Clipping-corrected performance ratio: A new metric for high DC:AC ratio PV systems

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Supporting information

1 Alternate algorithm for determining the clipping threshold

In certain cases, it is not possible to determine the clipping threshold using the method in 2.3 as the status of clipping is non-binary, or the maximum AC power is variable. For example, if a system contains different array or inverter configurations that have different clipping thresholds, then it is possible for the system be in a partially clipped state where some inverters are at maximum power while others are not. For these cases, we propose an alternate solution based on minimising the error resulting from the assumption of a fixed clipping onset. This method was not used to generate the results presented in this publication but has been tested on real systems data (unpublished). We include it here to support wider uptake.

The following algorithm can be used to determine $\mathrm{G}_{\mathrm{C},25\,°\mathrm{C}}$ from system simulations:

1. Simulate the system and record simulated $P_{out,k}$, $T_{mod,k}$ and $G_{POA,k}$ for each timepoint k.
2. Chose an initial guess value of $G_{C,25\,°\mathrm{C}}$ (e.g. $G_{C,25\,°\mathrm{C}} \sim G_{ref} P_{AC,0}/P_0$).
3. Calculate $\Delta P_{out,k}$ for each timepoint, where $\Delta P_{out,k} = P_{out,k} - \frac{c_{25\,°\mathrm{C},k}\, G_{POA,k}}{G_{C,25\,°\mathrm{C}}} P_{AC,0}$ for timepoints where $\left(c_{25\,°\mathrm{C},k}\, G_{POA,k}\right) < G_{C,25\,°\mathrm{C}}$ and $\Delta P_{out,k} = P_{out,k} - P_{AC,0}$ for other timepoints.
4. Adjust the value of $G_{C,25\,°\mathrm{C}}$ and repeat the above calculation until $\sum_k \Delta P_{out,k} \sim 0$, to within a tolerance of ± 1 W m^{-2} on $G_{C,25\,°\mathrm{C}}$.

2 Results for all locations

To simplify figures in the manuscript, we showed only one location. Here we present the same figures including all six locations. Figure S 1 is equivalent to Figure 3 of the manuscript.

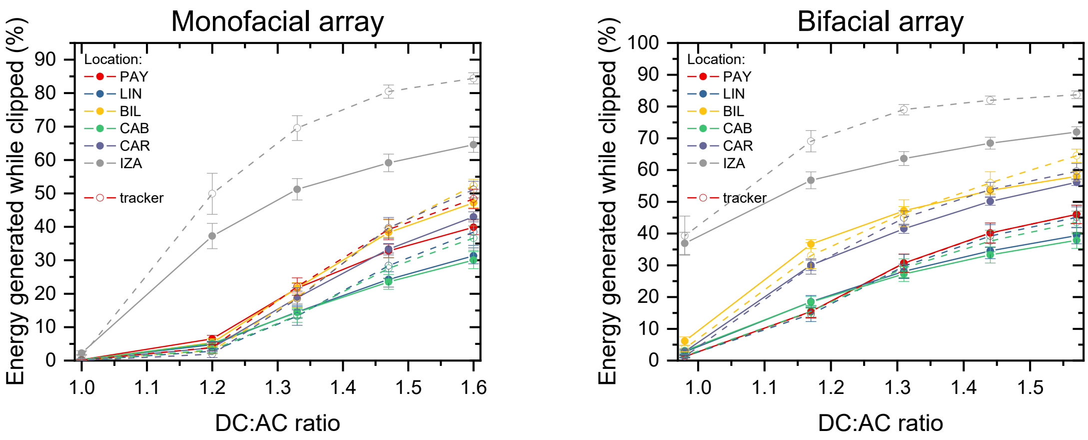

Figure S 1 Fraction of energy generated under clipping conditions as a function of DC:AC ratio for nominally performing systems. Different colours indicate different locations. Error bars indicate standard deviation between different 12 month periods. Dashed lines indicate single-axis tracker systems, solid lines are fixed-tilt. Left: monofacial array. Right: bifacial array.

Figure S 2 is equivalent to Figure 4 of the manuscript.

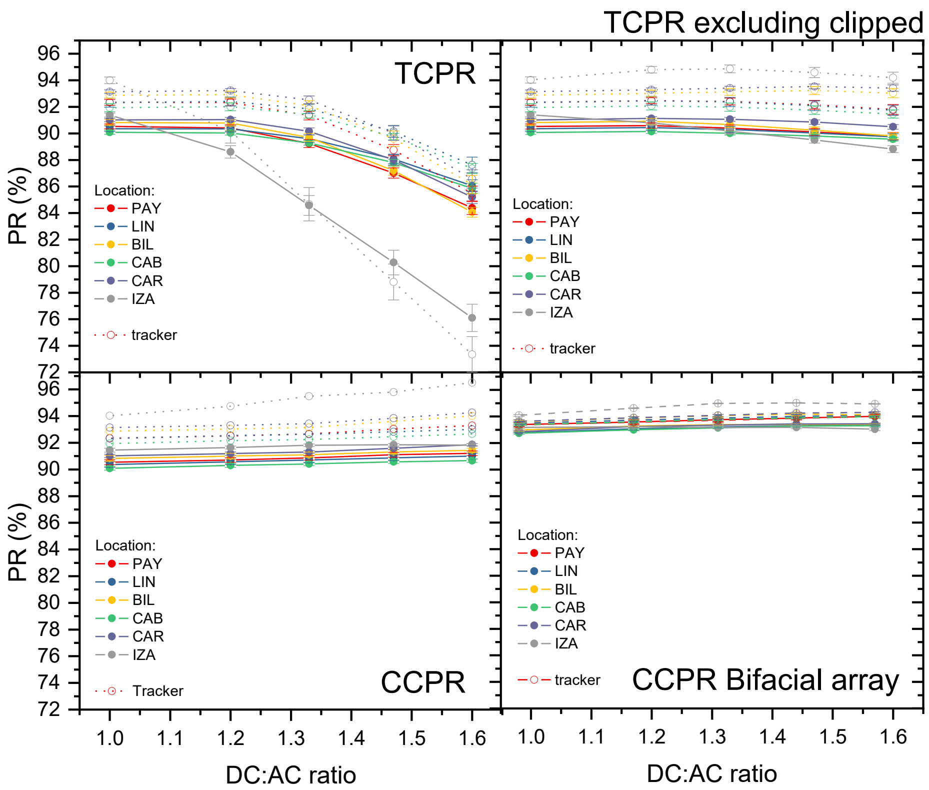

Figure S 2 Average (symbols) and standard deviation (error bars) of annual PR values determined for nominally performing (default) arrays as a function of DC:AC ratio for the default array in 6 different locations. Solid lines are fixed-tilt systems and dashed lines for single-axis trackers. Top-left: Temperature corrected PR on monofacial arrays. Top-right: The same but excluding datapoints where clipping occurs. Bottom-left: Clipping corrected PR on monofacial arrays. Bottom-right: Clipping corrected bifacial PR on bifacial arrays.

3 Performance Ratio Metrics for annual-temperature-equivalent performance ratio

Table 1 Annual variability for the default monofacial fixed-tilt array with different DC:AC ratios with nominal performance (no failures or degradation). This is the same as Table (5) in the manuscript, except annual-temperature-equivalent performance ratio is used here instead of 25 °C performance ratio.

DC:AC ratio	Annual variability			
	Uncorrected PR	**TCPR**	**TCPR excluding clipped data**	**CCPR**
1.60	0.83 %	0.57 %	0.22 %	0.18 %
1.47	0.74 %	0.49 %	0.21 %	0.18 %
1.33	0.64 %	0.39 %	0.20 %	0.17 %
1.20	0.56 %	0.27 %	0.19 %	0.18 %
1.00	0.50 %	0.18 %	0.18 %	0.18 %

4 Performance metric figures of merit for abnormally performing arrays

Table S2 Annual accuracy (calculated according to equation (8)) of difference between ratio of annual PR to expected PR and the true energy performance index for different classes of array issues and different PR metrics for monofacial arrays. All arrays have a DC:AC ratio of 1.6.

Array group	Annual accuracy			
	CCPR	Uncorrected	TCPR	TCPR excluding clipped data
	Monofacial fixed-tilt			
All	0.27%	1.01%	0.70%	2.68%
Module, string, wiring and mismatch issues	0.34%	0.97%	0.67%	3.16%
5 % more soiling	0.22%	0.92%	0.62%	1.83%
Derated inverter	0.15%	0.98%	0.67%	0.24%
Overclipping inverter	0.16%	1.12%	0.79%	3.21%
	Monofacial single-axis tracker			
All	0.35%	1.22%	0.92%	3.58%
Module, string, wiring and mismatch issues	0.44%	1.16%	0.89%	4.28%
5 % more soiling	0.34%	1.14%	0.86%	2.44%
Derated inverter	0.22%	1.20%	0.90%	0.35%
Overclipping inverter	0.19%	1.34%	1.01%	4.14%

Table S3 Annual accuracy (calculated according to equation (8)) of difference between ratio of annual PR to expected PR and the true energy performance index for different classes of array issues and different PR metrics for monofacial arrays. All arrays have a DC:AC ratio of 1.57.

Array group	Annual accuracy			
	monofacial CCPR	TCPR excluding clipped data	bifacial TCPR	bifacial CCPR
	Bifacial fixed-tilt			
All	0.35%	4.64%	0.92%	0.26%
Module, string, wiring and mismatch issues	0.39%	5.88%	0.88%	0.35%
5 % more soiling	0.21%	2.77%	0.84%	0.15%
Derated inverter	0.24%	0.56%	0.90%	0.09%
Overclipping inverter	0.36%	4.40%	1.02%	0.17%
	Bifacial single-axis tracker			
All	0.40%	5.06%	1.19%	0.33%
Module, string, wiring and mismatch issues	0.47%	6.33%	1.15%	0.44%
5 % more soiling	0.19%	3.16%	1.12%	0.21%
Derated inverter	0.25%	0.65%	1.18%	0.08%
Overclipping inverter	0.41%	5.06%	1.29%	0.15%

5 Nuances of clipping threshold

A nuance of CCPR is that the value of the clipping threshold irradiance $G_{C,25\,°C}$ must be determined and agreed before PR is calculated. When clipping occurs, the PR is fixed at a predetermined value that is inversely proportional to $G_{C,25\,°C}$. Therefore the value of $G_{C,25\,°C}$ directly affects the measured PR value for any system in which clipping occurs. We explored this effect by recalculating CCPR for arrays using different values of $G_{C,25\,°C}$. The results, shown in Figure S 3, confirm the impact of this effect – overestimation of $G_{C,25\,°C}$ leads to lower reported values of CCPR. There is also more variance in measured annual PR values when $G_{C,25\,°C}$ is far from its correct value, as the chances of false positive or false negative indications of clipping are increased. However, the value of $G_{C,25\,°C}$ determined by the algorithm presented in the manuscript is not precisely the value that minimises this variance.

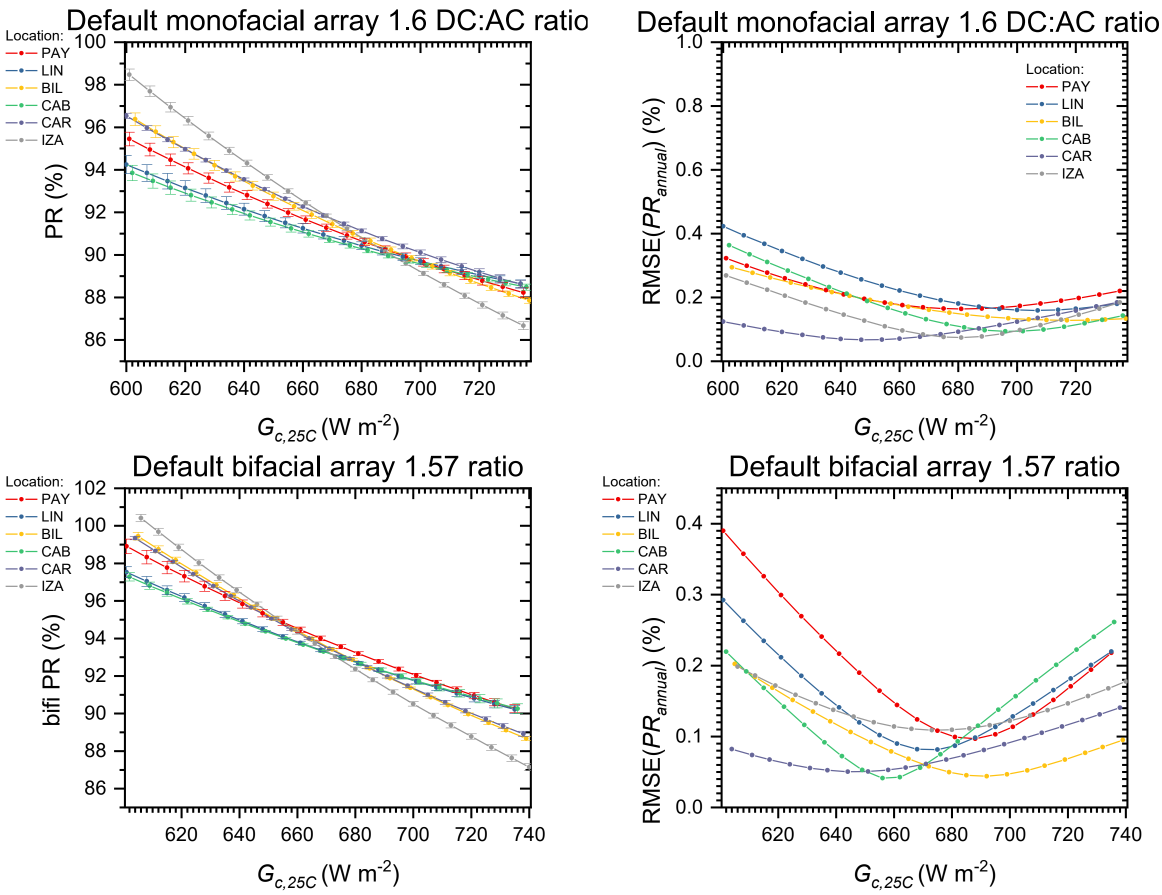

Figure S 3 Left: Impact of varying threshold irradiance $G_{C,25\,°C}$ on CCPR for default monofacial and bifacial fixed-tilt arrays simulated in 6 different locations. Right: Impact of the same on the RMS error in annual PR compared to "true" PR.

The change in PR in response to a change in $G_{C,25\,°C}$ is roughly approximated by the equation

$$\Delta PR \approx PR_0\, f_{Eclip}\, \frac{G_{C,25\,°C}}{G_{C,25\,°C,0} + \Delta G_{C,25\,°C}} - PR_0 \approx -PR_0\, f_{Eclip}\, \frac{\Delta G_{C,25\,°C}}{G_{C,25\,°C,0}} \qquad (1)$$

where

PR_0 is the CCPR evaluated for the array using a threshold of $G_{C,25\,°C,0}$;

$\Delta G_{C,25\,°C}$ $= G_{C,25\,°C} - G_{C,25\,°C,0}$ is an absolute change in the value of $G_{C,25\,°C}$; and

f_{Eclip} is the fraction of energy generated by the system under clipping conditions.

In the case that a system model underestimates or overestimates the performance of a system, the value of $G_{C,25\,°C}$ is also affected and there is a positive feedback effect on the measured CCPR. This effect is illustrated in Figure S 4, where an array was modelled with either increased or decreased module efficiency compared to the default case. There was a direct inverse proportionality linking the two, *e.g.* a 1 % overestimate of system DC performance leads to a 1 % reduction in the value of $G_{C,25\,°C}$.

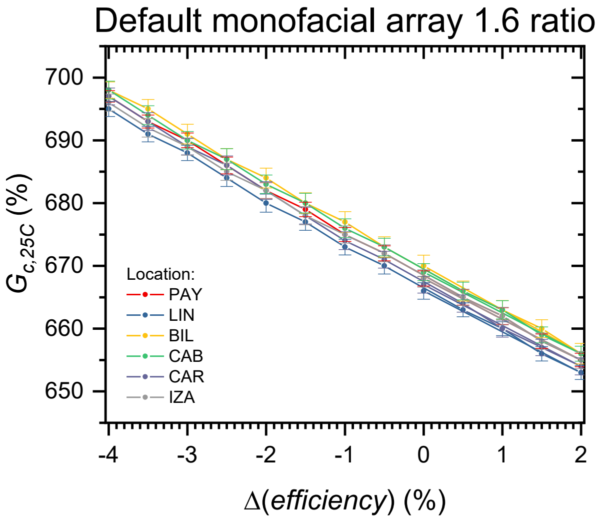

Figure S 4 Impact of changes in modelled module performance on the evaluation of $G_{C,25\,°C}$ for a monofacial fixed-tilt array.

The combination of these effects can be exemplified with a simplified hypothetical scenario: a system is modelled with a module efficiency that is 2 % higher than the efficiency of the modules actually installed. In a system without clipping, the modelled yield and PR values are therefore 2 % higher than they should be. The real system performs 2 % worse than the expected PR and a penalty may result. This is fair, as it represents the difference in the real value of the system versus the expected value.

In the case of a system with clipping, the agreed value of $G_{C,25\,°C}$ based on the modelling is 2 % lower than it should be, and the measured PR is increased by $f_{Eclip} \times 2\,\%$. Now the penalty is only based on an underperformance of $2\,\% \times (1 - f_{Eclip})$. For example, if f_{Eclip} is 40 % then the underperformance is measured as 1.2 %. Again, this is fair as the overoptimistic modelling will have overestimated yield by about 1.2 %, based on a 2 % overestimate for the 60 % of energy generated under non-clipping conditions.

This example highlights the importance of using the same modelling data to evaluate $G_{C,25\,°C}$ and yield for project valuation purposes, and of reporting expected PR, yield and $G_{C,25\,°C}$ together as a set of connected values.

Finally, the variability in weather used to model $G_{C,25\,°C}$ means that there is some uncertainty in the value of $G_{C,25\,°C}$ where only 1 year of weather data is used in system modelling. This can lead to additional uncertainty in the measured PR. In Figure S 5 we quantify this effect for a bifacial fixed-tilt system by calculating the standard deviation in $G_{C,25\,°C}$ when it is evaluated using different years of weather data. Generally the interannual variation in $G_{C,25\,°C}$ is <0.5 %, which would lead to an additional uncertainty of only 0.2 % in PR for a system with $f_{Eclip} = 40\,\%$. We used 1-minute resolution data in this simulation. The effect might be larger when using 1-hour resolution weather data for modelling, as there will be fewer data points around the clipping threshold.

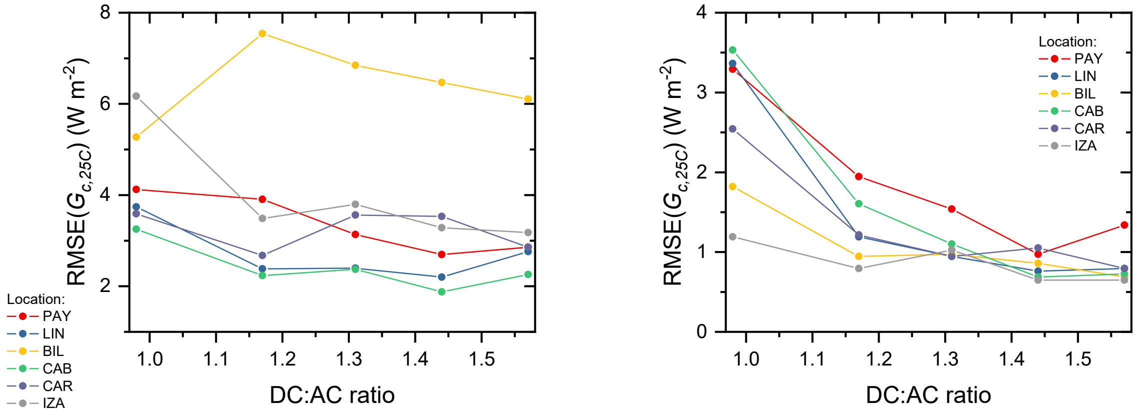

Figure S 5 Interannual variation, expressed as the RMSE compared to the mean value) in modelled $G_{C,25\,^{\circ}C}$ for default monofacial (left) and bifacial (right) fixed-tilt systems with different DC:AC ratios and locations.