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The Comparison of Three Photovoltaic System Designs Using the Photovoltaic Reliability and Performance Model (PV-RPM)

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Abstract

Most photovoltaic (PV) performance models currently available are designed to use irradiance and weather data and predict PV system output using a module or array performance model and an inverter model. While these models can give accurate results, they do so for an idealized system. That is, a system that does not experience component failures or outages. We have developed the Photovoltaic Reliability and Performance Model (PV-RPM) to more accurately model these PV systems by including a reliability component that simulates failures and repairs of the components of the system, as well as allow for the disruption of the system by external events such as lightning or grid disturbances. In addition, a financial component has also been included to help assess the profitability of a PV system.

In this report we provide some example analyses of three different PV system designs using the PV-RPM.

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NOMENCLATURE

A	ampere
AC	alternating current
DC	direct current
DOE	Department of Energy
kW	kilowatt
MW	megawatt
O&M	operations and maintenance
PV	photovoltaic
PV-RPM	Photovoltaic Reliability & Performance Model
SNL	Sandia National Laboratories
STC	standard test conditions
TMY	typical meteorological year
TMY2	The second iteration of the TMY datasets covering years 1961–1990
V	volt
W	watt

1. INTRODUCTION

Typical photovoltaic (PV) reliability studies have focused on components much more than on 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. The Photovoltaic Reliability and Performance Model (PV-RPM) is being developed at Sandia National Laboratories (SNL) to help buyers, system integrators, plant operators, financiers, and others who may be interested in the expected performance of a PV system. The PV-RPM can be used to predict such variables as a PV system's expected energy output, component and system availability, operation and maintenance (O&M) costs, and the profitability of the system. To accomplish this, the PV-RPM includes a performance model to predict the ideal performance of the PV system given the available solar resource; a reliability model to predict system component failures and repair times, and implement preventative maintenance strategies; and a financial model to predict O&M costs, financing costs, energy generation revenue, and ultimately cash flow for the PV system. The model can also include other effects, such as module output degradation over time or external disruptions such as electrical grid outages. In addition, the PV-RPM is a dynamic probabilistic model that can be used to run many realizations (i.e., possible future outcomes) of a system's performance using probability distributions to represent uncertain parameter inputs. This model can be used as a tool to test strengths and weaknesses of different PV system configurations and preventative maintenance strategies to help guide the design of more reliable, efficient, and profitable PV systems.

The PV-RPM was built using the GoldSim™ graphical simulation environment (1). GoldSim™ is an object-oriented graphical simulation program that can be used to build system models using graphical input elements that can represent data inputs, time series information, equations, stochastic distributions, disruptive events, and much more. This graphical modeling architecture can convey a more easily understandable representation of a complex system model over that which is possible using typical coding methods. GoldSim™ was chosen as the simulation environment for the PV-RPM due to its flexibility in representing complex dynamic system interactions. GoldSim™ also provides reliability modeling, financial modeling, and it provides for dynamic probabilistic modeling using Monte Carlo simulation with Latin Hypercube sampling.

To provide a demonstration of some of the capabilities of the PV-RPM, this report will show some of the simulation results of a comparison between three 2-megawatt (MW) PV system designs. The three systems designs are the following:

1. Fixed mount system using polycrystalline silicon modules,
2. fixed mount system using thin-film modules, and
3. single-axis tracking system using polycrystalline silicon modules.

These three system designs were procured from a PV integrator. However, these systems have not been physically built and no corresponding data exist. These designs include the physical layout and the summary of project costs for each system as of the summer of 2011.

Several simulations of the PV-RPM were run for these three system designs to show how the PV-RPM can be used to compare expected outcomes of the different system designs. First we provide a detailed comparison of the expected cumulative energy generation, component failure costs, and net cash flow for the three systems if they were located in Albuquerque, NM and operating for 30 years. Then we provide a comparison of expected result for these three systems for five different geographic locations within the US. Finally, we show the effect of several different O&M strategies on the expected performance of these systems.

2. DESIGN CHARACTERISTICS OF THE THREE PV SYSTEMS

SNL procured three different 2 MW PV system designs from a PV integrator. Each system design consists of layout drawings, component specifications, a bill of materials, and a cost breakdown summary. Each of the 2 MW systems uses eight identical 250 kW (AC) inverters, and all three systems use identical inverters.

The three system designs are the following:

- Poly-Si Fixed Tilt: this system uses only polycrystalline silicon PV modules mounted on fixed-tilt racks with two strings per rack.
- Thin-Film Fixed Tilt: this system uses only thin-film PV modules mounted on fixed-tilt racks with 12 strings per rack.
- Poly-Si Single-Axis Tracking: this system uses only polycrystalline silicon PV modules mounted on single-axis trackers with two strings per rack (tracker).

The fixed-tilt racks are set at latitude tilt, and the single-axis trackers are oriented in the north-south direction and rotate from east in the morning to west in the evening to track the movement of the sun across the sky. Table 1 provides a summary of the major components in each system design along with the expected land use required for each system. The summary of the project costs for each system design is given in Table 2.

Table 1. System Configuration Summary.

	Poly-Si Fixed-Tilt	Thin Film Fixed-Tilt	Poly-Si with Single-Axis Trackers
Size (DC STC)	2,163,840 W	2,160,000 W	2,163,840 W
Module Characteristics [1]	230 W, 29.9 V, 7.7 A	75 W,69.1 V, 1.1 A	230 W, 29.9 V, 7.7 A
Modules	9,408	28,800	9,408
Strings	672	5,760	672
Modules per String	14	5	14
Inverters (250kW AC)	8	8	8
Step-up transformers	2	2	2
Combiner boxes	48	1,680	48
Recombiner boxes	None	48	None
Trackers	None	None	336
Land use	11.22 acres	15.90 acres	14.89 acres

[1] Module rated power, voltage at maximum power point, and current at maximum power point.

Table 2. Summary of Project Costs for Each System.

Costs	Poly-Si Fixed-Tilt	Thin Film Fixed-Tilt	Poly-Si Single-Axis Tracking
Electrical Infrastructure Total [1] ($)	4,380,875	4,205,243	4,435,476
Mechanical Infrastructure Total [2] ($)	852,264	1,217,520	1,539,384
Civil Infrastructure Total [3] ($)	147,319	183,359	175,611
Soft Costs Total [4] ($)	853,000	853,000	853,000
Total Project Costs ($)	6,233,458	6,459,123	7,003,471
Electrical Infrastructure [1] ($/Watt)	2.02	1.95	2.05
Mechanical Infrastructure [2] ($/Watt)	0.39	0.56	0.71
Civil Infrastructure [3] ($/Watt)	0.07	0.08	0.08
Soft Costs [4] ($/Watt)	0.39	0.39	0.39
Project ($/Watt) (DC STC)	2.88	2.99	3.24

[1] Electrical Infrastructure total cost includes the cost of all the electrical components as well as the AC and DC wiring and the cost of installation.
[2] Mechanical Infrastructure total cost includes the cost of the module mounting assemblies, foundations, and installation.
[3] Civil Infrastructure total cost includes land cost, security fencing, clearing of the terrain, and inverter pads.
[4] Soft Costs are engineering and project management costs, inverter and AC subsystem commissioning costs, overhead costs, and profit margin.

Even though there are considerably more thin-film modules than there are polycrystalline silicon modules, the electrical infrastructure costs are almost the same. The total cost for the thin-film modules is actually more than $500,000 less than that for the polycrystalline silicon modules, but the added costs for so many more combiner boxes and wiring for all those modules make up the difference. As would be expected, the mechanical infrastructure costs for the thin-film and single-axis tracking systems is higher than that for the fixed-mount polycrystalline silicon system due to the much higher number of racks needed for the thin-film system, and the added cost of the trackers for the single-axis tracking system. Figure 1 shows a cost percentage breakdown for each of the three systems.

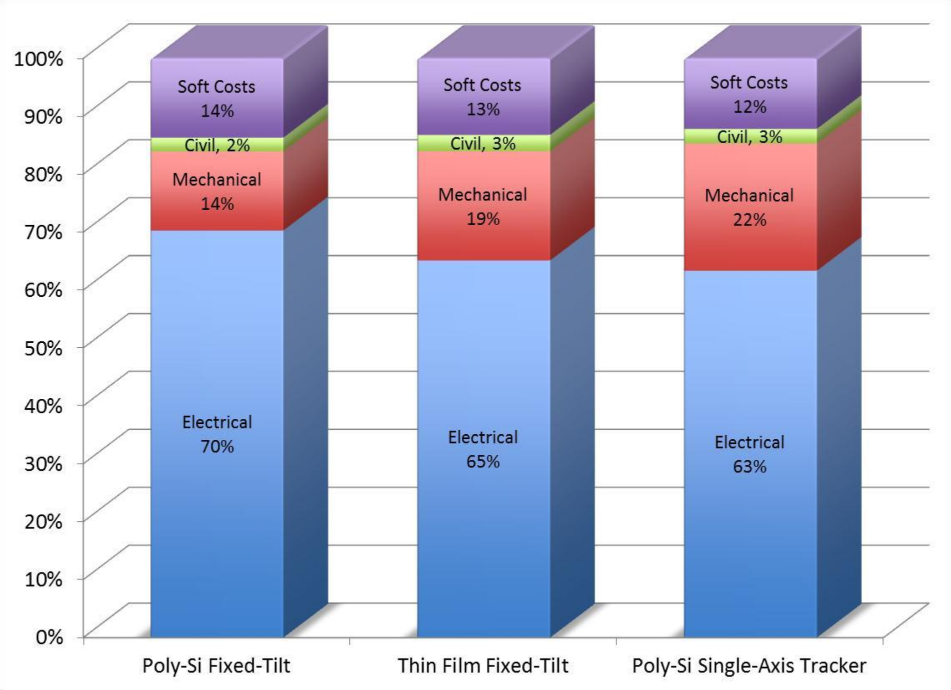

Figure 1. Cost Percentage Breakdown for Each System.

3. MODEL INPUTS

The PV-RPM requires many model inputs as well as a number of modeling assumptions. Inputs include irradiance, air temperature, and wind speed for the location of the PV site; performance parameters for the PV modules and inverters; coefficients for the radiation models; failure modes, failure rates, and repair times for each type of PV system component; module degradation rates and soiling factors; system and component cost information, loan terms, repair costs, inflation rate, and many more. Since the objective of the analysis presented here is to provide a comparison of three different systems at a particular location, many of the inputs will be the same for each system, and therefore, most of those inputs need not be enumerated here. However, the more salient inputs and assumptions are given in the following tables and the full listing of inputs is provided in Appendix A. Table 3 lists the financial model inputs, Table 4 gives the performance model inputs based on the Sandia Array Performance model (2) and the Sandia Inverter Performance model (3), and Table 5 gives the reliability model inputs based on a Reliability Block Diagram approach (4).

Table 3. Noteworthy Financial Model Inputs.

Input	Value
Loan Amount	80% of Total Install Cost
Loan Term	20 years
Loan Interest Rate	7%
Electricity Price [1]	$0.10/kWh
Labor Rate [1]	$100/hour
Inflation Rate [2]	3%
Module Warranty [3]	20 years
Inverter Warranty [3]	10 years
Fixed O&M Costs [1]	$8/kW-year
Module Cost	$322 Poly-Si, $86.25 Thin-Film

[1] Adjusts with inflation.

[2] Long term average for US.

[3] These warranty periods are assumptions, may not be typical. In the O&M comparison analysis in Section 4.2, the modules are assumed to not have warranties.

Table 4. Noteworthy Performance Model Inputs.

Input	Value
Inverter Performance Parameters	Sandia Inverter database [1]
Module Performance Parameters	Sandia Module database
Weather Inputs	TMY2 database
Module Soiling Factor	1.0 (no soiling)
Irradiance Model	Perez (1990 dataset)

[1] This database is now maintained at NREL and it is freely available.

Table 5. Noteworthy Reliability Model Inputs.

Input	Value
Module Degradation Rate (%/year)[1]	Poly-Si: Weibull (scale = 0.824, shape = 1.238)
	Thin-Film: Exponential/Poisson (scale = 1.805)
Module Failure[2,3]	Failure Mode 1: Defective Component (represents infant failures)
	Probability of defect = 0.05, Rate if defective = 0.5 yr^{-1}
	Failure Mode 2: Normal (35 years, 5 years)
Module Repair[2]	Lognormal: (60 days, 20 days)
Inverter Failure[2]	Failure Mode 1: Catastrophic Failure: Normal (10 years, 1 year)
	Failure Mode 2: Major Component Failure: Exponential/Poisson (0.2 yr^{-1})
	Failure Mode 3: Small Failure or Trip: Exponential/Poisson (1.0 yr^{-1})
Inverter Repair[2]	Failure Mode 1: Lognormal (10 days, 2 days)
	Failure Mode 2: Lognormal (5 days, 2 days)
	Failure Mode 3: Lognormal (0.5, 0.2)

[1] Based on module degradation data reported in Jordan and Kurtz (5). [2] Not from actual data, these inputs are for illustrative purposes only.
[3] The combination of failure modes chosen is intended to represent a bathtub type of failure curve.

The failure distributions chosen for the modules are intended to represent a “bathtub” type of failure curve. The lifetimes of a population of components is often characterized by reliability professionals as resembling a bathtub curve (invoking the visual of a curve that resembles the extended u-shape of the cross-section of a bathtub). The bathtub curve consists of three features, the first representing early-failures (also commonly referred to as infant-mortality) where the failure rate is initially high and decreases quickly with time as components that have some type of flaw (manufacturing defect, handling or installation errors, etc.) fail and are replaced. The second feature of the bathtub curve is known as the useful life (or normal life) in which the components operate with a low and relatively constant failure rate. The third feature of the bathtub curve is the wear out period which represents the period where the components have reached their design life and begin to fail at an increasing rate. The bathtub failure curve given here is not based on actual module failure data, but is used here for illustrative purposes only.

Three failure and repair modes were chosen for the inverters to illustrate some of the functionality of PV-RPM. The three inverter failure modes are intended to represent 1) small inverter events or trips, 2) major failures that would require service from the inverter vendor, and 3) failures that would require replacement of the inverter. Each of these failure modes has an associated repair time distribution and repair costs.

Labor costs can reasonably be expected to increase with inflation, therefore, the labor rates associated with the repair or replacement of failed system components are scaled with inflation using the present value to future value calculation [Future Value = Present Value * $(1 + \text{rate})^{\text{Time}}$]. However, the costs of the PV system components were not scaled with inflation. It could be argued that component costs would also increase over time with inflation, or conversely, that component costs will decrease over time as manufacturing costs go down with the wider utilization of PV power. Therefore, for this analysis, it was simply assumed that future component costs would be the same as those of today.

All components in this example model, with the exception of the inverter, are treated as simple “black-box” components. That is, the exact mechanism of failure is not known, only that the component failed and must be replaced. Detailed failure mechanisms are not modeled for the inverters either, but they are modeled in this example model by degrees of severity as noted in Table 5. The PV-RPM is fully capable of allowing detailed modeling of any component the analyst wishes. For example, the inverter could be defined in terms of its primary subcomponents; capacitors, IGBTs, cooling fans, circuit board, software, etc., and each subcomponent could be assigned one or more failure mechanisms. Generally though, failure rate information is difficult to find for many PV components and subcomponents.

4. RESULTS

It should be emphasized here that while the three system plans are actual architectural layouts with cost estimates, some of the other necessary model inputs such as component failure distributions and repair times as well as some of the financial inputs were chosen for illustrative purposes. The results shown below are used to demonstrate some of the capabilities of the PV-RPM and provide just a few examples of evaluations that could be done for a PV system or for comparison among different systems as was done here. Therefore, from the analysis provided here, the results shown below should not be construed to indicate that any of these systems is inherently better than the others.

The PV-RPM can carry out dynamic probabilistic model simulations to predict the possible future performance of a system. Because the future values of many of the system inputs cannot be precisely known (e.g., what the weather will be like a year from today, or what a module's degradation rate will be, etc.) the system model can be simulated many times to provide many possible realizations (possible future outcomes) of the system. GoldSim™ uses Monte Carlo simulation to do this and includes the option to sample the stochastic variables using Latin Hypercube sampling. Dynamic simulation allows the development of a representation of the system whose reliability is to be determined, and then observe that system's performance over a specified period. Thirty years was chosen as the period of interest for the performance of these three systems, and the simulations consisted of 100 realizations.

Figure 2 shows statistical results from a 100-realization simulation for the cumulative energy generated by these three systems using Albuquerque, NM as the location for the systems. The first three plots in Figure 2 show that there is considerable uncertainty in the energy output of these systems over 30 years. The percent difference between the greatest result and the least result is 38% for both the Fixed Poly-Si and Single-Axis Poly-Si systems and 35% for the Fixed Thin-Film system. For comparison, the mean results for the three systems are shown in the fourth plot of Figure 2. This plot shows that the single-axis tracking system would be expected to generate approximately 19% more energy than the fixed thin-film system and 24% more energy than the fixed poly-Si system.

In this example analysis, by far the largest single source of uncertainty for the energy generated by these systems is the module degradation rate. A sensitivity analysis performed within GoldSim™ calculates a regression coefficient of -0.984 for the module degradation rate on the cumulative energy generated result. Figure 3 shows the statistics for module degradation rates for the poly-Si and thin-film modules. These plots show a range of from almost no degradation in 30 years to a degraded output of less than 40% of the original output after 30 years.

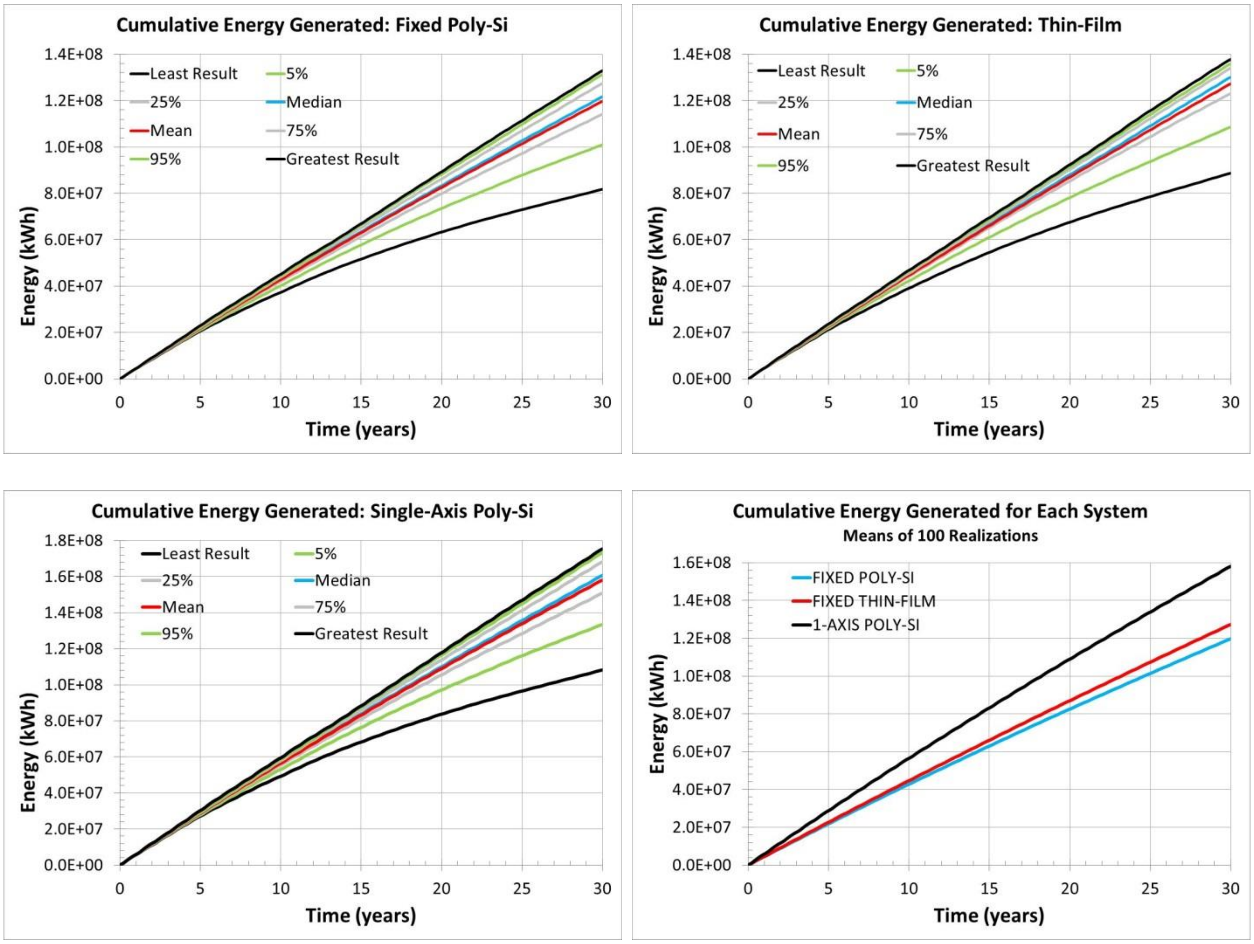

Figure 2. Cumulative Energy Generated for Each System - Albuquerque, NM.

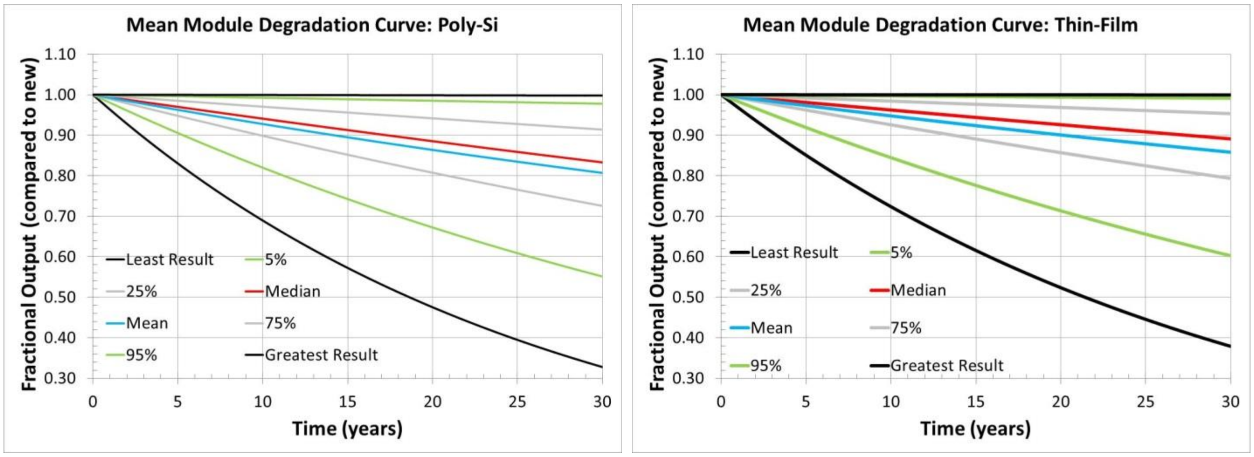

Figure 3. Statistics for the Module Degradation Rates for Poly-Si and Thin-Film Modules.

The module degradation rate distributions are based on module degradation data reported by Jordan and Kurtz (5). We recognize that their data includes data from older modules built using older manufacturing technologies, and this can lead to the large uncertainty in the degradation rates. Even so, new manufacturing technologies can also lead to unexpected increases in degradation rates, as well as the influx of new module manufacturing companies that do not have extensive experience manufacturing modules. Thus, these module degradation rates may still be representative.

When a failed component is repaired or replaced, the cost is determined in the PV-RPM by multiplying the current labor rate ($/hr), which grows with inflation, by the expected repair or replacement time for the component plus the cost of the component (if component is replaced). Additionally, modules and inverters are assumed to be covered under a warranty. This simulation has been set up such that if a warrantied component fails while still under warranty, no cost is incurred for the replacement of that component (note though that the system still experiences a loss of revenue from lost energy generation while the failed component is non-functional). The cumulative costs of component failures (component cost plus labor) for each system are shown in the plots of Figure 4. Note the repair times used to generate labor costs are not from real data and are for illustrative purposes only.

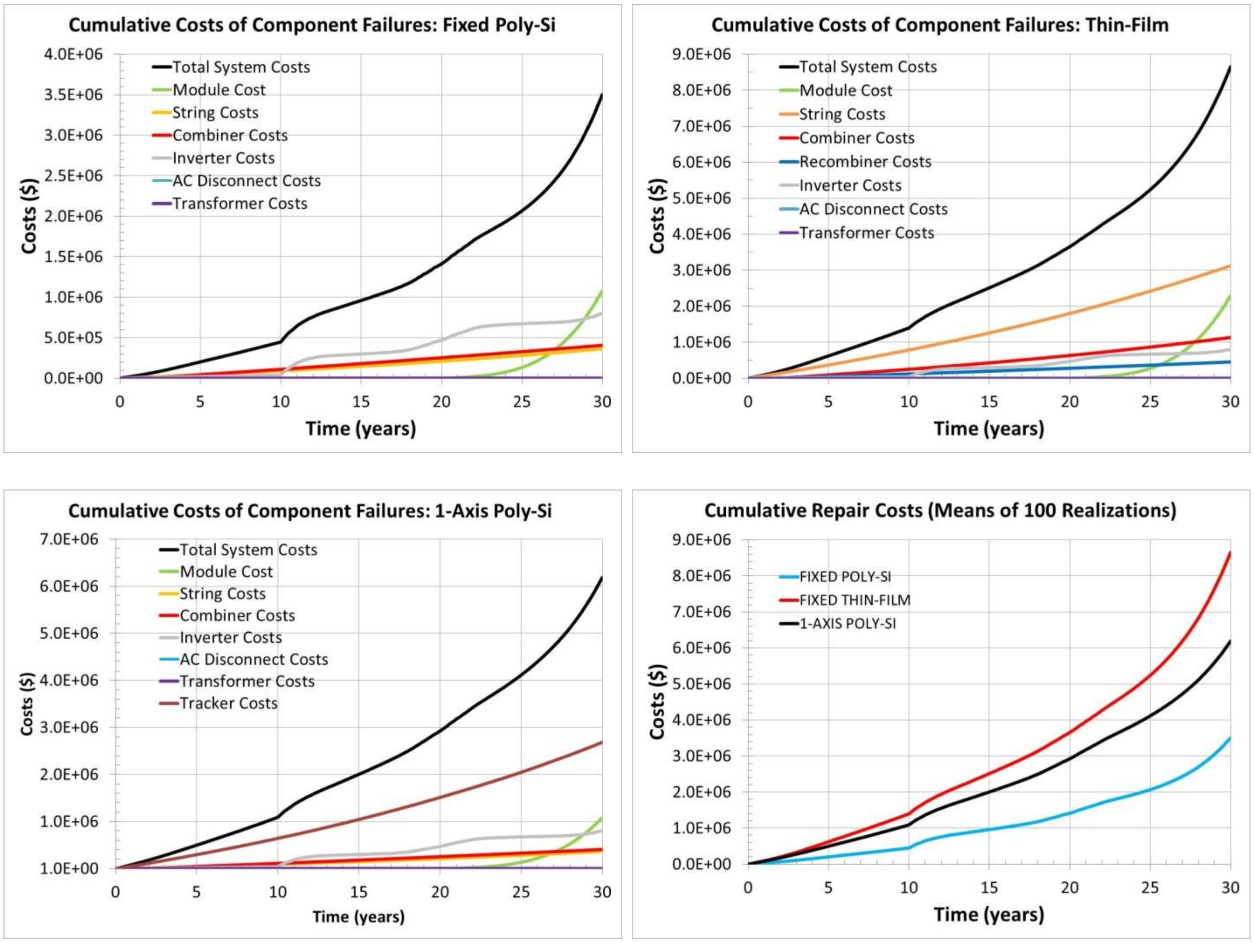

Figure 4. Cumulative System Repair Costs for Each System.

Notice on the plots that at ten years there is an upward bump in the curve for the inverter costs (and hence in the total system costs curve). This is due to the assumption that inverter failures that are either catastrophic or involve the repair or replacement of a major inverter component are fully covered under the inverter warranty (ten year inverter warranty in this example). Therefore, the assumption used here is that the only costs the owner bears while the inverters are under warranty are those associated with trips of the inverter. The Fixed Poly-Si graph provides a good example, after the first ten years an inverter failure has a pronounced impact on the curve. When those original inverters are all replaced, the cost curve flattens out again until those replacement inverters exceed their warranties and begin to fail starting around 18 years to about 22 years (note that these curves are the means of 100 realizations).

As noted in Table 3, the modules are also assumed to be covered by a warranty, in this case 20 years. These simulations used the assumption that modules that fail within the warranty period are replaced at no cost to the system owner - module, labor, and any other expenses are covered. As such, the curves for module cost do not show up in the plots of Figure 4 until after 20 years has elapsed. Note that later in this report the module replacement costs during the warranty period will be modified for a comparison of O&M strategies.

In addition, notice that the cumulative costs due to component failures for the Fixed Thin-Film system is more than double that of the Fixed Poly-Si system. Since the failure rates for each component in all three systems is the same, this difference is due entirely to the much larger number of modules, strings, and combiner boxes in the Fixed Thin-Film system. Similarly, the higher cost for the tracking system over the Fixed Poly-Si system is due entirely to tracker failure costs.

Figure 5 shows a comparison of the cumulative number of component failures for each of the three systems. Note how the modules curves clearly show the higher failure rate early, then a prolonged nearly flat failure rate, and then an increasing failure rate as the modules reach end of design life.

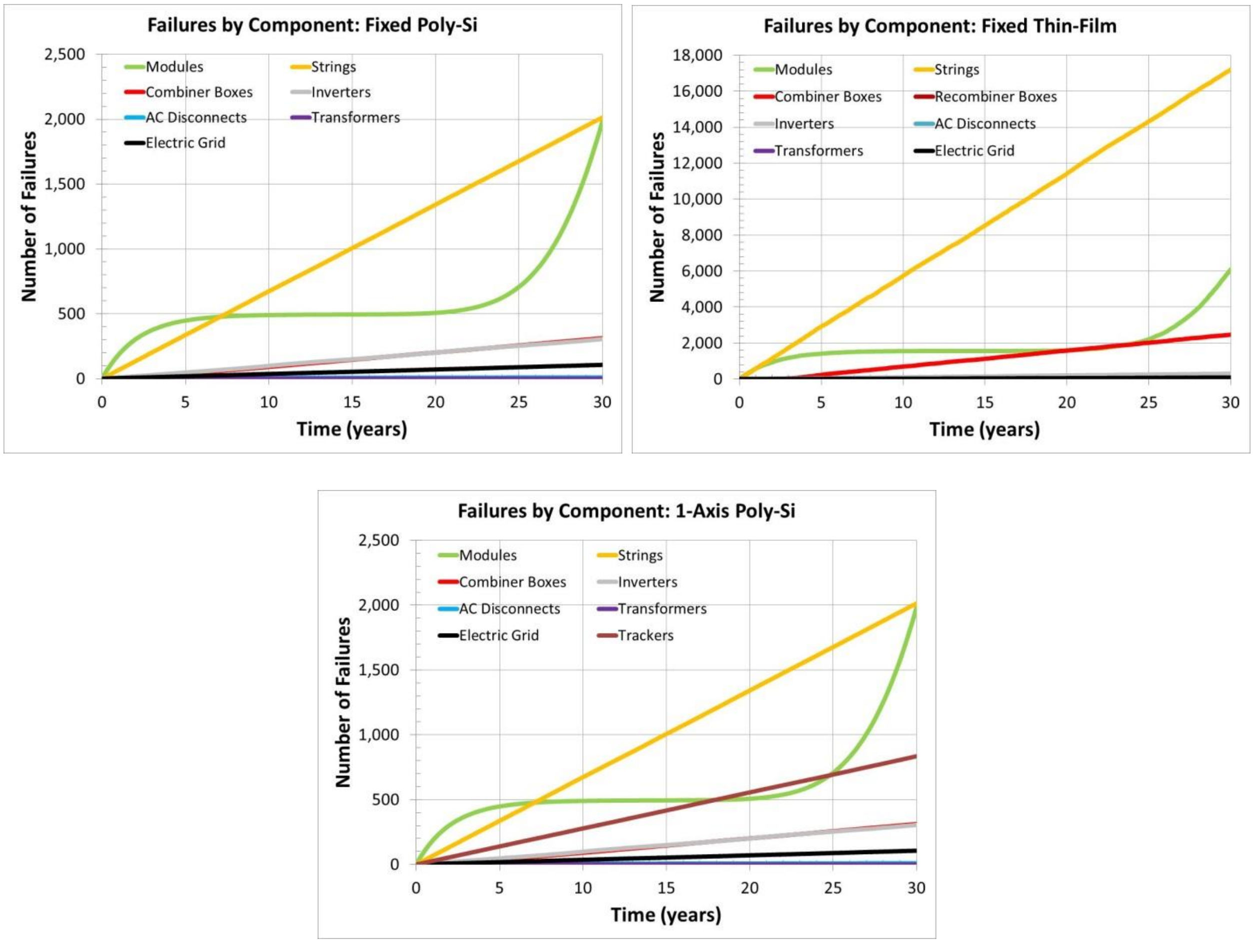

Figure 5. Cumulative Number of Component Failures for Each System.

Each plot in Figure 5 shows a curve for "strings" that shows a high number of failures. This represents a blown fuse between the string and combiner box. Even though this failure is given a failure rate of 1/10 years, this translates to a large number of failures in a 30-year simulation, especially for the thin-film system, which has 5,760 strings.

The statistical results of 100 realization simulations for the net cash flow for each of the three systems over 30 years is shown below in the plots of Figure 6. These cash flow plots show a large degree of uncertainty, primarily due to the large uncertainty in energy generation caused by the large uncertainty in module degradation rates.

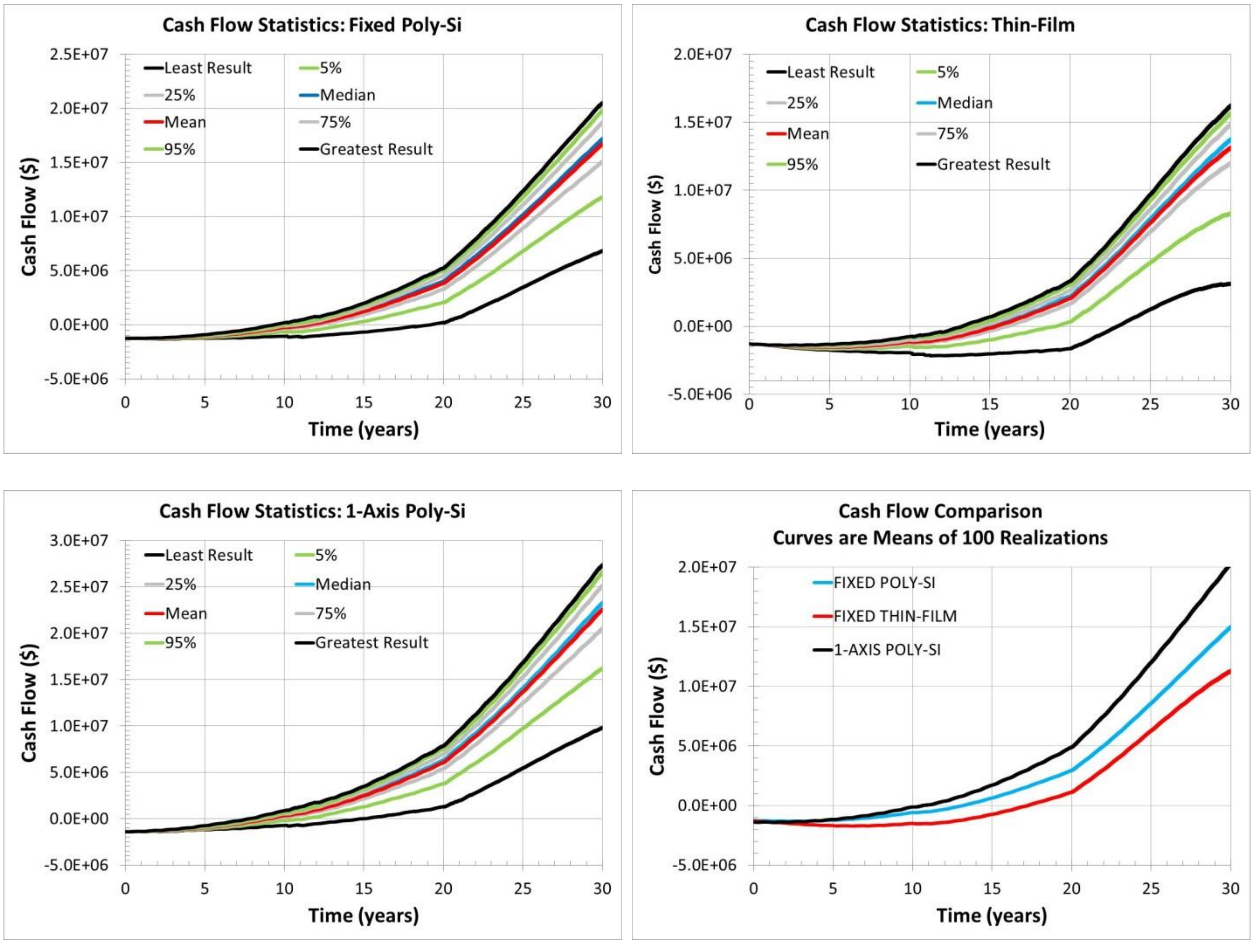

Figure 6. Cash Flow Curves for Each System - Albuquerque, NM.

Recall that the expected energy generation in Figure 2 for the Fixed Thin-Film system is higher than for that of Fixed Poly-Si, but the plot of the comparison of the mean cash flow of the three systems (the last plot in Figure 6) shows that the expected cash flow for the thin-film option is lower (about 24% lower) than that of the fixed Poly-Si option. This is primarily due to the larger maintenance costs associated with the thin-film system (physically a much larger system with many more components) as was shown in Figure 4.

One of the important outputs of the reliability model is a time history curve of the PV system availability. In the context of this example analysis, system availability is defined as the output of the system divided by the output of the system if all parts of the system were working. There is one caveat to this though, and that has to do with the availability of the electrical grid. When the electrical grid is offline the system availability is zero. Even though the PV system may be fully functional, it cannot send power to the grid when the grid is down. Figure 7 shows a graph of the system availability for part of a year for one of the realizations for the Fixed Poly-Si system.

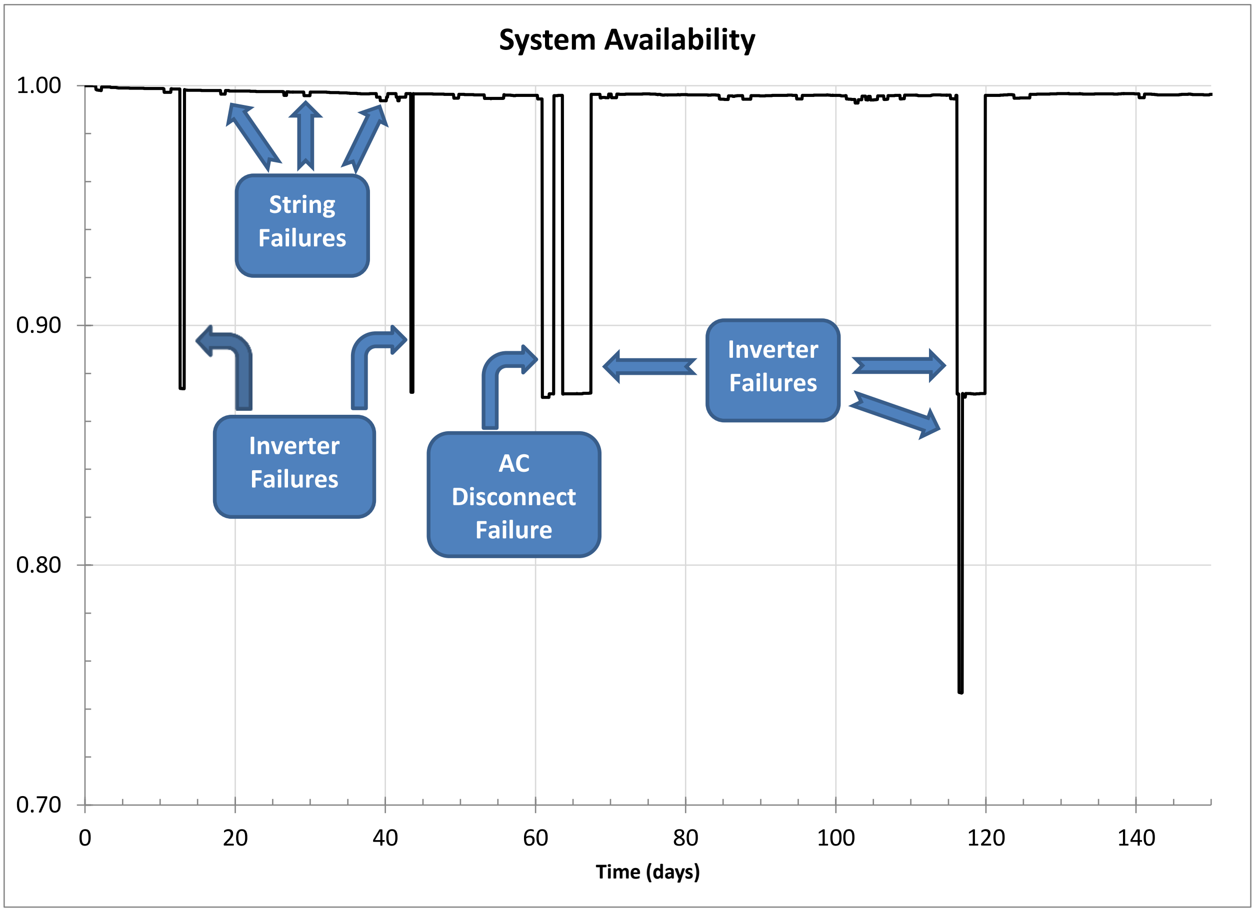

Figure 7. Example of a System Availability Curve for a portion of one realization of the Fixed Poly-Si system.

Using the failure histories of the system components, the graph in Figure 7 has been annotated to point out some of the features in the graph. For example, the first large drop in availability at about 13 days is due to a routine inverter trip and the inverter is restored after 14 hours. Recall that there are 8 inverters in this system (each inverter array contains 1,176 modules), so each inverter outage drops the system output by one eighth. The large double drop at about 116 days is caused by two inverter failures. The first drop is caused by a trip on one inverter, and before that inverter can be returned to service a second inverter experiences a major component failure which required warranty service. The first inverter was offline for 10 hours and the second inverter was offline for 89 hours.

4.1 Geographic Comparisons

In this section, results are shown for the expected performance of the three PV systems in five different locations in the U.S., ranging from the sunny high desert of Albuquerque New Mexico to a cloudier climate of Seattle Washington. These five locations (Albuquerque, NM; Fresno, CA; Topeka, KS; Albany, NY; and Seattle, WA) were chosen to show the variability in solar resource that can exist from location to location throughout the country and how that can affect the profitability of a system. For this comparison, electricity rate and weather inputs are location specific, all other inputs are as noted in Table 3 through Table 5. Table 6 provides a comparison of solar resource, climatic conditions, and electricity rates for these five locations.

Table 6. Summary of Location Specific Characteristics.

Location	Electricity Rate [1] (¢/kWh)	Solar Radiation [2,3] (kWh/m^2/day)	Min./Max. Temp. [2,4] (°C)	Rel. Humidity [2,4] (%)	Wind Speed [2,4] (m/s)
Albuquerque	10.6 ¢/kWh	6.4	5.7/21.2	44	4.1
Fresno	11.9 ¢/kWh	5.7	10.1/24.7	60	2.9
Topeka	9.5 ¢/kWh	4.9	6.0/18.4	69	4.3
Albany	8.9 ¢/kWh	4.3	2.6/14.5	70	3.9
Seattle	7.2 ¢/kWh	3.7	7.0/15.2	73	3.8

[1] Rates are from OpenEnergyInfo (OpenEI), Oct. 2012 for residential rates (6). [2] Source: Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors (7). [3] Average annual solar radiation for flat-plate collectors facing south at latitude tilt. [4] Average annual values.

As can be seen in Figure 8 through Figure 10 below, the difference in energy generation and therefore, profitability, can vary widely from location to location. For all three systems, Albuquerque produces the most energy, about 12% more than second place Fresno and about 41% more than the lowest, Seattle. Due to the differences in electricity rates at these locations, the cash flow results don't closely follow the energy generation results. Fresno produces a cash flow result very similar to Albuquerque's due to a higher electricity rate in Fresno. Seattle produces the least amount of energy of this group and it also has the lowest electricity rate. That combination leaves Seattle with a very unfavorable cash flow result in this example simulation.

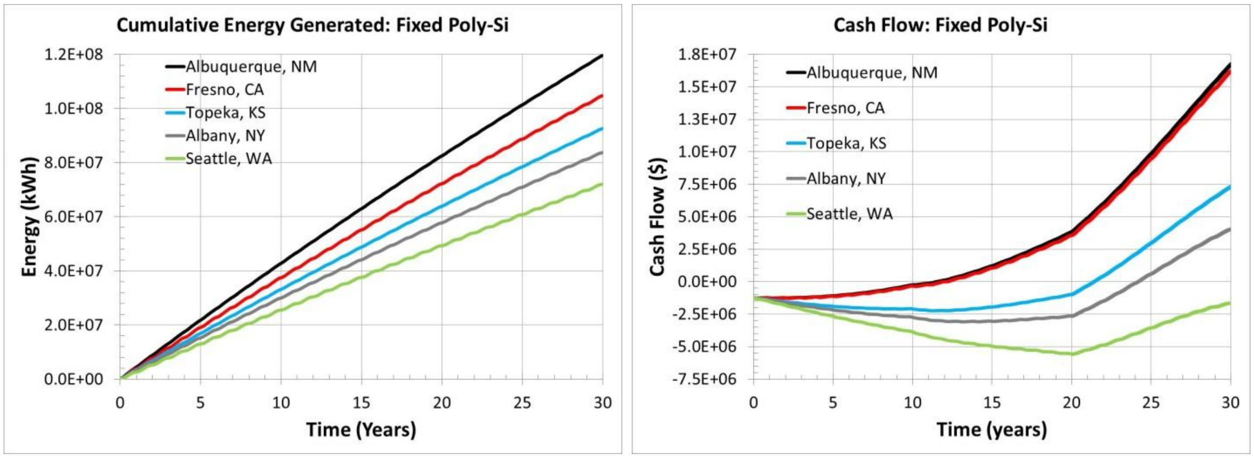

Figure 8. Energy Generation and Cash Flow Comparison for the Fixed Poly-Si System at Five Different Locations.

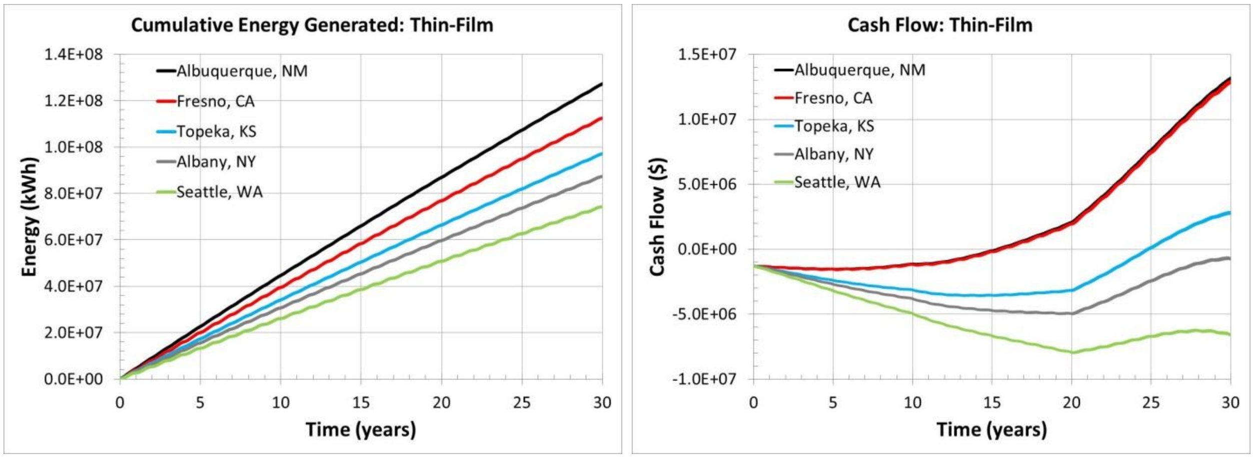

Figure 9. Energy Generation and Cash Flow Comparison for the Fixed Thin-Film System at Five Different Locations.

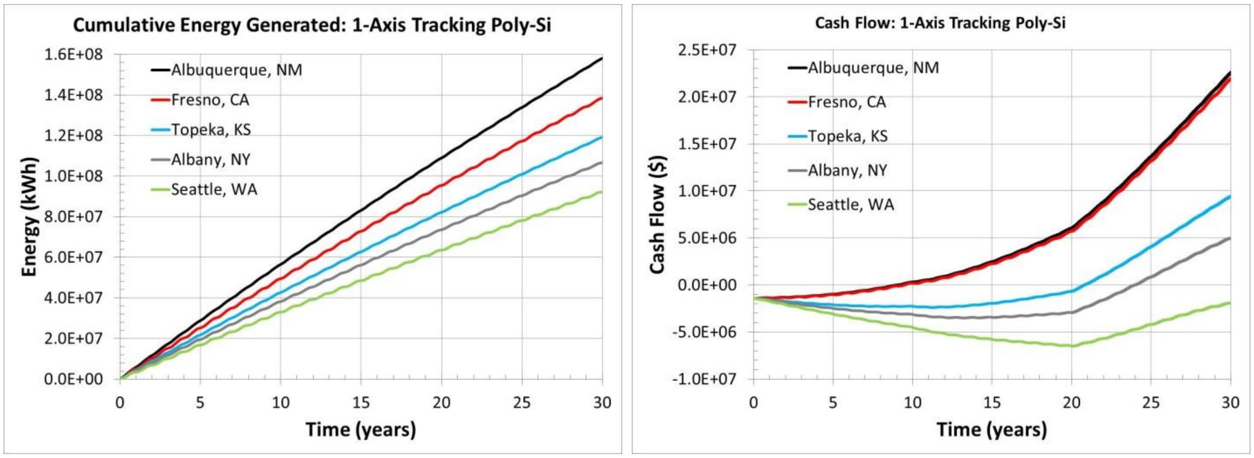

Figure 10. Energy Generation and Cash Flow Comparison for the Single-Axis Tracking System at Five Different Locations.

Table 7 provides a summary of the energy generation, cash flow, and component failure costs for each of the three systems at each of the five locations. Given the assumptions used in this example coupled with the relatively lower solar resource and lower electricity rates, siting any of the three systems in Seattle would be expected to lead to a net cash flow loss. Similarly, siting the fixed thin-film system in Albany would be expected to produce a net cash flow loss as well. The single-axis tracking system appears to be the most profitable option for all locations except Seattle.

As of this writing, there are typically local, state, and federal incentives available for the installation of solar power systems and such incentives were not included in this analysis.

Table 7. Summary of Simulation Results for Five Locations.

	Fixed Poly-Si [1]	Difference [2]	Fixed Thin-Film [1]	Difference [2]	Single-Axis Poly-Si [1]	Difference [2]
Energy Generated (kWh AC)						
Albuquerque	119,960,000	-	127,260,000	-	158,020,000	-
Fresno	104,750,000	-12.7%	112,480,000	-11.6%	138,410,000	-12.4%
Topeka	92,647,000	-22.8%	97,174,000	-23.6%	119,150,000	-24.6%
Albany	83,751,000	-30.2%	87,357,000	-31.4%	106,650,000	-32.5%
Seattle	70,864,000	-40.9%	74,307,000	-41.6%	92,212,000	-41.6%
Component Failure Costs ($)						
Same for All Sites	3,502,180	-	8,651,510	-	6,187,374	-
Cash Flow ($)						
Albuquerque	16,766,343	-	13,181,392	-	22,643,212	-
Fresno	16,228,750	-3.2%	12,929,924	-1.9%	21,966,668	-3.0%
Topeka	7,337,171	-56.2%	2,849,049	-78.4%	9,462,636	-58.2%
Albany	4,064,851	-75.8%	-686,776	-105.2%	5,026,455	-77.8%
Seattle	-1,643,178	-109.8%	-6,571,964	-149.9%	-1,897,746	-108.4%

[1] All values are the means of 100 realizations. [2] Percent difference from the location with the highest value.

4.2 Comparing O&M Strategies

The PV system owner would likely be interested in knowing the most cost effective way to maintain the PV system. Should every failure be fixed as soon as it is discovered, thereby maximizing energy generation? Can the system tolerate a certain number of failures for a period of time until a scheduled periodic maintenance event, thereby reducing maintenance costs, but at the expense of some energy generation potential? What would be the result if the owner decided to build the PV system but not provide for any maintenance of the system?

This set of results shows the effect of different O&M strategies on the expected repair costs, energy generation, and cash flow for each of the three systems. Failure of some of the components in a PV system would have a major impact on the output of the system, and it is reasonable to assume that those components (e.g., inverters, transformers, disconnect switches, etc.) would be repaired or replaced as quickly as possible. Therefore, O&M strategies tested here deal primarily with the modules, as well as the trackers in the single-axis tracking system, and all other repairs are treated as in the previous simulations.

The O&M strategies tested cover a wide range of options as follows:

- Immediately replace a failed module or repair a failed tracker upon discovery. This is expected to be the most costly option as it requires either full time personnel at the site, or an on-call service for someone to go to the site and make the repair or replacement when the failure occurs.
- Periodic maintenance events where all failed modules are replaced and all failed trackers are repaired on scheduled dates. The following maintenance intervals were simulated for this option: twice a year, once a year, every two years, every four years, and every 5 years.

- No repairs. This is a “do nothing option” where all failed modules and trackers are never replaced or repaired.

These scenarios require some assumptions for the inputs. For the results presented in the previous section, a generous assumption was used for modules under warranty. That is that the module manufacturer would cover the entire expense associated with a failed module, that is, remove and replace at no cost to the system owner. For these O&M scenario simulations, a different assumption will be used. Here, it is assumed that the module manufacturer warrants the module against failure and will provide a replacement module during the warranty period. However, the system owner has to have the failed module removed, shipped to the manufacturer, wait for a replacement module to be sent back, and then have the replacement module installed. It could be argued that this warranty claim would cost the owner as much, if not more, than if the system owner had purchased many spare modules and simply used those and did not invoke warranty claims except in the case of some design or manufacturing fault that caused a large number of modules to fail in a short span of time. Therefore, the assumption used for these O&M scenarios is that there effectively is no module warranty and the system owner pays for all module replacements (module cost plus labor cost).

The assumptions for replacement costs (repair costs for the trackers) for the immediate repair scenario is that the labor rate is $100 per hour (scaled with inflation) and it takes 2 hours to replace a module and 8 hours to repair a tracker. The assumption for the periodic maintenance scenarios is that the system owner hires a company to find and replace all failed modules and repair all failed trackers. The labor rate will be less than the immediate response scenario, but there will be a truck roll cost. The labor rate is $40 per hour and the truck roll cost is $1,000 (both scaled with inflation), and the repair times are the same as those used for the immediate repair scenario. For the no repair scenario, no money is spent on modules or trackers.

The expected repair costs for each of the three PV systems for these O&M scenarios are shown in Figure 11. In all three systems, it is not surprising that the immediate repair option is the most expensive and the no repair option is the least expensive option, with the periodic maintenance options in between based on the frequency of the periodic maintenance.

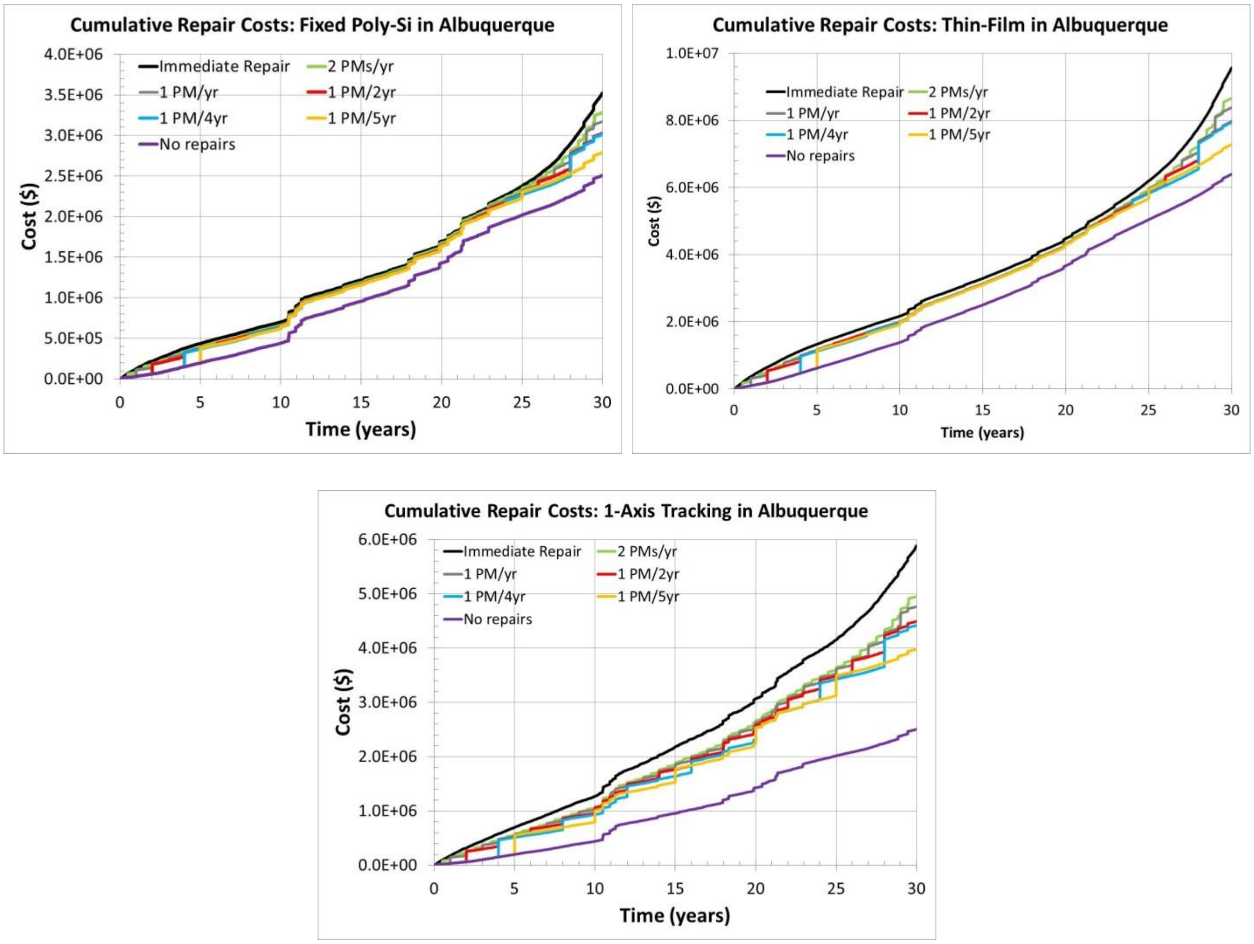

Figure 11. Expected Repair Costs for Each of the O&M Scenarios for Each System.

The difference between the immediate repair case and the no repair case is much larger for the single-axis tracking system than the other systems because repair of failed trackers is also included.

The effect that each of these O&M scenarios has on the energy generation of these systems is shown in Figure 12. It is somewhat surprising to see that, with the exception of the no repair scenario, all the O&M scenarios are expected to generate very close to the same amount of energy. The energy generation difference between the immediate repair scenario and the periodic maintenance every five years scenario is less than 2% for all three systems. For the no repair scenario, the Fixed Poly-Si and the Fixed Thin-Film system lose just over 6% energy over 30 years compared to the immediate repair scenario, while the Single-axis Tracking Poly-Si system loses 15%.

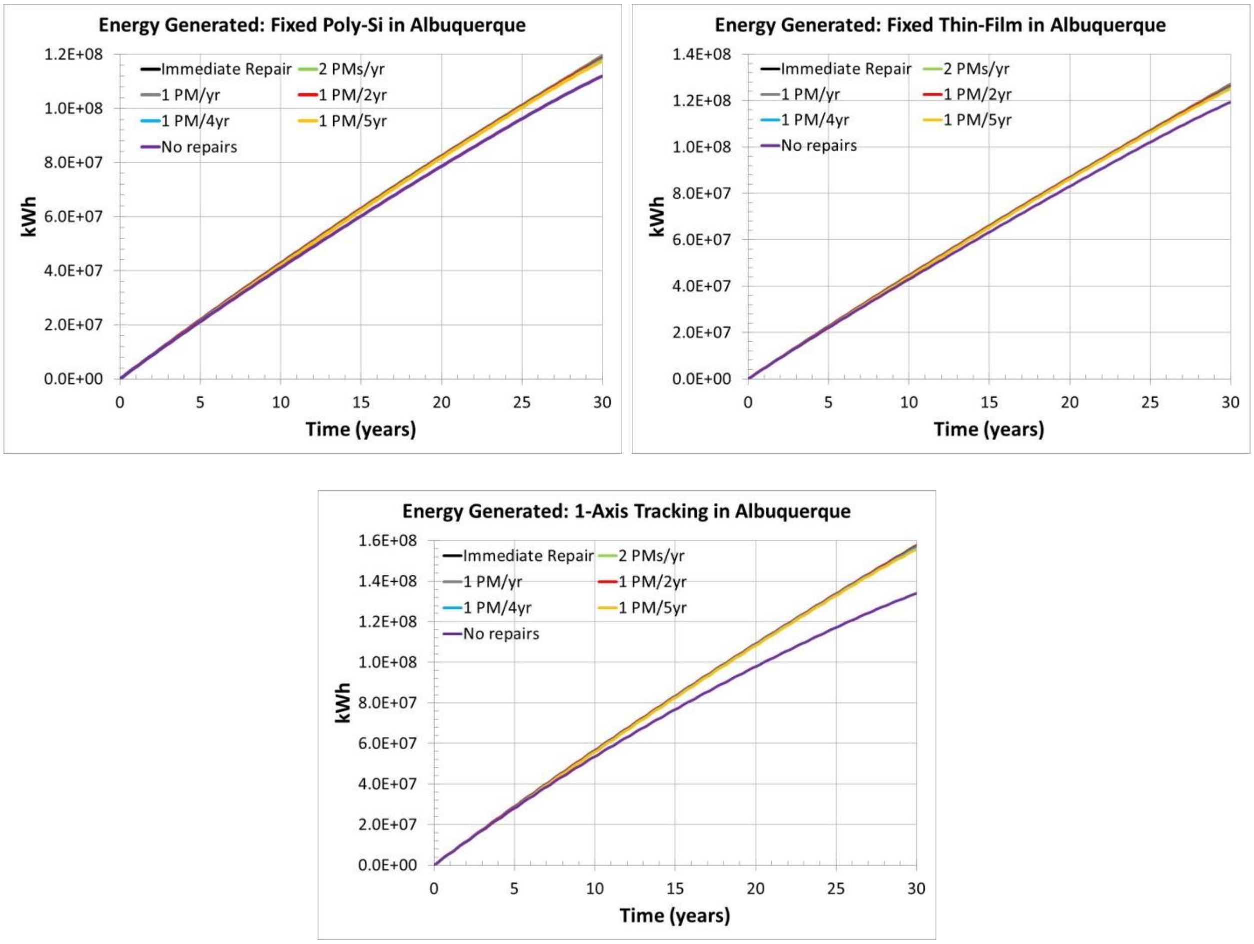

Figure 12. Expected Energy Generation for each of the O&M scenarios for each system.

Figure 13 shows the cash flow results for the O&M scenarios for each of the three systems and Table 8 provides a summary of the results for each system and each O&M scenario.

Starting with the cash flow results for the fixed Poly-Si system, the results show that it would be a little more profitable to choose a periodic maintenance strategy over the immediate repair strategy. All the periodic maintenance scenarios give similar results for the fixed Poly-Si system and show a cash flow improvement of between 1.4% and 2.1%. The no-repair scenario is not a desirable option because it leads to a reduction in cash flow of 5.2% compared to the immediate repair scenario. The cash flow results for the fixed Thin-Film system shows a more significant increase in cash flow from choosing a periodic maintenance strategy, with a cash flow improvement over the immediate repair scenario of between 8.9% and 17.5%, and even the no-repair strategy is much better (+12.6%) than the immediate repair strategy. The single-axis tracking system would also benefit from a periodic maintenance strategy with a 4.6% to 6.9% improvement in cash flow. The no-repair strategy is a very poor strategy for the single-axis tracking system though, with an expected cash flow reduction of 11.5%.

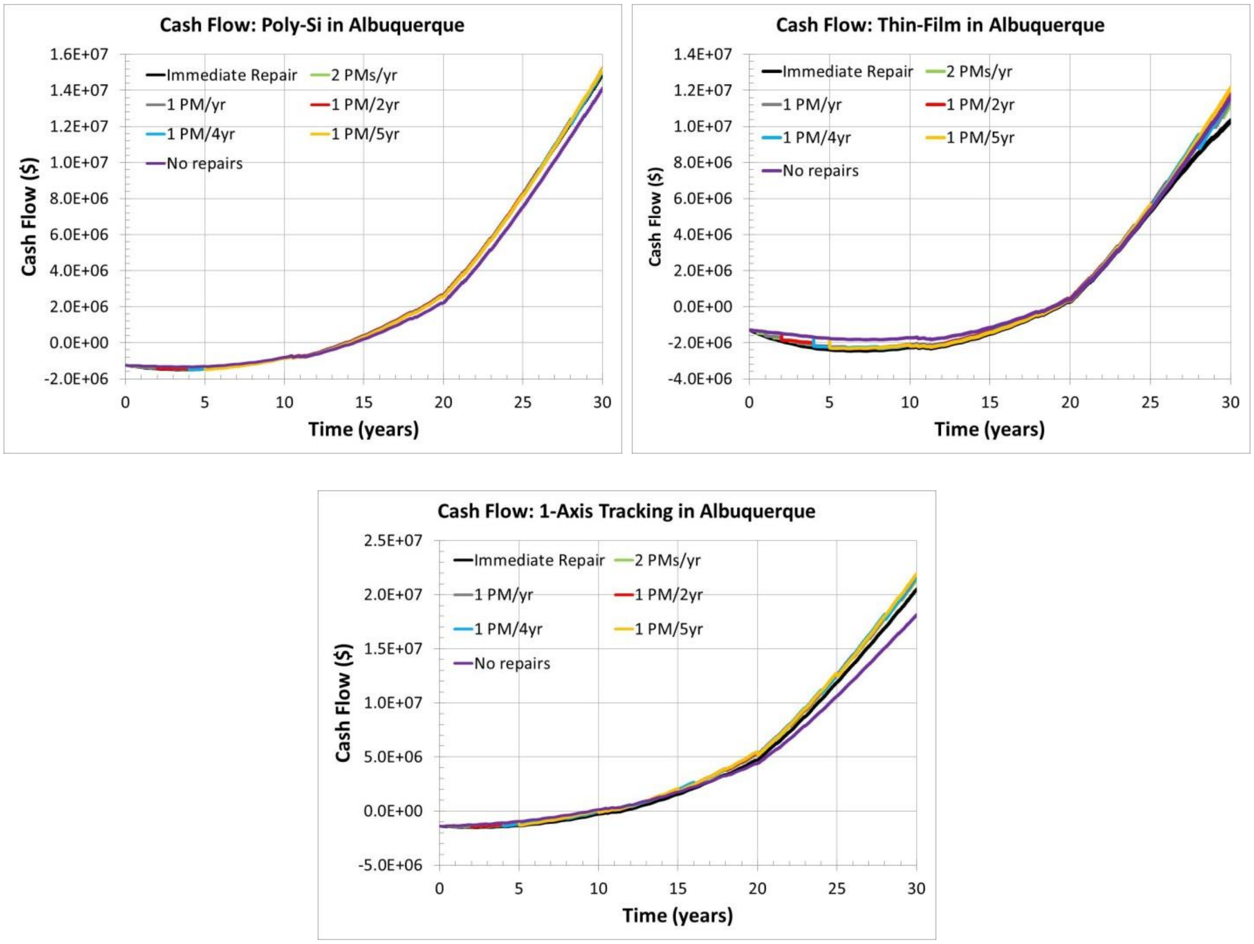

Figure 13. Expected Cash Flow for Each of the O&M Scenarios for Each System.

It should be noted that the no-repair option or those longer periodic maintenance periods may not be viable options if the system is required by contract to produce some minimum level of electricity output.

Table 8. Comparison of O&M Strategies – Albuquerque, NM.

System	O&M Costs ($)	Difference	Energy (kWh)	Difference	Cash Flow ($)	Difference
Fixed Poly-Si						
Immediate Repair	3,522,100	-	119,330,000	-	14,917,000	-
PM twice a year	3,284,000	-6.8%	119,200,000	-0.1%	15,123,000	1.4%
PM once a year	3,174,000	-9.9%	118,980,000	-0.3%	15,181,000	1.8%
PM every two years	3,027,100	-14.1%	118,580,000	-0.6%	15,229,000	2.1%
PM every four years	3,014,300	-14.4%	118,100,000	-1.0%	15,125,000	1.4%
PM every five years	2,790,200	-20.8%	117,480,000	-1.6%	15,200,000	1.9%
No repair	2,509,200	-28.8%	111,930,000	-6.2%	14,134,000	-5.2%
Fixed Thin-Film						
Immediate Repair	9,562,400	-	127,020,000	-	10,362,000	-
PM twice a year	8,658,000	-9.5%	126,830,000	-0.1%	11,281,000	8.9%
PM once a year	8,379,500	-12.4%	126,620,000	-0.3%	11,477,000	10.8%
PM every two years	7,956,900	-16.8%	126,190,000	-0.7%	11,780,000	13.7%
PM every four years	7,936,500	-17.0%	125,670,000	-1.1%	11,667,000	12.6%
PM every five years	7,279,800	-23.9%	125,060,000	-1.5%	12,174,000	17.5%
No repair	6,391,800	-33.2%	119,320,000	-6.1%	11,664,000	12.6%
Single-Axis Poly-Si[1]						
Immediate Repair	5,884,600	-	157,572,288	-	20,529,000	-
PM twice a year	4,949,800	-15.9%	157,540,000	0.0%	21,464,000	4.6%
PM once a year	4,764,000	-19.0%	157,450,000	-0.1%	21,627,000	5.3%
PM every two years	4,492,000	-23.7%	157,210,000	-0.2%	21,840,000	6.4%
PM every four years	4,416,600	-24.9%	156,590,000	-0.6%	21,767,000	6.0%
PM every five years	3,980,500	-32.4%	155,560,000	-1.3%	21,953,000	6.9%
No repair	2,503,200	-57.5%	133,880,000	-15.0%	18,167,000	-11.5%

[1] Also includes repair on the single-axis trackers.

5. CONCLUSIONS

The analyses described in this report provide just a few examples of the many possible uses of the PV-RPM. The PV-RPM has a base design for the performance, reliability, and financial models, but these models are intended to be flexible so that they can be modified to meet specific modeling needs. To date, we have used the PV-RPM on several analyses and presented our results at various PV conferences (8) (9) (10) (11).

The PV-RPM allows considerable flexibility in developing the system reliability model. The PV-RPM can be adapted to model almost any PV system configuration, and it can model down to the system component or even subcomponent level of detail. Typically, though, failure mechanisms and failure and repair data is not readily available for many of the PV components and subcomponents. The performance model has built in the TMY2 database for irradiance and weather data, but it can be supplied with other databases as desired, and if the user has site specific data, that could also be used. The performance model also includes several choices of solar radiation models, and others could be added as needed. The financial model can also be adapted to take into account various types of cost accounting.

A simplified “player” version (performance and reliability modules only) of the PV-RPM is available for download on the SNL PV Reliability website (12). This player model will require the GoldSim™ Player software. The GoldSim™ Player is a special version of GoldSim™, that can be obtained free of charge (13), and is used to “play” a specially prepared GoldSim™ model without having to purchase a license for the GoldSim™ software.

6. REFERENCES

1. GoldSim Technology Group. GoldSim. *GoldSim.* [Online] http://www.goldsim.com/Home/.

2. King, D. L., Boyson, W. E. and Kratochvill, J. A. *Photovoltaic Array Performance Model.* Sandia Report Number: SAND2004-3535. Albuquerque : Sandia National Laboratories, 2004. http://photovoltaics.sandia.gov/docs/PDF/King%20SAND.pdf. SAND2004-3535.

3. King, David L., et al., et al. *Performance Model for Grid-Connected Photovoltaic Inverters.* Sandia Report Number: SAND2007-5036. Albuquerque : Sandia National Laboratories, 2007.

4. *A Reliability and Availability Sensitivity Study of a Large Photovoltaic System.* Collins, E., et al., et al. Valencia, Spain : 25th European Photovoltaic Solar Energy Conference and Exhibition, September 5-11, 2010, 2010. p. 7.

5. *Photovoltaic Degradation Rates - An Analytical Review.* Jordan, D.C. and Kurtz, S.R. Golden : National Renewable Energy Laboratory, 2011. NREL/JA-5200-51666.

6. U.S. Department of Energy and the National Renewable Energy Laboratory. Electric Utility Rates. *OpenEI | OPENENERGYINFO.* [Online] http://en.openei.org/wiki/Gateway:Utilities.

7. National Renewable Energy Laboratory. *Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors.* NREL Report Number: NREL/TP-463-5607. Golden : National Renewable Energy Laboratory, 1994.

8. *Sandia's Photovoltaics Reliability Performance Model (PV-RPM).* Jennifer E. Granata, Steven P. Miller, and Joshua S. Stein. Boston : s.n., 2012. 2nd European American Solar Deployment Conference: PV Rollout. SAND2011-9293C.

9. *Coupled Performance and Reliability Modeling of PV Systems and Components: Evaluating Design and O&M Strategies.* Joshua S. Stein, Steven P. Miller, Jennifer E. Granata. Dallas : s.n., 2011. Solar Power International. SAND2011-7299C.

10. *Simulation of Time-Varying Throughput by Combining Availability and Solar Irradiance Models.* Mundt, Michael J., et al., et al. San Diego : s.n., 2011. North America Applied Reliability Symposium. SAND2011-2851C.

11. *Accelerated Testing Of Metal Foil Tape Joints And Their Effect On Photovoltaic Module Reliability.* N. Robert Sorensen, Michael A. Quintana, Michael J. Mundt, Edward V. Thomas, Steven P. Miller, and Samuel J. Lucero. Valencia : s.n., 2010. European Photovoltaic Solar Energy Conference and Exhibition. SAND2010-5961C.

12. Sandia National Laboratories. PV Reliability & Performance Model. *Sandia National Laboratories.* [Online] http://energy.sandia.gov/?page_id=6367.

13. GoldSim Technology Group, LLC. Download GoldSim Player. *GoldSim.* [Online] http://www.goldsim.com/forms/playerdownload.aspx.

14. *Reliability and Availability Analysis of a Fielded Photovoltaic System.* Collins, E., Dvorack, M., Mahn, J., Mundt, M., and Quintana, M. s.l. : 34th IEEE Photovoltaic Specialist Conference, 2009.

15. Fitchette, Stephanie. Distribution fits and parameter estimates based on literature review of PV module degradation rates. [Letter]. Albuquerque : Sandia National Laboratories, June 8, 2011. p. 2.

16. National Renewable Energy Laboratory (NREL). NSRDB 1961 - 1990: Hourly Data Files. *NREL National Renewable Energy Laboratory.* [Online] http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/hourly/.

17. Marion, W., and Urban, K.,. *User's Manual for TMY2s: Typical Meteorological Years.* Golden : National Renewable Energy Laboratory, 1995.

18. *Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance.* Perez, R., Ineichen, P., Seals, R., Michalsky, J., Stewart, R. 5, s.l. : Solar Energy, 1990, Vol. 44.

APPENDIX A: PV-RPM INPUTS

PV-RPM Inputs			
FAILURE & REPAIR INPUTS			
Input	**Value**	**Description**	**Source**
AC Disconnect			
Failure Dist.: Weibull			(14)
Scale Parameter	Triangular dist.	(minimum = 2980, most likely = 10883, maximum = 39742) days	(14)
Shape Parameter	0.3477		(14)
Location Parameter	3.9 days		(14)
Repair Dist.: Lognormal			(14)
Mean	1.75 days	Mean repair time of failed AC disconnect	(14)
Standard Deviation	1.62 days	Standard deviation for repair of failed AC disconnect	(14)
Module			
Failure Dist. #:1 Defective Component		Represents module early failures.	*
Probability of defect	0.05	Probability a module could be subject to a defect that will cause early failure.	*
Rate of failure if defective	0.5 yr-1	Failure rate if the module is subject to the early-failure defect.	*
Failure Dist.: #2: Normal		Represents useful-life and wear-out failures.	*
Mean lifetime	35 years	Mean age at failure for a module.	*
Standard deviation	5 years	Standard deviation of mean age at failure for a module.	*
Repair Dist.: Lognormal		Represents the replacement of a module.	*
Mean repair time	60 days	Mean delay time until repaired (includes failure discovery time).	*
Standard deviation	20 days	Standard deviation for mean repair time of a module.	*
Degradation Rate: Exponential		Represents the output degradation of a CdTe (thin-film) module.	(15)
Scale Parameter	1.805		(15)
Weibull		Represents the output degradation of a polycrystalline silicon module.	(15)
Scale Parameter	0.824		(15)
Shape Parameter	1.238		(15)
Combiner & Recombiner Boxes			
Failure Dist.: Lognormal		Represents the failure of a combiner or recombiner box.	(14)
Mean lifetime	Uniform dist.	(minimum = 1131, maximum = 2148) days	(14)
Standard deviation	700 days	Standard deviation of the combiner mean life.	(14)
Repair Dist.: Exponential		Represents the replacement of a failed combiner or recombiner box.	(14)
Mean repair time	4.89 days	Mean repair time for a combiner box.	(14)
String			

PV-RPM Inputs			
Failure Dist.: Exponential		Represents a blown fuse between the string and combiner box.	*
Failure Rate	1/10 years	Mean fuse failure rate.	*
Repair Dist.: Lognormal		Represents the replacement of a failed string fuse.	*
Mean repair time	1 day	Mean repair time for a string.	*
Standard deviation	0.5 days	Standard deviation for mean string repair time.	
Inverter			
Failure Dist. #1: Normal		Represents catastrophic failure requiring replacement of the inverter.	*
Mean lifetime	10 years	Mean lifetime of an inverter.	*
Standard deviation	1 year	Standard deviation of the mean inverter life.	*
Failure Dist. #2: Exponential		Represents a major inverter repair expense with a prolonged downtime.	*
Failure Rate	1/5 years	Mean failure rate for major inverter component failure.	*
Failure Dist. #3: Exponential		Represents those failures or trips that occur more frequently, are less costly to correct, and result in a shorter outage time.	*
Failure Rate	1/year	Mean failure rate for routine failures or nuisance trips.	*
Repair Dist. #1: Lognormal		Represent the repair of inverter failure mode #1.	*
Mean repair time	10 days	Mean repair time for inverter failure mode #1 (catastrophic failure).	*
Standard deviation	2 days	Standard deviation for inverter repair mean for failure mode #1.	*
Repair Dist. #2: Lognormal		Represent the repair of inverter failure mode #2.	*
Mean repair time	5 days	Mean repair time for inverter failure mode #2 (component failure).	*
Standard deviation	1 day	Standard deviation for inverter repair mean for failure mode #2.	*
Repair Dist. #3: Lognormal		Represent the repair of inverter failure mode #3.	*
Mean repair time	0.5 days	Mean repair time for inverter failure mode #3 (routine/nuisance trip).	*
Standard deviation	0.2 days	Standard deviation for repair time of inverter failure mode #3.	*
Grid			
Failure Distribution: Weibull		Represents an electrical grid outage.	(14)
Scale Parameter	Triangular	(minimum = 40, most likely = 80, maximum = 160) days	(14)
Shape Parameter	0.75		(14)
Transformer			
Failure Distribution: Weibull		Represents the failure of a transformer.	(14)
Scale Parameter	Triangular dist.	(minimum = 2E5, most likely = 1.28E10, maximum = 4.0E10) days	(14)
Shape Parameter	0.3477		(14)
Location Parameter	28 days		(14)
Tracker			
Failure Dist.: Exponential		Represents the failure of a tracker	*
Failure Rate	1/12 years	Failure rate of a tracker.	*
Repair Dist: Lognormal		Represents the repair of a tracker.	*
Mean repair time	30 days	Mean repair time for a tracker.	*
Standard deviation	10 days	Standard deviation for mean tracker repair time.	*

PV-RPM Inputs			
FINANCIAL INPUTS			
Input	**Value**	**Description**	**Source**
Total System Install Cost	$ 6,233,458 $ 6,459,123 $ 7,003,471	Fixed polycrystalline silicon. Fixed thin-film. Single-axis tracking polycrystalline silicon.	** ** **
Down Payment	20 %	Percent of the total cost that will be paid by the owner.	*
Inflation Rate	3 %	Inflation rate used to calculate increases in revenues, as well as any costs.	*
Interest Rate	7 %	Annual interest rate on PV system bank loan.	*
Electricity price (generic)	10 ¢/kWh	Electricity purchase price.	*
Electricity price Albuquerque Fresno Topeka Albany Seattle	 10.6 ¢/kWh 11.9 ¢/kWh 9.5 ¢/kWh 8.9 ¢/kWh 7.2 ¢/kWh	 Current residential rate in Albuquerque. Current residential rate in Fresno. Current residential rate in Topeka. Current residential rate in Albany. Current residential rate in Seattle.	 (6) (6) (6) (6) (6)
Inverter Warranty	10 years	Inverter warranty period.	*
Module Cost	$ 322 $ 86.25	Cost of a polycrystalline silicon module. Cost of a thin-film module.	**
Module Warranty	20 years (0 years)	Warranty period. (For the O&M comparison analysis, modules are assumed to have no warranty.)	*
PM Frequency	2/year 1/year 1/2 year 1/4 year 1/5 year 0/year	Used for O&M comparison. Used for O&M comparison. Used for O&M comparison. Used for O&M comparison. Used for O&M comparison. Used for O&M comparison.	* * * * * *
Loan Term	20 years	Loan term for the system cost that requires financing.	*
Truck roll cost	$ 1,000/trip	Cost to send workers to a PV site (used in O&M comparison).	*
Inverter replacement cost	$ 76,397	Cost to replace inverter in today's dollars.	**
Inverter major repair cost	$ 15,279	Assumed the cost of a major inverter component to be 20 % of the replacement cost of the inverter.	*
Inverter routine cost	$ 1,000	Cost of "fixing" a routine inverter outage.	*
String Cost	$ 20	Cost of a string-level fuse.	*
Combiner box cost	$ 976 $ 34.86	Replacement cost of a combiner box in the poly-si systems. Price sheet. Replacement cost of a combiner box in the thin-film system. Price sheet.	** **
Recombiner box cost	$ 960	Replacement cost of a recombiner box. Price sheet.	**
AC Disconnect cost	$ 500	Replacement cost of an AC disconnect switch.	*
Transformer cost	$ 32,868	Replacement cost of a transformer. Price sheet.	**
Tracker repair cost	$ 2,000	Repair or replacement cost of a tracker 1-axis tracker motor.	*
Module repair time	2 hours	Actual time a worker spends replacing a module (used to calculate labor costs).	*
String repair time	1 hour	Actual time a worker spends replacing a string fuse (used to calculate labor costs).	*

PV-RPM Inputs			
Combiner box repair time	2 hours	Actual time a worker spends replacing a combiner box (used to calculate labor costs).	*
Recombiner box repair time	3 hours	Actual time a worker spends replacing a recombiner box (used to calculate labor costs).	*
AC disconnect repair time	4 hours	Actual time a worker spends replacing a disconnect switch (used to calculate labor costs).	*
Transformer repair time	10 hours	Actual time a worker spends replacing a transformer (used to calculate labor costs).	*
Labor rate	$100/hour	Labor rate in today's dollars.	*
Fixed O & M costs	Normal (8, 1) $/kW-yr	Fixed Operation and Maintenance Costs.	*
PERFORMANCE MODEL INPUTS			
Input	**Value**	**Description**	**Source**
Ground reflectivity	0.2	Hemispherical ground reflectivity (albedo).	*
Soiling Factor	1.0	Module Soiling Factor - 0=completely covered, 1=no soiling	*
Yearly Weather Variability	Trunc. Normal (mean = 0, SD = 0.045, min. = -0.1, max. = 0.1)	Used to apply yearly variation to the weather file. Resamples each year.	(7)
Module Performance Parameters	Sandia Module Database	A set of PV module performance parameters for the Sandia Array Performance model. These parameters are compiled and maintained at the Photovoltaic System Evaluation Laboratory (PSEL) at SNL.	***
Inverter Performance Parameters	Sandia Inverter Database	A set of inverter performance parameters for the Sandia Inverter Performance model. These parameters are now maintained at NREL.	***
Weather Inputs	TMY2 Database	TMY2 database is a set of hourly values of solar radiation and meteorological elements for a 1-year period (8,760 hours) for 239 locations in the US and US territories. It consists of months selected from individual years and concatenated to form a complete “typical” year for each location.	(16) (17)
Radiation Model Inputs	Perez 1990 Coeffs	Circumsolar (F1) and Horizon (F2) brightening coefficients reported in the Perez 1990 paper.	(18)

*Assumed for illustrative purposes. ** From PV system design plans. *** Current updates available from SNL upon request.

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