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OUTDOOR DEGRADATION ANALYSES OF SIX DIFFERENT AGED PHOTOVOLTAIC MODULE TECHNOLOGIES UNDER THE ARID-STEPPE CLIMATE CONDITION

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Abstract: Outdoor tests of photovoltaics module are crucial both for marketing and for research and technological developments. The electric generation performance and their degradation rates and lifetime are also related to different climatic conditions of the regions. In this work, the outdoor tests are carried out for six different photovoltaic (PV) modules under Arid-steppe Climate condition of Ankara, Türkiye. Their degradation rates are calculated by using linear regression (LR) and year on year (YOY) methods. The comparison between LR and YOY are carried out and with the other performed studies of different regions of world. In addition, it is investigated that how effective the climatic conditions on daily degradation rates. The results obtained are as follows: Mono-Si and Hetero-junction Silicon (HIT) cell modules degradation rates of 0.71/1.56 %/year and 0.84 %/year are respectively obtained by LR method and 0.57/0.90 %/year and 0.85%/year are respectively by YOY method. The degradation rates for Cupper Indium Selenide (CIS), Cupper Indium Gallium Selenide (CIGS) and microcrystalline Silicon/Amorphous Silicon (μc-Si/a-Si) modules have 1.73/1.49 %/year, 11.55/9.52 %/year and 1.48 %/year for LR method and 1.28/1.12 %/year, 9.94/9.53 %/year and 0.99 %/year for YOY method are obtained respectively. It is also obtained for the Polycrystalline Silicon Modules as 1.20/1.86 %/year degradation rates by LR method and 0.79/1.88 %/year degradation rates by YOY method.
Keywords: Photovoltaic modules, Long-term outdoor testing, Degradation rates, Linear regression degradation method, year on year degradation method

INTRODUCTION

Utilization of renewable energy and especially solar energy has grown worldwide over the past decade as governments consider the increasing global warming and the supply of fossil fuels is declining (Grübler, Jefferson, and Nakićenović 1996). The Solar PV modules are one of the most important systems of generating electricity by renewable energy. Their properties are related with the PV module performances of electrical energy generation and also to their length of life time. Environmental and climate conditions are also effective for the lifetime of PV modules. Consequently, the degradation rates of PV modules are important property to identify their life time to be supplied for PV modules by the manufacturers, which is very important to make economic plan for solar energy power plant (Annigoni et al. 2019; Tsanakas, Ha, and Buerhop 2016) (Micheli et al. 2022).

Degradation rates of PV modules can be calculated by two different steps to reach overall degradation. The first one includes only PV module degradation using the measures of the energy generated by the module. The second is the degradation coming from system equipment loss such as the maximum power point tracking (MPPT), cables and/or invertor (Ozden et al. 2015). The overall degradation rate is together with the system and PV modules degradations.

Ishii et al (Ishii, Takashima, and Otani 2011) tested 14 different modules under moderate climate conditions for 4 years. The results of degradation rates are between 0.64 %/year and 0.92 %/year for mono-crystalline silicon modules while 0.4 %/year for poly-crystalline silicon modules within the same time interval. Besides, the obtained degradation rate for amorphous silicon modules is higher than 1.45 %/year.

Makrides et al (Makrides et al. 2010) studied on 11 solar modules under the Mediterranean climate in Cyprus region for the period June 2006 – June 2009 including 5 kind modules which are mono-crystalline, poly-crystalline, amorphous silicon, Cadmium Telluride (CdTe), and Cupper Indium Gallium Selenide (CIGS). They found that the first-year degradation rates are in range 2.12 %/year and 4.73 %/year, for mono-crystalline modules, changes between 1.47 %/year and 2.40 %/year for poly-crystalline, 0.26 %/year for CIGS modules, 0.32

%/year for CdTe Modules and 0.23 %/year for amorphous silicon modules.

Bogdanski et al. (Bogdanski et al. 2010) studied on the influence of the climate conditions on the solar modules in four different regions. The climates are warm moderate climate (Cologne, Germany), tropical climate (Serpong, Indonesia), cold high mountain climate (Zugspitze, Germany) and arid climatic conditions (Sede Boqer, Israel). They outline that the climate is very effective on the degradation rates. The highest degradation rate belongs cold high mountain climate due to high snowfall and wind stress. Because of high temperature and irradiation, in the desert and tropical climate, higher degradation is observed. In Israel and Indonesia, the contamination with sand were observed and this situation results in high decrease of the generated energy. All modules analyzed in the all-climate condition showed less than 1 %/year degradation although the mountain climate data.

Quansah et al. (Quansah and Adaramola 2018) studied using 29 crystalline solar modules at six different locations in Ghana. They found that the degradation rates in a range from 0.8 %/year to 6.5 %/year. In addition to I-V investigations, they observed some mechanical degradation such as broken glass, delimitation, yellowing encapsulates materials and bubbles.

Savvakis et al. (Savvakis and Tsoutsos 2015) work out a grid-connected system having 2.18 kWp micro crystalline and based amorphous silicon (μc-Si / a-Si) thin-film modules. The systems located in island of Crete in Mediterranean for two years and the authors used monthly average data. Their study included the module temperature to clarify the outdoor PV operating temperatures. This group found the performance ratio of 85.1 % with efficiency of about 7.25 %.

Tabatabaei et al. (Tabatabaei, Formolo, and Treur 2017) studied on the degradation rates of 23 PV modules installed on a roof of a family house in Netherlands. The time interval of the data obtained is from May 2013 to January 2017 and PV panels installed in the same location and with the same orientation are compared with respect to each other. They set the data to Seasonal and Trend decomposition using LOESS technique. Locally estimated scatterplot smoothing (LOESS) is a nonparametric method. This method is used for smoothing a series of data where no assumptions have been made about underlying structure of the data set. According to this study, panels at the same location and orientation have the same degradation rates and the average degradation rate of modules in this system is 0.92 %/year.

Limmanee et al. (Limmanee et al. 2017) presented a study about degradation rates analysis of 73 different PV modules of 4 different module types: multi c-Si, heterojunction Si, thin film Si and CIGS on Thailand Science Park with 4 years data from 2012 to 2016. According to this study, performance rates of thin film Si modules are having low efficiencies and they degraded seriously. Except that these modules, the degradation rates of other modules are in a range between 0.3 %/year and 1.9 %/year.

Solís-Alemán et al. (Solís-Alemán et al. 2019) in Spain studied on degradation rates of four different thin film solar module; a-Si, a-Si/μc-Si, CdTe and CIGS with a five-and-a-half-year and a six-and-a-half-year periods, respectively) by using classical seasonal decomposition technics and year-on-year statistical technics and they found ~1.3 %/year of average degradation rates.

Singh et al. (Singh et al. 2020) presented a study in 2020 about field analysis of three different PV system technologies. Analysis included monthly average performance rates, weather corrected performance rate series resistance and effective peak power of HIT, poly-crystalline and a-Si solar modules of three years data. Also, degradation rates were calculated by using three methods which were linear regression, classical seasonal decomposition (CSD), and locally weighted scatterplot smoothing (LOESS) via performance rate and normalized efficiency. The degradation rates were found as 1.24 %/year, 1.16 %/year and 1.16 %/year for a-Si modules, 0.14 %/year, 0.56 %/year and 0.11 %/year for HIT modules and 1.50 %/year, 0.82 %/year and 1.46 %/year for poly-Si modules using linear regression, CSD and LOESS analysis respectively. The average efficiency is found to be 5.17 % for a-Si, 15.40 % for HIT and 10.78% of poly-Si modules.

Frick et al. (Frick et al. 2020), at 2020, presented a unified methodology to calculate degradation rate of PV systems accurately and prove this calculation is location dependent. The PV systems were installed at different climatic locations by using different c-Si PV modules to compare long term degradation rates. After 7 years, the degradation rate results showed convergence between time series analytical methods applied and degradation results from the indoor standardized procedures. Hence the multi crystalline silicon systems at the warm climatic locations had more degradation rate in comparison with the system in moderate climatic location. They obtained in between 0.1%/year to 0.4%/year degradation rates of the modules.

Dhimish at al. (Dhimish and Alrashidi 2020) presented a study on degradation rates using 10 years of data (from 2008 to 2017) in U.K. and Australia. The degradation rates are changing from 1.05 %/year to 1.16 %/year and from 1.35 %/year to 1.46 %/year for the system in the U.K and Australia respectively. In Australia, because of rapidly changing ambient temperature and nonuniform irradiance, multiple faulty bypass diodes were found while, in U.K., damaged diodes were not observed. Also, performance rate of PV systems was calculated as 88.81 % and 86.35 % in U.K and Australia, respectively.

Dag at al.(Dag and Buker 2020), in 2020, studied on the degradation rates and performance characteristic of poly-crystalline and hetero-junction with intrinsic thin layer PV modules for half and two years. They installed the system on a roof, in the region of Central Anatolia

(Konya). In this study, they consider also the temperature, and the calculation of degradation rates were carried out by corrected performance rates. The results are lower than 0.1 %/year for thin film and within a range of 0.67 %/year and 0.83 %/year poly- crystalline. Kurtz and Jordan from National Renewable Energy Laboratory (NREL) (Jordan and Kurtz 2013), made an extensive analysis of degradation rates of PV modules and systems by using the results of outdoor measurements of five different types of modules and systems. To analyze degradation rates of PV modules, 2000 reported degradation rates in last 40 years before 2012 were worked out. The gaining value of average degradation rate for a-Si PV systems installed before the year 2000 was around 1.8 %/year, and after the year 2000 the average rate was about 1 %/year. For CdTe thin film PV systems, however, their reported values of average degradation rates were about 2 %/year for pre-2000 and about 0.6 %/year for post-2000. Finally, for Mono-Si arrays, the reported values were 0.7 %/year and 0.6 %/year for pre- and post-2000, respectively.
Daher et al. (Hassan Daher, Gaillard, and Ménézo 2022) presented a study on performance degradation of solar PV power plant in Djibouti whose climate is desert maritime over five years operation and the degradation rates was considered using Photovoltaics for Utility Scale Applications (PVUSA) regression analysis and PR analysis based on 1-min intervals data. The degradation rates were found 0.96 ± 0.37%/year and 1.01 ± 0.38%/year respectively for the DC and the AC parts of the PV solar system. For PVUSA under PTC conditions: 0.057 ± 0.68%/year for DC power and 0.085 ± 0.68%/year for AC power. Also Daher et al. (Daher et al. 2023)release a study at 2023 given an information about degradation rates of different area for different module technologies. According to this study, the degradation rates are in range between 0.03 % /year (Singapore, c-Si) and 6.5 %/year (Ghana, m-Si and p-Si). In addition to these studies, at the same location with this study Özden at al. (Ozden et al. 2015) studied on two system arrays with an μc-Si/a-Si and a CdTe thin film arrays and they found that the degradation rates are 0.39 %/year and 6.98%/year. Özden at al. (Ozden, Akinoglu, and Turan 2017) also studied the PV system performances and analyzed the degradation rates and performance ratios for three years. The systems consist of a mono-Si, an a-Si thin film and a CdTe thin film array. The degradation rates of these systems were 0.40 %/year, 1.88 %/year and 10.60 %/year for mono-Si, a-Si thin film and CdTe systems, respectively. Three different systems under the same climatic conditions of central Anatolia were analyzed with 44 months data. As a result of this study, the degradation rates are 0.4%/year, 1.88%/year and 10.60 %/year for Mono-Si, a-Si and CdTe thin film modules, respectively. The yearly average efficiencies of these modules are 11.86%, 6.49% and 5.30%, respectively (Ozden et al. 2017).

In this paper, 10 modules are performance tested in Middle Anatolia climate conditions for nine years in six different module groups, which are cupper indium selenide (CIS-1 & 2), cupper indium gallium selenide (CIGS-1 & 2), tandem cell (μc-Si / a-Si), mono-crystalline (Mono-Si-1 & 2) and heterojunction with intrinsic thin layer (HIT), poly- crystalline (Poly-Si-1 & 2), Their degradation rates are calculated by using Year-On-Year (YOY) Method and Linear Regression (LR). The results obtained are discussed and these two methods are compared to each other and to some other studies in different regions by the researchers.

MATERIAL AND METHODS

Test Site

This study includes the outdoor testing in middle Anatolia, Ankara-Turkey (latitude 39.9° N, longitude 32.8° E), nine years data obtained from solar modules on the roof of METU Physics Building; Figure 1. The climate of Ankara is cold semi-arid (Hasselbrink et al. 2013; Ǩoppen, Volken, and Brönnimann 2011; Peel, Finlayson, and McMahon 2007). The average monthly

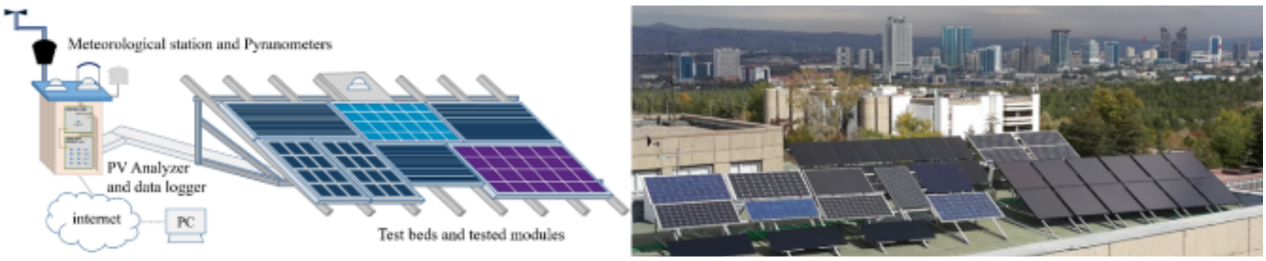

Figure 1: METU-GUNAM Outdoor Test Facilities (39.894204, 32.781977)

temperature is about 12 ºC with maximum and minimum values of around 41 ºC and -25 ºC for the months July and August, and January, respectively. In the recent 90 years' average value of precipitation depth are 387 mm
The modules have been connected separately to a multi-tracer that is a testing system of it. This system continuously measures the performances of modules, and the modules are individually controlled and operated at their peak power during daylight hours. The output data and several input data (like ambient temperature, tilted and horizontal irradiance and module temperatures) were automatically measured and logged in every 10 minutes.

Test Modules

The modules are in operation for nine years within the time interval of 2012-2021. They are connected to a data logging system which extracts the energy at maximum

Table 1 Tested PV Modules Specifications

Module Type	P_{MAX} [W]	V_{OC} [V]	I_{SC} [A]	V_{MPP} [V]	I_{MPP} [A]	Area [m²]	Testing Period	
							Started	**Ended**
CIS 1	130	59.5	3.28	44.9	2.90	1.05	Oct, 2014	Jun, 2021
CIS 2	130	59.5	3.28	44.9	2.90	1.05	Oct, 2014	Jun, 2021
CIGS 1	75	72.36	1.6	54.02	1.4	0.70	Jan, 2013	Sep, 2018
CIGS 2	75.5	74.10	1.6	56.71	1.3	0.70	Jun, 2012	Sep, 2018
µc-Si / a-Si	128	59.8	3.45	45.4	2.82	1.40	Apr, 2012	Jun, 2021
Mono-Si 1	160	43.7	5.06	35.3	4.58	1.28	Aug, 2012	Jun, 2021
Mono-Si 2	160	43.7	5.06	35.3	4.58	1.28	Apr, 2012	Jun, 2021
HIT	230	42.3	7.22	34.3	6.71	1.39	Apr, 2012	continue
Poly-Si 1	240	36.6	8.70	30.2	7.96	1.63	Apr, 2012	Jun, 2021
Poly-Si 2	130	21.7	8.18	17.8	7.30	1.02	May, 2012	Jun, 2021

power point (MPP) with a properly adjustable load. The elements of our testing system can be seen in Figure 1 and the specifications of all types of ten tested modules are tabulated in Table 1.

Data

For the years 2012-2016, we used the data taken by Türkiye State Meteorological Service (TSMS) where the station is located at some 20 km away from our testing site of PV modules (Anon n.d.). After that time, for the years 2016 to 2021, plane-of-modules irradiance was measured by a Kipp&Zonnen high precision secondary standard Pyranometer. The accuracy of the procedure for using data from the first four years was presented by Ozden (Akinoglu, Karaveli, and Özden 2017; Ozden et al. 2017) and Akinoglu (Akinoglu et al. 2017) The data we obtained from TSMS was horizontal global solar irradiation. To estimate the hourly global solar irradiation on tilted PV modules the anisotropic model of HDKR (Reindl, Beckman, and Duffie 1990) and later modified by Reindl et al. (Reindl et al. 1990)), entitled by in the book by Duffie and Beckman (Duffie and Beckman 2013). The equation used is given below:

$$I_t = (I_b + I_d A_i)_b + I_d(1 - A_i)\left(\frac{1+cos\beta}{2}\right)\left[1 + f sin^3\left(\frac{\beta}{2}\right)\right] + I\rho_g\left(\frac{1-cos\beta}{2}\right) \quad (1)$$

In this equation, I_t represents the hourly total irradiation incident to the module surface. I_b represents direct beam, I_d represents diffuse radiation from Sun. β is the tilt angle of the PV modules, which is between module and horizontal surface and ρ_g is a constant value that represents the coefficient of reflectance of ground. According to Liu et all (Liu and Jordan 1963), the average value of ρ_g is taken as 0.20 for all months during which the ground is free of snow (Ineichen, Guisan, and Perez 1990).

The output, that is the yield of the PV modules, are measured by multi-tracer in every 10-minutes interval. Because of the failure of some device's due to hard weather conditions, some small amount of data could not be obtained. To overcome this problem, data was normalized and non-computational data filtering is applied. In this calculation, data were filtered if solar irradiation coming to the plane of solar PV module was larger than 50 Watthour/m^2. Hence, after this process hourly, daily and monthly yields can be obtained. Also, for monthly calculation, some minor deficiencies were normalized but the greater deficiencies of the data in a month were accepted as "Outliers". The monthly yield data for modules resulted due to the input measured accurately for last one year (from January 2020 to December 2020) is presented in Figure 2. The yields of the modules clearly follow the seasonal variation of the input while also reflects the proper outputs that corresponds to the technology of the module.

Linear Regression Degradation Methodology

To calculate the degradation rates, firstly, the performance ratio (R_p) of modules are needed. R_p is the ratio of the final energy yield of the solar module (Y_f) to the reference yield (Y_r), as shown in Eq. 2 (IEC 61724 1998; Ozden et al. 2017) .

$$R_p = \frac{Y_f}{Y_r} = \frac{E_{out}/E_{STC}}{E_{in}/G_{STC}} \quad (2)$$

The first method used for calculating degradation rates is the simple linear regression (LR) method. This method is a simple linear regression analysis applied to the monthly time series of the performance parameter which is the performance ratio (Rp). By using the linear fitting of graphs to time series versus monthly performance ratios data set of each PV module and obtain an equation of the form as shown in the Eq. 3

$$y = mx + n \quad (3)$$

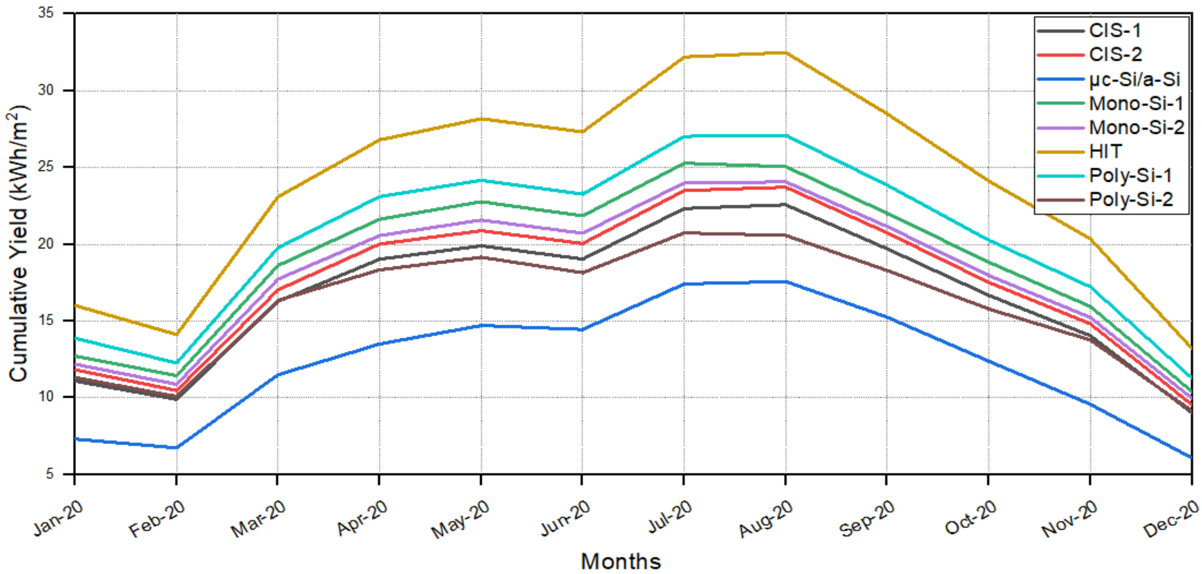

Figure 2: Monthly cumulative yields of 8 modules during 2020

Thus, the below equation 4, for the percent degradation rate can be expressed using the regression parameters *m* and *n* given in Eq. 3. Also, *N* is the number of the months of outdoor operation.

$$R_d = \left[\frac{n-y(N)}{n} \times \frac{12}{N}\right] \times 100 \quad (4)$$

Year on Year (YOY) Methodology

The other method used in this study was year-on-year (YOY) degradation method. Firstly, daily performance rates are calculated. Afterwards, daily degradation rates are calculated for each operation time, Eq. 5. At this equation, j represents j^{th} month and i represents i^{th} day and as mentioned in previous section, $R_{p,daily}$ is daily performance ratio and $R_{d,daily}$ is daily degradation rates of modules.

$$R_{d,daily,ji} = \frac{R_{p,daily(j+6)i} - R_{p,daily,(j-6)i}}{R_{p,daily,(j-6)i}} \times 100 \quad (5)$$

The final annual degradation ratio is accepted as the median value of the distributions of degradations after the frequency of degradations are plotted.

RESULTS AND DISCUSSION

Linear Regression Degradation

Figure 3 gives the time series of the monthly outdoor performance ratios for the module groups of (a) thin film, (b) monocrystalline and HIT and (c) polycrystalline. The trend lines are also drawn, and the regression equations are presented in the legend boxes. The linear regression expressions are used to obtain degradation rates of the modules as mentioned in section "Linear Regression Degradation Methodology" and with Eqn. (4) (Ozden et al. 2017). We should note again that the efficiencies before April 2016 were computed using the solar irradiation data taken from TSMS located at around 20 km away from GÜNAM's test facility.

As can be observed from Figure 3-a, CIS-1 & 2 and µc-Si/a-Si modules have similar performance ratios. Also, their degradation rates are close to each other. CIS-1 & 2 have 1.73 %/year and 1.49 %/year respectively while µc-Si/a-Si has 1.48 %/year annual degradation. The performance of the CIGS modules seems rather having manufacturing problem, one started rather with reasonable performance but degrades rapidly (CIGS 1) while the other starts with unexpectedly low performance value (CIGS 2). However, we calculated and presented the degradation rates for CIGS and the results are 11.55 %/year and 9.52 %/year, respectively.

Figure 3-b is the same time series for the two Mono-Si modules and one HIT module. The performance ratios of Mono-Si-1 and HIT modules are too close to each other while the performance rate of Mono-Si-2 module is a little higher than two other modules. On the other hand, the degradation of Mono-Si-2 module is 1.56 %/year and higher than Mono-Si-1 and HIT modules. The annual degradations rates are for Mono-Si and HIT 0.71 %/year and 0.82 %/year respectively. That is, Mono-Si-2 degrades faster than HIT and Mono-Si-1 as shown in the results. In the literature, according to Table-2, HIT modules showed lower degradation (Ozden et al. 2020). Although Mono-Si-1 and Mono-Si-2 modules are the same brand, some processes of making module such as cells, encapsulation material, lamination are different each other. So according to this study, Mono-Si-2 shows higher degradation rate.

As Poly-Si modules are shown at Figure 3-c, at the start of testing, two modules have the same performance ratio. However, the performance of Poly-Si-2 modules decreased faster than Poly-Si-1 in the test duration. Nevertheless, there is not too much difference among the degradation of these two modules. Poly-Si-1 has 1.20 %/year degradations and Poly-Si-2 has 1.86 %/year.

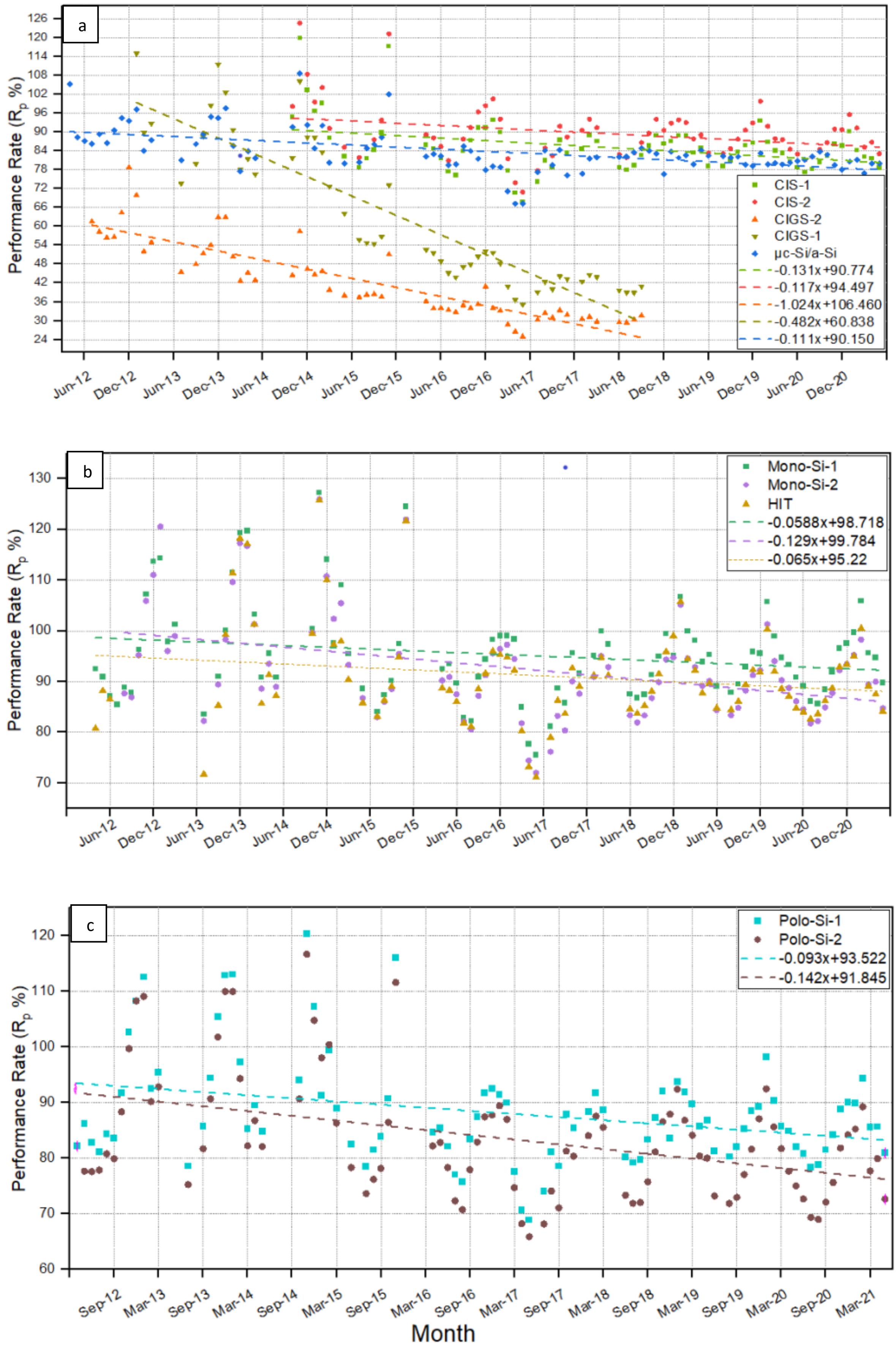

Figure 3: Monthly performance ratios of (a) Thin film, (b) Mono-Si and (c) Poly-Si module groups over the nine years

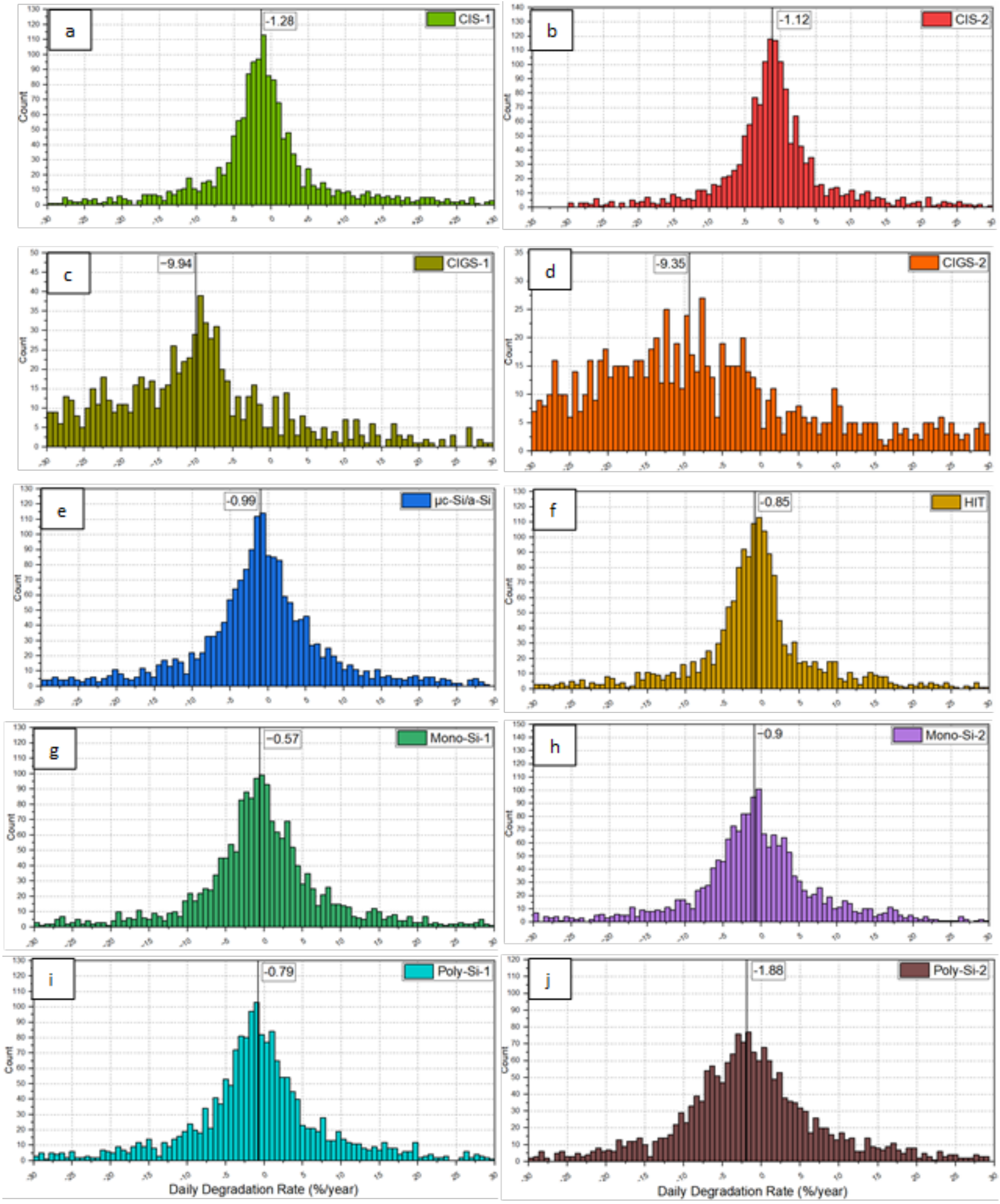

Figure 4: YOY Degradation Rate of PV Modules: (a) CIS-1, (b) CIS-2, (c) CIGS-1, (d) CIGS-2, (e) µc-Si/a-Si, (f) HIT, (g) Mono-Si-1, (h) Mono-Si-2, (i) Poly-Si-1, (j) Poly-Si2

Year on Year Degradation Method

For YOY degradation method, daily performance rates were calculated, and the annual degradation of PV module were calculated for each day during outdoor test process. At Figure 4, daily degradation rates are shown for each module separately. The median values of daily degradation data sets are also shown on this graph. In Figure 4-a and 4-b, CIS-1 & 2 modules demonstrate similar results. CIS-1 has 1.28 %/year and CIS-2 has 1.12 %/year degradation. Also, the distributions of degradations data set of CIS-1 & 2 are close to each other. When we look at the CIGS-1 & 2 modules as given in Figure 4-c and 4-d, they have a wide range distribution. Because of reasons aforementioned at the LR section, these modules demonstrate high degradation and according to results, these degradation rates increase in time. While CIGS-1 has 9.94 %/year degradation, the ratio of degradation of CIGS-2 is 9.35 %/year. In Figure 4-e, the distribution of data set of μc-Si/a-Si module accumulate ± 10 %/year daily degradation and its annual YOY degradation is 0.99%/year. μc-Si/a-Si modules is the best module in terms of degradation, among the thin film modules in our test area.

In Figure 4-f, HIT modules degradations data set are shown and the degradation of this module is annually 0.85 %/year, and it is not observed that the distribution accumulation of degradation is spread. Mono-Si-1 &2 have similar degradation distribution and their degradations are 0.57 %/year and 0.9 %/year annually respectively as shown at Figure 4g and 4-h. Poly-Si-1&2 is not different from Mono-Si Modules. In Figure 4i and 4-j, daily degradation distribution of data sets of Poly-Si-1 & 2 are shown and they degraded 0.79 %/year and 1.88 %/year annually. Poly-Si-1 much less degraded than Poly-Si-2.

Comparisons of YOY and LR

At the Table 2, annual degradation rates and process time of outdoor test of ten different modules are shown. The degradation rates are in the range of 1.88%/year and 0.71 %/year except CIGS 1 & 2. CIGS-1 & 2 modules were problematic and their degradation rates higher than expected. They were uninstalled in September 2018 and they could be tested roughly 6-year operation. Moreover, CIS-1 & 2 was installed October 2014 and their operation time is seven years.

The comparisons of these two methods and the literature are also shown at the Table 2. According to these results, the degradations are close to each other but there are some differences between the YOY and LR.

LR method show higher degradation rates than YOY method expect HIT and Poly-Si-2 but the differences are too small. If the LR Degradation method is used instead of YOY, the degradations values could be observed higher. On the other hand, the degradation rates found in As shown in figure 5, CIS-1 & 2, also CIGS-1 & 2 showed lower performance in the lower temperature over the years while higher temperatures did not show any effect on performance ratios. μc-Si/a-Si module performance ratio did not show any effect on performance ratios both lower and higher temperature. The group of monosilicone modules were not affected by temperature. Polysilicone modules have been affected by higher temperature. While ambient temperature increased, performance ratios decreased.

The wind speed annual average value is 0.9 km/h according to our data in the module's location. We can say that is not an area gets a lot of wind and the effect of the wind on modules has been not observed.

CONCLUSION

In this study, we tried to calculate degradation rates of ten different PV modules by using two different methods. Firstly, data getting the setup were adjusted to calculate by making needed filtering and normalizations. After that, performance ratios of modules are calculated, and degradations rates are found based on performance rates. Performance ratio of modules were compared with each other. According to these results Mono-Si-1 module shows better results in terms of degradation rates.

Table 2: Comparison of YOY and LR Degradation values of PV Modules

	This Study			Literature	
Module	Test Time (Month)	LR (%/year)	YOY (%/year)	LR (%/year)	YOY (%/year)
CIS	80	1.73 / 1.49	1.28 / 1.12	2.34 (Silvestre et al. 2016) 1.04 (Ozden et al. 2020)	----
CIGS	69/75	11.55 / 9.52	9.94 / 9.35	0.17(Makrides et al. 2010)	0.96 (Jordan and Kurtz 2013) 0.46 (Solís-Alemán et al. 2019)
μc-Si/a-Si	110	1.48	0.99	1.45(Ishii et al. 2011) 0.23(Makrides et al. 2010) 3.67~3.76(Solís-Alemán et al. 2019) 1.73 (Silvestre et al. 2016) 2.28 (Ozden et al. 2020)	0.87(Jordan and Kurtz 2013) 0.53 (Solís-Alemán et al. 2019)
Mono-Si	110	0.71 / 1.56	0.57 / 0.90	0.78 (Ishii et al. 2011) 0.10 (Makrides et al. 2010)	0.36 (Jordan and Kurtz 2013)
HIT	110	0.84	0.85	0.26~0.63(Singh et al. 2020) 0.109 (Dag and Buker 2020)	----
Poly-Si	110	1.20 / 1.86	0.79 / 1.88	0.40 (Ishii et al. 2011) 0.67 (Dag and Buker 2020)	0.64 (Jordan and Kurtz 2013)

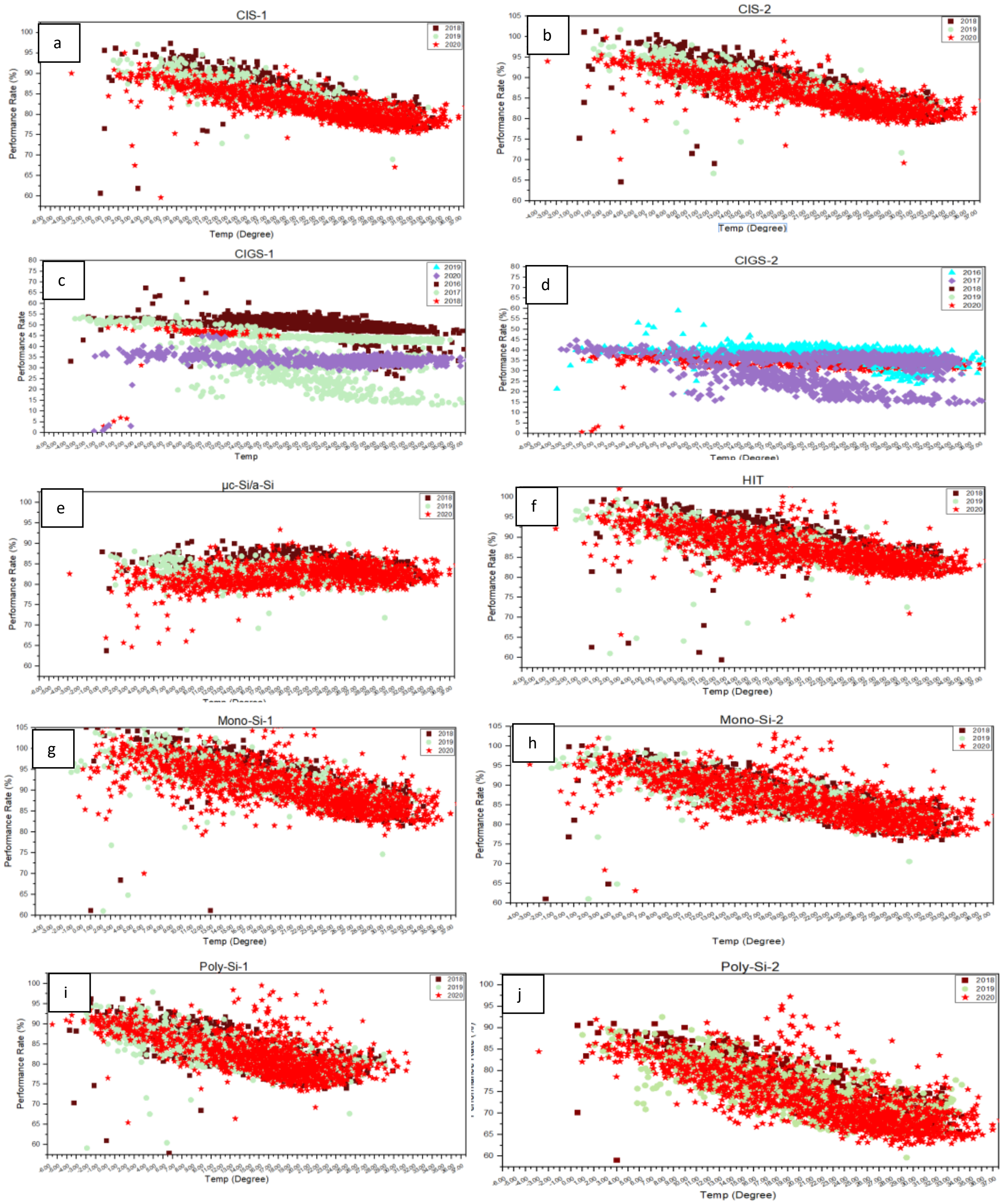

Figure 5: Temperature vs performance rates graphs according to years with: (a) CIS-1, (b) CIS-2, (c) CIGS-1, (d) CIGS-2, (e) μc-Si/a-Si, (f) HIT, (g) Mono-Si-1, (h) Mono-Si-2, (i) Poly-Si-1, (j) Poly-Si2

his study for both methods are in the range of values at the literatures except HIT and CIGS. HIT results for YOY and LR method are the same in this study but, in the literature degradation for HIT modules are lower for LR method.

The effect of weather conditions on performance rates

In this study the effect of weather condition on performance rate has been investigated such as humidity and ambient temperature. As shown in the appendix, humidity vs performance ratios graph there are not any effect or changes modules performance rates. However, ambient temperature shows different effect on different module technologies.

Although this module was working nine years, its performance decreased only 0.71 %/year in LR and 0.57 %/year YOY annually. Mono-Si-2 module shows 1.56 %/year and 0.90 %/year degradation according to LR and YOY method respectively. HIT module degraded 0.84 %/year for LR method and 0.85 %/year for YOY method. Overall Mono-Crystalline group (Mono-Si 1&2 and HIT) performed well. On the other hand, Poly-Si Group and thin film group except CIGS 1&2, show a similar performance. The degradation ratios of Poly-Si 1&2 are 1.20 /1.86 % /year according to LR method, 0.79/1.88 %/year according to YOY method. CIS 1&2 modules show a degradation amount of 1.73 %/year and 1.49 %/year according to LR method, 1.28 %/year and 1.12 %/year according to YOY method respectively. The degradation ratio of μc-Si/a-Si module 1.48 %/year and 0.99 %/year for LR method and YOY method respectively. CIGS 1&2 were problematic PV modules and they performed badly. Their degradation was highest with 10 %/year average. In conclusion, YOY method shows lower degradation rates compare to LR method. Used method in the calculation of degradation rates has a crucial impact.

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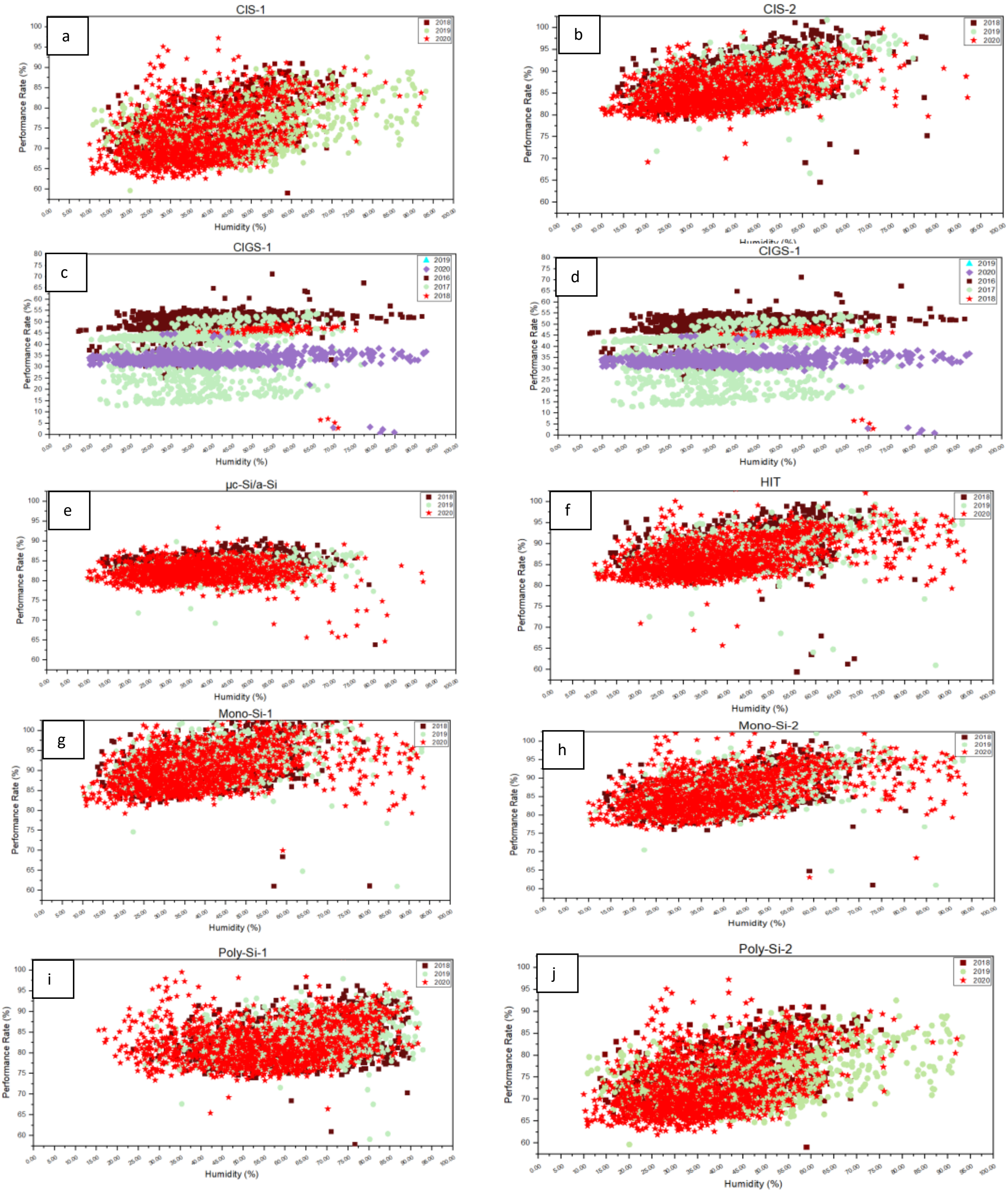
APPENDIX 1:



a
CIS-1
b
CIS-2
c
CIGS-1
d
CIGS-1
e
μc-Si/a-Si
f
HIT
g
Mono-Si-1
h
Mono-Si-2
i
Poly-Si-1
j
Poly-Si-2
Performance Rate (%)
Humidity (%)
2018
2019
2020
2016
2017

APPENDIX 2

Years	Annual wind speed (km/h)
2016	0.99
2017	0.94
2018	0.83
2019	0.79
2020	0.83
2021	0.77