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Quantification of Shading Tolerability for PV Modules

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Motivation

- UP to 25% Performance Ratio (PR) reduction caused by shading [1-3].
- The ability of the PV modules to oppose shading effects is expressed qualitatively in datasheets.

Better shading response
Excellent performance even When partially shaded
Patented bypass circuit
Shade tolerant
No information!
Outstanding low light behavior

Objective

- Establishment of a quantified parameter which classifies PV modules in terms of **Shading Tolerability (ST)** is the goal of this contribution.

PV MODULE DATASHEET
ST = x%

Challenges

- Infinite number of shade profiles.
- Unique shade profile causes unique influence on PV modules.
- Shade can not be absolutely predicted.

Methodology

- Probability laws.
- Decision making using mathematical expectation.

Assumptions

- All values of irradiation have an equal chance to occur (between 0 and 1 kW/m²).
- The chance of shading for different cells of a module is equal.

Experimental Work

if $ST^{(1)} > ST^{(2)} \rightarrow PR^{(1)} > PR^{(2)}$ **then** $ST^{(module_1)}_{(i=2,c_1)} > ST^{(module_2)}_{(i=2,c_2)} \rightarrow ST^{(module_1)}_{(i\rightarrow\infty,c_1)} > ST^{(module_2)}_{(i\rightarrow\infty,c_2)}$

Measured Indoors — Monitored Outdoors

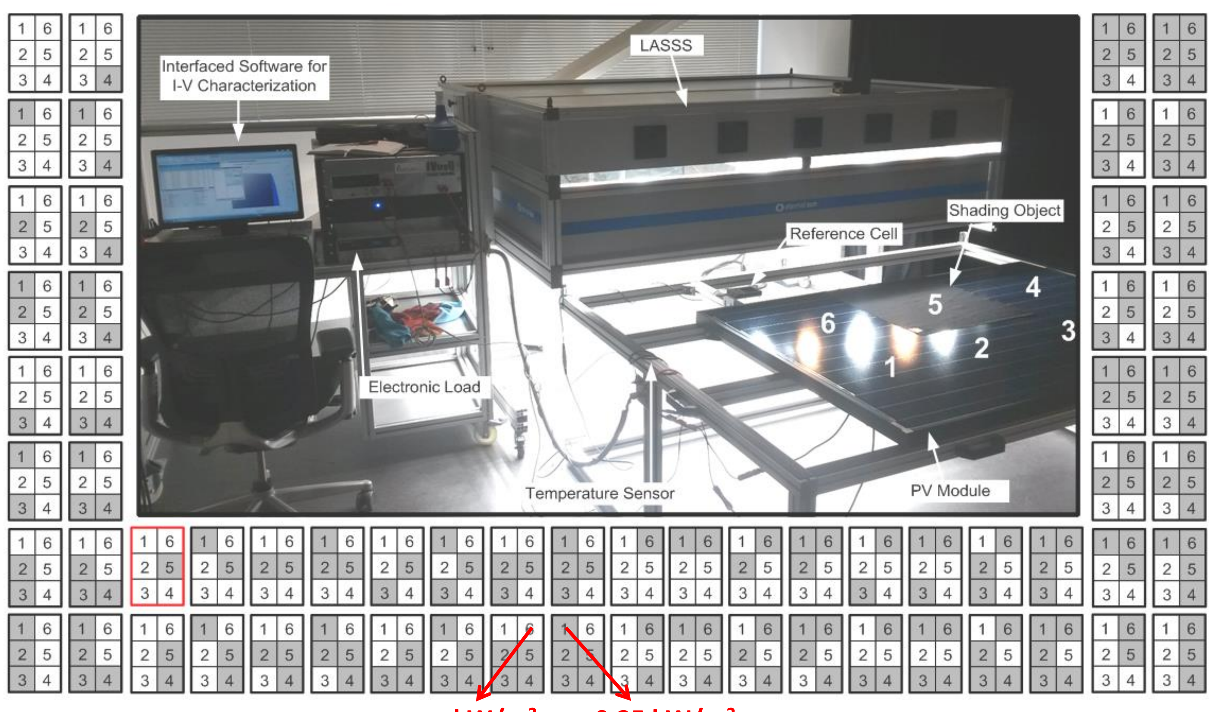
- Value of the $ST_{(i=2,c)}$ can be used instead of $ST_{(i\rightarrow\infty,c)}$ for comparison of shading tolerability of PV modules.

Indoor experiment

- ST values from indoors experiments using Large Area Solar Simulator.
- Indoor measurements setup.

Results

	Company/ Commercial Name	ST
1	Neste/Module PV A12	58%
2	Victron Energy/ SPM30-12	38%
3	**Wurth Solar/ GeneCIS module 80W**	**91%**
4	Scheuten/Multisol P6-54 series 200	35%
5	Calyxo/CX3-77 Thin film solar module	63%
6	**SunPower/SPR X20 327-BLK**	**33%**
7	Masdar PV/MPV-T	40%
8	IKS Photovoltaik/ STA14 SolarTrainer 10W	40%
9	Solland/SunWeb module-235 Wp	39%
10	**Hanergy/ PowerFlex 90W**	**50%**
11	Uni-Solar/ PowerBond ePVL	59%



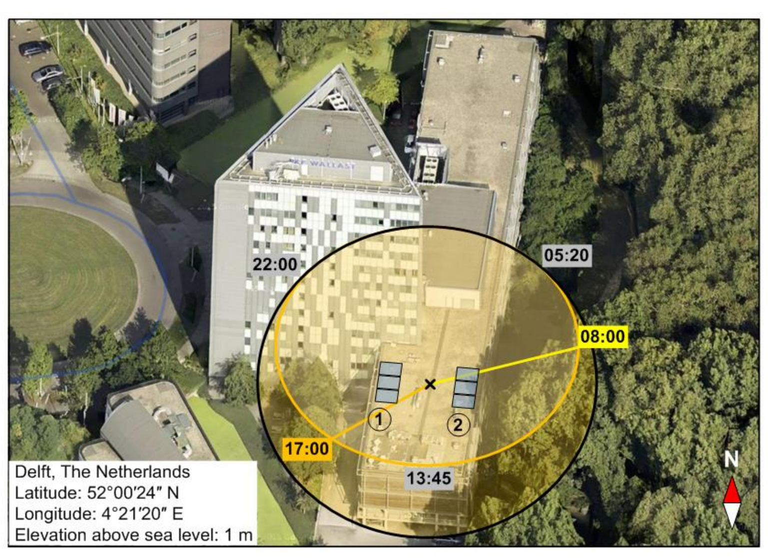
Outdoor experiment

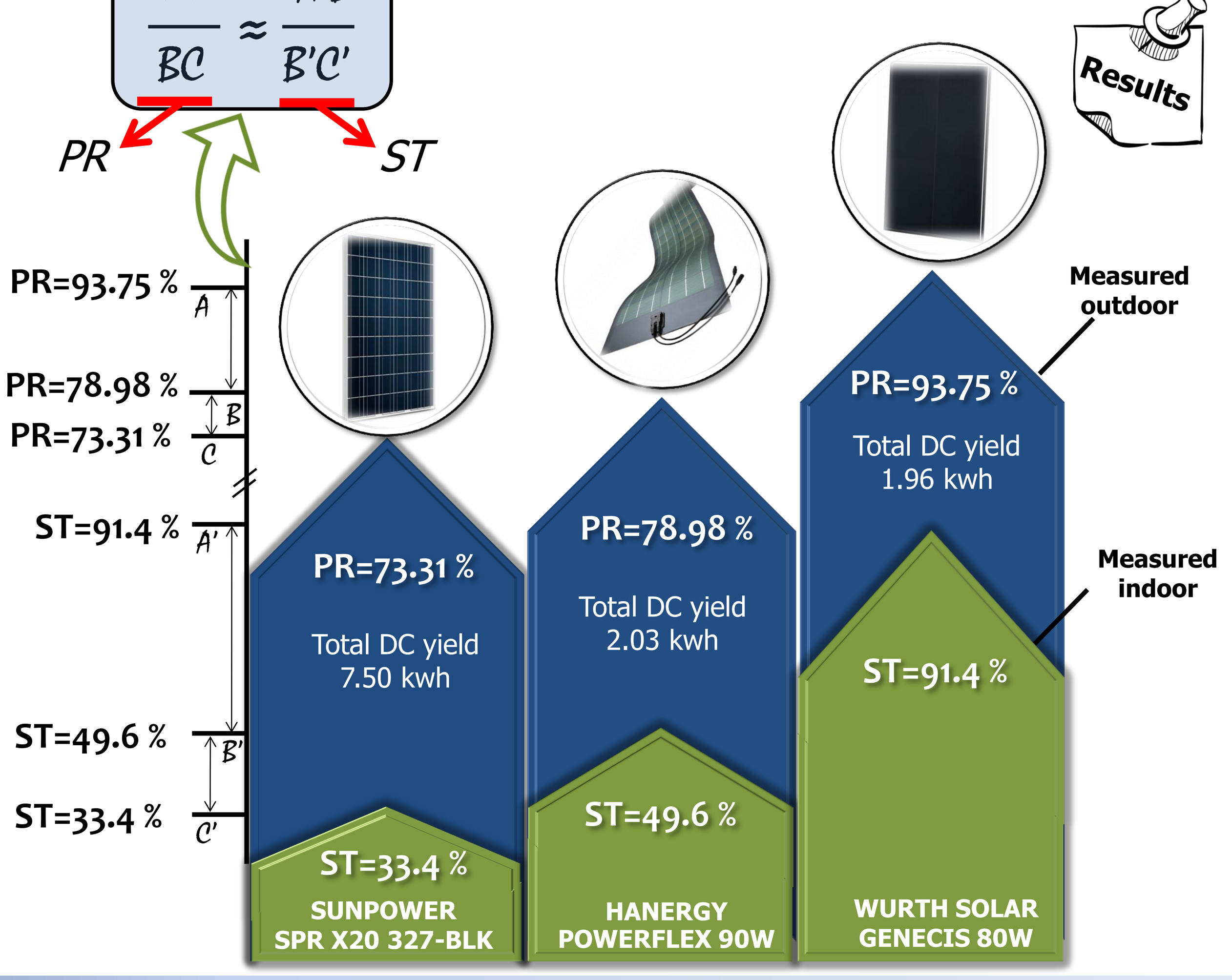
- Same ranking for ST and PR.
- The ratio of differences are equal for ST and PR values.

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

- PR values from outdoor experiments by long-term monitoring.
- Outdoor measurements location:

Delft, the Netherlands. 52.00° N 4.21°E.





Mathematical Modeling

Expected value of a random variable ***x*** with the occurring chance of ***p(x)***:

$$E(x)=\sum_{K=1}^{\infty} x_K\, p(x_K)$$

Shading tolerability of a PV module is defined as:

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

Boring mathematics!!

Shading Tolerability equation of a PV module:

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

Nomenclature:

- 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 $j = i-1$.
- $g_{(i,c)}$ is a coefficient defined for the ST equation to model the facilities that the manufacturer has used to make the PV module more tolerable to shade.

Conclusion

- It was mathematically proven that the **ST** of a PV module can be modeled by the function of **g/(n + 1)**.
- It is suggested to add **ST** on PV modules datasheet as a benchmark to distinguish PV modules regarding shading tolerability.

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