# Reliability and Geographic Trends of 50,000 Photovoltaic Systems in the USA

## Preprint

D. C. Jordan and S. R. Kurtz

*Presented at the European Photovoltaic Solar Energy Conference and Exhibition*
*Amsterdam, Netherlands*
*September 22–26, 2014*

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**Conference Paper**
NREL/CP-5J00-62801
September 2014

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**RELIABILITY AND GEOGRAPHIC TRENDS OF 50,000 PHOTOVOLTAIC SYSTEMS IN THE USA**

D.C. Jordan,* S.R. Kurtz
National Renewable Energy Laboratory (NREL), 16253 Denver West Parkway, Golden, CO 80401
*Tel: 1-303-384-6762; Fax: 1-303-384-6790; email: dirk.jordan@nrel.gov

ABSTRACT: This paper presents performance and reliability data from nearly 50,000 photovoltaic (PV) systems totaling 1.7 gigawatts installed capacity in the USA from 2009 to 2012 and their geographic trends. About 90% of the normal systems and about 85% of all systems, including systems with known issues, performed to within 10% or better of expected performance. Although considerable uncertainty may exist due to the nature of the data, systems in hotter climates appear to exhibit some decline that could be a combination of insolation variability, soiling and possible degradation. Special causes of underperformance and their impacts are delineated by reliability category. Hardware-related issues are dominated by inverter problems (totaling less than 0.5%) and underperforming modules (totaling less than 0.1%). Furthermore, many reliability categories show a significant decrease in occurrence from year 1 to subsequent years, emphasizing the need for higher-quality installations, but also the need for improved standards development. The probability of PV system damage because of hail is below 0.05%. Singular weather events, such as a single lightning strike to a transformer or a hurricane, can have a significant impact on production. However, grid outages are more likely to have a significant impact than extreme weather events that cause PV system damage.
Keywords: photovoltaic, PV system, system performance, reliability, durability

## 1 INTRODUCTION

Worldwide, trillions of dollars of capital are available for investing in photovoltaic (PV) systems, but technological and performance risks, among other barriers, remain limiting factors to investment in the PV asset class. In addition, PV module prices have declined dramatically since 2009, raising questions about the quality of modules and systems. Bankable PV—that is, PV that inspires investors' confidence—requires three components, as represented by the three-legged stool in Fig. 1. Consistent manufacturing, durable design, and system verification are required at the manufacturing and installation level for bankable PV. International standards enable consistent achievement and identification of quality components. When tracking performance in the field, the three elements of success are performance, reliability, and durability (where reliability is the discrete occurrence of disruptive events and durability is the gradual decline of performance). Therefore, documenting field performance, reliability, and durability enables investors and consumers to quantitatively assess risk of poor performance.

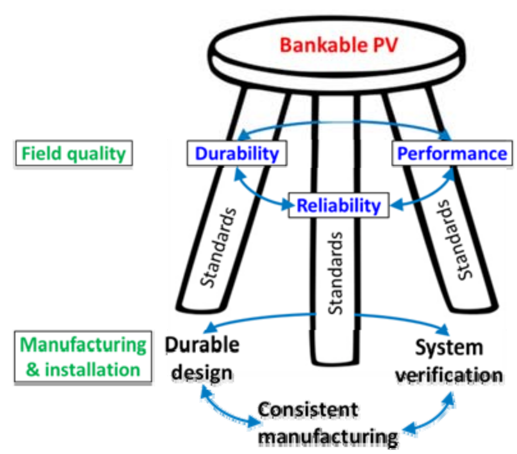


**Figure 1:** Three field-quality components (represented by the legs of the stool) for bankable photovoltaics.

Historically in the PV industry, as in many other industries, these field-quality components have been evaluated separately. Yet, it is their synergistic nature, as shown in Fig. 1, that determines risk.

To assess the current state of the industry as a whole, all three categories of PV field quality are needed for a large number of systems in multiple climates. However, such an assessment is difficult to execute due to its enormous complexity. A non-comprehensive synopsis of excellent field-quality studies is summarized in Table I. Recent years have seen an increased emphasis of more synergistic studies; however, these studies are typically limited by the number of systems or their geographical distribution.

**Table I:** Synopsis of field-quality studies.

| Performance | Reliability | Durability | Reference |
|---|---|---|---|
| x | | | [1]–[7] |
| | x | | [8]–[10] |
| | | x | [11] |
| | x | x | [12]–[16] |
| x | | x | [17], [18] |
| x | x | x | [19], [20] |

This study evaluates data from almost 50,000 systems installed in the USA between 2009 and 2012 and aims to statistically assess all three PV field-quality categories.

## 2 METHOD

The American Recovery and Reinvestment Tax Act (ARRTA) 1603 Program provided payments (in lieu of tax credits) as partial reimbursement for installation of renewable energy systems. The 1603 Program required that system operation or construction commence in 2009, 2010, or 2011. In general, residential systems were not eligible for the program unless the property was subject to depreciation. Applicants provided information describing each system before being approved for funding. Additionally, each recipient agreed to provide annual reports for each of the first five years of system operation.

**Table II:** Summary of data categories with examples.

| Data Category | Subcategory | Examples |
|---|---|---|
| Normal | N/A | Better-than-expected generation. Normal variance in solar irradiance. |
| Project | Delay | Delay in construction for up to two months. Initial start-up delay. |
| | Utility/Grid Interconnection | Erratic voltage on grid line shuts down inverter. |
| | Construction | PV system was turned off for building's renovation process. |
| | Design | The system design (tilt) changed after initial application. |
| | Financials | The house went into foreclosure and the system has been shut down. |
| Hardware | Inverter | The inverter had a problem and needed to be replaced. |
| | Repair | Maintenance interruptions. Difference due to unscheduled outages. |
| | Fuse, Wiring, Breaker | Multiple string fuses had to be replaced. |
| | Module Defective | Solar panel damage, system underperformed. |
| | Module Recall | System was shut down due to module recall. |
| Data Collection | Missing Data | We are missing production data from April and May. |
| | Data Acquisition | Monitoring equipment was not properly engaged until 2011. |
| | Poor Initial Estimate | We overestimated the system's base power output in optimal conditions. |
| Weather | Snow | Heavy snow fall in the winter reduced generation in the winter. |
| | Shading | Original production was based on the original shading analysis. |
| | Lightning | Transformer was struck by lightning; PV systems were shut down. |
| | Hurricane | Power outage due to Hurricane Sandy. |
| No information | N/A | For some unknown reason, the system is underperforming. |

This study analyzes a subset of the application data (the nameplate rating of the system, zip code, and estimated annual production) and the annual report data (annual AC electricity production and explanation if the actual production was lower than had been estimated). The analyzed data set included nearly 50,000 PV systems in the USA, as shown in Fig. 2, ranging in size from 0.5 kW to 25 MW. All systems combine to more than 1.7 gigawatts of installed capacity. The data summarized here arose from production in 2009 to 2012, resulting in more than 70,000 monitoring years.

The data set was created to document the value of the ARRTA investment. The data set consisted of annual AC energy production, zip code location, annual estimated production, the nameplate rating of the system, and annual comments relating to the performance of the system. One limitation was the lack of irradiance and system mounting-configuration data. Therefore, only relative performance with respect to expected performance and nameplate rating could be analyzed.

The challenge with such a large data set based on multiple party entries is to filter for physical implausibility. Thus, entries were eliminated that showed a predicted capacity factor outside the range of 3%–40%. In addition, annual production values that matched nameplate rating and consecutively matching annual production values were eliminated because those most likely originated from incorrect data entry. Lastly, in 0.5% of all cases, unit confusion—e.g., Wh or MWh entries instead of kWh entries—required adjustment.

As detailed previously, the data were classified into categories and subcategories according to their performance comments as reproduced in Table II for clarification [21].

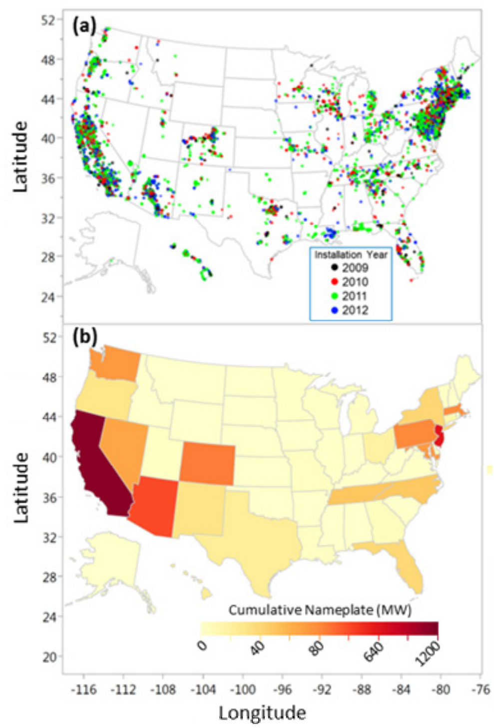


**Figure 2:** Geographical distribution of analyzed installations color-coded by year of installation (a), and cumulative nameplate capacity by state (b).

## 3 PERFORMANCE

Exceedance probabilities such as P50 and P90, where P stands for probability, are often used in quantitative risk assessment. The P50, the median, indicates that 50% of the data fall above this value and is equivalent to the mean for symmetric distributions. P50/P90 analyses for long-term weather data have been published recently [22]. Similarly, P50/P90 values can aid in the technical and financial performance risk assessment of a broad portfolio of PV systems.

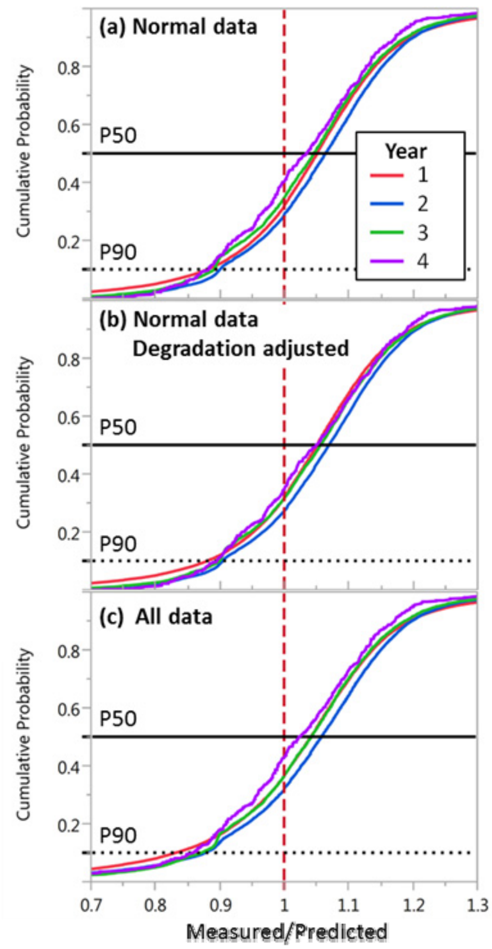


**Figure 3:** Cumulative distribution functions of measured production over predicted production for each operational year for: (a) normal systems, (b) normal systems taking into account 0.5%/year degradation, and (c) all data. Also shown are P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line).

Figure 3 shows the cumulative distribution functions (CDF) for the ratio of the measured to the predicted annual performance for (a) normal systems, (b) normal systems taking into account 0.5%/year degradation, and (c) all data, colored by year. The P50 and P90 values are shown by horizontal solid and dotted lines, respectively. In addition, as a guide to the eye, a unity ratio of measured and predicted production values is given by a vertical dashed line. The absence of any discontinuities or plateaus indicates that fairly smooth tails extend on both sides of the P50 value.

It is of considerable interest that the P50 value consistently exceeds the unity ratio, indicating that normal systems overproduce expectations by several percent. Assuming a degradation rate of 0.5%/year, which has been shown to be the most often reported rate in the literature [11], the yearly CDF curves collapse more around the 0.90 value at the P90 point. (Note, however, that the 0.5%/year degradation rate is dominated by module data and not system data.)

Analysis such as shown in Fig. 3 and described here implies that the data are consistent with historical annual degradation rates of about 0.5%–1% median and not significantly higher. The CDFs of Fig. 3 are useful for visualizing the overall distribution; however, the P50s and P90s are difficult to quantify from these graphs. Figure 4 shows the P50s and P90s for the normal data, normal data adjusted for degradation of 0.5%/year and 1%/year, and all data. For the P50s, 0.5%/year degradation appears to reduce the year-to-year variability to better than 1%/year degradation. For the P90s, the 1%/year degradation appears to give a better fit, with the exception of year 1. The P90 values for the normal categories are spread around 0.90. Thus, about 90% of all normal systems equal or exceed 90% of the predicted production. Finally, the P90 values for all systems, including systems with known issues, are somewhat lower but are still centered on 0.85.

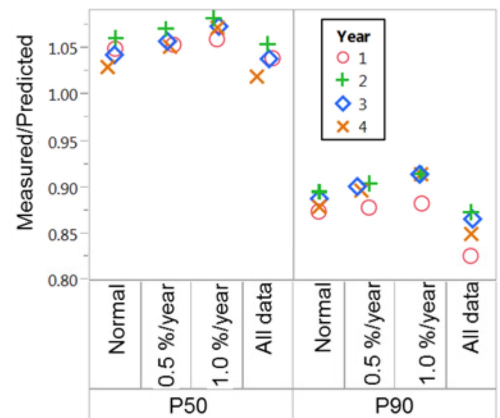


**Figure 4:** P50 and P90 values of the measured production over predicted production values for normal data, differently degradation-adjusted data, and all data.

## 4 CLIMATE

Regional or climatic performance difference is of interest, in addition to the performance of the entire PV portfolio. The performance of the 1603 Program systems is further analyzed according to the approximate outlines of the climate zones in the USA, as shown in Fig. 5.

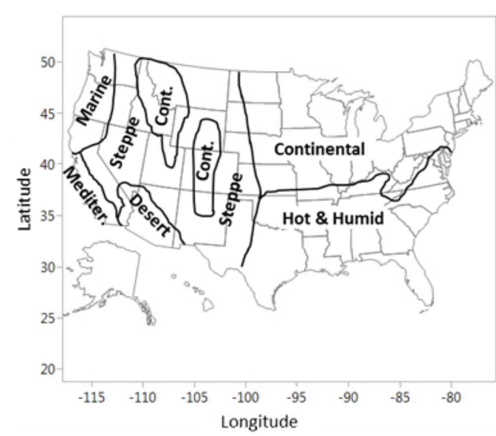


**Figure 5:** General geographic distribution of climate zones in the USA.

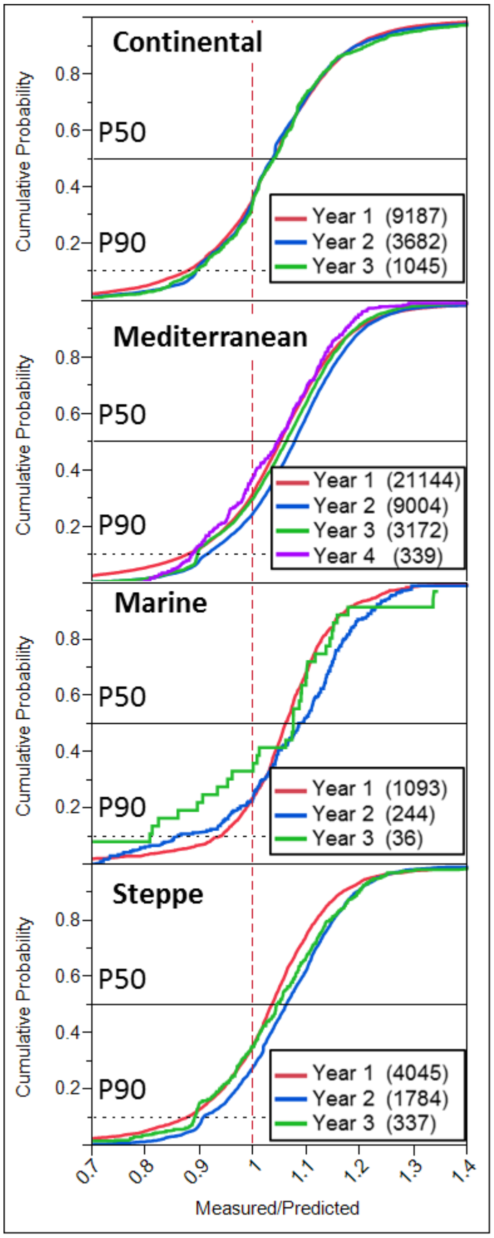


**Figure 6:** Cumulative distribution functions of measured production over predicted production for Continental, Mediterranean, Marine West Coast, and Steppe climates. Also shown are P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line).

Figure 6 shows cumulative distribution functions of the measured production over predicted production for five different climates. As in Fig. 3, P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line) are shown as guides to the eye. In addition, the number of data points per category is also given. In some climate zones, the fourth operational year is missing due to the low number of data points. The P50 for operational years 2 to 4 shows a value at or above the values for the first operational year, indicating that degradation, if present, may be very small. The P90 of the Marine West Coast climate shows a low tail, but this may be due to the low number of data points.

In contrast to these more moderate climates are the two hot climates shown in Fig. 7. The Desert climate of the North American Southwest and the Hot & Humid climate of the Southeast show a ratio that seems to decline with each operational year at the P50. The low value of the third operational year in the Hot & Humid climate may be affected by the relatively low number of data points. For the Desert climate, the P90 is consistent with the values of the moderate climates for the first year of operation, but then decreases with each subsequent year. In the Hot & Humid climates, the P90 is below 90% for all operational years. Considerable uncertainty could be present because of the nature of the data set and the relatively small geographic region of the desert Southwest; however, this downward trend could be a combination of interannual insolation variability, soiling or possible degradation. Figure 8 shows a subset of the desert systems that began production within 3 months in 2010 partitioned by different system size. The smaller systems show a broadening of the distribution in year 2 and a decline in year 3. The larger systems do not show the same trend for the approximate same calendar period indicating that perhaps regular cleaning of the larger systems could be responsible. If the decline for the smaller system was due to degradation, the rate would be ca. 1 %/year, consistent with recent findings. [23-26] A similar analysis for the hot and humid climate was not possible due to the low number of data points.

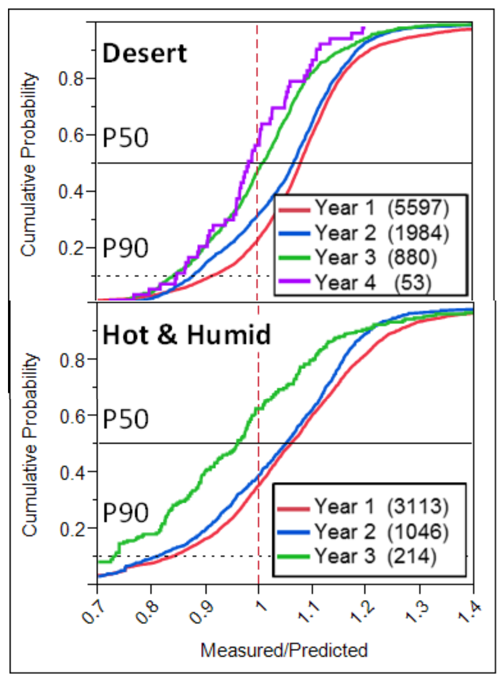


**Figure 7:** Cumulative distribution functions of measured production over predicted production for Desert and Hot & Humid climates. Also shown are P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line).

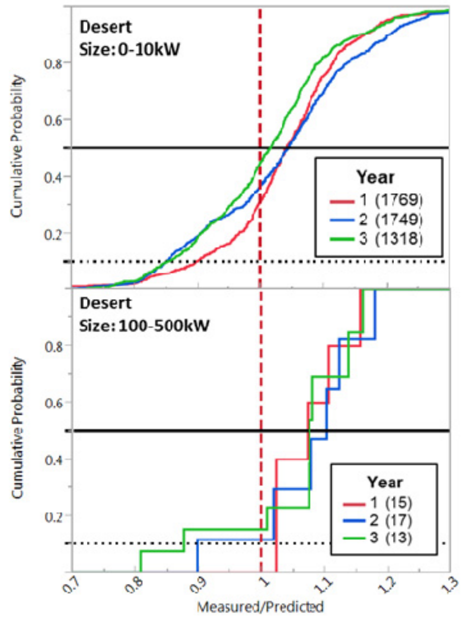


**Figure 8:** Cumulative distribution functions of measured production over predicted production for systems in the desert and system size. All systems began production within 3months in 2010. Also shown are P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line.

5 UNDERPERFORMANCE

The data for the vast majority of systems fall in the normal category—with only 2%–4% of all systems, depending on the operational year, underperforming with a known cause. In this section, we discuss the causes for the underperformance and their geographic distribution. Figure 9 shows project-related issues as a function of year with absolute count (top) and percentage (bottom). Hardware-related issues are primarily dominated by inverter problems and unspecified repair outages. Surprisingly, general electrical problems, such as those with fuses, breakers, and wiring, are important categories. "Defective or underperforming modules" is the next category and is split out from module recalls. "Unauthorized shutdowns" is a small but noticeable category and emphasizes the necessity of locks on interconnections.

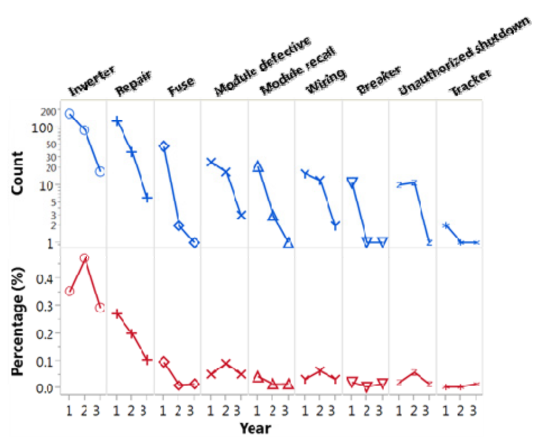


**Figure 9:** Categorized hardware-related issues as a function of operational year as the (top) number of occurrences and (bottom) percentage of total.

Because the hardware category is dominated by inverters and unspecified repairs, the number of occurrences is large enough to further partition the events by geographical location. Figures 10 and 11 show the CDFs for inverters and repairs, respectively, color-coded by climate. In addition, the number of data points available is given in parentheses.

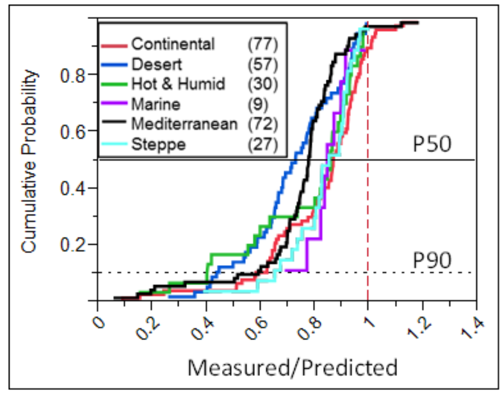


**Figure 10:** Cumulative distribution functions of measured production over predicted production for systems reporting inverter issues, colored by different climate zones. Also shown are P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line.

For systems reporting inverter issues, the P50 of the CDFs for all but two climates are virtually identical; only the Desert and the Mediterranean climates show significantly reduced values. The Hot & Humid climate shows a P50 that is similar to the moderate climates; however, it also displays a significantly lower tail, resulting in a much lower P90. Systems reporting unspecified repairs show similar P50s, but significantly lower P90s for the hotter climates. This may indicate that inverter and unspecified repairs have a more significant impact in the hotter climates, compared to the more moderate climates.

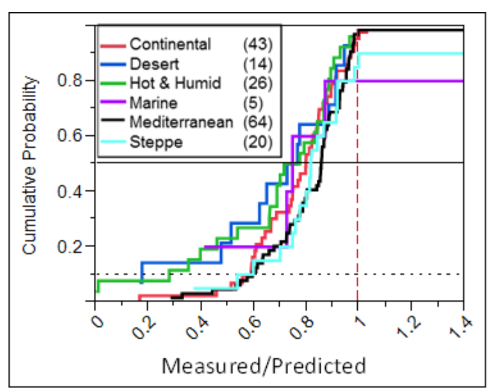


**Figure 11:** Cumulative distribution functions of measured production over predicted production for systems reporting unspecified repairs, colored by different climate zones. Also shown are P90 (dotted line), P50 (solid line), and unity ratio (vertical dashed line).

In the weather category, the lightning and hurricane subcategories show a surprisingly large impact. Similar to Fig. 9, Fig. 12 shows the count and percentage for each weather-related subcategory as a function of calendar year. Because singular weather events may occur during different operational years of the individual systems, the weather events are graphed as a function of calendar year. The lightning subcategory shows a low percentage of occurrence in 2010 and 2012, yet displays a significant increase in 2011. The cause was a single lightning strike to a transformer that led to the precautionary shutdown of all PV systems in the vicinity during the repair. Therefore, the impact of a lightning strike incident may be more widespread and significant than one would initially assume. Finally, the significant increase in the hurricane subcategory in 2012 was the well-publicized event of Superstorm Sandy.

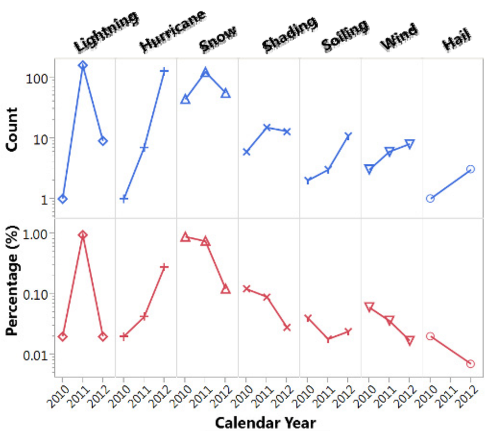


**Figure 12:** Categorized weather-related issues as a function of calendar year as the (top) number of occurrences and (bottom) percentage of total.

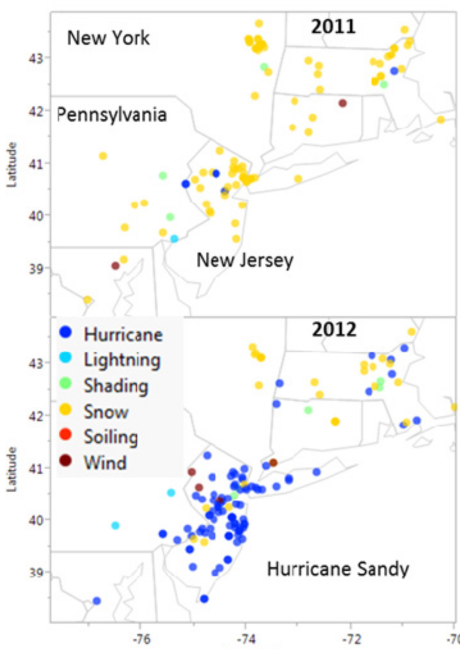


**Figure 13:** Weather impact on the Northeast USA during 2011 and 2012.

Figure 13 shows the impact of weather-related events in 2011 and 2012 for the Northeast USA. In 2011, the majority of the underperformance in the region was caused by snow losses, an important consideration for future production estimation. In 2012, the most influential event of the region was the impact of Hurricane (Superstorm) Sandy. When considering the impact of a hurricane on PV production, damage to the system is not necessarily the inevitable conclusion, as shown in Fig. 14.

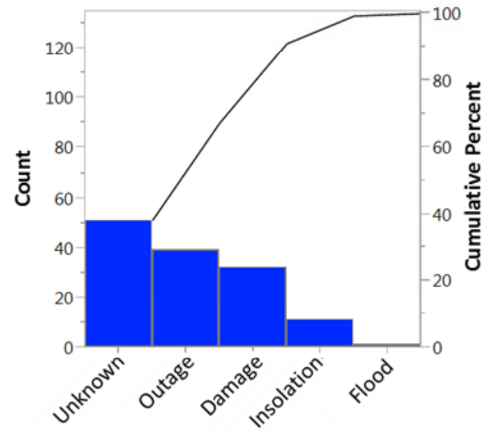


**Figure 14:** Pareto chart of hurricane impact on PV production.

In the majority of the cases, the exact impact on the PV system is unclear, typified by entries that the system was "affected by the hurricane." Although the entries may not be completely accurate, it is likely that if the PV system had been damaged, then the comments would note this explicitly. In 30% of all cases, grid outages resulting from the hurricane led to yearly underproduction of the PV system. Damage to the system consisting of unspecified damage, inverter, data acquisition, microinverter and panel damage was specified in only 24% of all cases. In less than 10% of all cases, prolonged overcast skies led to reduced insolation and therefore to slight underproduction. Lastly, flooding associated with the storm surge had an impact on yearly PV underproduction.

## 6 CONCLUSION

We have shown the annual performance analysis of nearly 50,000 PV systems in the USA totaling 1.7 gigawatts installed capacity. About 90% of the normal systems performed within 10% or better of expected relative performance. Considerable uncertainty exists due to the nature of the data, Systems in hotter climates appear to exhibit some decline that could be a combination of interannual irradiance variation, soiling and possible degradation. Special causes of underperformance and their impacts were analyzed and presented. Hardware-related issues were dominated by inverter problems (totaling less than 0.5%) and unspecified repairs. Both causes exhibit a low performance tail in hotter climates, possibly indicating a climate-specific impact. In contrast, underperforming modules composed less than 0.1% of all data. Furthermore, many reliability categories show a significant decrease in occurrence from year 1 to subsequent years, emphasizing the need for higher-quality installations but also the need for improved standards development. The probability of PV system damage because of hail is below 0.05%. Singular weather events, such as a single lightning strike to a transformer or a hurricane, can have a significant impact. However, the loss in production is more likely to be associated with subsequent grid outages than with PV system damage.

## 7 ACKNOWLEDGMENTS

The authors would like to thank Edward Settle, Jason Coughlin, Doug Gagne, and Dave Peterson. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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