PV reliability lessons from 100,000 systems

Performance | Despite the importance of reliability to the cost competitiveness of PV, large data sets enabling high-level investigation of the technology's performance in the field are relatively scarce. Dirk C. Jordan, Chris Deline, Bill Marion and Teresa Barnes of the National Renewable Energy Laboratory, and Mark Bolinger of the Lawrence Berkeley National Laboratory study a unique data set of 100,000 PV systems in the US, drawing out tips for better reliability that have relevance to other parts of the world

Credit: First Solar

Reliability plays a critical role in PV's cost competitiveness with traditional energy sources. Many research groups and institutions around the world pursue to quantify PV field performance, degradation and failures. However, data sets studying a large number of systems that provide a high-level overview of issues occurring in the field are still difficult to find [1]. In response to the global financial crisis of 2008, US Congress enacted the American Recovery and Reinvestment Act in 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). The award stipulated that annual PV production and comments relating to the performance needed to be reported. The data set comprised about 100,000 PV systems totaling to over 7 gigawatts (GW) direct current (DC) capacity or roughly 7% of the US fleet at the end of 2019. The insights gained from this data set provide valuable information of the performance and the state of reliability of the PV fleet in the USA.

The interrogation of data from 100,000 PV systems in the US provides fruitful insights into performance and reliability

While the dataset is limited to systems in the USA the same lessons are more generic and may be applicable to other parts of the world.

Fleet performance

The data set consisted of annual production data for five years for each of the systems, the nameplate rating, an estimated production value and the location. The ratio of measured over predicted production could be calculated for all systems to assess system perfor-

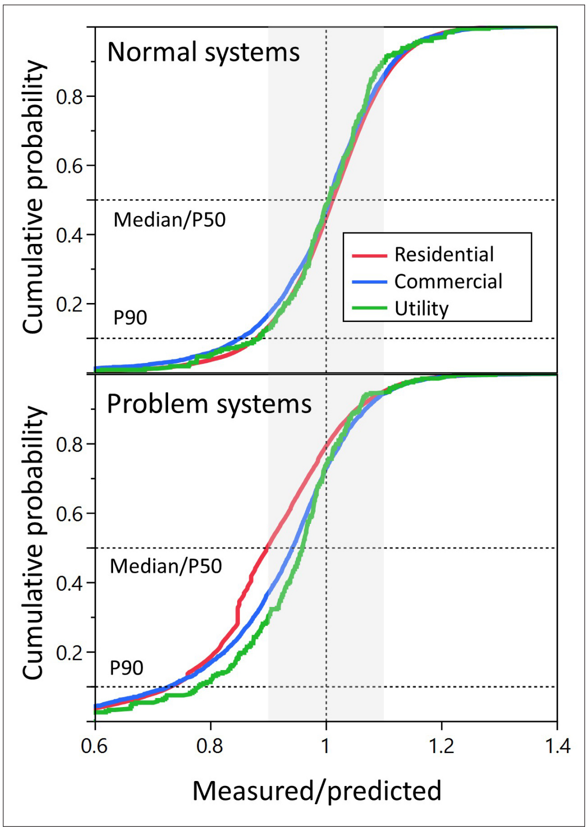


Figure 1. Cumulative distribution function of the five-year mean of the measured/predicted production ratio for normal systems not impacted by specific performance issues (top), and systems impacted by specific issues (bottom) discussed in the following sections. Different system sizes are indicated by different colour; the median (P50), the P90, and the unity ratio are indicated by dashed horizontal and vertical lines, respectively. A 10% band around the unity values is indicated in grey

mance health. The data set is approximately divided into residential (1–25kW), commercial (25kW–1MW) and utility-scale systems (>1MW). 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 over 5MW, in addition to the 1603 data, we generated our own production estimates using a separate data set acquired by the Lawrence Berkeley National Lab, which also included greater levels of detail on system specifics such as mounting configuration than was presented in the 1603 data. In general, we found good agreement between our own and the 1603 estimates, lending some credibility to the production numbers contained in the 1603 data set.

The five-year mean of the measured over predicted production ratio is displayed in Figure 1 as a cumulative distribution function (CDF). The advantage of a CDF compared to a histogram is that it more easily allows comparison of multiple large distributions.

The top graph shows all "normal" systems, i.e. systems that were not knowingly impacted by some issue. The data are colour-coded by the size of the systems and the median or the P50 is indicated by a black horizontal dashed line, as is the P90 that is often used in financial models.

The unity value, i.e. systems performing as expected, is indicated by a vertical dashed line together with a grey 10% band around it. 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, indicated by a steeper curve, is most likely aided by closer supervision in the planning and operation phase and/or more accurate predicted values. The P90 value falls between 0.8 to 0.9; in other words, 90% of all systems produce approximately within 10% of the expected production. 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 systems compared to standard meters more commonly used in residential applications.

"Installation quality was found to play an important role in PV reliability and emphasises the importance of installation best practices"

The bottom graph of Figure 1 shows similar CDFs of systems that were impacted by specific issues in any of the five-year reporting period. Similar to the "normally" operating systems, some systems greatly under- 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 to "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).

Hardware reliability lessons

The performance-related comments were mined by a combination of automatic and manual routines, such as keyword searches, sorting, classification and lastly reading. If multiple performance-impacting entries were recorded in a single year, each issue was counted in its respective subcategory, although the great majority of performance comments were single-entry issues. 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. Because it is not always known if all systems were operating for the full 12 months for each year the five-year mean values for each subcategory is shown in Figure 2.

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.

As has been reported before, inverters are the most common hardware problem for PV systems [2]. 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. However, it can be seen from the graph 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, three-quarters of which constituted replacement. "Unspecified repairs" are failure events that occurred,

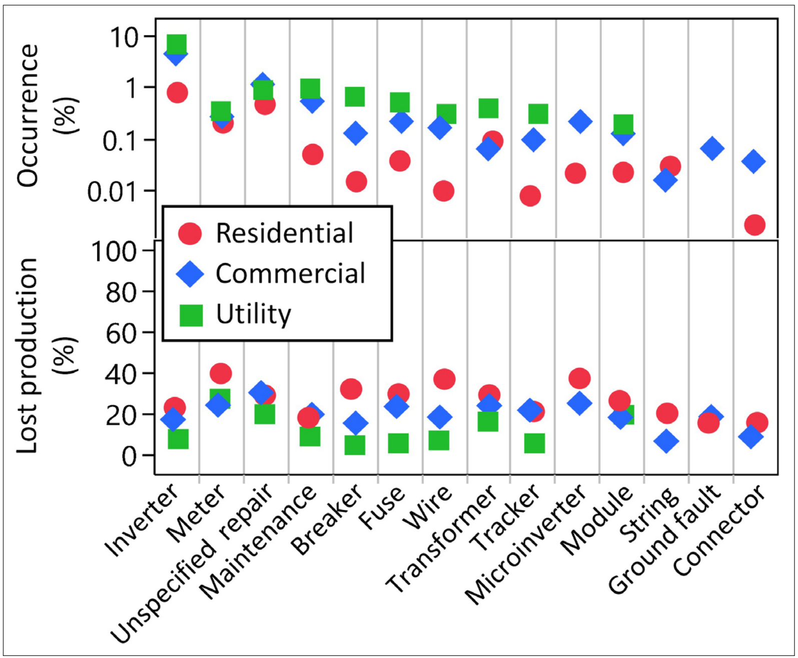


Figure 2. Hardware issue occurrences (top) and lost production (bottom) for each hardware subcategory. The different size of the systems is indicated by different-coloured symbols

All issues	Residential	Commercial	Utility
Mean lost (days)	44.5	27.3	8.8
Median lost (days)	38.5	21	5
Mean lost capacity (%)	9.4	6.1	2.3
Median lost capacity (%)	8.4	4.8	1.3

Table 1. Mean and median of lost production days and estimated lost capacity by system size for all hardware issues combined.

but from the comments it could not be deduced what item failed and what was fixed. It is interesting to note that maintenance events (a proactive approach) typically have lower occurrence than repairs (a reactive approach), yet they have lower impact on lost production, a general trend that is not limited to the PV industry. The next three subcategories are breakers, fuses, and wires, which may be somewhat unexpected and may indicate installation improvement possibilities. It is also conceivable that pressure to reduce installation costs leads to procurement and acceptance of nonconforming items, e.g. breakers have been found to be one of the most commonly counterfeited electrical products in the United States [3].

Also included here are transformer problems, although these hardware problems are on the utility side of PV systems, about half of which consisted of replacements. The occurrence appears fairly high because of three lightning strikes to substation transformers that led to outages of PV systems in the vicinity. The next two subcategories are tracker and microinverter or DC optimiser issues; the latter two are grouped together. However, both subcategories have in common that fact the occurrence numbers extracted from this dataset are most likely under-estimated. The reason is that mounting configuration was only available for a few hundred systems greater than 5MW but not for systems below 5MW. 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 5MW 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. Tracker systems in the residential category are 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-related issues that appear to be relatively low and in the historical range of 0.02% to 0.2%, however, the effect of underperforming modules may not have been fully captured here. String problems were typically caused by reverse connections—a problem that occurs most often at the residential level. The final two subcategories are ground faults and connector issues. Connectors are specifically related to module connectors that were incorrectly crimped and/or starting to separate under load. Both of these subcategories do not occur very often but could have serious safety implications by causing fires; thus, they deserve our full attention.

Additional insights into hardware issues may be gained by examining the time it takes to resolve specific issues. Some, but not all comments, recorded the start and end time of a specific repair issue. Unfortunately, that reduced the number of data points available for each subcategory markedly, as seen in Figure 3.

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. Similar to lost production, utility systems show the quickest resolution at a median of six days for inverter problems, followed by commercial and

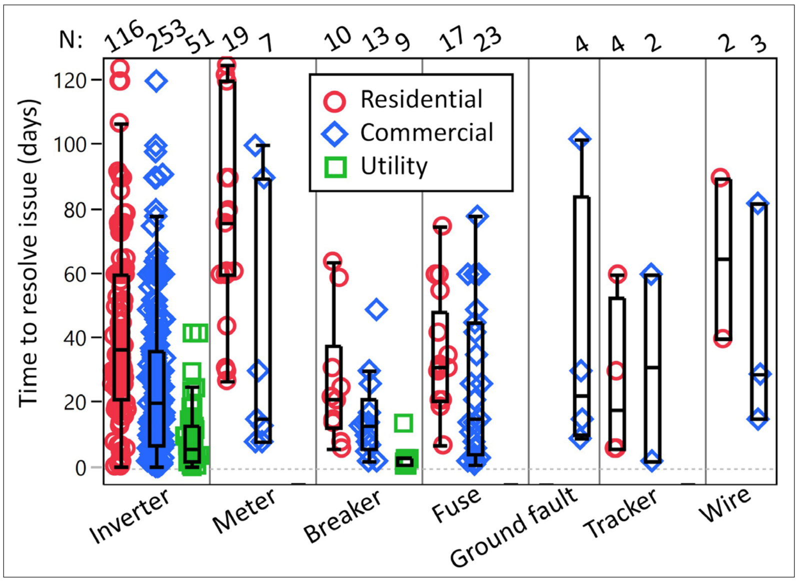


Figure 3. Days to resolve specific hardware issues partitioned by size of the installation category

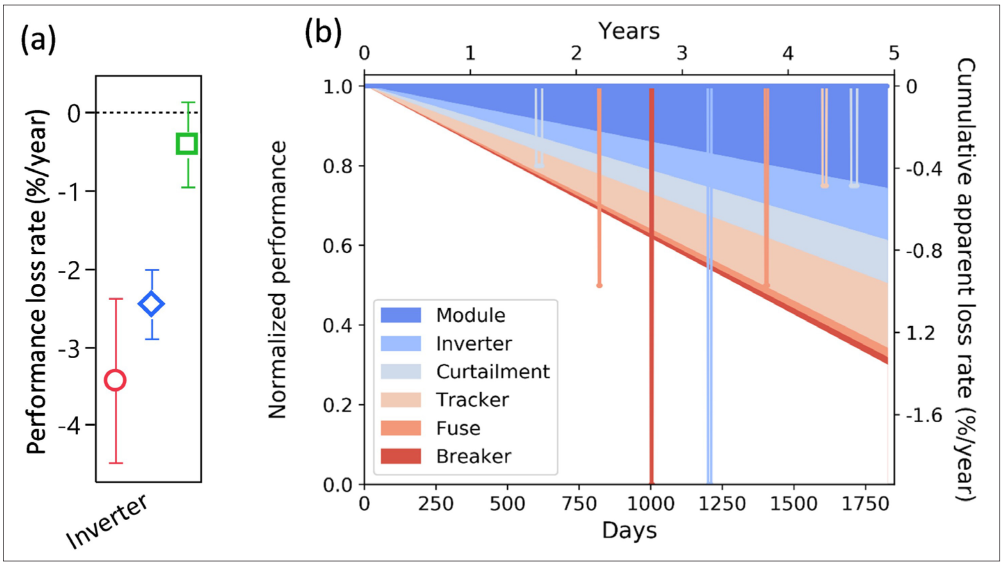


Figure 4. Apparent performance loss rates caused by inverter downtimes (a) and illustrating of module versus systems performance loss

correlate it with the downtime of the system, as shown in Figure 4 (a).

Because interruptions caused by inverters were in 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. This clearly emphasises that operations and maintenance (O&M) records must be carefully considered in evaluating performance loss at the system level. Figure 4 (b) illuminates the difference between module and system performance loss more clearly, although a different performance loss method, such as the year-on-year method incorporated in RdTools for example may lead to a different system performance loss rate [4]. Nevertheless, it can be seen that downtime from specific balance-of-system (BOS) components aggregate from an average module to a much greater system performance loss [5].

residential systems at the median of 20 days 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 but also similar resolution times as inverters. It is interesting to note that other hardware issues such as ground faults, trackers and wires can take considerably longer to resolve, probably because of a combination of the complexities in detection and repair.

Median and mean values of lost production days are given in Table 1 when all hardware issues are combined. In addition, an approximate value of the lost capacity by system size can be estimated. At the utility scale, only days of production are typically lost representing 1-2 % of capacity. For commercial systems typically weeks of production are lost and residential systems more than a month.

Recoverable and nonrecoverable performance loss

Long-term unrecoverable performance decline or performance loss rates have a great impact on the economics of PV projects. With only five years of data and limited weather correction, the resulting performance loss rates obtained from this data set would have high uncertainties. However, the inverter subcategory contained sufficient data points to calculate an apparent performance loss rate from the P50 values of each year with a standard least-squares regression approach and for each system size category and

Installation quality

Some of the BOS component failures raise questions about installation quality and its impact on reliability. Figure 5 displays the number of installers vs. the number of systems installed per installer as open circles colour-coded by the median size of the installed system. Large commercial installers can be found on the right side of the graph. In contrast, the left-hand side shows a large number of installers who installed only one or two systems. Hardware occurrence issues for the same installers are graphed as open diamonds on the right-hand axis. One hardware incidence per year would result in 100% occurrence; because more than one issue can occur per year, occurrence numbers greater than 100% are possible. Despite the imperfect metric, installers that install fewer systems have a higher occurrence of hardware issues than installers that install a great number of systems. This emphasises the benefits of installation experience, standards and certifications such as those provided through the IECRE, the IEC's system for certification to standards relating to equipment for use in renewable energy applications. Furthermore, training and certifications for installers could have a positive impact on long-term reliability.

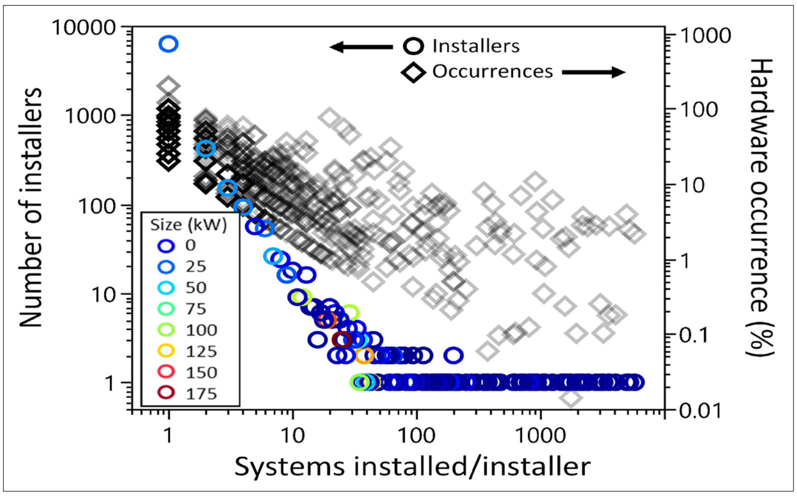
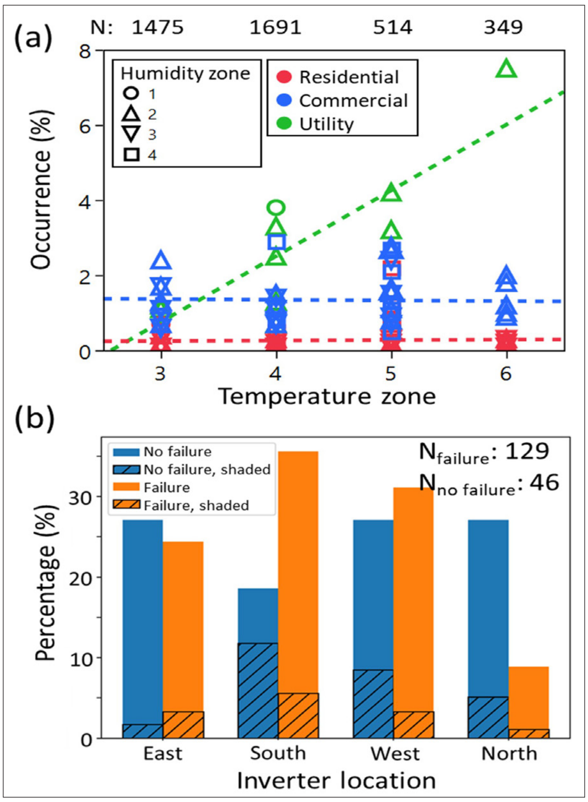
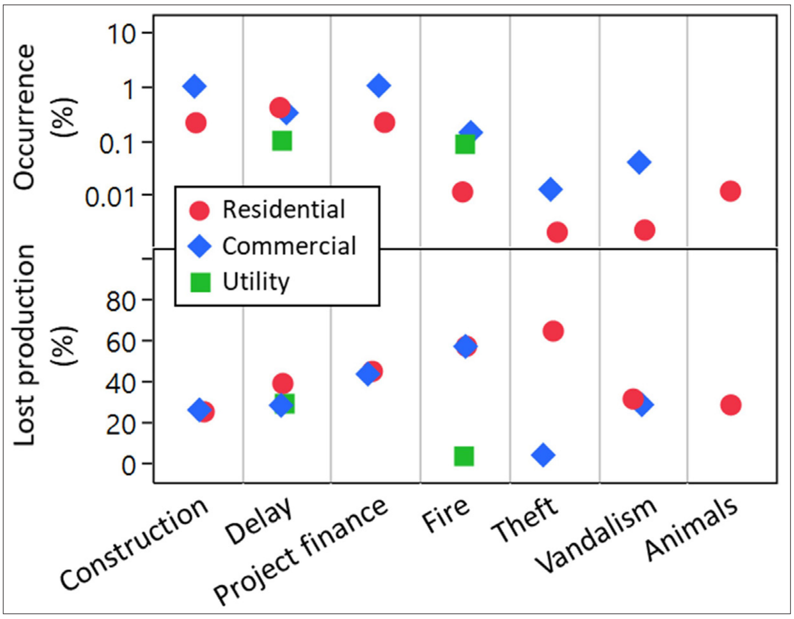


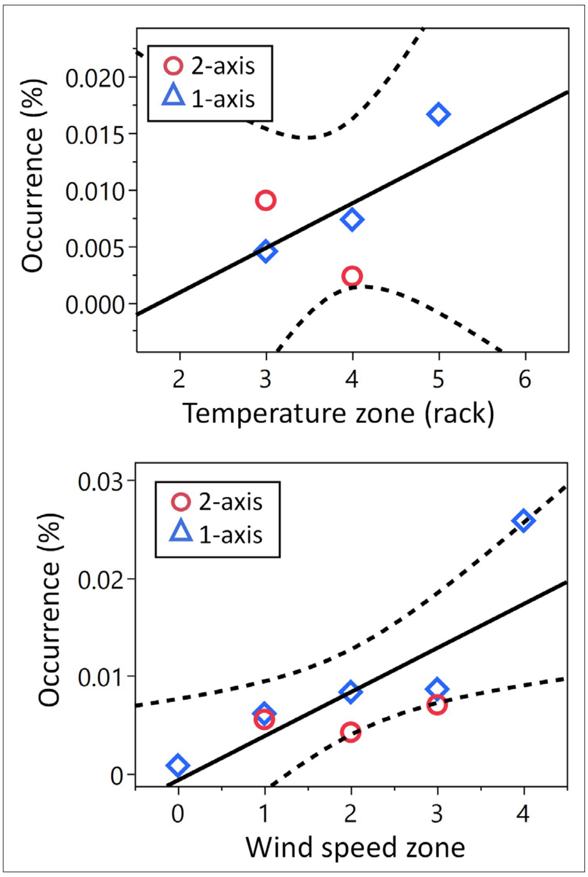
Figure 5. Number of installers versus systems installed per installer colour-coded by the median size of the installation (left axis). Occurrence of hardware issues for each installer as percentage (right axis)



▲ **Figure 6. Inverter failures occurrences (a) as a function of PV-specific temperature zones (model based on rack-mounting). The system size is colour coded and the humidity PV climate zone is indicated by different symbols. Regression lines are indicated by dashed lines. The number of data points for each zone is indicated on top of the graph. Inverter orientation for systems that experienced failures (orange) and without failures (blue) is shown in (b). Inverters that received some shading through adjacent buildings or vegetation are indicated by the cross-hatch pattern**



▲ **Figure 8. Hardware issue occurrences (top) and lost production (bottom) for each project subcategory. The different size of the systems is indicated by different-coloured symbols**



◀ **Figure 7. (a) Tracker issues as a function of PV-specific temperature zone (rack-mounting); (b) PV-specific wind speed zone. The tracker type is indicated by different colours and symbols. Standard least square regression fits are shown by black solid lines. 95% confidence intervals are indicated by dashed lines. The number of data points for each zone is indicated on top of the graph**

Climate trends and installation best practices – shade BOS components

An often-asked question is if certain failures are related to climatic conditions such as temperature, humidity and wind speed. To investigate this question, we adopt the PV-specific climate zones instead of the commonly used but insufficient Köppen-Geiger climate classification [6]. An increased number of inverter failures can be seen in hotter climate zones for utility-scale systems, as shown in Figure 6 (a). Yet, commercial and residential systems do not follow the same trend.

The explanation for this discrepancy may be that utility projects are typically large, ground-mounted systems where inverters are exposed in the field and may not always be shaded. In contrast, many commercial systems (but not all) and residential systems are rooftop installations where the inverter can be found facing different directions depending on the building orientation or located inside the building. The systems that experienced inverter failures were sampled, orientation recorded using Google maps and displayed in orange in Figure 6 (b).

Disproportionally, more inverters were facing south and west than east, with very few facing north. In addition, inverters that could experience some shading because of adjacent structures or vegetation are indicated by cross-hatching. In contrast, systems without inverter failures were randomly sampled because of the large number and are shown as blue bars for comparison. Orientation of these inverters is almost evenly divided between the four directions, with south-facing inverter having the lowest percentage. Furthermore, these inverters were also more likely to be shaded, which is again indicated by cross-hatching. Unshaded inverters facing south in the northern hemisphere are exposed directly to the sun and experience higher temperatures for longer periods than shaded inverters. West-facing inverters experience sun exposure coinciding with daily maximum ambient temperatures, possibly explaining the high failure percentage. Certainly, inverter manufacturer and type may have an impact on the number of failures too and may contribute to some data noise.

Trackers are often used in utility-scale systems and ground-mounted commercial installations and are similarly exposed to various weather conditions. We test the possibility of tracker failures in different climate zones, as shown in Figure 7. More data is required to confirm a tenuous trend of higher failures in hotter climate zones although hotter climate zones also often consist of more sandy climates that could be correlated to increased failure risk. In contrast, a much clearer trend of higher failures in higher wind speed locations can be seen in Figure 7 (b).

PV project issues

Hardware issues are not the only category that can have a substantial impact on PV production. In this section we discuss some project- or site-related problems. The most common of these losses, as shown in Figure 8, is post-installation construction at the PV site. Roof repairs or 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. Utility systems are typically ground-mounted and experience most of their construction prior to commercial operation date (COD); thus, 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, grid connection, monitoring, or other equipment installation. Furthermore, if the target COD falls into the winter, the weather often causes delays depending on the exact location. 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 characterised by larger impacts with increasing years. The project finance subcategory is any type of nonpayment that resulted in the shutdown of the site or the physical relocation of the system, 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 but were not caused by the PV system. Two incidents involved the inverter rather than the modules, indicating additional potential risks downstream of modules such as inverter and combiner boxes. The remaining subcategories are characterised as primarily affecting only residential and commercial systems. 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 a substantial impact on annual production. 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.

Conclusion

The 1603 data set consisting of 100,000 PV systems and totalling more than 7GW of capacity provided some fruitful insights into PV system performance and reliability. The majority of systems—80-90%—performed within 10% of expected production, which is a positive finding for the entire industry. In addition, module-related failures were found to be very low, ca. 0.2%/year, although the full effect of underperforming modules may not have been fully captured in this data set. These positive aspects were balanced with some findings of areas of concern, specifically some balance-of-system problems. For example, inverter failures were found to be high but were also found to be influenced by installation best practices. Installations where the inverter was exposed to less direct sun exposure showed significant lower failures.

Installation quality in general was found to play an important role in long-term PV reliability and emphasises the importance of installation best practices, training, certifications and standards, not only at the manufacturing level but also at the installation level. Moreover, general hardware issues at the utility level were resolved much more quickly than at the commercial and residential level, emphasising that a proactive approach to operations and maintenance and rapid detection of issues has room for improvement. 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.

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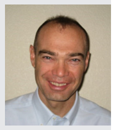

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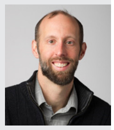

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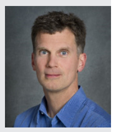

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