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PHOTOVOLTAIC DEGRADATION RATES: ON THE WAY OF IMPROVEMENT

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Abstract. Recently renewable energy has been enjoying a rising support from private organizations and individuals due to the gradual decline in its production cost. Usually, the lack of reliable data that supports the long-term viability of a project is the reason why most investors are hesitant to back a renewable energy venture. The ability to accurately predict power delivery over the course of time is of vital importance to the growth of the photovoltaic (PV) industry. Two key cost drivers are the efficiency with which sunlight is converted into power and how this relationship changes over time. Thanks to the latest big data and predictive analysis technology, renewable energy companies can now produce more energy with reduced costs.

Key words: photovoltaic modules, photovoltaic systems, performance, outdoor testing, field testing, degradation rates.

An accurate quantification of power decline over time, also known as degradation rate, is essential to all members—utility companies, investors, integrators, and researchers alike. Financially, degradation of a PV module or system is equally important, because a higher degradation rate translates directly into less power produced and, as a result, reduces future cash flows. Furthermore, inaccuracies in determined degradation rates lead directly to increased financial risk [1]. Technically, degradation mechanisms are important to understand because they may eventually lead to failure. Normally, a 20% decline is considered a failure, but there is no consensus on the definition of failure, because a high-efficiency module degraded by 50% may still have a higher efficiency than a non-degraded module from a less efficient technology. The identification of the underlying degradation mechanism through modeling and experiments can lead directly to lifetime improvements. Outdoor field testing has played a vital role in quantifying long-term behavior and lifetime for at least two reasons: it is the typical operating environment for PV systems, and it is the only way to correlate indoor accelerated testing to outdoor results to forecast field performance.

Figure 1 presents a summary histogram of degradation rates. The summarized rates are long-term degradation rates; short-term, light-induced degradation is not mentioned. A decrease in performance is defined as a positive degradation rate. Conversely, a negative rate indicates an improvement. This histogram provides some general insights. The distribution is skewed toward high degradation rates with a mean of 0.8%/year and a median of 0.5%/year. The majority of these reported rates, 78% of all data, are below a rate of 1%/year indicated by a red dashed line. In addition, this histogram is remarkably similar to (though slightly narrower than) the assumed degradation rate distribution Darling and others used to calculate the levelized cost of energy for PV. In addition, Figures 2(b) and 2(c) reflect a similar histogram for crystalline Si-based and thin-film-based technologies, respectively. Color coding is provided to distinguish data from installations prior to the year 2000 and after

2000 indicated by pre-2000 and post-2000.

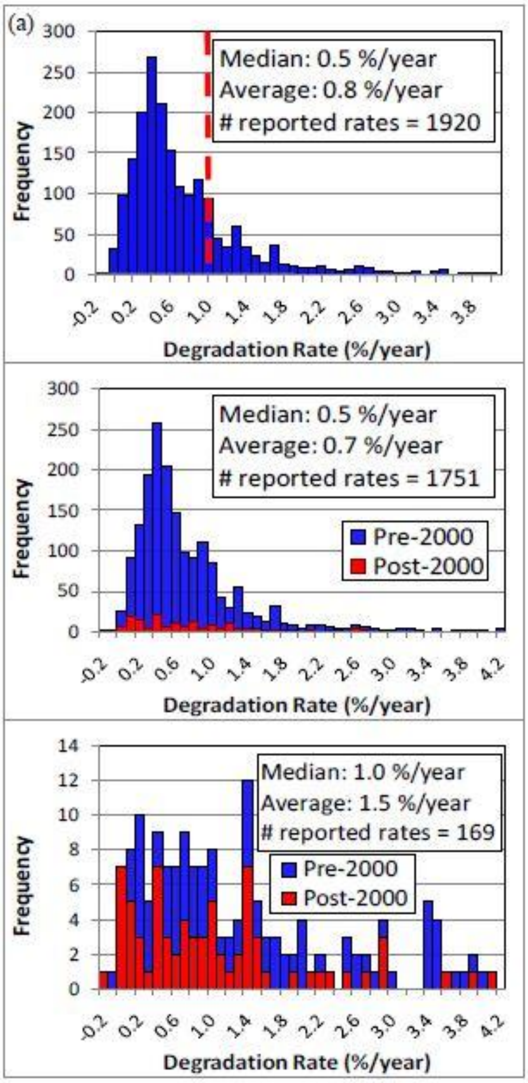

Figure 1. Histogram of reported degradation rates for all degradation rates (a), for Si only (b), and for thin-film technologies only (c). Median, average and number of reported rates are indicated

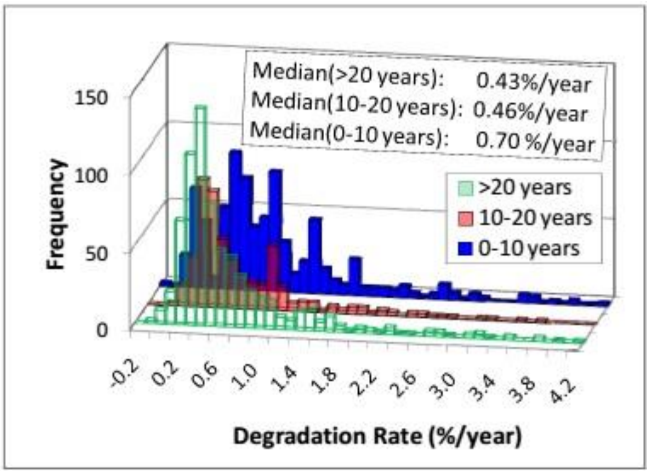

Figure 2. Degradation rates histogram grouped by outdoor exposure length

Modules with high degradation rates are unlikely to be left in the field and reported on as many times as modules with low degradation rates. This effect can be observed in Figure 2, which shows the degradation rates from Figure 1 partitioned by the field exposure length. Studies with monitoring times up to 10 years reflect that the distribution has a much more pronounced tail and a higher median than for field exposure times of more than 10 years.

Although an effort was made to eliminate the impact of short-term light-induced degradation, especially for thin-film technologies, it remains influential. In addition, many of the scientific studies include engineering prototypes that would not become commercial products based on the high degradation rates that can be observed in <2 years of deployment. It would be very interesting to create a similar plot only for crystalline Si and thin-film technologies; however, more data points are required, especially for thin films, to bring more meaningful results.

Further insight can be gained when the individual degradation rates are partitioned by technology and by date of installation, as shown in Figure 3. The denotations “pre” and “post” refer to a date of installation prior to and after the year 2000, respectively. The crossbars of the diamonds indicate the mean of each category, and the extent of the diamonds indicates the 95% confidence interval. Figure 3(a) presents the results for all data collected, whereas module-only data and system-only data are given in Figure 3(b) and 3(c), respectively. The crystalline Si technologies show similar low degradation rates for pre-2000 and post-2000 categories for all data and module-only data.

However, a one-way analysis of variance reveals a significant decrease in degradation rates from the pre-2000 to post-2000 installations for thin-film technologies. Just like the module trends, the systems also show a significant pre-2000 to post-2000 decrease in degradation for all technologies. In addition, a multiway analysis of variance reveals a significant difference between modules and systems for the same time frame only in two categories: the mono-Si and cadmium telluride (CdTe) technology before 2000. Each case demonstrates the confounding effects when comparing module and system degradation. For the mono-Si category (pre-2000), the system degradation is significantly higher than the module degradation. In general, systems degradation will also include balance-of-system effects, which can be most clearly seen for mono-Si (the category with the greatest amount of data).

In addition, it seems likely that a module investigation would also include a cleaning of the modules, whereas a systems investigation most likely would also include soiling effects. On the other hand, in the CdTe category (pre-2000), the systems degradation rate is much lower than the module degradation. The likely confounding effect revealed here is that module investigations often focus on prototypes, whereas system investigations are more likely comprised of commercial products. This effect may be revealed because of the small sample size. There are evidence showing that the outdoor exposure time for pre-2000 modules and systems is considerably longer than for newer investigation, therefore increasing the accuracy for the pre-2000 categories. Another observation, which is important, is that before 2000, crystalline Si technologies dominated the literature, whereas after 2000, thin-film technologies have become increasingly common.

Degradation rates have been determined from both discrete and continuous data sets. In the continuous data category are the PVUSA or the performance ratio (PR) [2] methodologies. Both methodologies display strong seasonality that can affect reported rates and uncertainties. I–V curves are typically taken at discrete time intervals either indoors on a solar simulator or outdoors. If to compare degradation rates pre-2000 and post-2000 it becomes clear that before 2000 indoor measurements were not very frequently used to determine degradation rates. Although after 2000, that percentage has grown almost to the levels of outdoor I–V and performance ratio methods. This trend is readily explainable by the more widespread availability of solar simulators. Figure 4 indicates the number of measurements that were taken to measure degradation rates. It is noteworthy that a high percentage of references take only one or two measurements to report degradation rates. This situation is often faced when baseline measurements were never taken or no longer exist today. Thus, modern measurements need to be compared with the original manufacturer's standard test condition (STC) ratings. This approach can add significant error to the measured degradation rates [3, 4]. The accuracy of STC measurements has significantly improved during the last three decades. A 10% deviation was added to the 759 of the 1920 degradation rates based on original power and the analyses recreated to estimate the impact of more accurate STC measurements on the presented results. The effect is limited to the third significant digit for the median and average in Figures 1 and 2.

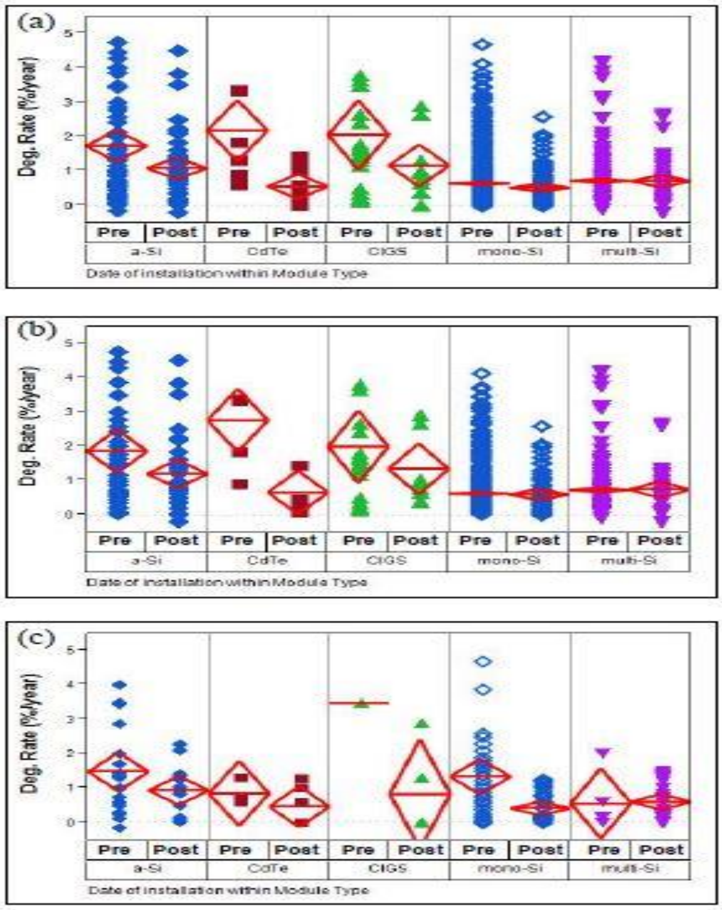

Figure 3. Degradation rates partitioned by technology for (a) all data, (b) only modules, and (c) only systems. Dates of installation prior to the year 2000 and after 2000 are indicated by “pre” and “post,” respectively

One of the approaches to deal with the problem of one measurement was presented by Becker and others. 8- to 12-year-old arrays were measured for the first time. The following year, another measurement was taken, bringing the total measurements to two and increasing the confidence level over the case where only one measurement was taken. The problem is, such a strategy may not always be practical, especially for systems in remote locations.

Another opportunity for improvement in reporting degradation rates is to place more emphasis on comprehensive uncertainty analysis, as uncertainty is directly related to financial risk. In addition, manufacturers often expose their products to tests in addition to the certification procedure. The lack of knowledge as to what accelerated testing modules have been exposed to, prior to outdoor deployment compounds, the difficulty in correlating indoor with outdoor testing

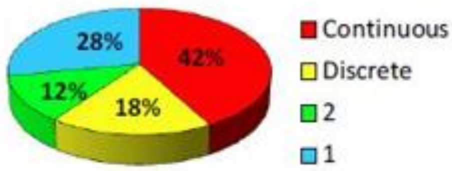

Figure 4. Percentage pie chart indicating the number of measurements taken to determine degradation rates

Degradation rate studies that compare multiple technologies are of particular interest because they exclude the effect of local conditions. Cereghetti and others reported a relatively low average degradation rate of 0·3%/year for various technologies. However, the outdoor exposure time was less than 2 years. Similar rates for crystalline technologies were found by Eikelboom and Jansen [5]. The exposure time was also relatively short: between 1 and 2 years, although high potential yields for thin-film modules in the Dutch climate are indicated.

Osterwald and others reported on a direct module-to-module comparison for various technologies in the same climate for 17 different modules [6]. Degradation rates were calculated from continuous data using the PVUSA method and compared with literature values. Most mono-Si exhibited degradation rates below 1%/year, while thin-film technologies showed rates above 1%/year.

Marion and others not only compared degradation rate results for different technologies but also compared rates obtained using the PVUSA method with rates obtained from the performance ratio[7]. Both methodologies seemed to agree well for different technologies.

Several crystalline and thin-film technologies were compared by Tetsuyuki and others [8]. The multicrystalline silicon modules were found to exhibit systematically smaller degradation rates than the mono-Si modules and substantially lower rates than the a-Si modules. Copper indium gallium selenide (CIGS) modules were found to show a slight improvement over the measuring period of 3 years; the improvement was attributed to light soaking.

Vaassen, in 2005, reported on the performance of six modules over 4 years, finding degradation rates slightly below 0·5%/year in the temperate climate of Germany [9]. Similar results were presented by Becker and Bettinger: 36 modules of various technologies showed an overall degradation rates of about 0·5%/year in the same climate [10].

Jordan and others compared more than 44 modules of various technologies side by side [11]. It was found that technology and date of installation were the most important factors determining degradation rates. Thus, modules were equally divided into modules installed prior to and after the year 2000. While the crystalline Si technologies appear to have stayed at degradation rates below 1%/year, thin-film technologies appear to have improved significantly, although some categories were limited by the small sample size.

Other degradation rate studies containing multiple technologies are more focused on methodology improvement rather than technology comparison. Jordan and Kurtz showed how analytical methods can be employed to reduce seasonal effects and therefore improve accuracy and the required length of monitoring time for multiple technologies. Another important effect to consider for continuous data collection is the effect of data filtering on the determination of degradation rates. Kimber and others showed that using only sunny days, provided the data size is not greatly reduced, may lead to reduced uncertainty in degradation rates[12]. Zhu and others proposed a different filtering approach based on short-circuit current (Isc) as a measure of irradiance [13].

After identification and elimination of outliers, module degradation rates are determined from the evolution of probability density functions instead of averages, thus providing more information on the degradation modes. Pulver and others developed a methodology to determine degradation rates when no local irradiance measurement exists [14]. A number of systems at the same location can be used to calculate degradation rates with respect to an average of all systems. A statistical correction procedure could be used to deduce absolute degradation rates.

A great number of degradation rates, measured on individual modules or entire systems, show a mean degradation rate of 0·8%/year and a median value of 0·5%/year. The majority, 78% of all data, reported a degradation rate of <1%/year. Thin-film degradation rates have improved significantly during the last decade, although they are statistically closer to 1%/year than to the 0·5%/year necessary to meet the 25-year commercial warranties. The significant difference between module and system degradation rates observed early on has narrowed, implying that substantial improvement toward the stability of the balance-of-system components has been achieved.

Despite the progress achieved in the last decade, several interesting questions, such as the linearity, the precise impact of climate and efficiency increase have not been satisfactorily answered. Nevertheless, the number of publications on long-term performance has been growing rapidly in recent years, reflecting the importance of the subject.

Thanks to the latest big data and predictive analysis technology, renewable energy companies can now produce more energy without yielding additional infrastructure costs. The ever-growing ability to extract useful information from big data is one of the reasons behind the gradual decline in the renewable energy prices. In the coming decade or so, renewable energy will be cost competent with its conventional counterparts.

Big data, just like any other industry is revolutionizing the renewable energy industry as well. However, the key is not one specific data tool, but using a combination of several different data techniques to increase the efficiency while reducing the production cost. The ever-evolving technology has already bought installation cost of renewable power plants (solar and wind) to the lowest point in history. The big data tools will not only bring it down further but also make such projects more bankable. The bottom line is big data is changing the renewable energy sector for better.

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