ANALYSIS OF NON-LINEAR LONG-TERM DEGRADATION OF PV SYSTEMS

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ABSTRACT: The current work presents the degradation evaluation of different PV systems under the weather conditions prevailed in the Swiss midlands, Jura and Alps. The purpose of this paper is to analyze degradation rates and change of degradation rates over time. The analysis is done for the degradation rates of three 25-30 years old PV systems in Switzerland, one of which is the oldest grid connected PV system in Europe of its size (30-year-old 555 kW PV system Mont-Soleil). The two other PV systems are located on Jungfraujoch and in Burgdorf. The examined degradation metric in this study is the performance ratio (PR) which is normalized energy yield with received insolation. The focus of this study is to examine the linear degradation rate of the PV plants and find the best non-linear fitting functions to the degradation. It is found that the annual degradation differs between the systems although they have identical PV modules. The highest linear degradation was found for Tiergarten East system with 0.6 %, 0.5 % for Tiergarten West, 0.3 % for Mont-Soleil and 0.02 %, for the Junfraujoch system. For non-linear degradation, 2nd order polynomial and breakpoint functions were used. The performance of both functions varies depending on to the PV system, and it is found that breakpoint function provided the best results and fit better than polynomial function.
Keywords: Degradation, Performance Ratio, Non-linear analylsis

1 INTRODUCTION

The performance of photovoltaic modules degrade due to several factors such as temperature, humidity, irradiation, dust or mechanical shocks. Each of these different factors can induce one or more types of degradation such as discoloration, delamination, corrosion and cell breakage and cracking, to name just a few. In recent years, research on photovoltaic modules has focused on the race to develop new technologies and on evaluating the degradation and performance of modules that are already operational. D. Atsu et al. [1] investigated the degradation rate of PV modules for twelve years under sub-Saharan climate. Different techniques are employed to assess the performance of PV modules, current-voltage characterization, infrared thermography and others. From their results, average drops of 11.7% and 14.8% were found in the short-circuit current and the open circuit voltages, respectively. Also, they concluded from the thermography assessment that the main failures which affect the PV modules are EVA and cell interconnects ribbons browning. Golive et al. [2] presented the results of a PV module reliability survey in All-India. Comparisons were done according to the age of PV modules and to the climate types. Young modules are considered for an age between one and 5 years, and old modules present modules with an age greater than 5 years. Achieved results showed that PV installations in hot regions degrade faster than in cold regions. Also, ground-mounted PV systems are less degrading than rooftop systems. Hadef Hefaidh [3] proposed a methodology for the reliability of PV modules using two methods.Failure Mode and Effects Criticality Analysis (FMECA) and Fault Tree Analysis (FTA) methods were used to identify the degradation modes and the influencing factors on the degradation of PV modules, respectively. In this work, considering the environmental inputs, such as temperature, relative humidity and dust is the main outcome to predict the reliability of PV systems. Also, Malvoni [4] investigated the degradation and reliability of a PV plant in the Mediterranean climate in Italy. PVsyst software was used to model the PV system and to simulate the output power. Operating conditions are considered as a factor that affect the reliability of the PV system. Otherwise, the reliability could be increased up 85% after the validation of theorical power output with the actual one. Hence, after 5 years of investigated period, the yearly estimated degradation was 1.12%.

For the calculation of degradation rate (DR), A. Phinikarides et al. [5] proposed a review work of several statistical methods mostly mentioned in literature. As concluded, the choice of DR calculation methodology affects the DR besides the manufacture and location dependent. It is found that IV method produces low DR compared to Linear Regression method. While other methods which are less popular and applied could provide DR with low uncertainty and good correlations, such as Autoregressive Integrated Moving Average (ARIMA) and Locally Weighted Scatterplot Smoothing (LOESS). A simulation study was done by C. Huang, L. Wang [6] about the degradation process of PV modules using a circuit-based model. This approach is used to relate different input parameters such as PV characteristics, weather parameters and aging factors of PV modulesIn this study, it is mentioned that the optical degradation of PV systems and the parasitic resistances degradation cause the loss in the power output and fill factor. Simulation results showed that the degradation process depends on the aging patterns of investigated factors. It is also noted that the climates and PV technology affect the aging patterns.

2 MATERIALS AND METHODS

2.1 Studied Regions and PV Systems

In this work, long-term degradation of three PV systems is analyzed. These systems are Tiergarten, Mont-Soleil and Junfraujoch and they are installed in Burgdorf (Swiss Midlands), Jura and Alps, respectively. . Table 1 presents the climate of these regions according to Köppen classification [7], besides the average annual temperature and the amount of annual precipitation (R_f).

Table 1. Climate characterization of the studied regions

Region	Climate	T (°C)	R_f (mm)
Swiss Midlands	Warm-temperate	7.8	1174
Jura	Warm-temperate	7.6	1619
Alps	Temperate-oceanic	-6	566.2

In the present work, four PV systems were investigated, which are installed in the different locations, as described above. Tiergarten PV system has a total capacity of 46 kWp, divided in two sub-systems, Tiergarten West and Tiergarten East. This system is mounted on the rooftop of Bern University of Applied Sciences in Burgdorf.Mont-Soleil PV system is the oldest PV power plants of its size in Europe. Moreover, Jungfraujoch system is studied and presented in this study.

2.2 Performance and Degradation Analysis

High-resolution datasets were recorded for all PV systems, 1 min for Tiergarten system and 5 min for Mont-Soleil and Jungfraujoch. To carry out this study, an algorithm was developed to process, treat, filter, and analyze the yield data from PV systems. To have a deep comprehension of the long-term performance of the PV systems, filtering approaches are applied for the input parameters as well for the simulated performance indicators. The aim of this paper is to define and test methods to calculate the performance ratio (PR) and degradation rate (DR) of PV systems.

To study the performance and the degradation of PV system, 25-30 years of recorded and measured data are explored, and different indicators were calculated. The performance ratio is the most crucial standard used worldwide for the assessment of the performance of the PV plant. It is defined as the ratio of the final yield and the reference yield [8]:

$$PR=\frac{Y_{DC}}{Y_r} \quad \text{(Equ.1)}$$

Where, Y_{DC} and Y_r denote the DC yield and the reference yield, respectively.

In the present work, the DC yield is defined by total DC energy output produced (E_{DC}) by the system by the nominal power of the PV system at STC (P_{nom}) [9] and it is expressed as:

$$Y_{DC} = \frac{E_{DC}}{P_{nom}} \quad \text{(Equ.2)}$$

The reference yield denotes the ratio of the total tilted solar irradiation (H_{gen}) to the refence solar irradiance (G_{STC}) [10], and it is presented as:

$$Y_r = \frac{H_{gen}}{G_{STC}} \quad \text{(Equ.3)}$$

In this study, the temperature corrected PR was calculated and used. Hence, the correction was considered for the temperature term and added to the Y_{DC}. Therefore, the expression presented in the Equation 2 is written as follows:

$$Y_{DC\text{-}corr}= \frac{E_{DC}}{P_{nom}} \times k_T \quad \text{(Equ.4)}$$

Where $Y_{DC\text{-}corr}$ is the corrected final yield. k_T is the temperature correction factor and it is given as:

$$k_T = 1+\alpha_{Pmpp}\times(T_{ref}\text{-}25) \quad \text{(Equ.5)}$$

Where T_{ref} is the solar generator cell temperature and α_{Pmpp} is the temperature coefficient (%/°C), and it differs according to the type of PV module. Thus, the temperature corrected PR is calculated using the new equation:

$$PR = \frac{Y_{DC\text{-}corr}}{Y_r} \quad \text{(Equ.6)}$$

For linear modelling, linear regression is applied on the studied PR time series using the regression fit formula:

$$y = ax+b \quad \text{(Equ.7)}$$

Where a and b are the fitting coefficients, presenting the slope and intercept, respectively.

For the calculation of DR, relative degradation (DR_r) is mostly used and it is calculated using the formula [11]:

$$DR_r= t \times \frac{a}{b} \quad \text{(Equ.8)}$$

In the present study, quadratic function is used to fit the non-linear degradation of investigated PV systems:

$$y=a+ bx+ cx^2 \quad \text{(Equ.9)}$$

Moreover, multi-linear function with one breakpoint is used. To quantify how well a model fits the data, the coefficient of determination (R^2) is calculated.

To analyse the degradation as a function of temperature and irradiance level, energy yield data is filtered and only values within the range of interest are processed. Non-relevant data for module degradation resulting of non-availability of the PV system such as downtime of inverters are removed. In this study, filtering is used for two different purposes. The first filtering is applied to prepare the data before using it. In this case, missing data, erroneous and duplicate values of 1 min data are deleted. Also, a "BFH filter" was proposed and applied, which includes the filtering of GTI, $Y_{DC\text{-}corr}$, Y_r and PR_{corr}.

2.3 Irradiance Effect

In the BFH filter, the GTI is ranged between 700 W/m^2 and 900W/m^2 and the purpose of this filter is to maintain the best irradiance level, which is the relevant range to reach crucial results. Also, the BFH filtering is high enough to have good system performance, low enough to avoid saturation due to inverter curtailment. Values greater than 1000 W/m^2 are removed to avoid the impact of saturated inverter. Hence, after applying this filter, only sunny periods are conserved, and uncertainties caused by low and high irradiance are reduced. Moreover, The DC energy and irradiance yields, and the performance ratio are also concerned in the BFH filter.

2.4 Temperature effect

Besides irradiance and performance metric filtering, temperature (T_{mod}) is also filtered in this step. The purpose of filtering T_{mod} is the description of the performance of PV systems at different temperatures. The flowchart presented in Figure 2 resumes the proposed approach to build the algorithm to achieve the purpose of this paper.

3 RESULTS

3.1 Linear degradation

Figure 1 presents the annual PR for the different studied PV systems. Linear fits are added to the plots to determine the linear DR of each system. In this study, monthly and annual DR_r is calculated as expressed in the equation 8 and the results are presented in Figure 1.

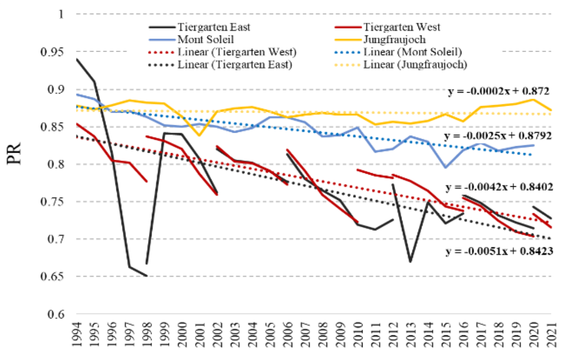
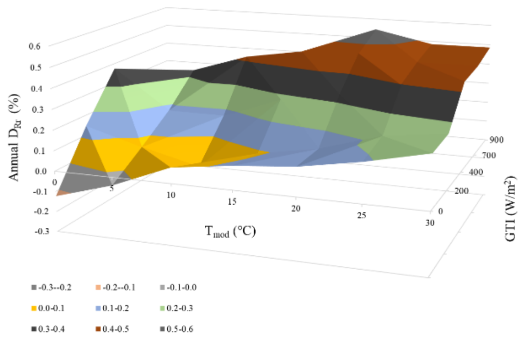


Figure 1. Annual PR of the studied PV systems

The 3D graphs presented in Figure 2 show the calculated annual degradation of each PV system according to the variation of the filter function of T_{mod} and GTI. The purpose of plotting these graphs is to find out the effect of both parameters individually on the PR/degradation. For Tiergarten West system, the DR_r is great at high T_{mod}, and it degreases with high GTI. The highest found DR_r was 0.44 % per year at GTI of 900 W/m^2 and 20 °C of T_{mod}. For Tiergarten East, the highest calculated annual DR_r was found at T_{mod} range of (5-10) °C with high irradiance level of (700-900) W/m^2 of 0.63 %. The annual DR_r is low at low temperature and irradiance levels, and it decreases with high GTI for the different T_{mod} levels.

For Mont-Soleil, the annual DR_r is less than Tiergarten systems. Hence, the highest DR_r was found to be 0.32 % at low T_{mod} and high GTI levels of (0-5) °C and (700-900) W/m^2, respectively.

For Junfraujoch, the annual degradation is lower compared to other PV systems. The highest DR_r reached 0.13 % at low T_{mod} range of (0-5) °C and high irradiances of (700-900) W/m^2. For GTI less than 400 W/m^2, and for different T_{mod} values, the annual DR_r is negative. At high irradiance level of (700 – 900) W/m^2, DR_r decreased at low temperature level of (0-15) °C.



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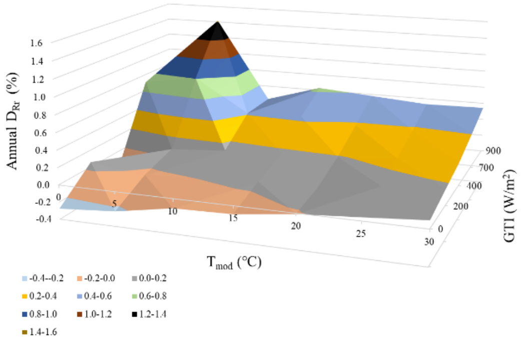

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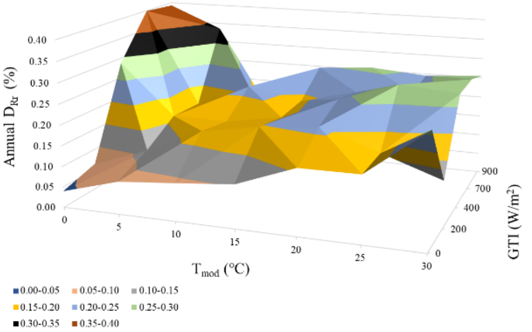

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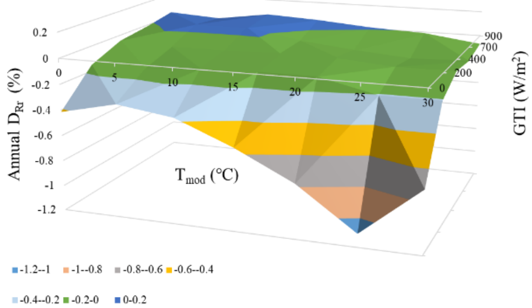

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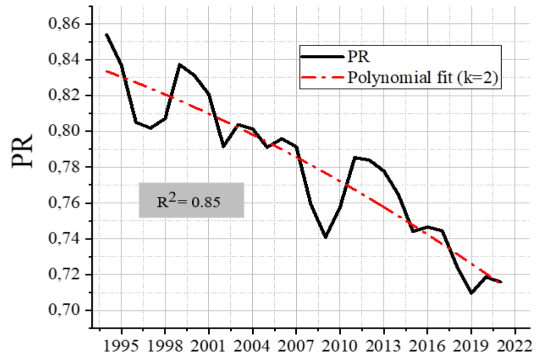
Figure 2. Annual DR_r according to T_{mod} and GTI of Tiergarten West (a), Tiergarten East (b), Mont-Soleil (c) and Junfraujoch (d)

3.3 Non-linear degradation

3.3.1 Quadratic function: 2nd order Polynomial

One important outcome in the investigation of PV system degradation is to find out the best fitting function for the non-linear degradation of this PV system. For this purpose, a 2nd order of polynomial function is applied to the annual PR of the investigated PV systems (Figure 3). As presented, the polynomial function showed relatively high R^2 of 0.85 to 0.77 for Tiergarten and MontSoleil systems, while for Junfraujoch system, R^2 was weak (0.31).



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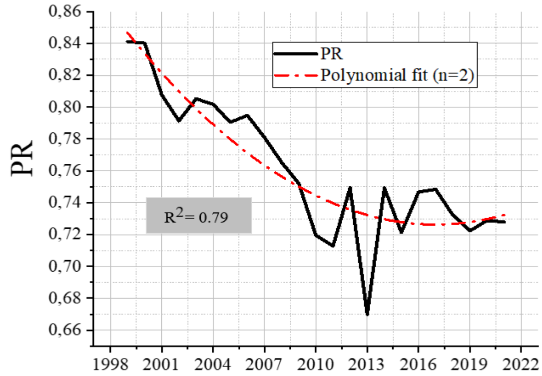

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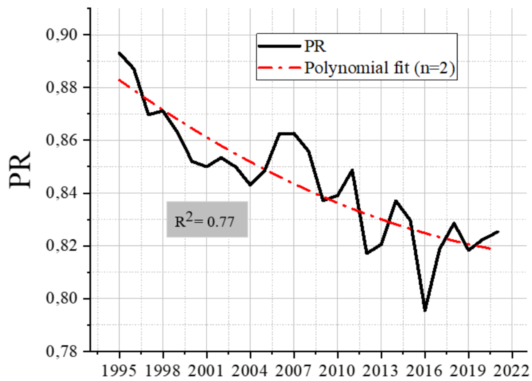

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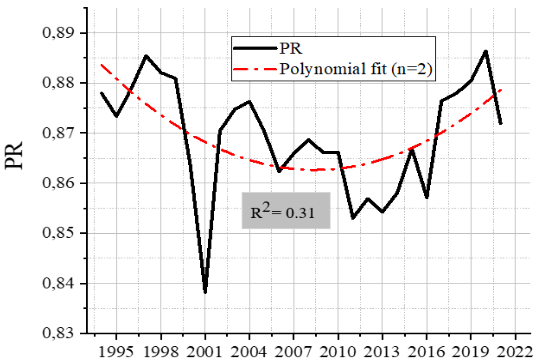

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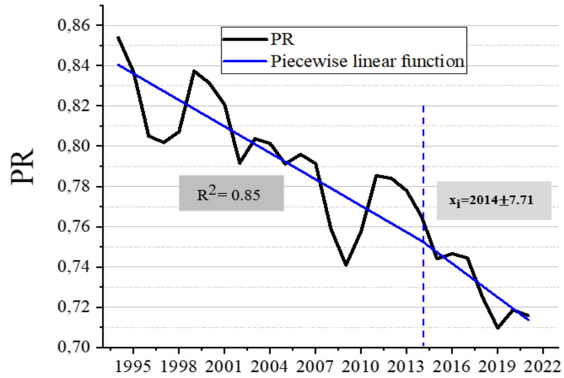
Figure 3. 2nd order Polynomial and Piecewise linear function with two segments for nonlinear degradation of Tiergarten West (a), Tiergarten East (b), Mont Soleil (c) and Jungfraujoch (d)

3.3.2 Multi-linear: 1 breakpoint

For the breakpoint linear function, the breakpoint, or the intersection (x_i) differs from system to other. In Figure 4, x_i is indicated by the blue dotted line and was detected between the years 2011 and 2016 for al PV systems.



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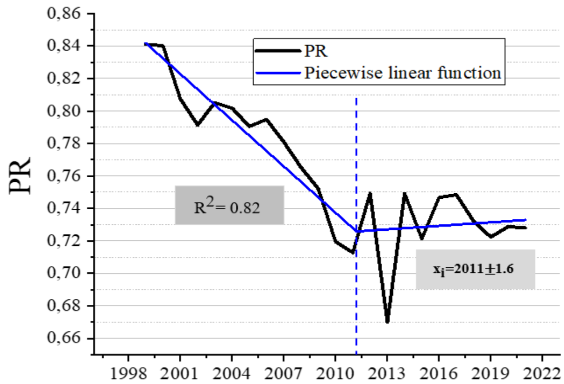

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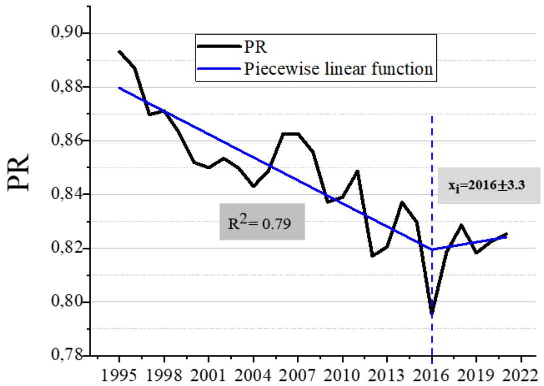

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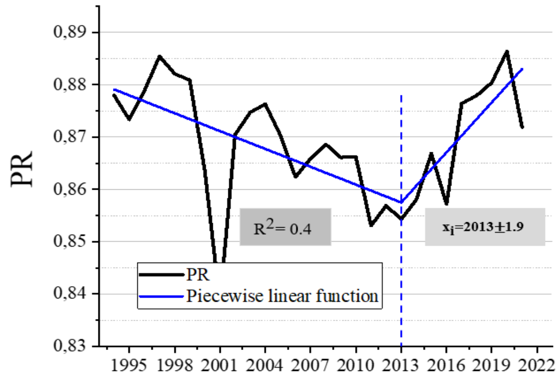

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Figure 4. Multi-linear function with one breakpoint of Tiergarten West (a), Tiergarten East (b), Mont Soleil (c) and Junfraujoch (d)

It is concluded that breakpoint is the best fitting function for the Tiergarten East, Mont Soleil and Junfraujoch systems with a R^2 of 0.82, 0.79 and 0.4, respectively. While for Tiergarten system, both functions fit the PR curve well with a R^2 of 0.85 (Table 2).

Table 2. R^2 of different fitting functions

System	Linear function	Quadratic function	Breakpoint function
Tiergarten West	0.83	0.85	0.85
Tiergarten East	0.67	0.79	0.82
Mont-Soleil	0.75	0.77	0.79
Junfraujoch	0.02	0.3	0.4

4 CONCLUSION

In the present work, long-term linear and non-linear degradation of four PV systems in Switzerland are investigated. To analyze the degradation rates, monthly and annual performance ratio are calculated, and the effect of PV module temperature and irradiance are examined. For monthly linear degradation, different ranges were found for the studied PV systems, (0.52 %-0.55 %), (0.38 %-0.56 %), (-11.06 %- 0.94%), (-5.6 %-0.61 %) for Tiergarten West, Tiergarten East, Mont Soleil and Junfraujoch, respectively. Moreover, the degradation is affected by the irradiance and module temperature and the effect varies according to each PV system. Non-linear degradation of the PV systems is also studied. The purpose of latter is to match the best function to the performance of these PV systems. Hence, 2^{nd} order polynomial and breakpoint functions were used, and it is found that the same correlation is reached by both function for Tiergarten system, since the performance of the breakpoint function surpassed the polynomial one for the rest PV systems.

Three out of four degradation curves show decreasing degradation rates over time. The only system which shows increasing degradation is Tiergarten West, where the DR increase is small.

5 REFERENCES

[1] D. Atsu, I. Seres, M. Aghaei, and I. Farkas, "Analysis of long-term performance and reliability of PV modules under tropical climatic conditions in sub-Saharan," *Renewable Energy,* vol. 162, pp. 285-295, Dec 2020, doi: 10.1016/j.renene.2020.08.021.

[2] Y. R. Golive *et al.*, "Analysis of Field Degradation Rates Observed in All-India Survey of Photovoltaic Module Reliability 2018," *Ieee Journal of Photovoltaics,* vol. 10, no. 2, pp. 560-567, Mar 2020, doi: 10.1109/jphotov.2019.2954777.

[3] H. Hefaidh, D. Mébarek, B. Negrou, and Z. Driss, "Reliability degradation prediction of photovoltaic modules based on dependability methods," *International Journal of Quality & Reliability Management,* 2021.

[4] M. Malvoni, M. G. Giorgi, and P. M. Congedo, "Study of degradation of a grid connected photovoltaic system," in *72nd Conference of the Italian-Thermal-Machines-Engineering-Association (ATI)*, Lecce, ITALY, Sep 06-08 2017, vol. 126, in Energy Procedia, 2017, pp. 644-650, doi: 10.1016/j.egypro.2017.08.263. [Online]. Available: <Go to ISI>://WOS:000426884100082

[5] A. Phinikarides, N. Kindyni, G. Makrides, and G. E. Georghiou, "Review of photovoltaic degradation rate methodologies," *Renewable & Sustainable Energy Reviews,* vol. 40, pp. 143-152, Dec 2014, doi: 10.1016/j.rser.2014.07.155.

[6] C. Huang and L. Wang, "Simulation study on the degradation process of photovoltaic modules," *Energy Conversion and Management,* vol. 165, pp. 236-243, Jun 2018, doi: 10.1016/j.enconman.2018.03.056.

[7] "Köppen and Geiger classification." Climate Bern: Temperatures, Weather & Climate Tables for Bern (climate-data.org) (accessed 10/03/2022.

[8] N. H. Reich, B. Mueller, A. Armbruster, W. van Sark, K. Kiefer, and C. Reise, "Performance ratio revisited: is PR > 90% realistic?," *Progress in Photovoltaics,* vol. 20, no. 6, pp. 717-726, Sep 2012, doi: 10.1002/pip.1219.

[9] S. Lindig, A. Louwen, D. Moser, and M. Topic, "Outdoor PV System Monitoring-Input Data Quality, Data Imputation and Filtering Approaches," *Energies,* vol. 13, no. 19, Oct 2020, Art no. 5099, doi: 10.3390/en13195099.

[10] IEC61724-1:2017, *Photovoltaic System Performance—Part 1: Monitoring*. International Electrotechnical Commission: Geneva, Switzerland, 2017

[11] S. Lindig, I. Kaaya, K. A. Weiss, D. Moser, and M. Topic, "Review of Statistical and Analytical Degradation Models for Photovoltaic Modules and Systems as Well as Related Improvements," *Ieee Journal of Photovoltaics,* vol. 8, no. 6, pp. 1773-1786, Nov 2018, doi: 10.1109/jphotov.2018.2870532.

[12] S. Lindig, A. Louwen, D. Moser, and M. Topic, "New PV Performance Loss Methodology Applying a Self-Regulated Multistep Algorithm," *Ieee Journal of Photovoltaics,* vol. 11, no. 4, pp. 1087-1096, Jul 2021, doi: 10.1109/jphotov.2021.3078075.

[13] M. Theristis, A. Livera, C. B. Jones, G. Makrides, G. E. Georghiou, and J. S. Stein, "Nonlinear photovoltaic degradation rates: Modeling and comparison against conventional methods," *IEEE Journal of Photovoltaics,* vol. 10, no. 4, pp. 1112-1118, 2020.