RACE for 2030 NETWORKS

RACE for Networks

Maximising Solar ROI: Advanced Diagnostics for PV Systems

Progress Report

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Maximising Solar ROI: Advanced Diagnostics for PV Systems

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What is RACE for 2030?

Reliable, Affordable Clean Energy for 2030 (RACE for 2030) is an innovative cooperative research centre for energy and carbon transition. We were funded with $68.5 million of Commonwealth funds and commitments of $280 million of cash and in-kind contributions from our partners. Our aim is to deliver $3.8 billion of cumulative energy productivity benefits and 20 megatons of cumulative carbon emission savings by 2030. racefor2030.com.au

Contents

1 Summary

This progress report outlines significant achievements across three core research areas for the "Maximising Solar ROI: Advanced Diagnostics for PV Systems" project. The research team has made substantial progress in solar irradiance dataset validation, distributed event correlation analysis, and automated shading detection algorithm development, directly supporting both Diagno's global expansion goals and enhanced PV system diagnostic capabilities.

Solar Irradiance Dataset Validation: A comprehensive evaluation of four major solar irradiance datasets identified ERA5 as the optimal solution for global deployment. The analysis, which used Bureau of Meteorology data as ground truth across all Australian states, demonstrated that ERA5 provides the most consistent performance with 3.0% average bias, superior global coverage, and cost-effective open-source accessibility compared to commercial alternatives.

Commercial-Scale PV Tripping Analysis: Working with AEMO's disturbance event data, the team analysed nine transmission-level incidents affecting commercial PV systems over 30 kVA. Key findings revealed that system size dominates tripping risk, with 39% of large systems (>30 kVA) experiencing unplanned disconnections compared to just 2% of smaller systems. The research identified critical protection setting correlations and developed a dual-evidence workflow combining power-signal analysis with inverter error logs to improve fault attribution accuracy.

Shading Detection Algorithm Development: The automated shading detection system demonstrates promising performance with high sensitivity for persistent shading patterns and significant false positive reduction compared to basic underperformance detection methods. The algorithm successfully distinguishes between genuine shading events and system malfunctions, indicating strong potential for deployment in autonomous monitoring systems.

Industry Engagement: The initial Industry Reference Group workshop established strong collaborative frameworks with key stakeholders including Fronius and the City of Sydney, confirming research priorities aligned with commercial needs and validating pathways for policy influence through grid monitoring capabilities.

Despite encountering challenges with data integration across multiple sources and cross-vendor API limitations, the project team has implemented effective solutions including standardised preprocessing pipelines and dual-evidence analytical approaches. These achievements position the project well for continued progress towards its goal of delivering advanced diagnostic capabilities for optimising solar PV system performance and reliability.

2 Project Progress

2.1 Update on research activities

The project has achieved significant milestones in three core research areas: solar irradiance dataset validation for global deployment, distributed event correlation via peer-to-peer intelligence, and automated shading detection algorithm development (WP 1, 4 & 5). These activities directly support Diagno's expansion goals and advanced PV system diagnostics capabilities. On this, UTS has made good progress on WP4 that supports the AEMO work package and has submitted the "High Tripping Rates in Solar PV Systems >30 kVA" final report to AEMO for review before sharing with UNSW and RACE.

Solar Irradiance Dataset Validation

We conducted a comprehensive evaluation of four major solar irradiance datasets to identify the optimal solution for Diagno's global operations. The analysis compared commercial providers (SolarGIS, Solcast) against open-source alternatives (ERA5, MERRA-2) using Bureau of Meteorology (BOM) data as ground truth across all Australian states. Please refer to Table A.**1** in Appendix for more information.

Our validation framework assessed accuracy, spatial resolution, temporal coverage, and cost-effectiveness through statistical metrics including RMSE, bias error, and correlation coefficients. The analysis covered multiple temporal scales and geographic regions to ensure robust performance characterisation.

Distributed Event Correlation via Peer-to-Peer Intelligence - WP4 (methods in brief)

To assess ride-through performance in the >30 kVA cohort during AEMO-notified disturbances, WP4 used a dual-evidence workflow pairing fleet-scale power-signal analytics with vendor error-log forensics. This approach enables both high-confidence detection of coincident trips and attribution of likely mechanisms, with UTC/DST normalisation and a harmonised cross-brand fault dictionary to manage data heterogeneity. Where complete, timestamped logs were available (notably from Inverter Brand 5), they were fused with the power-signal classifier; for other OEMs the classifier served as the primary detector. A targeted analysis of secondary mains protection (SMP) setpoints/delays was then performed on a subset of sites to examine correlations between protection coordination and trip/fault incidence. In summary:

- **Approach 1 — Power-signal analysis:** 5-minute AC generation; event-aligned zero/near-zero detection; logistic models against size, distance, DNSP, standard.]
- **Approach 2 — Inverter error-log interrogation:** Vendor API logs harmonised to a common dictionary and time-normalised; complete, timestamped logs consistently available from Inverter Brand 5 only.
- **SMP analysis (subset):** Correlated Over Voltage 2 (OV2), Sustained OV, Vector-shift, ROCOF, Under Voltage (UV) setpoints/delays with trip/fault incidence

2.2 Preliminary findings

Solar Irradiance Dataset Selection

Our comparative analysis led to the selection of ERA5 as a suitable dataset for Diagno's global expansion requirements. The validation assessed bias characteristics across all Australian states using BOM weather station data as reference measurements.

Bias Analysis Results: Figure **2.1** presents the mean absolute bias for each dataset across seven Australian states (2 sites at each state). ERA5 demonstrates the most consistent performance with the lowest overall bias (3.0%) compared to commercial alternatives. While SolarGIS shows competitive accuracy in some regions, it exhibits higher bias variability (5.8% average) with significant overestimation in Tasmania and Western Australia. Solcast displays moderate bias (5.3%) but with considerable regional variation, particularly underestimating solar radiation in Queensland and overestimating in Tasmania.

Key Decision Factors:

- **Accuracy**: ERA5 demonstrates reasonable accuracy with the most consistent bias characteristics across Australian regions
- **Global Coverage**: Provides consistent worldwide coverage without geographic restrictions
- **Cost Advantage**: Open-source availability eliminates licensing costs that could be prohibitive for global deployment
- **Data Accessibility**: Freely available historical and near real-time data supports both research and potential operational applications

The analysis indicates that while commercial datasets offer improved performance in some regions, ERA5's accuracy appears sufficient for solar performance monitoring applications, particularly considering its superior consistency and global accessibility.

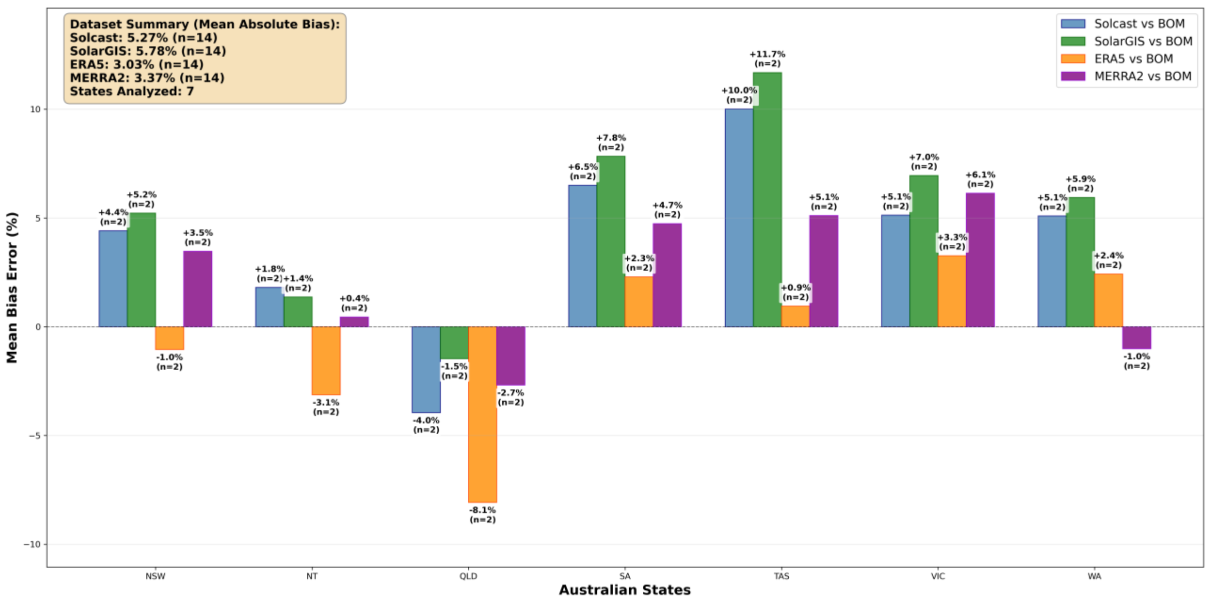

Figure 2.1: Mean absolute bias comparison of solar irradiance datasets (Solcast, SolarGIS, ERA5, and MERRA-2) against BOM reference measurements across seven Australian states. Positive values indicate overestimation; negative values indicate underestimation.

Commercial-scale PV tripping (WP4, AEMO)

Using Diagno's fleet and AEMO's event list, WP4 analysed nine transmission-level disturbances to quantify unplanned tripping in >30 kVA systems.

- **System size dominates risk:** In the VIC showcase event, 39% of >30 kVA systems tripped vs ~2% (1/60) for ≤30 kVA; logistic regression indicates ~38–40× higher odds once >30 kVA (Figure **2.2**).
- **Distance/DNSP weak predictors** after controlling for size/standard; large systems tripped both near and far from the fault.
- **Standards vs commissioning:** AS/NZS 4777.2:2020 installs did not consistently outperform 2016-era systems; field results point to commissioning/configuration/SMP effects.
- **Protection settings correlate:** Tripped/faulted fleets skew to OV2 ≈ 265 V, Sustained OV ≈ 258 V, Vector-shift 20°, ROCOF 4 Hz/s (Table A.**2**).
- **Dual-evidence improves certainty:** Pairing 5-min power-signal flags with vendor error logs (where available) confirms voltage-driven mechanisms.

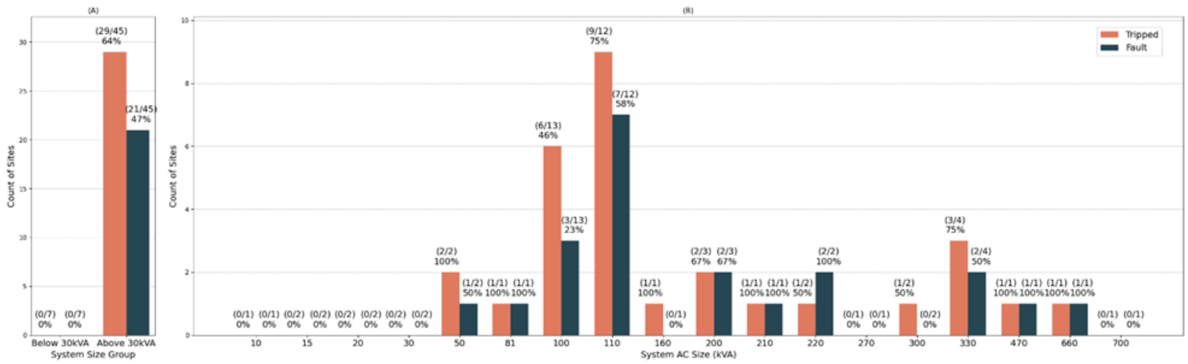

Figure 2.2: Tripping incidence by system size (Panel (A) compares sites ≤30 kVA with those >30 kVA; Panel B shows counts and trip fractions for individual AC system sizes (kVA); and Labels give tripped/total counts and corresponding percentages for each bar).

Shading Detection Algorithm Performance

The developed algorithm shows promising capability for autonomous shading detection with encouraging accuracy and low false positive rates in initial testing.

The validation results demonstrate high sensitivity for persistent shading patterns across 89 confirmed sites, with the algorithm successfully identifying the majority of known shading cases. The system health validation component achieved significant false positive reduction compared to basic underperformance detection methods, primarily through its ability to distinguish between shading events and system malfunctions such as inverter clipping or system tripping. Most confirmed shading sites achieved high confidence scores in the analysis, suggesting potential for reliable automated flagging in future applications.

The algorithm shows progress in addressing the challenge of differentiating potential shading from system faults, indicating feasibility for deployment in autonomous monitoring systems pending further development and testing.

2.3 Issues and difficulties encountered, if any, during the course of the research activities

Data Integration Challenges

Working with multiple solar irradiance datasets presented several technical hurdles. The primary challenge was dealing with different time formats - ERA5 provides data in UTC whilst other datasets use local solar time, requiring careful timestamp alignment across all Australian regions. Each dataset also operates at different temporal resolutions, from 5-minute intervals for commercial providers to hourly measurements for reanalysis products, necessitating robust resampling methods for fair comparison.

Commercial datasets imposed additional constraints through API rate limitations and data volume restrictions, limiting comprehensive historical analysis. BOM reference measurements also contained occasional gaps requiring interpolation or exclusion from validation datasets.

OEM API and timestamp fragmentation (WP4)

Cross-vendor inverter logs were uneven: limited retention windows, per-site tokens/rate limits, and inconsistent timestamps (DST/UTC/NTP drift) constrained event-aligned forensics. Only Brand 5 reliably returned complete, timestamped logs; other brands provided generic status flags or shallow history, limiting cross-brand comparisons.

Algorithm Development Complexities

Developing a universal shading detection algorithm proved challenging due to the diverse solar installation configurations across Diagno's portfolio. Variations in panel orientations, tilt angles, and inverter sizing ratios required flexible algorithm parameters whilst maintaining automated operation.

Initial seasonal pattern validation showed poor reliability across Australia's diverse climate zones, with northern tropical regions displaying different shading patterns compared to southern temperate areas.

Protection-coordination visibility (WP4)

Interpreting ride-through behavior depended on secondary mains protection (SMP) coordination. SMP setpoints/delays were not consistently captured in commissioning records, creating attribution gaps between inverter settings and site-level protection behavior.

2.4 Actions proposed or undertaken to overcome the issues difficulties

Standardised Data Processing

We developed a comprehensive preprocessing pipeline that systematically handles data integration challenges. This automatically converts all datasets to local solar time, resamples to common hourly resolution, and standardises coordinate systems. The pipeline manages missing data through validated interpolation methods and flags problematic periods for exclusion.

ERA5 selection as the primary dataset strategically addresses API restrictions whilst providing consistent global coverage at reasonable temporal resolution.

Event analytics & logging normalisation (WP4)

Adopted a dual-evidence workflow (power-signal + error-logs) with harmonised fault dictionary and UTC/DST normalisation. Prioritised Brand 5 logs where complete timestamps existed; cached API pulls and implemented rate-limit aware batching to stabilise retrieval.

Algorithm Refinement

Rather than forcing seasonal patterns across varied climate zones, we shifted to physics-based system health validation. The algorithm now focuses on detecting system malfunctions through power curve analysis, providing consistent performance regardless of geographic location.

The algorithm has been designed for potential integration into Diagno's existing monitoring infrastructure to help with future real-time deployment and ongoing validation through operational feedback as development continues.

Operational actions & standards pathway (from WP4)

- **Operational triage:** Prioritise audits of >30 kVA sites, with focus on OV2/Sustained-OV, Vector-shift, ROCOF settings (initially in networks showing higher trip/fault incidence).
- **Commissioning records:** Capture full SMP setpoints and reconnection delays in connection/commissioning databases to accelerate post-event forensics.
- **Logging baseline:** Propose a minimum cross-vendor API baseline (NTP-synced clocks; UTC timestamps with offsets; ≥90-day retention; bulk export/webhooks; stable IDs; shared fault-code taxonomy) for consideration in AS/NZS 4777 revisions and/or DNSP agreements.
- **Next steps:** Incorporate AEMO feedback on the report; then circulate to UNSW/RACE and schedule a joint technical session.

3 Outcome of initial IRG and stakeholder workshops

The initial Industry Reference Group (IRG) kick-off meeting was held on 27 May 2025, bringing together key stakeholders from industry partners including Fronius, City of Sydney, and project consortium members. The workshop successfully established the project's collaborative framework and gathered valuable industry insights to guide research priorities.

Industry Engagement and Feedback

The IRG demonstrated strong industry interest in the project's outcomes, particularly around diagnostic accuracy and commercial applications. Fronius representatives expressed keen interest in performance benchmarking capabilities across inverter brands and the potential value of Diagno insights for equipment manufacturers. The City of Sydney highlighted practical needs for detecting soiling and degradation in municipal solar installations.

A significant theme emerged around the global applicability of the research, with Danny Kennedy emphasising opportunities for international deployment and potential showcase at COP26. This aligns well with the project's meteorological data assimilation work package (WP5), which specifically targets Indian market expansion through GSES's gigawatt-scale opportunities.

Technical Validation and Priorities

Industry stakeholders validated the six work packages, with particular emphasis on grid disturbance detection (WP4) due to AEMO's interest in monitoring high-penetration PV effects on low-voltage networks. The IRG confirmed the importance of financial modelling capabilities and standardised reporting mechanisms for commercial viability.

Questions around diagnostic accuracy metrics and false positive/negative trade-offs highlighted the need for robust validation strategies in the fault code correlation framework (WP3). Industry partners emphasised the critical importance of reliable automated diagnostics for scaling solar asset management.

Strategic Outcomes

The workshop established a regular meeting cadence of 4-5 months, ensuring ongoing industry input throughout the project lifecycle. Key strategic outcomes include validated research priorities aligned with commercial needs, confirmed pathways for policy influence through grid monitoring capabilities, and established frameworks for intellectual property governance that balance commercial interests with public research outcomes.

The IRG's feedback reinforced the project's potential for significant industry impact, particularly in automated diagnostics, risk assessment, and international market applications.

APPENDIX

A. Tables and figures

1. Tables

Table A.1: Solar irradiance dataset comparison for global deployment assessment.

Dataset	Type	Spatial Resolution	Temporal Resolution	Coverage	Update Frequency	Cost	Access Method
ERA5	Reanalysis	25 km	Hourly	Global	5 days delay	Free	Open access
MERRA-2	Reanalysis	50 km	Hourly	Global	2-3 days delay	Free	Open access
SolarGIS	Satellite model	250m - 1km	5 min - yearly	Global	Near real-time	Commercial	Subscription
Solcast	Satellite model	90m - 1km	5 min - hourly	Global	5-15 minutes	Commercial	Subscription
IBM EIS	Weather service	Variable	15 min - monthly	Global	Near real-time	Commercial	Subscription

Table A.2: Secondary protection device settings for analysed sites.

Site #	SMP Brand	SMP Model	Protection Function	Over Voltage 1 (V)	Over Voltage 2 (V)	Under Voltage (V)	Sustained Over Voltage (V)	Over Frequency (Hz)	Under Frequence (Hz)	Vector Shift (DEG)	ROCOF (Hz/s)	Reconnection Delay (s)
1	SMP Brand 1	Model 1-A	Set point	260	N/A	180	255	52	47	20	4	
			Time delay (s)	2	N/A	2	15	2	2	0	0.25	60
2	SMP Brand 1	Model 1-A	Set point	260	N/A	180	255	52	47	20	4	
			Time delay (s)	2	N/A	2	15	2	2	0	0.25	60
3	SMP Brand 2	Model 2-A	Set point	260	265	180	258	52	47	8	1	
			Time delay (s)	2	0.2	2	15	0.2	2	2	2	60
4	SMP Brand 1	Model 1-A	Set point	260	N/A	180	255	52	47	8	1	
			Time delay (s)	1.8	N/A	1.8	0	1.8	1.8	0.045	0.5	60
5	SMP Brand 2	Model 2-A	Set point	260	N/A	180	255	52	47	8	1	
			Time delay (s)	2	N/A	2	15	2	2	2	2	60
6	SMP Brand 2	Model 2-A	Set point	260	265	200	N/A	52	48	8	1	
			Time delay (s)	1	N/A	1	N/A	N/A	1	N/A	1	60
7	SMP Brand 2	Model 2-A	Set point	260	N/A	180	255	52	47	8	1	
			Time delay (s)	2	N/A	2	15	2	2	2	2	60
8	Unknown	Unkno	Set point	260	N/A	180	255	52	47	8	3	

		wn	Time delay (s)	2	N/A	2	15	2	2	2	1	60
9	SMP Brand 2	Model 2-A	Set point	260	N/A	180	255	52	47	8	1	
			Time delay (s)	2	N/A	2	15	2	2	0	2	60
10	SMP Brand 1	Model 1-A	Set point	265	275	180	258	52	47	20	4	
			Time delay (s)	2	0.2	11	3	2	2	2	0.25	60
11	Unknown	Unknown	Set point	260	N/A	216	255	52	48	8	1	
			Time delay (s)	1.8	N/A	1.8	N/A	1.8	1.8	0.045	N/A	60
12	Unknown	Unknown	Set point	260	N/A	180	255	52	47	8	1	
			Time delay (s)	1.8	N/A	1.8	0	1.8	1.8	0.045	0.5	60
13	Unknown	Unknown	Set point	260	N/A	180	255	52	47	8	3	
			Time delay (s)	2	N/A	2	0	2	2	0	1	60

2. Figures

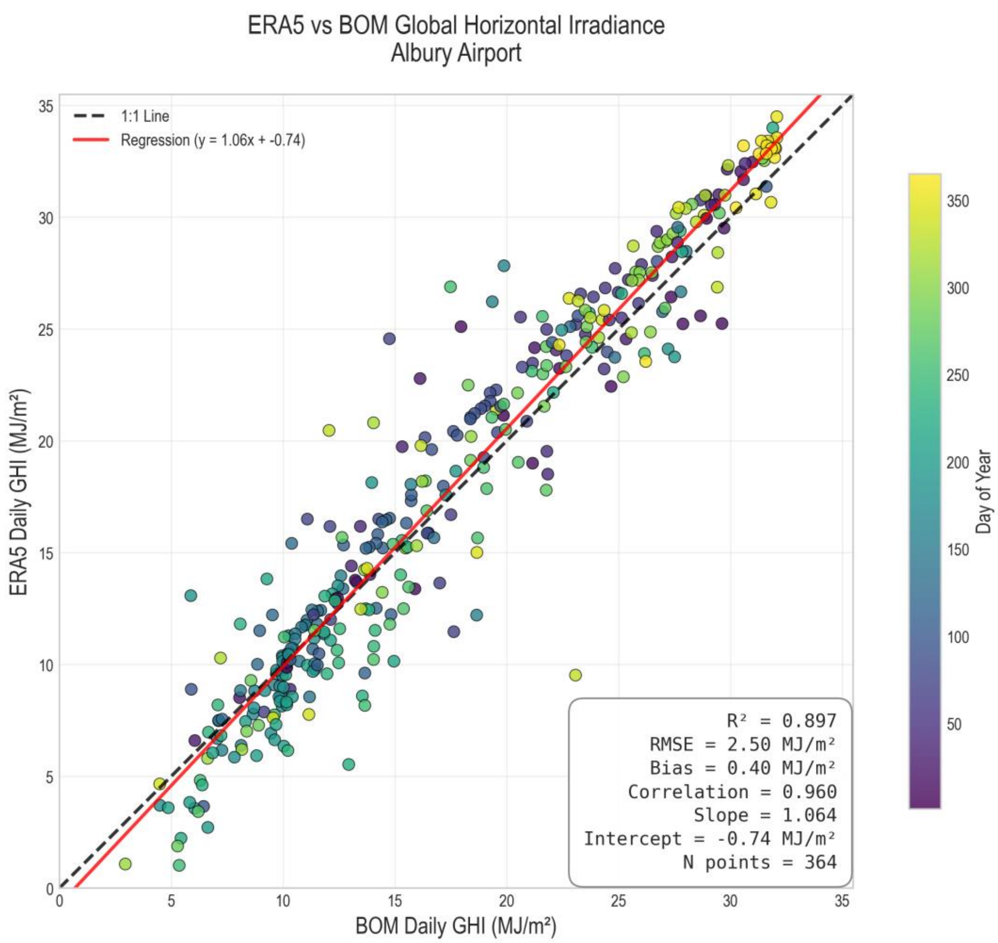

Figure A.1: ERA5 vs BOM daily global horizontal irradiance validation at Albury Airport. Points coloured by day of year demonstrate strong correlation with minimal bias, confirming ERA5's accuracy for solar monitoring applications.

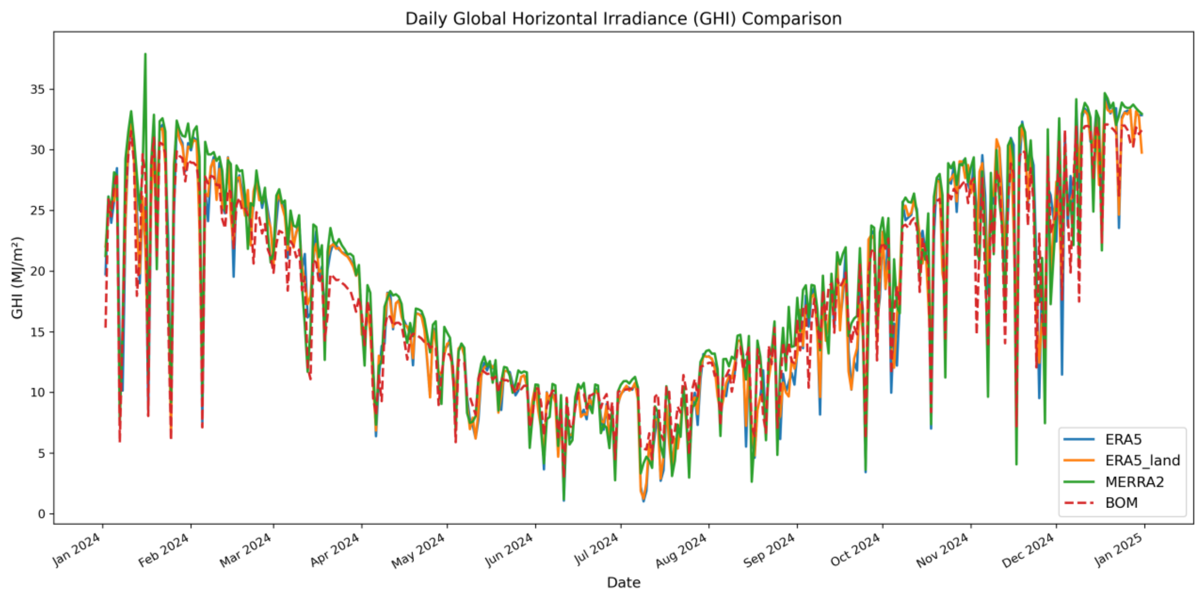

Figure A.2: Daily global horizontal irradiance comparison shows ERA5, ERA5-land, MERRA-2, and BOM measurements over one year. Close agreement between datasets demonstrates the reliability of reanalysis products for solar resource assessment.

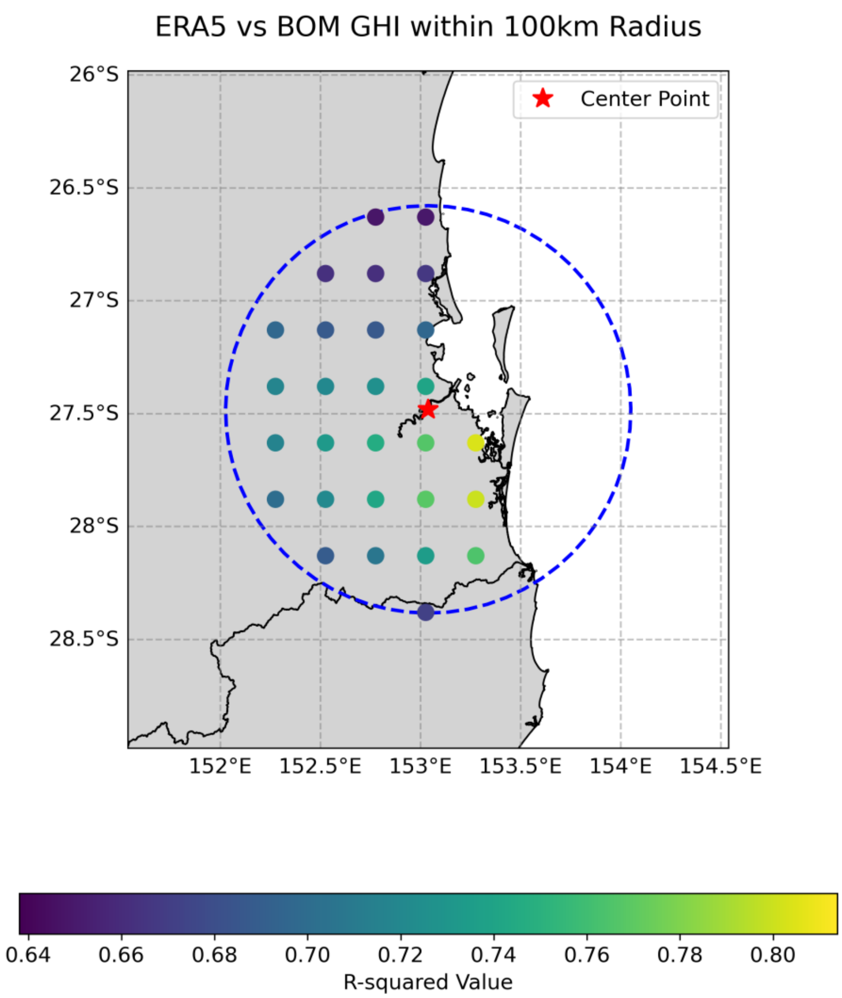

Figure A.3: Spatial correlation analysis of ERA5 vs BOM global horizontal irradiance within 100km radius of the validation site. Colour scale shows R-squared values demonstrating strong correlation across the region.

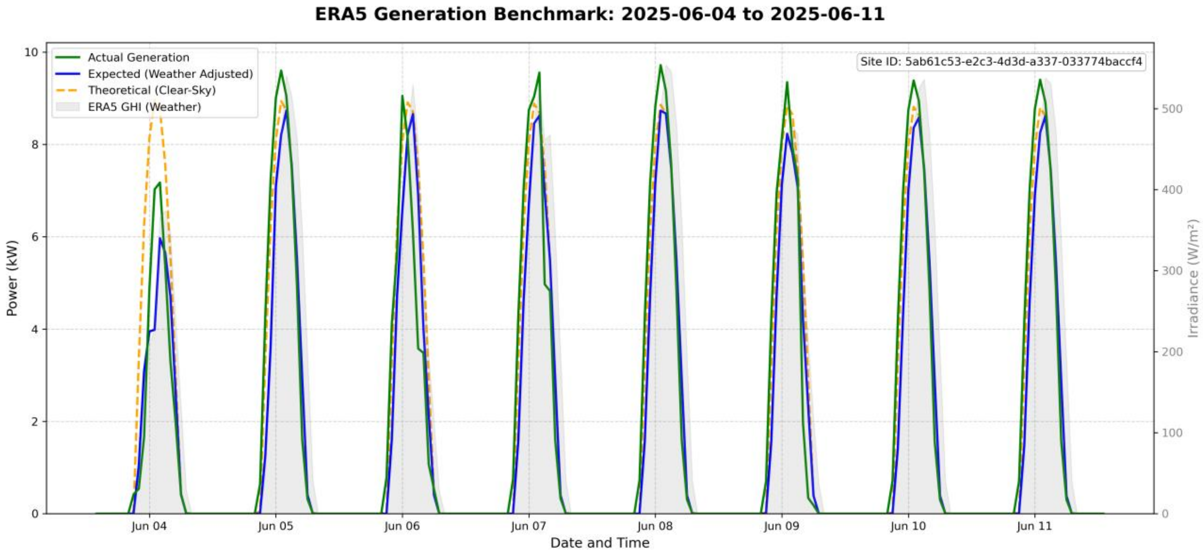

Figure A.4: ERA5-based solar generation benchmark showing actual vs predicted PV output over one week. Close alignment between measured generation (green) and ERA5 weather-adjusted predictions (blue) demonstrates ERA5's capability for accurate solar performance modelling and fault detection applications.

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