SHORT TERM OUTDOOR ENERGY RATING VS CLIMATE SPECIFIC ENERGY RATING (CSER)

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ABSTRACT: This study validates the Site Specific Energy Rating (SSER) of PV modules. The SSER follows the Climate Specific Energy Rating (CSER) according to the IEC 61853 series of standards, but uses a site specific meteorological profile. At first, the laboratory characterization is performed using the energy rating methodology on monocrystalline silicon heterojunction (SHJ) PV modules. Subsequently, a site specific climate profile for Freiburg, Germany, is generated using ground-based irradiance measurements. The Site-Specific Energy Rating (SSER) is then calculated based on this profile and compared with CSER results from the IEC 61853-4 data sets. For validation purposes, short-term outdoor characterizations of the same modules are conducted, capturing real-world performance. The results demonstrate a good correlation between the SSER derived from outdoor measurements and the one based on the standard methodology, with deviations ranging from 0.23% to 1.27%. However, we find that the IEC 61853-4 standard profiles fail to accurately represent locations like Freiburg, as the differences between CSER and SSER exceed the expected uncertainty. This study emphasizes the importance of incorporating site-specific climates profiles and validates, with short-term outdoor exposures, the seasonal behavior of the SSER. The findings contribute to refining the Energy Rating approach and improving the accuracy of PV module performance assessments.

Keywords: Energy Rating, Performance Ratio, Outdoor validation

1 INTRODUCTION

The accurate assessment of PV module performance is crucial for optimizing and ensuring the reliable operation of solar energy systems. The IEC 61853 1-4 series of standards offers a standardized approach to determine the energy output of PV modules under specific climate conditions, known as Climate Specific Energy Rating (CSER). Part 1 describes the test procedures for evaluating the behavior of PV modules in relation to irradiance and temperature. It involves power rating measurements conducted over a range of different irradiances and temperatures levels. Part 2 provides detailed procedures for considering various factors that impact module performance, including angle of incidence (AOI), module operating temperature, and spectral effects. Part 3 presents the energy rating calculation procedure using the defined climatic profiles in Part 4. Collectively, these standards offer a comprehensive framework for assessing the energy performance of PV modules in accordance with standardized reference climatic profiles [1].

Previous studies have compared PV module performance using the standard methodology, primarily conducted before the full publication of the IEC 61853 standard. For instance, simulation tools like PVsyst have shown agreements within 0.5% [2, 3], while methodologies from the European Union Joint Research Center (JRC), known as ESTI-ER, have shown comparable accuracies with differences of approximately 1.8% [4]. A modified IEC 61853 methodology was also compared to outdoor measurements, resulting in deviations of around 2% for different time periods [4]. Furthermore, a round-robin study comparing different energy rating methods, including a combination with IEC 61853, yielded deviations of +/- 3% with short and long term outdoor data (without considering spectral or reflection effects) [5]. In the latest publication on the comparison of measured data with the standard methodology, differences of 5% were estimated for SHJ PV modules, which improved to 3.5% by incorporating degradation rates into the procedure [6].

Therefore, this paper aims to contribute to the validation of the accuracy of the now complete standard procedure calculations by comparing them with outdoor measurements of DC Performance Ratio (PR_{DC}). The goal is to determine if effects like light reflection, real module temperature, and irradiance dependent behavior are well represented by the methodology. Furthermore, the study aims to demonstrate that the seasonal behavior of CSER can be correlated with short-term outdoor measurements, providing a comprehensive view of PV module performance, as specified in the standard, under a range of representative weather conditions.

Our outdoor measurements are carried out in Freiburg, Germany. However, previous studies have shown that the standard climate profile, *temperate continental*, does not adequately represent the conditions in southern Germany. The performance behavior of monocrystalline-silicon modules exhibited deviations (up to 3.32%) larger than the expected uncertainty in energy rating calculations of around 2% [7, 8]. Therefore, we utilize site-specific climate data for Freiburg and calculate the Site Specific Energy Rating (SSER) [9], which is directly compared and validated with the performance in outdoor conditions during the same time period.

2 METHODOLOGY

The energy rating (ER) of a PV module is defined as the ratio of the energy produced by the module under specific climate conditions over a period (1 year according to IEC 61853-3) to the energy that would have been produced if the module had worked at standard test conditions (STC). In this paper, the ER will be calculated for different periods of time (daily, weekly) to assess its seasonal variability (Equation 1).

$$SSER_T = \frac{G_{STC}\ \sum_n E_n}{P_{STC}\ \sum_n H_n} = PR_{DC,T} \qquad (1)$$

Where $SSER_T$ [dimensionless] is the Site Specific Energy Rating over a time period T; G_{STC} [W/m²] is the irradiance at STC; P_{STC} [W] is the PV module's maximum power at STC; $E_T = \sum_n E_n = \sum_n (P_{MPP,n} \times 1h)$ [Wh] is the total energy produced by the PV module during the time period T over hourly time steps according to IEC 61853-4; $\sum_n H_n$ [Wh/m²] is the total irradiation during the time period.

The SSER was calculated according to the IEC 61853-3 procedure (SSER_{MODEL}) for Freiburg, Germany, using hourly values of ground-based broadband and spectral irradiance, as well as weather monitoring parameters (ambient temperature, wind speed) from our monitoring station for the same time period of outdoor exposure, following the format of the climate data sets from IEC 61853-4. For the SSERREAL, the accumulated power output and irradiance in plane of array (POA) (Gpoa) measured in outdoor conditions are used to calculate the PRDC based on Equation 1 (Fig. 1).

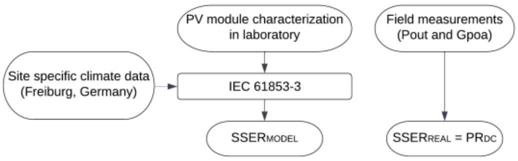


Figure 1: Methodology to calculate the modelled (left) and real (right) SSER.

2.1 Module characterization

We assessed the performance of four SHJ PV modules from two manufacturers (M01 and M02). To ensure the confidentiality of all parties involved, the PV modules are reported here anonymously. Our laboratory, CalLab PV Modules at Fraunhofer ISE, conducted tests to determine their angular, spectral, and thermal response, as well as their power matrix (according to IEC 61853-1). Table I and Figures 2 and 3 present their characteristics. From this characterization, it is possible to assess that M02 exhibits a higher power output at higher temperatures and a narrower spectral response compared to M01.

Measurement uncertainties for the IEC 61853 methodology have been evaluated in our laboratory for various technologies, including c-Si, a-Si, CdTe and CIGS, as documented in previous studies [7]. The uncertainty (k=1) in measuring the STC power range from 1.1% to 2%, depending on the specific technology. Additionally, for southern region of Germany, we estimated the uncertainty associated with factors influencing the energy rating as follows: 0.9%...1.8% for spectral effects, 0.6%...1.1% for irradiance effects, 0.1%...0.3% for temperature effects, and roughly 1% for angular effects. Among these factors, STC power measurements contribute the most to the overall uncertainty in the methodology. The characterization measurements in the laboratory are dependent on the PV module's previous exposure to light and temperature (metastability effects), especially for new cell technologies. Regarding the effects of light-induced degradation and dark storage, an uncertainty of 0.7% was estimated for c-Si modules and around 1% for thin film types.

For our study, these uncertainty values will also be considered for SHJ modules since no reference data has been found. Furthermore, in a recent round robin study on the metastability effects of SHJ, they shown lower deviation (2%) of their initial maximum power after exposure, compared to thin film technologies (13%). [10]

Table I: PV module characterization parameters acc. to IEC 61853-1 from CalLab PV Modules: angular response (*ar*), Pmpp temperature coefficient (TkPmpp) and thermal coefficients (*u0* & *u1*).

Module	**Area [m²]**	***ar***	**TkPmpp [%/°C]**	***u0* & *u1***
M01	1.89	0.10596	*-0.34*	*u0* = 30.1
M02	1.84	0.14720	-0.27	*u1* = 4.4

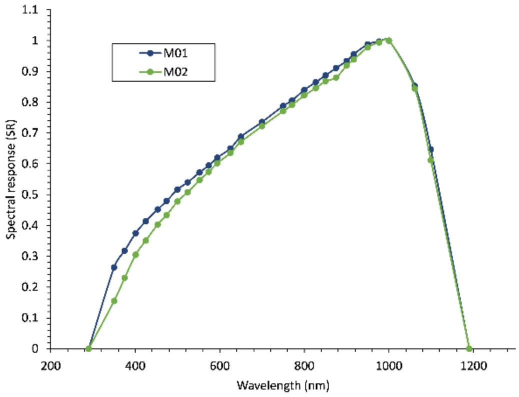
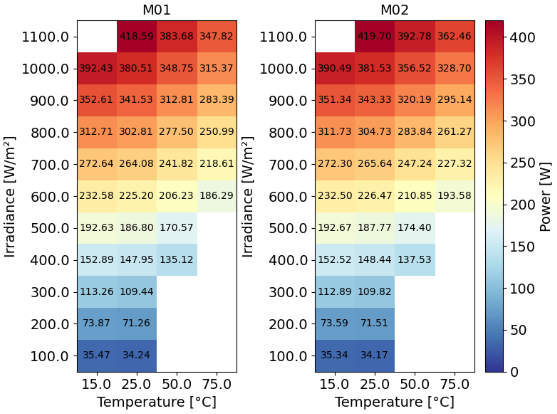


Figure 2: Spectral response of tested modules from manufacturers M01 and M02.



M01

Irradiance [W/m²]	15.0	25.0	50.0	75.0
1100.0		418.59	383.68	347.82
1000.0	392.43	380.51	348.75	315.37
900.0	352.61	341.53	312.81	283.39
800.0	312.71	302.81	277.50	250.99
700.0	272.64	264.08	241.82	218.61
600.0	232.58	225.20	206.23	186.29
500.0	192.63	186.80	170.57	
400.0	152.89	147.95	135.12	
300.0	113.26	109.44		
200.0	73.87	71.26		
100.0	35.47	34.24		

M02

Irradiance [W/m²]	15.0	25.0	50.0	75.0
1100.0		419.70	392.78	362.46
1000.0	390.49	381.53	356.52	328.70
900.0	351.34	343.33	320.19	295.14
800.0	311.73	304.73	283.84	261.27
700.0	272.30	265.64	247.24	227.32
600.0	232.50	226.47	210.85	193.58
500.0	192.67	187.77	174.40	
400.0	152.52	148.44	137.53	
300.0	112.89	109.82		
200.0	73.59	71.51		
100.0	35.34	34.17		

Figure 3: Power Matrices for both manufacturers M01 and M02.

2.2 Outdoor measurements

The PV modules were installed in Freiburg, Germany, on a rooftop, facing south with a tilt angle of 15°. Alongside the modules, a pyranometer and a silicon reference cell were placed in the same POA (Fig. 4). Additionally, a complete weather monitoring station and sun tracker were utilized to record the conditions during exposure time, ensuring representative site-specific conditions (Table II). To achieve data accuracy, we filtered the collected data for a time frame from 9:00 to 15:00, considering solar elevations larger than 5° and Gpoa larger than 10 W/m². The filtering process helped to avoid any erroneous values due to non-ideal shading conditions or high AOI.

Table II: Outdoor conditions in time of exposure. Minimum – maximum and mean values.

	Global irradiance in POA [W/m²]	Diffuse irradiance [W/m²]	Ambient temperature [°C]	Wind speed [m/s]
Autumn (28.10-21.12.2022)	(10.2 – 951.5 W/m²) 245.5 W/m²	(11.7 – 258.8 W/m²) 100.0 W/m²	(-7.5 – 30.5 °C) 8.9 °C	(0.02 – 5.8 m/s) 1.1 m/s
Winter (22.12-20.03.2023)	(10.4 – 1200 W/m²) 306.9 W/m²	(10.3 – 441.7 W/m²) 123.1 W/m²	(-3.0 – 23.7 °C) 8.8 °C	(0.03 – 10.7 m/s) 1.8 m/s
Spring (21.03-20.06.2023)	(10.1 – 1368.9 W/m²) 555.5 W/m²	(10.5 – 577.9 W/m²) 214.2 W/m²	(4.8– 35.9 °C) 19.5 °C	(0.02 – 7.9 m/s) 1.5 m/s
Summer (21.06-28.08.2023)	(15.8 – 1276.4 W/m²) 564.6 W/m²	(14.3 – 587.9 W/m²) 234.4 W/m²	(13.9 – 38.7 °C) 26.8 °C	(0.03 – 8.3 m/s) 1.7 m/s

Figure 4: Four PV Modules, with one pair for each manufacturer M01 and M02, installed on a rooftop in Freiburg, Germany.

During the time of outdoor exposure from autumn 2022 until summer 2023, we observed larger soiling depositions on the modules in the spring season, which was quantified during two cleaning periods. It's important to note that this soiling is attributed to occasional occurrences of soiling due to pollen and not something regular throughout the entire period of exposure at this site. The soiling ratio was calculated by comparing the performance ratio (PR), as the average power output divided by the Gpoa, over a period of 1 week when the module was soiled and 1 week after cleaning procedure. A soiling ratio (PRsoiled /PRclean) of 1 indicates no significant performance difference between both periods. For M01, the module presented a soiling ratio of 0.96, while for M02, it was 0.95.

Regarding degradation rates over this exposure period, we filtered the power output of the modules for conditions with Gpoa ranging from 800 to 1000 W/m² and with a percentage of fluctuation of less than 5%. Subsequently, we corrected the power for a Gpoa of 1000 W/m² and a more normal operating temperature condition of 45ºC, rather than the STC condition of 25ºC [11]. The linear fit to this power data revealed degradation rates of -0.19 %/year for M01 and -0.16 %/year for M02. It's essential to further analyze these degradation rates calculated with a shorter amount of data to understand any correlation with long-term calculations and datasheet estimations.

3 EVALUATION

3.1 Module behavior

In the initial phase of our evaluation, we present the differences in behavior between the two type of modules in this study by conducting a loss analysis in accordance with reference [9]. The quantification of losses attributed to each influencing parameter is derived from the correction procedures outlined in the ER methodology as specified in IEC 61853-3. Fig. 5 illustrates the percentage of losses in SSER, from the exposure time in Freiburg. It considers the effects of reflected irradiance resulting from variations in the AOI, the gains or losses from fluctuations in ambient temperature and irradiance levels, as well as the impact of spectral variations. Our findings reveal that during the fall and winter seasons, significant losses primarily result from low irradiance levels and losses related to angular response. Notably, M02 exhibits a greater susceptibility to AOI variations in comparison to M01. Conversely, during spring and summer, the primary cause of losses for both module types is the ambient temperature, with M02 displaying greater resilience in these conditions.

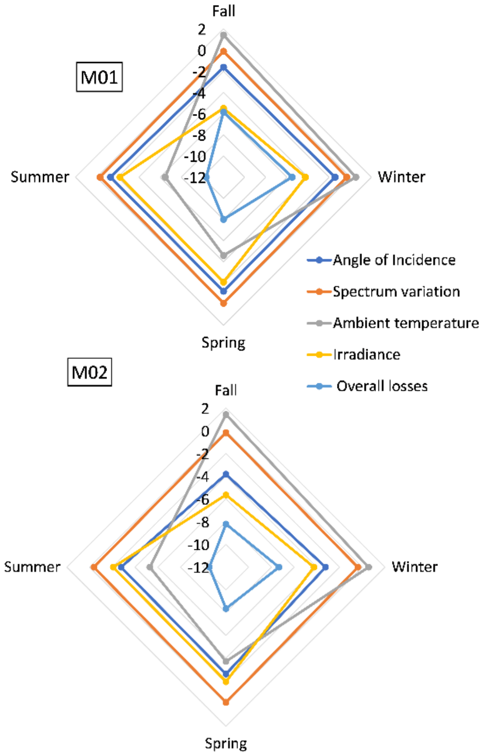


Figure 5: Seasonal ER loss analysis for module M01 (upper graph) and M02 (lower graph). Losses are expressed in percent with the higher values in inner curves (negative values) and include the overall losses.

3.2 CSER vs SSER

The SSER for the complete year 2022, modeled using the standard methodology in the specific location of Freiburg, Germany, was 0.93 for both type of modules. When modeling for a shorter period of 10 months, between October 2022 and August 2023, the results were very similar at 0.92. (Table III). However, whit the extension of the ER climate data sets to specific sites, it became evident that locations like Freiburg are not accurately represented by the standard profiles, such as the *temperate continental*, where modules present higher CSER of 0.99 (M01) and 0.98 (M02), resulting in differences between SSER and CSER larger than the expected uncertainty in the methodology [8, 9]. Notably, SSER values derived from direct field measurements (PR_{DC}) closely matched the modeled results for Freiburg, underscoring the need for region-specific modeling for energy rating assessments.

Table III: SSER results for Freiburg in years 2022 and short-term exposure between 2022-2023. CSER for the profile “temperate continental”.

Profile	**M01**	**M02**
CSER *“temperate continental”*	0.99	0.98
SSER Freiburg (2022)	0.93	0.93
$\text{SSER}_{\text{MODEL}}$ Freiburg (Oct. 2022 – Aug. 2023)	0.92	0.92
$\text{SSER}_{\text{REAL}}$ Freiburg (Oct. 2022 – Aug. 2023)	0.92	0.89

3.3 SSER validation

To further validate our site-specific modeled ($\text{SSER}_{\text{MODEL}}$) outcomes, we conducted calculations on a daily and weekly basis (Equation 1), enabling a comparative assessment with outdoor measurements ($\text{SSER}_{\text{REAL}}$). This approach allowed us to understand any seasonal deviations and the impact of weather conditions. The weekly analysis revealed deviations between the *temperate continental* CSER and Freiburg SSER, in both modeled and real values, larger than 10% during the winter period, while lower deviations of around 5% in summer (Fig. 6). Further examination of the weekly $\text{SSER}_{\text{MODEL}}$ and $\text{SSER}_{\text{REAL}}$ values in Freiburg highlighted a consistent seasonal pattern. Some of the disparity points are attributed to differences in the sources of irradiance in POA between the modeled and real datasets used for the calculations. The IEC 61853-3 method necessarily derives G_{POA} from DNI and DIF, while the measured PR_{DC} is based on measured G_{POA}.

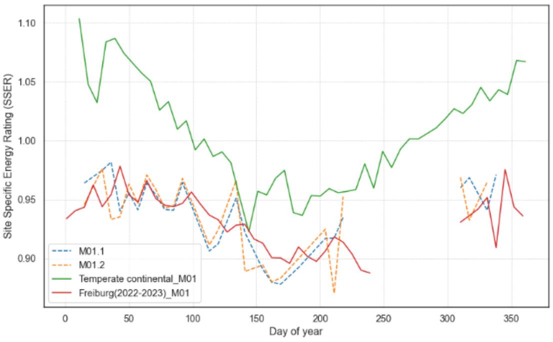


Figure 6: Weekly CSER acc. to IEC 61853 in *temperate continental* profile (green). Weekly $\text{SSER}_{\text{MODEL}}$ in Freiburg (red) and $\text{SSER}_{\text{REAL}}$ (dashed lines) in 2022-2023 for M01 (M01.1 and M01.2).

The daily analysis showed average deviations between *modelled* and *real* SSER for M01 of 1.27% (M01.1 and M01.2), whereas for M02, these deviations were 0.23% (M02.1) and 1.12% (M02.2). These small deviations indicate a good correlation between short term outdoor ER and the standard methodology. Fig. 7 and 8 show the daily SSER values with the corresponding deviations between modeled and real. Over the course of exposure is visible that warmer months with higher levels of irradiance result on smaller range of deviations.

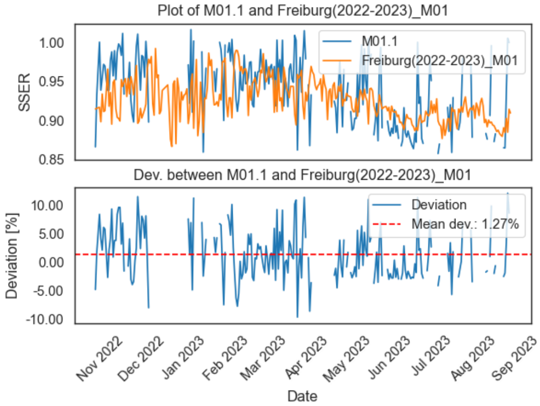


Figure 7: Upper graph shows the daily $\text{SSER}_{\text{REAL}}$ (blue) and $\text{SSER}_{\text{MODEL}}$ (orange) in Freiburg from November 2022 to August 2023 for M01 (M01.1). Lower graph shows the daily and average deviation (red line) between modeled and real SSER.

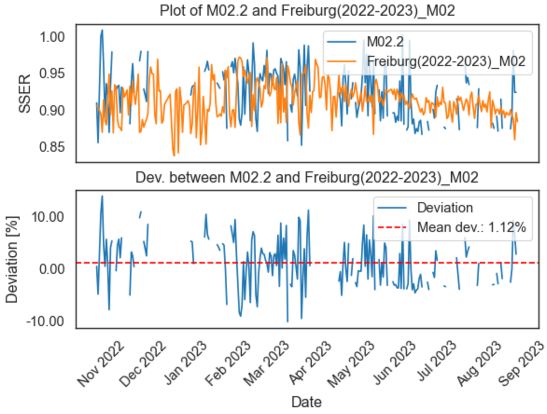


Figure 8: Upper graph shows the daily $\text{SSER}_{\text{REAL}}$ (blue) and $\text{SSER}_{\text{MODEL}}$ (orange) in Freiburg from November 2022 to August 2023 for M02 (M02.2). Lower graph shows the daily and average deviation (red line) between modeled and real SSER.

4 CONCLUSIONS

The study involved conducting short-term outdoor measurements of PV module performance in Freiburg, Germany, with the aim of validating the ER methodology. The focus was particularly on validating the modeling of SSER for this specific location and identifying seasonal variations, along with determining the primary sources of losses. The short-term behavior of SSER was assessed on weekly and daily basis. Weekly results provided insight into the variation of SSER across the different seasons of the year. These values tend to be higher during winter and lower in summer. The representation of SSER through weekly values also highlighted the significant deviations when compared to standard profiles (CSER) like "*temperate continental"*. This finding reinforces the necessity of employing site-specific data, as stated in previous studies [9].

The daily SSER derived from outdoor measurements ($SSER_{REAL}$) effectively validated site-specific modeled results ($SSER_{MODEL}$), exhibiting average deviations ranging from 0.23% to 1.27%, for both type of modules. These deviations fall within the anticipated uncertainty in the methodology, which was estimated on our laboratories' assessments and findings from previous studies [7]. The seasonal analysis revealed that the lowest range of deviation between real and modeled SSER occurs during spring, making it an optimal season for evaluating short-term outdoor measurements and validating the ER methodology. Notably, the occurrences of soiling in spring and the expected degradation rate did not have significant effects on the modules' ER.

The ER losses analysis aligned well with the indoor characterization of the modules, demonstrating its effectiveness not only in comparing different climates profiles but also in analyzing seasonal effects. These findings emphasize the significance of incorporating local climate data and acknowledging performance variations across the year. Such insights have the potential to enhance the testing and evaluation of modules, optimizing energy output in different seasons. Furthermore, this type of analysis can result in more precise energy yield predictions and well-informed decisions for solar energy systems situated in specific geographical locations.

5 FURTHER WORK

To deepen comprehension of the energy rating methodology, future work will involve the utilization of an expanded outdoor dataset to conduct both uncertainty and sensitivity analyses. Furthermore, we aim to undertake a comparative study involving indoor characterization and outdoor procedures, which could offer valuable insights into the advantages of adopting site-specific analysis and outdoor characterization for emerging technologies. For example, this could involve evaluating thermal coefficients and power matrices within both controlled indoor settings and actual outdoor conditions, according to the procedures outlined in IEC 61853 1-2. This approach has the potential to yield more accurate assessments of PV module performance in real-world applications.

6 REFERENCES

[1] *IEC 61853-3 Photovoltaic (PV) module performance testing and energy rating— Part 3: Energy rating of PV modules*, 2018.

[2] C. Monokroussos, Y. Zhang, E. W. Lee, F. Xu, A. Zhou, Y. Zhang, and W. Herrmann, "Energy performance of commercial c-Si PV modules in accordance with IEC 61853-1, -2 and impact on the annual specific yield," *EPJ Photovolt.*, vol. 14, p. 6, https://www.scienceopen.com/document_file/936f3a53-84e3-42d3-88eb-3d8989c8b208/API/pv220042.pdf, 2023.

[3] C. Monokroussos *et al., Eds., Energy Rating of c-Si and mc-Si commercial PV-modules in accordance with IEC 61853-1,-2,-3 and impact on the annual yield*, 2017.

[4] Y. Poissant, S. Pelland, D. Turcotte, Ed., *A Comparison of Energy Rating Methodologies Using Field Test Measurements*, 2008.

[5] S. Dittmann *et al., Eds., Results of the 3rd Modelling Round Robin within the European Project „PERFORMANCE"– Comparison of Module Energy Rating Methods*: WIP-Munich, 2010.

[6] B. Bora, R. Kumar, O. S. Sastry, B. Prasad, S. Mondal, and A. K. Tripathi, "Energy rating estimation of PV module technologies for different climatic conditions," *Solar Energy*, vol. 174, pp. 901–911, https://www.sciencedirect.com/science/article/pii/S0038092X18309630, 2018.

[7] D. Dirnberger, B. Müller, and C. Reise, "PV module energy rating: opportunities and limitations," (en), *Prog. Photovolt: Res. Appl.*, vol. 23, no. 12, pp. 1754–1770, https://onlinelibrary.wiley.com/doi/full/10.1002/pip.2618, 2015.

[8] T. Huld, E. Salis, A. Pozza, W. Herrmann, and H. Müllejans, "Photovoltaic energy rating data sets for Europe," *Solar Energy*, vol. 133, pp. 349–362, https://www.sciencedirect.com/science/article/pii/S0038092X16300391, 2016.

[9] M. Rivera, C. Reise, and U. Kräling, "Representativeness of Energy Rating acc. to IEC 61853 for Different Locations in Middle and South Europe," *Energy Tech*, 2023.

[10] M. Pravettoni and A. S. Rajput, "On the metastability of silicon heterojunction solar photovoltaic modules," (En;en), *MRS Bulletin*, pp. 1–9, https://link.springer.com/article/10.1557/s43577-023-00475-x, 2023.

[11] R. M. Smith, D. C. Jordan, and S. R. Kurtz, "Outdoor PV Module Degradation of Current-Voltage Parameters," Boulder, CO: American Solar Energy Society (ASES), National Renewable Energy Lab. (NREL), Golden, CO (United States), 2012.