Performance Characterization of Cadmium Telluride Modules Validated by Utility-Scale and Test Systems

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***Abstract* — Performance of First Solar CdTe modules deployed at both test and utility-scales are reviewed with characterization of the critical inputs to lifetime energy generation models. Systems reviewed in detail are a 15–month-old facility containing more than 30 MWdc, a 10-year-old 1.2 kWdc NREL test array, 19-year-old 600 Wdc NREL test array. A statistical analysis of an aggregate population of 600 MWdc of systems with up to 10 years of operation is undertaken. Data from the utility-scale installation are used to validate First Solar's energy prediction guidance and internal prediction software, Isis, which predicts energy to within +/- 0.2% of measured. Plane-of-array irradiance and module temperature accuracy are also reviewed. The field test arrays at NREL exhibit long-term degradation rates ranging from -0.3%/yr to -0.5%/yr for First Solar CdTe modules.**

***Index Terms* — CdTe, PV system performance, degradation rate, thin-film PV, PV energy modeling, photovoltaic cells.**

I. INTRODUCTION

This study aims to address energy prediction accuracy from three different perspectives. First, a detailed analysis is performed on a single utility-scale system in a hot, desert climate. In this analysis, measured plant performance is compared to the prediction at the system energy meter and at comparison points along the way in order to identify where discrepancies between the model and measurements may arise. This is similar to a prior paper published on another First Solar utility-scale system in 2011 but this time the system is located in a hot climate [1]. Next, data from over 50 systems around the world, comprising of more than 600 MWdc of modules, are shown to depict the expected distribution of performance within a large population of systems compared to their weather-adjusted predictions. Finally, data from two long term test installations at NREL are included for the purpose of validating First Solar's degradation rate guidance.

II. FIRST-YEAR PERFORMANCE OF A UTILITY-SCALE SYSTEM

A system located in the United States Desert Southwest containing more than 30 MWdc of First Solar modules was energized in 2012. This system is instrumented with high-quality measurements, including: secondary standard global horizontal irradiance (GHI) and plane-of-array irradiance (POAI) pyranometers, ambient temperature, wind speed, relative humidity, module surface temperature, and energy meters. In addition, the default inverter-supplied DC current, voltage, and AC power measurements are recorded. Sensor types and accuracies are shown in Table I.

TABLE I
MEASUREMENT SENSORS AND ACCURACIES

Measurement	Device	Accuracy	Number
GHI	Kipp & Zonen CMP-11	± 2.0% daily	5
POAI	Kipp & Zonen CMP-11	± 2.0% daily	5
Ambient Temperature	Campbell CS215	± 0.3°C at 25°C	5
Relative Humidity	Campbell CS215	± 4% at 25°C	5
Module Surface Temperature	RTD	0.08% drift <0.1°C per year	8
DC Current	Inverter Sensor	Unknown	40
DC Voltage	Inverter Sensor	Unknown	40
AC Power	Inverter Sensor	Unknown	40
Energy Meter	SEL-734	0.06% at PF = 1	1

A. Measured Data Preparation

Average 1-minute measured data are subjected to a variety of filters that are meant to exclude any data point which is invalid in an automated fashion. Flags are thrown when data do not meet the criteria summarized in Table II. After the automated filters are applied, an analyst manually reviews the results to ensure data integrity. Filter types are:

1. Limit Filter: detects data that are outside of a reasonable range for the measurement type.
2. Dead Filter: detects data where a measurement unexpectedly reports a repeated value.
3. Outlier/Pairwise Filter: detects data where one or more sensors for a given measurement type are reporting values that are significantly different from their peers.
4. Jump Filter: detects data with unrealistic changes from one measurement to the next.
5. Bad Sensor Filter: detects data from a sensor that is reporting chronically unrealistic values.
6. Time-series pairwise filter: compares trends of one sensor to the average of its peers as a function of time.

Most useful for detecting irradiance sensor calibration drift and misalignment.

7. Manual: analyst manual exclusion of a sensor for the entire time period.

After this filtering is run and data confirmed to be of poor quality are excluded, remaining data from all like sensors are averaged to give a single 1-minute value for each measurement type. Filtered 1-minute measured GHI and ambient temperature are averaged into hourly intervals for input into the prediction. Other filtered values are averaged into hourly time intervals for comparison to predicted values.

B. Prediction Preparation

Isis, First Solar's internally developed PV system simulation software, is used to predict energy output [2]. Although Isis is capable of running at sub-hourly time intervals and with advanced First Solar algorithms, for this analysis it is configured to mimic as closely as possible First Solar's guidance for predicting systems in well-known PVsyst PV system simulation software [3]. Data from on-site soiling stations are used to calculate monthly soiling levels [4]. Hourly relative humidity and ambient temperature data from ground-mounted meteorological stations are used to estimate monthly spectral shift factors [5, 6]. Monthly soiling levels and spectral shift factors are shown in Table III.

Filtered and averaged measured POAI, module temperature, DC current, DC voltage, inverter efficiency, AC power at the inverter and AC energy at the energy meter are compared to predicted values.

The availability due to forced and maintenance outages for this system was better than 99.5%. However, any hour in which an "unpredictable" event occurred is excluded from the comparison. Unpredictable events include system curtailment or lack of data critical to run an energy prediction; of the 10,968 hours studied, 412 are filtered due to unpredictable events.

TABLE III
MEASURED SOILING LEVELS AND SPECTRAL SHIFT BY MONTH

Month	Soiling Level (%)	Spectral Shift (%)
January	1.48%	97.7%
February	1.40%	98.2%
March	1.25%	98.4%
April	2.84%	98.2%
May	3.37%	99.0%
June	3.72%	99.3%
July	1.30%	101.5%
August	0.70%	101.4%
September	0.52%	101.1%
October	1.99%	99.7%
November	4.24%	98.7%
December	2.77%	98.8%

TABLE II
FILTERS APPLIED TO 1-MINUTE MEASURED DATA

Flag Type	Description	Irradiance (W/m^2)	Ambient Temperature (° C)	Module Temperature (° C)	Relative Humidity (%)	Power (kW)
Limit	unreasonable value	< -6 or > 1400	< -30 or > 50	< -30 or > 90	< 0 or > 100	< 0% or > 105% nameplate
Dead	values stuck at a single value over time; uses 1-minute derivative.	< 0.0001 while value is > 5	< 0.0001	< 0.0001	< 0.0001	< 0.0001 while value is > 5% nameplate
Jump	unreasonable change between data points; uses 1-minute derivative	> 800	> 4	not used	> 10%	> 60% nameplate
Outlier/Pairwise	significant difference between like sensors	> 100 or > 3*stdev	> 20 or > 3*stdev	> 20 or > 3*stdev	> 20 or > 3*stdev	Power < 0 while irradiance > 100 W/m^2
Time-Series Pairwise	values between like sensors change over time	Drift of average > 1%	Drift of average > 2	not used	not used	not used

C. Comparing Measured to Predicted Data

The Hay transposition model coupled with the Reindl diffuse decomposition model is used to translate measured GHI to POAI [7, 8]. This grouping of models has very good accuracy in this case, predicting 3013 kWh/m^2 over the 15 months studied while the five POAI sensors measured and average of 3017 kWh/m^2 over the same time period (0.17% underprediction). The hourly root mean squared error (RMSE) of the POAI prediction is 12 W/m^2. See Fig. 1.

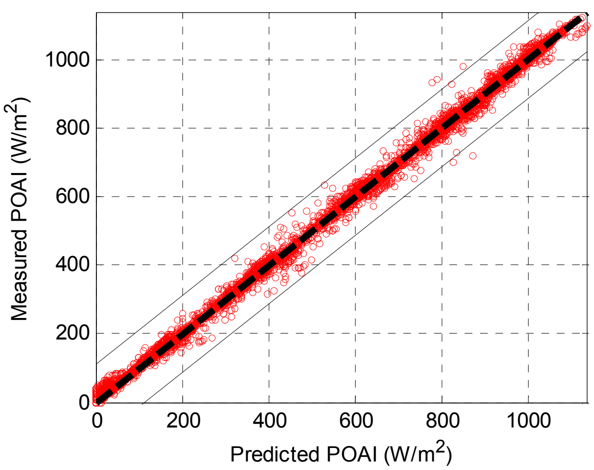

Fig. 1. Hourly POAI prediction accuracy

The simple heat balance model is used to predict module temperature with First Solar's recommended coefficients of U_c = 30.7 and U_v = 0 [9]. The annual energy-weighted average measured module temperature is 47.6°C while that predicted is 48.0°C, which translates to an annual mean error of 0.4°C (0.10% underprediction of energy with the temperature coefficient of -0.25%/°C for the modules comprising the studied system population). The hourly RMSE is 4.0°C. See Fig. 2.

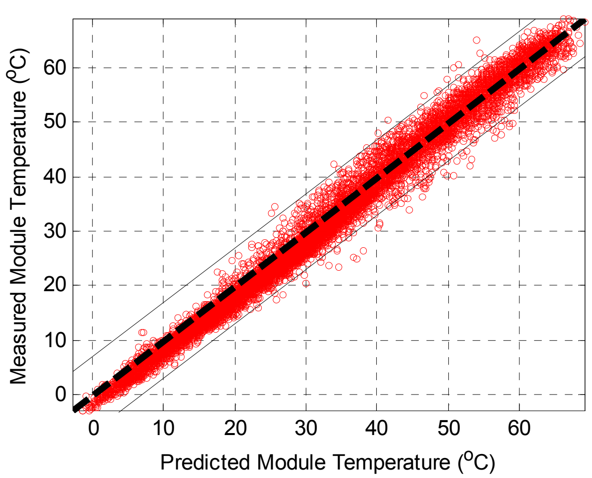

Fig. 2. Hourly module surface temperature accuracy

The one-diode model is used to compute the module current-voltage characteristics and Isis then computes aggregate values for the array. Figs. 3–5 compare measured to predicted inverter characteristics. There are 40 inverters on site; the measured data points represent the average of all inverters and the error bars represent two standard deviations of the inverter measurements.

The annual energy-weighted average measured DC voltage is 670 V and the predicted value is 684 V, an overprediction of 2.0%. The hourly RMSE is 16.2 V. For these predictions, degradation guidance is implemented on the AC side only; future implementation of advanced algorithms on the DC side will improve the prediction accuracy. See Fig. 3.

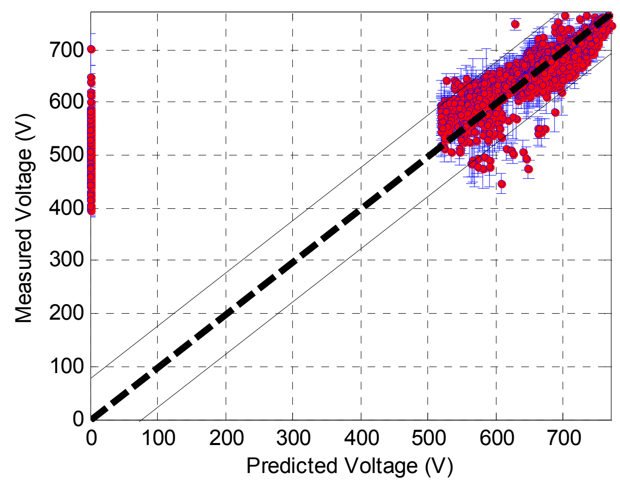

Fig. 3. Hourly DC voltage prediction accuracy. Error bars are two standard deviations of individual inverter values.

The annual energy-weighted DC current measured by the inverter is 765 A while Isis predicts 758 A, an underprediction of 0.9%. The hourly RMSE is 28.4 A. See Fig. 4.

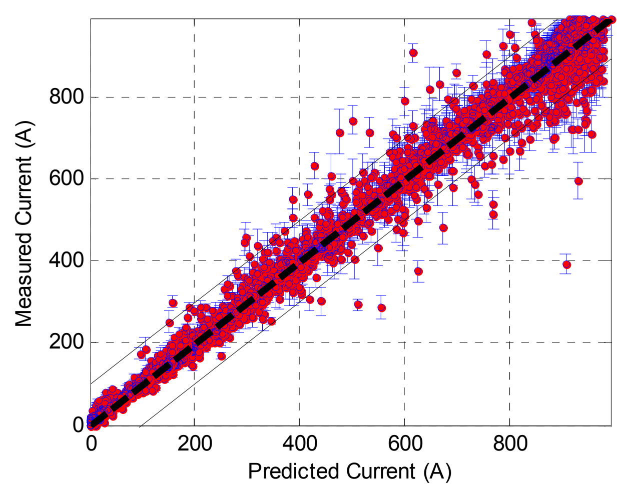

Fig. 4. Hourly DC current prediction accuracy. Error bars are two standard deviations of individual inverter values.

The inverter parameters and efficiency curve reported by the manufacturer are used in Isis to calculate the expected AC output of the inverter. The energy-weighted average measured total sum AC power of all inverters is 80.04 GWh compared to a prediction of 80.99 GWh, a total overprediction of 1.2%. The hourly RMSE when considering a single inverter is 17.7 kW (see Fig. 5).

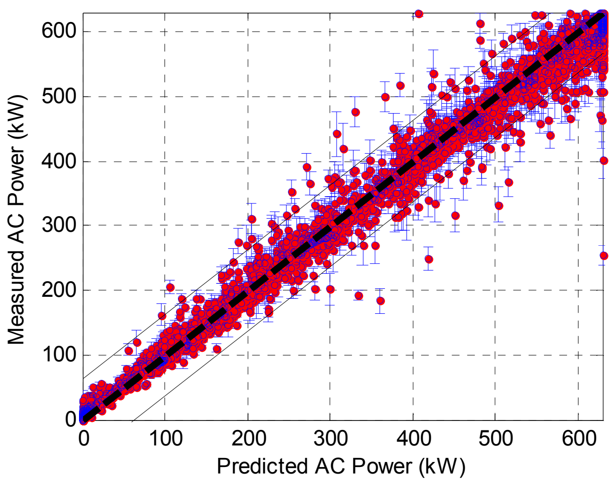

Fig. 5. Hourly inverter AC power prediction accuracy. Error bars are two standard deviations of individual inverter values.

The measured inverter efficiency is calculated every hour using the inverter-measured AC power, DC voltage, and DC current. The energy-weighted average measured inverter efficiency is 97.5% and 98.2% is predicted, a 0.7% overprediction (see Fig. 6). Further analysis of manufacturer-provided versus measured inverter efficiencies is necessary to resolve this discrepancy. More information on this topic can be found in [12].

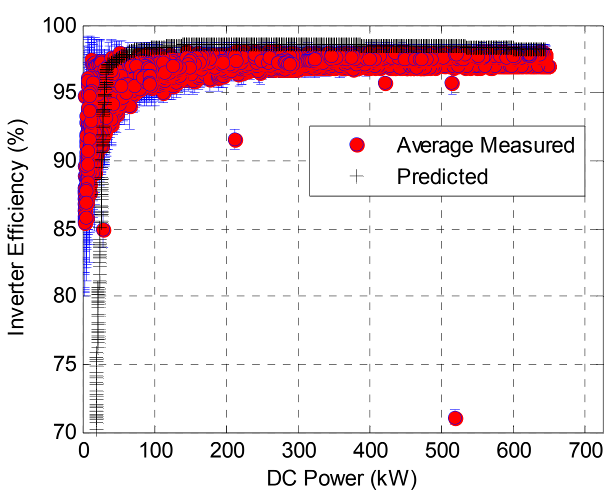

Fig. 6. Measured and predicted inverter efficiency. Error bars are two standard deviations of individual inverter values.

The DC current and voltage and AC power match the prediction relatively well, especially considering the unspecified and suspect accuracy of the inverter measurements. However, it is challenging to make concrete technical conclusions from measurements with unspecified error. It is highly desirable that future inverter measurement accuracies be improved and that associated uncertainties are listed on inverter manufacturer specification sheets.

Isis predicts the energy at the system energy meter with a high degree of accuracy. Over the 15 months studied, Isis predicts 78.43 GWh of energy production while 78.54 GWh is measured by the system energy meter (0.13% underprediction). The hourly RMSE is 0.6 MW. See Fig. 7.

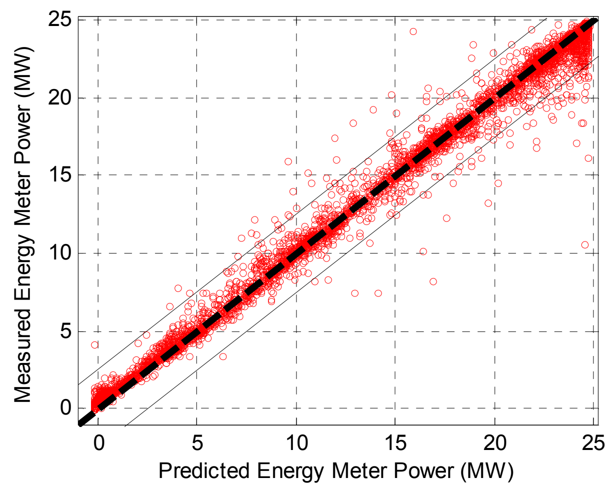

Fig. 7. Hourly system energy prediction accuracy.

Prediction accuracies at various measurement points throughout the system are summarized in Table IV. The comparison points marked with an asterisk represent energy-weighted averages. A positive value indicates overprediction and a negative value indicates underprediction.

In general, all measurement points agree relatively well. The transposition-decomposition model pair performed very well with less than 1% error in this case. Although not reflected by the mean error listed in Table IV, there was a large amount of scatter in the module temperature trend which will be improved with advanced thermal models available in Isis [13]. DC current and voltage and AC power deviated from the prediction the most of all comparison points, but considering the unknown measurement accuracies associated with these points, it's difficult to conclude if this is due to measurement error or modeling error. The prediction accuracy at the plant energy meter was superb, with less than 0.2% error. This level of accuracy is only possible with the inclusion of measured soiling and correcting for spectrum [4, 14].

TABLE IV
PREDICTION ACCURACY AT COMPARISON POINTS

Comparison Point	Measured	Expected	Prediction Accuracy
POAI (kWh/m^2)	3017	3012	-0.17%
Module Temperature (°C)*	47.6	48.0	-0.10%
DC Inverter Current (A)*	765	758	-0.92%
DC Inverter Voltage (V)*	670	684	2.1%
DC Inverter Energy (GWh)	82.1	82.4	0.4%
Inverter Efficiency (%)*	97.5	98.2	0.7%
AC Inverter Energy (GWh)	80.0	81.0	1.3%
Plant Energy (GWh)	78.5	78.4	-0.13%
Performance Ratio (--)	0.773	0.773	0.0%

III. MANY SYSTEMS TOGETHER

As of early 2014, First Solar actively monitors systems totaling over 2.5 GWdc. This population is downselected to include only mature systems with sufficient operating history. Comparisons of predicted to measured energy at the energy meter for 600 MWdc composed of 54 globally distributed systems are shown in an effort to assess the distribution of performance expected compared to weather adjusted predictions.

For each of the systems in this distribution, an energy prediction is run using typical meteorological year (TMY) or measured weather data as input to either PVsyst or Isis. In cases in which the prediction is run using TMY weather data, the predicted energy is scaled on a monthly basis by the ratio of measured to predicted POAI. Most of the systems do not include soiling measurements; for those systems that do not include soiling stations, simple soiling assumptions are made and used in the prediction (1%, 2% or 3% flat soiling loss depending location). For sites that have high quality relative humidity measurements available, measured spectral shift is included in the prediction. However, only recently was this included into First Solar's prediction guidance [14] so only those systems predicted after this change are affected by this adjustment. To maintain credibility, the energy predictions used to calculate performance are those from which the system was originally predicted on. Only slight modifications to accommodate new software models have been included.

On average, the systems perform at 99.4% of predicted, with a standard deviation of 2.6%. The standard deviation is an indication of the uncertainty of a weather-adjusted energy prediction. Also included into this calculation is the multi-year power degradation model. For example, the first data point from 2004 operating at 99.4% has built in an assumption of -0.5% per year degradation rate. This close operation to the P50 predicted energy over many years supports that the system is degrading as guided. This gives confidence surrounding the long-term financial impact of the energy prediction.

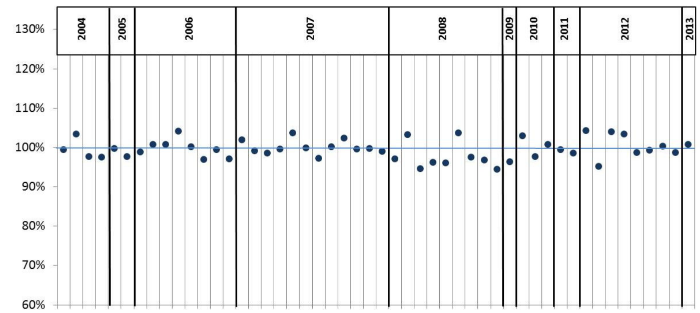

Fig. 8. Ratio of lifetime measured to lifetime predicted energy for 54 systems comprised of over 600 MWdc of First Solar modules.

IV. LONG-TERM DEGRADATION RATES

Two test systems with First Solar modules have been installed for 10 years or more at the National Renewable Energy Laboratory in Golden, Colorado. These systems, installed in 1995 and 2003, contain 600 and 1200 watts of modules, respectively. Degradation rates are calculated using 10 different metrics, including some time-series modeling such as classical decomposition and autoregressive integrated moving average (ARIMA) that have been shown to reduce uncertainty by removing seasonality [11]. The 600 Wdc system, which has been installed for 19 years, shows a median linear degradation rate of -0.47% +/- 0.07% per year.

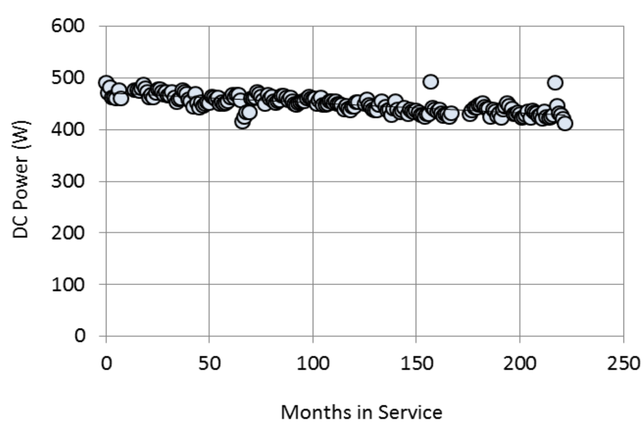

Fig. 9. Monthly PVUSA rating more than 19 years of 600 Wdc NREL test system operation.

The 1.2 kW system experienced an initial power drop of 6% to 8% cumulative over the first three years. In subsequent years after this initial stabilization period, the rate of power drop was significantly reduced. This is consistent with First Solar expected exponential degradation trends. This initial stabilization is compensated for in First Solar's commercial products by applying an engineered performance margin to the initial production flash power measurement, yielding a derated nameplate power value [10]. The median linear degradation rate over the more than 10 years of system operation is -0.33% +/- 0.19% per year. This later system represents First Solar's current module technology much closer than the prototype modules deployed in 1995, indicating a prudent buffer from First Solar's degradation guidance of -0.5% per year. The decrease of the performance in months 47 and 79 were caused when fractured modules due to mishandling after an indoor measurement were replaced with sister modules from this production batch. After replacement, the modules were not light-soaked prior to installation, leading to a temporary decline and subsequent recovery in performance. In total, 4 modules were replaced during the more than 10 year deployment.

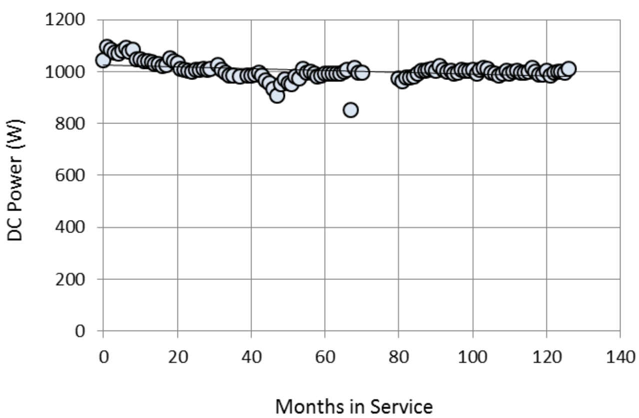

Fig. 10. Monthly PVUSA rating more than 10 years of 1.2 kWdc NREL test system operation

V. Conclusions

Careful analysis of a utility-scale system in a hot climate has shown that Isis, First Solar's internal prediction tool, predicted energy within 0.2% of measurements when set to mimic First Solar's guidance for running PVsyst, with measured soiling and adjusting for spectrum. The module temperature model was shown to produce increased scatter when compared to measured data (4°C hourly RMSE). The Hay transposition model coupled with the Reindl diffuse decomposition model was shown to predict POAI within 0.2% of the average of five secondary standard measurements on site.

A high-level look at more than 600 MWdc of First Solar modules composed of 54 globally distributed systems showed an average performance of 99.4% of predicted with a standard deviation of 2.6%.

Finally, long-term performance data from two independently managed systems at NREL showed degradation rates of -0.47% +/- 0.07% per year and -0.33% +/- 0.19% per year over the 19 and 10 years they have been fielded, respectively. This supports First Solar's guided -0.5% per year degradation rate.

In order to continually improve the accuracy of the energy prediction we recommend more sophisticated thermal models and improvement of inverter measurement accuracy. We are hopeful that as we continue to develop new models and refine old ones, we will be able to continue to reduce the uncertainty of PV system energy predictions.

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