Performance assessment of field deployed multi-crystalline PV modules in Nordic conditions

Basant Raj Paudyal[1], Anne Gerd Imenes[1]

[1]University of Agder, Department of Engineering Sciences, 4879 Grimstad, Norway

Abstract — **This paper presents an investigation of data monitoring quality and evaluation of performance degradation of four different multi-crystalline silicon (mc-Si) photovoltaic (PV) modules installed in the higher latitude conditions in southern Norway. Degradation of each module has been investigated in terms of degradation of short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), fill factor (*FF*) and maximum power (P_{MPP}). The analysis for the period of monitoring data from 2014 to 2018 show no considerable module degradation compared to the standard degradation rate of all parameters. The statistical analysis of I_{SC} shows an average degradation of 0.17% for all modules. Spectral corrections were applied to I_{SC} and P_{MPP}, in addition to temperature and irradiance corrections. Among the parameters, *FF* and I_{SC} show slight degradation based on the yearly average method. Infrared images were used for validation of findings, but due to the unavailability of images from the initial installation period, the image results are inconclusive. Performance ratio plots based on corrected I_{SC} values show very stable performances over the five-year period. The results suggest that PV modules in cold conditions may undergo lower degradation compared to typical degradation rates experienced in other regions.**

Keywords **— multi-crystalline silicon, photovoltaic modules, outdoor monitoring, performance evaluation, degradation.**

I. INTRODUCTION

PV modules, as any other materials, suffer through the wear and tear while being exposed to the outdoor environment for extended periods. This process may cause the deterioration in electrical parameters of the PV modules, technically termed as degradation. The precise determination of the degradation rate of PV modules within a system is a matter of concern for all stakeholders alike, from researchers to producers and investors.

The electrical parameters of PV modules are expressed in terms of standard test conditions (STC), which are rarely encountered in the outdoor operation. The parameters therefore have to be translated to the STC conditions from their operating conditions to be assessed of the deviation. Usually short circuit current (I_{SC}), open circuit voltage (V_{OC}), maximum power (P_{MPP}) and fill factor (*FF*) are the electrical parameters of most interest. In addition to the basic electrical parameters, other parameters like nominal operating temperature and temperature coefficients of power, voltage and current are used to determine performance variations from the standard conditions. Factors like spectral variation, angle of incidence and effects of increased diffused irradiance are known to influence the module performance [1], but are not described by the standard module parameters. While irradiance and temperature are the major parameters, other parameters like humidity, precipitation, altitude, and wind speed may also affect the PV performance as well as module lifetime.

From a study in [2] of the degradation rates from more than 2000 studies, the average degradation rate was found to be around 0.8% per year for all modules and 0.5% per year for the crystalline silicon modules. In the same study, I_{SC} was found to be the largest contributor to module performance degradation for most climate zones, which can be described by Köppen-Geiger climate classification. Degradation in I_{SC} can be correlated to discoloration , delamination and cracked cells and sometimes soiling. According to [3], significantly less degradation comes from *FF*, which is typically associated with corrosion and interconnects breakage due to brittleness of EVA at lower temperatures, while even less degradation is contributed by V_{OC}.

Various methods based on indoor laboratory tests and outdoor monitoring are used to detect faults in PV modules. International guidelines [4] recommend visual inspection as the quickest and most effective method to observe defects and faults in a PV module, while other frequently used fault detection methods include current-voltage (I-V) curve analysis, electroluminescence, thermography/infrared imaging, UV-fluorescence and signal transmission methods. PV modules may suffer from internal defects that are hard to detect through visual inspection. These defects can primarily cause increased temperature at cells, which in turn can affect the performance of the whole PV module. These kinds of internal defects can be easily detected using infrared (IR) images.

In case of faults caused by micro-cracks, solder breakages and corrosions in modules, IR imaging is one of the preferred diagnostic method. IR imaging is a non-destructive and contactless measurement method which provides a fast and reliable status of module. The defective or inactive regions in the PV module normally appear hotter than the active regions around them. A simple reason is that incident radiation on the active parts of the module surface is extracted as electrical current, whereas for the inactive regions, this incident energy remains unutilized and the excess heat raise the temperature of the module [5].

High latitude locations are different from the locations near equator as long winters with lesser daylight periods coupled with low solar elevation and cloud cover contribute to the lower annual solar radiation. Authors in [6] have discussed the irradiance and temperature distribution in these conditions with high share of diffused parameter in low irradiance conditions. The irradiance conditions of 1000 W/m^2 are limited in higher latitudes compared to other locations. Analysis of module output under varying irradiance conditions show a very significant spread of maximum power in lower irradiances [7]. There is a possibility of module degradation being masked by module performance in low irradiance conditions. Therefore, it is important to continuously track the module performance through long term monitoring in these regions.

Different parameters influence the performance degradation of PV systems. But degradation analysis is also governed by the availability, integrity and reliability of the data. Performance monitoring is an essential pre-requisite for the degradation analysis of a PV system with continuous tracking of power production and healthiness of the system [8]. Effective and efficient monitoring and analysis procedures not only identify the inherent issues, but also help in their rectification.

General data filtering techniques for PV performance evaluation include limiting the measurement of environmental parameters to their reasonable range for the specific site. Irradiance and temperature are the two most used parameters for performance assessment . Angle of incidence has also been used as a filtering criterion to minimize reflection losses and spectral impacts where these measurements are unavailable [1] [9].

Errors in the data analysis are introduced if there is inconsistency in measurements. One such error is instances where module parameters and atmospheric parameters are measured and stored in different time stamps. Also, the issues of either sensor or instrument shading could interfere with the actual values of the parameters. For a proper investigation, it is expected that the relative performance of modules follow a trend according to variation of atmospheric parameters. Various data filtering methodologies, such as self-referencing of Isc and the linear regression of I_{SC} to irradiance are employed to analyze the module performances [7, 10].

II. Experimental Procedures

I-V characteristics of four mc-Si modules, made with Elkem Solar Silicon (ESS®) material, have been recorded since late summer of 2013. The performance testing facility includes an outdoor test station comprising of solar irradiance, ambient and module surface temperature sensors, while measurement for the electrical parameters consisting of I_{SC}, V_{OC}, V_{MP} and P_{MPP} is done through a variable electronic load controlled by LabVIEW based custom made software [11]. The modules are installed at the tilt angle of 39° facing almost due south in the present location (58.15°N, 8.33°E) as shown in Fig. 1. The climate of testing facility is characterized as region 'Dfb' in Köppen climate classification with distributed rain throughout the year. The frequent rain events and a low number of suspended particles lead to low soiling impact. Therefore, the soiling effects are neglected in this work. Table I presents the name plate ratings and measured parameters of the mc-Si PV modules analyzed in this study.

Fig. 1. PV monitoring at University of Agder, Grimstad, Norway.

Missing data due to outages, sensor and acquisition failures are normally experienced problems in the field [12], which this setup also suffered. Basic data screening is applied to remove outliers and faulty readings before advancing with the analysis. Simple data screening included the realistic positive values of electrical parameters i.e. (> 0), while irradiance is limited between 25 and 1200 W/m^2 to reduce the effects of instrumentation uncertainty at lower irradiance level and possible contribution of cloud brightening effects at higher irradiances [13].

TABLE I
Summary of PV Module Parameters

Module Parameters	Name plate ratings	Measured values (2013) [11]			
		STP422	STP423	STP433	STP459
P_{MPP} (W)	225 (+5%)	235	235	236	234
I_{SC} (A)	8.15	8.49	8.47	8.57	8.36
V_{OC} (V)	36.7	36.8	37.0	37.1	37.0
I_{MP} (A)	7.61	NA	NA	NA	NA
V_{MP} (V)	29.6	NA	NA	NA	NA
Temp. Coeff. (I_{SC}) (%/^{0}C)	0.045	0.056	0.056	0.059	0.055
Temp. Coeff. (V_{OC}) (%/^{0}C)	-0.34	-0.351	-0.321	-0.354	-0.307
Temp. Coeff. (P_{MP}) (%/^{0}C)	-0.47	-0.459	-0.421	-0.471	-0.396

The dataset from the PV monitoring scheme normally contains a number of outliers and large spread [14].Outliers can arise as a result of instrumentation or measurement errors. Even with the precise setup, outliers may appear due to abnormal events like shading of irradiance sensor, shading of the PV module or even failures within PV module. The uncertainty of performance degradation analysis is directly related to the measurement techniques employed as well as the method of data filtering used. The atmospheric conditions for the monitoring period are here represented by the distribution of irradiation in the plane of array, the module temperature and the ambient temperature as shown in Fig. 2. The values are calculated from the monthly average of daily values recorded between sunrise and sunset.

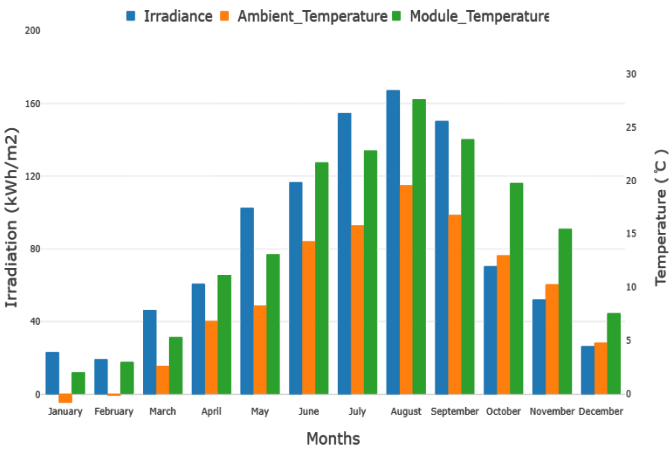

Fig. 2. Monthly average daily values of environmental parameters in testing location for the period of 2014 to 2018.

The PV performance was not available for total duration of monitoring due to events of outages discussed earlier. The available irradiance distribution for every month during the measurement period is presented in Fig. 3. Monthly irradiance distribution from Each data points in the figure denote a daily average of 1-minute irradiance data.

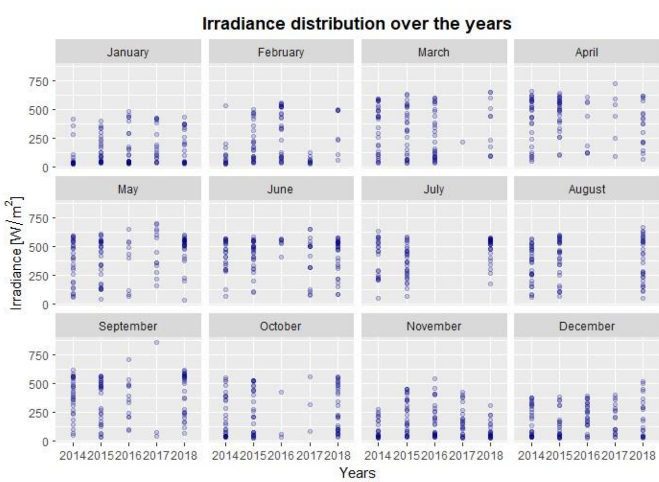

Fig. 3. Monthly irradiance distribution from 2014 to 2018.

With the per minute resolution of I-V curves, it is possible to have data points around 1000 W/m^2 of irradiance. Interestingly, with the colder climate in Nordic regions, there are even considerable data points satisfying irradiance of 1000±50 W/m^2 and module temperature of 25±5℃.

Two methods have been used for the evaluation of data. In the first method discussed in[7] , degradation rate in module output is analyzed by selecting measurements around STC for evaluation. Spectral variations and incidence angles are fairly limited in this range, so the effect of both these parameters can be minimized. Therefore, the first method uses irradiance and temperature bins close to Standard Irradiance and Temperature (SIT) conditions (i.e. 950-1050 W/m^2 irradiance and 25±5℃ temperature). The range of ±50W/m^2 was chosen due to the reasonable stability of the temperature coefficients mentioned in[15]. The temperature coefficients provided by the manufacturers are used for temperature correction of the electrical parameters of PV module to STC conditions.

In this first method, the ratio of I_{SC} to incident irradiance in the plane of array (G_{POA}) is calculated and the distribution of the ratio over the years is analyzed. Since these values are the near representation of STC reference values, the distribution of these parameters is an important indicator of performance reduction. The filtering technique for this ratio is simply expressed as $\bar{A} \pm 2\sigma$, where $\bar{A}$ is the mean of I_{SC}/G_{POA} for each module and σ is the associated standard deviation. Using this criteria will ensure inclusion of 95% of validated data points, thus eliminating outlier values corresponding to inhomogeneous irradiance conditions on the irradiance sensor and the PV module [16].

Since the electrical parameters measured under changing conditions cannot be compared to the standard rating of modules, data for these parameters have to be corrected for the irradiance and temperature. The other method applied in [9], consists of filtering out datasets of G_{POA} < 400 W/m^2 and angle of incidence (AOI) > 50° to reduce the effects of low irradiance, spectrum variation and incident angle reflection losses. The metrics used for the determination of performance degradation rates are temperature- and irradiance-corrected I_{SC} and P_{MPP}, normalized to their measured values here presented in Table I. Due to its low dependence on irradiance and negligible effect on degradation rates, V_{OC} is just temperature-corrected[15]. Also, FF is calculated through these corrected parameters and normalized to the measured value given by Table I. Expressions used for the STC conversion of each parameter are as follows:

$$I_{SC,STC} = \frac{I_{SC}}{\{1 + \alpha(T - 25)\}} \times \frac{G_{STC}}{G_{POA}} \quad (1)$$

$$V_{OC,STC} = \frac{V_{OC}}{\{1 + \beta(T - 25)\}} \quad (2)$$

$$P_{MPP,STC} = \frac{P_{MPP}}{\{1 + \gamma(T - 25)\}} \times \frac{G_{STC}}{G_{POA}} \quad (3)$$

$$FF_{STC} = \frac{P_{MPP,STC}}{I_{SC,STC} \times V_{OC,STC}} \quad (4)$$

Here, α, β and γ are the temperature coefficients of I_{SC}, V_{OC} and P_{MPP} respectively. G_{POA} is the measured incident irradiance over the tilted surface of PV modules and T is the measured module temperature. The electrical parameters are then normalized to the measured values to investigate the deviation of STC-corrected parameters over the duration of the exposure period. These performance metrics are evaluated in daily, monthly, and annual intervals. The daily performance ratios of I_{SC}, V_{OC} and FF are calculated in a similar way as P_{MPP} using (5).

$$PR(P_{MPP}) = \frac{P_{MPP} \,/\, P_{MPP,STC}}{G_{POA} \;/ G_{STC}} \qquad (5)$$

The annual averages provide a good approximation of module performance as they are inclusive of seasonal variations and hence represent the module performance reliably compared to daily and monthly averages.

The module temperature have been logged for individual modules, but due to sensor malfunction and instrumentation issues, only two of the sensors attached to modules STP422 and STP422 are in order. So, for this analysis, module temperature from module STP423 is used for all modules. The module temperature for STP422 is used for cross validation of the STP423 temperature data, which shows a good correlation with variations within 1-2℃.

III. RESULTS AND DISCUSSION

A. Degradation of I_{SC}

As discussed in the introduction, I_{SC} is found to be the major contributor of the module degradation in various locations. For the analysis of the degradation in I_{SC}, measurements around SIT were chosen. The normalized I_{SC}/G_{POA} plot for each module is given in Fig. 4, where the I_{SC} is corrected to the STC temperature. Each data points in the figure represent the daily mean of all the data points within SIT conditions.

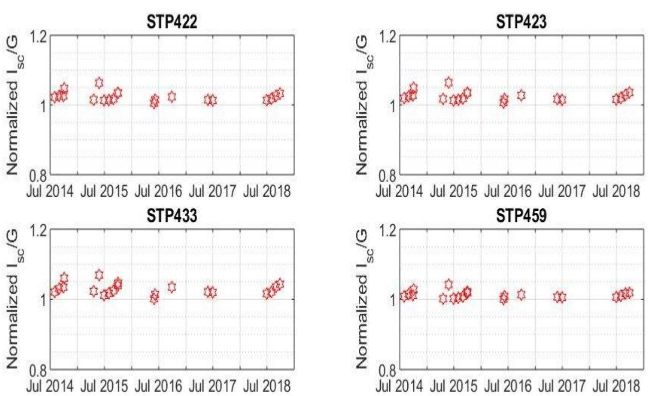

Fig. 4. Normalized I_{SC}/G_{POA} plot for each module at SIT conditions.

The I_{SC}/G_{POA} ratio is almost constant at SIT conditions for each module for the duration of exposure. The modules show no significant degradation from inspection of these plots. But this can also be studied in more detail by means of the probability density distribution of these values, provided a sufficiently large number of datapoints is available.

Assuming the distribution of I_{SC}/G_{POA} ratio to be gaussian, the shift of mean in probability density function can lead to a more noticeable conclusion. The data at SIT conditions have been filtered to remove the values outside 2 standard deviations from the mean. The probability distribution function (pdf) of I_{SC}/G_{POA} in Fig. 5 shows a shift of mean towards left for every module from 2014 to 2018. Additionally, the values of mean and standard deviation of normalized I_{SC}/G_{POA} for individual modules in both the years have been presented in TABLE II.

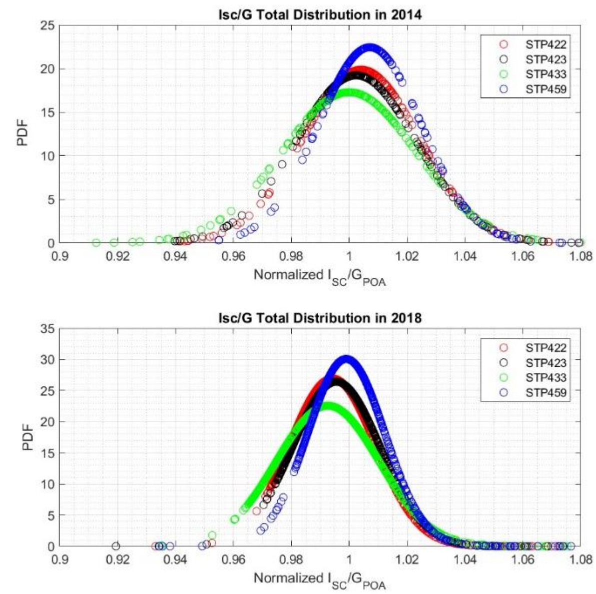

Fig. 5. Probability density function of (I_{SC}/G_{POA}) based on SIT-filtered 1-minute values for all modules in 2014 and 2018.

As seen from the table, subsequent change of mean in these two years is very small, indicating a very small degradation of I_{SC} but not statistically significant. The average yearly degradation rate for all modules is 0.17%, while it varies from 0.14% to 0.2% for individual modules. Generally, the degradation of I_{SC} is considered to be between 0.6% and 1% per year [3], hence, the degradation rate of I_{SC} calculated in the present study suggests a considerably smaller degradation of the monitored modules in this location.

TABLE II
SUMMARY OF DISTRIBUTIONS

Modules	μ(2014)	σ(2014)	μ(2018)	σ(2018)	Change
STP422	1.004	0.020	0.994	0.014	0.010
STP423	1.002	0.021	0.995	0.015	0.007
STP433	1.000	0.023	0.992	0.017	0.008
STP459	1.007	0.018	0.998	0.013	0.009

B. Performance ratio variation of P_{MPP} and I_{SC}

Performance ratio evaluation was undertaken for the degradation assessment of module parameters. A time series was constructed of the daily, monthly and yearly average PR for the exposure period of five years. Fig. 6 presents the average monthly PR values over the monitoring period in terms of the respective temperature- and irradiance-corrected P_{MPP} and I_{SC} values. These PR values were first calculated for each data points with irradiance and temperature corrections which were than averaged to calculate subsequent daily, monthly and annual means which is basis of the analysis.

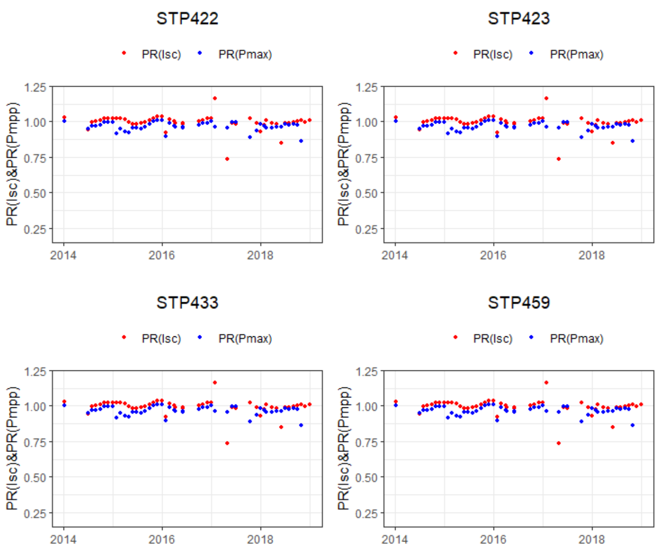

Fig. 6. Normalized module monthly PR with respect to P_{MPP} and I_{SC}.

Small seasonal behavior of the mc-Si PV modules is evident even with the temperature correction, with higher PR values during the cold winter months and lower PR values in the summer. The PR for I_{SC} and P_{MPP} are also influenced by the spectral variations, which has a relatively smaller impact compared to temperature.

C. Spectral Impacts

Spectral effects are usually quantified using spectral irradiance readings integrated over a certain wavelength range. But these readings are not available everywhere due to the cost and complexity of instrumentation. Authors in [17] proposed to use short circuit measurements in absence of spectral irradiance measurements, to deduce the spectral factor values from a standard relation defined in IEC60904-7 [18] and given in (6).

$$SF = \frac{I_{SC} \times G_{STC}}{I_{SC,STC} \times G_{POA}} \qquad (6)$$

Here, I_{SC} and G_{POA} are the measured values of short circuit current and global in-plane irradiance, while $I_{SC,STC}$ and G_{STC} are the respective reference values. Values of spectral factor (*SF*) greater than 1 mean that the when considering spectral effects only, PV modules under the actual solar spectral distribution produce a higher short-circuit current than under the standard AM1.5 spectrum. Values of $SF > 1$ can be interpreted as spectral gains, while $SF < 1$ mean spectral loss. Fig. 7 presents the box plot of monthly variation of spectral factor, which has been calculated for measurement duration with irradiance measurements greater than 200 W/m^2. The horizontal line within the box plot presents the median of the data, while the ends of boxes present the first and third quartile of the data. The error bars present the minimum and maximum values while the outliers are discarded. The figure shows a seasonal trend with spectral gains in winter and losses in summer.

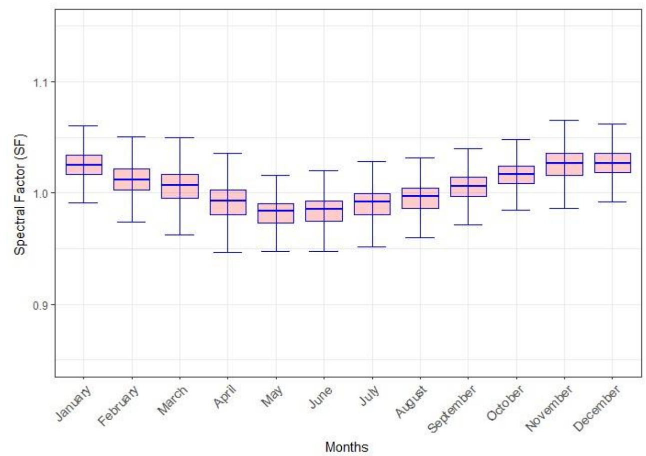

Fig. 7. Average monthly spectral factor values.

In winter, the increase in air mass causes the spectrum to shift towards red, thus increasing the energy performance of mc-Si modules. Fig. 8 presents the corrected I_{SC} values based on irradiance and temperature corrections only, and after inclusion of also the spectral factor correction. Additional correction of short circuit values in (1) by spectral factor clearly improves the performance ratio estimate and subsequently the degradation study of I_{SC} and P_{MPP} is more reliable.

While most literature use temperature and irradiance correction of these two parameters, the additional inclusion of spectral correction factor thus provides an improved estimation of performance of PV modules. The spectral correction brings a clear improvement in terms of reducing the annual variation and spread in data. With the inclusion of spectral factor, the performance ratio calculation of P_{MPP} can be re-written from (5) as;

$$PR\ (P_{MPP}) = \frac{P_{MPP} \times G_{STC}}{P_{MPP,STC} \times G_{POA}} \times \frac{1}{\{1 + \alpha(T - 25)\}} \times \frac{1}{SF} \qquad (7)$$

The I_{SC} and P_{MPP} are now spectrum-corrected in addition to the temperature- and irradiance-correction, and all four parameters are averaged annually.

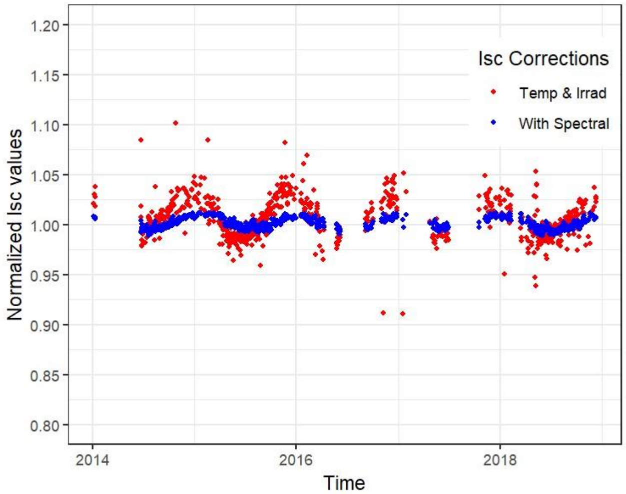

Fig. 8. Difference in correction techniques of I_{SC}.

The degradation rate for individual parameters are determined from a slope of linear least-square fit line of these annual means. The results from such method is presented in Fig. 9 and show a very small, if any, degradation of all parameters.

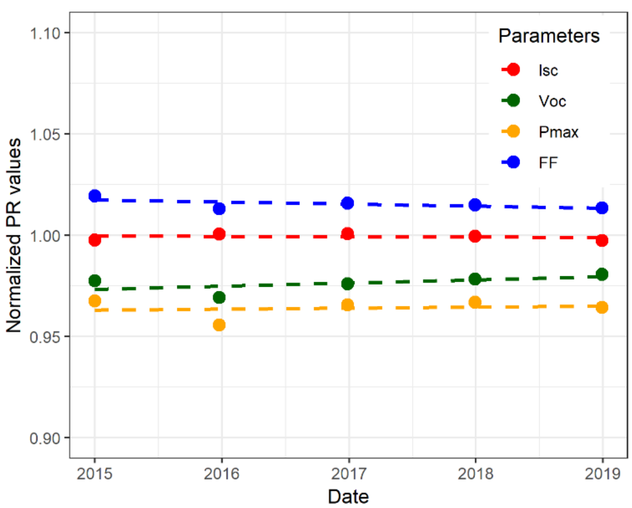

Fig. 9. Normalized PR distributions of corrected module parameters.

P_{MPP} and V_{OC} are found to be almost constant throughout the study period, whereas I_{SC} and FF seem to have experienced some slight degradation. The degradation rate for both these parameters is very small though. While the smaller scale of thermal cycling and/or lower maximum temperatures in cold climate at higher latitudes seem to prevent modules from temperature induced degradation of V_{OC}, the degradation of fill factor could be attributed to the corrosion and solder bond breakages [3]. But the visual inspection of modules shows no signs of corrosion, burns marks or delamination.

D. Thermal Imaging

To supplement the results from the performance data analysis, infrared imaging was performed using FLUKE Ti400 camera in both short circuit and MPP conditions. Images were taken in stable environmental conditions with irradiance values above 700 W/m^2. Ambient conditions and module reflections were carefully considered to reduce error in the infrared images. Measurements were done at ambient temperature of 10 °C with the emissivity of 0.85, which is a typical value for a glass surface. Fig. 10 presents thermal images of both MPP and short circuit conditions.

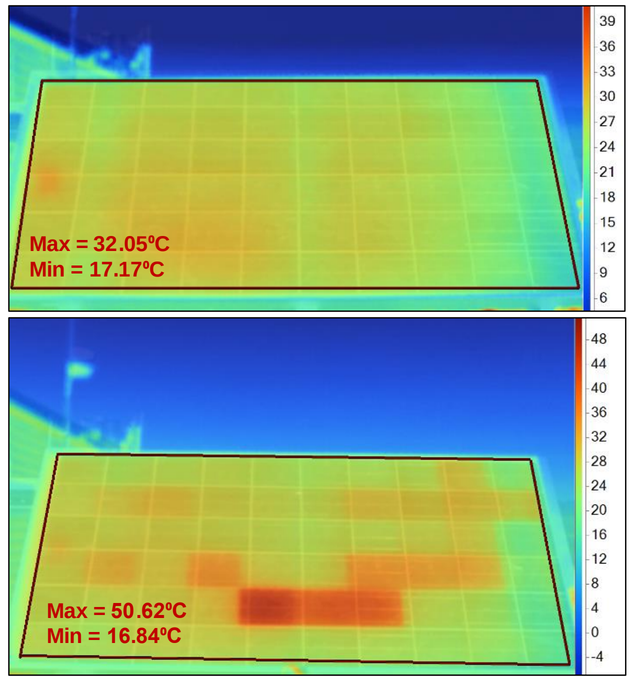

Fig. 10. Infrared image of STP433 module in MPP (top) and short circuit (bottom) conditions.

The infrared images at MPP do not reveal significant temperature differences or presence of hotspots, confirming the earlier finding of no significant degradation. The hottest part of the modules were only a few degrees above the rest of the module. From the image of STP433 module it is clear that the module edge is colder due to the cooling effects of wind, whereas the hottest part is around the junction box due to the electrical contacts. At short circuit conditions, STP433 show a higher overall temperature of the module and higher temperatures of some cells than others due to cell mismatches within the module. Whether these mismatches are related to degradation factors is difficult to determine due to the unavailability of images from the initial installation phase.

IV. Conclusion

Performance of four multi-crystalline silicon PV modules from the same manufacturer are analyzed for signs of degradation after five years of outdoor exposure. Two different data filtering and analysis methods are used, which are complimented with infrared images. Infrared images under short circuit conditions showed some cells with quite high temperatures compared to the others, but results are inconclusive whether this could be due to degradation modes.

For the degradation of I_{SC}, the mean of the normal distribution of I_{SC}/G_{POA} is compared at SIT conditions for the start and end years 2014 and 2018. Data outside two standard deviations are rejected. Average degradation of I_{SC} is found to be 0.17% per year from the first method. From the second method, a yearly average analysis is used to calculate the degradation of module parameters. The temperature and irradiance corrected performance ratio of I_{SC}, V_{OC}, P_{MPP} and FF are calculated for each data point and then transformed into annual averages. No significant degradation is discovered, but FF and I_{SC} appear to have a very small, but visible trend of degradation. V_{OC} and P_{MPP} however show no signs of degradation, in fact V_{OC} is seen to have had a performance improvement possibly due to low thermal stress over the years.

Compared with the general degradation rate of P_{MPP} for PV modules, in literature found to be around 0.5% per year, the stable value of normalized PR seen in this study indicate that mc-Si PV modules may not degrade with the same rate at this high latitude location compared to other more typical PV regions. Also, the amount of missing data could also have possibly influenced the degradation rates from both methods. The degradation of I_{SC} seems to follow the same trend from both the methods, which in comparison to the standard degradation rates is much lower.

By applying spectral factor corrections to I_{SC} and P_{MPP}, in addition to temperature- and irradiance-corrections, the annual variability and spread in data is reduced. This improves the reliability of the analysis of degradation, as long-term data of module parameters can be better estimated with spectral corrections included. The PV modules will continue to be monitored in the years to come, to build up large datasets that will help to identify and quantify the long-term degradation mechanisms for higher latitude regions.

References

[1] A. Louwen, A. C. de Waal, R. E. I. Schropp, A. P. C. Faaij, and W. G. J. H. M. van Sark, "Comprehensive characterisation and analysis of PV module performance under real operating conditions," *Progress in Photovoltaics: Research and Applications*, vol. 25, no. 3, pp. 218-232, 2017.

[2] D. C. Jordan and S. R. Kurtz, "Photovoltaic Degradation Rates—an Analytical Review," *Progress in Photovoltaics: Research and Applications*, vol. 21, no. 1, pp. 12-29, 2013.

[3] D. C Jordan, J. H Wohlgemuth, and S. R Kurtz, "Technology and Climate Trends in PV Module Degradation," presented at the EUPVSEC, Frankfurt, 2012.

[4] M. Kontges *et al.*, "IEA-PVPS {Task 13}: Review of failures of PV modules," 2014.

[5] M. U. Jahn, M. Köntges, and D. J. I. P. t. Parlevliet, "Review on Infrared and Electroluminescence Imaging for PV Field Applications," vol. 13, 2018.

[6] A. G. Imenes and J. Sclj, "Irradiance and temperature distributions at high latitudes: Design implications for photovoltaic systems," in *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 2017, pp. 619-625.

[7] J. Zhu, Y. Qiu, T. Betts, and R. Gottschalg, *Effects of Different Data Collection Strategies on Outdoor Performance Measurements and Degradation*. 2009, pp. 3439-3444.

[8] Y. Matsumoto, C. Norberto, J. A. Urbano, M. Ortega, and R. Asomoza, "Three-year PV system performance in Mexico City," in *2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC)*, 2016, pp. 3168-3172.

[9] U. J. TJ Silverman, G Friesen, M Pravettoni, M Apolloni, A Louwen, W Van Sark, M Schweiger, G Belluardo, J Wagner, A Tetzlaff, P Ingenhoven, D Moser, , "Characterisation of Performance of Thin-film Photovoltaic Technologies," IEA 2014.

[10] J. A. d. Cueto and T. J. McMahon, "Performance of single-junction a-Si modules under varying conditions in the field," in *Conference Record of the Twenty Sixth IEEE Photovoltaic Specialists Conference - 1997*, 1997, pp. 1205-1208.

[11] G. Yordanov, "Characterization and analysis of photovoltaic modules and the solar resource based on in-situ measurements in southern Norway," Ph. D. Thesis, Department of Electric Power Engineering, NTNU, 2012.

[12] A. Livera, A. Phinikarides, G. Makrides, and G. E. Georghiou, "Impact of Missing Data on the Estimation of Photovoltaic System Degradation Rate," in *2017 IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 2017, pp. 1954-1958.

[13] D. C. Jordan and S. R. Kurtz, "The dark horse of evaluating long-term field performance—Data filtering," *IEEE Journal of Photovoltaics*, vol. 4, no. 1, pp. 317-323, 2014.

[14] J. Zhu, Y. Qiu, T. R. Betts, and R. Gottschalg, "Outlier identification in outdoor measurement data - effects of different strategies on the performance descriptors of photovoltaic modules," in *2009 34th IEEE Photovoltaic Specialists Conference (PVSC)*, 2009, pp. 000828-000833.

[15] R. M. Smith, D. C. Jordan, and S. R. Kurtz, "Outdoor PV module degradation of current-voltage parameters," National Renewable Energy Lab.(NREL), Golden, CO (United States)2012.

[16] G. Belluardo, P. Ingenhoven, W. Sparber, J. Wagner, P. Weihs, and D. Moser, "Novel method for the improvement in the evaluation of outdoor performance loss rate in different PV technologies and comparison with two other methods," *Solar Energy*, vol. 117, pp. 139-152, 2015/07/01/ 2015.

[17] M. Alonso-Abella, F. Chenlo, G. Nofuentes, and M. J. E. Torres-Ramírez, "Analysis of spectral effects on the energy yield of different PV (photovoltaic) technologies: The case of four specific sites," vol. 67, pp. 435-443, 2014.

[18] IEC60904, *Photovoltaic devices-Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices*, 2008.