Variation with irradiance of temperature coefficients of outdoor photovoltaic modules in Palaiseau, France

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1 Motivation

The accurate assessment of solar energy production is important to increase its deployment and integration in the energy mix.
Two main factors determining the power output of a photovoltaic (PV) solar panel are the irradiance received and panel temperature. The maximum power temperature coefficient (γ) of a panel is technology dependent and tells us how much power production is lost per degree above 25° Celsius as PV panels are rated at standard conditions (STC; 1000 W/m², AM1.5, 25°C).
Performance models assume this value remains constant through the different weather conditions to which a module is exposed, however, previous works have shown this is not the case.
For this reason, we study the variation of γ per irradiance level of panels of five different technologies (µc-Si / a-Si, c-Si, CIGS , HIT, CdTe) operating under outdoors in Palaiseau, France from 2018-2021.

2 Methodology

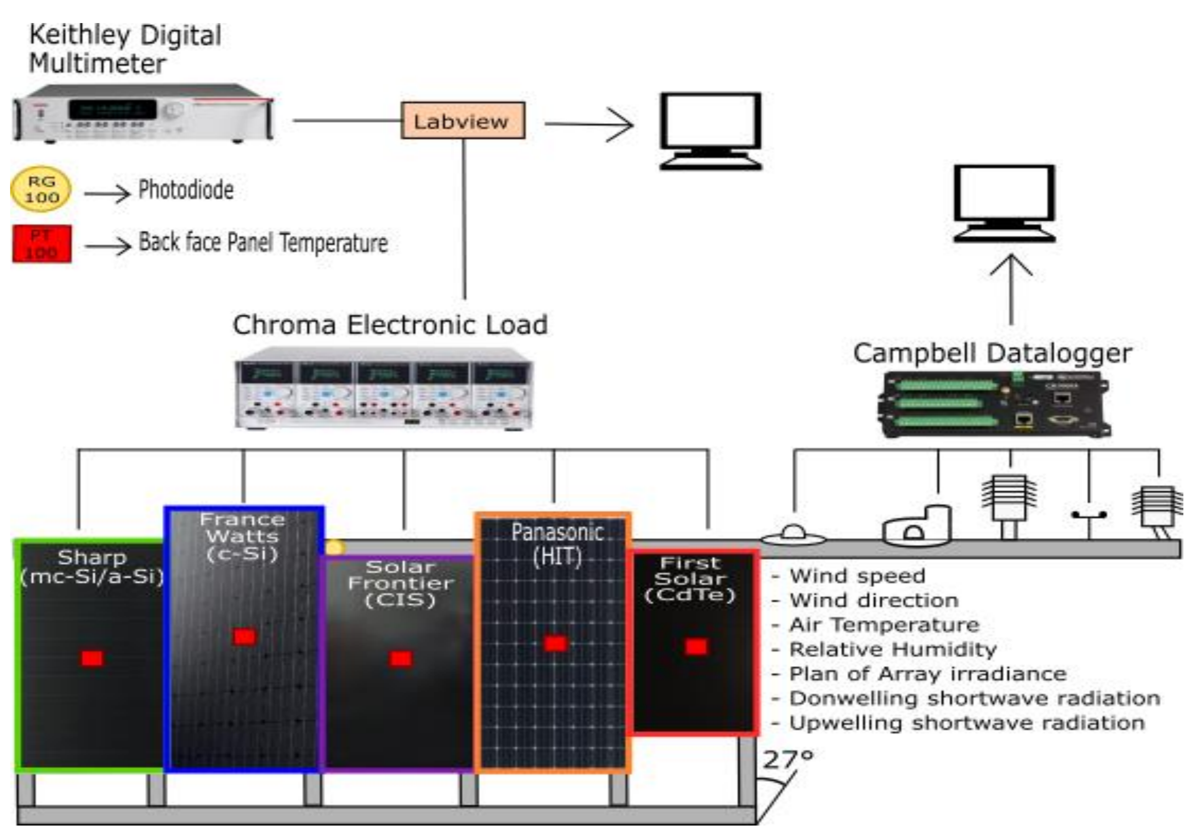


Figure 1 Diagram of PV panel layout and data acquisition system at test site. Listed are the atmospheric variables measured.

$$Energy\ Yield = \frac{\sum Pmpp}{P_{STC}}$$

P_{mpp}: instantaneous power output
P_{STC}: power output at STC

Number of equivalent hours that a solar panel produced electricity at its maximum capacity

$$Reference\ Yield = \frac{\sum G_i}{1000}$$

G_i: measured in-plane irradiance

Ratio of actual energy produced by a PV module to the energy produced by the panel when operating at standard conditions

$$Performance\ Ratio = \frac{AY}{RY}$$

Number of equivalent hours that a solar panel received the reference amount of irradiance (1000 W/m²)

$$PR_c = \frac{\sum \frac{P_{mpp}}{1-\gamma(Tp\ -25)} \Big/ P_{STC}}{RY}$$

Tp: instantaneous panel temperature
Γ: power temperature coefficient

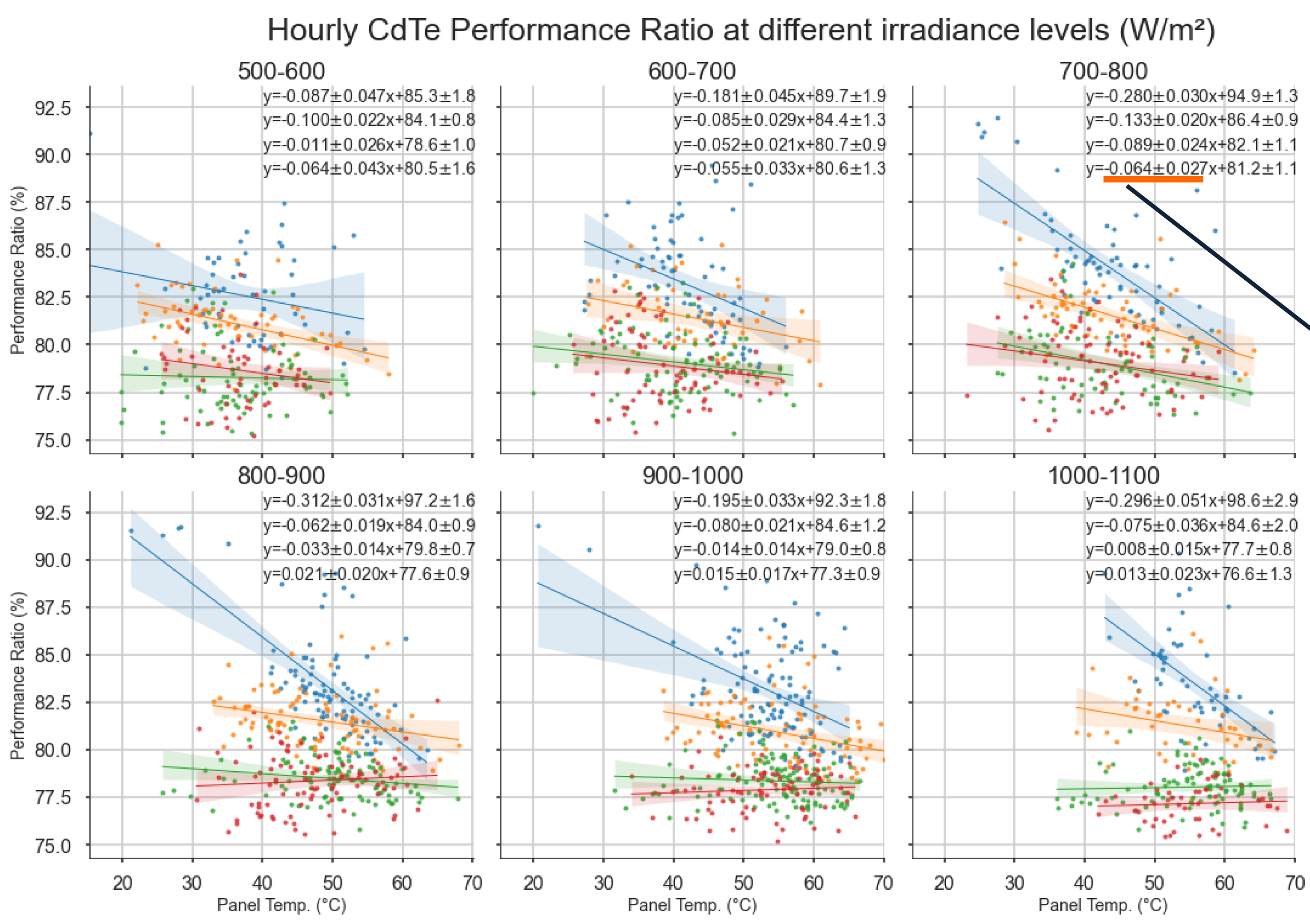
Performance Ratio (PR) corrected by the effect of the panel temperature

3 Results

(W/m2)	µc-Si / a-Si (%/°C)	C-Si (%/°C)	CIS (%/°C)	HIT (%/°C)	CdTe (%/°C)
500 – 600	0.17	-0.37	-0.24	-0.26	-0.04
600 – 700	0.10	-0.50	-0.30	-0.36	-0.04
700 – 800	0.01	-0.46	-0.30	-0.35	-0.13
800 – 900	0.03	-0.43	-0.27	-0.30	-0.09
900 - 1000	-0.02	-0.42	-0.28	-0.29	-0.07
1000 – 1100	-0.01	-0.42	-0.29	-0.29	-0.06
STC	**-0.24**	**-0.48**	**-0.31**	**-0.29**	**-0.25**

Table 1 γ values per plane-of-array irradiance level for each PV module. Those provided by the manufacurer (under STC conditions) are provided in the last line.

Between 500-1100 W/m², intervals of 100 W/m² were established with a mean γ value estimated by a linear fit between the performance ratio and the module's temperature.
The obtained values per irradiance interval are listed in Table 1 with the STC values presented in the last row.
There is an inflection point for all technologies between 500-800 W/m² at which γ has the most negative value, it becomes less negative as we move to higher and lower irradiance levels.



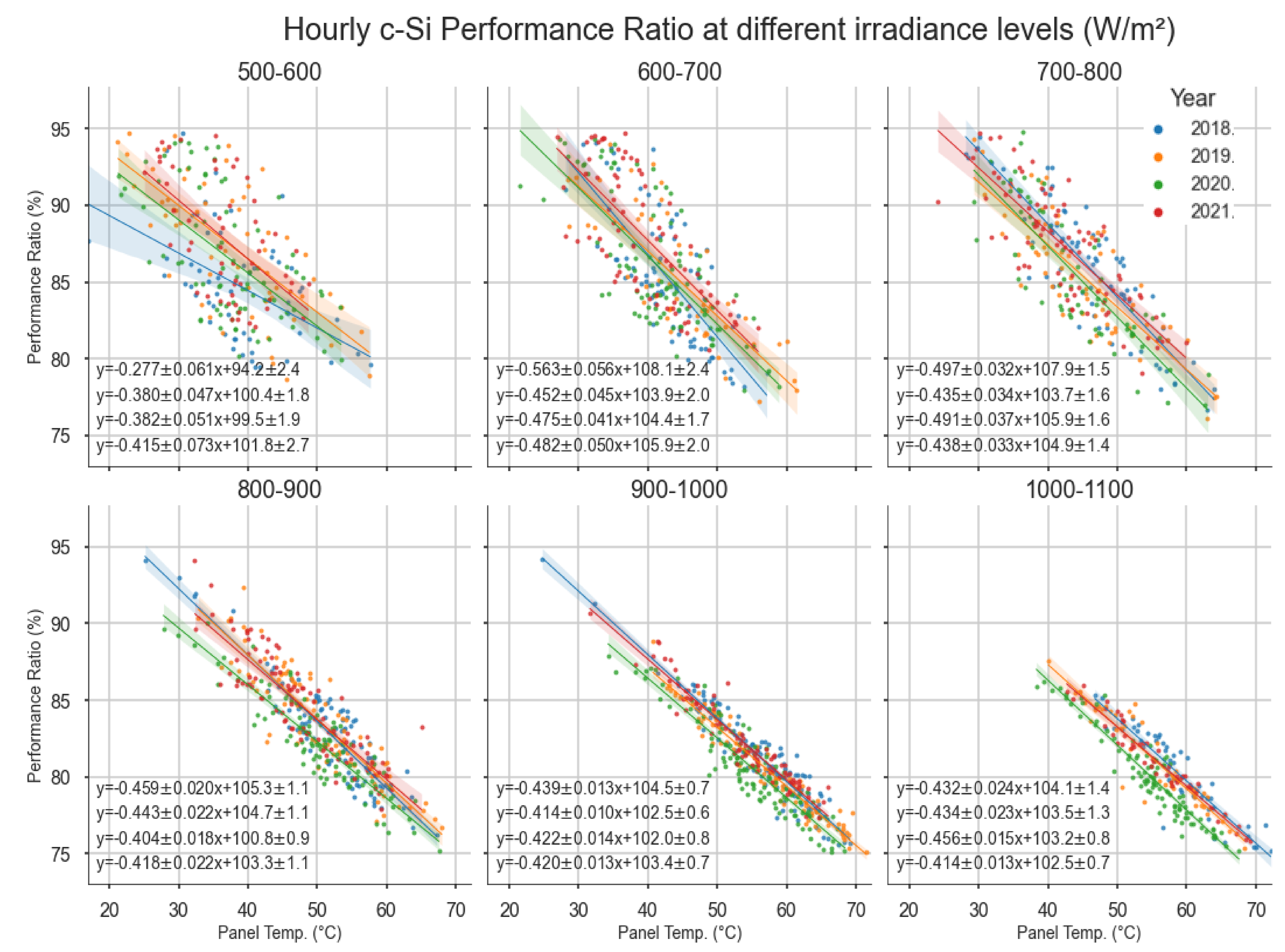


Figure 2 Monthly performance ratio in % vs panel temperature in °C for c-Si and CdTe panels. The lines represent the least squares polynomial fit for each set of measurements with each year being a different color.

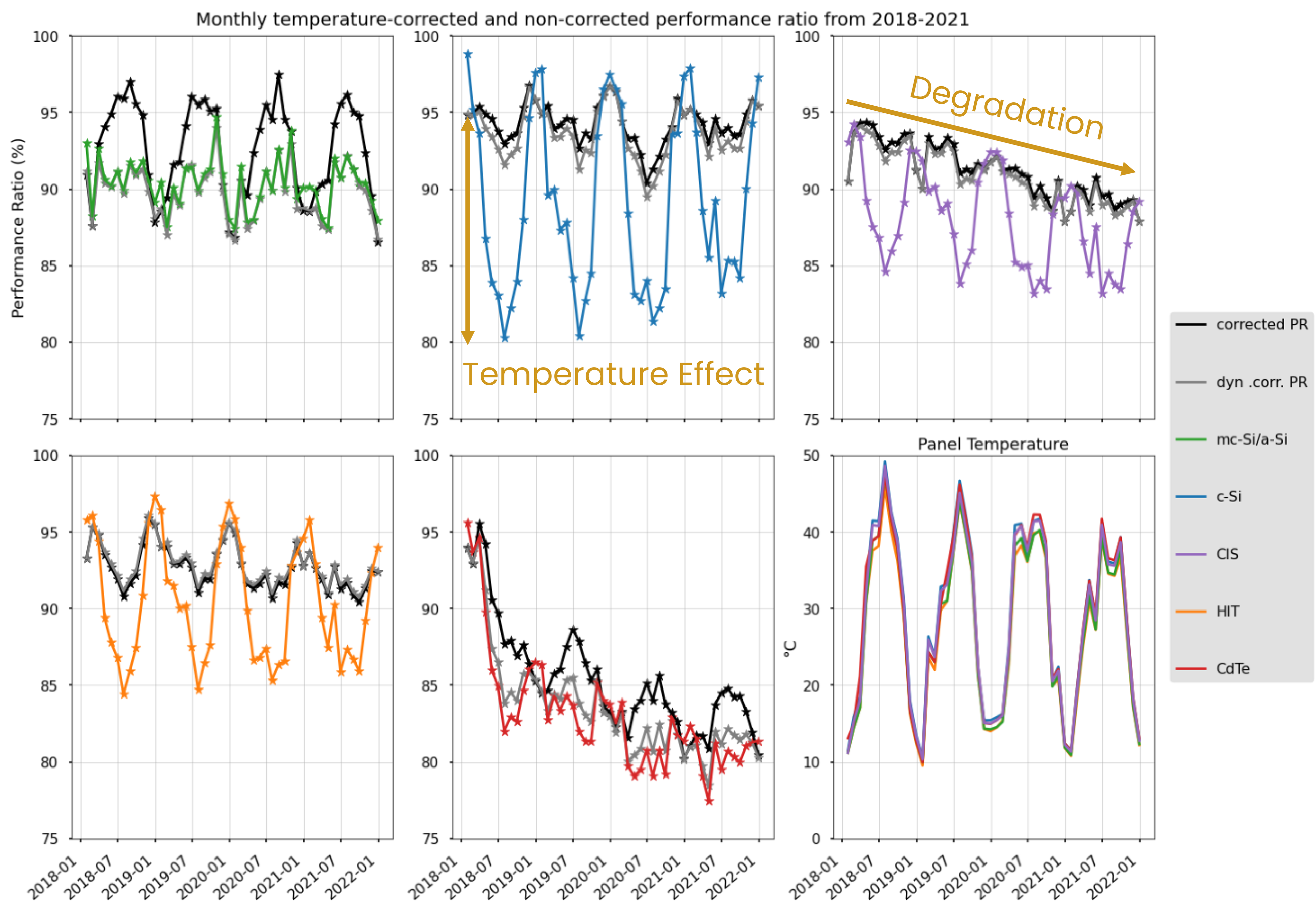


Figure 3 Monthly performance ratio (left axis in %) of each technology. On the lower right figure, the temperature of each panel is plotted in °C. The black line corresponds to PR_c using the γ provided by the manufacturer while the gray line is when the γ per irradiance level from Table 1 is used.

$$PR = mT + b$$

$$\gamma\ (\%/°C) = \frac{m}{PR_{T=25°C}} * 100$$

Figure 2 shows the hourly values of performance ratio and panel temperature of the c-Si and CdTe panels.
Each frame corresponds to an interval of 100 W/m² with the linear fits corresponding to different years and indicating the estimated power temperature coefficient γ .
The separation (or lack thereof) between the polynomial fits is deemed to be partially due to the degradation sustained by the panels, estimated as -0.24 %/year for c-Si and -2.16 %/year for CdTe in a previous study not shown here.
Maximum values of γ are reached between 600-800 W/m² and decrease at lower or higher irradiances. With a range of variation of-0.27 to -0.56%/°C for c-Si and -0.01 to -0.31 %/°C for CdTe.

Figure 3 illustrates the effect of temperature on monthly performance ratio.
There is a marked seasonality for c-Si and HIT while thin-film panels are more stable throughout the year.
Part of the seasonality is removed when using a changing γ but not entirely, indicating there are other environmental factors impacting the PR.
Degradation is visible for the CIS and CdTe modules with a decreasing performance ratio while c-Si, HIT and µc-Si / a-Si remain stable.

4 Conclusions

The power temperature coefficient provided by the manufacturer does not correspond to the true sensitivity to temperature of each panel when exposed to outdoor conditions. An improvement in the estimation of this parameter could lead to the betterment of power performance models which use a fixed one rather than one dependent on the irradiance level.
The significant difference between the value provided by the manufacturer and the one obtained experimentally for thin-films could be due to the inherent deterioration of the material, which is greater than that of c-Si or HIT technologies.
When comparing the values of γ from year to year, it's possible to see the degradation suffered by the photovoltaic module.