results are comparable to the field data, as shown in Figure 2 (a), with CFD results on the temperature distribution on the PV shown in Figure 2 (b). The module temperature, influenced by flow dynamics, is higher in selected areas, where degradation is likely to increase.



(a) (b)

Figure 2. (a-b) PV module temperature (a) daily variations in a point (field and CFD data); (b) surface distribution (CFD data).

The spatial variations of PV module temperature have a negligible impact when the module cells are in series; however, there is some impact when there are parallel strings. Figure 4 presents simulations of a half-cell and full cell module in the extreme case where the top and bottom halves of the module have a temperature difference of 10°C, along with a more realistic case of 5°C temperature difference. The primary impact of increased temperature on the cell I-V curve is a reduction in the open-circuit voltage. Therefore, when cells are in series, mismatch issues are negligible, and the output of the string matches closely with simulations using the average temperature. Since all cells in a full-cell module are in series, the average temperature is adequate to simulate the output. However, for the half-cell module, the mismatch between strings at the top and bottom of the module results in a reduction in output of 0.38% relative for a 10°C difference and 0.10% relative for a 5°C difference when compared with average temperature simulations.



(a) (b) (c)

Figure 3. I-V and P-V curves of (a) half-cell and (b) full-cell modules with a top-half module temperature of 50°C and bottom half at 40°C. (c) Presents a half cell module with the top half temperature at 45°C. Illumination for all simulations was 1000 W/m^2.

Discussion/Conclusions

Fluid flow and heat transfer model has been developed and validated for a 5B MAVERICK PV site in Western Australia. An up to 10°C variation on the surface of the PV module has been observed, which may significantly impact the localized degradation rates. The CFD model can be used to provide information to improve forced convection and yield correlations used in the industry, and to estimate performance of a new site. According to field data, such as (McIntosh *et al.*, 2022), the temperature variations are higher with lower tilt, in 2P than in 1P SAT, and with lower wind speeds.

The CFD simulations can also be used to determine temperature variations across the modules themselves, which can lead to electrical mismatch between parallel strings. While under most conditions this mismatch will be a minor effect, which has been estimated to result in 0.1% to 0.4% reduction in electric output, a further consideration is that temperature is an important driver of degradation within solar modules. This could potentially lead to differing rates of degradation of different cells and to the associated resulting mismatch losses.

References

Ascencio-Vásquez, J., Kaaya, I., Brecl, K., Weiss, K.-A., and Topič, M., 2019, Global Climate Data Processing and Mapping of Degradation Mechanisms and Degradation Rates of PV Modules. Energies, 2019. 12, DOI: 10.3390/en12244749.
Brinkworth, B. J., Cross, B. M., Marshall, R. H., and Yang, H., 1997, 'Thermal regulation of photovoltaic cladding ', *Solar Energy* 61(3): p169 - 178.
Dabaghzadeh, N. and Eslami, M., 2019, 'Temperature distribution in a photovoltaic module at various mounting and wind conditions: a complete CFD modeling', *Journal of Renewable and Sustainable Energy*, 11(5).
Deardorff, J. W., 1978, 'Efficient prediction of ground surface temperature and moisture, with inclusion of a layer of vegetation', *Journal of Geophysical Research: Oceans*, 83(C4): p1889-1903.
Faiman, D., 2008, 'Assessing the outdoor operating temperature of photovoltaic modules', *Progress in Photovoltaics: Research and Applications*, 16(4): p307-315.
Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Munoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., and Rozum, I., 2020, 'ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS)'.
Holmgren, W. F., Hansen, C. W., and Mikofski, M. A., 2018, 'pvlib python: A python package for modeling solar energy systems', *Journal of Open Source Software*, 3(29): p884.
Jubayer, C. M., Siddiqui, K., and Hangan, H., 2016, 'CFD analysis of convective heat transfer from ground mounted solar panels', *Solar Energy*, 133: p556-566.
Jutta Trube, P. B., 2022, 'International Technology Roadmap for Photovoltaic (ITRPV). 2022 Results'.
McIntosh, K. R., Abbott, M. D., Sudbury, B. A., Aneja, S., Bowman, M., Brown, L., Kahane, B., Nicholas, N., and Nolde, K., 2022, 'The influence of wind and module tilt on the operating temperature of single-axis trackers'. in *IEEE 49th Photovoltaics Specialists Conference (PVSC)*. IEEE.
Notton, G., Cristofari, C., Mattei, M., and Poggi, P., 2005, 'Modelling of a double-glass photovoltaic module using finite differences', *Applied thermal engineering*, 25(17-18): p2854-2877.
Park, N. C., Oh, W. W., and Kim, D. H., 2013, 'Effect of temperature and humidity on the degradation rate of multicrystalline silicon photovoltaic module', *International Journal of Photoenergy*, 2013.
Roache, P. J., 1976, 'Fundamentals of Computational Fluid Dynamics'. Hermosa.
Salvaire, F., 2023. 'PySpice'. Available from: https://pyspice.fabrice-salvaire.fr.
Zhou, J., Ke, H., and Deng, X., 2018, 'Experimental and CFD investigation on temperature distribution of a serpentine tube type photovoltaic/thermal collector', *Solar Energy*, 174: p735-742.