# COMPARISON OF DEGRADATION RATES OF INDIVIDUAL MODULES HELD AT MAXIMUM POWER[1]

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## ABSTRACT

In this paper, we present a comparison of maximum power degradation rates of individual modules under outdoor conditions in Golden, Colorado. Test modules include single- and polycrystalline-Si (x-Si, poly-Si), amorphous Si (a-Si, single, dual, and triple junction), CdTe, Cu-In-Ga-Se-S (CIS), and c-Si/a-Si heterostructure, from nine difference manufacturers. From monthly blocks of output power data, ratings were determined using multiple regressions to Performance Test Conditions (PTC). Plotting the power ratings versus time allowed degradation rates to be calculated from linear regressions. We also include a summary of module degradation rates obtained from the open literature over the past five years. Compared with the common rule-of-thumb value of 1% per year, many modules are seen to have significantly smaller degradation rates. A few modules, however, degrade significantly faster.

## INTRODUCTION

Accurate calculations photovoltaic (PV) of the energy delivered during the lifetime of a PV system require knowledge of the rate at which the output power of the modules installed in the system degrade over time. Actual values for degradation rates ($R_D$) are difficult to obtain because of the time required to observe the performance changes in a module. As a result, PV performance models have little or no actual $R_D$ data available for use. An example would be the PVWATTS system sizing software, which has the ability to include a loss due to age, but defaults to no loss [1]. Ref. [1] recommends a nominal value of 1% per year for module performance loss, which is a common rule-of-thumb in the PV industry. Therefore, the objective of this paper is to quantify module degradation rates.

## PUBLISHED DEGRADATION RATES

The first step toward this objective was a literature search to see what information about $R_D$ is currently available. A search of the PV literature going back five years yielded only nine references, which itself is an indication of how difficult $R_D$ values are to obtain. These results are presented in Table 1. All but refs. [7] and [10] report degradation in modules exposed while operating as part of systems. It should be noted that $R_D$ values derived from system operation data can include unrelated factors such as inverter operation, maximum power tracking, or interconnect degradation, and therefore may not be indicative of module degradation rates. Gauging degradation rates from systems has the advantage of providing better statistics if all the component modules can be measured individually, as was done in refs. [2] and [3].

Refs. [2] and [3] include comparisons of degradation rates with earlier work. The studies documented in refs. [2] and [6] were of systems that had been dismantled at the end of their useful life. Of these, the high $R_D$ (-5% per year) observed in the Tunisian system was attributed to browning of encapsulation and increased shunting at grain boundaries [6]. Encapsulation browning, delamination, and hot spots were observed in the Arcata, CA, x-Si system [3]. Ref. [7] represents a formal study of a variety of individual modules exposed outdoors while held at the maximum power. Unfortunately these results represent just a single year of exposure so it is difficult or impossible to see long-term trends.

## DEGRADATION RATE MEASUREMENTS

Since 1993, a measurement system called the Performance and Energy Ratings Testbed (PERT) located on the roof of the Outdoor Test Facility (OTF) at NREL in Golden, CO (see Fig. 1). The PERT consists of latitude-tilt open exposure racks; modules under test are connected to three Raydec Multi-Tracer II 15-channel electronic loads with individual four-wire electrical connections. Thermocouples measure back-of-module temperatures (the PERT has been described in detail previously [11]). The electronic loads perform maximum power point tracking, and also periodically measure the current-voltage (I-V) curves of the test modules (typically every 15 minutes).

Each individual I-V curve is stored as a separate file and archived. Next, the I-V data are post-processed by fitting each curve to a polynomial. The maximum power is calculated from the polynomial and then stored in a monthly summary file along with the total irradiance *E*

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(measured with a global pyranometer in the same plane), the ambient temperature $T$, and the wind speed $s$.

Fig. 1. The Performance and Energy Ratings Testbed.

For each month of module maximum power data, a multiple linear regression to Eq. 1 is performed (the monthly power data are filtered by excluding points with irradiance values below 800 W/m$^2$).

$$P = E\left(a_1 + a_2 E + a_3 T + a_4 s\right) \quad (1)$$

In Eq. 1, $a_1$, $a_2$, $a_3$, and $a_4$ are the coefficients resulting from the regression analysis. Using the regression coefficients, the power produced by a test module at Performance Test Conditions (PTC), which are 1000 W/m$^2$ irradiance, 20°C ambient temperature, and 1 m/s wind speed, is calculated by substitution back into Eq. 1. This power value is termed the PTC rating power [9]. Plotting the PTC ratings versus time reveals trends in the module performance. An example is shown in Fig. 1 for a BP Solar x-Si module, and Table 2 lists all the $R_D$ values obtained from PERT I-V data. Note that a number of the rows in Table 2 are for non-commercial prototype modules and therefore these $R_D$ values should not be construed to be representative of current products.

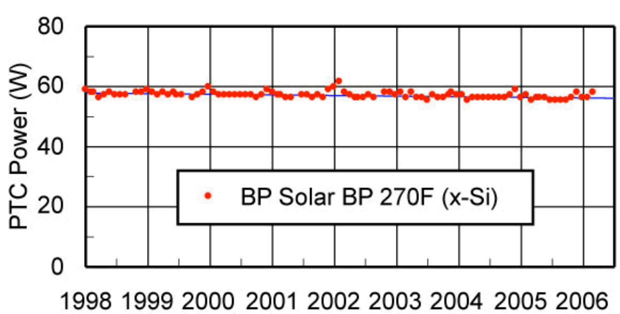


Fig. 1 Monthly PTC power ratings versus time for a BP Solar x-Si module obtained from PERT I-V data. The blue line is the linear least-squares fit that was used to calculate $R_D$ (-0.25%/year).

In most cases power degradation appears to be linear with time, so the slope of the PTC power versus time obtained from a simple least-squares linear fit is sufficient to calculate $R_D$. a-Si modules are an exception because the initial light-induced degradation will be greater than the $R_D$ after stabilization. This can be seen in Fig. 2 where the rate is much higher during the first few months of exposure. Note that it is possible for the rapid initial loss of short-circuit current in some crystalline Si modules to also skew $R_D$ determinations (although the stabilization time period is much shorter than that of a-Si — a few hours versus a few months). Using monthly data will probably mask this effect.

Caution should be observed with $R_D$ values measured over time durations shorter than about three years. For amorphous-Si modules, one year is usually not long enough for the performance to stabilize upon initial exposure. Seasonal variations, such as those visible in Fig. 2, can give erroneous indications of performance changes in all types, so at least three years are needed to see longer-term trends.

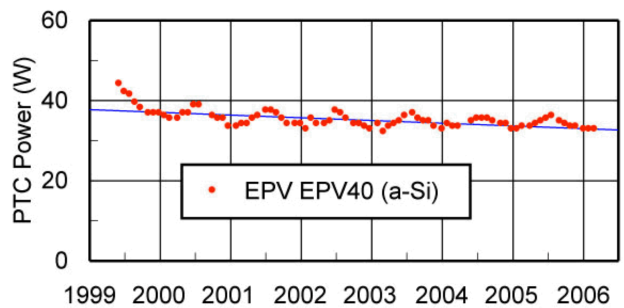


Fig. 2 Monthly PTC power ratings versus time for an EPV a-Si module obtained from PERT I-V data. After stabilization, this module has been degrading at -1.32%/year.

## DISCUSSION

Although the PTC regression method has been shown to be a sensitive indicator of performance losses [8,9], it does not provide information about the nature of losses, such as decreasing fill factor due to series resistance increases. These have to be determined through analysis of changes in I-V parameters and examination of the modules. $R_D$ values as high as those observed in ref. [6] are likely indicative of abnormal problems with the module or system design.

It should be noted that degradation rates are related to failure rates, but not directly. Consider the so-called bathtub curve model of failure rates, which uses the Weibull cumulative distribution function *F(t)* (see Fig. 1 and Eq. 2 in ref. [12]) to describe the mean time between failures. Because modules continue to operate while the output power is decreasing, slow degradation can't be considered either infant mortality or useful life failures. Instead, it should be regarded as a factor contributing to wear-out. If all the modules in a system degrade at a similar rate, all will be considered unacceptable simultaneously (for example, if the array is no longer able to meet the input voltage window of the inverter), and thus the slope of wear-out period will be steep (i.e. the shape parameter $\beta$ for *F(t)* will be large, >> 1).

It is interesting to note that many of the $R_D$ values for crystalline Si modules in Tables 1 and 2 are significantly lower than the 1 % per year rule-of-thumb. This is also true for some thin-film modules, although most are slightly above this level. These are an indication of the excellent quality of PV modules, even when in continuous operation outdoors for many years. A few degradation rates are significantly higher, with obvious implications for system performance over time. Thus, $R_D$ information should be available for the system designer.

The values reported in Table 2 represent the climate conditions in Golden, CO. Although they are comparable in magnitude with previously published values, it is possible that $R_D$ could vary in other climates for the same module type. This might be an interesting research topic.

## CONCLUSIONS

A number of conclusions can be made from these results. First, module degradation rate determinations should be made from performance data over periods of at least three years. Shorter time spans are likely to give inaccurate $R_D$ values because of seasonal variations and initial module performance stabilization.

Second, many (but not all) crystalline Si modules degrade at rates slower than the 1% per year rule-of-thumb. A more reasonable rule-of-thumb is probably 0.5% per year. Conversely, many (but not all) thin-film modules appear to have $R_D$ values somewhat higher than 1% per year.

Third, $R_D$ appears to vary over a fairly wide range, from values as high as several percent per year, down to zero (no measurable degradation). It would therefore seem important for system designers to have accurate degradation rate information available.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] B. Marion, M. Anderberg, P. Gray-Hann, "Recent Revisions to PVWATTS," Proc. 2005 DOE Solar Energy Technologies Program Review Meeting, Nov. 7-10, 2005, Denver, CO. See also: <http://rredc.nrel.gov/solar/calculators/PVWATTS/system.html>

[2] F. De Lia, S. Castello, L. Abenante, "Efficiency Degradation of C-Silicon Photovoltaic Modules After 22-Year Continuous Field Exposure," Proc. 3rd World Conf. on PV Energy Conversion, May 11-18, 2003, Osaka, Japan.

[3] A.M. Reis, N.T. Coleman, M.W. Marshall, P.A. Lehman, C.E. Chamberlin, "Comparison of PV Module Performance Before and After 11-Years of Field Exposure," Proc. 29th IEEE PV Spec. Conf., New Orleans, LA, May 19-24, 2002, pp. 1432-1435.

[4] R. Ruther, M.M. Dacoregio, A.A. Montenegro, "Four Years and Counting: The Continuous Operation of the First Grid-Connected, Building-Integrated, Thin-Film Photovoltaic Installation in Brazil," Proc. 17th Eur. PV Solar Eng. Conf, Oct. 22-26, 2001, Munich, Germany, pp. 2697-2700.

[5] A. De Lillo, S. Li Causi, S. Castello, "Long-Term Performance of Casaccia Plant," Proc. 3rd World Conf. on PV Energy Conversion, May 11-18, 2003, Osaka, Japan.

[6] A.B. Rabii, M. Jraidi, A.S. Bouazzi, "Investigation of the Degradation in Field-Aged Photovoltaic Modules," Proc. 3rd World Conf. on PV Energy Conversion, May 11-18, 2003, Osaka, Japan.

[7] N. Cereghetti, E. Bura, D. Chianese, G. Friesen, A. Realini, S. Rezzonico, "Power and Energy Production of PV Modules Statistical Considerations of 10 Years Activity," Proc. 3rd World Conf. on PV Energy Conversion, May 11-18, 2003, Osaka, Japan.

[8] J. Adelstein, B. Sekulic, "Performance and Reliability of a 1-kW Amorphous Silicon Photovoltaic Roofing System," Proc. 31st IEEE PV Spec. Conf., Orlando, FL, Jan. 3-7, 2005, pp. 1627-1630.

[9] B. Marion, J. Adelstein, K. Boyle, H. Hayden, B. Hammond, T. Fletcher, B. Canada, D. Narang, A. Kimber, L. Mitchell, G. Rich, T. Townsend, "Performance Parameters for Grid-Connected PV Systems," Proc. 31st IEEE PV Spec. Conf., Orlando, FL, Jan. 3-7, 2005, pp. 1601-1606.

[10] C.R. Osterwald, A. Anderberg, S. Rummel, and L. Ottoson, "Degradation Analysis of Weathered Crystalline-Silicon PV Modules," Proc. 29th IEEE PV Spec. Conf., New Orleans, LA, May 19-24, 2002, pp. 1392-1395.

[11] J.A. del Cueto, "Closed-Form Solutions and Parameterization of the Problem of Current-Voltage Performance of Polycrystalline Photovoltaic Modules Deployed at Fixed Latitude Tilt," Proc. 31st IEEE PV Spec. Conf., Orlando, FL, Jan. 3-7, 2005, pp. 331-335.

[12] A. Pregeli, M. Begovic, A. Rohatgi, A. Ristow, "Estimation of PV System Reliability Parameters," Proc. 17th Eur. PV Solar Eng. Conf, Oct. 22-26, 2001, Munich, Germany, pp. 558-561.

| Manufacturer | Module Type | Exposure (years) | Degradation Rate (% per year) | Measured at System Level? | Ref. |
|---|---|---|---|---|---|
| ARCO Solar | ASI 16-2300 (x-Si) | 23 | -0.4 | N | 2 |
| ARCO Solar | M-75 (x-Si) | 11 | -0.4 | N | 3 |
| [not given] | [not given] (a-Si) | 4 | -1.5 | Y | 4 |
| Eurosolare | M-SI 36 MS (poly-Si) | 11 | -0.4 | Y | 5 |
| AEG | PQ40 (poly-Si) | 12 | -5.0 | N | 6 |
| BP Solar | BP555 (x-Si) | 1 | +0.2 | N | 7 |
| Siemens Solar | SM50H (x-Si) | 1 | +0.2 | N | 7 |
| Atersa | A60 (x-Si) | 1 | -0.8 | N | 7 |
| Isofoton | I110 (x-Si) | 1 | -0.8 | N | 7 |
| Kyocera | KC70 (poly-Si) | 1 | -0.2 | N | 7 |
| Atersa | APX90 (poly-Si) | 1 | -0.3 | N | 7 |
| Photowatt | PW750 (poly-Si) | 1 | -1.1 | N | 7 |
| BP Solar | MSX64 (poly-Si) | 1 | 0.0 | N | 7 |
| Shell Solar | RSM70 (poly-Si) | 1 | -0.3 | N | 7 |
| Würth Solar | WS11007 (CIS) | 1 | -2.9 | N | 7 |
| USSC | SHR-17 (a-Si) | 6 | -1.0 | Y | 8 |
| Siemens Solar | M55 (x-Si) | 10 | -1.2 | Y | 9 |
| [not given] | [not given] (CdTe) | 8 | -1.3 | Y | 9 |
| Siemens Solar | M10 (x-Si) | 5 | -0.9 | N | 10 |
| Siemens Solar | Pro 1 JF (x-Si) | 5 | -0.8 | N | 10 |
| Solarex | MSX10 (poly-Si) | 5 | -0.7 | N | 10 |
| Solarex | MSX20 (poly-Si) | 5 | -0.5 | N | 10 |

Table 1. PV module degradation rates published within the past five years.

| Manufacturer | Module Type | Exposure (years) | Degradation Rate (% per year) | No. of Modules |
|---|---|---|---|---|
| BP Solar | BP 585F (x-Si) | 7 | -0.30 | 2 |
| BP Solar | BP 270F (x-Si) | 8 | -0.32 | 2 |
| Kyocera | KC40 (poly-Si) | 4.5 | -0.91 | 2 |
| Solarex | SX40U (poly-Si) | 5.6 | -0.01 | 2 |
| Siemens | PC-4-JF (x-Si) | 9.5 | -0.51 | 1 |
| Photowatt | PWX500 (poly-Si) | 6 | -0.13 | 1 |
| Sanyo | H124 (a-Si/x-Si HIT) | 2.6 | -1.59 | 1 |
| ECD Sovonix | [none] (a-Si) † | 12 | -1.17 | 1 |
| Solarex | SA5 (a-Si) | 12 | -0.69 | 1 |
| Uni-Solar | UPM-880 (a-Si) | 12 | -0.62 | 2 |
| APS | EP55 (a-Si) | 9.5 | -1.62 | 2 |
| Solarex | MST-22ES (a-Si) | 6 | -0.86 | 1 |
| Uni-Solar | US-32 (a-Si) | 8.5 | -0.39 | 1 |
| EPV | EPV40 (a-Si) † | 6.5 | -1.40 | 2 |
| BP Solarex | MST-50 MV (a-Si) | 4 | -2.47 | 2 |
| Siemens | ST40 (CIS) † | 7 | -1.63 | 1 |
| Solar Cells Inc. | [none] (CdTe) † | 10 | -1.84 | 1 |

Table 2. PV module degradation rates obtained from monthly PTC regressions of PERT I-V data. Module types marked with a '†' indicate non-production prototypes that are not indicative of current products.