MEDIUM-TERM DEGRADATION OF DIFFERENT PHOTOVOLTAIC TECHNOLOGIES UNDER OUTDOOR CONDITIONS IN ALPINE AREA

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ABSTRACT: The assessment of module degradation is a key factor for the development of the photovoltaic market. Investors and utility companies need to accurately predict the energy production of PV systems in the long-term, manufacturers need to improve the reliability and durability of their products.
Degradation rates warranted by manufacturers are estimated through accelerated indoor tests, even though module technology and manufacturing processes are not the only factors affecting module durability over the years: climatic and weather conditions at the PV system location must be adequately taken into consideration. For this reason, many studies in the past processed outdoor PV monitoring data to assess the degradation rate.
This work focuses on the evaluation of degradation rates of different PV technologies installed at the Airport Bolzano Dolomiti (ABD) test plant, monitored by EURAC: monocrystalline silicon (mc-Si), polycrystalline silicon (pc-Si), amorphous silicon (a-Si), micromorph silicon (a-Si/μc-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS). The second and third year of plant operation are considered, in order to evaluate the medium-term degradation process. Three different methodologies: PVUSA, Performance Ratio and Maximum Power at Standard Test Conditions are employed and the results compared.
Keywords: degradation, PVUSA, Performance Ratio, outdoor conditions

1 INTRODUCTION

Degradation of photovoltaic modules depends on the resistance of the single components to the stress caused by meteorological conditions, especially temperature, solar spectrum and humidity. Typical degradation effects are delamination, encapsulant browning, degradation of cell material due to interaction with solar spectrum, degradation of solder bonds. The gradual corrosion of components is directly related to the long-term degradation of modules in terms of energy production decrease, which is commonly expressed with the annual degradation rate R_d (%/year).

In this paper, the second and third year of module operation of different PV technologies installed at Airport Bolzano Dolomiti (ABD) are taken into consideration, in order to assess their medium-term degradation. After an initial filtering of data, monthly values of module performance calculated with three different methodologies - PVUSA, Performance Ratio, Maximum Power at Standard Test Conditions (STC) - are used. The degradation rate is then assessed using the least-square fit method.

2 EXPERIMENTAL SETUP

The PV installation of the Airport Bolzano Dolomiti (ABD), developed with a co-financing of the European Regional Development Fund (ERDF) has been connected to the medium voltage (MV) network in August 2010. It is divided into two main parts: a 662 kW commercial installation with 8538 CdTe modules, and a 62 kW experimental installation with 24 different types of modules, divided into 39 arrays ranging between 1 and 2 kW each, and mounted on fixed racks as well as on single- and dual axis trackers [1].

The technologies considered in this work are mounted on a 30° fixed rack, have an orientation of 8.5° West of South, and are placed at an altitude of 262 m above the sea level. The DC-side electrical parameters (P_{MPP}, V_{MPP}, I_{MPP}) of each group are recorded by the inverter every 15 minutes [2]. In addition to that, weather data are logged by a meteo station on site, equipped with sensors for the measurement of irradiance on horizontal and module plane, ambient temperature, wind speed and direction. The acquisition frequency of the weather parameters is one minute, and data are then averaged on 15-minutes time intervals.

3 METHODOLOGY

The methodologies used in this work are well-established and commonly recognized as a tool for the calculation of medium- and long-term degradation rates [3-7]. The second and third year of plant operation (July 2011 – June 2013) are taken into consideration. In fact the initial degradation of PV modules, which is more evident in thin film technologies, can be reasonably considered completed after a period of 6 up to 12 months of outdoor exposition [8]. The uncertainty of the degradation rate assessment decreases exponentially with time, and a two-year period is considered as the minimum time-span in order to obtain reliable results [3].

As a first step, the outdoor data are filtered. Plane-of-array (POA) irradiance higher than 800 W/m^2 is taken into consideration, in order to focus the analysis on a restricted field of module temperature range, thus lowering the variability of PR. Furthermore, this condition allows for a better correction of maximum power to STC conditions, since the temperature coefficient from datasheet is used in a range of irradiance (800 up to about 1200 W/m^2) close to irradiance under STC (1000 W/m^2). Finally, it has been demonstrated that PVUSA method increases its effectiveness at higher irradiance levels [3].

A second filter on the 15-minutes based values of Performance Ratio is applied on a monthly basis for every considered technology. Only points in the range $PR_{avg} \pm \sigma$ are considered, where:

- PR_{avg} is the average PR of all the points, for a given month and technology
- σ is the standard deviation

This method ensures that 68 % of the data points are in this range [9]. In this way, values corresponding to situations in which the incoming irradiance on the module is larger than the one measured by pyranometer (high PR values) and the other way around (low PR values) are excluded. This is the case for example of a not-uniform cloud cover or of shading due to obstacles, which are more evident the longer is the distance between module and irradiance sensor. In our case, the plant is surrounded by mountains both on the east and the west sides, and shading prevents from same irradiation conditions of pyranometer and modules during sunrise and sunset.

The effect of the two abovementioned filters is shown in Figure 1 for a pc-Si technology (valid points are those within the green lines).

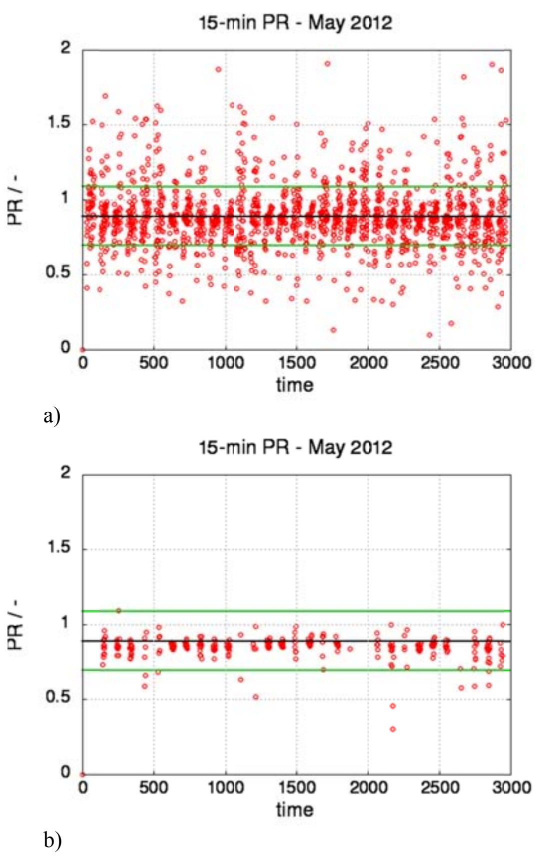

Figure 1: effect of filtering by a) $PR_{avg}\pm\sigma$ and b) G>800 W/m^2 for a pc-Si technology, May 2012 (average PR: black line, $PR_{avg}\pm\sigma$: green line)

The three methodologies considered in this paper use monthly-filtered data and calculate a representative value for each month. A linear least-square fit is then performed in order to obtain the degradation rate and its uncertainty.

Photovoltaics for Utility Scale Applications (PVUSA) has been developed by NREL in the 1990´s [10] as a methodology to evaluate the performance of PV systems under Performance Test Conditions (PTC). It is based on a regression of system output power, *P*, against a parameterized expression which considers irradiance, *G*, wind speed, *W*, and ambient temperature, *T*:

$$P = G(a + bG + cW + dT)$$

where *a, b, c, d* are the regression coefficients which are then used to calculate the power at PTC conditions (G=1000 W/m^2, T=20 °C, W=1 m/s). It has to be pointed out that the cell temperature T_{cell} under PTC conditions (about 50°C) differs from that of STC conditions (G=1000 W/m^2, T_{cell}=25 °C, Air Mass=1.5).

Performance Ratio methodology calculates the monthly value of PR using the expression defined by the international standard IEC 61724 [11]:

$$PR = \frac{P}{P_n}\frac{G_{STC}}{G}$$

where P_n the array nominal power (W) and G_{STC} the irradiance under STC conditions (1000 W/m^2).

The last methodology used in this paper calculates the output power of the PV array, P_{max}, corrected for temperature and irradiance to STC conditions using the following expression [12]:

$$P_{STC} = P\frac{G_{STC}}{G}\frac{1}{[1+\gamma(T_{cell} - T_{cell_{STC}})]}$$

that is

$$P_{STC} = P\frac{1000}{G}\frac{1}{[1+\gamma(T_{cell} - 25)]}$$

where γ is the temperature coefficient in power (%/°C) from datasheet. In this work, the cell temperature is in turn calculated using the formula described in Skoplaki et al. [13]:

$$T_{cell} = T + (NOCT - T_{NOCT})\frac{G}{G_{NOCT}}$$

that is

$$T_{cell} = T + (NOCT - 20)\frac{G}{800}$$

where NOCT is the Nominal Operating Cell Temperature, calculated under the conditions G=800 W/m^2, T=20 °C, W=1 m/s, given by the manufacturer. This formula can be improved by adding a term which takes into account wind speed. As demonstrated by Schwingshackl et al. [14], the integration of wind data within Skoplaki formula improves the estimation of cell temperature at ABD site. This may in turn improve the estimation of P_{max} corrected to STC, and will be verified in a future work.

4 RESULTS AND DISCUSSION

Figure 2 shows the monthly values for two technologies calculated with the three different applied methodologies, and their linear fit. Points corresponding to some winter months (December 2011, December 2012 and January 2013) are missing since no or few irradiance points did exceed 800 W/m^2. On the other hand, lowering the irradiance acceptance value down to e.g. 600 W/m^2

ensures a complete set of monthly values, but drastically increase the uncertainty values for the reasons mentioned in section 3.

It is interesting to note that the typical seasonal performance trends shown by several studies [5, 15, 16] are evident for all the methodologies, thus indicating still a residual influence of temperature effects.

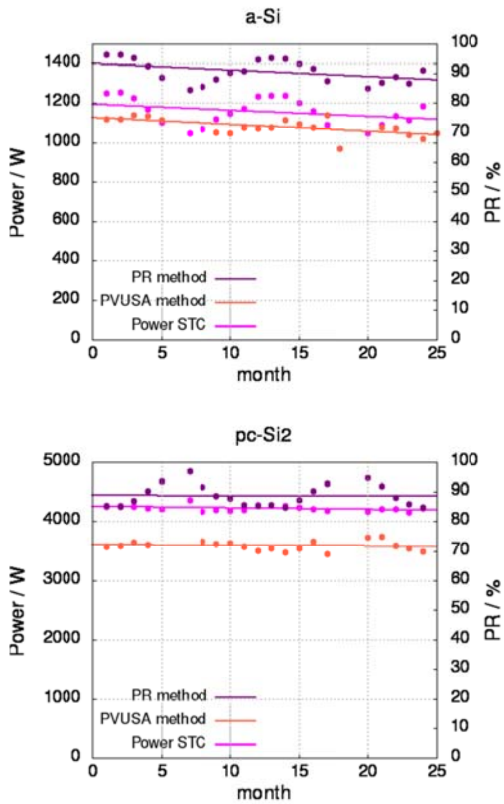

Figure 2: medium-term degradation using monthly PR (right y-axis), and PVUSA method and P_{max} corrected to STC (left y-axis), for an a-Si and a pc-Si technology (month 1 = July 2011, month 24 = June 2013)

The results of the application of the three methodologies are reported in Table 1. Both annual degradation rate R_d and its uncertainty value are reported for 10 arrays representing 6 different PV technologies.

As expected, crystalline-silicon based technologies show degradation rates lower than 1% (specifically lower than 0.75%/year in our case), as reported by other studies [3, 4, 7, 17]. Positive values calculated for two pc-Si and all the mc-Si arrays with PR methodology actually indicates that no or very slight degradation occurred in these modules. In any case, the PR methodology seems in general to generate higher values of R_d than PVUSA methodology, as shown also by Makrides et al. [7]. Amorphous-silicon technology shows the highest degradation rate, about 3% (even close to 3.8% according to PVUSA methodology). It has still to be clarified whether the initial degradation affects the second year of operation considered for this work, thus affecting the calculation of R_d. This will be object of a future study involving the first months of plant operation through the application of other methodologies. Copper Indium Gallium Selenide and micromorph are affected by degradation rates between 2 and 3% on average. Degradation occurring on Cadmium Telluride results the lowest amongst the thin film technologies, with a degradation rate lower than 2%.

Table 1 Degradation rate R_d and uncertainty values calculated with PVUSA, PR and P_{max} corrected to STC methodologies, for 10 different arrays for the period July 2011 – June 2013

	PVUSA		PR		P_{max} corr	
Module name	**R_d %**	uncert %	**R_d %**	uncert %	**R_d %**	uncert %
pc-Si1	**-0.05**	0.9	**0.15**	1.6	**-0.04**	0.7
pc-Si2	**-0.30**	0.9	**-0.05**	1.6	**-0.73**	0.4
pc-Si3	**-0.24**	1.4	**0.14**	1.6	**-0.67**	0.6
mc-Si1	**0.31**	0.9	**0.46**	1.6	**-0.33**	0.6
mc-Si2	**-0.51**	1.6	**0.32**	1.4	**-0.51**	0.6
a-Si	**-3.79**	1.3	**-2.81**	1.5	**-3.08**	2.1
microm1	**-2.26**	1.0	**-1.90**	0.6	**-2.26**	1.1
microm2	**-3.27**	1.1	**-2.10**	1.2	**-2.45**	1.9
CdTe	**-1.91**	0.8	**-1.64**	0.5	**-2.00**	0.6
CIGS	**-2.86**	1.3	**-2.64**	0.4	**-3.10**	0.8

5 CONCLUSIONS

The medium-term degradation of five different PV technologies is assessed using three different methodologies on a time-span of two years (second and third year of operation). Preliminary irradiance and outlying points filtering is performed to improve the methodology reliability. Results show a general accordance between the applied methodologies, with a slight tendency of PR method towards higher values of degradation rate R_d.

The results show a degradation lower than 0.75%/year for both monocrystalline and polycrystalline silicon. Amongst the thin film technologies, the highest degradation occurs in amorphous silicon (about 3%), the lowest in Cadmium Telluride (lower than 2%). Copper Indium Gallium Selenide and micromorph show intermediate degradation rates, between 2 and 3%.

In order to confirm the results presented in this paper, more operational years must be taken into account, as well as the first year of plant operation.

6 ACKNOWLEDGMENTS

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7 REFERENCES

[1] G. Belluardo, M. Pichler, D. Moser, M. Nikolaeva-Dimitrova, One-year comparison of different thin film technologies at Bolzano Airport Test Installation. Fuelling the Future: Advances in Science and Technologies for Energy Generation, Transmission and Storage, pp. 229 - 234

[2] L. Fanni, M. Giussani, M. Marzoli, M. Nikolaeva-Dimitrova, How accurate is a commercial monitoring system for photovoltaic plant?, Progress in Photovoltaics: Research and Applications, December 2012

[3] D. C. Jordan, R. M. Smith, C. R. Osterwald, E. Gelak, S. R. Kurtz, Outdoor PV degradation comparison, 35th IEEE Photovoltaic Specialists Conference, Honolulu, June 2010

[4] C. R. Osterwald, A. Anderberg, S. Rummel, L. Ottoson, Degradation analysis of weathered crystalline-silicon PV modules, 29th IEEE Photovoltaic Specialists Conference, New Orleans, May 2002

[5] C. Cornaro, D. Musella, Performance analysis of PV modules of various technologies after more than one year of outdoor exposure in Rome, 3rd International Conference on Applied Energy, Perugia, May 2011

[6] N. Sorloaica-Hickman, K. Davis, A. Leyte-Vidal, S. R. Kurtz, D. C. Jordan, Comparative study of the performance of field-aged photovoltaic modules located in a hot and humid environment, 38th IEEE Photovoltaic Specialists Conference, 2012

[7] G. Makrides, B. Zinsser, G. E. Georghiou, M. Schubert, J. H. Werner, Degradation of different photovoltaic technologies under filed conditions, 35th IEEE Photovoltaic Specialists Conference, 2010

[8] D. L. King, J. A. Kratochvil, W. E. Boyson, Stabilization and performance characteristics of commercial amorphous-silicon PV modules, 28th IEEE Photovoltaic Specialists Conference, 2000

[9] D. Moser, M. Pichler, M. Nikolaeva-Dimitrova, Filtering procedures for reliable outdoor temperature coefficients in different photovoltaic technologies, Journal of Solar Energy Engineering, Vol. 136, August 2013

[10] C. M. Whitaker, T. U. Townsend, D. L. King, Application and validation of a new PV performance characterization method, 26th IEEE Photovoltaic Specialists Conference, pp. 1253-1256, 1997

[11] IEC. Photovoltaic System Performance monitoring – Guidelines for Measurement, Data Exchange, and Analysis. IEC Standard 61724, Geneva, Switzerland, 1998

[12] A. Colli, W.J. Zaaiman, Maximum-Power-Based PV Performance Validation Method: Application to Single-Axis Tracking and Fixed-Tilt c-Si Systems in the Italian Alpine Region, Progress in Photovoltaics: Research and Applications, Vol. 4, October 2012, pp. 555-563

[13] E. Skoplaki, A.G. Boudouvis, J. A. Palyvos, A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting, Solar Energy Materials & Solar Cells, Vol. 92, 2008, pp. 1393-1402

[14] C. Schwingshackl, M. Petitta, J. E. Wagner, G. Belluardo, D. Moser, M. Castelli, M. Zebisch, A. Tetzlaff, Wind effect on PV module temperature: analysis of different techniques for an accurate estimation, Energy Procedia, Vol. 40, 2013, pp. 77-86

[15] G. Belluardo, M. Pichler, D. Moser, M. Nikolaeva-Dimitrova, one-year comparison of different thin-film technologies at Bolzano Airport Test Installation, The Energy & Materials Research Conf. Proceedings, Torremolinos, Spain, 20-22 June 2011

[16] G. Makrides, B. Zinsser, M. Schubert, G. E. Georghiou, Seasonal performance comparison of different photovoltaic technologies installed in Cyprus and Germany, International Journal of Sustainable Energy, 2013

[17] D. C. Jordan, S. R. Kurtz, Photovoltaic degradation rates – an analytical review, Progress in Photovoltaics: Research and Applications, Vol. 21, January 2013, pp. 12-29