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# PV field reliability status—Analysis of 100 000 solar systems

Dirk C. Jordan[1] | Bill Marion[1] | Chris Deline[1] | Teresa Barnes[1] | Mark Bolinger[2]

[1]National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO, 80401

[2]Energy Analysis & Environmental Impacts Division, Lawrence Berkeley National Laboratory, MS90-4000, One Cyclotron Road, Berkeley, CA, 94720

**Correspondence**
Dirk C. Jordan, National Center for Photovoltaics, National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401.
Email: dirk.jordan@nrel.gov

## Abstract

In this study, we analyzed annual production data from 100 000 photovoltaic systems as well as comments relating to their performance and maintenance. Our analysis revealed that 80% to 90% of all systems performed within 10% of the predicted production or better. Also, 56% of the systems were still performing above P50 or the median at 5 years. However, a small but significant tail of about 7000 systems perform below P90 expectations. In general, residential systems have a lower rate of failure than utility or commercial systems. Despite higher rates of component failures, utility systems lose less power than residential or commercial systems. This outcome is likely due to closer monitoring and better operations and maintenance practices. Inverters are still the components that reportedly fail most often (4%-6%), but other failures such as unspecified repair and meters cause more production loss. Reported module failures are relatively rare (0.2%) and are within the range of historical values. Installation quality affects performance and safety as indicated by data showing connector, wiring, breaker, and fuse failures due to undersizing, electrical design, and improper connection. Lastly, early detection of degradation and proactive response resulted in less impact on production than reactive, unplanned repairs.

KEYWORDS

field failure, field performance, photovoltaic, reliability

## 1 | INTRODUCTION

Photovoltaics (PV) has continued its extraordinary growth worldwide to reach a total installation capacity of about 500 gigawatts (GW) direct current (DC) at the end of 2018.[1,2] As a consequence, more than half of all PV systems today are less than 3 years old. Reliability plays a central role in PV being cost competitive with traditional energy sources; therefore, it is important to rapidly assess whether any quality deficits exist in the equipment or installation practices, in order to enable timely continuous improvement.[3] In addition, other macrotrends in the PV industry lead to questions about reliability: (a) Cell and module technology continues to evolve to higher efficiencies. As cell technology has evolved from aluminum back-surface field (Al-BSF) to passivated emitter and rear cell (PERC) technologies and beyond, so have module technologies, eg, with the advent of bifacial technologies. (b) At the system level, systems are moving towards higher operating voltages (from 1000 to 1500 V), increasing use of trackers and employing higher inverter loading ratios. (c) Finally, emerging applications such as installations in new environments—eg, higher mounting to increase bifacial gains or floating PV—could have implications on the long-term viability of these systems. Consequently, an increasing number of reliability-concerned studies have been conducted in recent years.[4-8] However, reliability studies on a large scale are difficult to conduct and to report. The dataset analyzed in this paper is a notable exception because of the large numbers of systems that are included, as some of the authors have reported previously.[9]



  

In response to the 2008 financial crisis, the US Congress enacted the *American Recovery and Reinvestment Act of 2009* (ARRA). Section 1603 of ARRA gave qualified renewable energy projects the option to elect a cash payment in lieu of the federal investment tax credit (ITC). Similar to the ITC, these "Section 1603 payments" reward investment rather than production, which raises concerns about the long-term performance of PV systems funded under the program. However, our earlier analysis of systems funded under the first few years of the program found that most systems performed within expectations.[10,11] The Section 1603 payment program has now concluded with awarding applications, and the dataset was updated with additional systems and years of operation. In this study, we present an updated analysis that enables a more thorough investigation into the state of PV systems' reliability, characterized by the following differences to our initial analysis: (a) The number of systems in this study doubled to about 100 000 from our previous investigation, which is roughly 7% of all installed PV systems in the United States at the time of writing[12]; (b) the cumulative installed capacity more than quadrupled—to more than 7-GW DC—due in part to a large number of utility-scale systems; (c) in our previous analysis, we had up to 4 years of performance data, with a sharp decline of systems reporting after year 3. This time, we have performance data up to 5 years and a larger number of systems reporting up to year 5, with longer system lifetimes yielding richer datasets for reliability issues; and (d) in our previous investigation, we could show that the predicted performance values were credible, but we had no information about how they were generated. For the present analysis, in addition to the annual performance data from the Section 1603 dataset, we have monthly production data and other system specifications (eg, mounting configuration and inverter loading ratio) for a subset of systems greater than 5 megawatts (MW) allowing for cross-comparison of generation with our own predicted values. Figure 1 shows the nonuniform distribution of the PV systems locations in the United States in the 1603 program, color-coded by the year of installation commensurate with the general PV market distribution.

The paper is organized into two parts: The first section examines the overall fleet performance, while the second part investigates performance-related comments, with five detailed subsections discussing hardware issues, installation quality, project-related issues, grid and data collection, and finally, weather-related problems.

## 2 | FLEET PERFORMANCE

In addition to the annual production data sourced from the Section 1603 program, monthly production data for systems greater than 5 MW were sourced from the Lawrence Berkeley National Laboratory (LBNL) *Utility-Scale Solar* report series[13]; this allowed us to generate and validate predicted values. More detailed system specifications were available such as mounting configuration, module types, and DC and AC power rating, which is information often missing for larger systems. This information allowed us to chart the DC/AC ratio over time, which is also known as the loading or inverter loading ratio. This ratio is important because at high ratios, the inverter limits system output during the most productive times of the day and year; this phenomenon is also colloquially known as inverter clipping. As shown in Figure 2 and confirmed elsewhere,[13] the ratio has increased substantially from 2009 to 2016—to an average of about 1.3 in 2016 for utility-scale systems. At the same time, system size has also increased, as shown with the color coding. Furthermore, more large systems are now using tracking although some fixed-tilt systems are still constructed today.

From the raw Section 1603 dataset, all solar thermal systems were removed, as were all PV systems below 1 kW because they typically consist of single modules powering traffic signs; this procedure still left a total of more than 94 000 PV systems in the dataset. As a requirement for the payment, applicants were required to file an annual performance report for a period of 5 years that included the annually generated production and comments regarding the

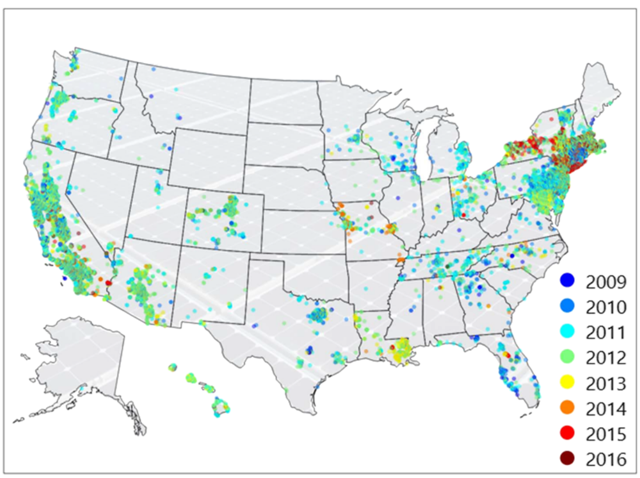


**FIGURE 1** Location of the 1603 data throughout the United States color-coded by the installation year [Colour figure can be viewed at wileyonlinelibrary.com]

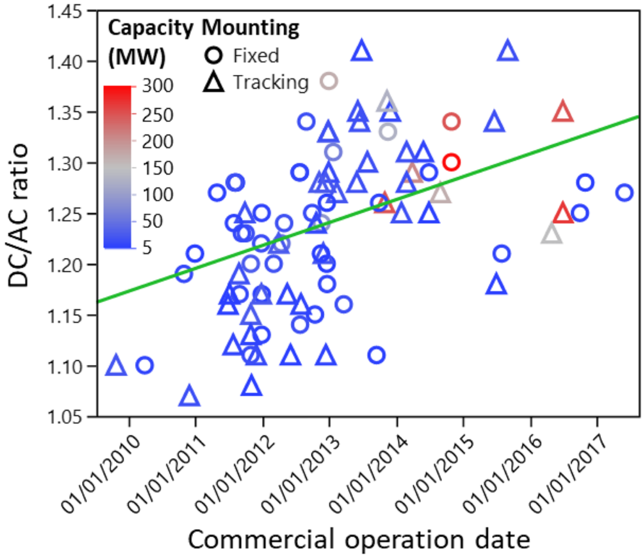


**FIGURE 2** DC/AC power ratio of utility-scale system during the 8-year installation period. Data points are color-coded by the size of the system and symbol-coded by the type of mounting [Colour figure can be viewed at wileyonlinelibrary.com]

performance and operations and maintenance (O&M). Four comment fields were available for use: "Explanation for difference between annual and estimated production," "Explanation for decreased production," "Explanation for replaced or ceased to produce," and "Explanation for interruptions." The ratio of measured over predicted production could be calculated for all systems to assess system performance health. The dataset is approximately divided into residential (1-25 kW), commercial (25 kW-1 MW), and utility-scale systems (>1 MW). The division between groups is somewhat arbitrary but reflects the general trend between different types of systems, although individual systems at the respective limits may have been incorrectly classified. For systems greater than 5 MW, the details of the mounting and location allowed us to generate our own predicted performance estimate using PVWatts.[14] Figure 3 displays the measured/predicted production ratio for the same systems using PVWatts-generated estimates for the predicted values and two different measured production values—the 1603 (horizontal axis) and LBNL data (vertical axis), respectively. These systems were not knowingly impacted by curtailment, maintenance, failures, capacity expansion after initial commercial operation date (COD), etc. Each year is represented by a different color-coded vertical slice with 95% confidence intervals indicated by ellipses.

In general, most points fall within the fairly tight interval of 0.1 along the unity line, indicating that the PVWatts-generated predicted values are reasonably good. In generating our own predicted values, we adopted default PVWatts values for shade, soiling, and balance-of-system (BOS) losses. In addition, the exact module type was not always known, leading us to accept one of the default PVWatts

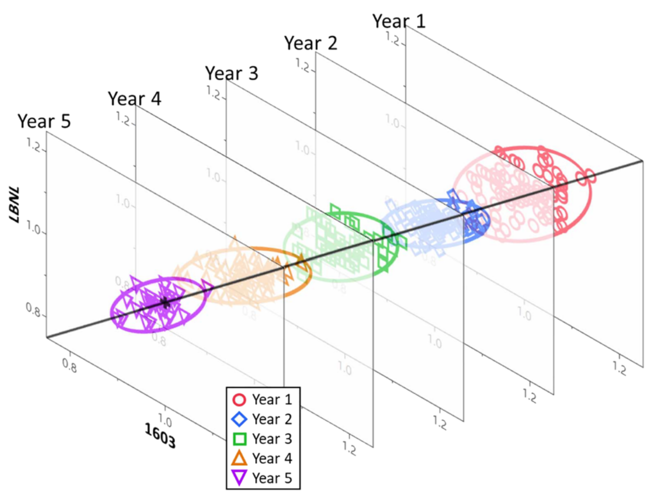


**FIGURE 3** Measured/predicted production ratio for the same systems greater than 5 MW as a function of year. PVWatts was used as the predicted production in the denominator. The measured production was taken from the 1603 dataset (horizontal axis) and Lawrence Berkeley National Laboratory (LBNL) dataset (vertical axis). The black solid line is a unity line indicating equal ratio for each year. The ellipses indicate 95% confidence intervals. The unity point is also indicated by a black cross [Colour figure can be viewed at wileyonlinelibrary.com]

categories of standard, premium crystalline silicon, and thin-film. PVWatts-generated production estimates are based on typical meteorological year (TMY) data that could also contribute to the variation.[15] Another possible factor that might be contributing to the variation is that, for large systems, it is not always clear whether the rating is based on DC or AC power; however, we have fairly high confidence in the capacity rating through the LBNL data. Year 1 exhibits a slightly higher variation because, in addition to the above reasons, larger systems also typically come online gradually, one large block at a time. That the COD for some systems was different between the two different datasets may indicate this situation. Furthermore, unreported start-up issues in O&M can also increase variability in the first production year. Subsequent years show approximately the same behavior, although slight broadening may be caused by unreported maintenance or repairs.

To study the performance of the entire fleet, not just the systems greater than 5 MW, a cumulative distribution function (CDF) of the measured/predicted production ratio is shown in Figure 4 and is partitioned by the size of the system. Unless otherwise specified, we will use predicted production value from the 1603 program. Figure 4A displays the CDFs for all "normal" systems that were not knowingly impacted by performance-impeding issues, and Figure 4B shows all those systems that were impacted by specific performance issues that we will discuss in more detail in the following section. This self-reporting system relied on user input at the annual installation anniversary, which may have varied, so the 5-year mean of the measured/predicted ratio is shown, with more detailed year-by-year information presented in Table A1. The median or P50 value and P90 value are indicated by dashed horizontal lines. The unity value, ie, a system performing as expected, is indicated by a vertical dashed line. At the median, the CDFs of the "normally" operating systems show slightly higher production than expected. In addition, the utility-scale category exhibits a tighter distribution, most likely aided by closer supervision in the planning and operation phase and/or more accurate predicted values. The general asymmetry of the CDFs indicates the limited upside of the production ratio but the much greater risk for energy loss. A minority of systems greatly underperform and overperform, clearly indicating a problem with the system, production estimate, or reporting. However, because no comments regarding the performance were entered, these systems had to be treated as "normally performing" systems and are included. An additional source of uncertainty might be the difference in accuracy of revenue grade meters typically used in utility-scale system compared with standard meters more commonly used in residential applications.

Figure 4B shows similar CDFs of systems that were impacted by specific issues in any of the 5-year reporting period. Similar to the "normally" operating systems, some systems greatly underperform and overperform because of the different impact of certain issues on performance. However, some general observations can be made: Utility systems show a reduced performance at the median compared with "normal" systems, but they perform substantially higher than residential systems. This is a difference that we will explore in more detail below. Commercial systems fall between the utility systems (similar performance at the median) and the residential systems (similar performance at the P90).

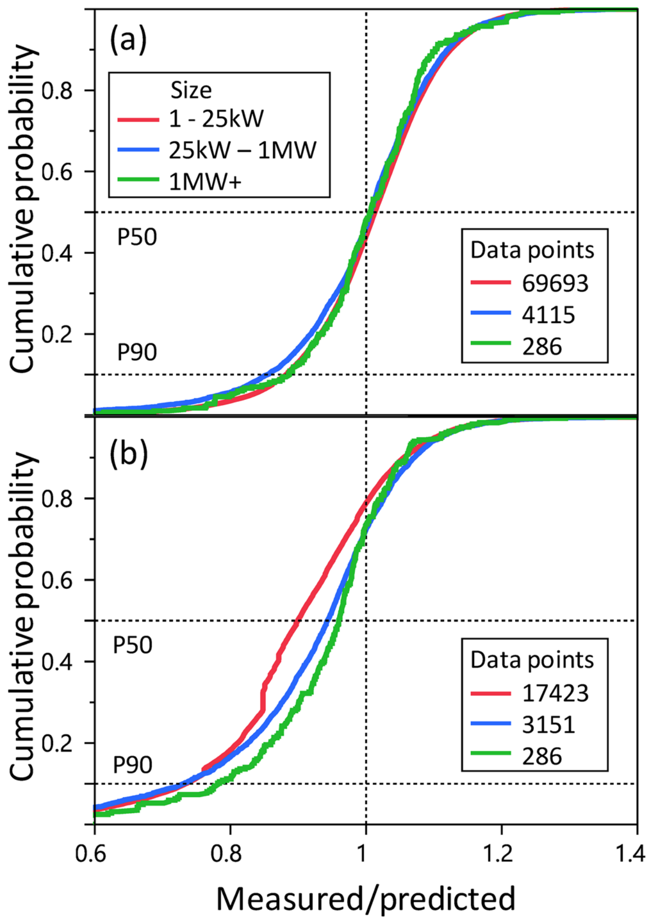


**FIGURE 4** Cumulative distribution function of the 5-year mean of the measured/predicted production ratio for normal systems not impacted by specific performance issues (A) and systems impacted by specific issues (B) discussed in the following sections. Different system sizes are indicated by different color; the median (P50), the P90, and the unity ratio are indicated by dashed horizontal and vertical lines, respectively. The number of data points contained in each CDF is also given [Colour figure can be viewed at wileyonlinelibrary.com]

## 3 | PERFORMANCE COMMENTS QUANTIFICATION

In this section, we examine the causes of certain underperforming issues of the systems shown in Figure 4B. The comments regarding the annual performance of the systems provide valuable insight into the state of PV system reliability on a fairly large scale. To prepare the performance remarks for quantitative analysis, the text was mined for keywords and classified into broad categories of hardware, project, grid, data collection, and weather-related issues. Because of different context usage and misspellings, the text mining was subsequently accompanied by sorting, reading, and division into subcategories;

examples are provided in Table A2. If multiple performance-impacting entries were recorded in a single year, each issue was counted in its respective subcategory. The great majority of performance comments—89%—were single-entry issues; double entries accounted for 10.7% and triple entries for just 0.3% of all comments. The number of occurrences is then obtained by simply integrating the number of issues for each subcategory and dividing by the total number of systems reporting for each year. This annualization might not be as accurate as desired because it is not known if all systems were operating for the full 12 months. Therefore, we also calculated 5-year mean values for each subcategory, which may improve accuracy. The lost production for each subcategory is obtained by examining the subsequent, or preceding, years of the affected year and determining the normality of operation by the performance comments. The performance of such normally producing years is then averaged for each affected system, allowing a rudimentary estimation of the performance-impacting issue. Because of the uncertainty in reporting and confounding effects of multiple entries, these numbers should be regarded as estimates. The occurrence, number of data points, 5-year mean values for lost production, and their respective standard deviations for all subcategories are provided in Tables A3–A6.

## 4 | HARDWARE ISSUES

This section will investigate in more detail hardware-related problems such as modules, inverters, and other BOS components. Occurrences of specific hardware issues are shown as percentage (top row) and estimated lost production (bottom row) in Figure 5. As has been reported before, inverters are the most common hardware problem for PV systems.[16] The occurrences for residential systems are slightly lower than commercial- and utility-scale systems, possibly indicating more reliable inverters (microinverter or string inverters) or underreporting. In addition, residential systems have fewer components; therefore, an individual system is less likely to report a hardware problem. However, it can be seen from the graph—and Table A3 documents it more clearly—that the lost production for utility systems is substantially lower than commercial and residential systems. This trend is observable not only for inverters but for many hardware issues, most likely because of the closer monitoring and supervision of larger systems.

Meters are a somewhat surprisingly high-occurrence hardware issue, with the problems ranging from communication problems to accurately recorded data, to complete failures. Three-quarters of these instances were meter replacements with the remaining cases related to data collection issues. Unfortunately, the differentiation between these obviously very different mechanisms is not always clearly documented in the comments and has to be viewed as an estimate. Residential systems lose much more production than commercial and utility systems in this subcategory. Not only are residential systems often less monitored, but they may be leased by the property owner; thus, even if the failure is detected promptly, the PV system and property owner must arrange repair schedules, which can quickly exacerbate the production loss.

Particularly interesting is the "unspecified repair" subcategory, which needs to be considered alongside maintenance, because it may provide a glimpse into the state of the PV industry as a whole. "Unspecified repairs" are failure events that occurred, but from the comments, it could not be deduced what item failed and what was fixed. It is interesting to note that preventive maintenance events (a proactive approach) typically have lower occurrence than repairs (a reactive approach), perhaps with the exception of the utility systems, where it appears about equal. Furthermore, these preventive maintenance events appear to have a much lower impact on lost production than when hardware items need to be replaced or fixed. These hardly surprising facts should encourage the industry to pursue

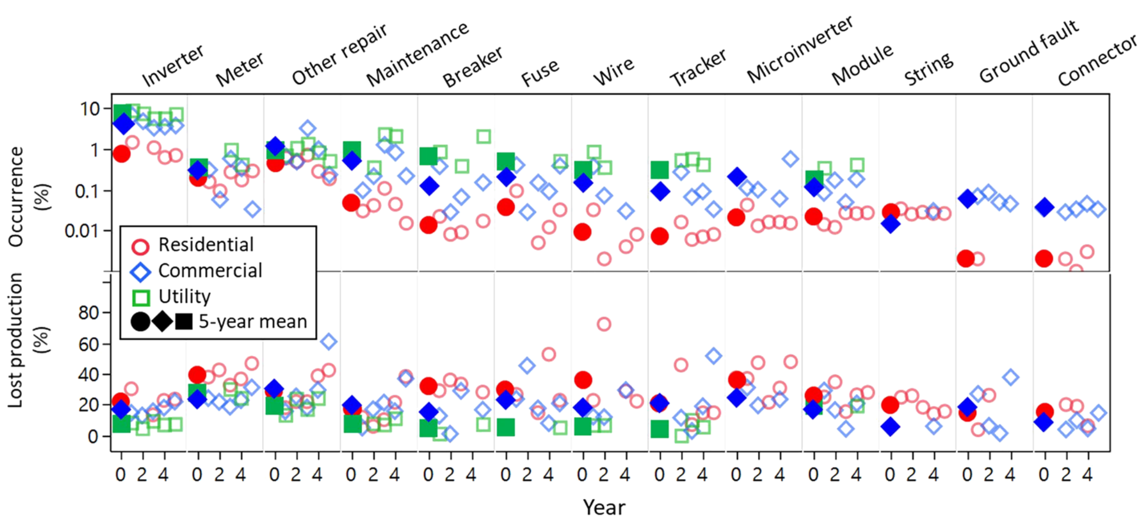


**FIGURE 5** Hardware issue occurrences (top) and lost production (bottom) as a function of years in the field. The different size of the systems is indicated by different-colored symbols. The filled symbols situated at the nominal year 0 are the 5-year mean values for each subcategory [Colour figure can be viewed at wileyonlinelibrary.com]

a more proactive rather than reactive approach to O&M, because the effect can be felt immediately on the rate of return.

The next three subcategories are breakers, fuses, and wires, which may be somewhat unexpected and may indicate installation improvement possibilities, especially when they occur in the first few years of a fielded system. It is also conceivable that pressure to reduce installation costs leads to procurement and acceptance of non-conforming items, because breakers have been found to be one of the most commonly counterfeited electrical products in the United States.[17] Fuse failures and wire issues highlight the problem of correctly sizing these BOS components, because most wire problems were caused by undersized wires, which may not only be a performance but also a safety concern. Cloud enhancement on partly cloudy days can lead to brief intense spikes in irradiance and produced power that can quickly exceed the rating of fuses if an unsatisfactory safety margin has not been allowed.[18] Similar to inverters and meters, these BOS problems appear to occur less at the residential level, probably because of underreporting of residential systems in the dataset; yet, the lost production is considerably higher than larger systems.

The next two subcategories in Figure 5 are tracker and micro-inverter or DC optimizer issues; the latter two are grouped together. However, both subcategories share in common that the occurrence numbers extracted from this dataset are most likely underestimated. The reason is that mounting configuration was only available for the few hundred systems greater than 5 MW but not for systems below 5 MW. Therefore, to calculate the occurrence, we had to use the total number of available systems. It is likely that not every commercial and utility system below 5 MW employs trackers, just as not every residential system employs microinverters; thus, we can conclude that we most likely underestimated the numbers for these two subcategories. Tracked system in the residential category is most likely an artifact of the division line between the residential and commercial category because residential systems are typically deployed in fixed-tilt configuration.

Next are module issues that appear to be relatively low and in the historical range of 0.02% to 0.2%.[19] String problems seem superficially related to modules, but they may indicate that one or two strings were connected backwards—a problem that occurs most often at the residential level, not very often at the commercial level, and not at all at the utility level.

The final two subcategories are ground faults and connector issues. Connectors are specifically related to module connectors that slipped or were incorrectly crimped. Both of these subcategories do not occur very often but could have serious safety implications; thus, they deserve our full attention. Integrating all hardware issues for all systems, about 9% of all systems were affected by some hardware issue during the 5-year reporting period, although this does not necessarily entail underperformance. Some of those systems could have had more than one hardware issue during these 5 years.

Additional insights into hardware issues may be gained by examining the time it takes to resolve specific issues. Unfortunately, the date of detection or initial loss and date of resolution are not always recorded. Therefore, this markedly reduces the number of available data points for each subcategory, as seen in Figure 6A. Only the inverter and breaker subcategory allowed an estimation of resolution time for all three PV system–size categories. Boxplots with the median indicated by a crossbar are also shown for each subcategory. Similarly to lost production, utility systems show the quickest resolution at a median of 6 days for inverter problems, followed by commercial and residential systems at the median 20 and 37 days, respectively. A comparable trend, but with slightly shorter resolution times, can be seen for breaker problems. Meter issues took considerably longer to resolve for residential systems than for commercial systems although a large variability exists because of the relatively low number available. Fuses show a similar trend and similar resolution times as inverters. It is interesting to note that other hardware issues such as ground faults, tracker, and wires can take considerably longer to resolve, probably because of a combination of difficulties in detection and repair.

Long-term unrecoverable performance decline or performance loss rates have great impact on the economics of PV projects.[20] It may be possible to extract performance loss rates from the accumulated production ratios by inspecting Table A1. The P50 and P90 for each size category appear to decline from year 1 to year 5. With only 5 years of data and limited weather correction, the resulting loss rates would have high uncertainties. Some of the apparent performance

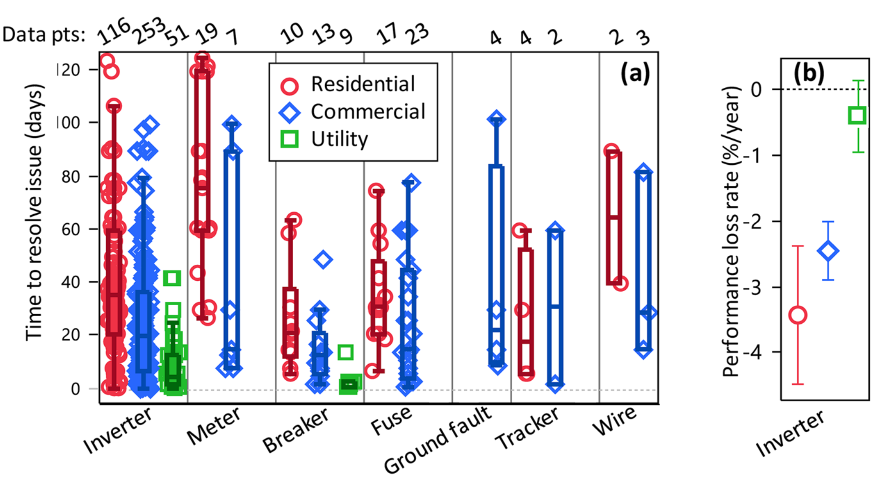


**FIGURE 6** Days to resolve specific hardware issues partitioned by size of the installation category (A). Resulting apparent performance loss rate for recoverable inverter related issues (B). Other hardware subcategories do not have enough data points to partition them by year and extract performance loss rates [Colour figure can be viewed at wileyonlinelibrary.com]

loss may actually be recoverable if it is caused by an increase in maintenance or repair events or delayed repairs. The inverter subcategory contained a sufficient number of data points to further partition the data by fielded year. Apparent performance loss rates could be extracted from the P50 values of each year with a standard least-squares regression approach and for each system size category, as shown in Figure 6B. Because interruptions caused by inverters were on the order of a few days for utility systems, no apparent "degradation" was visible for this category. However, commercial and residential system interruptions caused by inverters were in the order of several weeks to more than a month. These apparent "performance loss rates" due to the inverter outages outside the uncertainty are clearly visible and may be recoverable due to downtime. This clearly emphasizes that O&M records must be considered in evaluating performance loss because O&M events may incorrectly skew performance loss rates due to recoverable production losses.[21]

## 5 | INSTALLATIONS AND QUALITY ASSURANCE

Some of the hardware issues, such as strings installed backwards, breakers, wires, and fuses, which occur relatively frequently in the first year, raise concerns about installation quality. If installed properly, no system should require replacements of these hardware items in the first year. Figure 7 graphs the number of installers against the number of systems installed per installer in the 1603 dataset by open circles. The data points are color-coded by the median installation size per installer. Large-corporate installers who install hundreds to thousands of (primarily residential) systems can be found on the right of the horizontal axis. The left side of the graph shows a substantial number of installers who installed only one or two systems, which parallels the findings of a US residential market trend study.[22] Hardware issues were similarly integrated per installer and are shown as black open diamonds on the right-hand axis of the same graph. The annualization assumes that the systems were all fielded for 12 months per year, which may not be accurate for every system. Furthermore, one hardware issue per year results in an occurrence of 100%. Because installations can have multiple hardware issues per year, occurrences of more than 100% are possible. Despite the imperfect accounting and annualization, a clear trend emerges that generally indicates fewer hardware issues for installers who install many systems as opposed to those installing only a few.

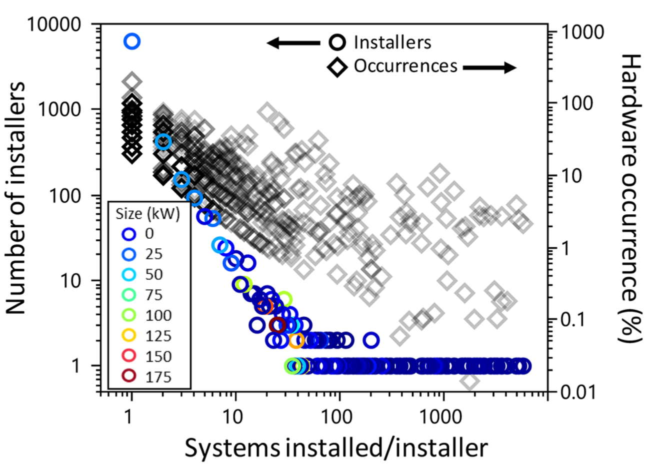


**FIGURE 7** Number of installers versus systems installed per installer color-coded by the median size of the installation (left axis). Occurrence of hardware issues for each installer as percentage (right axis) [Colour figure can be viewed at wileyonlinelibrary.com]

Installation risk may not be entirely eliminated, but it may be mitigated with proper training and inspections. For example, the North America Board of Certified Energy Practitioners (NABCEP) is an organization that offers certification and training for individuals and organizations in the renewable energy field and has recently offered their certifications internationally.[23] Additionally, the IEC system for certification to standards relating to equipment for use in renewable energy applications (IECRE) was founded to facilitate trade in equipment and service in the renewable energy sector at an international level.[24] The IECRE offers comprehensive quality assurance for components and installations through standards and certifications that can help reduce risk.[25] No information in the dataset is provided on the accreditation of installers; however, continuous education and training is undoubtedly of vital importance in an ever-evolving industry. This area requires further research and is left for future studies.

## 6 | PROJECT ISSUES

The most common site- or project-related cause of performance loss, as shown in Figure 8, is postinstallation construction at the PV site (Table A4). Roof repairs/renovations during which the PV system must be turned off and removed are common causes of power loss in residential and commercial systems. The lost production averages in the 20% range, with a gradual increase in subsequent years. Utility systems are typically ground mounted and experience most of their construction prior to COD; so, these systems are typically unaffected by construction. Delays in COD can occur for a variety of reasons and commonly occur in the first year. The causes range from delayed permitting, delayed grid connection, delayed monitoring, or other equipment installation. And if the target COD falls into the winter, the weather often causes delays. In this subcategory, commercial and residential systems are more affected by delays than utility systems. In contrast, project finance is a subcategory mainly affecting residential and smaller commercial systems and is characterized by larger impacts with increasing years. Project finance is any type of nonpayment that resulted in the shutdown of the site or of the physical relocation of the system to a new location, which can have a tremendous impact on the annual production. Fire, or thermal events, is an alarming subcategory because of its widespread visibility and ramifications for the entire industry. However, most events reported in this subcategory were not caused by the PV system. The two events in the utility group were caused by forest fires near the PV system. Two incidents involved the inverter rather than the modules, indicating additional

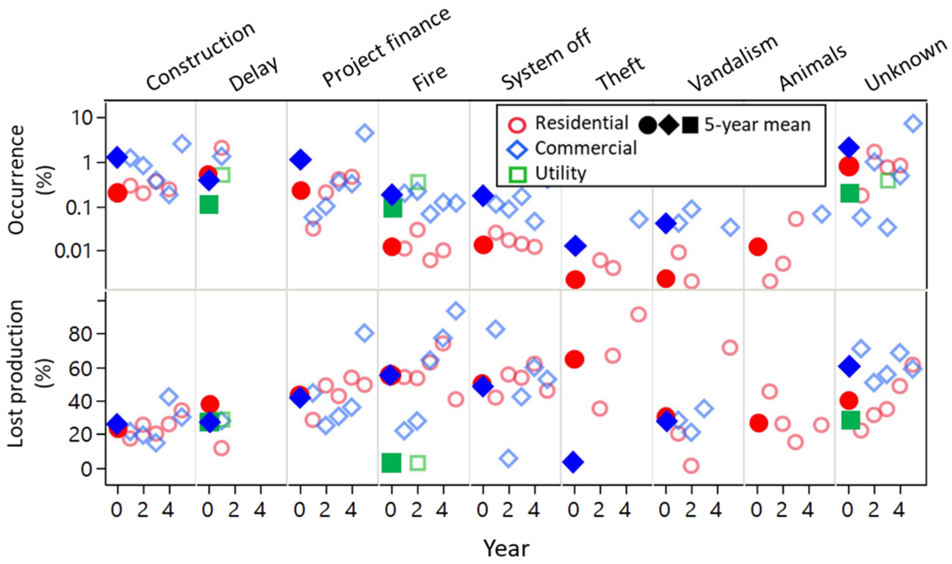


**FIGURE 8** Project-related issue occurrences (top) and lost production (bottom) as a function of years in the field. The different size of the systems is indicated by different-colored symbols. The filled symbols situated at the nominal year 0 are the 5-year mean values for each subcategory [Colour figure can be viewed at wileyonlinelibrary.com]

potential risks downstream of modules such as inverter and combiner boxes. The remaining subcategories are characterized as primarily affecting only residential and commercial systems. Systems that were turned off were typically the result of some maintenance procedure after which the system was inadvertently not turned back on. The closer supervision of utility systems may again explain the absence of these events at the largest system size. Theft affects mainly modules in residential systems, whereas commercial systems are more impacted by the theft of copper wires. Vandalism and damage caused by animals may not occur often, but they can have substantial impact on annual production. The last subcategory is unidentified issues that are more common in nonutility systems, probably because of a lack of closer supervision and dedicated O&M staff. Finally, *force majeure* events (not shown here)—events where a site was completely destroyed by fire or wind without hope of recovering at least parts of the system—average one to two events per 100 000 sites per year.

## 7 | GRID AND DATA COLLECTION ISSUES

Grid and data collection issues have been combined in this section and in Figure 9 because each category contains only three subcategories (Table A5). Because this dataset contains a substantial number of utility systems, it is perhaps no surprise that curtailment is one of the highest occurrence events applying only to these large systems. However, the total impact is typically contained to below 20% of the annual production. Transformer problems typically occur only in the first few years with utility systems affected more often but with lower impact on production. General interconnection issues such as reclosure problems remain relatively constant for utility systems. In contrast, a marked decline from the first to the last year in commercial and residential systems can be seen, indicating typical start-up problems. Yet again, utility systems show less impact on production than smaller systems.

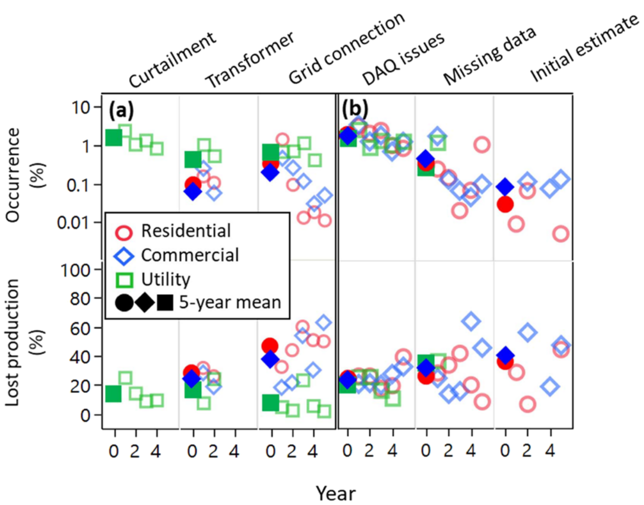


**FIGURE 9** Utility-related (A) and data collection (B) issue occurrences (top) and lost production (bottom) as a function of years in the field. The different size of the systems is indicated by different-colored symbols. The filled symbols situated at the nominal year 0 are the 5-year mean values for each subcategory [Colour figure can be viewed at wileyonlinelibrary.com]

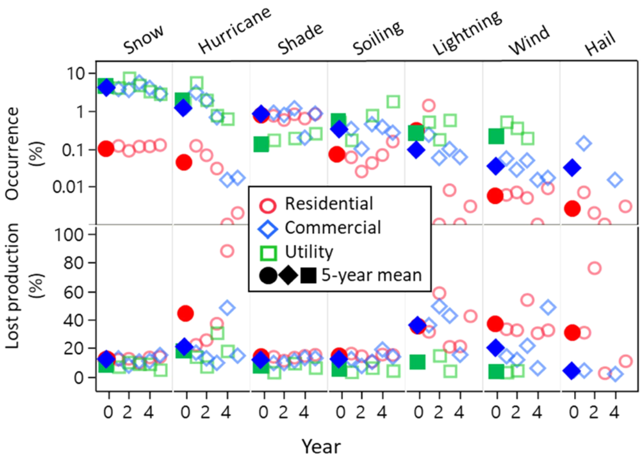


**FIGURE 10** Weather-related issue occurrences (top) and lost production (bottom) as a function of years in the field. The different size of the systems is indicated by different-colored symbols. The filled symbols situated at the nominal year 0 are the 5-year mean values for each subcategory [Colour figure can be viewed at wileyonlinelibrary.com]

Data collection problems are dominated by data acquisition (DAQ) system issues such as the data logger, regardless of system size. Missing data or incomplete years primarily affect utility systems in the first year upon start-up, whereas residential and commercial systems are impacted throughout 5 years. Finally, incorrect estimates or predicted values only affect commercial and residential systems.

## 8 | WEATHER ISSUES

Finally, the last category is the weather category shown in Figure 10, which means particularly unusual weather (Table A6). Some unusual weather events such as hurricanes may be better grouped by calendar year instead of year of operation; however, other subcategories such as snow may be better evaluated by operation year. The most common subcategory is unusual snow events or snow losses that had not been taken into account for the predicted values. Although the occurrence is fairly high, especially for the larger systems, the lost production is fairly small. Causes for the notable discrepancy in occurrence between residential and larger systems may be that relatively more residential systems are located in snow-less climates such as Arizona or Southern California compared with larger systems or that the events are underreported. Hurricane is a fairly sizeable subcategory because of Superstorm Sandy and the large concentration of systems along the East Coast. Lost production due to shade occurs more often for residential and commercial systems that tend to be roof-mounted, in contrast to ground-mounted utility systems. Lightning strikes can have a catastrophic effect on PV systems, although direct strikes to systems are exceedingly rare. The most common situation is a lightning strike to a nearby transformer or utility line. Wind damage occurred through inclement weather such as tornadoes. Finally, visible hail effect concerned only residential and commercial systems and does not include damage detectable in electroluminescence imagery that can have more significant impact with continued field exposure through thermal cycling.

## 9 | CONCLUSION

The 1603 dataset consisting of 100 000 PV systems and totaling up to more than 7-GW DC of installed capacity was examined for performance and performance comments. It provides some valuable high-level insights into PV field performance because of its large scale. Overall, the conclusion contains some positive aspects in addition to some areas of concern. The positive aspects are that the vast majority of systems performed within 10% of the predicted, failures were relatively low, and no indications of widespread failure were detected. In contrast, considerable hardware issues in the first few years are clear indications that training, certificates, and standards for installations could have substantial positive lasting impact on PV system performance. Furthermore, rapid detection of failures and performance-impacting issues remain a goal, as opposed to be common practice; however, encouraging results occurred at the utility level, where most issues were resolved within a few days. The industry should pursue a more proactive approach to O&M because of its greater impact on the financial bottom line rather than a reactive style. Finally, further research is required to better estimate lost production for specific causes, as confounding factors could not always be clearly separated in this study. In the future, we would like to be able to analyze by technology type, such as PERC, which at this time, has only a small amount of field data.

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## ORCID

*Dirk C. Jordan* https://orcid.org/0000-0002-2183-7489
*Chris Deline* https://orcid.org/0000-0002-9867-8930

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## APPENDIX A

**TABLE A1** Summary of the measured/predicted ratios for the different system sizes and fielded years

| Size | Year | P50/Median | P90 | Systems ≥P50 | Systems <P90 | Systems without Known Issues | Systems with Known Issues |
|---|---|---|---|---|---|---|---|
| Residential (1-25 kW) | 1 | 1.02 | 0.86 | 39 801 | 8020 | 78 844 | 8273 |
| Residential (1-25 kW) | 2 | 1.03 | 0.87 | 40 217 | 7932 | 78 287 | 4931 |
| Residential (1-25 kW) | 3 | 1.02 | 0.86 | 36 283 | 7429 | 74 159 | 5010 |
| Residential (1-25 kW) | 4 | 1.01 | 0.84 | 35 163 | 7122 | 73 280 | 3416 |
| Residential (1-25 kW) | 5 | 0.99 | 0.81 | 31 028 | 6201 | 63 665 | 3567 |
| Commercial (25 kW-1 MW) | 1 | 1.01 | 0.81 | 2892 | 573 | 5603 | 1663 |
| Commercial (25 kW-1 MW) | 2 | 1.02 | 0.85 | 3007 | 615 | 5936 | 1110 |
| Commercial (25 kW-1 MW) | 3 | 1.01 | 0.82 | 2820 | 601 | 5858 | 1056 |
| Commercial (25 kW-1 MW) | 4 | 0.99 | 0.79 | 2957 | 582 | 5834 | 827 |
| Commercial (25 kW-1 MW) | 5 | 0.99 | 0.78 | 2636 | 545 | 5379 | 656 |
| Utility (>1 MW) | 1 | 1.01 | 0.87 | 209 | 42 | 415 | 157 |
| Utility (>1 MW) | 2 | 1.01 | 0.88 | 216 | 44 | 409 | 147 |
| Utility (>1 MW) | 3 | 1.00 | 0.87 | 203 | 42 | 409 | 114 |
| Utility (>1 MW) | 4 | 1.00 | 0.85 | 192 | 39 | 399 | 75 |
| Utility (>1 MW) | 5 | 0.98 | 0.82 | 161 | 35 | 338 | 50 |
| Residential (1-25 kW) | 5-y mean | 1.01 | 0.88 | 35 660 | 6780 | 69 693 | 17 428 |
| Commercial (25 kW-1 MW) | 5-y mean | 1.01 | 0.85 | 1978 | 397 | 4115 | 3151 |
| Utility (>1 MW) | 5-y mean | 1.01 | 0.89 | 138 | 27 | 286 | 286 |
| All systems | 5-y mean | 1.01 | 0.88 | 37 776 | 7347 | 74 094 | 20 865 |

**TABLE A2** Example comments for all subcategories examined

| Category | Subcategory | Example Comments |
|---|---|---|
| Hardware | Inverter | Inverter was down for 2-3 mo. Now it is repaired and functioning. |
| | Meter | System experienced a meter failure in April 2016; this has subsequently been rectified and the system is performing as expected. |
| | Repair | The interruption was the result of a failed component that required repairs. |
| | Maintenance | The actual and estimated annual production varied slightly due to routine maintenance issues. |
| | Breaker | We had to shut down a portion of the project for 2 mo due to a breaker failure. The problem was corrected, and we were placed fully back in service within approximately 35 d. |
| | Fuse | Half of the system was offline for 6 d due to a blown fuse and difficulty locating a replacement. |
| | Wire | For a period of time, the system was down due to faulty wiring. This has been repaired. |
| | Tracker | We had a critical failure on the tracking mechanisms due to poor design of system. We are currently in process of repairing system. |
| | Microinverter | 8 microinverters down for several months. |
| | Module | Had one broken panel that had to be replaced. |
| | String | One of the strings was not producing power, resulting in performance below estimates, and this issue has been resolved. |
| | Ground fault | There was a ground fault early found in part of the system that was time consuming to correct and resulted in lower production from January through mid-March. |
| | Connector | Multiple connectors were replaced on 06/24/2013. |
| Project | Construction | The system was temporarily removed due to construction to the property. It was reinstalled on 2/24/2014 and is operational. |
| | Delay | The system did not go online until 1 mo after it was placed in service. |
| | Project finance | System temporarily shut off in June 2013, homeowner defaulted on mortgage. |
| | Fire | A fire near the property caused a temporary lapse of system production. |
| | System off | System was turned off for 6 mo by previous owner. |
| | Theft | Panels were stolen off the roof. No production since that date. |
| | Vandalism | Six days of downtime in December due to vandalism to a combiner box. |
| | Animals | There was a pigeon infestation. Modules had to be removed temporarily in order to clean the space underneath them. |
| | Unknown | Unknown issue with system. |
| Grid | Curtailment | As a result of the buyer curtailments, the project did not achieve the forecasted production estimate. |
| | Transformer | The utility undersized the transformer, which caused some downtime. This has since been corrected. |
| | Grid connection | Underperformance due to grid irregularity. |
| Data collection | DAQ issues | Monitoring system was not engaged properly, and this issue has been resolved. The system is now recording data accurately. |
| | Initial estimate | Estimated annual production was overestimated by installer. |
| | Missing data | There is missing production information. |
| Weather | Snow | Heavy snow cover during winter |
| | Hurricane | The project was damaged by hurricane Sandy. A roof from an adjacent building damaged the system. |
| | Shade | Shade from trees on the south side of solar array could have contributed to lower production. |
| | Soiling | System soiling resulted in less production than expected. |
| | Lightning | The system is fully functional and operational; however, the local power transformer was struck by lightning, and all solar power systems in the area had be shut down for safety reasons while it was replaced. |
| | Wind | System support damaged in storm. No production from mid-November for 7 mo until repair was completed in the spring. |

(Continues)

**TABLE A2** (Continued)

| Category | Subcategory | Example Comments |
|---|---|---|
| | Hail | Due to hail storm, customer suffered roof damage and had to have their panels removed in order to repair roof damage. |

*Note.* The comments were only grammatically edited but not for content. Some dates were changed to protect the proprietary nature of the data set.
Abbreviation: DAQ, data acquisition.

**TABLE A3** Summary of hardware issues for occurrences and lost production

| Size | Subcategory | Occurrence (%) | Mean Lost Production (%) | SD Lost Production (%) | Systems Affected |
|---|---|---|---|---|---|
| Residential (1-25 kW) | Inverter | 0.76 | 22.5 | 6.9 | 3028 |
| Commercial (25 kW-1 MW) | Inverter | 4.35 | 16.7 | 3.5 | 1464 |
| Utility (>1 MW) | Inverter | 6.95 | 7.5 | 1.8 | 177 |
| Residential (1-25 kW) | Meter | 0.20 | 39.3 | 5.4 | 748 |
| Commercial (25 kW-1 MW) | Meter | 0.26 | 23.7 | 4.6 | 85 |
| Utility (>1 MW) | Meter | 0.35 | 27.3 | 4.1 | 7 |
| Residential (1-25 kW) | Unspecified repair | 0.45 | 28.6 | 11.0 | 1819 |
| Commercial (25 kW-1 MW) | Unspecified repair | 1.10 | 29.9 | 18.2 | 354 |
| Utility (>1 MW) | Unspecified repair | 0.89 | 19.8 | 5.4 | 21 |
| Residential (1-25 kW) | Maintenance | 0.05 | 17.6 | 12.9 | 179 |
| Commercial (25 kW-1 MW) | Maintenance | 0.52 | 19.2 | 11.5 | 165 |
| Utility (>1 MW) | Maintenance | 0.95 | 8.8 | 2.2 | 24 |
| Residential (1-25 kW) | Breaker | 0.01 | 31.6 | 18.1 | 44 |
| Commercial (25 kW-1 MW) | Breaker | 0.12 | 14.9 | 11.5 | 42 |
| Utility (>1 MW) | Breaker | 0.66 | 4.5 | 4.3 | 13 |
| Residential (1-25 kW) | Fuse | 0.036 | 29.2 | 16.3 | 115 |
| Commercial (25 kW-1 MW) | Fuse | 0.21 | 23.0 | 13.7 | 69 |
| Utility (>1 MW) | Fuse | 0.52 | 5.4 | 4.1 | 2 |
| Residential (1-25 kW) | Wire | 0.01 | 36.5 | 24.0 | 38 |
| Commercial (25 kW-1 MW) | Wire | 0.16 | 17.9 | 20.4 | 34 |
| Utility (>1 MW) | Wire | 0.31 | 6.9 | 0.1 | 7 |
| Residential (1-25 kW) | Tracker | 0.01 | 20.6 | 17.4 | 28 |
| Commercial (25 kW-1 MW) | Tracker | 0.09 | 21.2 | 21.1 | 31 |
| Utility (>1 MW) | Tracker | 0.31 | 5.4 | 5.1 | 8 |
| Residential (1-25 kW) | Microinverter | 0.02 | 36.9 | 11.2 | 83 |
| Commercial (25 kW-1 MW) | Microinverter | 0.21 | 24.7 | 5.4 | 19 |
| Utility (>1 MW) | Microinverter | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Module | 0.02 | 25.9 | 6.9 | 81 |
| Commercial (25 kW-1 MW) | Module | 0.12 | 17.7 | 27.8 | 33 |
| Utility (>1 MW) | Module | 0.19 | 19.5 | 10.3 | 2 |
| Residential (1-25 kW) | String | 0.03 | 19.7 | 5.3 | 110 |
| Commercial (25 kW-1 MW) | String | 0.02 | 6.0 | 0.8 | 2 |
| Utility (>1 MW) | String | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Ground fault | 0.001 | 14.9 | 31.6 | 2 |
| Commercial (25 kW-1 MW) | Ground fault | 0.06 | 18.1 | 22.5 | 17 |

(Continues)

**TABLE A3** (Continued)

| Size | Subcategory | Occurrence (%) | Mean Lost Production (%) | SD Lost Production (%) | Systems Affected |
|---|---|---|---|---|---|
| Utility (>1 MW) | Ground fault | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Connector | 0.002 | 15.1 | 6.64 | 3 |
| Commercial (25 kW-1 MW) | Connector | 0.035 | 8.2 | 4.65 | 4 |
| Utility (>1 MW) | Connector | 0 | 0 | 0 | 0 |
| All | All | 9.3 | 18.0 | 9.6 | 8827 |

*Note.* Some systems had more than one hardware issue; therefore, the total number of affected systems in the last row and column is less than the sum of all hardware issues.

**TABLE A4** Summary of project issues for occurrences and lost production

| Size | Subcategory | Occurrence (%) | Mean Lost Production (%) | SD Lost Production (%) | Systems Affected |
|---|---|---|---|---|---|
| Residential (1-25 kW) | Construction | 0.21 | 24.6 | 6.4 | 874 |
| Commercial (25 kW-1 MW) | Construction | 1.02 | 25.5 | 10.8 | 332 |
| Utility (>1 MW) | Construction | 0 | 0 | 39.0 | 0 |
| Residential (1-25 kW) | Delay/redesign | 0.41 | 38.5 | 38.1 | 1783 |
| Commercial (25 kW-1 MW) | Delay/redesign | 0.33 | 27.8 | 17.0 | 95 |
| Utility (>1 MW) | Delay/redesign | 0.10 | 26.8 | 0.6 | 2 |
| Residential (1-25 kW) | Project finance | 0.22 | 44.5 | 9.8 | 861 |
| Commercial (25 kW-1 MW) | Project finance | 1.05 | 43.2 | 21.8 | 320 |
| Utility (>1 MW) | Project finance | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Fire | 0.01 | 56.8 | 12.3 | 47 |
| Commercial (25 kW-1 MW) | Fire | 0.14 | 56.8 | 31.0 | 48 |
| Utility (>1 MW) | Fire | 0.09 | 3.2 | 2.0 | 2 |
| Residential (1-25 kW) | System off | 0.01 | 51.6 | 8.0 | 56 |
| Commercial (25 kW-1 MW) | System off | 0.16 | 48.4 | 28.2 | 51 |
| Utility (>1 MW) | System off | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Theft | 0.002 | 64.265 | 28.1 | 8 |
| Commercial (25 kW-1 MW) | Theft | 0.0125 | 3.3 | – | 1 |
| Utility (>1 MW) | Theft | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Vandalism | 0.002 | 30.9 | 36.3 | 10 |
| Commercial (25 kW-1 MW) | Vandalism | 0.04 | 28.1 | 13.7 | 11 |
| Utility (>1 MW) | Vandalism | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Animals | 0.0116 | 28.0 | 12.5 | 46 |
| Commercial (25 kW-1 MW) | Animals | 0 | 0 | 0 | 0 |
| Utility (>1 MW) | Animals | 0 | 0 | 0 | 0 |
| Residential (1-25 kW) | Unknown | 0.6792 | 39.6 | 15.4 | 2750 |
| Commercial (25 kW-1 MW) | Unknown | 1.7554 | 60.7 | 8.6 | 543 |
| Utility (>1 MW) | Unknown | 0.1935 | 28.4 | 11.3 | 2 |
| All | All | 6.4 | 29.2 | 13.5 | 6084 |

*Note.* Some systems had more than one project issue; therefore, the total number of affected systems in the last row and column is less than the sum of all project issues.

**TABLE A5** Summary of utility and data collection issues for occurrences and lost production

| Size | Subcategory | Occurrence (%) | Mean Lost Production (%) | SD Lost Production (%) | Systems Affected |
|---|---|---|---|---|---|
| Residential (1-25 kW) | Curtailment | 0 | 0 | 0 | 0 |
| Commercial (25 kW-1 MW) | Curtailment | 0 | 0 | 0 | 0 |
| Utility (>1 MW) | Curtailment | 1.42 | 14.6 | 7.5 | 31 |
| Residential (1-25 kW) | Transformer | 0.09 | 28.8 | 22.2 | 221 |
| Commercial (25 kW-1 MW) | Transformer | 0.06 | 23.5 | 18.8 | 22 |
| Utility (>1 MW) | Transformer | 0.39 | 16.1 | 11.3 | 9 |
| Residential (1-25 kW) | Grid connection | 0.31 | 47.4 | 10.2 | 1323 |
| Commercial (25 kW-1 MW) | Grid connection | 0.18 | 37.3 | 18.2 | 63 |
| Utility (>1 MW) | Grid connection | 0.60 | 7.9 | 8.8 | 16 |
| All | All grid | 1.7 | 19.5 | 10.8 | 1607 |
| Residential (1-25 kW) | DAQ issues | 1.89 | 25.5 | 8.5 | 7688 |
| Commercial (25 kW-1 MW) | DAQ issues | 1.69 | 24.2 | 5.4 | 570 |
| Utility (>1 MW) | DAQ issues | 1.43 | 19.5 | 7.2 | 37 |
| Residential (1-25 kW) | Missing data | 0.31 | 26.2 | 12.8 | 1096 |
| Commercial (25 kW-1 MW) | Missing data | 0.42 | 32.5 | 21.5 | 148 |
| Utility (>1 MW) | Missing data | 0.24 | 36.5 | 34.3 | 7 |
| Residential (1 kW-25 kW) | Initial estimate | 0.03 | 35.6 | 31.2 | 66 |
| Commercial (25 kW-1 MW) | Initial estimate | 0.08 | 40.6 | 17.5 | 21 |
| Utility (>1 MW) | Initial estimate | 0 | 0 | 0 | 0 |
| All | All data collection | 7.5 | 25.7 | 17.0 | 7161 |

*Note.* Some systems had more than one grid and data collection issue; therefore, the total number of affected systems is less than the sum of all grid and data collection issue, respectively.

**TABLE A6** Summary of weather issues for occurrences and lost production

| Size | Subcategory | Occurrence (%) | Mean Lost Production (%) | SD Lost Production (%) | Systems Affected |
|---|---|---|---|---|---|
| Residential (1-25 kW) | Snow | 0.11 | 12.2 | 1.7 | 437 |
| Commercial (25 kW-1 MW) | Snow | 3.96 | 11.4 | 2.7 | 1304 |
| Utility (>1 MW) | Snow | 4.52 | 8.0 | 2.1 | 118 |
| Residential (1-25 kW) | Hurricane | 0.04 | 43.2 | 30.5 | 186 |
| Commercial (25 kW-1 MW) | Hurricane | 1.12 | 20.4 | 15.7 | 395 |
| Utility (>1 MW) | Hurricane | 1.81 | 17.5 | 1.8 | 51 |
| Residential (1-25 kW) | Shade | 0.71 | 13.6 | 1.6 | 2787 |
| Commercial (25 kW-1 MW) | Shade | 0.78 | 11.2 | 1.7 | 255 |
| Utility (>1 MW) | Shade | 0.13 | 6.3 | 3.1 | 3 |
| Residential (1-25 kW) | Soiling | 0.07 | 14.3 | 2.2 | 259 |
| Commercial (25 kW-1 MW) | Soiling | 0.30 | 12.6 | 4.4 | 99 |
| Utility (>1 MW) | Soiling | 0.55 | 4.7 | 1.5 | 12 |
| Residential (1-25 kW) | Lightning | 0.28 | 34.8 | 15.9 | 1219 |
| Commercial (25 kW-1 MW) | Lightning | 0.09 | 35.8 | 14.7 | 31 |
| Utility (>1 MW) | Lightning | 0.26 | 9.5 | 7.6 | 7 |
| Residential (1-25 kW) | Wind | 0.01 | 36.4 | 9.7 | 22 |
| Commercial (25 kW-1 MW) | Wind | 0.03 | 20.4 | 16.6 | 11 |
| Utility (>1 MW) | Wind | 0.21 | 3.8 | 0.9 | 6 |
| Residential (1-25 kW) | Hail | 0.002 | 29.9 | 32.8 | 11 |
| Commercial (25 kW-1 MW) | Hail | 0.03 | 3.0 | 1.7 | 11 |
| Utility (>1 MW) | Hail | 0 | 0 | 0 | 0 |
| All | All | 5.5 | 16.6 | 8.4 | 5211 |

*Note.* Some systems had more than one weather issue; therefore, the total number of affected systems in the last row and column is less than the sum of all weather issues.