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Advanced Determination of Temperature Coefficients of Photovoltaic Modules by Field Measurements

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Abstract. In this work data from outdoor measurements, acquired over the course of up to three years on commercially available solar panels, is used to determine the temperature coefficients and compare these to the information as stated by the producer in the data sheets. A program developed in MatLab App Designer allows to import the electrical and ambient measurement data. Filter algorithms for solar irradiance narrow the irradiance level down to ~1000 W/m^2 before linear regression methods are applied to obtain the temperature coefficients. A repeatability investigation proves the accuracy of the determined temperature coefficients which are in good agreement to the supplier specification if the specified values for power are not larger than -0.3%/K. Further optimization is achieved by applying wind filter techniques and days with clear sky condition. With the big (measurement) data on hand it was possible to determine the change of the temperature coefficients for varying irradiance. As stated in literature we see an increase of the temperature coefficient of voltage and a decline for the temperature coefficient of power with increasing irradiance.

Keywords: Solar Modules, Temperature Coefficients, Field Measurement

1. Introduction

Temperature and irradiance are the most important factors which affect the performance of solar modules and hence determine the module output power along with specific data. This specific data belongs to the module and is determined by the solar cell technology, the module architecture as well as module materials. Since installed solar modules typically do not operate at standard test conditions (STC) the key parameters as given in the supplier data sheet are efficiency and temperature coefficients. Both strongly depend on irradiance and temperature. For this the weak light performance of panels is specified in the data sheet. But only few know or acknowledge that temperature coefficients itself are not a constant value and alter significantly with irradiance [1], [2]. As long as the temperature correction of I/V-data is performed close to STC and the temperature coefficients are determined at 1000 W/m^2 no deficiencies will appear. But if these coefficients are used for example to model the performance behaviour of PV panels or systems at all light conditions larger deviations will result. In general, is the determination of temperature coefficients complex, requires a lab environment and procedures as stated in IEC 60891 or advanced outdoor techniques [3], [4]. On the other hand, temperature coefficients can accurately be determined with “big” data from high precision outdoor measurements if the proper mathematical procedures are applied. In this paper, a methodology for the determination of temperature coefficients and its light dependency is proposed. The temperature coefficients for six modules consisting of different technologies in terms of solar cell and cell interconnection have been evaluated by the proposed methodology and compared to the values as given by the manufacturers data sheet.

2. Metrological and mathematical approach

For this study a long-term outdoor measurement series has been consecutively started in April 2020 on commercially available solar panels as shown in Table 1. The measurement on panels with the ID 1-3 is still ongoing. All panels were regularly dismounted and tested in the lab with an A+A+A+ mbj solar flasher.

Table 1. Type of solar modules including specific data from the data sheets.

Module type	ID	Cell /module technology	P (W)	T_{KPmpp} (%/K)	T_{KVoc} (%/K)	NOCT (°C)
Panasonic VBHN 340 SJ53	1	HIT / standard	340	-0.26	-0,24	44
Sunpower P3 325 BLK	2	PERC / shingled	325	-0.36	-0,29	45
REC-Alpha-Series 365 W	3	HJT / SmartWire	365	-0.26	-0,24	44
QCELLS-QPeak_Duo_G8	4	Q.ANTUM / standard	350	-0.35	-0,27	43
Hyundai_HiE-S310-RG	5	PERC / standard	310	-0.39	-0,29	45
REC_N-Peak-Series	6	n-type PERT/ standard	330	-0.35	-0,27	44

During outdoor exposure solar panels were permanently kept at P_{mpp} and the I/V-performance individually measured every 10 seconds and averaged each minute by a calibrated Papendorf SOL.Connect® meter which comes with an (I/V) inaccuracy <1%. A PT1000 sensor measures the solar panel temperature at module rear side and an ISET sensor the irradiance in module plane. For the determination of the temperature coefficients long term measurement data over weeks up to months is used. A linear regression method on the plot of short circuit current I_{sc}, open circuit voltage V_{oc} and calculated power P_{mpp} versus module temperature $T_{Modul,measured}$ is applied to obtain the related temperature coefficients T_{KIsc}, T_{KVoc} and T_{KPmpp}. To restrict irradiance to a narrow range between 950 W/m^2 – 1050 W/m^2 a filter function for irradiance measurement data is used. Due to the large overall number of data points filtering still leads to sufficient data points for applying linear regression even if the interval is as small as 980 W/m^2 – 1020 W/m^2.

In general, it can be stated that R^2 for the regression of V_{oc} vs. $T_{Modul,measured}$ is close to 1 and for P_{mpp} vs. $T_{Modul,measured}$ it is in the range between 0.9-1. Only for I_{sc} vs. $T_{Modul,measured}$ the linear fit shows larger deviations due to the nature of T_{KIsc} which is a power of ten smaller than the other TK's. If days with clear sky conditions are selected the determination of T_{KPmpp} and T_{KIsc} lead in most cases to matching results as given by the supplier. Cloudy conditions will mostly render evaluation data for T_{KIsc} invalid. The only parameter which can be determined with high accuracy independently of the weather conditions is T_{KVoc} due to the almost perfect linear behavior and very high measurement accuracy over the total measurement range. To further optimize the methodology a wind speed filter function was implemented into the evaluation software. With this functionality larger outliers in the measurement data which do not reflect the real cell temperature are removed from the data sets. These outliers are driven by fast temperature changes on the rear side surface of the solar module caused by forced heat convection.

3. Application and results

3.1 Verification of STC results

To verify the accuracy of the applied fitting algorithms 3 months of outdoor measurement data is used to determine I_{sc}, V_{oc} and P_{mpp} close to STC. For this, all I/V-data points not matching the range between 1000 ± 20 W/m^2 and 25 ± 0.5°C are filtered out. Due to the immense number of data points sufficient data exists for averaging the related STC-values for I_{sc}, V_{oc} and P_{mpp}. As Table 2 shows, flasher results and outdoor data for determined STC parameters match nicely, with a deviation not exceeding 2.1% for I_{sc}, 1.1% for V_{oc} and 1.9% for P_{mpp}. Larger module performance degradation for module 1 and 3 after three years of outdoor exposure is revealed if the measurement data is compared against the data sheet information. This degradation is mainly because of a decline in fill factor FF which is not displayed in Table 2.

Table 2. STC data for module ID 1, 2 and 3.

ID	Data sheet (supplier)			Flasher (mbj flasher)			Outdoor results (fitting)		
	I_{sc} (A)	V_{oc} (V)	P_{mpp} (W)	I_{sc} (A)	V_{oc} (V)	P_{mpp} (W)	I_{sc} (A)	V_{oc} (V)	P_{mpp} (W)
1	6.1	71.3	340	6	70.9	320	6.1	70.1	326
2	9.7	43.6	325	9.4	43.5	321.1	9.6	43.1	322
3	10.3	44.3	365	10.1	43.6	337.1	10.2	43.3	335.3

3.2 Repeatability of temperature coefficient determination

Due to the complexity of the determination of temperature coefficients by using outdoor measurement data the repeatability of the suggested methodology is determined in a first step which also gives insights into the accuracy of the method itself. For this, the temperature coefficients of the same module are determined for 3 individual years with measurement data coming from weeks in August of the years 2020, 2021 and 2022. The available data sets are used to determine the related temperature coefficients for current, voltage and power. The results are exemplarily shown for the Sunpower module (ID 2) in Table 3.

Table 3. Repeatability results for temperature coefficient determination of module ID 2.

Date	T_{KPmpp} (%/K)	T_{KVoc} (%/K)	T_{KIsc} (%/K)
August 2020	-0.35	-0,29	0.10
August 2021	-0.34	-0,28	0.09
August 2022	-0.37	-0,29	0.05

The results prove that the T_{KVoc} and T_{KPmpp} parameter determination is repeatable over three years with very small deviations. T_{KIsc} requires perfect clear sky conditions which cannot be found over a larger time scale in the month of August for most years. R^2 of the related linear regression is too far away from 1 due to larger data scattering. The reason for this is shading by clouds which lead to sudden module current and cell temperature changes and hence is only reflected with a time lag in the module temperature as measured by the PT1000 at the outside of the module. Additionally, the measurement method of electrical current itself comes with a larger measurement error if compared to the voltage measurement.

3.3 Determined temperature coefficients versus supplier data

The developed methodology is finally used to determine the temperature coefficients for all modules as shown in Table 1. For this, months of outdoor data with clouded and clear sky condition or both are used. Table 4 shows the temperature coefficients T_{KPmpp} and T_{KVoc} and compares this data to the supplier information from the data sheets. T_{KVoc} matches for almost all modules perfectly and T_{KPmpp} agrees if the supplier data is not >-0.3%/K. The T_{KVoc} determination for module ID 4 shows a larger difference to the given value by the supplier data sheet which at least cannot be explained by the quality of the measurement data and the measurement period itself.

Table 4. Comparison of temperature coefficients against supplier information for all modules.

ID	Datasheet		Outdoor results (fitting)	
	T_{KPmpp} (%/K)	T_{KVoc} (%/K)	T_{KPmpp} (%/K)	T_{KVoc} (%/K)
1	-0.26	-0.24	-0.30	-0.24
2	-0.36	-0.29	-0.37	-0.29
3	-0.26	-0.24	-0.35	-0.24
4	-0.35	-0.27	-0.34	-0.18
5	-0.39	-0,29	-0.39	-0.25
6	-0.35	-0,27	-0,36	-0,27

3.4 Optimization

To improve the accuracy of the applied method it is necessary to apply additional filter techniques on the measurement data. Since the largest errors originate from the time lag of the temperature measurement – the modules back side is measured and not the cells temperature directly – the causes for larger uncertainties in the determination of the temperature coefficient are investigated. It is found that mostly two factors determine the accuracy: homogeneity of the ambient light condition and wind speed. For sunny days but with larger occurrences of casted conditions the modules heat capacity introduces a larger error: The irradiance value can be measured with high accuracy in fractions of a second but the change in cell temperature is only measurable at the modules rear side after a considerable time by the PT1000. This way the applied methodology will automatically lead to larger errors if casted days are used to determine the temperature coefficients. The other source is wind speed: For days with significant wind occurrence the panel is cooled by forced heat convection at the outside in proximity to the temperature sensor hence the measurement data does not reflect the cells temperature. Therefore, irradiance and temperature measurements are not aligned in a timely manner.

To reduce errors sourcing from non-matching temperature and irradiance measurements in terms of the time stamp two measures are applied. First of all, a wind speed filter is integrated into the software which allows to filter out all data above a certain wind speed threshold. And secondly, only days with clear sky conditions are used for the evaluation. For this, another function was integrated into the evaluation software which allows to inspect the irradiance in module plane during the course of a day over weeks and months. This way days with clear sky condition can be selected and added to the data set used for the evaluation.

Figure 1 shows the results for the FF($T_{Modul,measured}$) curve and the determined T_{KFF} as determined by linear regression for various climatic situations in summer 2022 with and without a wind speed filter applied and an irradiance band of 1000 ± 20 W/m^2. As a measure for how well the linear regression is matching the data points the coefficient of determination, denoted as R^2 is given. The better the linear regression fits the measurement data in comparison to the simple average, the closer the value of R^2 is to 1. The worst result for T_{KFF} is obtained for days with mixed sky conditions (casted and clear sky), also expressed by an R^2 of only 0.87 (Fig. 1, upper left). If the same data set is used with applied wind filter no larger change in R^2 is observed but a significant change in the value of T_{KFF} (Fig.1, upper right). Only for days with clear-sky condition R^2 is close to 1 and T_{KFF} reaches a stable value which is almost not influenced by the wind speed anymore (Fig. 1, lower left and right).

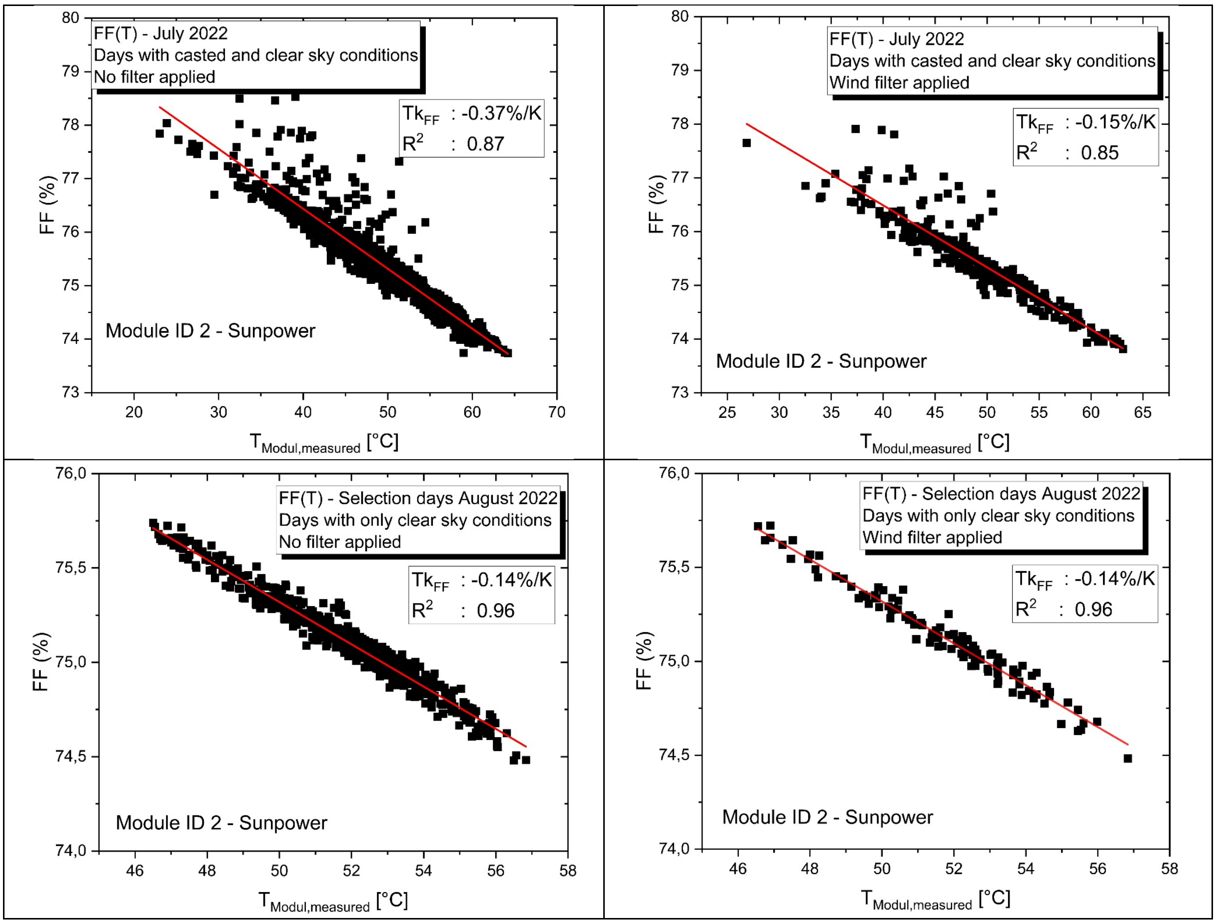

Figure 1. Temperature dependency of the fill factor and determined T_{KFF} for various climatic conditions for module ID 2.

Both optimization measures: applying a wind speed filter and using days with only clear sky conditions allow to finally determine the temperature coefficients for all module parameters with high accuracy. Table 5 shows the results for module ID 2 and compares the determined values with the ones from the data sheet.

Table 5. Determined temperature coefficients for module ID 2.

	Temperature coefficients			
	T_{KVoc} (%/K)	T_{KIsc} (%/K)	T_{KPmpp} (%/K)	T_{KFF} (%/K)
Data sheet (supplier)	-0.29	0.05	-0.36	n.a.
Outdoor results (fitting)	-0.29	0.06	-0.36	-0.14

3.5 Irradiance dependency of temperature coefficients

With almost three years of high accuracy measurement data on hand it is possible to calculate the temperature coefficients in dependency of the irradiance. For this evaluation the time period between May and August 2022 is chosen which results in more than 125.000 measurement points for each individual module. The irradiance band for each temperature is as narrow as ±20 W/m^2. For example, the T_K`s at 1000 W/m^2 are determined by using measurement data inside an irradiance range of 980 W/m^2 – 1020 W/m^2. As stated in literature a slight increase for T_{KVoc} and a strong decline for T_{KIsc}, T_{KFF} and T_{KPmpp} with higher irradiance is seen [1]. T_{KFF} is close to the data as previously reported by Berthoda [5].

The temperature coefficient of P_{mpp} can be written as the sum of the temperature coefficients of V_{oc}, I_{sc}, and FF

$$T_{KPmpp} = T_{KVoc} + T_{KIsc} + T_{KFF} \quad (1)$$

This relationship allows for an elegant way to show that the data for T_{KPmpp} (Irradiance) resulting from the measurement data fit is correct. Figure 2 shows the related temperature coefficients T_{KPmpp}, T_{KVoc}, T_{KIsc} and T_{KFF} as a function of the measured irradiance. The T_{KPmpp} graph additionally contains the T_{KPmpp} (Irradiance) values as calculated by formular (1). Both, calculated and fitted data points match to a high degree.

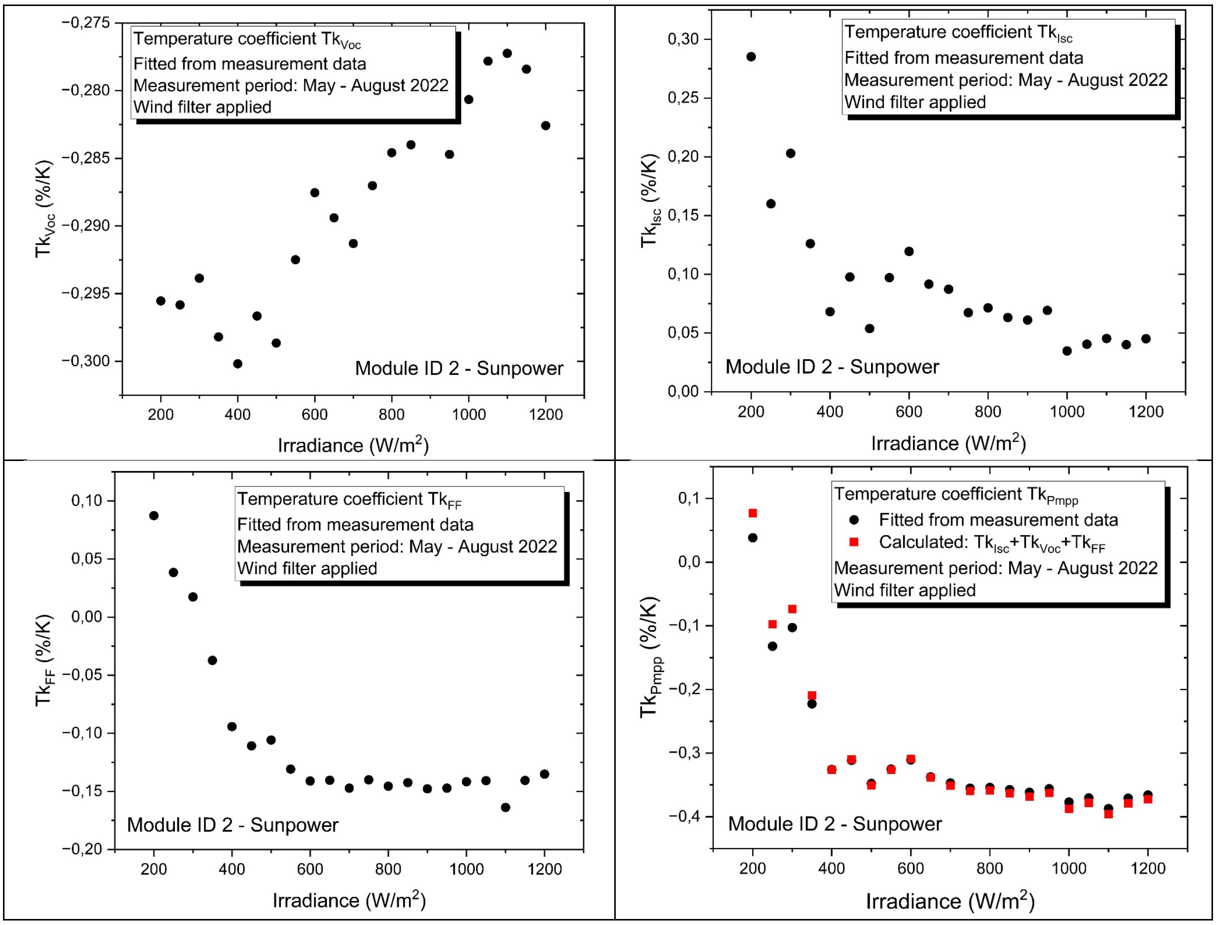

Figure 2. T_{KVoc}, T_{KPmpp}, T_{KIsc} and T_{KFF} as a function of irradiance for module ID 2.

As can be seen in Fig. 2 T_{KFF} and T_{KPmpp} are reaching zero and even change the sign for irradiance <400 W/m^2. Further studies must be conducted to verify if the obtained results for lower irradiances are correct. So far it can only be stated that the data for P_{mpp} agrees to with previously published data [1] in which the T_K(Irradiance) behavior is listed down to 400 W/m^2

but if the data for P_{mpp} is extrapolated down to 200 W/m^2 T_{KPmpp} also becomes positive. Beside this, several days from September 2022 with clear sky condition are used to verify if for lower irradiances power and fill factor is constant. Important is that data from this month was not part of the data which has been used for the T_K evaluation procedure. For 300 W/m^2 and at a temperature of 19.8 ± 0.6°C the measured P_{mpp} was 98.6 ± 5.4 W, FF was 79.6 ± 0.1% and at a temperature of 30.9 ± 1.1°C P_{mpp} was 98.3 ± 6.5 W, FF was 79.1 ± 0.1%. This data at least does not conflict with or negate the fitting results for lower irradiances.

4. Conclusion

This paper presents a novel way on how to determine temperature coefficients of PV modules from outdoor measurement data with high accuracy. Large data sets, containing more than 100.000 individual measurements of module temperature and I/V-data as well as ambient data such as solar irradiance in module plane and wind speed allow for applying filtering techniques and to calculate the related temperature coefficients by linear regression. The developed methodology was applied on six commercially available solar modules installed since almost three years. One of the most important outcomes of this study is that the utilization of outdoor measurement data for the determination of the related T_K`s requires the solar irradiance and module temperature information to align time wisely in a very good manner. Since module temperature is typically measured on the rear side of the module it always reflects the cell temperature with a time lag in the scale of up to several minutes but on the other hand the solar irradiance is measured instantly. Therefore, the best practice is to use days with clear sky condition and to apply a wind speed filter to reject measurement data with a well determined wind speed threshold. This way the presented methodology allows to determine the T_K`s with highest accuracy, at least if compared to the manufacturer data sheet. The second outcome of this study is the determination of the irradiance dependency of the $T_K$`s. The obtained data aligns nicely with the behavior of the individual T_K`s for varying irradiances as stated in literature. For $T_{KFF}$ and $T_{KPmpp}$ at irradiances below 400 W/m$^2$ values of the related $T_K$`s are close to zero or even positive. Even if by no means errors in the determination are found further studies must prove if the change of sign in the T_K`s is valid.

Data availability statement

The data that support the findings of this study are available from the corresponding author, [A.S.], upon reasonable request.

Author contributions

This study was designed, directed and coordinated by A.S. as the principal investigator. A.S designed the experiments, planned and performed the data analysis. J.C. designed and programmed the evaluation software for the study, implemented supporting algorithms and performed evaluation tasks. J.C. suggested and commented on the design of experiments. T.N. performed the indoor measurements, maintained the measurement tools and provided the ambient measurement data. The manuscript was written by A.S. and J.C. and commented on by all authors. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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References

1. D. T. Cotfas, P. A. C., O. M. Machidon, “Study of Temperature Coefficients for Parameters of Photovoltaic Cells,” International Journal of Photoenergy, Volume 2018, Article ID 5945602, https://doi.org/10.1155/2018/5945602
2. F. Perin Gasparin, F. Detzel Kipper, F. Schuck de Oliveira, A. Krenzinger, “Assessment on the variation of temperature coefficients of photovoltaic modules with solar irradiance,” Solar Energy, Volume 244, 15 September 2022, Pages 126-133
3. D. King, J. Kratochvil, W. Boyson, “Temperature Coefficients for PV Modules and Arrays: Measurement Methods, Difficulties, and Results,” Proceedings of the 26th IEEE Photovoltaic Specialists Conference, Anaheim, California, USA, 1997, pp. 1183 -1186
4. R. Dubey, P. Batra, S. Chattopadhyay, A. Kottantharayil, B. M. Arora, K. L. Narasimhan and J. Vasi, “Measurement of Temperature Coefficient of Photovoltaic Modules in Field and comparison with Laboratory Measurements,” IEEE 42nd Photovoltaic Specialist Conference (PVSC), 2015, DOI: 10.1109/PVSC.2015.7355852
5. C. Berthoda, R. Strandberga, G. H. Yordanova, H. G. Beyera, and J. O. Oddenb, “On the variability of the temperature coefficients of mc-Si solar cells with irradiance,” Energy Procedia 92 (2016) 2 – 9