Australian Government
Australian Renewable Energy Agency

ARENA

1-UFA005 Improving translation models for predicting the energy yield of photovoltaic power systems

Summary of results and lessons learnt

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CSIRO NREL NATIONAL RENEWABLE ENERGY LABORATORY Lend Lease CAT PROJECTS

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Executive Summary

The output of a PV system under field conditions is not constant, but fluctuates throughout the year according to four key variables, the solar irradiance, the module temperature, the solar spectrum and the solar angle. With new infrastructure constructed as part of this project, we demonstrate that careful measurements of these parameters allows the output to be mathematically corrected back to the standard reference conditions used to nameplate the modules in the factory. This will work provided the irradiance is predominantly direct in nature, i.e. for times when the sky was clear. We find that the error in this correction scales with the proportion of the sunlight that is diffuse in nature at the time of the measurement. This highlights the difficulty in accurately predicting PV output during cloudy periods, or for cloudy climates.

We find that by correcting the output of a PV system back to standard reference conditions we can compare the performance of the system with the rated performance of the installed modules, thus measuring the quality of system design as well as the health of the system. This relatively simple approach can be applied to acceptance testing for new PV systems, as well as output monitoring to ensure a rapid response to any faults during operation.

Since it is not practical to install expensive equipment for measuring the solar spectrum at every possible site, we show that a simple method exists for simulating the above correction based only on measurements of irradiance and temperature. The method is practical and reasonably accurate, with its only shortcoming being a small error arising from the difference between the mean local AM1.5 solar spectrum and the standard AM1.5 reference spectrum. We introduce the term *site spectral offset* to describe this error.

Knowing the site spectral offset for a given location improves the ability to anticipate the energy yield of a PV system, which is important for utility scale PV projects. To avoid the need for costly measurement equipment, we have examined the practicality of estimating the offset based only on known solar geometry and widely available broadband irradiance data. By extending a published model we have been able to correctly predict variations in PV output due to spectral effects for any given (clear sky) time at the Newcastle site, as well as the overall site spectral offset. We now have a framework for predicting the impact of solar spectral variations for sites across Australia. Next steps include determining whether an Australian spectral effects map can be developed using the same framework.

The new infrastructure developed under this project includes unique indoor and outdoor testing capability and is now accessible to Australian PV research and industry under the brand ‘PV Performance Laboratory’. The indoor laboratory has received the internationally recognised IEC 17025 technical competency accreditation and is the first PV laboratory to achieve this in the Southern Hemisphere.

Background

At utility scale, the ability to predict the long term output of a PV system is fundamental to its viability, from the earliest stage of planning through to decommissioning some decades later. At the concept stage, the value of the project is expressed through the expected volume of clean energy produced and the contribution this will make to electricity supply and renewable energy targets. At the capital raising stage, energy yield prediction provides the basis for calculating the revenue stream – a critical exercise in optimisation where proponents must articulate a proposal that is simultaneously both valuable and low risk. At the design stage, understanding the cost-benefit proposition of every aspect of the system guides decision making to produce the lowest possible levelised cost of electricity over the life of the project. At the commissioning stage any discrepancies between the predicted and actual performance must be understood in detail. Once the system is functional, plant operators are typically required to provide grid operators with 24-hr forecasts of hourly output, whilst the equity holders need the earliest possible notice of any drop in performance that could lead to a loss of revenue.

In every example above, the cost-benefit proposition for PV is influenced by the accuracy of the yield calculations. These calculations are complex, since they involve a series of modelling steps which progressively account for the response of the system to the different variables. In some cases the modelling steps are physical, but in others they are at least partly empirical, requiring determination of coefficients to produce accurate results. For some steps the model is widely accepted as the best practice option, but for others there are several alternatives. The choice of alternative may depend on the circumstances, or it may be the case that insufficient research has been conducted to confirm the best approach. For this reason financiers typically require yield calculations to be performed by “appropriate experts”. These experts form a global community of practice, interacting through conferences and research literature, to which this work is intended to contribute.

The obscurity of the link between the nameplate rating of a PV module and its energy output over time has for decades seen calls for the industry to create a practical and credible energy rating scheme. In 2011, after more than fifteen years of debate, the International Electrotechnical Commission Technical Committee 82 (IEC TC82) released the first of a series of standards designed to make such a system possible. IEC standard 61853-1 describes a 23 element matrix of values for the irradiance and module temperature at which representative testing might be performed. In the future this performance matrix may become a labelling requirement for all manufactured PV modules, and could be used as a standard input to a standard method to determine a nameplate energy rating. It is proposed that such a standard method will be described in parts -3 and -4 of the 61853 standard, however no clear timeframe exists for these documents, due to a lack consensus as to the best method. The lack of clarity is in part due to a lack of reliable verification studies, particularly in regard to the identification of a model that will underpin the method.

Outcomes

PV Performance Laboratory

NATA Accredited Laboratory
Number: 165
Corporate Site 22466
Accredited for compliance with ISO/IEC 17025

CSIRO developed a new PV Performance Laboratory as part of this project. Outcomes are:

- Australian researchers now have access to an accredited facility for the measurement of PV efficiency according to international standards. Previously only available at selected labs in the Northern Hemisphere, the facility allows independent measurements of reference and prototype cells. This type of measurement is increasingly becoming a contractual obligation of research funding agreements and adds significant weight to published research results.
- Two novel measurement systems were invented as part of the PVPL development; (1) an optical system for measuring cell area with a typical uncertainty of 0.4 % for a 2 cm × 2 cm cell, unmatched by any other system reported in the literature; (2) a new electrical approach to current-voltage measurement that achieves typical uncertainties of 0.001 % in voltage and 0.01 % in current, exceeding the accuracy required by the standard by factors of 200 and 20 respectively.

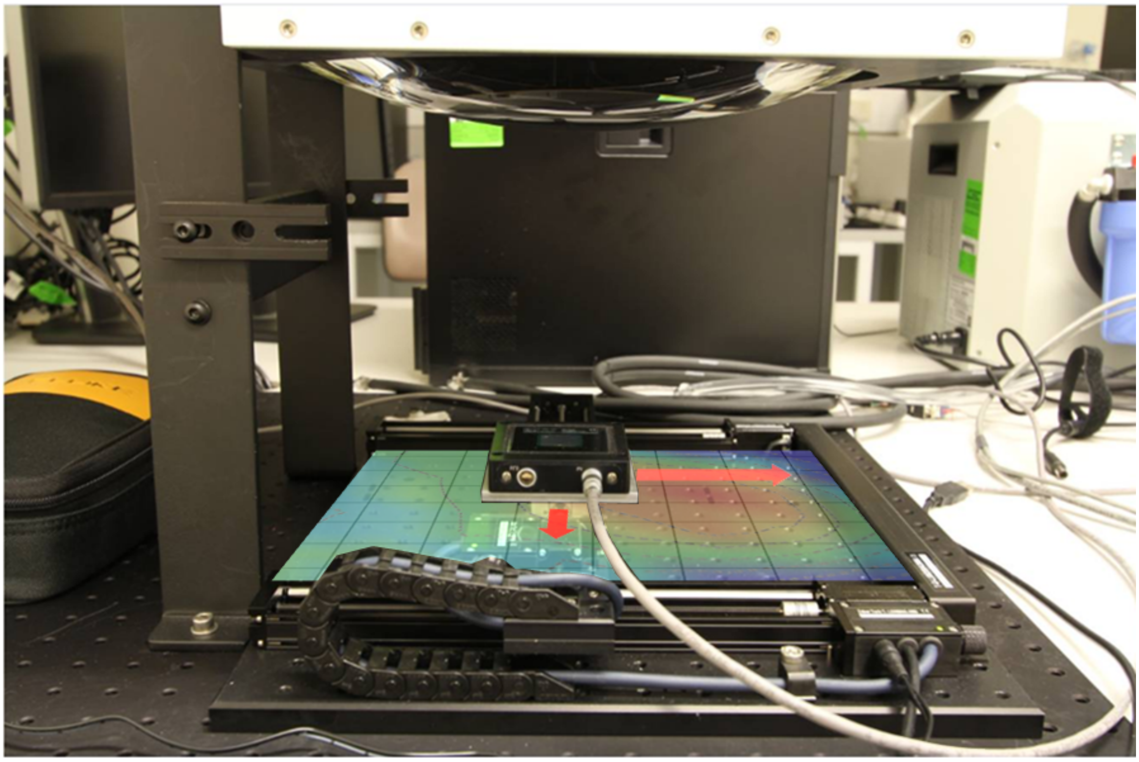

Figure 1 Solar simulator spatial uniformity testing at CSIRO's accredited PV Performance Laboratory

PV Outdoor Research Facility

A new PV Outdoor Research Facility was developed as part of this project. Outcomes are:

- A significant new piece of solar research infrastructure for Australia, this facility is designed to perform laboratory grade diagnostic measurements on PV devices up to commercial scale in a field environment. When combined with accurate measurements of the key solar and weather parameters the facility allows an almost unprecedented depth of analysis over a range of climatic conditions applicable to a large proportion of the Australian population.
- As part of the PVORF task, a high quality solar ground measurement station was designed and constructed. This is the most advanced station of its type in Australia, and exceeds the technical requirements of the key global weather monitoring collaboration known as the *Baseline Surface Radiation Network*.

Figure 2 PV Outdoor Research Facility at the CSIRO Energy Centre in Newcastle

Figure 3 Solar Ground Station at the CSIRO Energy Centre in Newcastle

New software tools and methods for analysing PV module (panel) output

Based on I-V curves measured for 59 different PV modules every 10 minutes, including 17 different manufacturers and 12 different technology variations, we have developed software tools for translating the power output under the measured conditions to the power that would be output under the international standard reference conditions. This is achievable due to the advanced measurement capabilities of the PV Outdoor Research Facility. The new tools allow a direct assessment of the performance of any given PV module under the same conditions at which it is rated for labelling purposes. This allows:

- Assessment of the true outdoor performance of a PV module for comparison with its nameplate power rating
- Detailed information about each module's response to the four environmental variables irradiance, temperature, spectrum and incidence angle. These parameters influence the true energy yield of the module over time and can identify modules that are more effective (or less) than others with equivalent nameplate rating
- A highly sensitive observation and analysis of changes in output due to degradation
- The ability to determine the efficacy of a given PV system design
- The ability to detect system faults with high sensitivity

Research outcomes are:

- For measurements taken under clear sky conditions the correction is successful, leading to a measured output that is invariant over time (with the exception of true changes in performance such as degradation or annealing) and is consistent with the nameplate power rating of the module. However, the translation breaks down where the irradiance contains an appreciable diffuse component. The accuracy of the corrected result appears to scale with the relative contribution of diffuse light to the total irradiance. In part this reflects the limitations of even high end solar measurement equipment (pyranometers and spectroradiometers) at high solar angles of incidence (early mornings and late afternoons), but it also suggests that new approaches are needed for modelling PV output during cloudy conditions;

- We show that the complex corrections for short term spectral variation, angle of incidence and low irradiance performance can be pragmatically replaced by a simple filtering of the measured output to within a small window around an irradiance of 1000 Wm^{-2}. The error introduced by this simplified correction is due to a difference between the average prevailing solar spectrum at the site and the standard reference spectrum. We term this difference the *site spectral offset*.

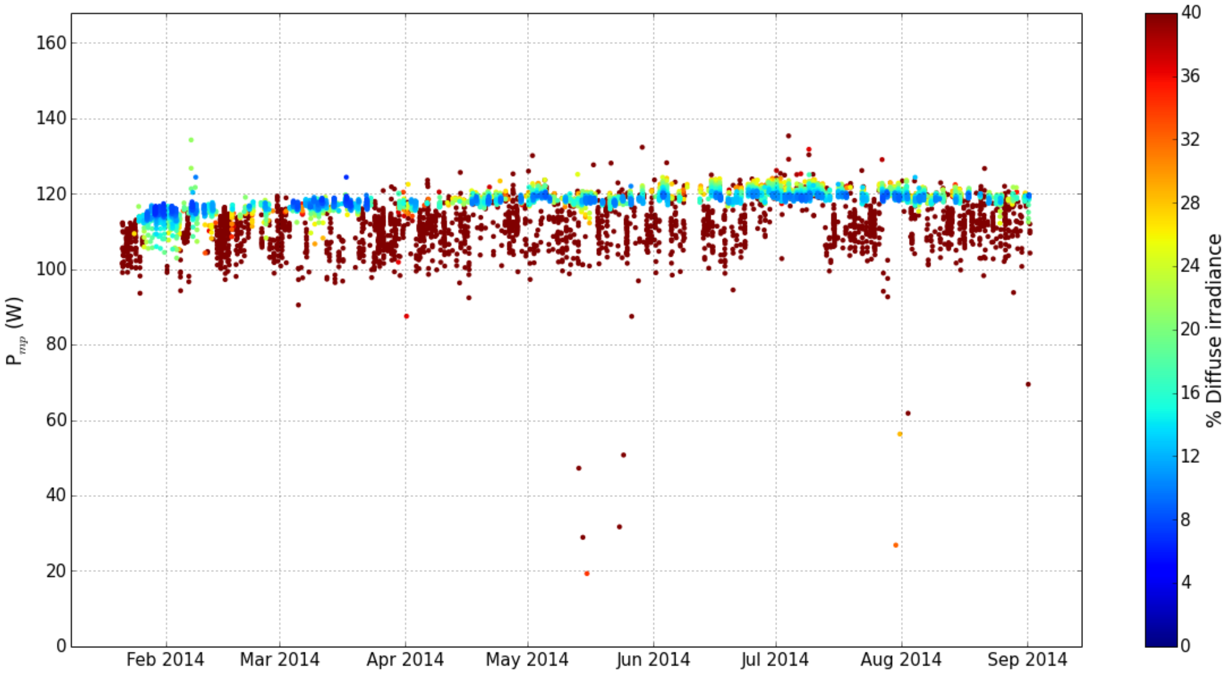

Figure 4 DC power output over time for a CIGS module, translated to Standard Test Conditions. The colour scale indicates that points measured under clear skies can be translated to an invariant value (the nameplate rating of the module) but our understanding of the translation process is much less clear when skies are cloudy.

Measuring the effectiveness of PV system design

The health and effectiveness of a PV system is usually evaluated using a metric known as the Performance Ratio (PR), however this parameter is not invariant with climate and solar conditions. Our process for standardising PV output to reference conditions allows the reporting of a *normalised performance ratio* (NPR). The NPR is independent of site, climate and conditions, hence represents a much more stable metric for quantifying losses that occur at the system level, i.e. the quality of the design of a PV system.

We examine five residential scale PV systems and observe NPR values in the range 83.6% to 95.2%. These results suggest that system level losses (100% minus NPR) can differ by more than a factor of 3 between systems.

The breakdown of loss factors at a system level is often not well understood by system designers. In particular, the loss component due to module mismatch is challenging to predict. Using large sets of flash test data from two different manufacturing lines (different technology types) and a published model, we have conducted a theoretical examination of this effect on different PV system configurations. We find loss contributions ranging from 0.02% to 0.05%. These values are much smaller than values typically anticipated by system designers.

Improving temperature estimation for more accurate energy yield prediction

Models for predicting the temperature of PV modules under varying field conditions are important because they influence predictions of the electrical output, both instantaneous and over time. We have examined the effectiveness of two better known models in the literature. The results indicate that for either model, obtaining accurate temperature predictions requires system specific parameters (coefficients) to be determined. We find that the difference between using correct values for these coefficients and using the default values in commercial yield modelling packages can lead to annual yield prediction errors of several percent. This highlights the value for developers in pre-determining coefficients during the planning stage of the project. Although the research literature does contain some guidance as to appropriate ranges of these coefficients for different system configurations, further research could improve the accuracy of these guidelines.

Predicting the impact of solar spectrum on energy yield in Australia

The project investigated the complex role of solar spectrum on PV output. Using spectral measurements at Newcastle and Alice Springs we examined the performance of the only two models available for predicting spectral effects based on solar resource data. Research outcomes are:

- We introduce a parameter we term the *spectral impact factor* (SIF) which is indicative of the overall impact of spectral effects on a given PV module type at a given site over a defined period;
- Based on solar resource data at 74 sites around Australia, we determine the annual SIF according to the Sandia Array Performance Model. This model by definition fails to account for any site spectral offset, since it assumes the AM1.5 reference spectrum when the sun angle corresponds to air mass 1.5. We map the predicted SIF across Australia and observe factors in the range 0.995 to 1.005, depending on the module type;
- Based on spectroradiometric measurements over several months at the Newcastle and Alice Springs sites, we report measured values of the spectral mismatch for each module type at these two sites. For each point in the datasets we also determine this parameter as predicted by the Sandia model. A comparison indicates that the Sandia model predicts the variation with air mass reasonably well, but as expected fails to account for the site spectral offset. For the desert climate of Alice Springs the offset is small, ranging from -0.1 % for crystalline silicon modules to -0.5 % for cadmium telluride (thin film) modules. For the coastal climate of Newcastle however, the offset is larger and varies in sign, at -1.9 % for CIGS (thin film), -1.4 % for crystalline silicon and +1.5 % for cadmium telluride. The CIGS result is consistent with the site spectral offset identified during the project. We conclude that the Sandia model does not completely account for the impact of spectral effects, particularly for coastal climates;
- We examine an alternative, the CREST model, which as published is only valid for amorphous silicon modules. We modify the model to allow it to make use of full spectral response curves, thus unlocking its use for most PV module types commercially available. We use Newcastle spectral data to develop coefficients that are appropriate for each module type. With the new coefficients, our modified CREST model provides a much more accurate prediction of the spectral conditions at Newcastle, including the site spectral offset for each module type;
- With the aim of developing new and more accurate spectral maps for Australia, we use Alice Springs spectral data to see if the CREST coefficients are similar to those determined for Newcastle.

The Alice Springs coefficients are significantly different, possibly indicating that the coefficients vary according to the site climate. As a result, further work is needed to establish these coefficients for a range of Australian climate zones before an accurate Australian spectral effects map can be developed.

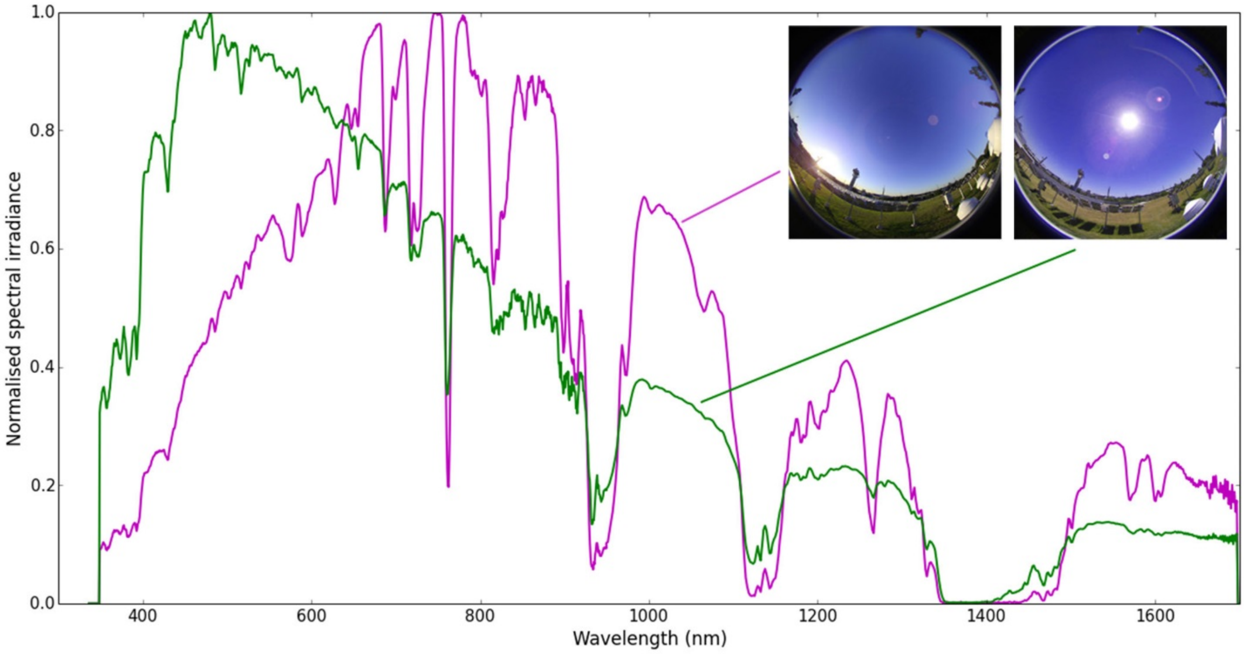

Figure 5 Solar spectra measured at Newcastle for a high sun (green) and a low sun (pink)

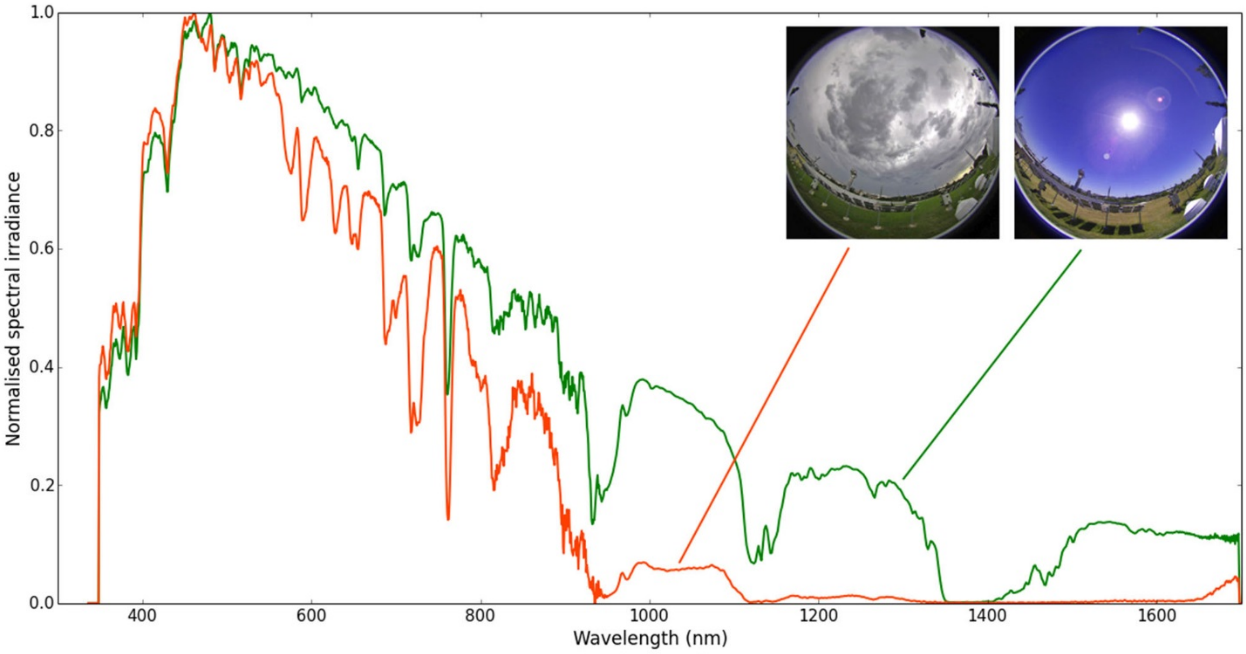

Figure 6 Solar spectra measured at Newcastle for a clear sky (green) and a cloudy sky (orange)

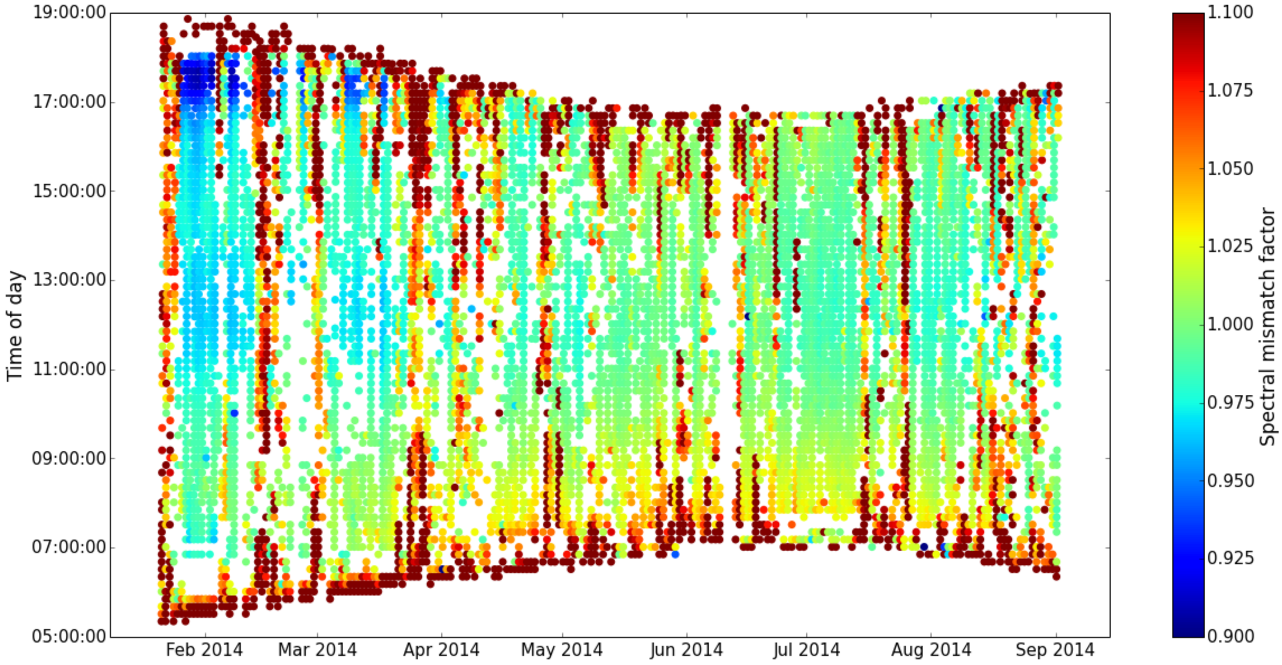

Figure 7 Spectral mismatch factor measured at Newcastle for a crystalline silicon PV module

Which translation equation is best for predicting energy yield?

Another important step in the energy yield prediction process is the mathematical translation of PV output between different solar conditions. IEC 60891 contains three alternative methods for this translation, however until now there has been neither the data nor the analysis to indicate which methods are best for which applications. Under the project we have developed a new framework for analysing and communicating the strengths and weaknesses of each method. The framework involves:

- The use of a synthetic data approach to alleviate the impact of measurement errors when using real measurements to compare the translation methods;
- Colour maps to represent the accuracy and precision of the methods over a 2D parameter space for irradiance and module temperature;
- A Monte Carlo approach to propagating uncertainties in measurements, where such measurements would be used as input to a translation model for the purpose of defining a standard energy yield rating.

We apply the framework to thoroughly investigate the performance of the three alternative I-V translation methods proposed in IEC 60891, plus a fourth method that has become popular since it captures the impact of angle of incidence and spectrum. The project has provided a combination of synthetic, laboratory and field data, which we apply for four different module technologies. The result is a set of performance maps that indicate both the accuracy and the precision for each of the four methods. The high level findings are:

- The use of a strict framework such as we have developed is essential for comparing mathematical approaches to translation fairly, since each method responds differently to the level of error in the experimental data used to test the method;
- In regard to the accuracy of the four translation methods when they are applied for predicting energy yield: Although there are combinations of temperature and irradiance that favour each of

the four methods, the Sandia Array Performance Model and IEC Method 3 both clearly outperform IEC Methods 1 and 2 over the full parameter space, with the SAPM the most accurate and Method 2 the least accurate;

- In regard to the propagation of measurement uncertainty in reference data through to energy yield predictions: IEC Method 3 is the most susceptible to measurement uncertainty, with the other three methods all behaving comparably with respect to this metric.

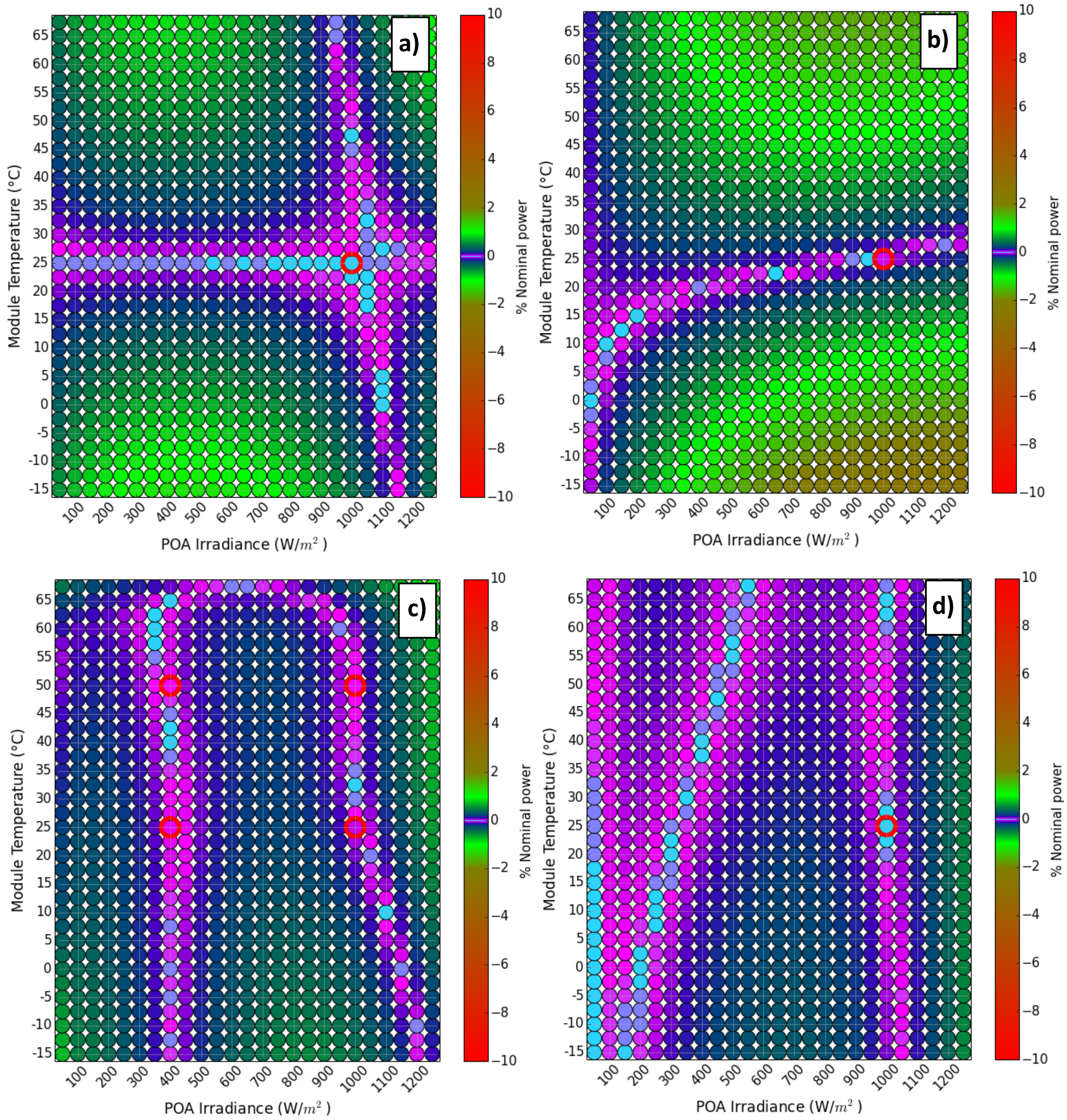

Figure 8 Maps depicting the accuracy of four different models that could be used to translate PV output from one set of conditions to another; a) IEC 60891 Method 1; b) IEC 60891 Method 2; c) IEC 60891 Method 3 and d) Sandia Array Performance Model

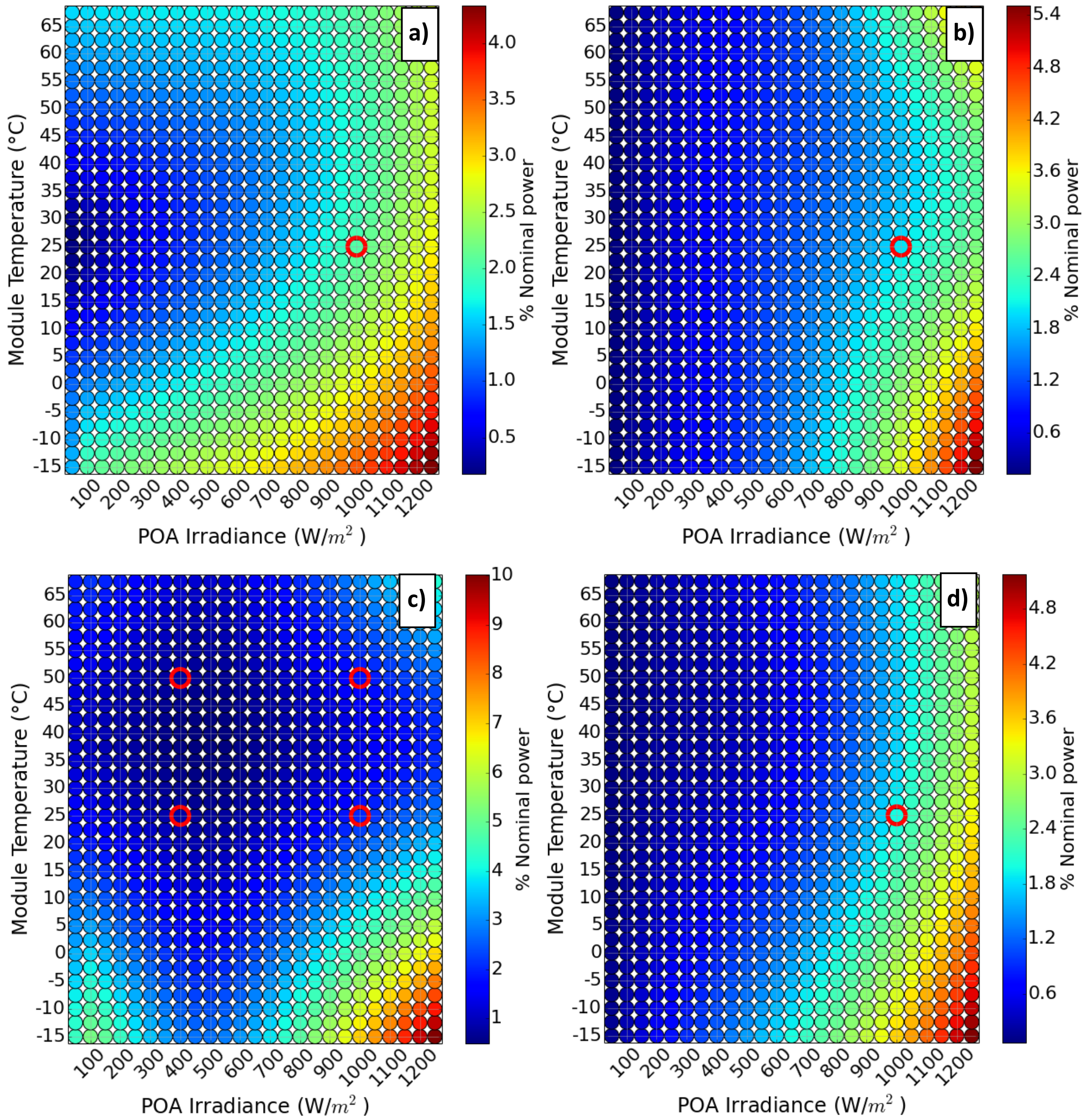

Figure 9 Maps depicting the precision of the four different models treated in Figure 8

Transfer of outcomes and next steps

PVORF

This new infrastructure will enable research by CSIRO and its partners for:

- Exploring the performance of new PV technologies in the field. This will apply not only to new PV devices, but also to ancillary developments such as cooling systems, cleaning systems, surface coatings for self-cleaning and heat elimination etc., and the true impact of aesthetic modifications such as colour;
- Understanding the durability of PV devices, both in research, pre-commercial and commercial;

- Improving the link between lab measurements (flash testing for nameplate rating) and real world outdoor performance, particularly in regard to the relative advantages of the different module technology types.

The PVORF will also be available commercially to assist the industry (manufacturers, importers, accreditation bodies, industry groups etc.) to maintain a high standard of supply for the Australian PV market.

PVPL

The PV Performance Laboratory will operate commercially as an accredited facility for confirming PV cell efficiency claims, including those reported as milestones to research funding bodies;

The new method for area measurement and the new electrical design for current-voltage measurement will both be published in research literature.

Site spectral offset

The identification and quantification of a spectral offset that varies between sites will be published in the research literature. Further work would allow extension of this concept to sites around Australia and hence potentially the development of a map that indicates the true impact of spectrum at different sites. This would identify whether, and to what extent, the conditions at a given site favour the use of a particular PV technology type.

Normalised performance ratio

The approach for determining a normalised performance ratio will be published in the research literature. Some further refinement of the approach could lead to standardisation of a method, particularly in regard to its use in measuring the efficacy of a PV system design.

The study of module mismatch effects will be published in the research literature.

Predicting PV temperatures in the field

This research outcome is useful to the partners in the pursuit of their operations. Further work would allow publication of improved guidelines around the choice of coefficients used in the models, and hence more accurate energy yield predictions.

Comparing translation equations

Our investigation into the performance of the four translation models will be published in the research literature. The results are likely to be of interest to IEC Technical Committee 82, which is responsible for the international standards associated with solar photovoltaic energy systems. The standards development process requires high quality data and research to make informed judgements on the merits of the methods and guidelines described in the standards. CSIRO's work in this project is directed at the content of two standards, IEC 60891 and IEC 61853. Both these standards deal with the translation of PV output from known conditions to unknown conditions, a procedure that fundamentally underpins the process of PV output modelling on both short and long timescales.

The framework we have developed provides a powerful tool for comparing different methods for predicting PV output under arbitrary conditions.