Improved Thermal Modelling of the 5B MAVERICK

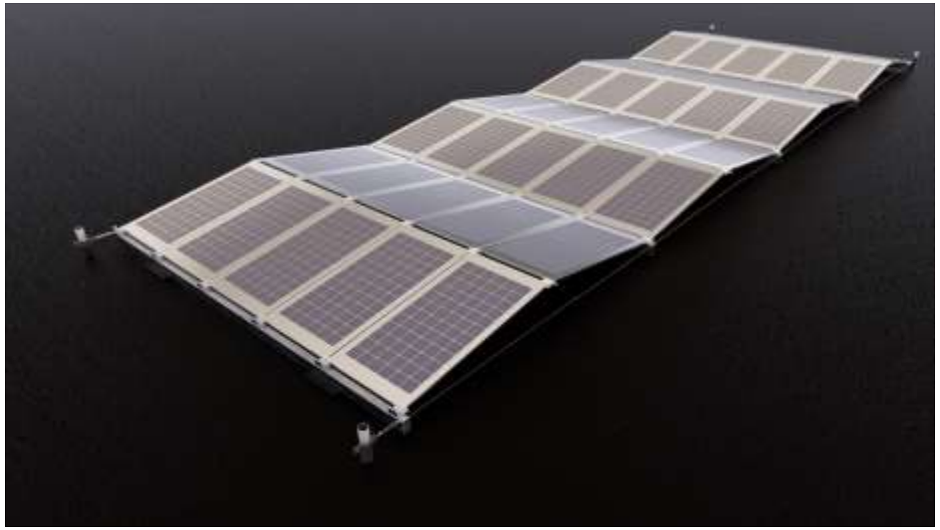
P. Hamer, S. Wang, M. Kim, M. Juhl, J. Fletcher, K. McIntosh, B. Hoex

Asia-Pacific Solar Research Conference 2023

Introduction

The 5B MAVERICK

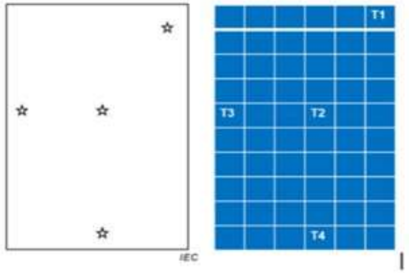
- Factory integration leads to low cost, high speed, high reliability deployment
- 79 MW installed over 140 project sites globally
- Thermal Performance?



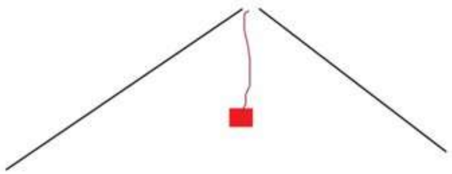
Site Details

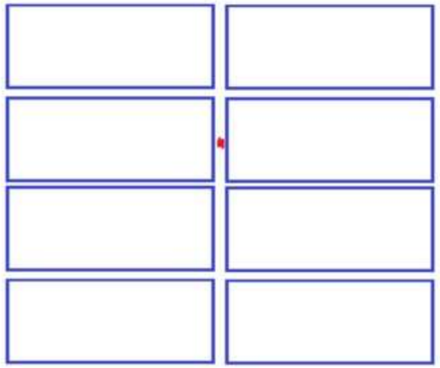
- 5B test site near Bungedore (35.175°S, 149.522°E)
- Jinko JKM315PP-2 modules (η=16.23%, thermal coefficient P_{MPP}=-0.40%/K)
- 16 strings of 19 modules each
- NE-SW alignment

Measurement Details



Positions recommended by IEC standard 61853-2 for measuring temperature of the module and how the four Jinie temperature sensors were mounted at CPLSD2.

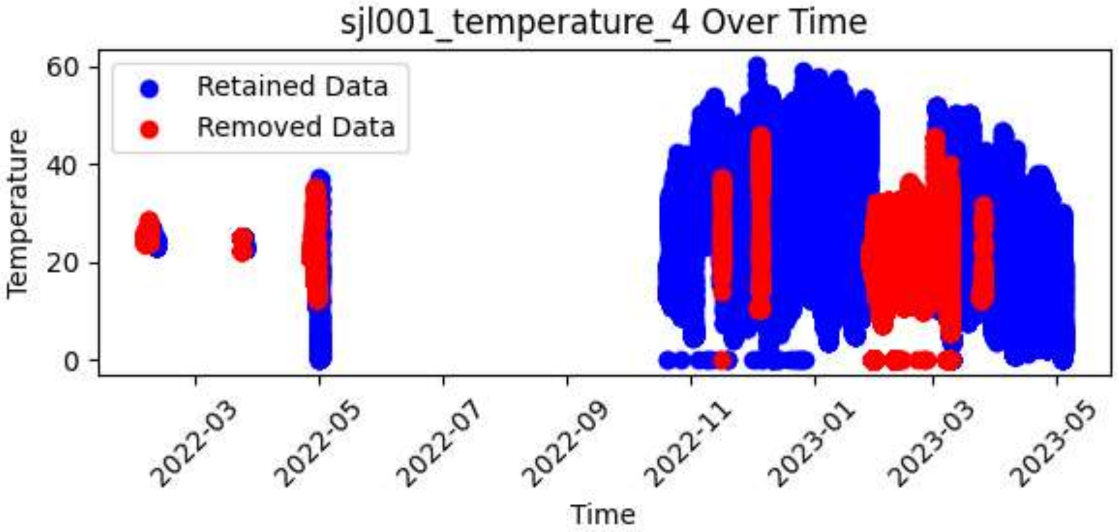


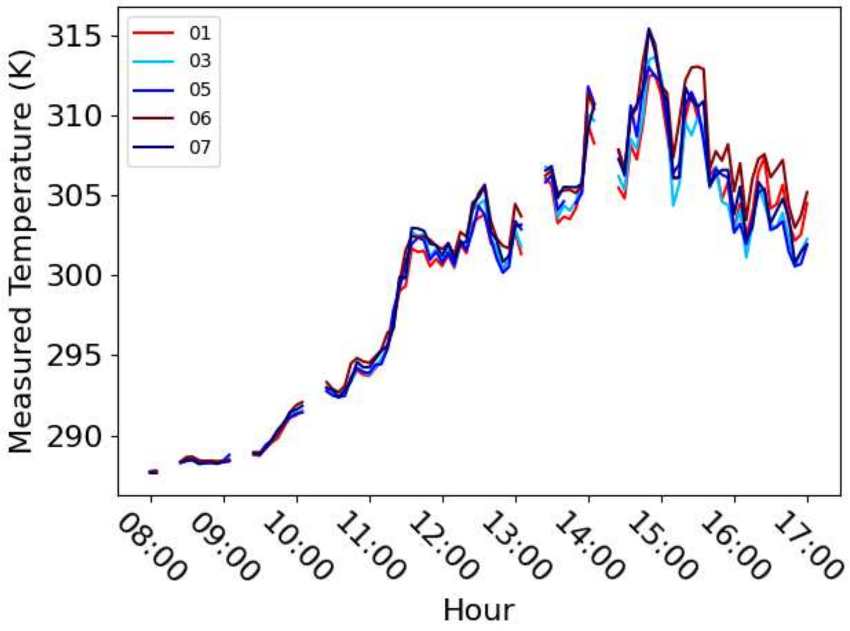


- 5 thermocouples per module, 4 arranged as per IEC 61853-2, 1 in the air-space underneath the MAV
- Current, Voltage, Power at the inverter
- Meteo station ~50m from site provides POA irradiance, ambient Temp, wind speed and direction
- Data at 3-5 minute intervals

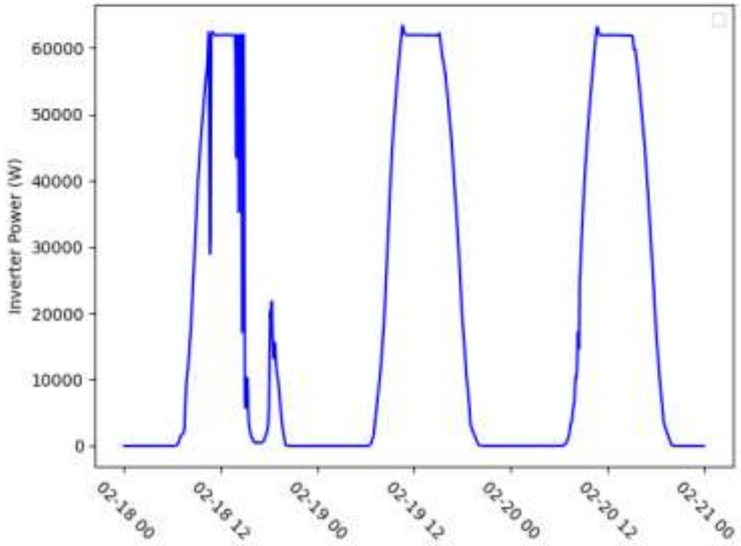
Data Cleaning

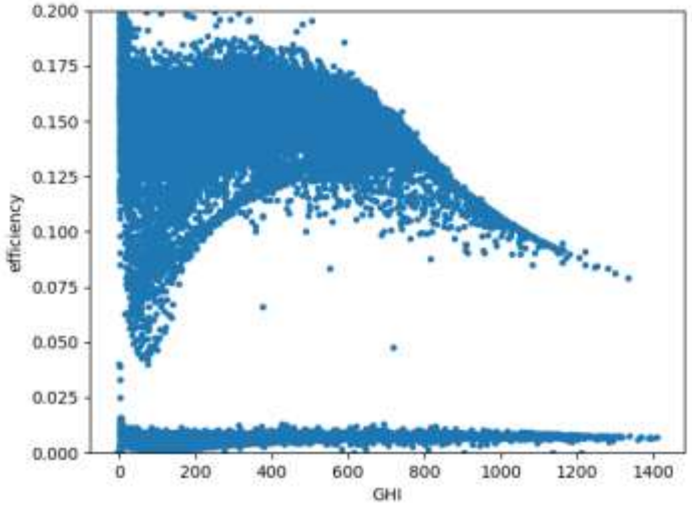
- Basic cleaning for repeated values, physical limits
- Additional cleaning for “complex technical issues”
- Data at 3-5 minute intervals, interpolated to 5 minute dataset
- Frequent gaps in data (painful for transient)





Data Cleaning





- Significant clipping observed in dataset
- Use inverter data for $Q_{out.elec}$ rather than simulated output
- 304 modules per inverter (single string)

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

Thermal Modelling: State of the Art

- Attempt to cover a wide range of conditions
  - 2.9% error in temperature losses reported at previous APSRC[1]
- Nominal Operating Cell Temperature (NOCT) - SAM

$$T_c = T_a + \left(\frac{9.5}{5.7 + 3.8 \times WS_{adj}}\right)\left(\frac{G_T}{G_{NOCT}}\right)\left(T_{NOCT,adj} - T_{amb,NOCT}\right)\left[1 - \frac{\eta_{ref}}{\tau\alpha}\right]$$

- The Faiman Model - PVSyst

$$T_c = T_a + \frac{\alpha G_T (1 - \eta_c)}{U_C + U_V \times WS}$$

default U_C=29, U_V=0 for "open" racks, U_C=27, U_V=0 for "domes"

- Biggest areas for improvement[2]: Sky temperature and transience, RMSE (4.8) 4.0 → 1.9

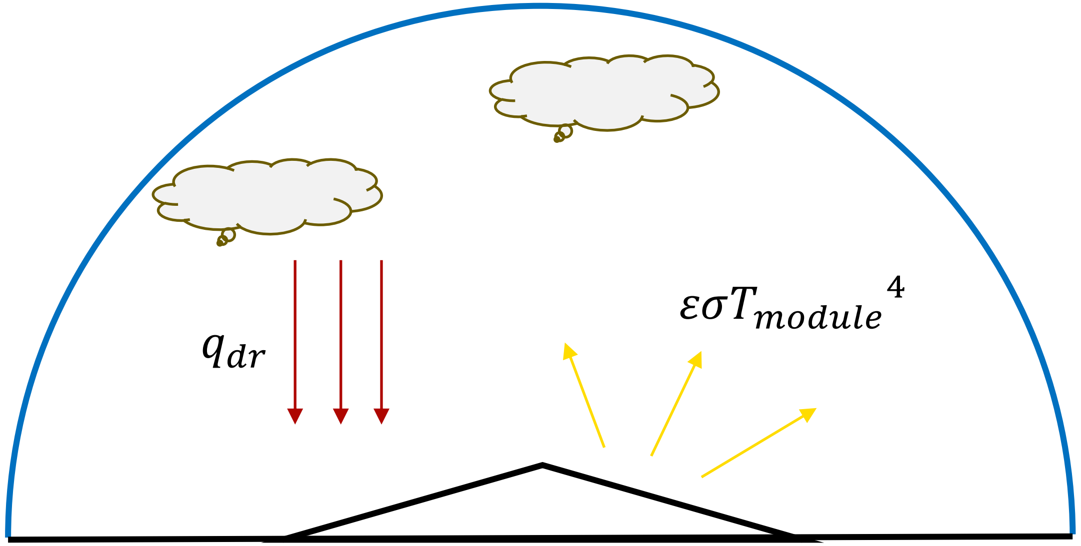
[1]Lyndon Frearson, Spectral and temperature loss characteristics of different PV technologies, *APSRC*, 2014
[2]K.R. McIntosh *et al*. The influence of wind and module tilt on the operating temperature of single-axis trackers, *49th IEEE PVSC*, 2022

Sky Temperature

- Accounts for radiative heat exchange between the modules and the sky dome
- More useful to talk about "downwelling", long wavelength radiation from the sky dome
- Dependent on ambient temperature and cloud cover

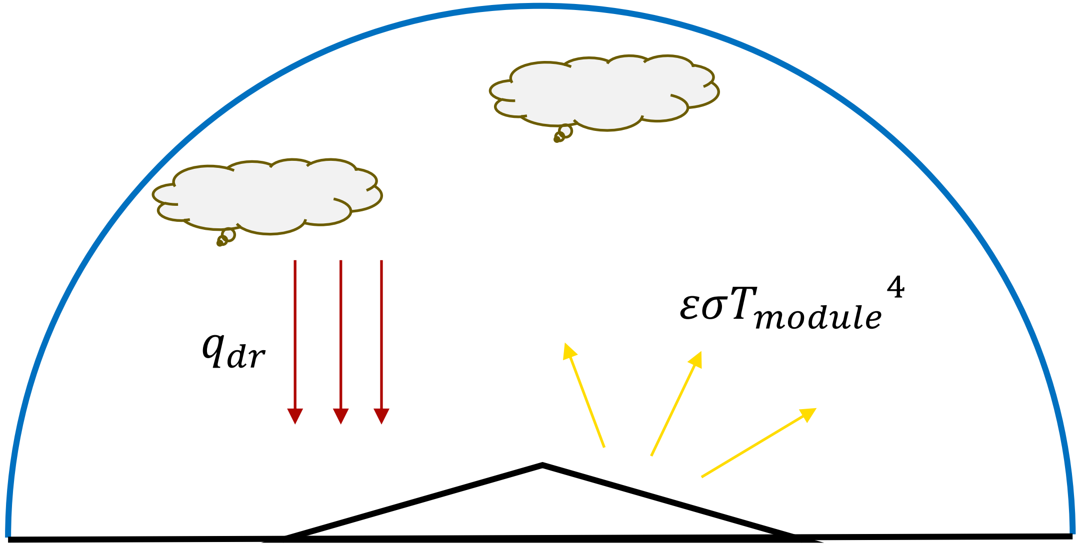
$$Q_{out.sky} = vf \cdot \varepsilon \cdot \sigma \cdot \left({T_{module}}^4 - {T_{sky}}^4\right)$$

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



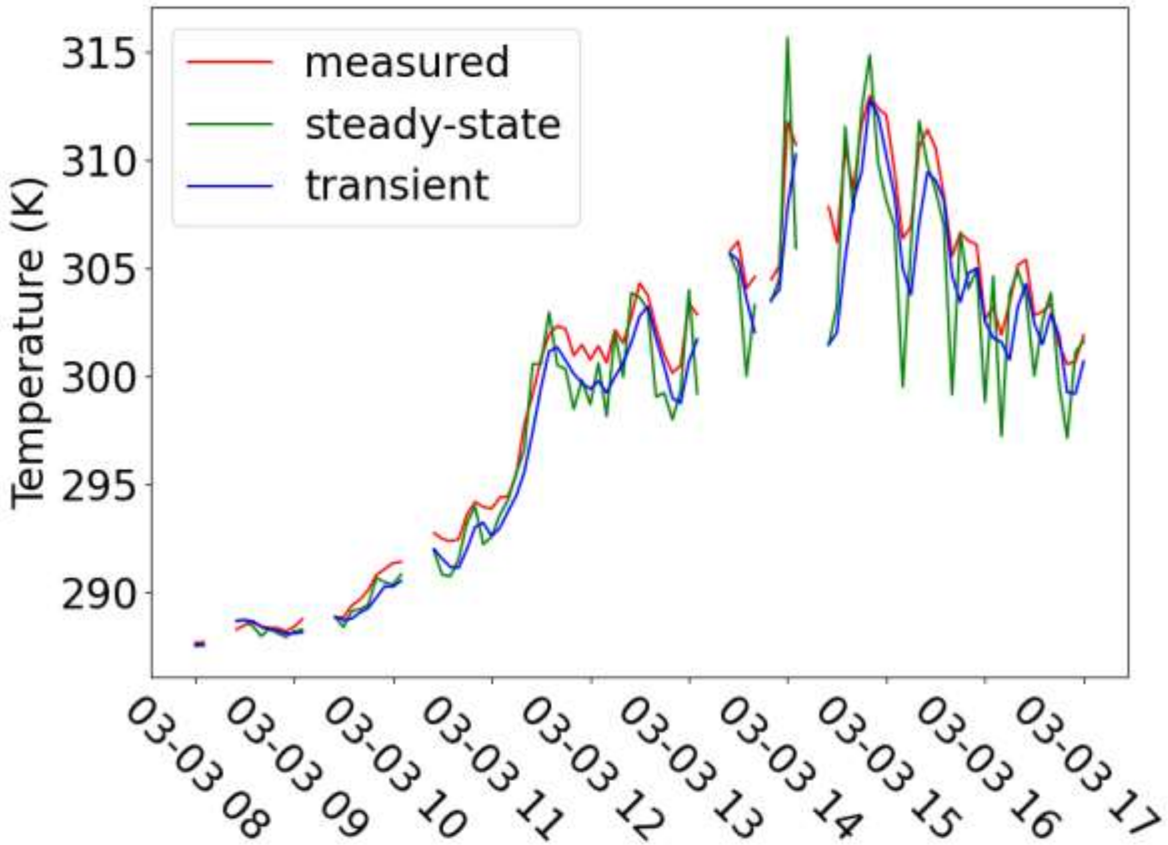
Sky Temperature

- Four approaches considered in this work:
  - Swinbank[1]: $T_{sky} = 0.0552 \cdot T_{amb}{}^{1.5}$
  - Fuentes[2]: $T_{sky} = 0.68 \cdot \left(0.0552 \cdot T_{amb}{}^{1.5}\right) + 0.32 \cdot T_{amb}$
  - ERA-5 reanalysis[3]
  - MERRA-2 reanalysis[4]
- Downwelling modified by ε and view factor after the method of Driesse *et al.*[5]



1: W. C. Swinbank, "Longwave radiation from clear skies", Q. J. R. Meteor. Soc. 89, 1963
2: M. K. Fuentes, "A simplified thermal model for flat-plate arrays", Sandia National Laboratories, 1987
3: ECMWF, "Climate Reanalysis | Copernicus", 2022, https://climate.copernicus.eu/climate-reanalysis
4: GMAO (2015), inst1_2d_lfo_Nx, doi:10.5067/RCMZA6TL70BG
5: A. Driesse *et al.*,"SANDIA REPORT Improving Common PV Module Temperature Models by Incorporating Radiative Losses to the Sky." Available: https://classic.ntis.gov/help/order-methods/

Transient Effects



- Most models assume steady state operation
- When using 1 hour timesteps this has minimal effect
- Trend towards shorter simulation periods (15 min, 5 min) as DC:AC ratios increase

$$\Delta T = \frac{1}{C_{th}}\left(\frac{Q_{in.i-1} + Q_{in.i}}{2} - \frac{Q_{out.i} + Q_{out.i-1}}{2}\right)$$

$$C_{th} = C\left(\frac{m_{module}}{A_{,module}}\right) \approx 11{,}000\ J/K/m^2$$

Model Equations

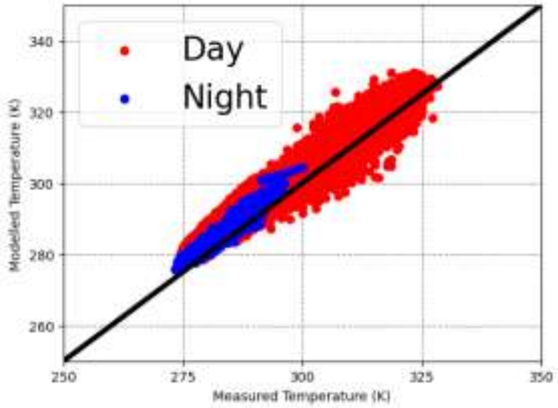
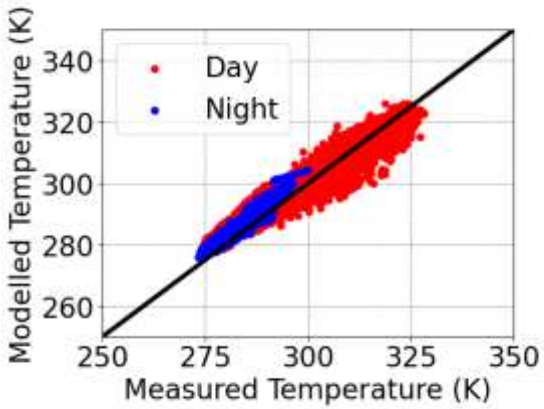
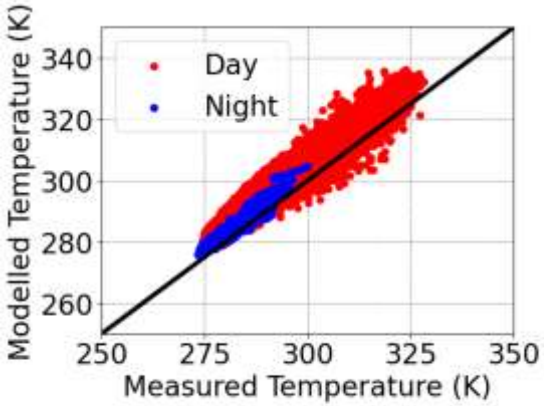
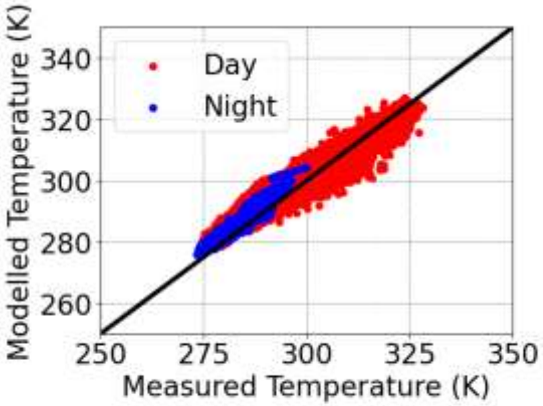
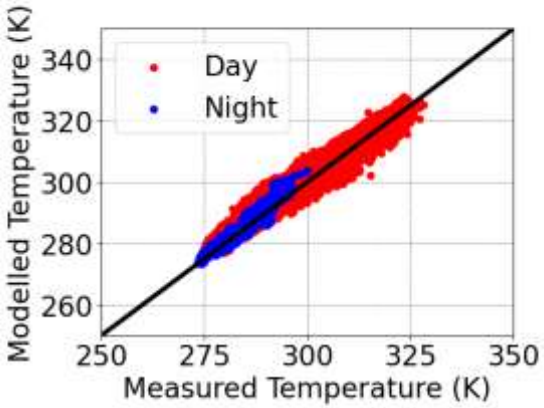
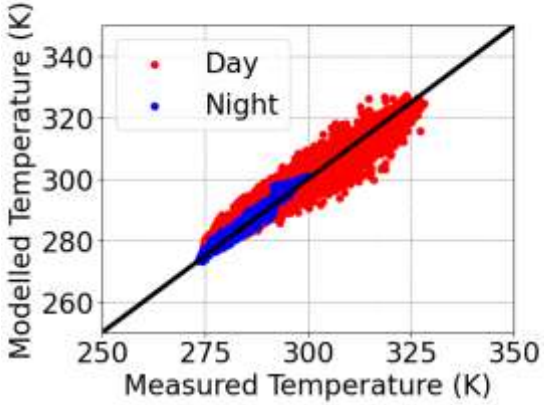
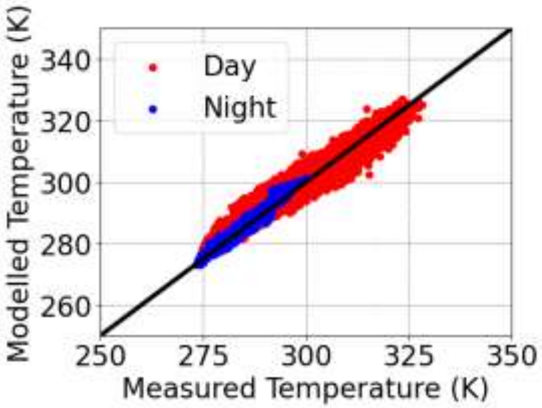
$$Q_{in} = \Phi_m \alpha - \frac{P_{electrical}}{A_{module}}$$

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

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

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

$$\Delta T = C_{th} \left(\frac{Q_{in.i-1} + Q_{in.i}}{2} - \frac{Q_{out.i} + Q_{out.i-1}}{2} \right)$$

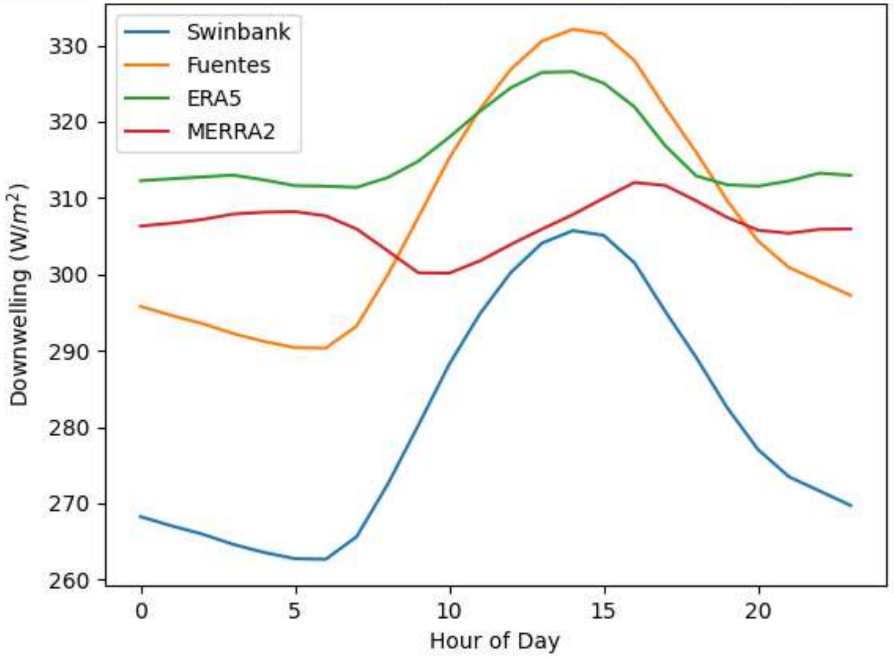
	Default	Steady-State Fit	Transient Fit
PVSyst			
Faiman			
Faiman + Sky			

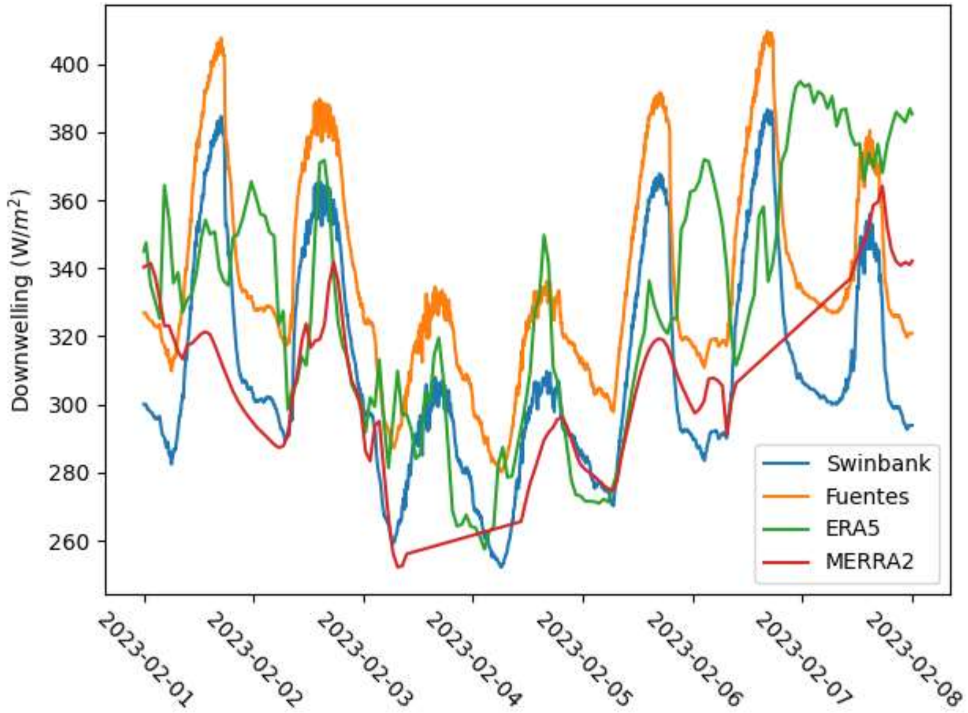
Parameters and Metrics

Model	U_C	U_V	MBE All	RMSE All	CRMSE All	MBE Day	RMSE Day	CRMSE Day	MBE Night	RMSE Night	CRMSE Night
PVSyst Default	29	0	1.52	3.04	2.63	0.64	3.07	3.01	2.64	2.99	1.4
U_C Fit	30.2	0	1.27	3.01	2.73	0.2	3.02	3.01	2.64	2.99	1.4
Faiman Default	25	1.2	2.45	3.47	2.46	2.31	3.81	3.04	2.64	2.99	1.4
Faiman Fit	25.7	3.4	1.29	2.82	2.5	0.23	2.67	2.66	2.64	2.99	1.4
Faiman Transient	24.7	3.6	1.37	2.64	2.26	0.35	2.31	2.28	2.67	3.02	1.4
Faiman + Sky	15.4	3.65	0.02	2.12	2.12	-0.26	2.67	2.66	0.37	1.05	0.98
F+S Transient	13.9	4	0.09	1.71	1.71	-0.09	2.1	2.1	0.31	1.02	0.97

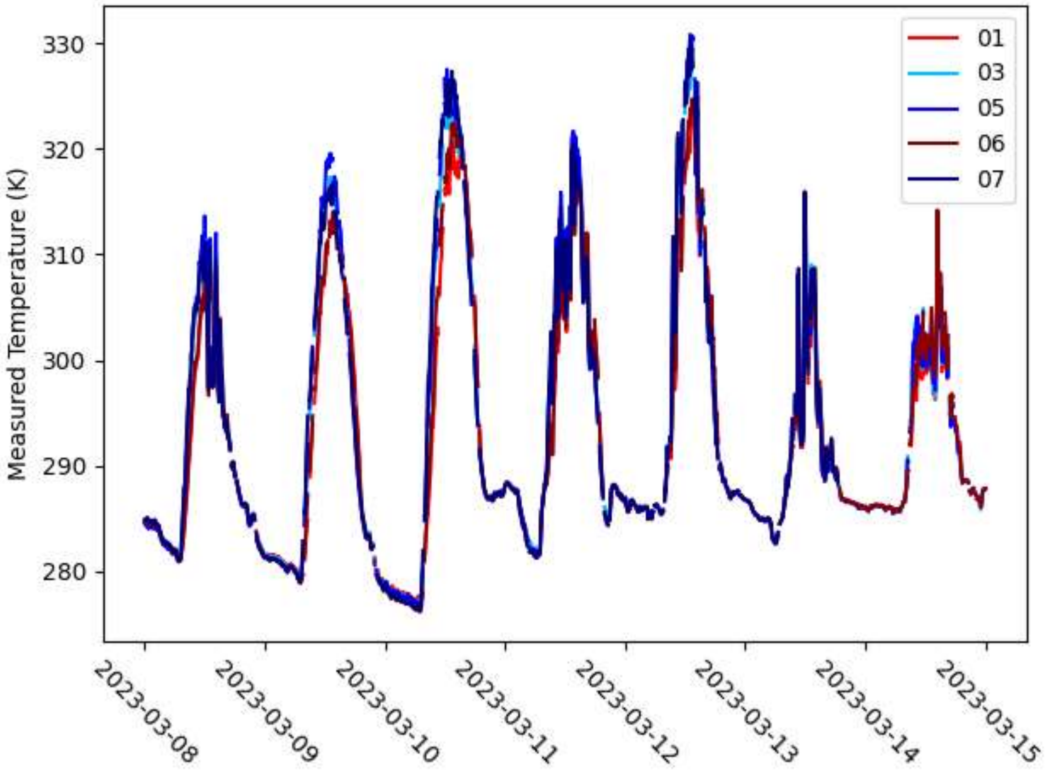
Impact of Sky Model

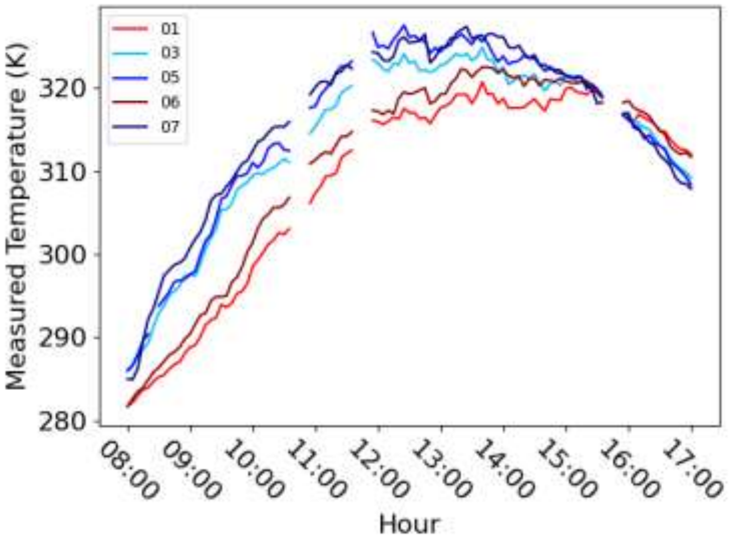
	Uc	Uv	MBE All	RMSE All	CRMSE All	MBE Day	RMSE Day	CRMSE Day	MBE Night	RMSE Night	CRMSE Night
ERA5	13.9	4	0.09	1.71	1.71	-0.09	2.1	2.1	0.31	1.02	0.97
MERRA2	13.7	3.8	0.05	1.79	1.79	-0.19	2.18	2.17	0.36	1.13	1.07
Swinbank	15.3	3.4	-0.52	1.97	1.9	-0.68	2.4	2.3	-0.31	1.19	1.15
Fuentes	14.7	4	0.05	1.87	1.87	-0.25	2.24	2.23	0.44	1.24	1.16





Variation Across Field





- Expected variation according to orientation
- Clear trend from north-west (hotter) to south-east (colder)
- South-west of field observed to be ‘damp’

Variation Across Field

North-East Orientation

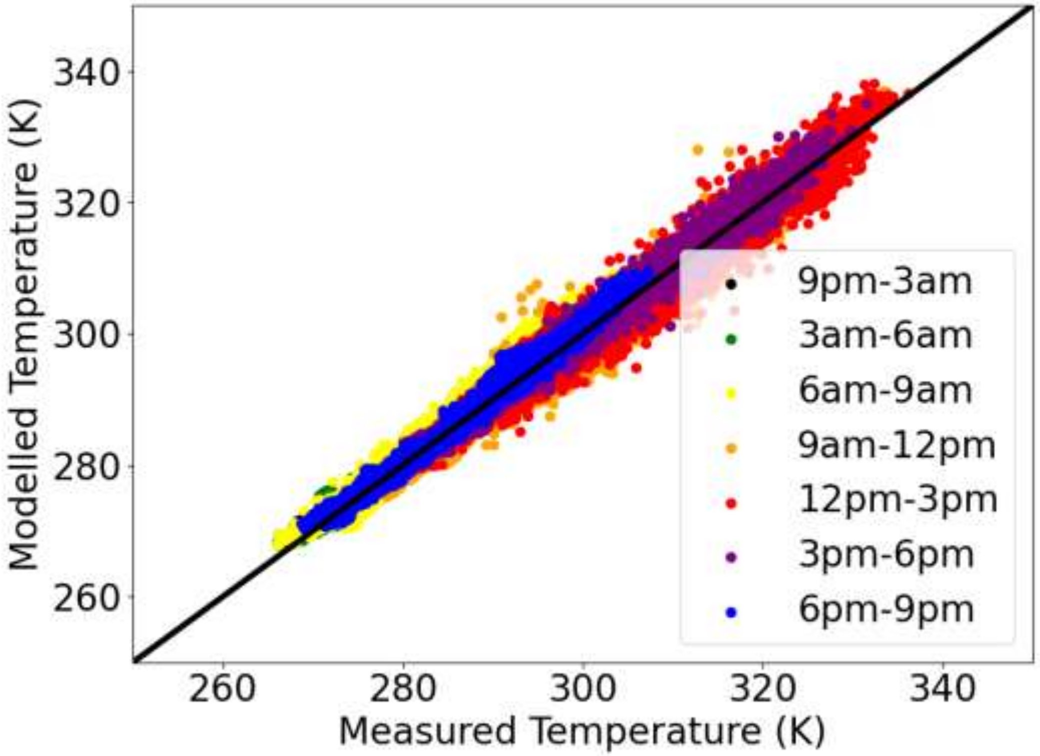
	U_C	U_V	MBE all	RMSE all	CRMSE all	MBE day	RMSE day	CRMSE day	MBE night	RMSE night	CRMSE night
SLJ001	19.2	3.9	0.21	2.21	2.20	-0.09	2.72	2.71	0.63	1.20	1.02
SLJ005	13.9	4	0.087	1.71	1.71	-0.09	2.10	2.10	0.31	1.02	0.97
SLJ007	11.4	4.3	0.20	1.54	1.53	0.20	1.91	1.90	0.20	0.93	0.91

South-West Orientation

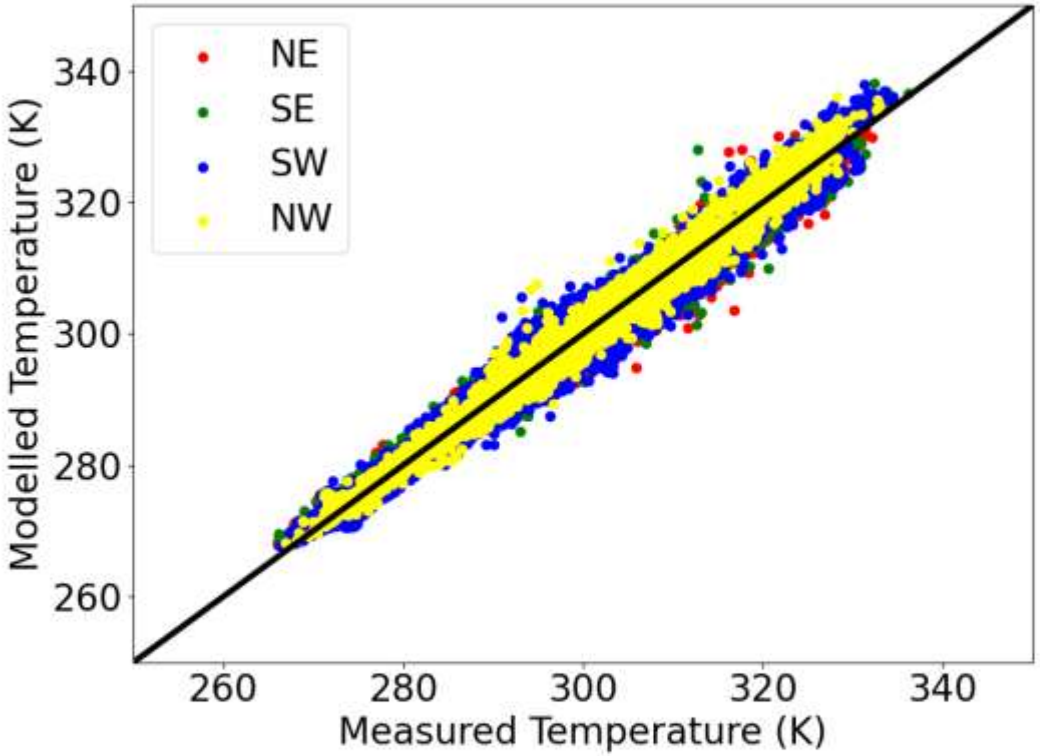
	U_C	U_V	MBE all	RMSE all	CRMSE all	MBE day	RMSE day	CRMSE day	MBE night	RMSE night	CRMSE night
SLJ003	10.1	3.7	-0.26	2.36	2.34	-0.32	3.08	3.07	-0.20	1.06	1.05
SLJ006	12.3	3.9	0.16	1.43	1.41	0.12	1.71	1.70	0.21	1.01	0.99

Other factors

Hour of Day

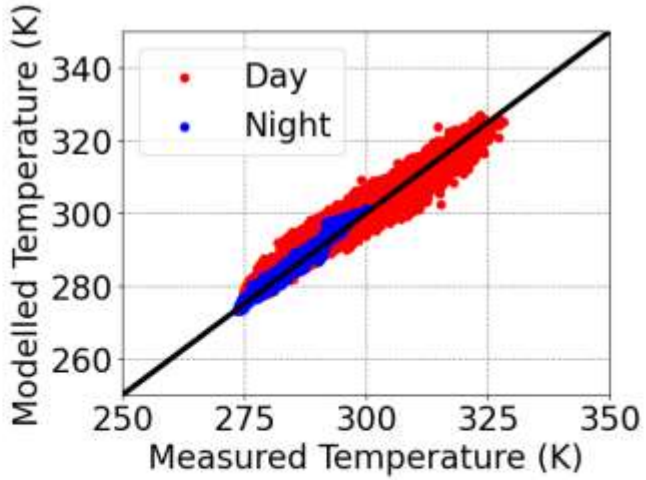


Wind Direction



Summary

- Including downwelling and transience improves fit, CRMSE 2.73 → 1.71
- Coefficients for 5B MAVERICK system very close to those obtained by McIntosh et al. (2022) for a single-axis tracking system (U_C 13.9 c.f. 15.0, U_V 4 c.f. 3.4)
- Significant Variation across the field – Potentially related to ground conditions



Contact p.hamer@unsw.edu.au

This work was funded by the Australian Government through the Australian Renewable Energy Agency (ARENA). The views expressed herein are not necessarily the views of the Australian Government, and the Australian Government does not accept responsibility for any information or advice contained herein.

ARENA

Australian Government

Australian Renewable Energy Agency

ACAP

UNSW SYDNEY