Sandia's Photovoltaic Reliability and Performance Model

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INTRODUCTION

Accurately predicting the performance of photovoltaic systems can be a challenging undertaking, but a necessary one to assess the financial viability of a PV system and to accelerate the wide scale deployment of PV. PV system energy production can be affected by numerous factors including the choice of location, component technology, and system design. While these modeling factors are generally considered by most PV performance models, other factors are typically not, including: 1) solar resource variability, 2) degradation due to environmental conditions (humidity, temperature swings, UV exposure, wind, salt spray, rodent damage, etc.), 3) component reliability (failure rates of inverters, modules, trackers, etc.), and 4) operations and maintenance (O&M) strategies.

Sandia is developing an analytical, scenario-based predictive tool that helps owners, operators, risk managers, and financiers simulate planned PV projects to avoid costly design and O&M flaws prior to development. The Photovoltaic Reliability and Performance Model (PV-RPM) has been developed with industry partners on behalf of the Solar Energy Technologies Program of the U.S. Department of Energy (DOE) [1].

WHAT IS PV-RPM?

To date, PV reliability studies have focused on components rather than entire systems. As the size of PV installations continues to grow and profit margins continue to shrink, the PV industry recognizes the need to better understand how component reliability affects overall system performance. Sandia's PV-RPM provides risk management experts with a rich analytical and visualization tool to simulate detailed PV plant operational scenarios. PV-RPM represents a plant as a hierarchal system of components (e.g., modules, combiner boxes, trackers, inverters). This model restricts each component's failure to only those elements that are affected by the failed component. Figure 1 shows a conceptual flow diagram for PV-RPM. PV-RPM calculates hourly simulated plant life cycle data including energy production and component availability. System availability — a fraction of the time that the system is available to supply energy — is calculated as a function of time. PV-RPM can be used to carry out dynamic probabilistic model simulations to predict the range in future system performance. Because some model parameters cannot be known with complete certainty (e.g., inverter lifetime or module degradation rate) these inputs can be defined using probability distributions. The model can be run many times using a different sampled value from the distributions, to provide a range of possible future outcomes for the system. PV-RPM can optimize this Monte Carlo approach by using Latin Hypercube sampling.

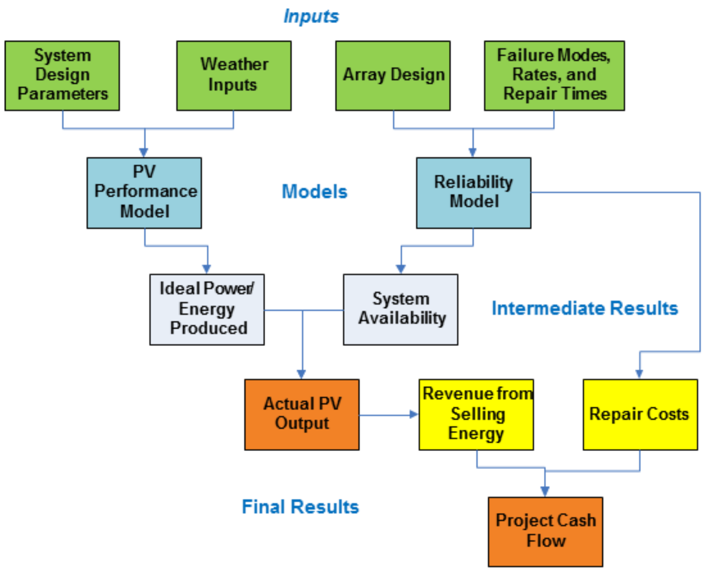

Figure 1. PV-RPM Conceptual Flow Diagram

The PV-RPM is built using the GoldSim™ Probabilistic Simulation Environment. It allows the user to define a PV system (inverters, modules, tracking, etc.) and select or input weather data, and the model calculates the performance of the system using the Sandia Photovoltaic Array Performance Model [2] and the SNL Performance Model for Grid Connected Photovoltaic Inverters [3]. These performance predictions represent an idealized case in which the PV system does not experience any disruptions, component failures, or degradation. The PV-RPM modifies this ideal case by including energy lost due to random component failures and repair times. Other effects, such as module degradation and grid outages are also included. The GoldSim platform provides considerable flexibility for representing alternate designs and can simulate processes other than simply energy production (e.g., financial). For this discussion we will focus primarily on the coupled reliability and performance features in the PV-RPM.

Any component can be represented by a reliability element. Each reliability element can have up to ten failure modes for the component. In addition, a reliability element can also contain other reliability elements in a Parent/Child type of hierarchy if it is desired, for example, to model subcomponents of the component of interest. Each failure mode has a defined rate of occurrence and a repair time definition, each of which can be represented as a distribution. The available options to describe failure modes, rates, and repair times provide flexibility to investigate how changes in product design for performance or reliability can impact the operating costs and expected energy generation over the lifetime of a system.

PV-RPM can be used for many types of PV system analyses. For example, below we use it to evaluate the value of string-level monitoring, which increases installation costs but allows operators to identify and fix string-level failures shortly after they occur, thus minimizing lost energy.

EXAMPLE ANALYSIS

The following analysis uses a hypothetical 16.4 kW system in Fort Worth, TX to demonstrate the capabilities of the PV-RPM and the trade-off studies that can be performed using the PV-RPM. While the model inputs used are not necessarily representative of real data; they are based on Sandia's experience with analyzing operations and maintenance data sets on actual systems.

The system consists of three inverters modeled as single-point efficiency inverters (94% efficiency) and uses 170 W polycrystalline silicon modules mounted at latitude tilt and arranged in 8 strings with 12 modules per string for a total of 96 modules. Table 1 describes the failure and repair distributions used for each of the major components of the system. The simulations were run for 30 years using an hourly time step. We ran 100 stochastic realizations. The module output was based on parameters from Sandia's PV Module Database and was analyzed using the Perez diffuse radiation model with the 1990 parameters [4]. Soiling was assumed to negligible, and the modules degradation was assumed to be 0.5% per year.

Table 1. Component Failure and Repair Inputs

Component	*Failure Distr.*	*Failure Rate*	*Repair Distribution*	*Repair Time*
Inverter	Poisson	0.2 yr^{-1}	Lognormal	Mean = 3 days, St. dev. = 1.5 days
Module	Poisson	0.05 yr^{-1}	Lognormal	Varies by PM scenario
Combiner Box	Lognormal	Mean = Uniform: 1131 to 2148 days, St. dev.= 700 days	Exponential	4.88 days
Transformer	Weibull	Mean life = 2.5e8 years, Slope = 0.35	Lognormal	Mean = 0.22 days, St. dev. = 0.25 days
AC Disconnect	Weibull	Mean life = 251.8 years, Slope = 0.35	Lognormal	Mean = 1.75 days, St. dev. = 1.62 days
Electrical Grid	Weibull	Mean life = 111 days, Slope = 0.75	Exponential	0.155 days

To assess the benefits of string level monitoring, we simulated four other preventative maintenance (PM) options for comparison. The five cases simulated in PV-RPM for this particular system are the following:

1. *String level monitoring*: Every module failure is immediately detected, and the module is assumed to be replaced in a relatively short time of one day.

2. *PM occurs annually*: Any module that fails will remain in a failed state until the end of the year when all failed modules are replaced.
3. *PM occurs every two years*: Any module that fails will remain in a failed state until the end of every second year when all failed modules are replaced.
4. *PM occurs every five years*: Any module that fails will remain in a failed state until the end of every fifth year when all failed modules are replaced.
5. *No PM, no repair*: The modules are never maintained and those modules that fail are never replaced.

Figure 2 shows the mean cumulative energy output of the example PV system over a 30 year lifetime for each of the five PM strategies. Each curve on the plot represents the mean of 100 realizations for the particular PM strategy. Figure 3 shows the mean curves for the total number of functional modules at any time during the simulation. It can be seen on this plot how at each PM event (i.e., every year, every two years, and every five years) the failed modules are repaired and the number of functional modules returns to 96. Figure 4 provides a plot of the mean cumulative energy lost for each of the five PM strategies. Note that the energy lost comparison is against the so-called ideal system in which there are no component failures or degradation. This plot indicates that for this small example system, the extra energy produced with the string level monitoring PM strategy may not be worth the investment versus the one year, two year, and maybe not even over the five year PM strategy. The value of the energy produced must be compared with the cost of repairs associated with each strategy. Other scenarios can be imagined for this type of analysis, particularly for larger systems, including a comparison between string level monitoring on each string with monitoring at the sub-combiner

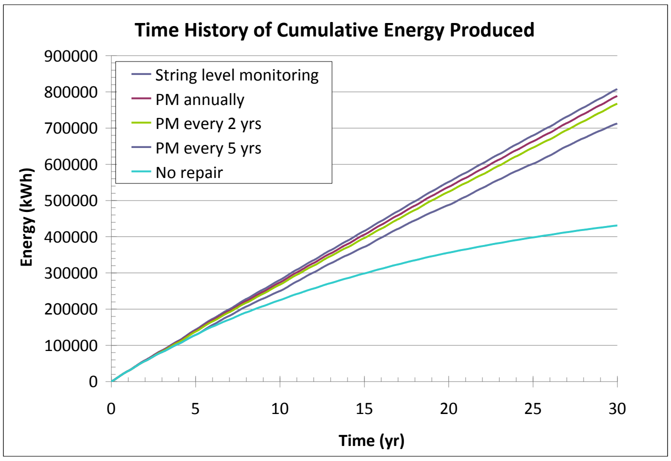

Figure 2 Mean Cumulative Energy Production for Each of the PM Strategies

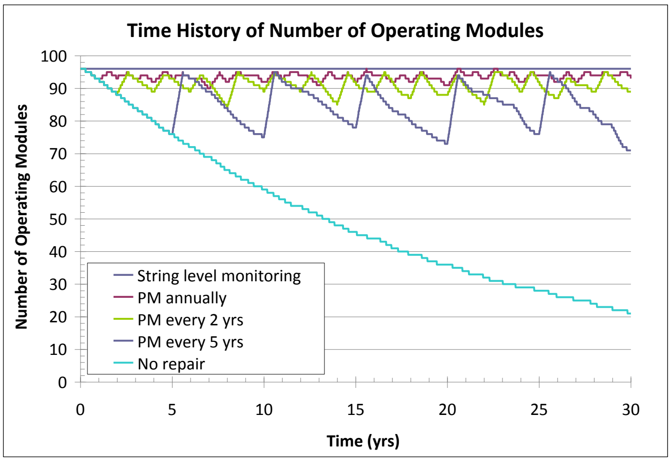

Figure 3 The Time Histories for the Number of Non-Failed Modules.

box, or performing repairs when there are five or more failures detected instead of responding to each failure, as an example.

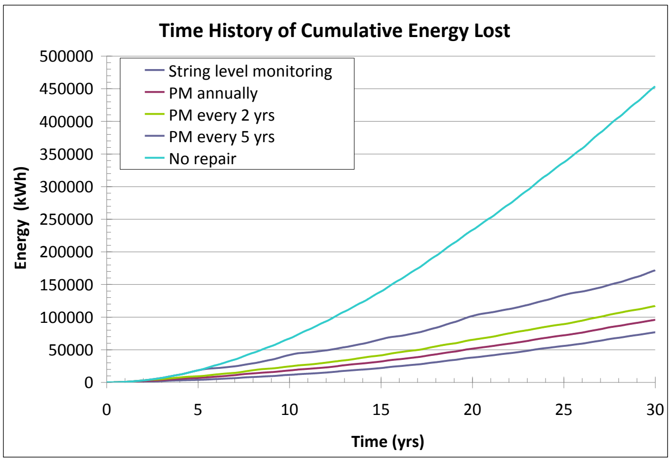

Figure 4 Cumulative Total Energy Lost (compared to an ideal system with no component failures).

CONCLUSIONS

Sandia National Laboratories has developed a unique modeling capability for PV systems that incorporates performance, reliability, weather, and cost models in a stochastic environment. The PV-RPM model can be used to predict kWh produced with uncertainty bands as well as evaluate cost and benefits of various design options, new technologies, and O&M strategies and programs. PV-RPM is intended to be customizable to any PV system design and to use any performance, weather or reliability models of interest. This capability provides a tool for system designers, owners, operators and financiers to understand the best case and worst case scenarios, thereby informing evaluations of risk and allowing optimized PV systems to be deployed.

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