

Validation Master Plan

Regional Test Centers (RTCs)

Revision

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Rev 3.0	1/14/2012	All sections reformatted to include example graphs
Rev 5	2/3/2012	Reduced scope to include the graphs that are needed in a validation report and deleted the graphs that are relevant to developing new techniques
Rev 6	2/9/2012	Downsized to limit scope of the document to the things that we know must be included and we cut out the parts that are still more in an R&D phase.
Rev 7	2/10/2012	Cleaned up several things
Rev 8	2/17/2012	Calendar plot and a new paragraph, plus things cleaned up

VALIDATION, VERIFICATION AND TESTING PLAN

TABLE OF CONTENTS

Purpose	3
Scope	4
Roles and Responsibilities	5
Definitions	7
Analytical Methods	8
Commissioning	8
Data Collection	15
Performance	17
Analysis & Modeling	21
Reliability & Safety	24
References	30

Purpose

The Regional Test Centers (RTCs) have been established by DOE at five different locations to independently validate the performance and reliability of Photovoltaic (PV) systems, particularly for emerging US manufacturers, and to develop standardized processes for such validation procedures. These locations (Albuquerque, NM; Denver, CO; Orlando, FL; Essex, VT; and Las Vegas, NV) were picked in part due to their different climate conditions, which have larger effects on system performance, degradation, and durability. The RTCs will provide the land and electrical infrastructure required to install up to 500-kW system blocks for validation. More importantly, the RTCs will provide the expertise of DOE's national laboratories to assess and validate the performance and initial reliability in such detail that manufacturers, integrators and the financial community will develop greater confidence in the bankability of these systems.

There are many reasons why systems could perform differently at different sites (solar resource, environmental conditions, etc.). One of the objectives of the validation work is to measure and document these differences with the goal of improving industry's ability to predict the output of new technologies regardless of where they are deployed. Detailed performance monitoring is essential to ensure that the performance and reliability modeling tools used by industry and by independent engineers to assess bankability are able to predict power and energy output from such systems for any location over time. Detailed monitoring also enables early detection of module degradation, infant mortality failures, and early indicators of potential failure modes. The RTCs will draw on many years of experience with installing and validating renewable energy systems with industry partners, to lead the analysis of data gathered, and to assess the initial durability and reliability of the systems.

Scope

This Validation Plan is organized to cover a range of issues related to validating PV systems and specific PV components with the ultimate aim of making U.S. technologies “bankable”. The table below outlines specific validation needs, the RTC approach to the need, roles for the National Labs, and the time frame for each specific evaluation activity.

Validation need	Approach	Roles for National Labs	Time
Installation	Apply, evaluate and improve standard processes	Ease of installation; problems with installation; damage during shipment; Cost of land prep; Acceptance testing	1-3 months
Baseline (modules)	Indoor & outdoor IV	Verify RTC partner’s data and distribution	Several weeks
Product quality	Outdoor deployment when failure modes are not known	RTC can identify module uniformity (agreement with manufacturer specs), infant mortality (short-term) and long-term issues depending on design and location not caught by qualification standard.	2+ years
kWh/kW	Deploy and monitor continuously	Does the product do what we expect? Can we make accurate performance predictions?	1 year
Measure degradation rate	Deploy and monitor continuously	Degradation rates including uncertainty	2-3+ years

Roles and Responsibilities

The primary role of the RTCs is to develop validation processes that can be accepted by and applied to the entire PV industry. Part of that process will involve working with installed systems, and performing an initial validation of those systems based on the validation processes under development. We anticipate there will be different groups involved in each aspect of the validation process. This section outlines the primary roles and responsibilities of each group. Specific responsibilities are delineated in the sections of this Validation Master Plan.

- DOE SETP

The DOE Solar Energy Technologies Program (SETP) is funding the development of the RTCs. As such, the DOE SETP oversees the progress and approves the processes proposed by the RTC Teams. DOE SETP has the primary responsibility for determining the business models to be employed at the RTCs and for selecting RTC Partners.

- RTC Teams

The RTCs Teams are comprised of the laboratory personnel and any contractors working directly for the laboratories at the Regional Test Center sites. The RTC Teams are responsible for providing input and guidance to DOE SETP on determining the business models to be employed at the RTCs and for selecting RTC Partners. The RTC Teams will provide the RTC Partners with guidelines for installation at each location and will review system designs. The primary role for the RTC Teams is to develop and document the validation processes for PV systems according to this validation plan. The implementation will include purchasing and installing data monitoring equipment on each system; performing baseline testing on modules and systems; developing performance models for each system; collecting and analyzing system data; performing periodic system inspections and retests; and providing periodic performance reports to each RTC Partner. The results and lessons learned with each RTC Partner will be used to update and iterate on the validation guidelines. The ultimate goal of this process is to publish PV system validation processes and to develop a standardized technical bankability report.

- RTC Partners

RTC Partners are those companies that will install systems at each Regional Test Center site. Each RTC Partner may be a single company or may be a team with a primary lead company. If the primary partner is a module manufacturer, we recommend they work with an architecture and engineering (A&E) firm, a PV integrator, or an experienced installer for the design and installation. The RTC Partner will be responsible for supplying and installing the PV systems and for delivering the designs and bills of material to the RTC Teams. The systems in each location supplied by a given RTC Partner should be identical in design except for any location-dependent considerations. The RTC Partner will be responsible for providing all information required in the Commissioning section of this document.

- Integrators/A&E Firms

- PV integrators on the team will be responsible for the system design or for reviewing the system design with the A&E firm. The integrator or A&E firm will be responsible for working with each RTC Team to ensure all site-specific considerations are understood and incorporated into the system designs.
 - Manufacturers

Module, inverter and any other component manufacturers on the team will be responsible for supplying all components including spares, standard test data, inventory lists and installation requirements to the RTC Teams. Each manufacturer is responsible for their standard warranty.
 - Installer
 - Each RTC Partner must use a qualified PV systems installer. There may be a different installer for each site as appropriate. The installer will be responsible for adhering to the local codes, for installing the systems as designed or working with the system designer when issues arise, and for performing the appropriate system inspections.
 - Negotiated Items: The following areas will be negotiated with each RTC Partner based on the specific agreements.
 - Data ownership
 - Each RTC Partner will own the data taken on their systems, provided they supply the systems. The RTC Team will retain the right to use the data for developing standard protocols, procedures and analysis techniques with regard to PV system validation. The RTC Team and the RTC Partner(s) may publish the data specifically or in aggregate format by mutual agreement.
 - Operations and Maintenance
 - The specific aspects will be negotiated with each RTC Partner.
 - Permitting
 - The specific aspects will be negotiated with each RTC Partner.

Definitions

Energy [1]: DC or only AC

t: time

P_i: power

$$E_{i,t} = t \cdot \sum P_i \quad (1)$$

AC efficiency [2]:

$$\eta_{AC} = \frac{E_{AC}}{H_{POA} \cdot A}, \quad (2)$$

E_{AC}: AC energy produced by the system measured in consistent intervals, i.e. daily, weekly, monthly, and yearly.

H_{POA}: cumulative plane-of-array irradiance for the same time interval.

A: Device active area

PR: Performance Ratio [1,3]:

$$PR = \frac{Y_f}{Y_r} \quad (3)$$

Y_f: final yield,

$$Y_f = \frac{E_{i,t}}{P_0} = \frac{t \cdot \sum P_i}{P_0} \quad (4)$$

P₀: the rated power

Y_r: reference yield

$$Y_r = \frac{H_{POA}}{G_r} = \frac{t \cdot \sum H_i}{G_r} \quad (5)$$

G_r: irradiance used to determine the rated power

Analytical Methods

1. Commissioning

1.1 Purpose

The purpose of commissioning a PV plant is to assure that the plant components and systems have been designed, installed, and tested according to the requirements of the RTC Partner. A main feature of commissioning is acceptance testing, which involves a specific set of measurements, documentation, reviews, and analysis that are used to determine if a set of requirements have been met by the system. Acceptance testing of a PV system insures that the system/equipment and its components are installed correctly and to the original manufacturer's specifications. Calibration of PV measurement and metrology equipment should be performed and documented in this step as well.

1.2 System Design (Information provided by RTC Partner)

Each RTC will provide interface drawings that describe site infrastructure available for systems and for interconnection to the local grid and to the monitoring instrumentation. In addition, all requirements (code, safety, etc.) for prospective system designs will be clearly articulated by each RTC. RTC teams will work with RTC partners on design, monitoring and the details of the validation plan specific to their design. Before system installation, the RTC teams will review the system design and Bill of Materials for compliance with codes and standards and to ensure that the design meets all requirements to support validation. In accordance with section 4.2 of IEC 62446 (*Grid connected photovoltaic systems – Minimum requirements for system documentation, commissioning tests and inspection*) useful information about the system shall be provided to the RTCs.

The basic system information specified in 4.2.1 of IEC 62446 shall include an indication of the RTC and system identification. Installation date should include the time period of installation, not just the completion date. The customer name in IEC 62446 4.2.1.f shall be replaced by the phone numbers and e-mail addresses for the technical points of contact at both the RTC partner and the RTC site-specific point of contact. The information about system designer and installer shall be tabulated as specified by IEC 62446 sections 4.2.2 and 4.2.3.

A description of the wiring diagram shall be included as specified in section 4.3 of IEC 62446.

Additionally, the RTC partner shall provide information about safety issues, hazardous materials, and plans for decommissioning. Specifically, the RTC partner shall provide, on the PV module manufacturer's letter head, the measured or calculated content of heavy metals considered hazardous under the Resource Conservation and Recovery Act (RCRA), such as lead,

silver, cadmium and selenium, by percent weight of the total PV module to be used in the PV system. The manufacturer’s letter shall include the model number and a range of serial numbers for which the data are valid. Alternately, the RTC Partner shall provide the results from a toxic characteristic leaching procedure (TCLP) performed by a certified laboratory for a representative sample of the PV module to be used. The PV manufacturer letter shall include the model number and a range of serial numbers for which the data are valid. OR, the Contractor shall provide information about any bonded recycling program, if applicable.

The wiring diagram shall additionally include the module serial number location within each string, and the locations and identification of combiner boxes, inverter enclosures, etc.

Datasheets shall be provided as specified in IEC 62446, section 4.4. A data sheet shall be provided for the array mounting systems for both flat plate and tracking structures. The datasheet for the mounting system shall comply with UL 2703. The mechanical design for fixed-rack systems shall also be described according to the tilt angles from the horizontal and from due south. Similarly, the orientations of one-axis tracked systems shall be described. In all cases, the spacing between rows, height, and any 3-dimensional spacings needed to assess shading shall be defined.

The RTC partner shall provide indication of plans for decommissioning or otherwise determining the disposition of the system at the end of the project.

Level	Part Number	Part Description	Part Version	Serial Number	Quantity	Build Date	Ship Date	Catalog	Manufacturing Code
1	SGSSS	SGS Solar System Power Block		SGS-1	1	07/13/2001			
2	TXL	480V/34.5kV Transformer		SCL-2	1	07/13/2001			
2	TXS	208V/480V Transformer		TXS-1	1	07/13/2001			
2	ADS	AC Disconnect Switch		ADS-1	1	07/13/2001			
2	DDS	DC Disconnect Switch		DDS-1	1	07/13/2001			
2	ECON	Array Electrical Connections		ECON-1	1	07/13/2001			
2	INV	Inverter		INV-1	1	07/13/2001			
2	LIGHT	Lightning Event		L-1	1	07/13/2001			
2	MOD	PV Module		M-U1-1	1	07/13/2001			
2	MOD	PV Module		M-U1-2	1	07/13/2001			
2	MOD	PV Module		M-U1-3	1	07/13/2001			
2	MOD	PV Module		M-U1-4	1	07/13/2001			
2	MOD	PV Module		M-U1-5	1	07/13/2001			
2	MOD	PV Module		M-U1-6	1	07/13/2001			
2	MOD	PV Module		M-U1-7	1	07/13/2001			
2	MOD	PV Module		M-U1-8	1	07/13/2001			
2	MOD	PV Module		M-U1-9	1	07/13/2001			
2	MOD	PV Module		M-U1-10	1	07/13/2001			
2	MOD	PV Module		M-U1-11	1	07/13/2001			
2	MOD	PV Module		M-U1-12	1	07/13/2001			
2	MOD	PV Module		M-U1-13	1	07/13/2001			
2	MOD	PV Module		M-U1-14	1	07/13/2001			
2	MOD	PV Module		M-U1-15	1	07/13/2001			
2	MOD	PV Module		M-U1-16	1	07/13/2001			
2	MOD	PV Module		M-U1-17	1	07/13/2001			
2	MOD	PV Module		M-U1-18	1	07/13/2001			
2	MOD	PV Module		M-U1-19	1	07/13/2001			
2	MOD	PV Module		M-U1-20	1	07/13/2001			
2	MOD	PV Module		M-U1-21	1	07/13/2001			

Bill of Materials example. This gives example of level of detail, but the specifics will be determined via discussion with RTC Team and RTC Partners.

Operations and maintenance information will be provided as specified in IEC 62446, section 4.6.

1.3 System Inspection (Information provided by RTC Partner)

Inspection of the installed system will be done according to IEC 62446 as described in section 5.3 and documented as described in Annexes A and B of IEC 62446.

A horizon survey shall be carried out to identify potential shading issues.

1.4 Prediction of performance done by RTC Partner

As part of the design of a PV system, performance calculations are done to help optimize system design parameters (e.g., row spacing, module orientation, inverter size, etc.). As part of the validation process the RTCs aim to help validate these model predictions. In order to perform model validation it is necessary for the RTC teams to know some details of how these initial energy yield predictions were made.

1.4.1 Specification of model and input parameters

The RTC Partners who submit initial yield predictions with their design shall identify the model used to generate the prediction (model name, version number, etc). In addition they shall provide input parameter values used, description of assumptions made, and clearly identify the source of the weather and irradiance used for the calculations.

1.4.2 Predicted monthly output based on historical weather data

The yield predictions shall be provided in estimates of monthly system AC Energy output (kWh/month). Additional outputs, such as daily profiles for representative clear, partly cloudy, and overcast conditions shall be provided along with detailed weather inputs.

1.5 Baseline Module Characterization and Testing

Manufacturers will provide data typically found on product data sheets, production data including flash tests for each module, and data from third-party tests performed for the manufacturer including all of the data required in sections 11 and 12 of IEC 61730-1. The data variation will be examined to determine an appropriate sample size for the RTC to target component testing to provide representative statistics for the whole data set, see summary table at the end of the section. The sample modules will be identified and flash tested by RTCs to compare with the manufacturer's data and for a baseline for retests at the end of the evaluation period, or at some interim date if determined necessary. This data set will provide baseline, as-manufactured data for use in analysis and for understanding any change in performance or reliability that might be observed.

	Manufa specs (from data sheet)	Manufacturer data (from specific measurements)	Sample size from manufacturer	RTC initial (STC)	RTC (STC) after LID	Sample size for RTC measurements
Pmax (W)		ave ± SD range uncertainty		ave ± SD range uncertainty	_ ± _	
Vmax (V)		_ ± _		_ ± _	_ ± _	
I _{max} (A)		_ ± _		_ ± _	_ ± _	
Voc (V)		_ ± _		_ ± _	_ ± _	
I _{sc} (A)		_ ± _		_ ± _	_ ± _	
FF		_ ± _		_ ± _	_ ± _	
Efficiency (%)		_ ± _		_ ± _	_ ± _	

Table 1.1: Sample summary of manufacturer data compared to RTC measured data. Measurements shall be made after light-induced degradation in accordance with IEC 61215 (*Crystalline silicon terrestrial photovoltaic (PV) modules – Design qualification and type approval*) [4] of 20kWhr/m², or IEC 61646 (*Thin Film terrestrial photovoltaic (PV) modules – Design qualification and type approval*) [5] unless otherwise specified by the manufacturer and negotiated with RTC Teams.

As a supplement to Table 1, the manufacturer will supply information about how the measurements were completed and the uncertainty of their measurement.

To determine whether the data from the manufacturer and RTC measurements come from the same distribution the 2 distributions will be compared using an appropriate statistical test such as the t-test. [6]

The results from this test can be divided into 2 broad categories;

1. Manufacturer and RTC data are consistent, indicated by a probability or p-value from the above-mentioned statistical test of 1 to 0.15.
2. If the p-value is below 0.1 there is sufficient evidence that the data come from 2 distinct distributions requiring follow-up investigation. One possibility would be to take a larger sample especially when the initial distribution is non-normal. If the difference can be traced to measurement technique, the data need to be re-compared after the measurement techniques are aligned. If the p-value is below 0.001, i.e. the probability of this result due to chance is less than 0.1% the product deviates substantially from expectation (perhaps damaged during shipping) and must be replaced by the manufacturer.

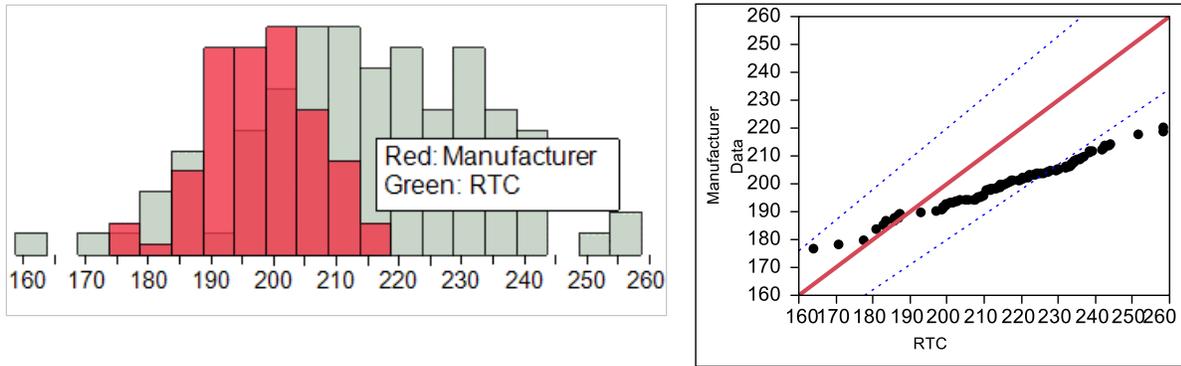


Fig. 1.1a. Sample parameter distribution manufacturer measurements vs. RTC measurements for Pmax, Voc, Isc, and FF will be plotted in a similar way. 1.1b. UL1703 limits of +/- 10% are indicated by blue dashed lines.

1.6 Performance Coefficients

Outdoor performance of PV modules will be measured to determine angle-of-incidence dependence, irradiance behavior, and temperature coefficients. Thin-film modules will require preconditioning to obtain the best results. The module will be characterized according to the procedures defined in IEC 61853-1 (performance as a function of irradiance and temperature) ⁷, entering the data into the following table and creating similar tables for Pmax, Voc, Isc, and FF.

Irradiance W/m ²	Spectrum	Module temperature*				T Coefficient
		15°C	25°C	50°C	75°C	
1100	AM1.5	NA				
1000	AM1.5					
800	AM1.5					
600	AM1.5					
400	AM1.5				NA	
200	AM1.5			NA	NA	
100	AM1.5			NA	NA	

*As average of 3 places (center, corner, and edge)

For each irradiance level the values will be fit as a function of temperature and the coefficient recorded in the rightmost column. These values will be compared to the manufacturer's values in the following table:

	Manufacturer's value @ 1000 W/m ²	RTC initial T coefficient @ 1000 W/m ²
Isc T coeff (%/C)	__ ± __	__ ± __
Voc T coeff (%/C)	__ ± __	__ ± __

Pmax T coeff (%/C)	_ ± _	_ ± _
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The module temperature will be characterized as a function of prevailing coefficients according to IEC 61853-2, to fit the equation:

$$T_J - T_{amb} = G / (u_0 - u_1 v)$$

The coefficient u_0 describes the influence of the irradiance and u_1 the wind impact.

From all acceptable data points, making sure that data points from both before and after solar noon are utilized, calculate the average module-temperature, plot $G/(T_J - T_{amb})$ as a function of wind speed. Use linear regression analysis to determine the slope and intercept (u_1 and u_0) of the model.

NMOT will be determined according to IEC 61853-2.

The data from this initial characterization can then be utilized to provide the parameters necessary to run most of the available PV performance models (e.g. PVSYST etc.). If discrepancies exceed measurement uncertainty, the RTC team will assist the RTC partner in updating the coefficients and the performance prediction. This set of performance prediction parameters will then be used as the baseline for further validation for each RTC location.

1.7 Images of selected modules (Performed by RTCs)

1.7.1 Optical images

Digital images of strings and modules shall be taken. For each image data are recorded according to:

- a) System ID/Product description
- b) Module/string ID
- c) Date
- d) Lighting conditions
- e) Camera settings including distance from camera to module
- f) Camera identification

1.7.2 IR images

Digital images of strings and modules shall be taken. For each image data are recorded according to:

- a) System ID/Product description
- b) Module ID
- c) Date
- d) Bias current and voltage (including sign)
- e) Length of application of bias

- f) Exposure time
- g) IR camera identification
- h) Camera settings, including distance to camera

1.7.3 EL images

Digital images of strings and modules shall be taken. For each image data are recorded according to:

- a) System ID/Product description
- b) Module ID
- c) Date
- d) Bias current and voltage (including sign)
- e) Filters used during imaging
- f) Exposure time
- g) EL camera identification
- h) Camera settings, including distance to camera

1.8 Verification of Initial System-Level Performance

Verification that the PV system produces the energy predicted for this technology is an important part of the RTC process. The details of the performance measurement process are given in Section 3. The initial performance level will be defined as the first full quarter of operation after commissioning of the system.

Commissioning date will be agreed upon between the RTC and the partner. Commissioning requires that the PV system be providing ac electricity into the grid and that the data acquisition system be fully functional, collecting the data defined in Section 2.

At the end of the first quarter of operation the partner will be provided with the weather data collected for the site. From this weather data the partner will then calculate the expected PV system performance for that quarter and provide the data to the RTC. The RTC will then evaluate the system performance according to the procedure given in Section 4. This first quarterly report will then serve as the Initial System Level Performance, showing how close the actual system performance was to the Prediction (See Table 4.1)

1.9 Decommissioning Review

RTC teams will review the RTC partner's statement of safety issues, material hazards and plans for decommissioning. An initial review should take place before the project is started. At the time of acceptance, the RTC partners must address the RTC teams' concerns before the validation will commence.

2. Data Collection

2.1 Meteorological Data

A site weather station will collect data every second and average for one minute intervals with synchronized timestamp when supported by the instrumentation, including:

2.1.1 Irradiance (Pyranometers will be used, plus reference cells as appropriate for each technology)

- a) Plane-of-array diffuse (fixed tilt shadowband) for each tilt angle
- b) Direct normal incidence irradiance (NIP)
- c) Total horizontal irradiance
- d) Total diffuse irradiance

2.1.2 Rain gauge

2.1.3 Wind

- a) 10 m wind speed
- b) 10 m wind direction
- c) Sets of portable systems (ambient temperature, wind speed, and direction) that can be moved and deployed in and around an array to gather data on local winds and their affect on module temperatures

2.1.4 Temperature

Wet and dry bulb using a solar radiation shield to prevent direct solar heating of the sensor

2.1.5 Snow coverage

Camera to record snow or other major events.

2.1.6 Solar Spectrum

A spectroradiometer will be used to measure the global spectrum with the sampling rate determined by the instrument capabilities.

2.1.7 Cleaning

Weather station irradiance sensors will be cleaned 5 days per week. Other irradiance sensors and reference modules will be cleaned 2–3 days/week.

2.2 System Data

At a minimum, system data will include the following:

2.2.1 DC Electrical

- a) DC current for (selected) strings
- b) DC current at the combiner box level

- c) DC voltage, and current and/or power at the inverter

2.2.2 Array Environment

- a) Plane-of-array pyranometer (total and diffuse)
- b) Module back-surface temperatures (multiple). Distributed through array, including center and edges
- c) Reference modules – minimum 2 per array, 1 cleaned regularly, 1 cleaned only with array [8]
- d) Tracker angle and parasitics
- e) Tracking accuracy

2.2.3 AC Electrical

- a) AC power from each inverter
- b) Revenue grade AC power measurement from system
- c) AC power from the test site (combined for all systems) using a revenue-grade meter with a utility interface for revenue
- d) Site-level frequency/power quality including voltage, power factor (assumes this does not need to be measured for each system because all will see the same grid-induced transients, unless advanced inverters that can provide ancillary services are deployed)

2.2.4 Inverter parameters

- a) Inverter errors and data as provided by the manufacturer (digital communications to the data acquisition system), including performance parameters measured by the inverter for comparison with independent instruments
- b) Additional data logged every minute, e.g., heat-sink temperature

2.2.5 Additional automated data

- a) Inter-string voltages or inverter-compatible DC-DC power optimizers on one string to measure/quantify mismatch especially for a partially shaded string
- b) Communications as provided by the system supplier, e.g., from micro-inverters or string-level monitors.
- c) Utility control signals for dispatch of ancillary services, if applicable

3. Performance

3.1 Performance Summarized in Quarterly Reports

The performance and inspection data will be summarized and shared with the RTC partners quarterly.

The RTC partners may inspect their data at any time. In order to prevent RTC partners from calibrating their performance models to the measured data there will be a managed process to gaining access to performance data. The sequential procedure for their extraction of the data will include:

1. Download the weather data
2. Upload their prediction of the performance
3. Download the actual performance data

Quarterly reports will include the following tables and graphs:

Monthly summary plots:

- Irradiance and power over time
- Performance ratio

Daily plots with daily profiles (calendar view) – can fit a month’s worth on a page (irradiance, power)

Table 3.1. Comparison of energy production data for entire system with meteorological data

Time period	June, 2012	July, 2012	August, 2012	September, 2012
$H_{I,d}$ = Ave Daily DNI (kWh/m ² /day)				
$E_{A,d}$ = Ave Daily Net energy from array (DC) (kWh/day)				
Cumulative kWh produced in 2012				
Predicted cumulative kWh in 2012				
$E_{TUN,d}$ = Ave Daily Net energy to utility grid (AC) (kWh/day)				
Y_A = Ave Array Yield (DC) (h/d)				
Y_r = Ave Reference Yield (h/d)				
Y_f = Ave Final Yield (AC) (h/d)				
R_p = Ave Performance Ratio				
Parasitics (kWh used by tracker and any other controls)				

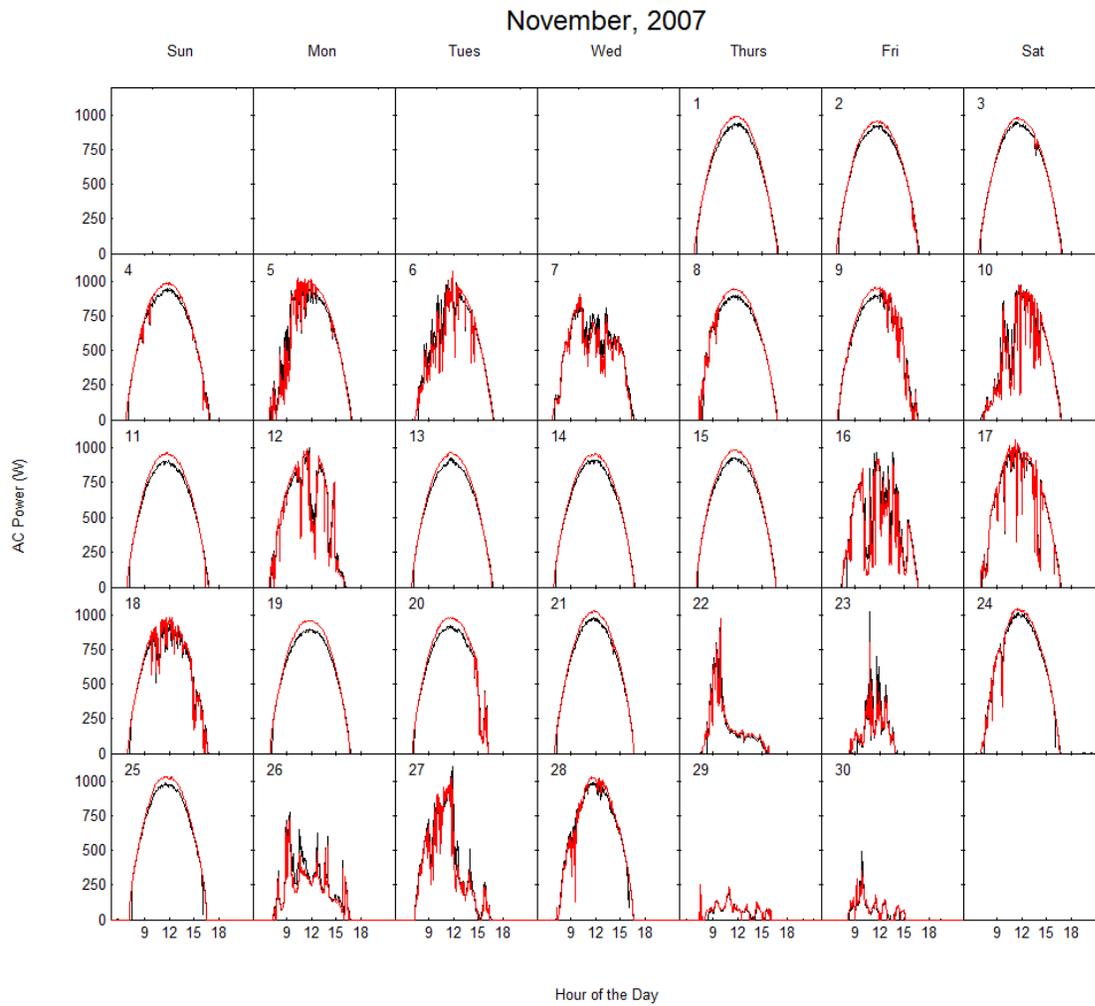


Fig. 3.1. Example “Calendar” plot comparing measured PV output power (black) and modeled PV output (red) for a fixed tilt system in Albuquerque. Data are 2-min averages.

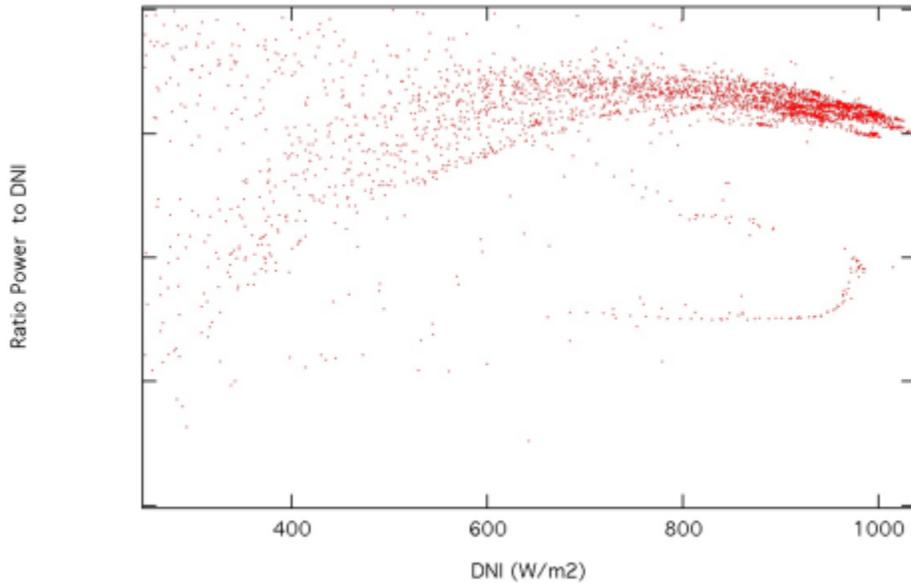


Fig. 3.2. Summary of same data as presented in figure 3.1 (most recent 3 months), but presented as a ratio of power to POA.

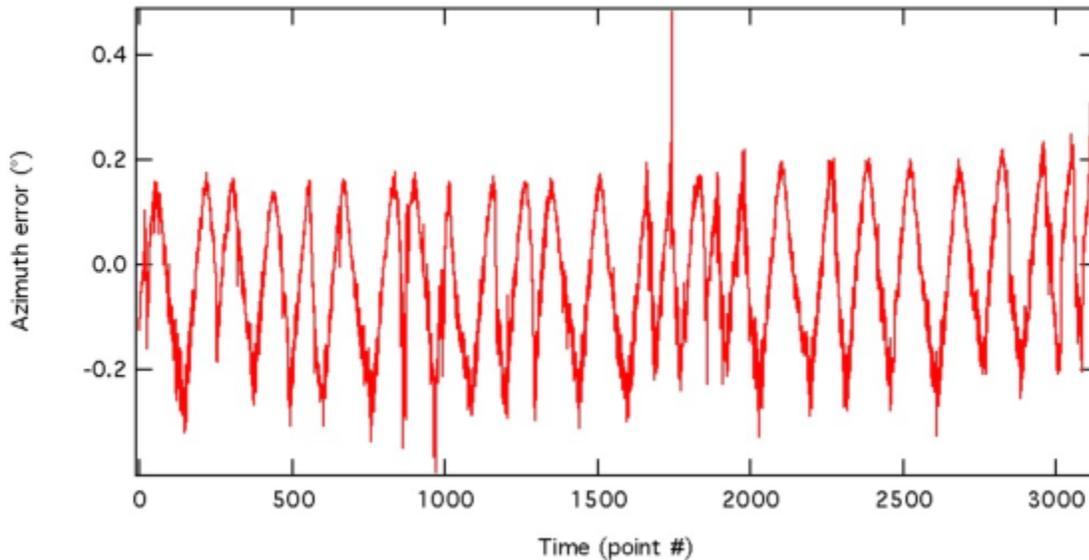


Fig. 3.3. Tracker error (both azimuth and elevation) as a function of time (reported only for CPV systems).

3.2 Performance Monitoring and “Real-Time” Analysis

Each system will be monitored in order to detect component and system failures as well as to validate that the various components or parts of the system behave consistently and predictably.

At the top level, output power from each full system will be monitored at near real time. Monitoring at this level captures electrical performance of the entire system and will include monitoring on the AC and DC sides of the system relative to weather data recorded from a research grade meteorological system.

Monitoring at lower levels in the system (e.g., subarray, string, or even module) provides more detailed information about how consistently each part of the system is performing. Figure 3.4 shows an example of monitoring data at the string level. It demonstrates how monitoring data can help to identify problems. Data obtained at this lower level is especially useful for identifying component failures and problems, uneven soiling and possibly even degradation. For example, if a system is monitored at the string level, output from each string will be compared by normalizing output (e.g., by DC capacity) (example in Figure 3.4.)

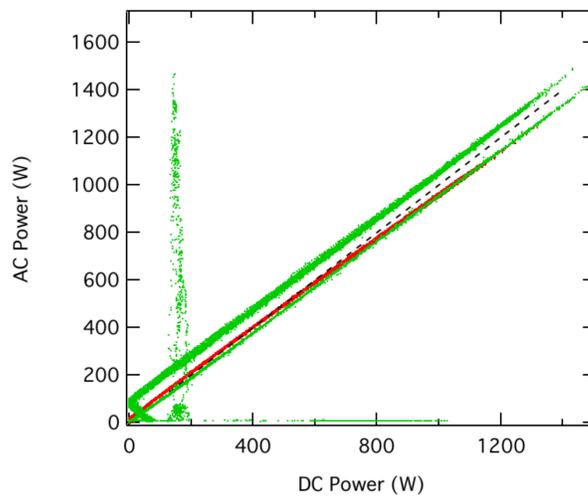


Fig. 3.4. AC power vs string-level DC power for most recent three months. Different colors differentiate the strings. The dashed line indicates 100% inverter efficiency.

Monitoring at points internal to the system (e.g., subarray, string, module) captures the DC electrical performance at the component or subsystem level but also costs more to implement and maintain. The RTCs will work with the specific RTC partner to define the appropriate level of monitoring. At a minimum we recommend monitoring 10% of the strings in the system. Systems with the largest number of strings will be 250 kW, 600 V systems with low-power modules. Such a system may have up to 325 strings.

4. Analysis & Modeling

4.1 Purpose

In order for a PV technology to be “bankable” it must be predictable so that investors understand how the systems will function in a variety of environments and climates. The RTCs will provide a unique opportunity to test out the ability of selected performance models in three distinct environments. Since performance models require sets of calibrated coefficients in order to run, it will be important to maintain a separation between calibration and model evaluation (and validation) activities.

4.2 Approach

A modeling analysis of a system’s performance will be done at regular intervals and will be reported to the partner. For each interval (TBD), the analysis will follow a series of steps:

- 1 Weather and performance data will need to be filtered to remove outliers and problematic data that cannot be explicitly represented in the model and will be rigorously documented (e.g., operational events, component failures, snow, etc.).
- 2 Model will be run to predict quantities of DC and AC power, module temperature, and DC voltage.
- 3 Both measured and modeled quantities will be used to calculate values listed below in Table 4.1.
- 4 Comparisons between predicted and measured data will be performed. This comparison can be done at a number of different levels.
 - a. Compare power and total energy produced over period
 - b. Calculate a model residual (modeled quantity – measured quantity) and evaluate whether this “error” exhibits any systematic patterns (e.g., are residual errors correlated with other variables such as irradiance and temperature?). Such correlations can suggest possible model improvements and/or problems with the PV system or components.

Table 4.1. Quantities that will be measured as well as calculated using a model. Ideally, all items in this table will be evaluated. However, the evaluation specifics will be negotiated with each partner.

Parameter	System Level	Technology	Analysis Frequency	Comments
Energy	System		Monthly	
Energy yield =kWh/kWp	System		Monthly	
PR	System		Monthly	
AC efficiency	System	Flat-plate & CPV	Monthly	
Power rating	System	Flat-plate & CPV	Monthly	DC/POA Temp-corrected for flat-plate PVUSA, ASTM E2527 [9,10] for CPV

Commercial Model (PVSYST, SAM, PVWatts)	System		Quarterly	Accuracy of models
Manufacturer Model	System		Quarterly	
Sandia Model [11]	System		Quarterly	
Degradation Rate [12]	System		Quarterly	
Energy & POA P90	System		Yearly	

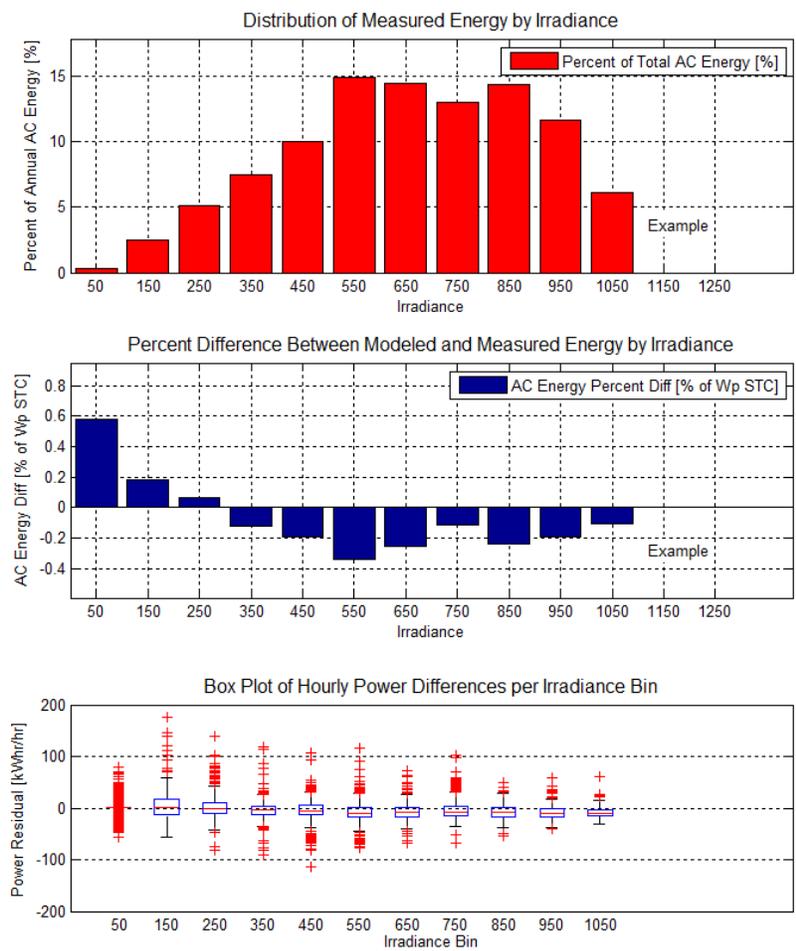


Fig. 4.1. Residual analysis plot showing the effect of irradiance on the accuracy of the model. ¹³

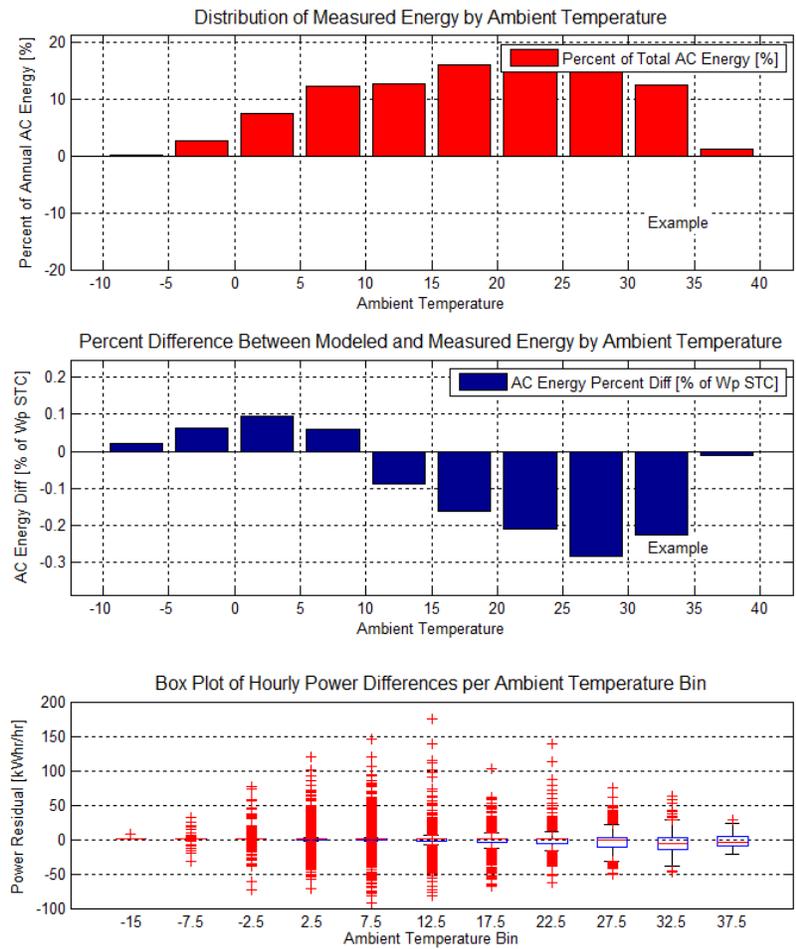
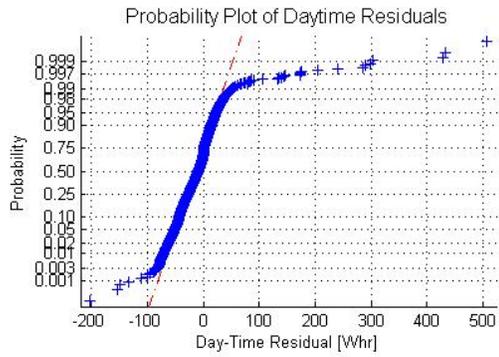


Fig. 4.2. Residual analysis plot showing the effect of ambient air temperature on the accuracy of the model.



Root Mean Square Error = 32.1561 Whr

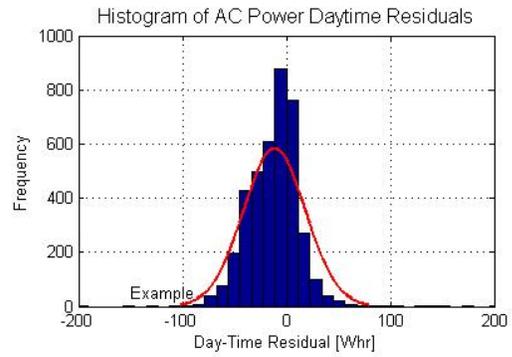


Fig. 4.4. Example plots showing the distribution of the model residuals.

5. Reliability & Safety

Periodic Inspection

In addition to the standard schedule specified below, any discrepancies will trigger an investigation. If necessary, we will remove modules from the field for repeated indoor testing and/or to undergo reliability and failure analysis including dry and wet high potential testing for safety.

5.1 Visual Inspection

Monthly visual inspections will be conducted according to IEC 62446. Any reliability issues will be noted and included in the event log (e.g. Glass breakage, wire abrasion, module discoloration).

5.2 O&M Event Log

All operations and maintenance events shall be logged electronically. The data will be uploaded to a database along with the corresponding bill of materials for event monitoring and statistical analysis of events and failures. Events shall be logged in a format as shown in Figure 5.1. Items to be logged include:

- a) Incident Occurrence Date/Time
- b) Bill of Material Part Number
- c) Part Serial Number
- d) Part Commissioning Date
- e) Incident Description
- f) Incident Category
- g) Service Response Date/Time
- h) Service Completion Date/Time
- i) Restoration to Duty Date/Time
- j) Energy Lost (kWh)
- k) System availability lost (number of daylight (sunrise to sunset) hours if outage affects one day; number of days if outage affects multiple days)

	E	G	H	J	K	P	R	T	U
1	Date/Time	Number	20 characters	20 characters	20 characters	Date/Time	50 characters	50 characters	50 characters
2	Occurrence Date	Repair Duration	BOM Level 1 Part Number	Level 1 Part Serial Number	BOM Level 2 Part Number	Service Response Date	Incident Status	Incident Category	Report Type
3	2/7/03 3:54:00 AM	6.64540278	SGSSS	SGS-9	DDS		closed	Hardware Failure	Unplanned Field
4	2/14/03	0	SGSSS	SGS-10	INV		closed	Software application problem	Unplanned Field
5	2/11/03	5.86	SGSSS	SGS-3	MOD		closed	Hardware Failure	Unplanned Field
6	3/9/03 8:21:00 PM	3.86697222	SGSSS	SGS-3	DDS		closed	Hardware Failure	Unplanned Field
7	3/1/03	0	SGSSS	SGS-10	INV		closed	Software application problem	Unplanned Field
8	3/31/03	5.86	SGSSS	SGS-10	INV		closed	Software application problem	Unplanned Field
9	4/1/03 7:30:00 AM	6.14486111	SGSSS	SGS-10	INV		closed	Hardware Failure	Unplanned Field
10	4/1/03	0	SGSSS	SGS-10	INV		closed	Software application problem	Unplanned Field
11	4/23/03	17.58	SGSSS	SGS-10	INV		closed	Hardware Failure	Unplanned Field
12	4/29/03 7:30:00 AM	1.02956944	SGSSS	SGS-9	INV		closed	Preventive Maintenance	Planned Field Ex
13	4/8/03	128.92	SGSSS	SGS-3	MOD		closed	Hardware Failure	Unplanned Field
14	5/29/03 1:17:00 PM	0.88713889	SGSSS	SGS-6	DDS		closed	Hardware Failure	Unplanned Field
15	6/10/03	70.32	SGSSS	SGS-7	ECON		closed	Preventive Maintenance	Planned Field Ex
16	6/28/03 3:44:00 PM	6.13672222	SGSSS	SGS-12	INV		closed	Hardware Failure	Unplanned Field
17	6/30/03 4:31:00 PM	5.94138889	SGSSS	SGS-12	INV		closed	Hardware Failure	Unplanned Field
18	4/10/03	480.52	SGSSS	SGS-8	MOD		closed	Hardware Failure	Unplanned Field
19	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-3	INV		closed	Grid-induced disturbance	Unplanned Field
20	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-5	INV		closed	Grid-induced disturbance	Unplanned Field
21	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-13	INV		closed	Grid-induced disturbance	Unplanned Field
22	7/11/03	1.78241667	SGSSS	SGS-7	INV		closed	Grid-induced disturbance	Unplanned Field
23	7/11/03	1.78241667	SGSSS	SGS-12	INV		closed	Grid-induced disturbance	Unplanned Field
24	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-8	INV		closed	Grid-induced disturbance	Unplanned Field
25	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-9	INV		closed	Grid-induced disturbance	Unplanned Field
26	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-10	INV		closed	Grid-induced disturbance	Unplanned Field
27	7/11/03 7:14:00 AM	0.01627778	SGSSS	SGS-11	INV		closed	Grid-induced disturbance	Unplanned Field
28	7/21/03	128.92	SGSSS	SGS-1	INV		closed	Environment-induced disturbance	Unplanned Field
29	7/21/03	128.92	SGSSS	SGS-5	INV		closed	Environment-induced disturbance	Unplanned Field
30	7/21/03	87.9	SGSSS	SGS-6	INV		closed	Environment-induced disturbance	Unplanned Field
31	7/21/03	128.92	SGSSS	SGS-7	INV		closed	Environment-induced disturbance	Unplanned Field
32	7/21/03	152.36	SGSSS	SGS-8	INV		closed	Environment-induced disturbance	Unplanned Field
33	7/21/03	87.9	SGSSS	SGS-9	INV		closed	Environment-induced disturbance	Unplanned Field

Figure 5.1 Example entry into O&M database.

5.3 Images of selected modules

5.3.1 Optical images

Digital images of strings and modules shall be taken quarterly. For each image data are recorded according to:

- System ID/Product description
- Module/string ID
- Date
- Lighting conditions
- Camera settings including distance from camera to module
- Camera identification

5.3.2 IR images

Digital images of strings and modules shall be taken quarterly. For each image data are recorded according to:

- System ID/Product description
- Module ID
- Date
- Bias current and voltage (including sign)

- f) Length of application of bias
- g) Exposure time
- h) IR camera identification
- i) Camera settings, including distance to camera

5.3.3 EL images will be taken of selected modules quarterly

- a) Module ID
- b) Date
- c) Bias current and voltage (including sign)
- d) Filters used for taking image
- e) EL camera identification
- f) Camera settings, including distance to camera
- g) Exposure time

Periodic Testing

5.4 Field IV curves

At least once a year, the RTC team will measure string-level IV curves in the field for each system. Spring and autumn near the equinox are the best times of year for field-level IV curves.

Documentation will include:

- Conditions of testing
- Translation method
- Documentation as specified in IEC 60904-1

After 6-12 months have passed, the field I-V data will be summarized on a time graph such as:

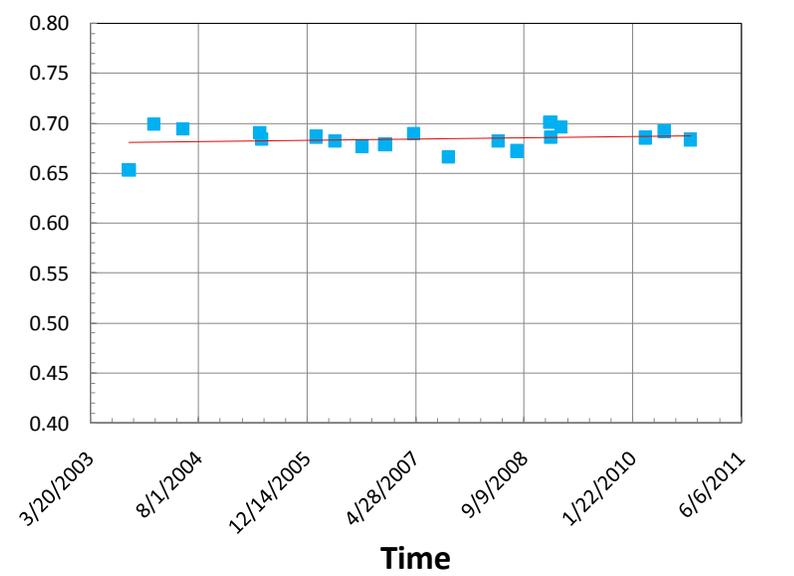


Fig. 5.2 Pmax, Voc, FF, and Isc plotted as a function of time for field I-V data corrected as described in figure above. Show one graph for all strings together.

5.5 Simulator IV

Indoor I-V curves will be taken annually on all of the baseline modules. Documentation will be as specified in IEC 60904-1.

Table 5.1 Summary of Baseline Data and Simulator Data taken periodically through project

	Manuf a specs (from data sheet)	Manufacturer data (from Table 1.1)	RTC initial (STC) (from Table 1.1)	RTC (STC) after LID (from Table 1.1)	RTC repeated measurement #1 taken at Date 1	RTC repeated measurement #2 taken at Date 2
Pmax (W)		ave \pm SD range uncertainty	ave \pm SD range uncertainty	ave \pm SD range uncertainty	ave \pm SD range uncertainty	ave \pm SD range uncertainty
Vmax (V)		_ \pm _	_ \pm _	_ \pm _	_ \pm _	_ \pm _
Imax (A)		_ \pm _	_ \pm _	_ \pm _	_ \pm _	_ \pm _
Voc (V)		_ \pm _	_ \pm _	_ \pm _	_ \pm _	_ \pm _
Isc (A)		_ \pm _	_ \pm _	_ \pm _	_ \pm _	_ \pm _
FF		_ \pm _	_ \pm _	_ \pm _	_ \pm _	_ \pm _
Efficiency (%)		_ \pm _	_ \pm _	_ \pm _	_ \pm _	_ \pm _

5.6 Degradation rates

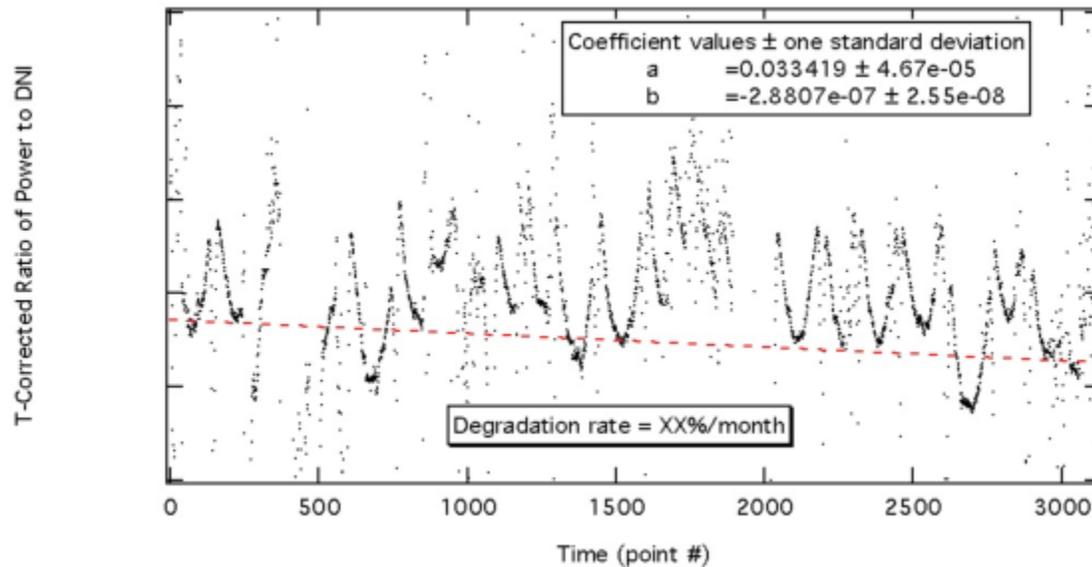


Fig. 5.3. Degradation rate measurement from real-time data. Plot temperature-corrected Pmax/POA for data that have been filtered for high irradiance (1000 W/m^2 at Sandia and NREL and 800 W/m^2 at FSEC) and for low irradiance (200 W/m^2) using Clearness index > 0.7 and Clearness index < 0.3 .

Unusual results will be discussed in the monthly report.

Table 5.2. Summary of Periodic Measurements

Parameter	Level	Frequency	Sample	Comments
Visual inspection	Systems	Monthly*	all	Take photographs
Field IV	Strings	Semiannually*	All/or representative sample for systems with more than 10 strings	Further inspection depending on findings
IV as a function of irradiance & T & AOI according to IEC 61853 [Error! Bookmark not defined.3]	Module	Beginning & end*	3	Simulator or field IV depending on technology
Simulator IV	Module	Annually*	Same 20 that were measured the first time. Measure others if signs of failure	Depending on degradation observed, taken from different parts of field.
IR	Strings	Quarterly*	All/or representative sample for systems with more than 10 strings	Further inspection depending on findings

*Or, whenever there is an issue.

The timing of the measurements may be staggered and may depend on weather.

Reference module will be used for measurements and could be used for continuous monitoring

Details may depend on funding

General References

[1] International Electrotechnical Commission (IEC) 61724 Ed.1 1998. Photovoltaic system performance monitoring –Guidelines for measurement,data exchange and analysis.

[2] King DL, More “efficient” methods for specifying and monitoring PV system performance, *Proceedings of the 37th IEEE PV Specialists Conference*, Seattle, WA, USA, 2011.

[3] Marion B, Adelstein J, Boyle K, Hayden H, Hammond B, Fletcher T, Canada B, Narang D, Kimber A, Mitchell L, Rich G, Townsend T, Performance parameters for grid-connected PV systems, *Proceedings of the 31st PV Specialists Conference*, Lake Buena, FL, USA, 2005, 1601–1606.

[4] International Electrotechnical Commission (IEC) IEC 61215 Ed.2 2005-04: Crystalline silicon photovoltaic (PV) modules – Design qualification and type approval.

[5] International Electrotechnical Commission (IEC) IEC 61646 Ed. 2 2008-05, Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type Approval

[6] Maas E, McNair P, *Applying Design for Six Sigma to Software and Hardware Systems*, Prentice Hall, August 2009.

[7] International Electrotechnical Commission (IEC) IEC 61853 Ed.1: Photovoltaic (PV) module performance testing and energy rating
Part 1: Irradiance and temperature performance measurements and power rating.
Part 2: Spectral Response, Incidence Angle and Module Operating Temperature Measurements.
Part 3: Energy Rating of PV Modules.

[8] Reference modules are not connected to the inverter, but are used to monitor effective irradiance (E_e) in the plane-of-array by measuring I_{sc} . For some technologies, V_{oc} can also be monitored to determine cell temperature. Reference modules are fielded in pairs with one module being cleaned regularly and the other being allowed to soil with the array

[9] Kimber A, Dierauf T, Mitchell L, Whitaker C, Townsend T, NewMiller J, King D, Granata J, Emery K, Osterwald C, Myers D, Marion B, Pligavko A, Panchula A, Levitsky T, Forbess J, Talmud F, Improved test method to verify the power rating of a photovoltaic (PV) project, *Proceedings of the 34th IEEE PV Specialists Conference*, Philadelphia, PA, USA, 2009, 316–321.

[10] American Society for Testing and Materials (ASTM), ASTM E2527 - 09 Standard Test Method for Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Systems Under Natural Sunlight

[11] King DL, Boyson WE, Kratochvil JA, Photovoltaic Array Performance Model, SAND2004-3535, August 2004.

[12] Jordan DC, S.R. Kurtz SR, "Photovoltaic Degradation Rates – An Analytical Review", *Progress in PV, October 2011*.

[13] Stein, J.S.; JS, Cameron, C.P.; CP, Bourne, B.;, Kimber, A.;, Posbic, J.;, Jester, T. " A standardized approach to PV system performance model validation",, Proceedings of the 35th IEEE PV Specialists Conference, Honolulu, HI, USA, 2010, 1079 – 1084.

[] IEC 62670 Ed. 1.0, Concentrator photovoltaic (CPV) module and assembly performance testing and energy rating - Part 1: Performance measurements and power rating - Irradiance and temperature