Outdoor PV Degradation Comparison

D.C. Jordan, R.M. Smith, C.R. Osterwald,
E. Gelak, and S.R. Kurtz

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OUTDOOR PV DEGRADATION COMPARISON

D.C. Jordan, R.M. Smith, C.R. Osterwald, E. Gelak, S.R. Kurtz
National Renewable Energy Laboratory, Golden, CO 80401, USA

ABSTRACT

As photovoltaic (PV) penetration of the power grid increases, it becomes vital to know how decreased power output may affect cost over time. In order to predict power delivery, the decline or degradation rates must be determined accurately. At the Performance and Energy Rating Testbed (PERT) at the Outdoor Test Facility (OTF) at the National Renewable Energy Laboratory (NREL) more than 40 modules from more than 10 different manufacturers were compared for their long-term outdoor stability. Because it can accommodate a large variety of modules in a limited footprint the PERT system is ideally suited to compare modules side-by-side under the same conditions.

INTRODUCTION

The ability to accurately predict power delivery over the course of time is key to growth of the maturing photovoltaic (PV) industry [1]. For realistic PV lifespan estimation, the knowledge of power decline over time is essential and important to all stakeholders—utility companies, investors, and researchers alike. Outdoor field testing has played a vital part of determining PV field performance and lifetime for at least two reasons: (1) It is a non-trivial task to correlate indoor testing to outdoor results [2] and (2) it is the typical operating environment of PV modules [3]. A wealth of excellent information has been reported in the literature measuring degradation rates with respect to technologies, age, manufacturers, and geographic locations. Instead of citing the most significant contributions here, which would certainly be incomplete, an attempted summary of reported degradation rates is shown in Fig. 1. The histogram has to be understood as a temporary frame in time since new data are continuously being added. The above mentioned factors such as technology and location all have different influence on the determined degradation rate, however, it is important to note that most frequent degradation rate is below 1 %/year.

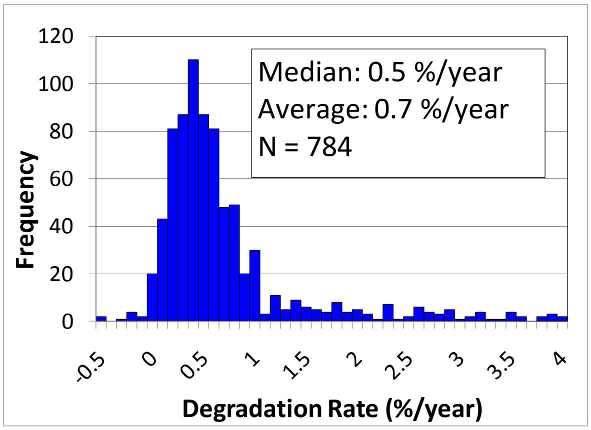


Figure 1 Histogram of published degradation rates.

In this paper we will focus on determining degradation rates from continuous data obtained from the PERT system at NREL which has been described in detail previously [4,5]. More than 40 different modules from more than 10 manufacturers were compared for their long-term outdoor stability. Module installations varied greatly with the earliest installations occurring in 1993. There was an equally large variation in the monitoring times from merely a few months to more than 16 years of continuous data. Due to increased uncertainty, no degradation rates were calculated for monitoring times below two years. Different technologies included amorphous-, mono- and poly-crystalline silicon, cadmium telluride (CdTe) and copper indium gallium selenide (CIGS).

Figure 2 Performance Energy Testbed (PERT) at NREL. Photo credit: Warren Gretz, NREL PIX 03877.

DEGRADATION RATE MEASUREMENTS

The modules, mounted at latitude tilt of 40º facing south, are held at maximum power with IV curves taken every 15 minutes. The Photovoltaics for Utility Scale Applications (PVUSA) methodology was used to determine long-term degradation rates. In this methodology, as a first step, the maximum power in monthly intervals is normalized to PVUSA Test Conditions (PTC) [6] by using Eqn. 1 [7,8].

$$P = E \cdot \left(a_1 + a_2 \cdot E + a_3 \cdot T_{ambient} + a_4 \cdot ws\right) \qquad (1)$$

In Equation 1, P is the maximum DC power, E the irradiance, $T_{ambient}$ the ambient temperature, ws the wind speed, and a_1 to a_4 are regression coefficients. Data at irradiance levels below 800 W/m^2 were eliminated from the analysis because extrapolation from low-irradiance levels to PTC increases the model uncertainty. In the second step, the monthly normalized data are graphed as a time series and degradation rates determined from a linear least square fit, as shown by the example in Fig. 3. The statistical uncertainty for the degradation rates, the Type A uncertainty according to the ISO guide to the Expression of Uncertainty [9], is calculated from the standard errors of the slope and intercept of the linear fit using error propagation.

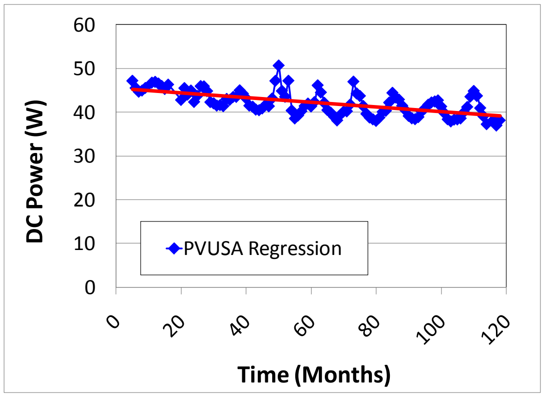


Figure 3 Example of an amorphous Si module with a linear fit using standard least square.

PYRANOMETER CALIBRATION

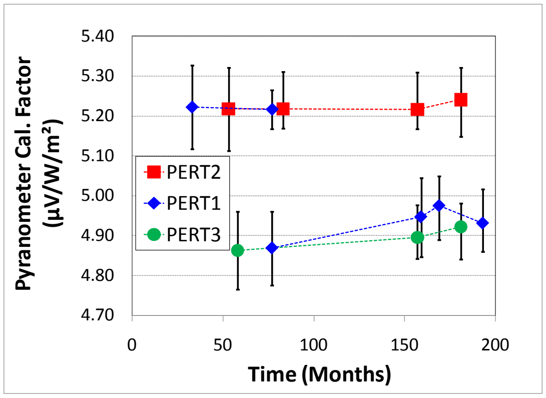


Figure 4 Pyranometer calibration factors determined at 45º at the Solar Radiation Research Laboratory at NREL.

The PERT system consists of three subsystems, each equipped with its own plane-of-array Kipp & Zonen CM11 pyranometer. The pyranometers are regularly calibrated at the Solar Radiation Research Laboratory (SRRL) at NREL using the Broadband Outdoor Radiometer Calibration (BORCAL) procedure [10]. Figure 4 shows the calibration factors in µV/W/m² for all pyranometers used for the PERT system. A systematic change in the calibration procedure in 2000, month 82, led to decreased measurement uncertainty and has been accounted for in Fig. 4 [11]. The large jump for PERT1 was caused by a change to a pyranometer with a different calibration factor. These calibration factors were subsequently used to normalize the irradiance measurements for each month of observation for each module. As a simplifying approximation, it was assumed that the respective pyranometers changed linearly between calibration dates.

ANALYSIS & DISCUSSION

For non-spectrally corrected measurements, particularly using pyranometers, it is well known that due to seasonal changes, several complete cycles (typically 3-5 years) need to be completed to obtain reasonably accurate degradation rates [12]. Figure 5 gives the explanation for this requirement. In this figure the degradation rate uncertainty is plotted against the monitoring length of time separated by technology. The uncertainty appears to decrease exponentially and seems independent of technology. For a desired statistical uncertainty the required observation time can then be directly determined from this curve. As shown in Fig. 1, the median historically reported degradation rate is 0.5 %/year and the average 0.7 %/year which results in circa 3-5 years from Fig. 5.

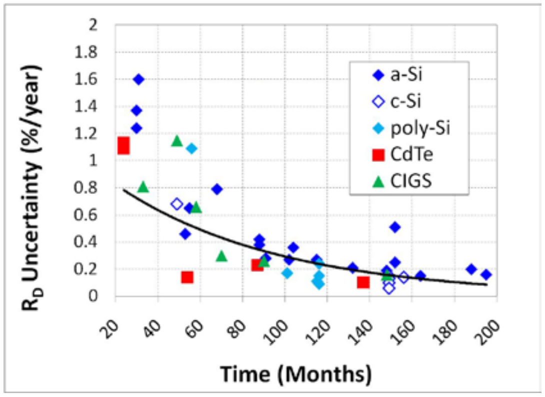
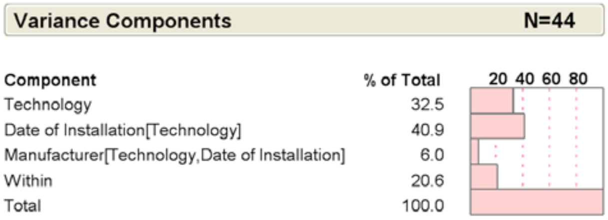


Figure 5 Degradation rate uncertainty versus observation time, separated by technology.

The next step is to investigate the determined degradation rates. Modules were divided by installation date as pre-2000 and post-2000. The choice of the year 2000 is somewhat arbitrary and was mostly driven by the decision to have a roughly equal number of modules for each category. Furthermore, the effect of different manufacturers was investigated although the sample size for that was small since only two different manufacturers had multiple technologies installed on the PERT system. It was then possible to statistically analyze the calculated data by doing an Analysis of Variance (ANOVA). The ANOVA partitions the overall observed variation of the degradation rates into its components depending on the variables technology, manufacturer and date of installation (DOI) of the module. From the partition in Fig. 6 it can be seen that manufacturer contributed only a small part to the overall variation, although the small sample size must be born in mind. Date of installation of the module, however, dominates the overall variation, followed by technology. The category “within” is the error variance within each group.



Variance Components N=44

Component	% of Total
Technology	32.5
Date of Installation[Technology]	40.9
Manufacturer[Technology,Date of Installation]	6.0
Within	20.6
Total	100.0

Figure 6 Variance components of determined degradation rates. N is the total number of modules.

Since the variable manufacturer contributed only minutely to the overall degradation rate variation, only technology and date of installation were considered for the following analysis. Figure 7 shows the degradation rates partitioned into DOI and technology only. Amorphous Si modules installed before and after 2000 had similar degradation rates. Unfortunately, no new crystalline Si modules were installed after 2000, therefore no direct comparison was possible. It appears that great improvements of the technologies CdTe, CIGS and poly-Si have been achieved although only one new CIGS module has been tested long enough to produce a believable degradation rate. .

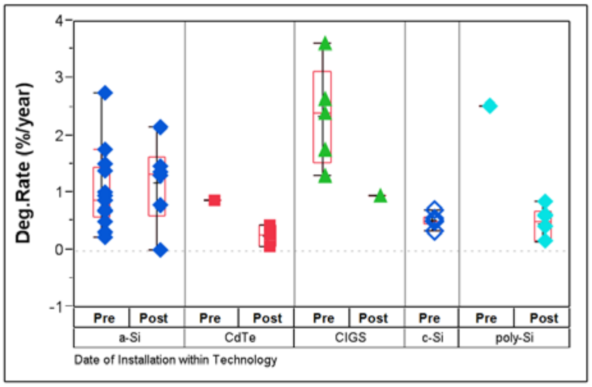


Figure 7 Degradation rates partitioned by technology and age.

CONCLUSION

Over 40 modules of different age, technology and manufacturer were directly compared for their degradation rates. The uncertainty in the degradation rate decreases exponentially with increasing monitoring time and appears to be independent of technology. The most important factor contributing to the degradation rate is the date of the installation of the module followed by the diverse technologies. It appears that CdTe, CIGS and poly-Si modules manufactured after the year 2000 exhibit improved stability relative to older designs.

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We would like to thank Bill Marion, Joe Del Cueto and David Trudell for their contribution to the operation of the PERT system. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

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