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Publication date
2018

Citation (APA)
Ziar, H., Mishra, S., Isabella, O., & Zeman, M. (2018). *Selection map for PV module installation based on shading tolerability and temperature coefficient*. Poster session presented at EU PVSEC 2018, Brussels, Belgium.

Selection Map for PV Module Installation Based on Shading Tolerability and Temperature Coefficient

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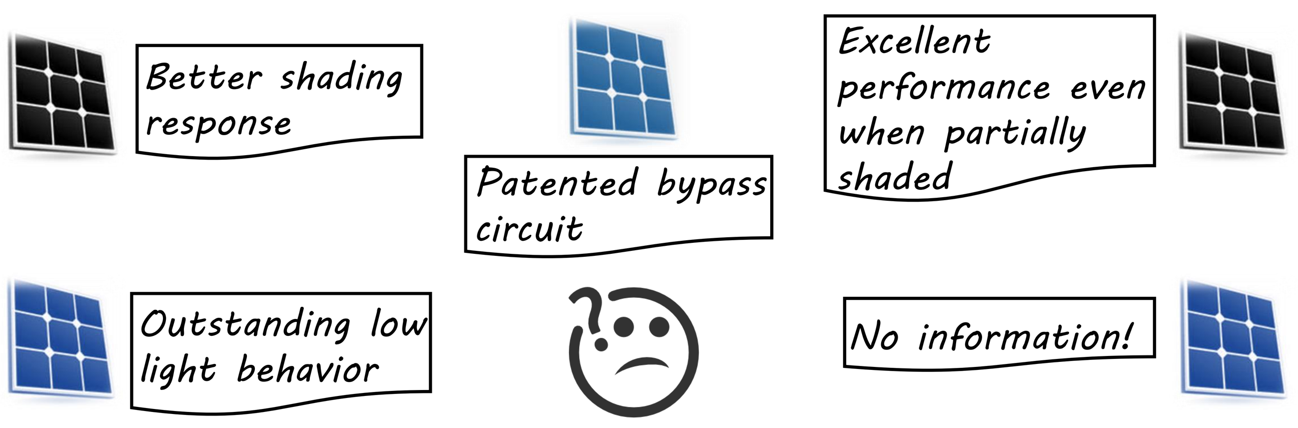
Motivation

- Partial shading on PV modules is responsible for up to 25% Performance Ratio (**PR**) reduction, depending on system design and equipment selection [1-3].
- The ability of PV modules to oppose shading effects is expressed only qualitatively in datasheets:



Complications with shading

- Unique shade profile causes unique impact on PV module.
- Infinite number of shade profiles can cast on PV module.
- Shade cannot be absolutely predicted.

Objective

Establishment of a quantified parameter which classifies PV modules in terms of **Shading Tolerability (ST)**.

Methodology

- Probability laws provide the tools for the design of systems that involve randomness.
- Decision making concerns with mathematical expectation.
- Higher mathematical expectation of power production at shading, or higher shading tolerability, persuades designers to select that module.

Assumptions

1) On the surface of a PV cell (encapsulated in a module), irradiation is homogenous and can have any value between 0 and 1 kW/m^2, and all values have an equal chance to occur.
2) The chance of shading for different cells of a module is equal and independent from their location in the module or in the array where their module is mounted.

Mathematical modelling

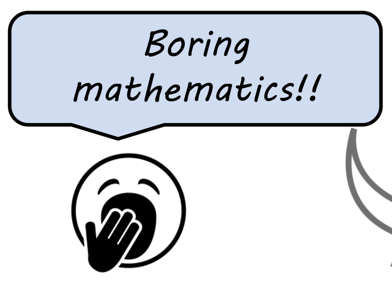
Expected value of a random variable $\boldsymbol{x}$ with the occurring chance of $\boldsymbol{p(x)}$:

$$E(x) = \sum_{k=1}^{\infty} x_k . p(x_k)$$

Shading tolerability of a PV module is defined as:

$$ST_{(i,c)} = \frac{1}{P_{Module-MPP}} \sum_{k=1}^{i^c} P_k\left(\frac{1}{i^c}\right)$$

Normalization factor



Final general equation for Shading Tolerability of a PV module:

$$ST_{(i,c)} = \frac{\lambda_{(i,c)}}{(n+1)}$$

where:

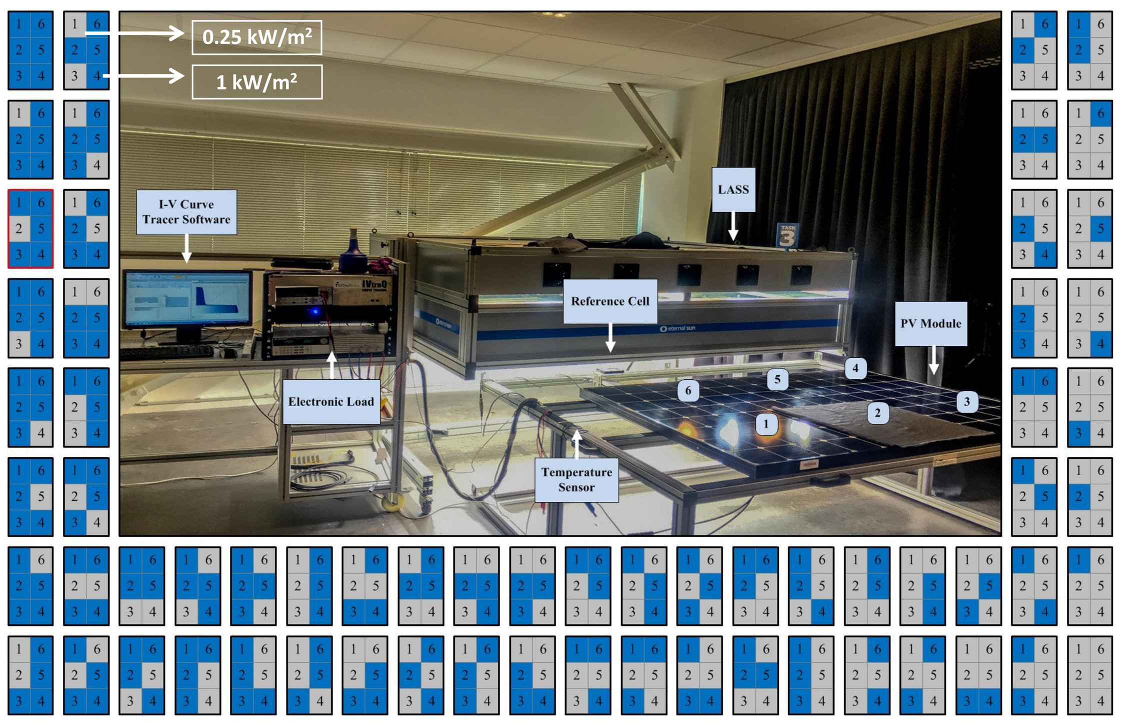
- n is the number of series-connected PV cells, m is the number of PV cell strings in a module ($c = n \times m$), i is the number of possible irradiation levels on PV modules surface, and $j = i-1$.
- $\lambda_{(i,c)}$ is a coefficient defined to model the facilities that the manufacturer has used to make the module more tolerable to shade [4].

Experimental work [4]

$$ST^{(module_1)}_{(i=2,c)} > ST^{(module_2)}_{(i=2,c)} \Rightarrow ST^{(module_1)}_{(i\to\infty,c)} > ST^{(module_2)}_{(i\to\infty,c)}$$

Indoor experiment

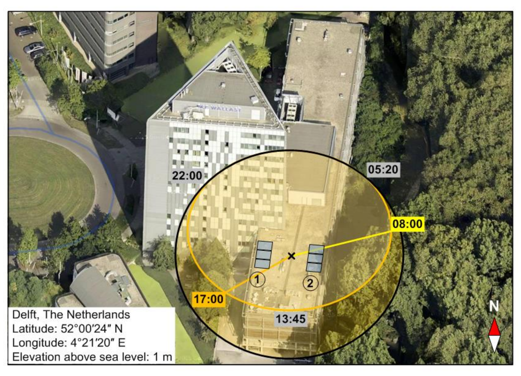
(as a condition in which $i = 2$) with Large Area Solar Simulator to determine the ST of PV modules.



	Company/ Commercial Name	ST
1	Neste/Module PV A12	58%
2	Victron Energy/ SPM30-12	38%
3	Wurth Solar/ GeneCIS 80W	91%
4	Scheuten P6-54 series 200	35%
5	Calyxo/CX3-77 Thin film	63%
6	SunPower/SPR X20 327-BLK	33%
7	Masdar PV/MPV-T	40%
8	IKS Photovoltaik/ 10W	40%
9	Solland/SunWeb module-235	39%
10	Hanergy/ PowerFlex 90W	50%
11	Uni-Solar/ PowerBond ePVL	59%
12	BenQ SunForte PM096B00-335	49%
13	AERspire Deluxe 60	48%
14	BISOL Premium Series BMU-260	45%
15	JA Solar JAM6-60-270 (BK)	43%
16	Solar Frontier SF170-S	73%

Outdoor experiment

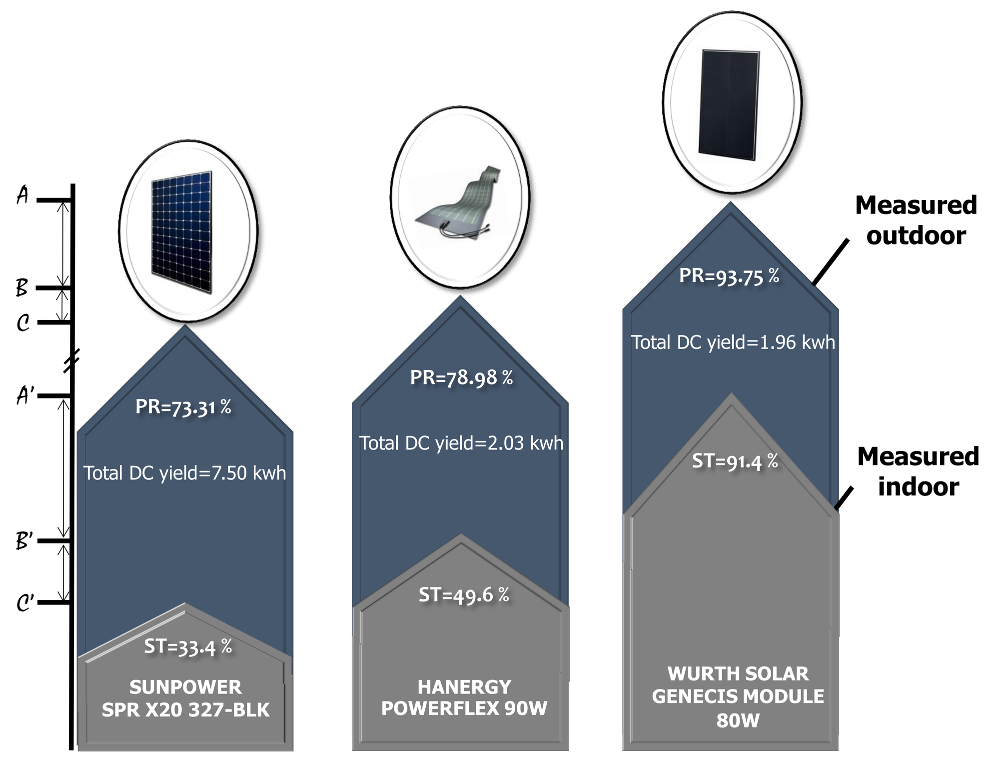
(as a condition in which $i \to \infty$) to investigate the relation between ST and PR at shading condition.



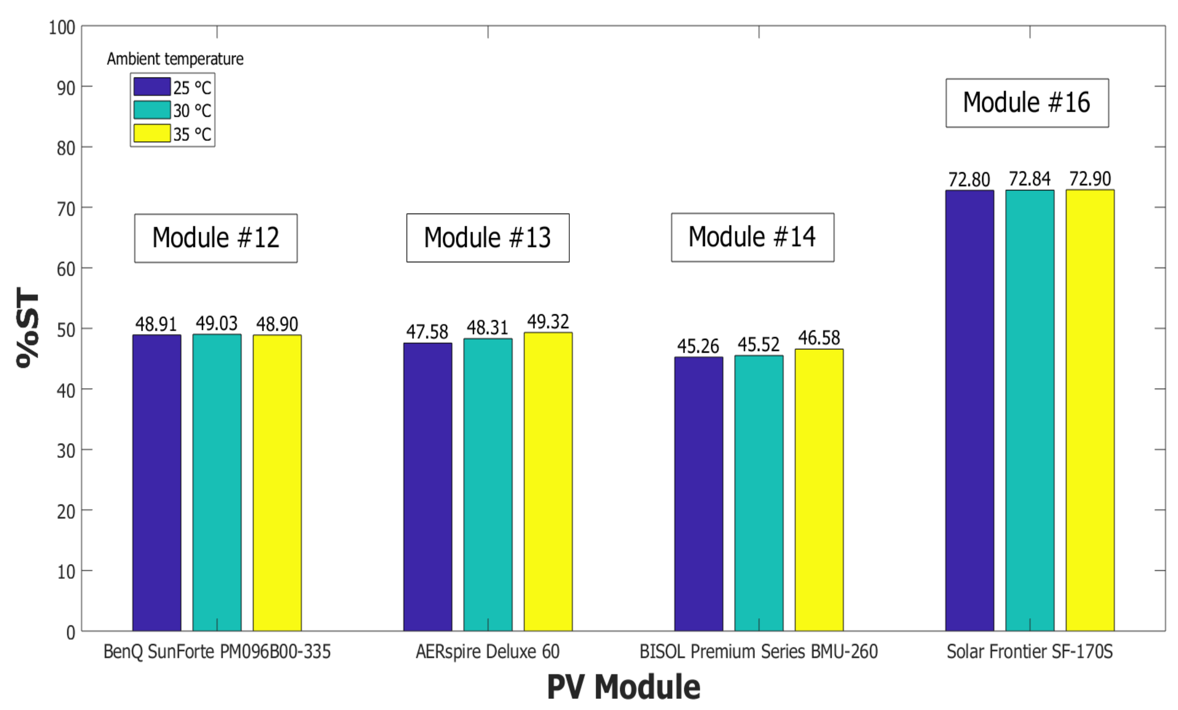
The ranking of the modules for ST is the same as the PR ranking of PV modules at real outdoor shading conditions.

The ratio of differences of the measured outdoor PR values are surprisingly close to the ratio of differences of the obtained indoor ST values.

$$\frac{AB}{BC} \approx \frac{A'B'}{B'C'}$$

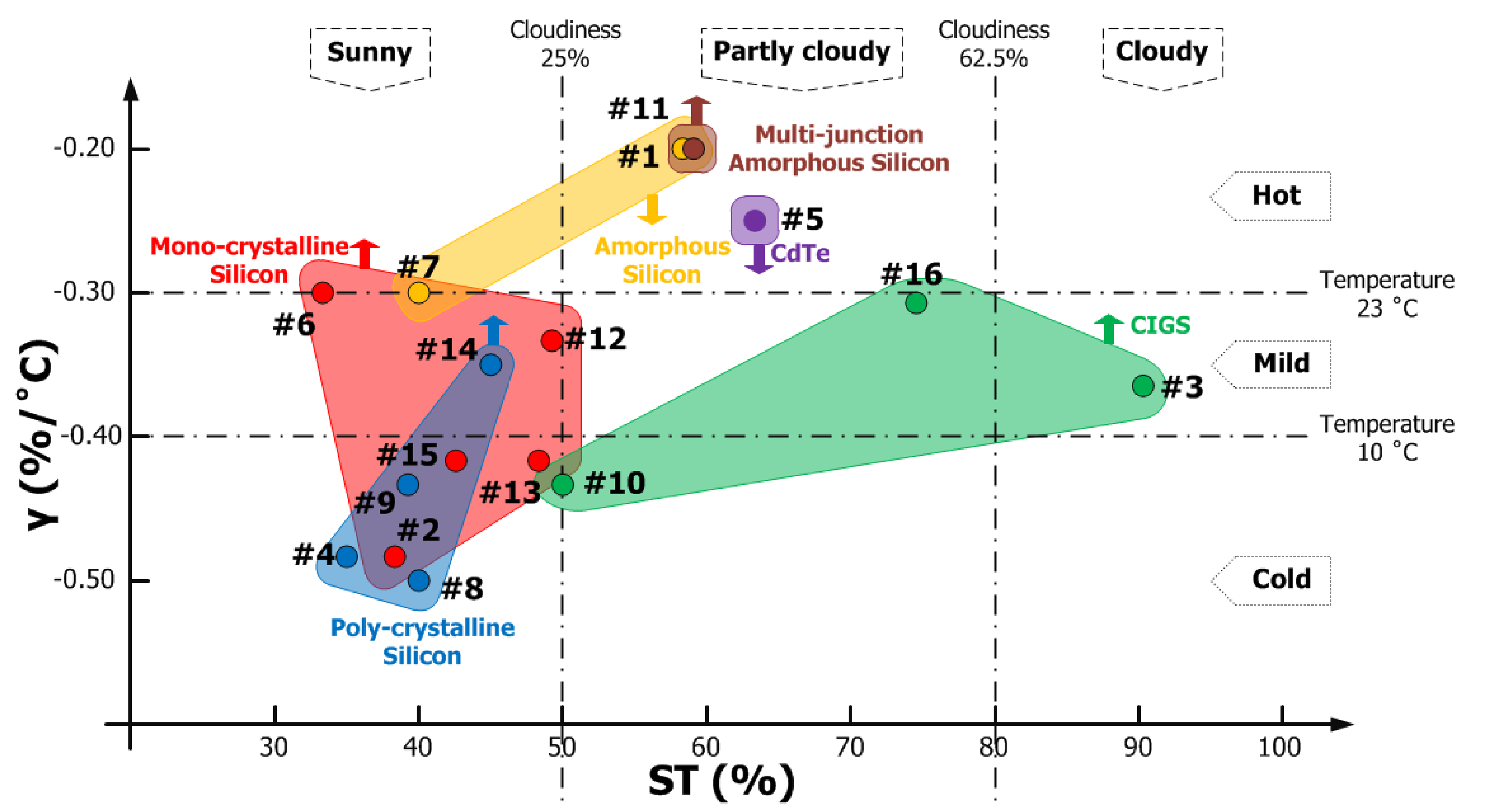


Temperature dependence of ST



- Change in ST with ambient temperature is found to be negligible.
- ST can be treated as a characteristic parameter of a PV module.
- ST and temperature coefficient for maximum power (γ) are independent.

Selection map [5]



- Three shade classes are introduced: Sunny, Partly Cloudy and Cloudy.
- Three temperature classes are suggested: Hot, Mild and Cold.
- Climate classification as in meteorology used to obtain climate boundaries.
- Optimal PV module selected by module specifications and location climate conditions.

Conclusion

- PV module ST modeled by **λ/(n+1)**.
- ST is independent from ambient temperature.
- ST value on datasheets benchmarks performance in shading.
- ST-γ enables optimal location dependent choice of PV modules.

[1] U. Jahn and W. Nasse, *Prog. Photovolt.: Res. Appl.*, vol. 12, no. 6, pp. 441–448, 2004.
[2] A. Woyte, J. Nijs, and R. Belmans, *Sol. Energy*, vol. 74, no. 3, pp. 217–233, 2003.
[3] M. García *et al.*, *Prog. Photovolt.: Res. Appl.*, vol. 17, no. 5, pp. 337–346, 2009.
[4] H. Ziar et al., IEEE Jour. Of Phot., vol. 7, no. 5, pp. 1-10, 2017.
[5] S. Mishra, MSc. Thesis, TU Delft, 2018.

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