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Photovoltaic Degradation Rates — An Analytical Review

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Abstract

As photovoltaic penetration of the power grid increases, accurate predictions of return on investment require accurate prediction of decreased power output over time. Degradation rates must be known in order to predict power delivery. This article reviews degradation rates of flat-plate terrestrial modules and systems reported in published literature from field testing throughout the last 40 years. Nearly 2000 degradation rates, measured on individual modules or entire systems, have been assembled from the literature, showing a median value of 0.5%/year. The review consists of three parts: a brief historical outline, an analytical summary of degradation rates, and a detailed bibliography partitioned by technology.

Keywords: Photovoltaic modules, photovoltaic systems, performance, outdoor testing, field testing, degradation rates

1. Introduction

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. An accurate quantification of power decline over time, also known as degradation rate, is essential to all stakeholders—utility companies, integrators, investors, 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, therefore, reduces future cash flows [1]. Furthermore, inaccuracies in determined degradation rates lead directly to increased financial risk [2]. Technically, degradation mechanisms are important to understand because they may eventually lead to failure [3]. Typically, 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 experiments and modeling 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.

Although every reference included in this paper contains a brief to slightly extensive summary of degradation rate literature, a comprehensive review could not be found. This article aims to provide such a summary by reviewing degradation rates reported globally from field testing throughout the last 40 years. After a brief historical outline, it presents a synopsis of reported degradation rates to identify statistically significant trends. Although this review is intended to be comprehensive, it is possible that a small percentage of the literature may not have been included.

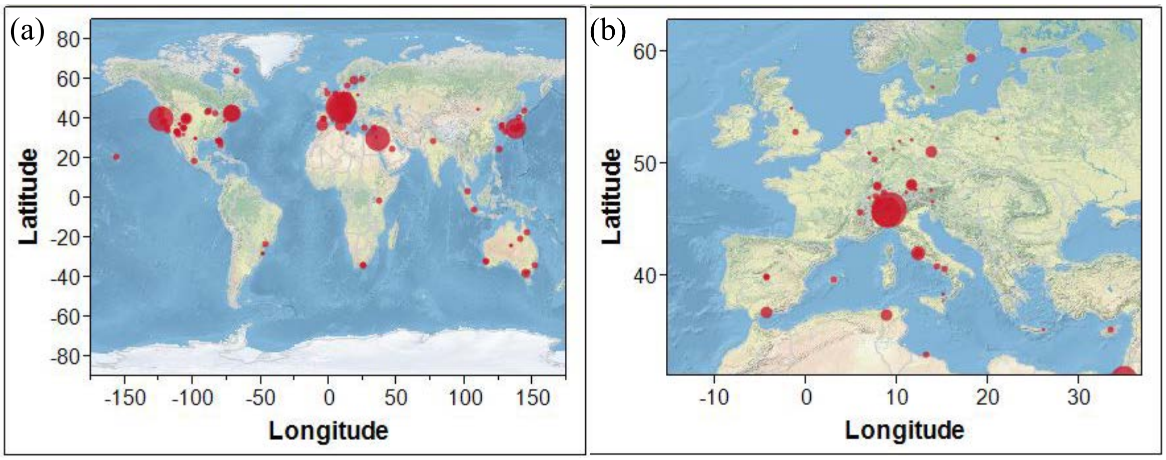

Figure 1. Geographical distribution of degradation rates reported in publications, (a) worldwide and (b) a large part of Europe. The size of the circle is indicative of the number of data points from a given location.

2. Historical Overview

Figure 1 shows a map with degradation rates reported in publications discussed in this article. The size of each circle is indicative of the number of degradation rates reported at a given location. The four major regions prior to the year 2000 wherein long-term field observations have taken place are the USA, Europe, Japan, and Australia. These four regions are discussed within their historical context, as understanding the PV history for terrestrial applications elucidates time and place of degradation rate field observations. After 2000, a large number of observations have been reported with equal diversity in technology and geography.

2.1. USA

The modern era of PV technology could be claimed to have started in the 1950s at Bell Telephone Laboratories [4, 5]. When the Space Age officially started with the launch of the Russian Sputnik satellite in 1957, PV technology and satellites were ideally suited for each other. The first satellites such as Vanguard I required only moderate power, and the weight of the solar panels was low. Reliability was ensured by protecting the cells with a quartz or sapphire cover sheet from energetic particles outside the atmosphere and by using n-on-p type cells [6]. The oil crisis of 1973 changed the focus of PV from space to terrestrial applications, particularly applications in remote locations. Major oil companies were among the first to provide PV a terrestrial market in the form of supervisory controls, cathodic well corrosion protection, buoys, oil platform lights, and horns [7] that were much more economical than traditional battery-powered solutions for remote locations on land and water [8]. However, with an environment drastically different from space applications, the long-term reliability of PV modules faced vastly different challenges. These were addressed starting in 1975 through the Flat-Plate Solar Array project under the auspices of the Energy Research and Development Administration, which in 1977 was integrated into the U.S. Department of Energy [9-11]. Because of its PV experience in space, the National Aeronautics and Space Administration was involved through two laboratories, the Jet Propulsion Laboratory (JPL) in California and the Lewis Research Center in Ohio. JPL conducted a block buy program, procuring state-of-the-art modules and testing them [12]. Based on field experience and failure analysis of degraded modules, each of the five block buys placed more and more stringent accelerated stress tests on the modules, providing valuable information toward later standards such as module qualification standard IEC 61215 [13, 14]. Field tests were conducted via installation at various sites including the Lewis Research Center and the Lincoln Laboratory at MIT, constituting the first systematic outdoor testing [15]. While Block I modules did not experience high failure rates in the field, they exhibited high degradation rates and provided insights into the various types of outdoor degradation mechanisms [16-18]. Roesler *et al.* also reported high degradation rates for pre-Block V modules in a 60-kW plant at the Mt. Laguna Air Force Station; these were probably caused by hot spot problems (Wohlgemuth, private communication) [19].

From 1983 to 1985, the Atlantic Richfield Oil company constructed the first large PV site at what is known today as the Carrizo Plain National Monument in central California. The produced electricity was sold to the Pacific Gas and Electric Company, which also supervised the data monitoring. The Carissa Plains project, as it was known at the time, used mirror enhancement resulting in high module temperature and ultraviolet exposure. The rapid power decline and maintenance experience at this site were initially attributed to the significant encapsulant browning [20-22]. Wohlgemuth and Petersen later demonstrated that much of the power loss in these modules was due to bad solder bonds, not ethylene vinyl acetate (EVA) browning [23]. In 1986, the Photovoltaics for Utility Scale Application (PVUSA) was initiated, a cost-sharing collaboration between private companies and government [24]. The project was designed to bridge the gap between large utility companies unfamiliar with PV technology and the small PV industry unfamiliar with the requirements of large utility companies [25]. The main PVUSA sites were Davis, CA, USA, and Maui, HI, USA [26]. In addition to valuable hands-on experience and detailed knowledge about maintenance costs, PVUSA also provided a new rating methodology that is still used today [27, 28]. The long-term performance of the main sites can be found in the PVUSA progress reports [29, 30]. The PVUSA project required qualification to tests developed at the National Renewable Energy Laboratory (NREL), Sandia National Laboratories, and JPL[30]. In an extensive field survey of systems consisting of pre- and Block V modules, Rosenthal *et al.* found that the failure rates decreased significantly from 45% for pre-Block V to less than 0·1% for Block V modules [31]. In addition, degradation rates for 10 selected systems were found to be larger than 1%/year. Atmaram *et al.* reported on Block IV and V monocrystalline Si systems deployed in Florida and found degradation rates well below 1%/year [32].

In 1977, the Department of Energy established the Solar Energy Research Institute in Golden, Colorado. In 1991, it was renamed as the NREL. Outdoor testing of modules and submodules started at the Solar Energy Research Institute in 1982. When amorphous silicon (a-Si) modules first became commercially available, NREL began to report degradation rates that were substantially higher than 1%/year for single and tandem junction modules although the continuous testing time rarely exceeded 1 year, implying that some of this was the initial light-induced degradation [33, 34]. Pratt and Burdick reported on the multiyear progress of a 4-kW a-Si array commissioned in Michigan in 1987. Although the degradation rate was found to be much lower, it still exceeded 1%/year in the first year of operation and then was stable between years 2 and 3 [35-37]. Kroposki and Hansen showed similar results (initial light-induced degradation, followed by a small, ≤1%/year degradation) for four separate single and tandem junction 1–2-kW a-Si systems deployed at NREL [38].

2.2. Europe

Akin to almost every country, the terrestrial focus of PV in Europe can be traced to the oil crisis of the 1970s. The development and institution of PV sites can be divided into publicly and privately funded projects. The publicly funded part in Europe can be additionally divided into the umbrella organization of the Commission of the European Communities and individual national programs. The Commission of the European Communities actively pursued PV installations among its member states beginning in 1975 [39]. The Directorate General (DG XII) initiated a PV pilot program with 16 systems installed across Europe from 1982 to 1984 with a total capacity of 1 MWp. The Directorate General "Energy" (DG XVII) initiated a demonstration program to bridge the gap between research and development and commercialization [40]. A minority of these installations were grid-connected applications, with the majority of them being for remote applications including housing, lighthouses, warning systems, water pumping, and telecommunications. Whereas the PVUSA project in the USA utilized a regression method to document the power performance under a set of reference conditions, the European analysis more frequently documented the energy output (performance ratio or array yield) as an indicator of the ongoing performance of the PV systems [42]. The Joint Research Centre (JRC) in Ispra, Italy was founded in 1959 as a research center focusing on nuclear energy. In 1974, part of the center, the European Solar Test Installation, was dedicated to solar research [41]. Until 1983, JRC was largely concerned with test installations, testing of modules, and developing standard test procedures. The focus then shifted to also include data monitoring of pilot and demonstration plants [42]. Since 1985, JRC has coordinated a European Working Group on PV plant monitoring criteria, plant performance, quality control, analysis, and lessons learned. In the monitoring guidelines published by JRC in 1987, the monitoring length is specified to be 2 years [43]. Therefore, the literature that immediately followed contained data for at least 2 years. Kaut et al. reported on experiences and performance declines for several of these demonstration program plants in 1989 [44]. Nentwich et al. showed excellent stability for a plant at a high-altitude location in Austria [45]. The study was updated and expanded to include other high-latitude locations as the Alpsolar project [46]. Häberlin and Beutler also reported good stability for a crystalline Si array at a high-altitude location at the Jungfrau in the Swiss Alps [47]. The array was installed as a facade and does not experience any snow load. The study was later updated, and the system continued to exhibit excellent stability [48]. Berman et al. investigated nearly 200 multicrystalline silicon (multi-Si) modules installed in the Negev desert of Israel in 1995 [49]. The mirror-enhanced modules experienced degradation rates of less than 1%/year after 5 years. Further interesting studies before 2000 included reports from Italy [50], Finland [51], Switzerland [52], and Spain [53].

2.3. Japan

In Japan, the first outdoor installations were carried out by Sharp for lighthouses, the first one being on the island of Ogami in the Nagasaki prefecture in 1966. By the 1970s, over 200 lighthouses were equipped with PV [8]. Further PV development started with the implementation of the "Sunshine Program" by the Japanese government in 1974. Beginning in 1982, the Japan Quality Assurance Organization, sponsored by the New Energy and Industrial Technology Development Organization, conducted outdoor testing at five sites in Japan and four sites abroad.

As part of the “Sunshine Program,” Takigawa *et al*. found fairly large degradation rates for early a-Si prototype modules compared with more advanced models during the 3 years of outdoor exposure [54]. After the start of the “New Sunshine” program in 1992, an extensive field testing section was integrated into the program. Fukae *et al*. reported on the performance of triple junction a-Si modules and crystalline Si control modules at three different locations in Japan and Malaysia [55]. Although the observation time was only around 1 year, Fukae *et al*. showed that the a-Si modules performed better at higher temperatures. In 1997, Akhmad *et al*. reported a much larger degradation rate for a-Si than multi-Si, similarly showing that the performance of the a-Si increased during the summer, whereas that of the multi-Si decreased [56]. Ikisawa *et al*. from Japan Quality Assurance Organization reported on a-Si modules at three different sites in two different climate zones and found degradation substantially below 1%/year [57]. Machida and Yamazaki reported on six module samples taken from a 50-kW array near Tokyo. Outdoor exposure was for more than 5 years, with monocrystalline silicon (mono-Si) showing larger power decline than multi-Si [58].

2.4. Australia

Australia, with its large geographic size relative to population size, was in need of telecommunications from remote locations. PV provided an inexpensive alternative to generators and high-maintenance batteries. Therefore, telecommunication companies were the first to install PV modules and arrays and also the first to survey the long-term field performance and outcome in different climates. Muirhead and Hawkins reported first on the large Telstra PV network experience in 1995, including 35 mono-Si modules deployed for 8 years in the Melbourne climate, showing an average decline of 0·4%/annum with a normal distribution [59]. One year later, the same authors expanded their findings in terms of technologies and sites. Higher degradation rates were found for thin-film modules compared with crystalline Si modules [60].

2.5. Global Organization

The International Energy Agency established the Photovoltaic Power Systems program in 1993 to enhance international collaboration. Task 2 of this program was dedicated to the performance, reliability, and trend analysis of PV systems. This effort has been continued in Task 13. Degradation information can be found in the technical reports and on the web page of the International Energy Agency (http://www.iea-pvps.org/) [61].

3. Analysis & Discussion

3.1. Synopsis of Degradation Rates

Figure 2 shows a summary histogram of degradation rates reported in this review. The summarized rates are long-term degradation rates and do not include short-term, light-induced degradation. A decrease in performance is defined as a positive degradation rate. Conversely, a negative rate indicates an improvement. Although this histogram needs to be updated frequently as new information becomes available, some general insights can be drawn from it. 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 *et al.* used for their calculations for the levelized cost of energy for PV [62]. In addition, Figures 2(b) and 2(c) show 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.

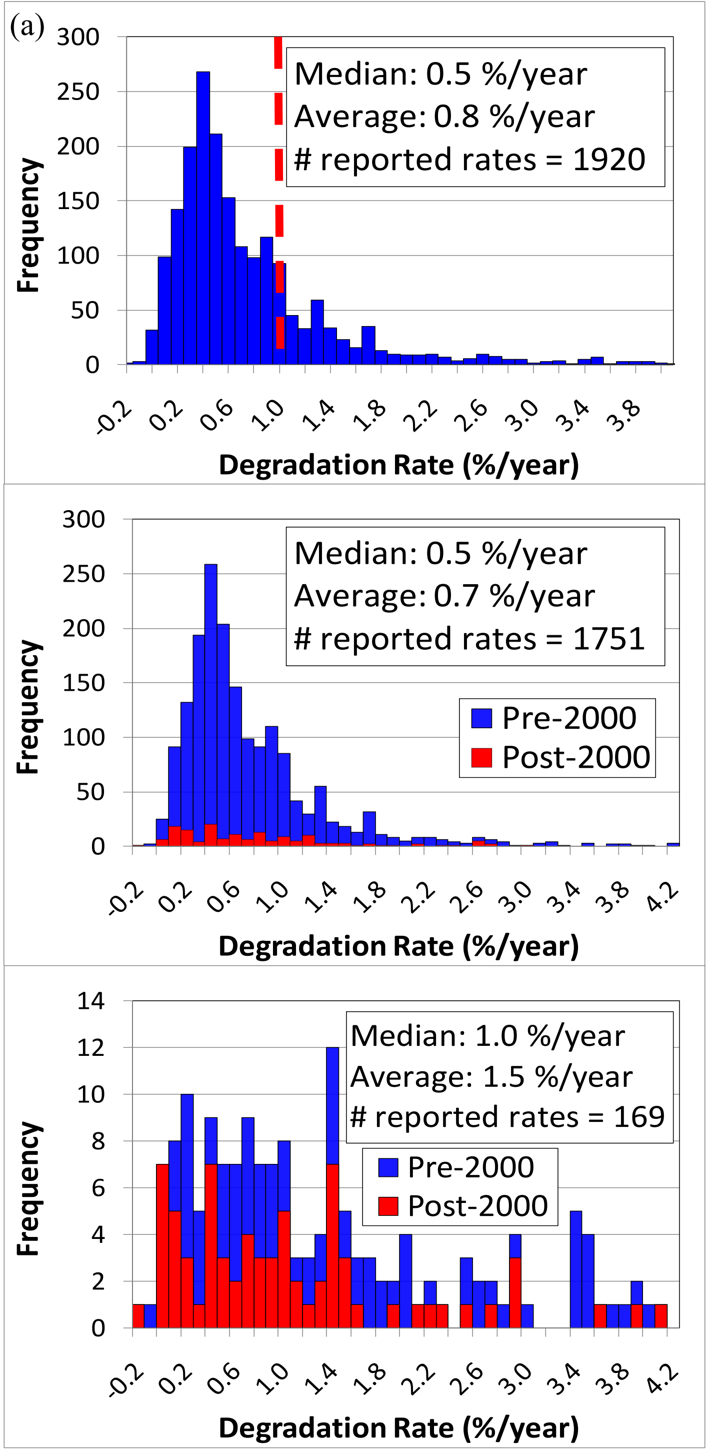

Figure 2. Histogram of reported degradation rates for all degradation rates (a), for Si only (b), and for thin-film technologies only (c). Median, average and number of reported rates are indicated. In addition, Si and thin-film are color-coded by date of installation into pre-2000 and post-2000.

This compilation of degradation rates is a survey of literature results and not a scientific sampling. 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 seen in Figure 3, which shows the degradation rates from Figure 2 partitioned by the field exposure length. For studies with monitoring times up to 10 years, it can be seen 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 included in this review, its influence cannot be completely excluded. 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 make the graph meaningful.

As module durability increased during the last three decades, module warranties increased accordingly. Figure 4 shows the outdoor exposure length versus the publication year. A typical module manufacturer warranty [63], shown for comparison, exceeds the field-testing length for most of the last 25 years. Only in the last 5 years have there been studies that meet or exceed a typical module warranty.

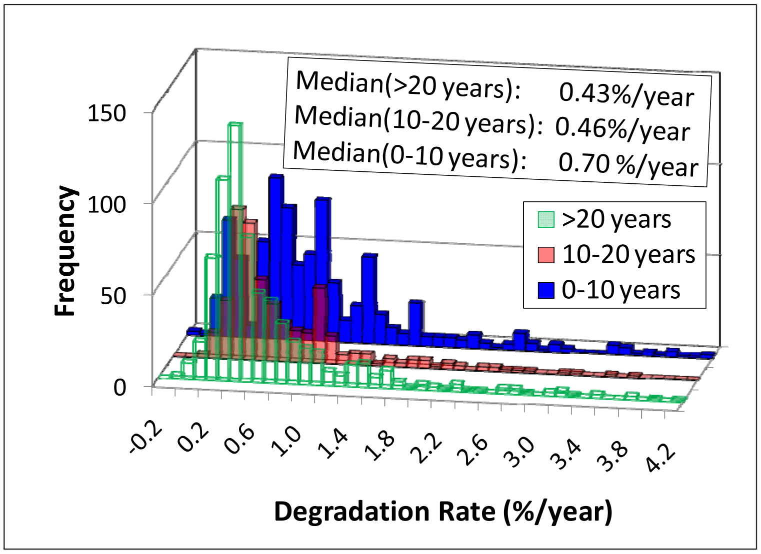

Figure 3. Degradation rate histogram grouped by outdoor exposure length. The median rate for exposure length up to 10 years is significantly higher than for studies of 10 years and longer.

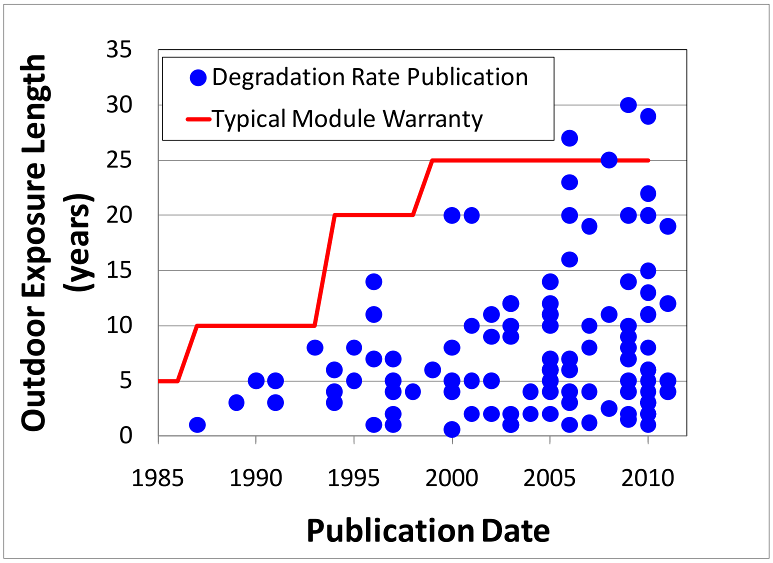

Figure 4. Outdoor field exposure in years versus date of publication. Module warranty from one manufacturer is shown as comparison.

Further insight can be gained when the individual degradation rates are partitioned by technology and by date of installation, as shown in Figure 5. The denotations "pre" and "post" refer to a date of installation prior to and after the year 2000, respectively. The choice of the year 2000 is somewhat arbitrary and was mostly driven by the decision to have an approximately equal number of data points for each category. The crossbars of the diamonds indicate the mean of each category, and the extent of the diamonds indicates the 95% confidence interval. Figure 5(a) shows the results for all data collected, whereas module-only data and system-only data are given in Figure 5(b) and 5(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. Similarly to 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 to 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).

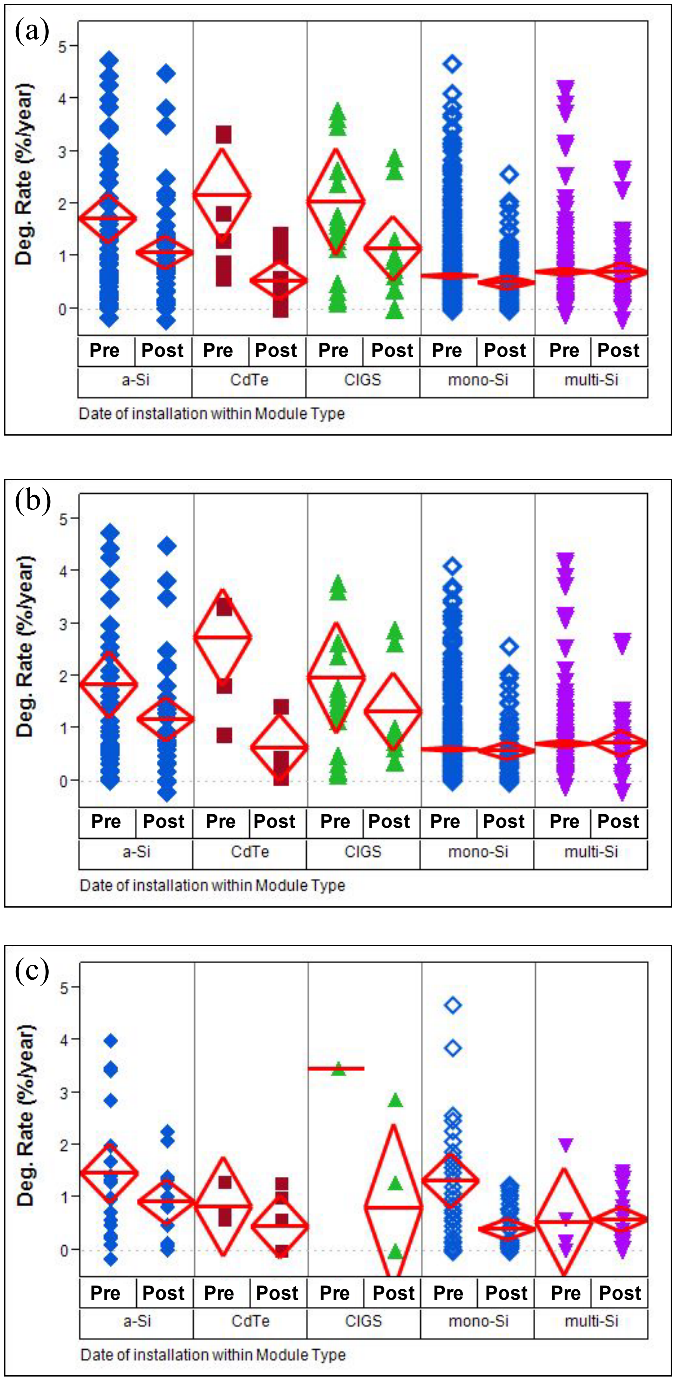

Figure 5. Degradation rates partitioned by technology for (a) all data, (b) only modules, and (c) only systems. Dates of installation prior to the year 2000 and after 2000 are indicated by "pre" and "post," respectively. The crossbars denote the mean for each category, and the diamond, the 95% confidence interval. a-Si, amorphous silicon; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; mono-Si, monocrystalline silicon; multi-Si, multicrystalline silicon.

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. The modules were prototype modules from the early to mid-1990s, while the system category consisted of commercially available modules from the late 1990s. This effect may be revealed here because of the small sample size. Table 1 also shows 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 that can be made from Table 1 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 continuous and discrete data sets. In the continuous data category are the PVUSA or the performance ratio (PR)[64] 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. Figure 6 shows a pie chart of the methodologies used to determine degradation rates pre-2000 and post-2000. The greatest change is that before 2000, indoor measurements were not very frequently used to determine degradation rates. However, 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 7 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 encountered 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.[1] This approach can add significant error to the measured degradation rates [65, 66]. 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 2 and 3.

An interesting approach to mitigate the problem of one measurement was presented by Becker *et al.* [67] Eight- 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. However, 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 correlated to financial risk [2]. 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.

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[1] STC: irradiance = 1000 W/m², air mass = 1.5, module temperature = 25°C.

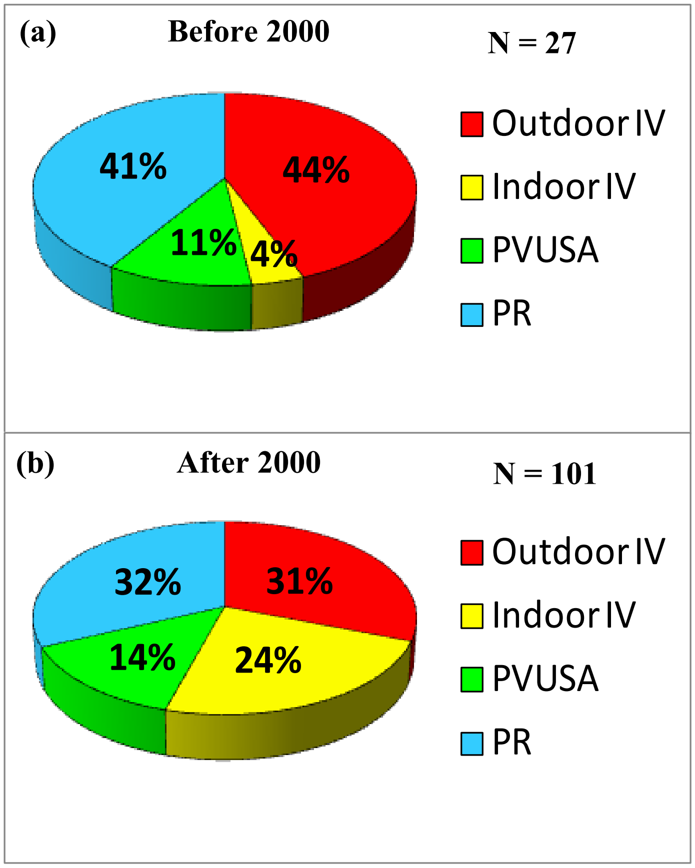

Figure 6. Pie chart of the number of references deploying the indicated methods to determine degradation rates, (a) prior to and (b) following the year 2000. PVUSA, Photovoltaics for Utility Scale Application; PR, performance ratio.

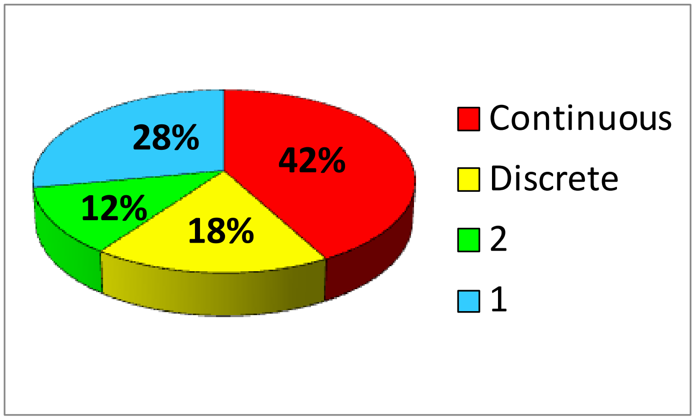

Figure 7. Percentage pie chart indicating the number of measurements taken to determine degradation rates.

Detailed Bibliography

Multiple Technologies

Degradation rate studies that compare multiple technologies are of particular interest because they exclude the effect of local conditions. Cereghetti *et al.* reported a relatively low average degradation rate of 0·3%/year for various technologies. However, the outdoor exposure time was less than 2 years [68]. Similar rates for crystalline technologies were found by Eikelboom and Jansen [69]. 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 *et al.* reported on a direct module-to-module comparison for various technologies in the same climate for 17 different modules [70]. 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. Raghuraman *et al.* investigated mono-Si, multi-Si, and a-Si module technologies from eight different manufacturers. Amorphous Si modules showed higher performance scatter [71]. Marion *et al.* 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 [72]. Both methodologies seemed to agree well for different technologies. Granata *et al.* investigated eight systems, and almost all degradation rates were within the experimental uncertainty [73]. Another important lesson learned was that proper commissioning is required to discover improperly installed systems early and prevent reliability issues. This may require sensitive monitoring at the string level. In 2008, Vázquez and Rey-Stolle presented results of reliability modeling based on literature degradation results and demonstrated that a degradation rate of less than 0·5%/year is required to satisfy long-term warranties [74]. Several crystalline and thin-film technologies were compared by Tetsuyuki *et al.* [75]. 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 [76]. Similarly, Becker and Bettinger presented results from 36 modules of various technologies with an overall degradation rate of approximately 0·5%/year in the same climate [77]. Makrides *et al.* examined the outdoor performance of several modules and technologies in Cyprus [78, 79]. A substantial difference in results was observed when comparing the PR and the PVUSA methodologies, possibly due to the combination of seasonality and relatively short monitoring time of 2 to 3 years [80]. Jordan *et al.* compared more than 44 modules of various technologies side by side [81]. 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 [82]. Another important effect to consider for continuous data collection is the effect of data filtering on the determination of degradation rates. Kimber *et al.* showed that using only sunny days, provided the data size is not greatly reduced, may lead to reduced uncertainty in degradation rates [83]. Zhu *et al.* proposed a different filtering approach based on short-circuit current (I_{sc}) as a measure of irradiance [84, 85].

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 *et al.* developed a methodology to determine degradation rates when no local irradiance measurement exists [86]. 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. Additional studies of interest comparing multiple technologies have been reported in Australia [87], France [88], Switzerland [89], South Korea [90], and USA [91].

Crystalline Silicon

Because crystalline Si technology is the oldest module technology, several outdoor studies exceeding 20 years in length can be found [90, 92, 101-105, 107-116, 125, 131, 136]. Quintana *et al.* documented the increased degradation rate for an entire system compared with module degradation for the Natural Bridges National Park PV system in Utah, USA. The module degradation rate for these Block II modules was a remarkable 0·5%/year; however, the system degradation rate was a much higher 2·5%/year, highlighting the above-mentioned balance-of-system and soiling effects in long-term field investigations [92]. Reis *et al.* investigated 192 mono-Si modules in Arcata, CA, USA, over 11 years of exposure and found on average a low 0·4%/year degradation rate. Most of these losses were losses in I_{sc} [93]. Osterwald *et al.* made similar observations for a set of two monocrystalline and two multicrystalline modules. The rapid initial degradation was attributed to oxygen contamination in the bulk of the Si junction, whereas the slow long-term degradation correlated linearly with ultraviolet exposure. However, it appeared unlikely that the slow loss was due to EVA browning [94]. Morita *et al.* found the increase in series resistance as the cause for degradation [95]. Sakamoto and Oshiro confirmed similar findings through the inspection of more than 2000 modules, 150 of which were studied in more detail. The average degradation rate was less than 0·5%/year with dominant losses in fill factor (FF) and I_{sc} [96]. Hishikawa *et al.* also reported I_{sc} losses on 2400 investigated modules in Japan [97]. King*et al.* found a median degradation rate of 0·5%/year in a mono-Si system and traced the decline to the solder joints in the modules [98]. Similarly, Wohlgemuth *et al.*, in an extensive survey of field returns of more than 4000 modules, found that more than 90% of field failures were caused by corrosion and interconnect breakage. High degradation rates in a system were usually due to individual module failures or other electrical components [99, 100]. Dunlop *et al.* initially investigated 40 modules installed at the European Solar Test Installation over the period of 1982–1984 [101, 102]. The analysis was then expanded by Skoczek *et al.* to a total of 204 modules installed between 1982 and 1986 [103-105]. No statistical difference was found between mono-Si and multi-Si technologies; however, modules left in open-circuit conditions exhibited lower degradation rates than modules connected to an inverter. The observation is attributed to the thermomechanical fatigue of the interconnects. Furthermore, modules incorporating silicone encapsulant showed lower degradation than EVA and polyvinyl butyral encapsulants. Glass–glass modules exhibited larger degradation rates than glass–polymer modules. High degradation rates were attributed to high losses in FF, i.e., significant increases in series resistance, while moderate degradation rates were due to optical losses in I_{sc}. In addition, visual appearance is not indicative of electrical behavior. Sanchez-Friera *et al.* found a fairly large degradation rate of almost 1%/year over 12 years in Spain, with most of the losses in I_{sc}. One of the potential loss mechanisms is ascribed to the antireflective coating, in addition to front delamination and inherent junction degradation [106]. Another important question is whether long-term degradation rates are inherently linear or nonlinear. De Lia *et al.* reported on the efficiency degradation of an array in Italy after 22 years of field exposure. The degradation appeared to be linear; however, in a retest of the same array after 30 years, it was found that the failure rates appeared to increase nonlinearly. A similar statement about the degradation rate cannot necessarily be made because of the low number of data points [107-110]. Realini *et al.* reported on a 10-kW system in Southern Switzerland that showed only a small 0·2%/year system degradation after approximately 20 years [111, 112]. Later, Sample provided measurements on the individual modules for the same system [105]. Different climate conditions may have an important influence on degradation rate. Therefore, degradation rate studies from diverse geographical locations are of great interest. Hedström and Palmblad presented data on 20 modules exposed for more than 25 years at a northern latitude in Sweden. The average degradation rate was a remarkably low 0·17%/year [113]. Bing also observed good stability for two separate systems in the similar continental climate of Massachusetts, USA, after more than 20 years [114]. In contrast, Saleh *et al.* found a degradation rate of approximately 1%/year for a stand-alone system in the desert climate of Libya after 30 years [115]. Tang *et al.* found a similar degradation rate for a system of approximately the same age located in the similar climate of Phoenix, AZ, USA [116]. Bogdanski *et al.* reported on a systematic study of crystalline modules in four different climates: the moderate temperate climate of Germany, the alpine climate of the German Alps, the hot and humid climate of Indonesia, and the hot and dry climate of Israel [117]. Evidence indicated that not only weathering but also failure mechanisms are location dependent. The highest degradation rates were observed in the polar/alpine climate, apparently because of high snow and wind loads. It is of interest to note that two other studies of crystalline Si technologies in the polar/alpine climate, one in the Canadian Arctic[118] and the other at a very high altitude in the European Alps, [48] found very low degradation rates. In both cases, the systems were installed in a facade and therefore bear no snow load. Marion and Adelstein found a decline of approximately 1%/year for two separate mono-Si arrays in Golden, CO, USA; most of that loss was attributed to the array. A small part originated from the maximum power tracking of the inverter, highlighting the importance of taking array decline into account for appropriate sizing [119]. Kiefer *et al.* surveyed several sites and found no degradation within the measurement uncertainty. To avoid the influence of seasonality, they only used the data from the same time period of the year for the evaluation [120]. The need for accurate measurements is pointed out by Vignola *et al.*, who observed degradation rates between 0·6% and 1·5%/year in Oregon, USA [121]. Given accurate measurements, a degradation rate of 1%/year may be detected in as little as 2 years. Davis *et al.* determined degradation rates from several systems in Florida, USA, and employed different analytical methods to determine uncertainties [122]. Bunea *et al.* presented results of a side-by-side comparison of an array with and without an antireflective coating. The multiyear stability of the two arrays is comparable within the uncertainty [123].

Alonso-Abella *et al*. measured over 3000 modules from a 1-MW plant near Toledo, Spain, that was mentioned above and estimated degradation rates below 0·5%/year for one type of module and above 1%/year for another [53, 124]. Guastella provided an update on the Vulcano, Italy, plant and found degradation rates close to zero after 20 years of field exposure [125]. Additional studies on mono-Si in diverse geographical locations and climates from Mongolia [126], India [127], Spain [128], Brazil [129, 130], Tunisia [131], Japan [132], South Korea [133, 134], Saudi Arabia [135, 136], and Greece [137] have been reported.

Amorphous-Si

Rüther *et al*. reported on a round-robin study of four dual junction and one triple junction a-Si modules deployed simultaneously at three different sites in three different climates: Colorado and Arizona, USA, and Brazil [138]. Over the course of 4 years, all modules were exposed for 1 year at each of the locations and investigated [139, 140]. Outdoor minimum temperature was found to be the determining factor for long-term stabilized performance. Fanni *et al*. investigated the annealing and degradation processes in flexible triple junction a-Si modules [141]. The degradation depended on the electric load: it was faster in open-circuit conditions than in short-circuit conditions.

Dhere *et al*. examined a triple junction system in the hot and humid climate of Florida, USA. The reported degradation rate was 0·5%/year [142, 143]. Gottschalg *et al*. examined five different dual junction systems in different climate zones [144]. Seasonal effects commonly observed for a-Si systems were not attributed to seasonal annealing effects but due to incident spectra. Adelstein and Sekulic found a degradation rate of approximately 1%/year for a triple junction roof shingle a-Si system over 6 years [145]. The performance was assessed with the PVUSA and PR methods. McNutt *et al*. found a degradation rate above 1%/year after a 1-year stabilization period for a dual junction system that was decommissioned soon afterwards [146, 147]. Gregg *et al*. demonstrated a degradation rate of less than 1%/year for a triple junction system [148]. Davis and Moaveni compared the economics of a mono-Si with an a-Si system in the hot and humid climate of Florida, USA [149]. While the degradation rate for the a-Si system was significantly larger than that for the mono-Si system, lower upfront costs resulted in two closely matched systems. Comparable economics was also pointed out by Osborn for degradation rates below 1%/year [150, 151]. Abete *et al*. reported a fairly high degradation rate for a dual junction a-Si 12-kW system near Torino, Italy. A one-diode model was used to simulate the beginning of life performance as a baseline [152]. Apicella *et al*. reported a degradation rate of approximately 1%/year for a single junction a-Si system in Italy [153]. A much higher rate was found for a microcrystalline Si system, possibly reflecting the maturity of the technology. Pietruszko *et al*. analyzed the performance of a dual junction a-Si system in the continental climate of Poland and observed a degradation rate of less than 1%/year [154]. Dirnberger *et al*. compared the degradation rates of several thin-film systems [155]. Degradation rates were close to zero and within the measurement uncertainty except in the moderate climate of Germany for a CdTe system. Single, double, and triple junction a-Si systems were investigated that displayed the predictable early light-induced degradation. Long-term stability depended more on module type than on technology. Häberlin and Schärf found the performance of several a-Si and a CIGS system comparable with that of mono-Si plants in the same location of Switzerland[156]. Guastella found very small degradation for an a-Si plant in Italy [157], as did Rüther *et al*. for an a-Si system in Brazil [158, 159]. Other long-term tests of interest include comparison of CIGS to a-Si and of single to triple junction a-Si in South Africa [160, 161] and for single junction a-Si modules in the Kenyan market [162].

Copper Indium Gallium Sellenide (CIS)

Tarrant *et al*. reported on CIGS systems deployed at different sites in the USA [163]. On the basis of engineering modules, degradation rates were examined with respect to two different frame configurations. Del Cueto *et al*. detailed CIGS outdoor stability over two decades, utilizing three different testbeds in Colorado, USA [164]. It was shown that degradation rates can vary significantly depending on module type. The primary loss mechanism appears to be in the FF that is associated with an increase in series resistance. Musikowski and Styczynski demonstrated virtual stability of a CIGS array in Germany [165]. The performance was evaluated for different temperature and irradiance windows and showed no measureable degradation after 6 years of operation. A comparable observation was made by Jordan *et al*. at NREL in Colorado, USA [166]. Outdoor observation showed no significant decline after 5 years of operation. This was confirmed by indoor measurements. Only one out of 14 modules showed appreciable degradation owing to an initial manufacturing defect.

Cadmium Telluride (CdTe)

Marion *et al*. analyzed a CdTe system at NREL in Colorado, USA [167]. Individual module efficiencies varied widely, with some improving by more than 10% while others degraded by more than 10% over a 5.5-year test period. However, the overall system degraded by approximately 0·6%/year. Ross *et al*. found a similar degradation rate for a system located in the hot and dry climate of Tucson, AZ, USA, over 3 years [168]. In addition, a system in the moderate climate of Germany was found to be virtually stable. Foster *et al*. found degradation rates ranging from close to zero to 1%/year for several systems installed in a hot and humid climate of Mexico [169].

Conclusion

A history of degradation rates using field tests reported in the literature during the last 40 years has been summarized. Nearly 2000 degradation rates, measured on individual modules or entire systems, have been assembled from the literature and 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 and the precise impact of climate, 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. It is the hope of the authors that this trend continues such that the increased information can better guide the development of accelerated tests. Finally, there may now be cumulative field experience to support long-term warranties, both because there are now products in the field for more than 25 years and because the average degradation rate still allows reasonable performance after 25 years.

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Table 1. Summary of the median degradation rate, number of data points reported, and number of publications partitioned by date of installation, technology, and configuration. “Pre” and “post” refer to installations prior to and post 2000.

		Number of. references		No. of Data Points		Median Exposure time (years)		R_d median (%/year)		Reference
Technology	**Configuration**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre & Post**
a-Si	Module	10	12	45	31	7	2	0.96	0.87	34, 55-57, 61, 71-74, 78, 81-84, 87, 88, 90-92, 141-145, 163-165
	System	14	9	21	14	5	4	1.30	0.95	31, 35-39, 75, 85, 94, 147, 146-162
CdTe	Module	3	4	7	6	3	2	3.33	0.40	61, 73, 81-84, 91, 92
	System	3	2	3	6	10	3	0.69	0.30	75, 85, 170, 171
CIGS	Module	2	6	20	10	8	3	1.44	0.96	71-73, 78, 84, 90, 91, 163, 166, 168, 169
	System	1	5	1	5	4	6	3.50	0.02	89, 158, 159, 169
mono-Si	Module	31	11	1133	55	21	3	0.47	0.36	54, 59-61, 70-74, 77-84, 90-93, 95-99, 102-118, 120, 129-134
	System	19	13	42	37	7	5	0.90	0.23	19-23, 30-33, 46-49, 51-54, 62, 75, 76, 86, 89, 94, 95, 100, 101, 113, 119, 121-128, 135-139
multi-Si	Module	15	9	409	36	10	3	0.61	0.64	50, 51, 57, 59, 61, 71, 74, 78-84, 90, 92, 97-99, 102-108, 117, 120, 129
	System	6	8	5	21	9	5	0.60	0.59	31, 47, 51, 62, 63, 76, 85, 86, 89, 94, 123-125, 129, 140

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