Fleet Performance of Large Scale PV in Australia

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Abstract

Experience in installation and operation of systems provides performance data which can be used to increase the accuracy of prediction models of future plants. First Solar's fleet of Australian photovoltaic (PV) plants across the country, including at Geraldton in Western Australia (WA), Broken Hill and Nyngan in New South Wales (NSW) is the best source of long-term operational plant data in Australia. This study investigates the performance of these solar plants, including the alignment between expected and actual performance, demonstrating the accuracy of First Solar's modelling guidance and energy prediction software, PlantPredict. Factors that impact performance are considered, including spectral shift, soiling and temperature which are measured on site and used to predict energy performance of a system at a given geography.

1. Introduction

This paper shares the predictive modelling approach optimised by First Solar and third parties and compares these with actual performance data to date of the fleet of Australian large-scale solar plants. Experience in installation and operation of systems provides access to meaningful performance data which can be used to increase the accuracy of prediction models of future plants. Given the range of locations and climates, data from the First Solar fleet can be used to compare the suitability of different modelling approaches across a large geographical area and to validate the accuracy of prediction methodology for thin-film PV technology in Australia.

2. Australian Fleet

First Solar's installed, operated and maintained fleet of large-scale solar PV plants in Australia has grown to 165 MW (AC) since 2012 covering a range of locations and climates across the continent.

Table 1. Australian fleet of First Solar large-scale PV plants

Plant	Location	MW (AC)	Comm'd	Climate	Module
Greenough River Solar Farm	Geraldton, WA	10	Sept 2012	Hot summer Mediterranean	Series 3
Nyngan Solar Plant	Nyngan, NSW	102	Sept 2015	Hot semi-arid	Series 3 Black +
Broken Hill Solar Plant	Broken Hill, NSW	53	Dec 2015	Hot desert	Series 4/4A/4V2

The 10 MW (AC) Greenough River Solar Farm, located in Geraldton, WA and commissioned in September 2012, was Australia’s first commissioned and operational large-scale power plant. Australia’s largest operational PV plant, the 102 MW (AC) Nyngan Solar Plant, is located in Nyngan, NSW and was commissioned in September 2015. The 53 MW (AC) Broken Hill Solar Plant, located in Broken Hill, NSW, is the sister plant to the Nyngan Solar Plant and was commissioned in December 2015.

These plants are constructed using a range of First Solar module technologies and follow the advancement of Cadmium Telluride (CdTe) technology improvements in efficiency and reliability over recent years. First Solar’s Series 3 modules, released to market in 2010, improved on Series 2 modules by enhancing current/voltage characteristics for use in large-scale solar plants. Series 3 Black Plus modules introduced in 2013 brought an increase in reliability, demonstrated by third party long-term sequential and thresher testing, as well as continued improvement in efficiency and a reduction of long term degradation guidance. In 2015 First Solar started production of Series 4 modules, continuing efficiency improvements as well as introducing compatibility for 1500V systems. Series 4V2 modules, in production by mid-2015, exhibit an improved quantum efficiency curve resulting in efficiency improvements and increased spectral response.

2.1. Performance Prediction Accuracy

Through the design, construction, and ongoing operation of over 5 GW of PV power plants and with total module sales exceeding 13.5 GW globally, First Solar has developed energy prediction methodologies that accurately reflect the unique field performance of their CdTe thin-film modules. Historically, First Solar has used a combination of the PVsyst software and in-house post-processing tools to create energy models for its PV plants, and this approach has been extensively validated across our operating fleet as illustrated in Figure 1.

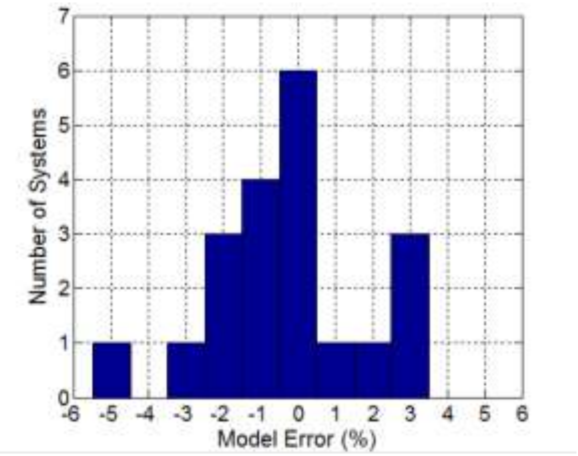

Figure 1. PlantPredict average model error (Passow, et. al. 2015)

While it can improve the accuracy and configurability of the energy models and is common practice amongst independent engineering firms, post-processing is undesirable because it is more time consuming to complete an analysis using multiple tools and for reasons of transparency. PlantPredict is a web application developed by First Solar designed to simplify the creation of large-scale PV power plant energy models. The tool also allows users to easily factor in conditions that influence solar system performance, such as spectral adjustments, that are notably absent from other commonly used modelling software. In previous work, PlantPredict has been validated against both measured performance and PVsyst simulations

(Passow 2015), and is available for public use. First Solar also provides specific guidance documentation and tools for use with PVsyst, which enable users to achieve modelling results that are consistent with PlantPredict.

3. Expected vs. actual performance

3.1. Methodology and Tools

Both PlantPredict and PVsyst are used in this analysis to compare predicted results with actual performance data. In the analysis of PV plant performance, actual performance can be compared to expected energy referencing either the contractual or the as-built design. While First Solar's ongoing performance monitoring is typically assessed against contractually agreed performance, the purpose of this analysis is to assess the accuracy of performance models. Therefore, actual performance as measured at the facility connection point, excluding HV transformer losses and HV transmission losses, is compared against the expected energy based on the as-built design and measured weather data.

3.2. Loss Assumptions

Energy modelling software requires the user to enter input assumptions for the various losses that occur within the system. The following losses were assumed:

Table 2. Summary of loss factor inputs

Loss	Value	Source of input assumption
Horizon Shading	n/a	Observed by onsite measurement stations
Near Shading	Calculated (%)	Calculated by PVsyst and PlantPredict based on actual plant layout
Incidence Angle Modifier (IAM)	Tabular (%)	Series 3 modules: ASHRAE model B_0=0.05 Series 4 modules: Measured tabular values supplied by First Solar, and determined by a third party laboratory, according to module series.
Soiling	Measured (%)	Measured on First Solar reference module soiling stations
Temperature Coefficient	S3: -0.25%/°C S3 Black+: -0.29%/°C S4: -0.29%/°C S4V2: -0.34%/°C	PV module temperature coefficient supplied by First Solar and determined by a third party laboratory, according to module series.
Thermal Loss Factor (Uc)	30.7 W/m^2K	Thermal loss coefficient determined by First Solar
Module Quality	0.0 %	First Solar module performance guidance
DC Health	1.0 %	Standard First Solar input
Spectral Adjustment	Calculated (%)	Calculated based on measured temperature and humidity according to First Solar's 2-parameter spectral model
Module Mismatch	1.0 %	First Solar module performance guidance
DC Ohmic Loss	1.5 %	Standard First Solar assumption
Auxiliaries	0.2 %	Standard First Solar guidance
AC Ohmic Loss	1.0 %	Standard First Solar guidance
Transformer Loss (resistive/inductive)	0.9 %	According to MV transformer manufacturer data

Transformer Loss (iron loss)	0.1 %	According to MV transformer manufacturer data
Degradation	Series 3: 0.7% p.a. Series 3 Black+ onwards: 0.5% p.a.	Applied linearly to total plant output each month after year 1

3.2.1. *Module Quality*

All PV modules have a tolerance associated with their nameplate output. First Solar Series 3, Series 3 Black Plus, Series 4, and Series 4V2 PV modules are binned in steps of 2.5W_{DC}. A key point of difference of First Solar's CdTe modules is that they are de-rated to account for the initial stabilisation that occurs with CdTe thin-film PV modules. First Solar applies an Engineered Performance Margin (EPM) to the measured output on the production line, designed to account for this initial efficiency loss and ensure that the output at the end of year one is equal to or exceeds the nameplate power. This is the basis for First Solar's guidance of a 0.0% loss for module quality.

3.2.2. *DC Health*

The DC Health Factor Loss is a steady-state loss which accounts for faults such as under-performing strings due to module connection issues, blown fuses, defective modules, as well as array in-homogeneities due to temperature gradients and the impact of hourly averaging, and MPPT tracking efficiency on system performance. A portion of this loss is attributed to the time delay between the onset of small distributed failures and their detection and repair. PV plants with string-level monitoring may achieve an improvement in DC Health, but at some increased capital cost. PVsyst does not offer a specific loss input to capture DC Health loss, so generally it is included through Module Quality Loss or Availability Loss. First Solar has assumed a DC Health loss of 1% in these studies, matching the original energy predictions that were done for the project.

3.2.3. *Soiling*

Dust from various sources will accumulate over time, and reduce the amount of irradiance reaching the active material in the PV module. The soiling losses incurred are primarily a function of the frequency of rainfall, as well as the ground and soil conditions and associated dust levels at the site.

Soiling monitoring stations are installed at First Solar's large-scale sites to compare actual soiling data with that used in predictions. The stations consist of two side-by-side calibrated reference modules, one of which is cleaned weekly.

3.2.4. *Spectral Adjustment*

Typical PV system modelling assumes a constant solar spectrum based on the ASTM G173 standard with an air mass (AM) of 1.5 and a precipitable water (Pwat) value of 1.42 cm. However, both seasonal and time of day changes in the solar spectrum compared with standard test conditions (STC) are known to induce shifts in the performance of PV modules. Due to the distinct quantum efficiency (QE) curves of their respective cell technologies, CdTe and c-Si (as well as other PV devices) exhibit different sensitivities to changes in the solar spectrum relative to observed solar energy measured by broadband pyranometers. To manage the increased sensitivity to short wavelengths of CdTe devices, First Solar has done extensive research to quantify the impact of changes in the solar spectrum on expected performance and is developing increasingly accurate, yet easy to implement, models for calculating spectral shift (M). The first such model was a function of Pwat only, after identifying that atmospheric water vapour was the primary driver of spectral shift in CdTe devices (Lee & Panchula, 2016). However, to develop a model that was also applicable to other module technologies, other secondary atmospheric parameters that affect PV performance were investigated. As a result, First Solar has recently developed and published a 2-parameter spectral model which considers both Pwat and AM, suitable for use with both CdTe and c-Si devices. This model results in improved accuracy for expected versus. measured spectral shift for both technologies (Lee & Panchula, 2016).

Accordingly, the 2-parameter spectral model has been applied for both the PVsyst and PlantPredict analysis of the Nyngan and Broken Hill solar plants. Results of this study are shown in Figure 2. Spectral shift due to Pwat and AM for CdTe and multi c-Si. The model and field results indicate that First Solar modules will experience positive spectral shift (increased performance) under conditions of high Pwat and low AM, when field conditions are hot and humid. This usually occurs seasonally during the summer and in the middle of the day, when irradiance is high and the majority of energy is generated. Conversely, negative spectral shift (decreased performance) is experienced by First Solar modules under conditions of low Pwat and high AM under cool, dry conditions, which typically take place during early morning and late afternoon and seasonally during the winter, when irradiance and production are lower.

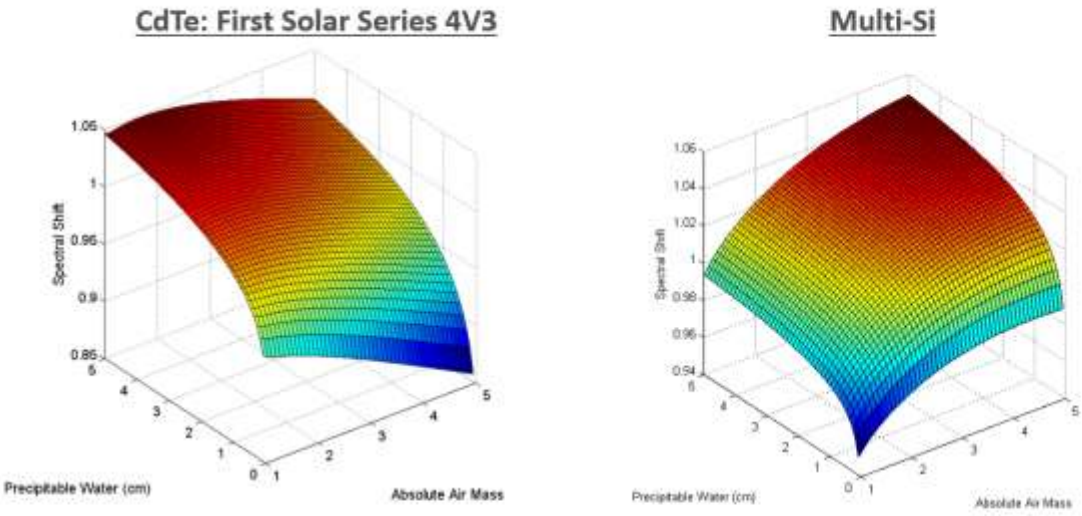

Figure 2. Spectral shift due to Pwat and AM for CdTe and multi c-Si

Unfortunately, most commercial energy modelling tools such as PVsyst do not yet offer the capability to apply a spectral adjustment. In the meantime, First Solar has created a spectral adjustment calculation aid which calculates the spectral shift factor ’M’ on an hourly basis and aggregates the effect into irradiance-weighted monthly values. The current version of this tool uses Pwat (measured in cm) and AM based on the geographical coordinates, elevation (or pressure if hourly data is available), and hour of the day. The tool applies an algorithm depending on the module series and version according to an application note in the First Solar energy prediction bundle. If the meteorological dataset does not contain Pwat values, the calculation aid also provides an option to estimate Pwat from ambient temperature and relative humidity. This tool can also be used for c-Si technology.

Once the monthly spectral shift factors are calculated, the effect is combined with soiling for input into the PVsyst soiling loss dialogue. When the effect of soiling plus spectral effects are net positive, since PVsyst does not allow a soiling *gain*, this limitation is bypassed by adjusting the module quality loss to compensate and bring the minimum soiling input to 0. One significant advantage of PlantPredict is that none of this post-processing is required. The user simply selects the spectral model he or she wishes to apply (the 2-parameter model is now the default), and the software will apply an hourly spectral shift to the Plane of Array (POA) irradiance.

3.2.5. *Models of the PV Plants*

Both Nyngan and Broken Hill solar plants utilise a combination of different module bin classes, and in the case of the Broken Hill Solar Plant, modules of different series. In PlantPredict this is managed through a nested hierarchy of blocks and arrays, which allows the user to define separate DC and AC architectures for sections within a PV Plant. The software then aggregates the output from each sub-component to obtain a final result. PVsyst provides a similar function through the use of sub-arrays; however, because the soiling losses are defined globally for the whole system, it is not possible to apply independent spectral shift values to each sub-array using First Solar's Spectral Adjustment Tool. Since the Broken Hill Solar Plant contains array types using both Series 4 and Series 4V2 modules which have different spectral responses due to the advancement of a graded band gap, it was necessary to run two separate PVsyst simulations for the Broken Hill Solar Plant for the S4 arrays and S4V2 arrays and then manually sum the results.

3.2.6. *Determination of Adjusted Expected Performance*

The output of the PVsyst and PlantPredict models provide the 'expected performance' of the PV Plants based on actual weather. The expected performance then requires an adjustment to account for degradation, monthly recorded availability losses, and other lost energy to determine the 'adjusted expected performance,' against which we can compare the actual measured output.

In accordance with First Solar guidance, degradation is not applied to the expected performance in the first year of operation. In the case of the Nyngan Solar Plant, which has now been operational for more than one year, degradation was applied on a monthly basis at a rate of 0.5% per year after May 2016 (for example, June 2016 degradation is 0.5% / 12 = ~0.04%).

For availability and other lost energy, the operations and maintenance contractor (in this case First Solar) logs forced outages, planned outages, maintenance outages, out of management control events, and curtailments. Lost energy is then calculated, using a methodology developed by Hunt et al (2015), during the outage period, and subtracted from the expected performance.

3.3. *Results*

Figure 3. Nyngan Solar Plant actual vs. adjusted expected performance modelled in PlantPredict and PVsyst (NYSP, 2016) and Figure 4 show the PVsyst and PlantPredict models compared to actual metered data for the Nyngan and Broken Hill solar plants in the post-commissioning operational phase.

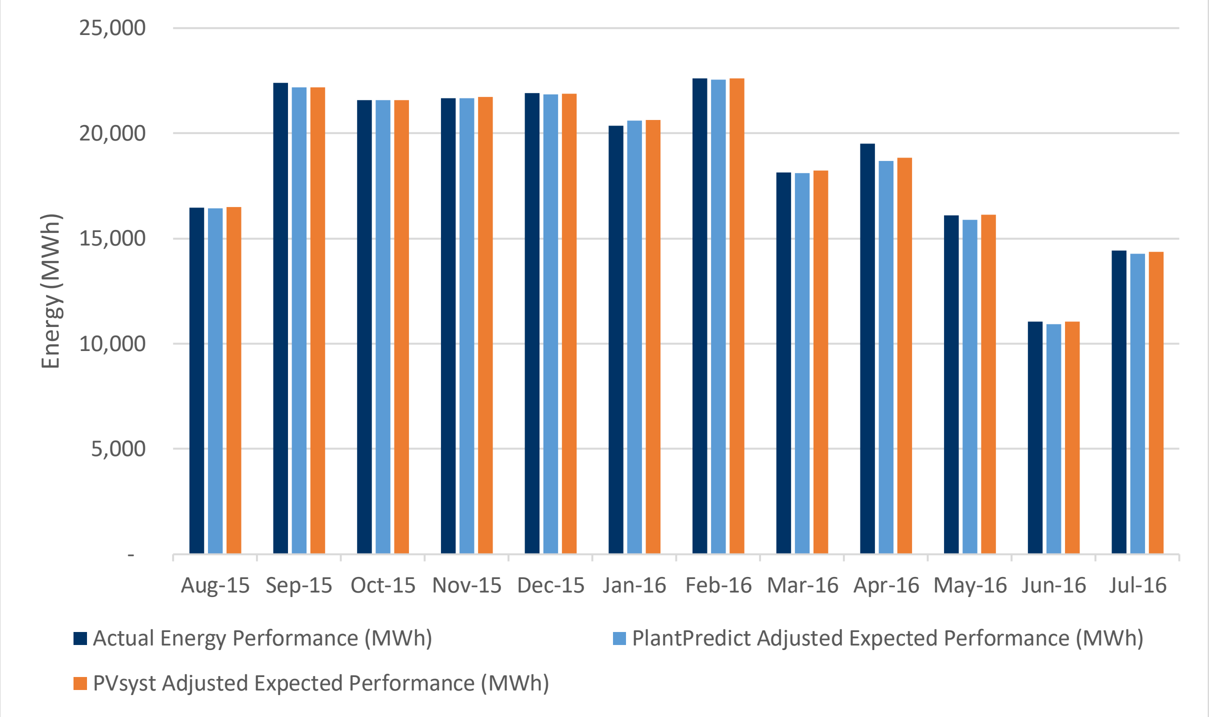

Figure 3. Nyngan Solar Plant actual vs. adjusted expected performance modelled in PlantPredict and PVsyst (NYSP, 2016)

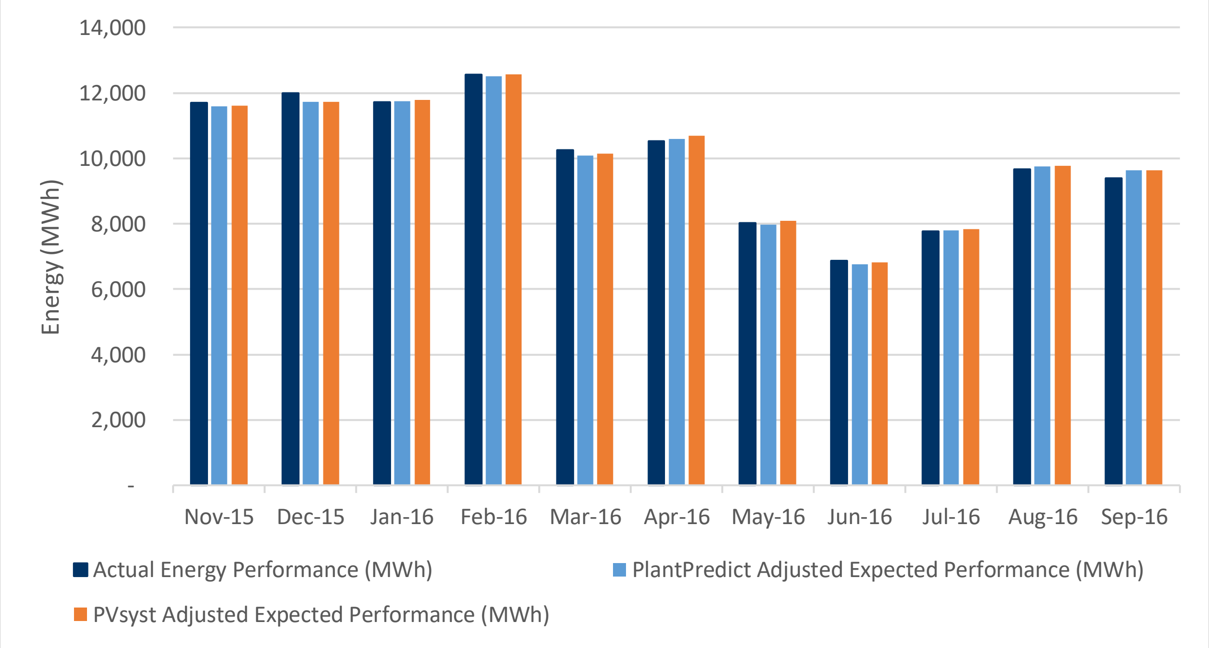

Figure 4. Broken Hill Solar Plant actual vs. expected performance modelled in PlantPredict and PVsyst (BHSP, 2016)

Figure 5**Error! Reference source not found.** shows previous benchmarking results for Greenough River between October 2012 and the end of 2015 (Passow et. al., 2015). Expected monthly energy using PlantPredict and the methodology described in the study is compared with metered generation data at Greenough River Solar Farm, with degradation applied at 0.7%p.a. in accordance with the guidance for Series 3 modules in hot climates.

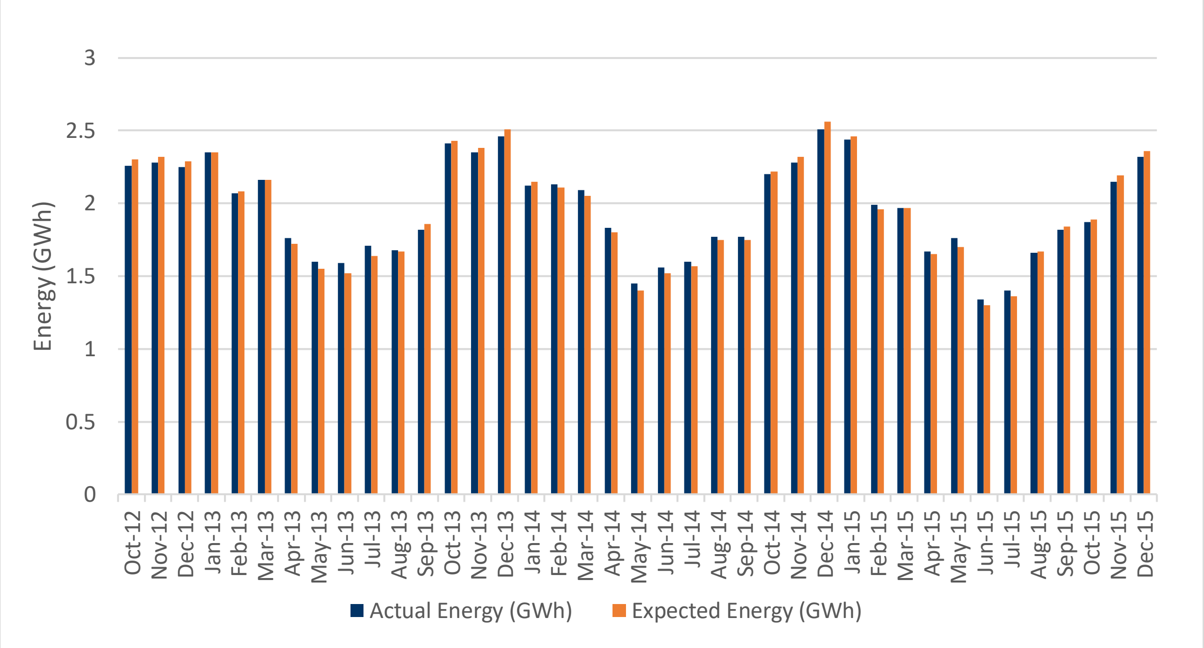

Figure 5. Greenough River Solar Farm actual vs expected site performance using PlantPredict and 1-parameter Spectral Adjustment (GRSF, 2016)

The existing fleet of large-scale solar plants in Australia using First Solar modules is performing within 1% of predicted, further validating the accuracy of First Solar's modelling guidance. A breakdown of the results is shown in Table 3. Summary of results (positive values indicate actual performance exceeded expected performance):

Table 3. Summary of results

Site	Validation period	Actual vs PVsyst adjusted expected performance	Actual vs PlantPredict adjusted expected performance
Greenough River Solar Farm	3 years 3 months	n/a	+0.17%
Nyngan Solar Plant	1 year	+0.20%	+0.64%
Broken Hill Solar Plant	11 months	-0.21%	+0.29%

These results indicate that First Solar's large-scale fleet in Australia is on average, slightly exceeding modeled P50 energy. Particularly considering that energy modelling uncertainty is generally considered to be approximately 3%, the results are a firm indication that the energy prediction guidance and assumptions are accurate, without being overly conservative. Results also show strong alignment between PVsyst, and PlantPredict, providing further evidence that PlantPredict delivers results comparable with industry-standard tools.

One source of uncertainty in the Broken Hill Solar Plant analysis is the numerous curtailments by the market operator, which appear to limit the plant output to a value just below expected on a five-minute basis. The lost energy from these minor curtailments has not been included in the availability calculation due to their high frequency and the correspondingly large amount of computational effort required to accurately determine the loss. While the impact is likely to be small, the inclusion of this lost energy would increase the actual output of the plant versus expected.

3.4. Plane of Array Transposition

In keeping with previous work by First Solar and others on the topic (Lave & Hayes, 2015), the Hay transposition model was used in the analysis to match the original energy predictions for these projects. In assessing the accuracy of the transposition model for the Broken Hill Solar Plant, measured POA data from October 2015 was included to have a complete year of data, despite the exclusion of this month from the performance analysis due to the site still undergoing commissioning. Table 4 shows that while the error at the Broken Hill Solar Plant is essentially negligible, there is greater uncertainty in the transposition at the Nyngan Solar Plant, likely due to more frequent variable, low irradiance conditions. PVsyst is over-predicting POA by approximately 0.5%, and PlantPredict under-predicting POA by approximately 0.2%. Applying this error linearly to the actual versus adjusted expected performance brings the results from both PVsyst and PlantPredict within 0.25%.

Table 4. Hay transposition error

Site	Measured POA (W/m^2)	PVsyst (%)	PlantPredict (%)
Nyngan Solar Plant	2145	+0.49	-0.19
Broken Hill Solar Plant	2168	-0.04	-0.03

3.5. Soiling

Table 5 and Figure 6 illustrates measured soiling losses at each site of First Solar's Australian large-scale fleet. These losses have been applied on a monthly basis as an input to PVsyst and PlantPredict to determine the expected performance. As the graphs below indicate, measured soiling is relatively low at all sites. Local site conditions must always be factored in for a detailed energy performance analysis.

Table 5. Average measured soiling Greenough River Solar Farm, Nyngan and Broken Hill solar plants (GRSF, NYSP, BHSP, 2016)

Site	Average actual measured soiling
Greenough River Solar Farm	0.31%
Nyngan Solar Plant	0.27%
Broken Hill Solar Plant	0.14%

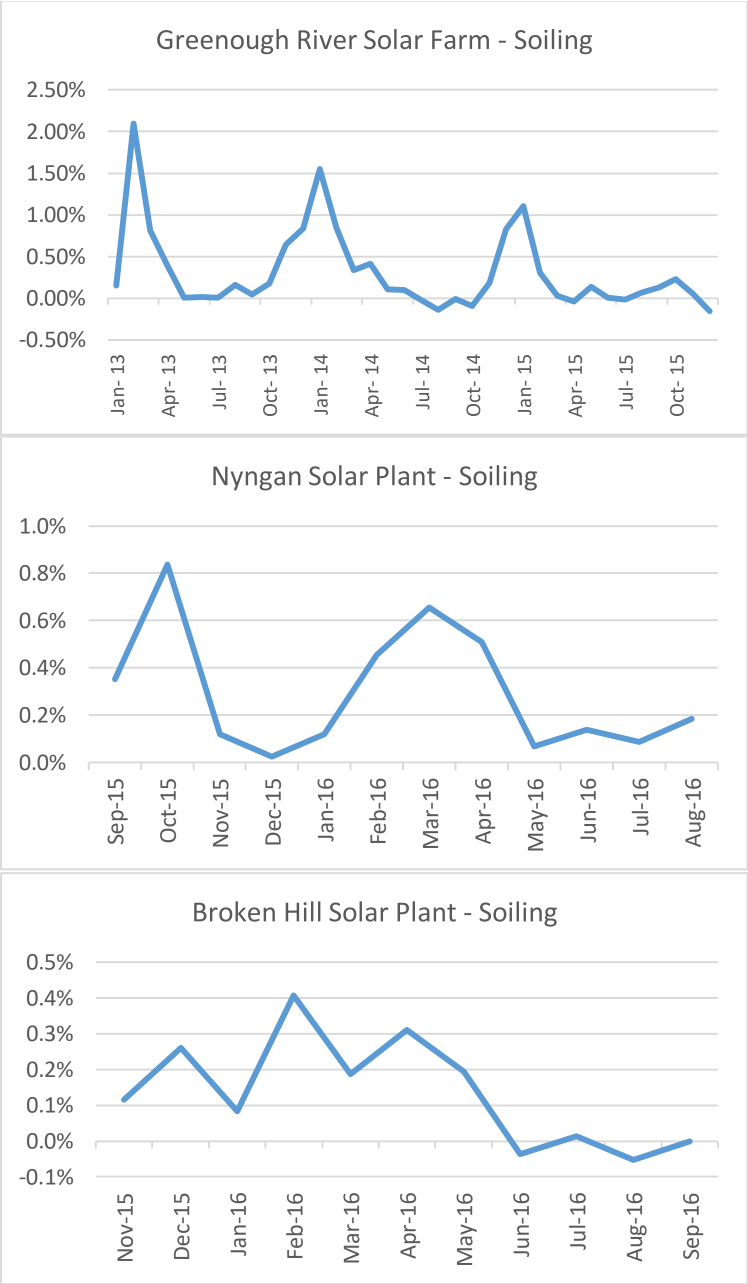

Figure 6. Actual measured soiling at Greenough River Solar Farm, Nyngan and Broken Hill solar plants (GRSF, NYSP, BHSP, 2016)

3.6. Temperature impact

There is a strong negative correlation with increasing temperature and PV module voltage, and a weak positive correlation between increasing temperature and PV module current. The overall impact on module output is that PV modules will decrease in output with higher temperatures versus their STC rating at 25°C. These performance changes are a function of the semiconductor material and the influence the temperature has on the QE of the semiconductor junction.

Temperature coefficients for open circuit voltage, short circuit current, and power at maximum power point are defined according to IEC 61215 and IEC 61646 as part of PV module design qualification and are specified on the module datasheet. The losses calculated at the Nyngan and Broken Hill solar plants by PVsyst and PlantPredict are shown in Table 6. These have been compared to expected losses for a PV plant using a generic c-Si module with a temperature coefficient of -0.41%/ºC. Calculated in PlantPredict, the results demonstrate a 1.8% and 1.6% temperature advantage at the Nyngan and Broken Hill solar plants respectively, based on the measured weather during the 2015-2016 period.

Table 6. Summary of temperature losses at Nyngan and Broken Hill solar plants

Site	**Array module type**	**Temperature coefficient (%/°C)**	**PVsyst calculated temp. loss (%)**	**PlantPredict calculated temp. loss (%)**	**PlantPredict c-Si calculated temp. loss (%)**
Nyngan Solar Plant	Series 3	-0.29	5.5	5.5	7.3
Broken Hill Solar Plant	Series 4	-0.29	5.2	5.4	7.0
	Series 4V2	-0.34	5.9		

4. Spectral Shift Analysis

The spectral shift has been analysed previously at the Greenough River Solar Farm using the spectral model with ground measured air temperature and relative humidity (results are shown in Figure 7). The spectral adjustment was shown to vary between approximately 0.3% and 2.0%, resulting in an expected energy gain throughout the year.

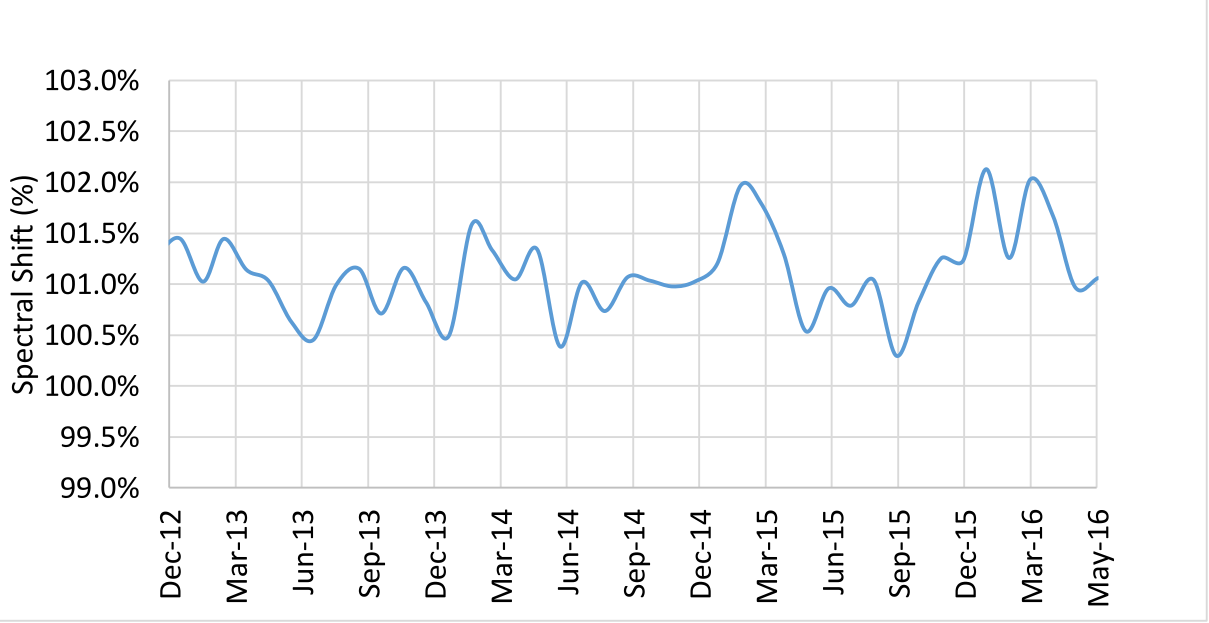

Figure 7. Calculated spectral shift at Greenough River Solar Farm (GRSF, 2016)

A similar analysis has been performed for Nyngan and Broken Hill using the latest spectral model, shown in Figure 8 and Figure 9. The strong fit between monthly actual and expected generation at both sites is a good indication that the adjustment has improved the energy prediction accuracy.

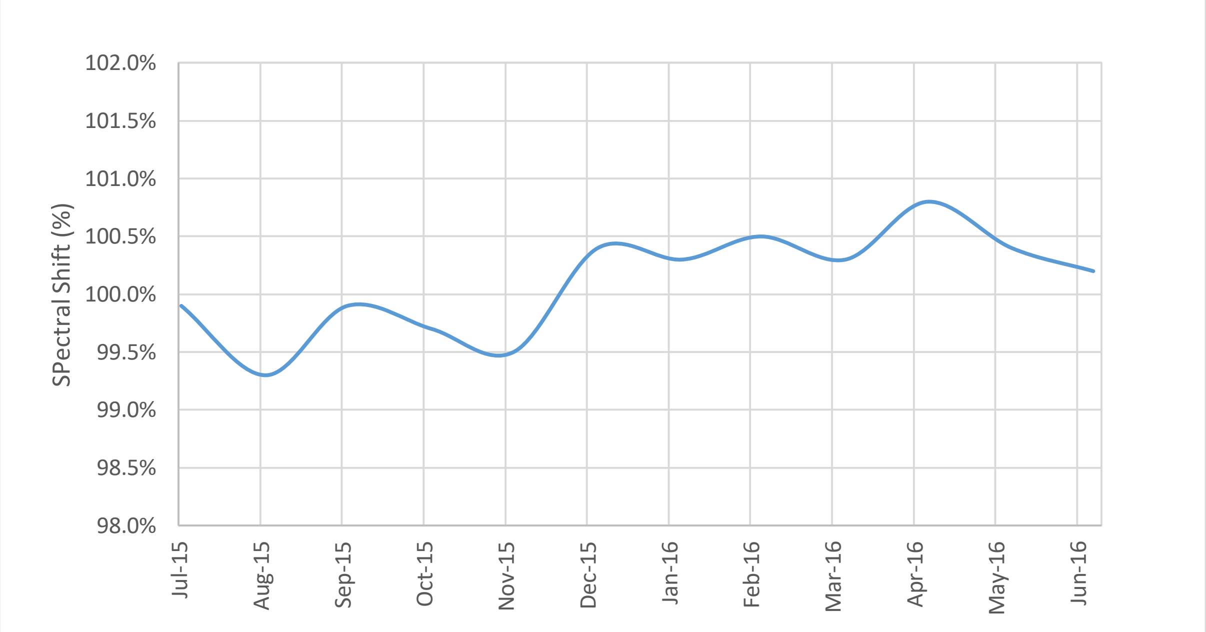

Figure 8. Calculated spectral shift at Nyngan Solar Plant (NYSP, 2016)

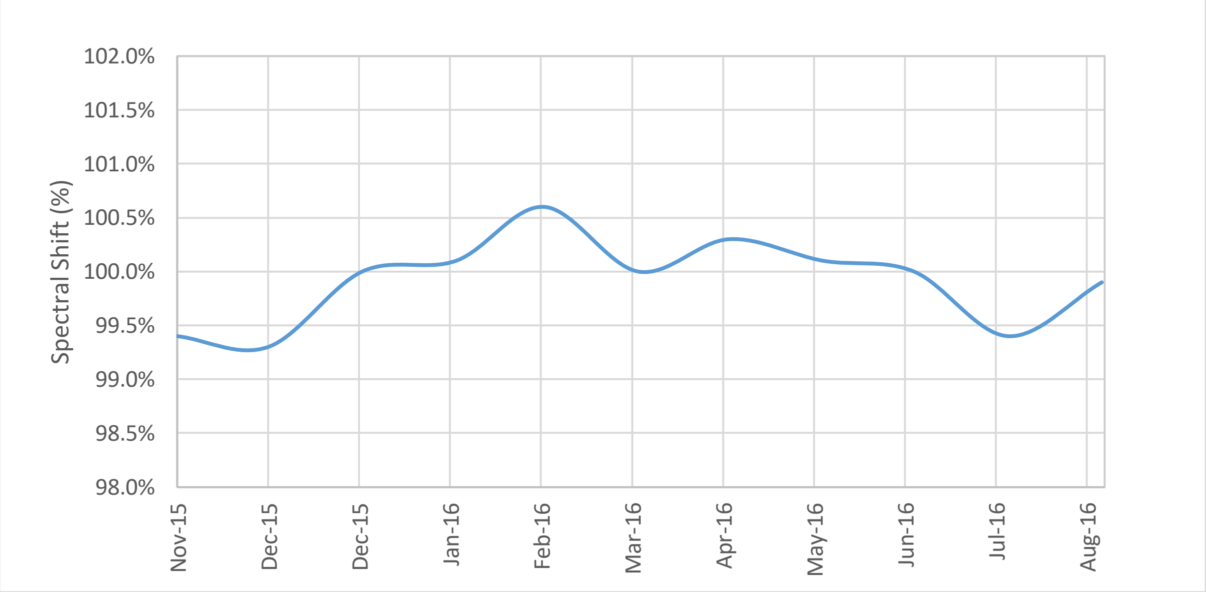

Figure 9. Calculated spectral shift at Broken Hill Solar Plant (BHSP, 2016)

5. Conclusion

The accuracy of prediction models is a critical requirement for reducing the contractual performance risk of PV projects. These results indicate a strong correlation between expected and actual energy when the energy model is designed according to First Solar’s modelling guidance and should act to increase the viability of future PV projects in Australia.

Furthermore, the close correlation between actual performance and results obtained using both PVsyst and PlantPredict validate the accuracy of First Solar’s energy prediction software in the Australian climate, with results closely matching previous studies performed in the USA. The demonstrated performance of First Solar's Australian fleet also highlights the importance of modelling guidance that takes into consideration spectral shift and accurately models parameters beyond the standard functionality and default settings of pre-existing modelling software.

Finally, in validating input parameters to the model which include temperature coefficients, degradation, and first-year output, the analysis demonstrates the performance and reliability advantages inherent to First Solar's CdTe PV modules in a range of Australian environments.

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GRSF performance data courtesy of Synergy and GE Energy Financial Services

NYSP and BHSP performance data courtesy of AGL