DECOUPLING PERFORMANCE GAINS OF SILICON HETERO-JUNCTION BIFACIAL MODULES

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ABSTRACT: Silicon heterojunction (SHJ) solar cells and bifacial modules are expected to rapidly grow in the PV market, with their high power conversion efficiency, good performance at low irradiation and better temperature coefficients (TCs) allowing for improved energy yields. It is therefore increasingly relevant to have comparative analyses with conventional monofacial modules and market leading PERC cells. The aim of this contribution is to assess the performance of five PV modules on a rooftop monitoring station in Neuchâtel: two bifacial SHJ, two monofacial SHJ and one benchmark monofacial PERC. These three module types allow for detailed comparisons of performance enhancing factors both on the module structure and solar cell technology levels, allowing to decouple individual performance effects. After almost two years of monitoring, results show that bifacial modules yield 7.2% energy gains over both monofacial technologies, and 5% improved performance ratio (PR). For the corrected PR, current bifacial corrections may not fully describe the angular, optical and seasonal effects, as a 2.2% bifacial gain is still observed after temperature and rear irradiance corrections, leaving room for improvement in the current bifacial PR definition. In terms of temperature dependence, field-based TCs are found to be better for SHJ cells than PERC (-0.16%/°C vs. -0.31%/°C at STC, respectively), although performance gains also vary with irradiance conditions.
Keywords: Silicon Heterojunction, Bifacial, Monitoring, PERC, Performance Ratio

1 INTRODUCTION

With their high energy conversion efficiencies, low temperature coefficient (TC) and intrinsic bifacial nature, silicon heterojunction (SHJ) solar cells are soon expected to become competitive with Passivated Emitter and Rear Contact (PERC) cells, the current go-to technology [1, 2]. As SHJ cells become more prominent in PV markets, it is increasingly relevant to have robust analyses of their performance and characteristics when compared to industry standards, evaluating their potential gains and advantages. This contribution aims to provide an up-to-date and in-depth comparison of three commercial technologies, focusing on bifacial vs. monofacial applications and SHJ vs. PERC solar cells, which will allow to decouple the contributions to increased energy yields and performance. The bifaciality of the SHJ modules raises important questions for PV system designers, installers and users, given that rear irradiation level also needs to be taken into account. The promise of dual-sided PV modules is that they can make use of more incoming irradiance than typical modules by collecting additional light at the rear side, however quantifying the gains is not straightforward and depends on many factors: the substrate behind the system (e.g. white panels, grass, gravel,…), the system geometry, and solar cell types. Having the two cell technologies and three module structures in the same monitoring conditions is therefore ideal to establish the performance differences. For example, it is expected that SHJ cells will perform better in clear-sky and elevated temperature conditions due to their lower temperature coefficients, and that the bifacial modules will have improved yields and performance in diffuse irradiance conditions.

The main outcomes of this work will therefore be: (1) detailed data analysis pipelines for reproducible and standardised measurements, (2) a practical comparative analysis of PV module technology performances, focusing on energy yield, performance metrics and temperature coefficients, leading to (3) proposals for improved bifacial system modelling and monitoring guidelines.

2 EXPERIMENTAL

The monitoring station is situated in Neuchâtel, Switzerland (temperate oceanic climate, Cfb in Köppen climate classification), and modules are installed with a 15° tilt and 175° orientation (South-facing) on aluminum mounting racks at 0.1 m from the gravel-covered rooftop. Five modules are monitored: two bifacial SHJ, two monofacial SHJ, and one PERC monofacial. **Table I** summarises the characteristics and nominal electrical parameters of the installed modules (nameplate manufacturer values) measured at standard test conditions (STC), where P_0 [Wp] is the rated power, I_{sc} [A] the short-circuit current, V_{oc} [V] the open-circuit voltage and γ [%/°C] the maximum-power temperature coefficient.

Figure 1 shows photographs of the setup with the three module types. The monitoring station setup measures the module-level I-V curves at 180 sec. timesteps to retrieve electrical outputs (keeping modules at maximum power point (MPP) between acquisitions), and back-surface sensors collect module temperatures. For the bifacial modules, a dummy glass-glass module is setup in the module array to retrieve module temperature without having to shade the rear of the measured modules. Additionally, global horizontal, diffuse irradiance and a back-surface irradiance sensor (albedometer) measure irradiation at 10 min. intervals. Data is available starting January 2021, however the rear-side irradiance measurements only start in February 2022.

3 METHODOLOGY

The available data allows for a two-fold comparative analysis: (i) comparing module topologies with the bifacial and monofacial layouts (based on the two types of SHJ panels), and (ii) investigating cell technologies by comparing the performance of SHJ to the benchmark PERC cells. The following subsections will describe the metrics, methods and filtering approaches used in this work.

Table I. Characteristics of the studied modules (Mo=Monofacial, Bi=Bifacial) at standard test conditions (STC).

ID	Bifacial	P_0 [W_p]	I_{sc} [A]	V_{oc} [V]	γ [%/°C]
SHJ-Bi-1	✓	380	53.4	9.17	-0.25
SHJ-Bi-2	✓	380	40.6	10.4	-0.25
SHJ-Mo-1	×	380	53.4	9.17	-0.25
SHJ-Mo-2	×	380	53.4	9.17	-0.25
PERC-Mo	×	330	53.4	9.17	-0.37

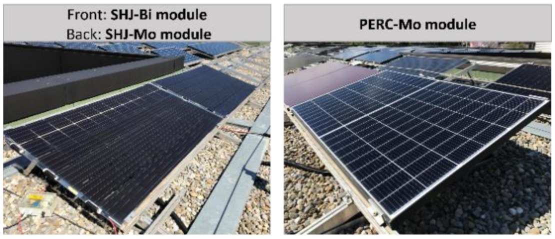

Figure 1. Photographs of the outdoor test facility and monitored devices.

3.1 Performance metrics

The main metric used for the analysis is the performance ratio (PR), defined as the quotient between the system's final and reference yield. Following the IEC 61724-1 guidelines, the PR can be further adjusted for temperature coefficients (denoted PR'), and bifaciality (denoted PR'_{bi}). This notation will be followed to differentiate the various correction levels of PR. Equations (1), (2) and (3) summarise the metric definition:

$$PR'_{bi} = \frac{\left(\sum_k P_{mp,k} \cdot \tau_k\right)}{\left(\sum_k \frac{\left(C_{k,25°\mathrm{C}} \cdot P_0\right) \cdot G_{i,k} \cdot BIF_k \cdot \tau_k}{G_{i,ref}}\right)} \quad (1)$$

$$C_{k,25°\mathrm{C}} = 1 + \gamma \cdot (T_{mod,k} - 25°\mathrm{C}) \quad (2)$$

$$BIF_k = (1 + \varphi_{max} \cdot \rho_i) \quad (3)$$

Where for the k timesteps with recording interval τ, P_{mp} [W] is the measured power at MPP, P_0 [Wp] the rated power, G_i [Wm^{-2}] the measured in-plane irradiance, $G_{i,ref} = 1000$ Wm^{-2} the irradiance at which P_0 is determined (STC), $C_{k,25°C}$ the power rating temperature adjustment factor, T_{mod} [°C] the module temperature, γ [%/°C] the relative maximum-power TC, BIF the bifacial irradiance factor, φ_{max} the maximum-power bifaciality coefficient and ρ_i the in-plane rear-side irradiance ratio. For PR', the bifacial irradiance factor is set to 1, and for PR both bifacial and temperature correcting terms are set to 1. The energy yield Y is also used to compare the module performances (sometimes referred to as specific yield), and is defined as the module energy output (DC) E [Wh] per rated installed W_p.

For a more detailed analysis, the change rates of available electrical parameters are also evaluated. The maximum power P_{mp} and short-circuit current I_{sc} are corrected for irradiance and normalised by the reference values of **Table I**, while V_{oc} is simply normalised [3].

3.2 Temperature coefficients

It is well established that solar cell performance declines with increasing temperature, primarily due to the reduction of open-circuit voltage and FF [4]. Silicon heterojunction solar cells are considered ideal for bifacial modules due to their good low-light performance and lowest temperature coefficients amongst silicon solar cells [5]. Moreover, it has been shown that TCs are in reality nonuniform, and vary depending on the environmental and operating conditions [3], [6]. With the available datasets, it is possible to study the temperature dependency of cell technology performance, as well as the variability of the TCs, usually defined at STC. This will allow both the comparison of module performances and the data-based characterisation of TCs. To do so, the methodology outlined in [6] is followed: the DC Power is plotted as a function of module temperature for different irradiance conditions and filters, and a linear regression is used to extract the irradiance-dependent TCs. This analysis method also allows to extrapolate the STC power from field data using the 1000 Wm^{-2} irradiance corresponding to STC, which can be compared to nominal values.

3.3 Data filtering

In terms of filtering, three procedures were applied for the performance metrics: (i) an irradiance filter applied to the G_i measurements removing very low (< 200 Wm^{-2}) irradiance values to filter night-time and variable cloudy conditions and very high (> 1200 Wm^{-2}) irradiance (i.e. due to extreme cloud reflections), (ii) for daily or higher aggregations, a day type classification algorithm was applied to filter out overcast days, where high weather variability would generate noise in the data, (iii) for PR measurements, an additional threshold filter excludes outlier values due to shading or nonuniform irradiance conditions ($0.75 \leq PR \leq 1.2$).

For the temperature coefficient vs. irradiance level analysis, data is filtered for ten irradiance steps G_i = 50, 100, 200, 300, …, 800, 1000 Wm^{-2} with $\pm$5% tolerance, where 900 is excluded due to outlier values. To avoid further outliers in the power measurements, the PR filter used for the performance metrics is applied to remove shading faults.

4 RESULTS AND DISCUSSION

4.1 Performance gains analysis

As a first step, the performance metrics described in section 3.1 are used to quantify the differences between the studied module technologies and structures. **Figure 2** shows the production profiles of the five modules during a clear-sky day, where nonuniform behaviours are minimised. The specific power (normalisation by the rated power), standard PR and corrected PR'_{bi} are represented, allowing to compare the different capacity modules through various lenses. Starting with the specific power, a zoom in the midday hours shows the performance gains observed for the monofacial SHJ modules over the PERC module, as well as the bifacial gains. Over the entire day, the SHJ monofacial modules outperform the PERC module by 1.7%, and the bifacial SHJ modules show a 6.1% gain over the monofacial SHJ. Moreover, looking at individual timesteps, peak gains for specific power (up to 3%) for the SHJ vs. PERC were observed around midday, directly correlated to peak irradiance and temperature. From this simple clear-sky day comparison, we therefore observe and quantify both the temperature and bifaciality performance effects. Looking at the entire monitoring period, the energy yield gain due to bifaciality (comparing with SHJ and PERC monofacial modules) is 7.2%, with the bifacial modules producing ~2200 Wh/Wp from January 2021 – July 2022. Monofacial SHJ modules also produced ~1.5% more than PERC, likely due to the TC. A potential caveat is the measured value of the nominal power, which in this case is the manufacturer rated value, which is notoriously unreliable. Ideally, the rated power should be measured in an accredited lab for optimal accuracy, in which case the difference between SHJ and PERC would likely increase.

Looking at the standard PR, one can further quantify the gains, although without decoupling the individual effects leading to increased performance, as there is no temperature or rear-irradiance correction. Considering most commercial systems will only have access to the standard PR, it nevertheless remains a valuable metric for standardised comparisons of modules. Here, during the studied clear-sky day, we observe 4.8% and 8.7% gains for bifacial SHJ over monofacial SHJ and PERC, respectively. The advantage of SHJ is notably only at high temperature and irradiance conditions, as the PR equalises for the monofacial modules in the morning and evening hours.

Finally, in order to further detail and decouple the bifacial and cell technology gains, the corrected performance ratio PR'_{bi} is considered, and the measured rear-irradiance G_{rear} [Wm^{-2}] is represented for the studied clear-sky day. The rear irradiance profile shows two peaks in the morning and evening, likely due to the sensor angular response or reflections at low sun angles. The PR'_{bi} profiles also show an angular trend: the performance ratios match well around noon, with the PERC module even outperforming the SHJ modules, which can be attributed to the TC difference. Interestingly, bifacial gains are still present in the morning and evening, even after correction, indicating that the applied rear-irradiance correction is not sufficient to account for all bifacial enhancements. This effect is likely due to environmental factors decreasing the measured rear-irradiance (e.g. sensor shaded by aluminum frame or surroundings). Another possible explanation is the sun angle dependency of both the solar cells and albedometer. Firstly, given that the glass-glass bifacial modules are frameless, internal light reflections at low sun angles coming from the module sides could contribute to increased current. Secondly, during morning and evening hours with lower sun angles, the rear-irradiance sensor likely does not capture the total irradiance reaching the module backside, which includes not only diffuse and reflected components, but also direct irradiance. The combination of these two factors, along with other optical effects possibly linked to the installation environment, could lead to the bifacial enhancements observed, even after correction.

In order to confirm the angular dependency, the relative difference between SHJ bifacial and monofacial PR'_{bi} is aggregated and averaged per hour of the day during the period of February-July 2022, as shown in **Figure 3**. A clear pattern of low angular gains is isolated, confirming the seasonal and sun angle-dependent bifacial behaviour. This result shows that a simple rear-irradiance correction model, as described in IEC 61724-1, might not be sufficient for capturing all bifacial enhancement factors, or that special attention should be placed on the rear-irradiance measurements. A future improvement for the standard could therefore be an angular-corrected bifacial factor.

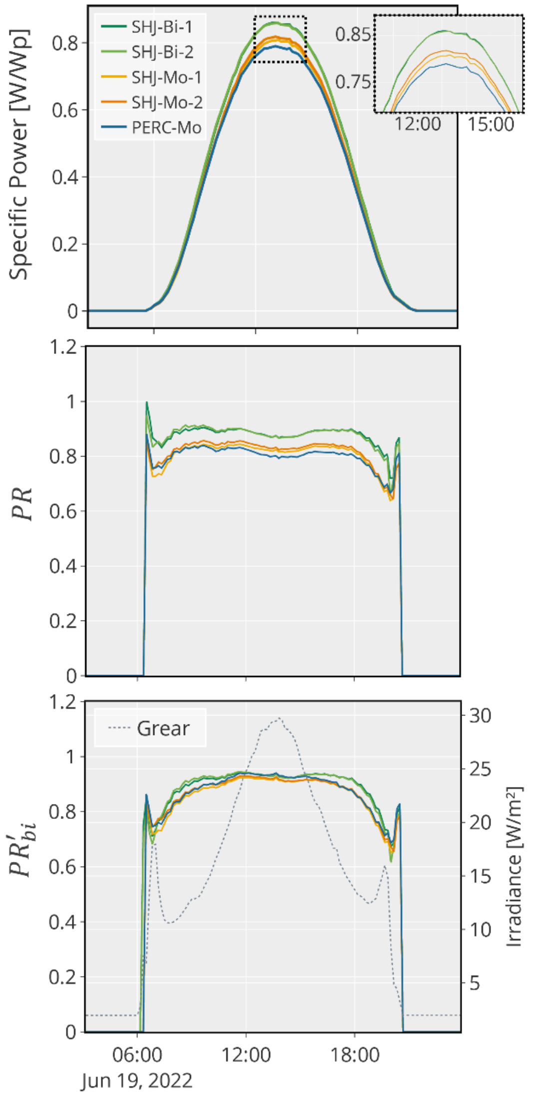

Figure 2. Daily production profile during a clear-sky day, for the specific power (normalised with rated power), standard $\boldsymbol{PR}$, and temperature and rear irradiance corrected $\boldsymbol{PR'_{bi}}$ (shown with rear-irradiance measurement).

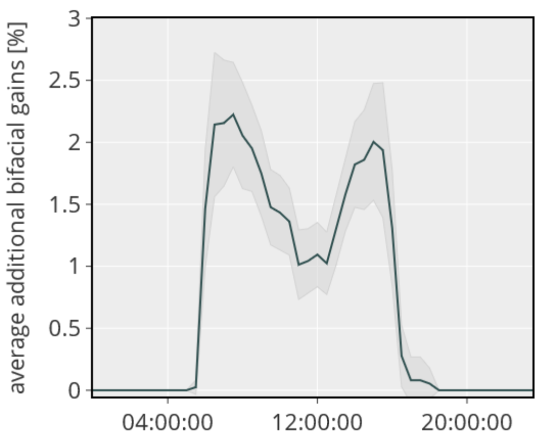

Figure 3. Hourly aggregated and averaged additional SHJ bifacial gains after temperature and rear-irradiance corrections when compared to SHJ monofacial module performance, isolating the remaining angular-dependent

gains. Standard deviation is used for uncertainty (shaded area). A pattern of morning and evening gains is observed.

Long-term temporal trends of the normalised power (equivalent to standard PR) and I-V curve parameters are shown in **Figure 4**. Normalisation, filtering and analysis procedures are described in sections 3.1 and 3.3. Results show the impact of bifaciality on the PR over the monitoring duration, with a ~5% performance gain over the SHJ monofacial modules, while the SHJ cells show a ~1% gain over PERC. The observed temporal trends of the electrical parameters show a better short-circuit current performance for the bifacial vs. monofacial SHJ modules. Given that current is linearly correlated to light intensity reaching the cells [7], the difference is simply explained by the increased irradiance due to bifaciality.

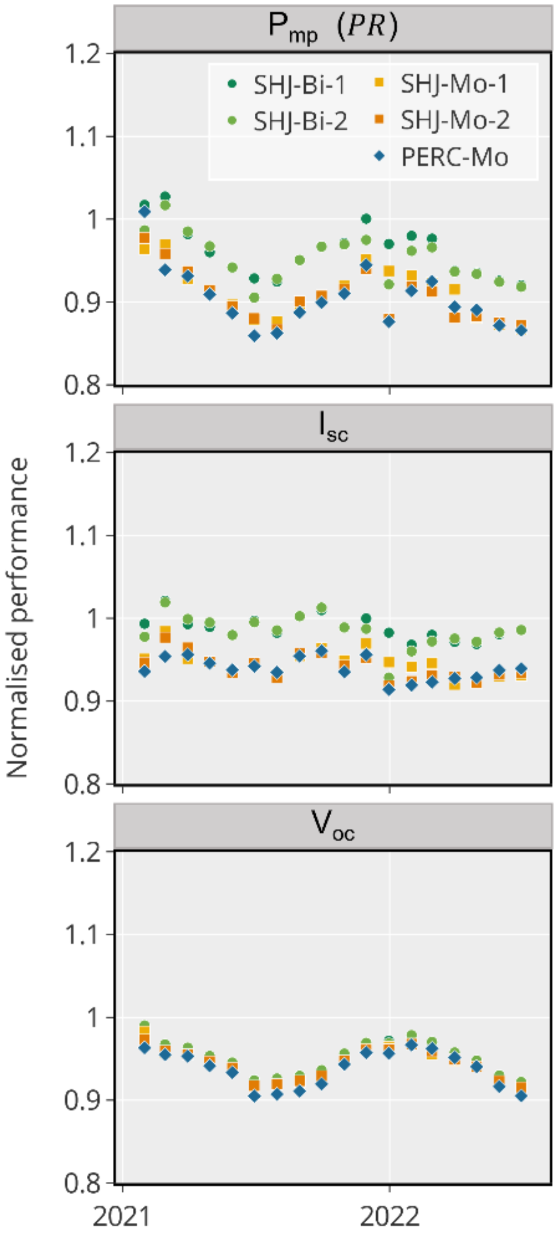

Figure 4. Normalised monthly performance rates of the DC power (equivalent to standard $\boldsymbol{PR}$) and I-V parameters for the studied modules.

Table II. Average performance ratios (Feb. – Jul. 2022).

ID	Mean PR	Mean PR'	Mean PR'_{bi}
SHJ-Bi-1	0.932	0.949	0.927
SHJ-Bi-2	0.930	0.948	0.925
SHJ-Mo-1	0.883	0.908	0.908
SHJ-Mo-2	0.880	0.904	0.904
PERC-Mo	0.882	0.916	0.916

As discussed with the corrected performance ratio, the rear irradiance is highly dependent on the sun angle and environmental conditions, as it can be composed of a combination of sky diffuse, reflected or direct back-surface irradiance. At low sun angles, the glass-glass structure of the bifacial modules could also contribute to additional internal reflective gains, leading to the improved current. The open-circuit voltage trend is stable for all modules, however the SHJ initial degradation rate is steeper than the PERC cells. A long-term analysis (>2 years) would be necessary to conclude, however it has been observed in literature that SHJ cells could degrade more in V_{oc} than typical c-Si cells in long-term field exposure [8].

Having seen how the performance metrics can be used to analyse and decouple the bifacial gains, the next step is to focus on solar cell technolgy differences, which mostly come down to temperature coefficients.

4.2 Temperature effects on performance and TC variability

The methods described in 3.2 are applied to the available datasets to study the temperature dependence of performance, as well as the variability of the TCs for different irradiance conditions. **Figure 5** shows heatmaps of the standard PR as a function of the irradiance and module temperature. From this visualisation, it is clear that bifaciality offers the most gains in performance, especially in mid to low light conditions. Moreover, the differences in TCs between SHJ and PERC cells are also visible, with lower performance ratios over a wider array of high irradiance and temperature values for the PERC cells: for module temperatures above 55°C, the SHJ monofacial outperform PERC by ~2.5%.

As a next step, the maximum-power TC variability is quantified for different irradiance conditions. **Figure 6** shows an example of the irradiance level splitting and linear fitting for the SHJ-Bi-1 module data. The linear regressions coefficients, once normalised by the module rated power at each given condition, give the TCs at the various irradiance levels. Results for all modules are shown in the lower part of **Figure 6**, where the preliminary results from the heatmaps and performance metrics analyses are confirmed: SHJ solar cells have better TCs, with all four SHJ modules converging to -0.16 %/°C at STC conditions, while the PERC module TC is estimated at -0.31 %/°C. Interestingly, the TCs only diverge for the different cell technologies for mid to high irradiance values, confirming the nonuniform temperature behaviours. The TCs tend to higher values for low irradiance conditions, which could be a data artefact due to angular dependencies or measurement errors, although such effects have been previously observed and discussed in literature [6, 9, 10]. Nevertheless, TCs are often considered uniform in PV modelling tools, which could lead to errors and uncertainties, which is why field-based measurements could bring valuable additional insights.

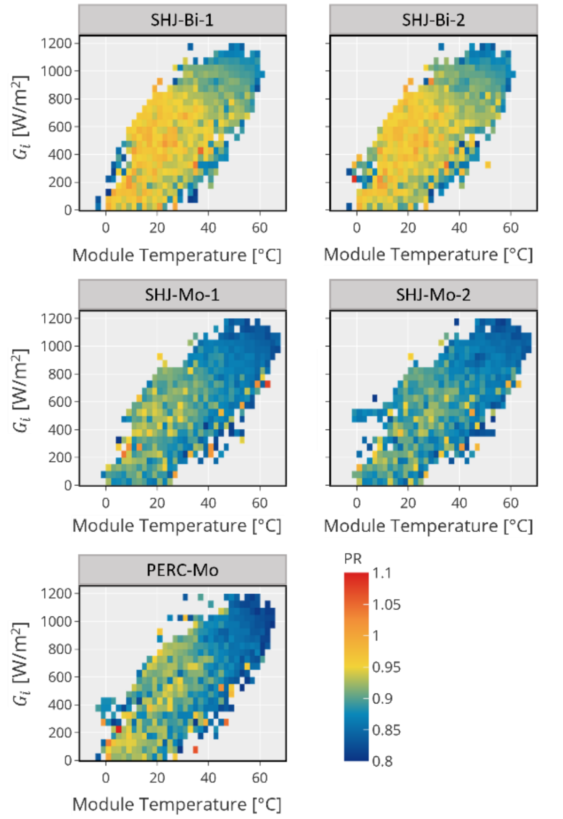

Figure 5. Performance ratio heatmaps of the irradiance vs. module temperature relationship. $\boldsymbol{PR}$ is averaged over intervals of 50 W/m² and 2 °C.

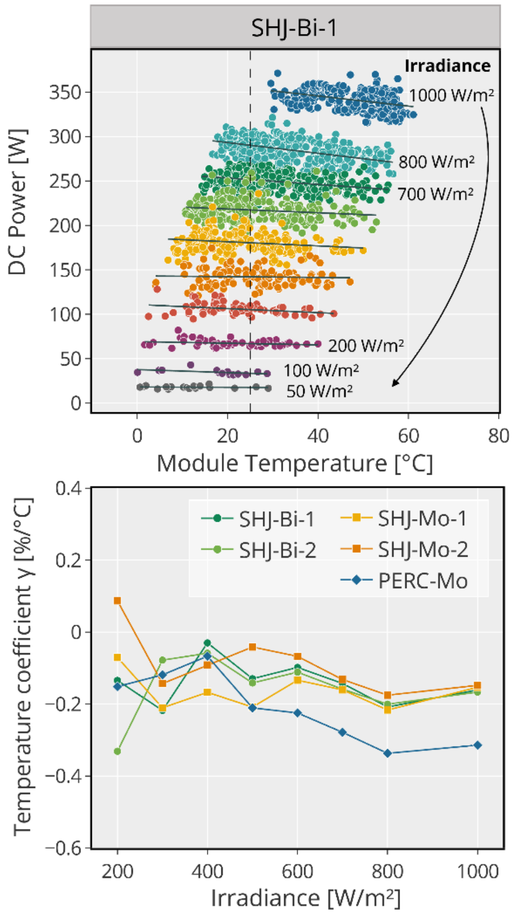

Figure 6. Top: module power vs. temperature relationship, with irradiance level filtering. Bottom: Irradiance dependence of the temperature coefficients.

5 CONCLUSIONS

Bifacial modules and SHJ solar cells are rapidly entering the PV market, creating the need for more advanced understanding of their advantages over conventional, widely studied PERC cells. This contribution aimed at decoupling the performance gains due to bifaciality (module structure) and differing solar cells (module technology), using data from five monitored modules in Neuchâtel, Switzerland. Based on the analysis of performance metrics such as the performance ratio, as well as temperature and irradiance dependencies, the following main outcomes are deduced:

- The bifacial SHJ modules showed an average 7.2% increased energy yield compared to both monofacial technologies over the monitoring period.
- The standard, non-corrected performance ratio is a valuable metric to quantify bifacial and cell technology gains. Overall, bifaciality improves the PR by ~5% when comparing the bifacial and monofacial SHJ modules.
- The IEC 61724-1 guidelines for PR corrections may not account for all bifacial enhancements, as a 2.2% average gain is still found after correction. This is likely due to angular dependency, which is confirmed with morning and evening peak gains, along with seasonal variability. A future proposal may include angular corrections to account for all rear irradiance components.
- SHJ solar cells are found to have significant advantages over PERC in terms of maximum-power temperature coefficients, although the gains are not uniform depending on the irradiance conditions, with the highest impact of cell technology found at mid to high irradiation. The field-based TC values at STC are found to be -0.16%/°C and -0.31%/°C for SHJ and PERC respectively.

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