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QUANTIFICATION OF SHADING TOLERABILITY FOR PV MODULES

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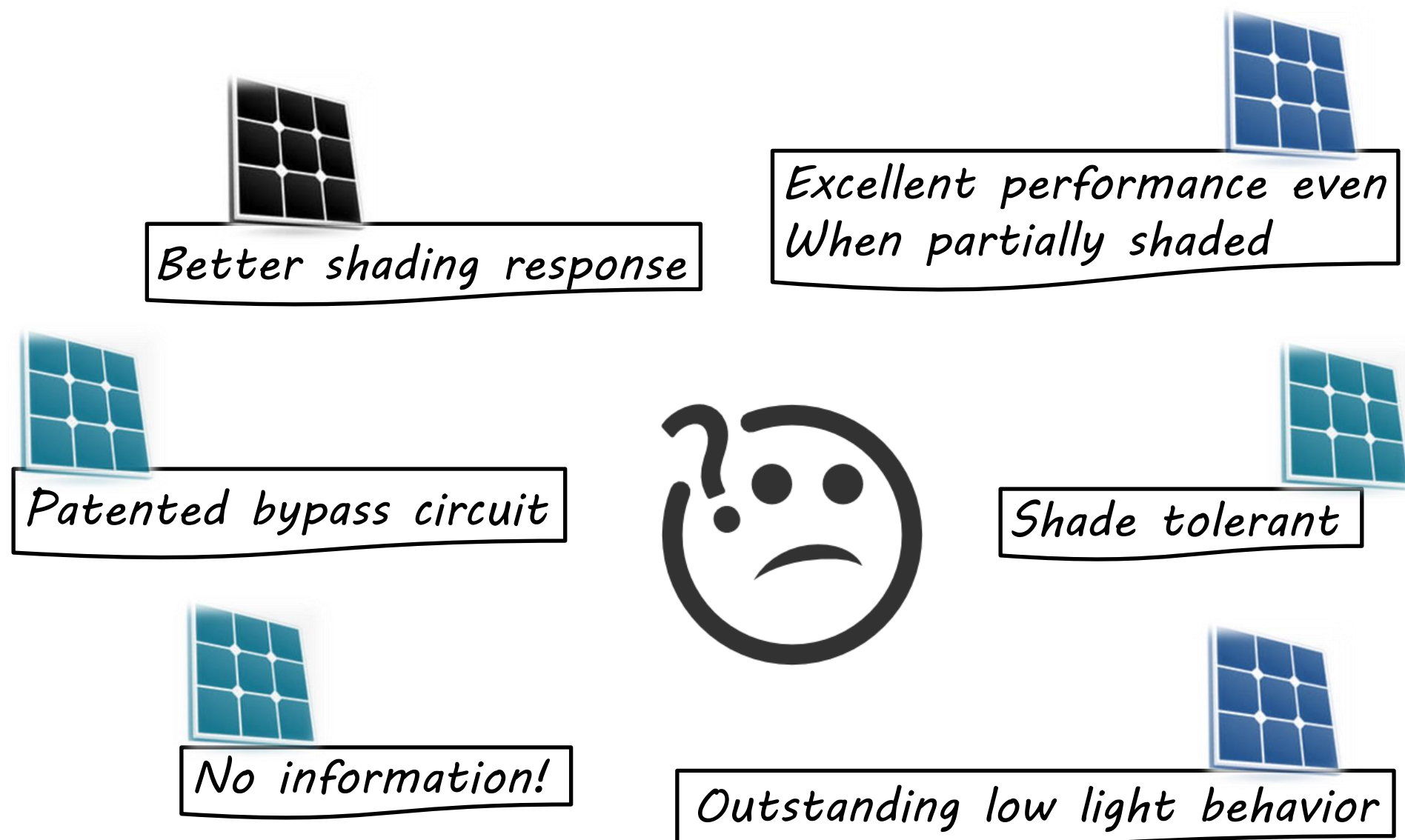
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Motivation

- 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.



Objective

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

Challenges

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

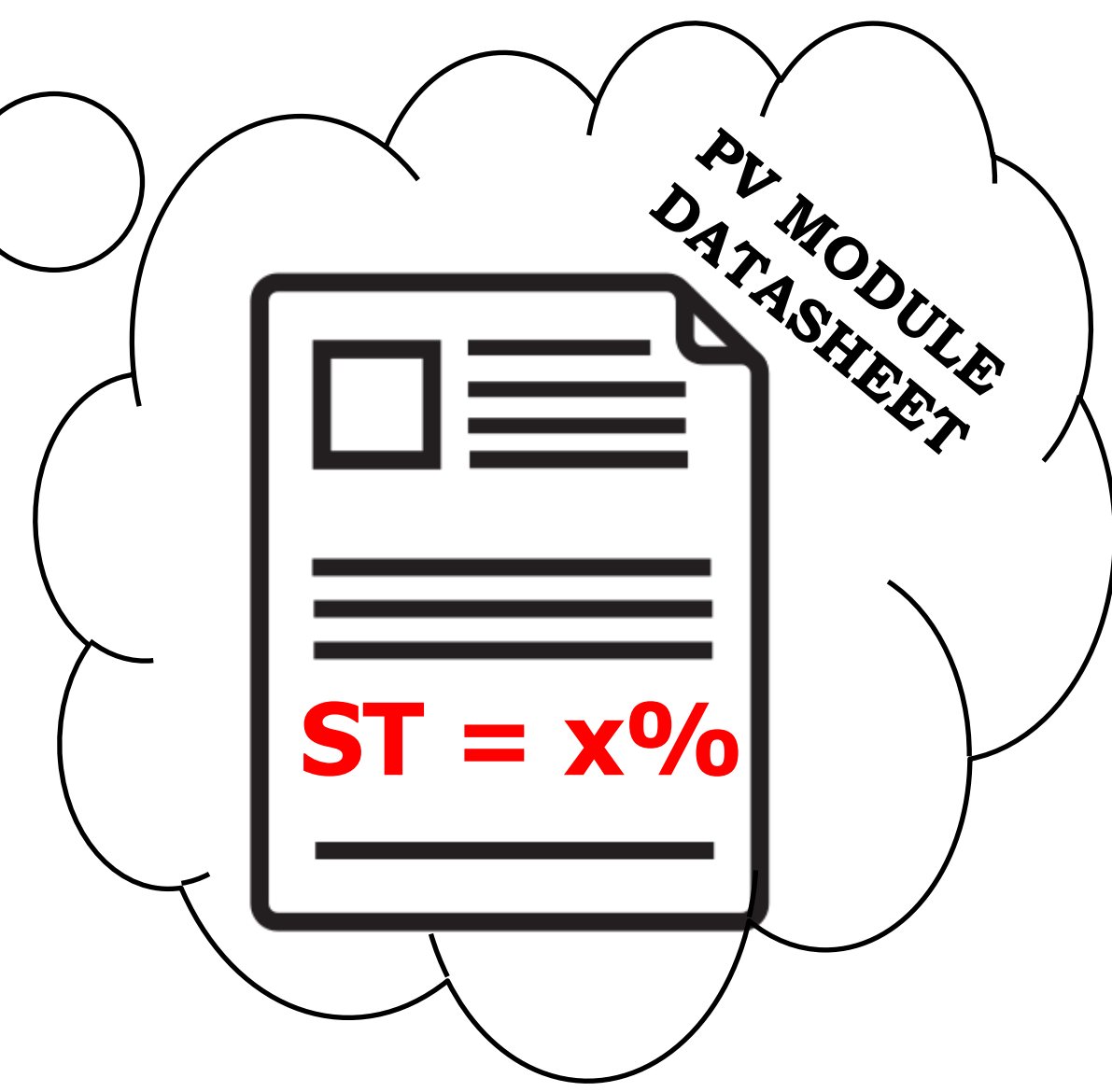
Methodology

- Probability laws.
- Decision making using mathematical expectation.

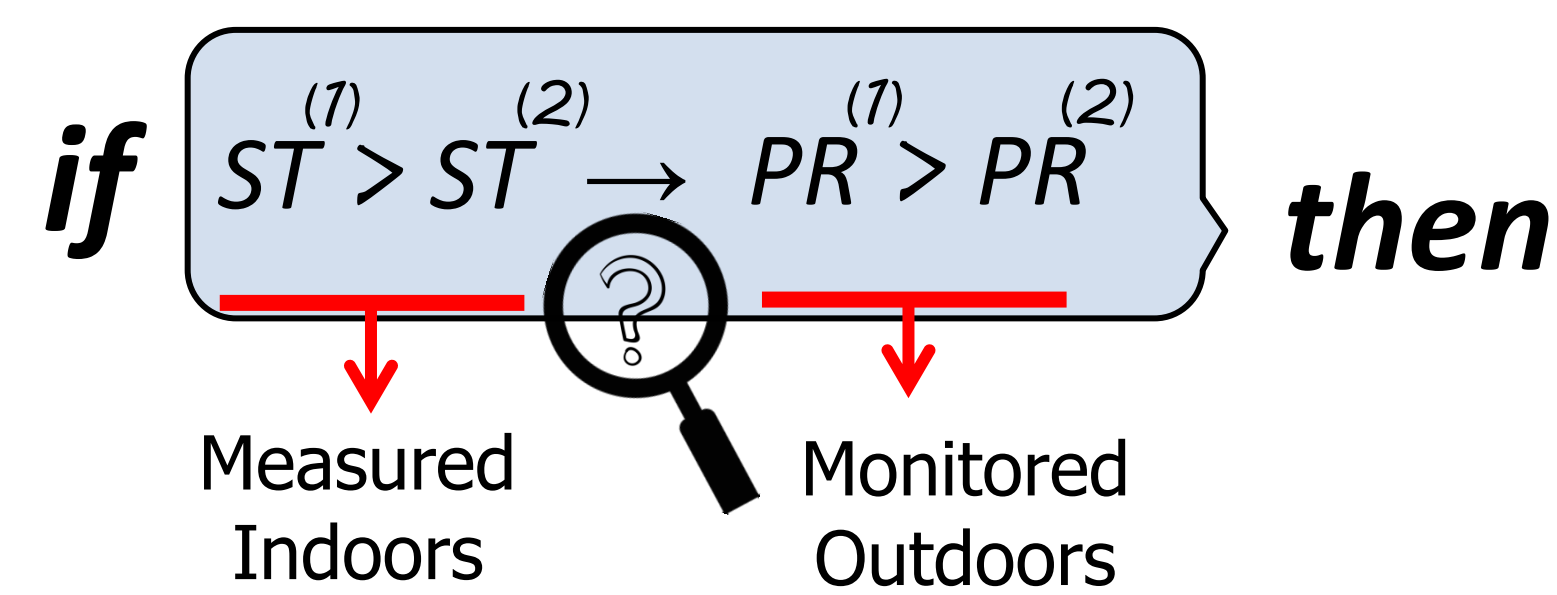


Assumptions

- 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

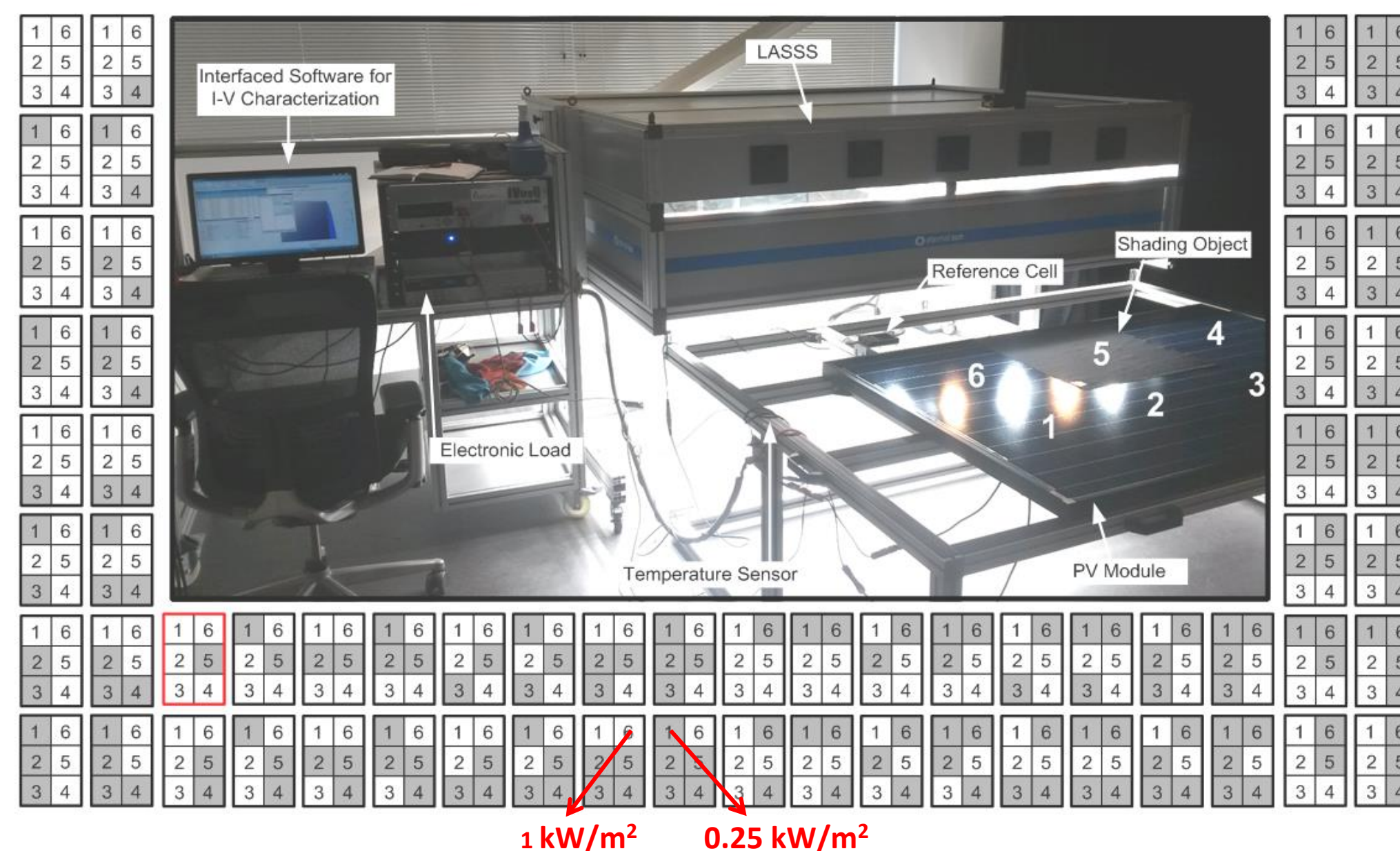


Company/ Commercial Name	Results	ST
1 NESTE/Module PV A12		58%
2 Victron Energy/ SPM30-12		38%
3 Wurth Solar/ GeneCIS module 80W		91%
4 Scheuten/Multisol P6-54 series 200		35%
5 Calyxo/CX3-77 Thin film solar module		63%
6 SunPower/SPR X20 327-BLK		33%
7 Masdar PV/MPV-T		40%
8 IKS Photovoltaik/ STA14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

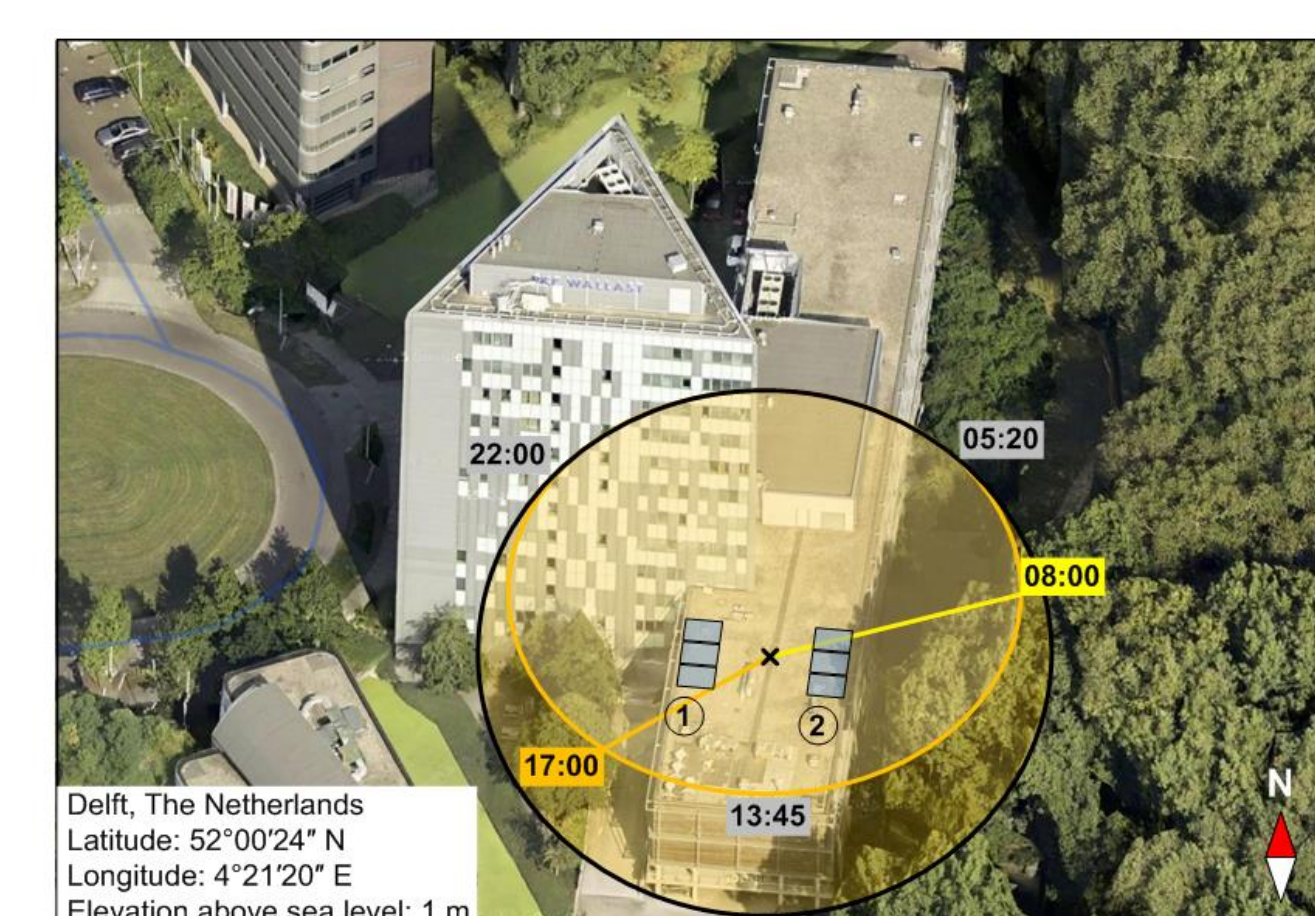
$$\text{if } ST_{(i=2, c_1)}^{(module_1)} > ST_{(i=2, c_2)}^{(module_2)} \rightarrow ST_{(i \rightarrow \infty, c_1)}^{(module_1)} > ST_{(i \rightarrow \infty, c_2)}^{(module_2)}$$

- 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.

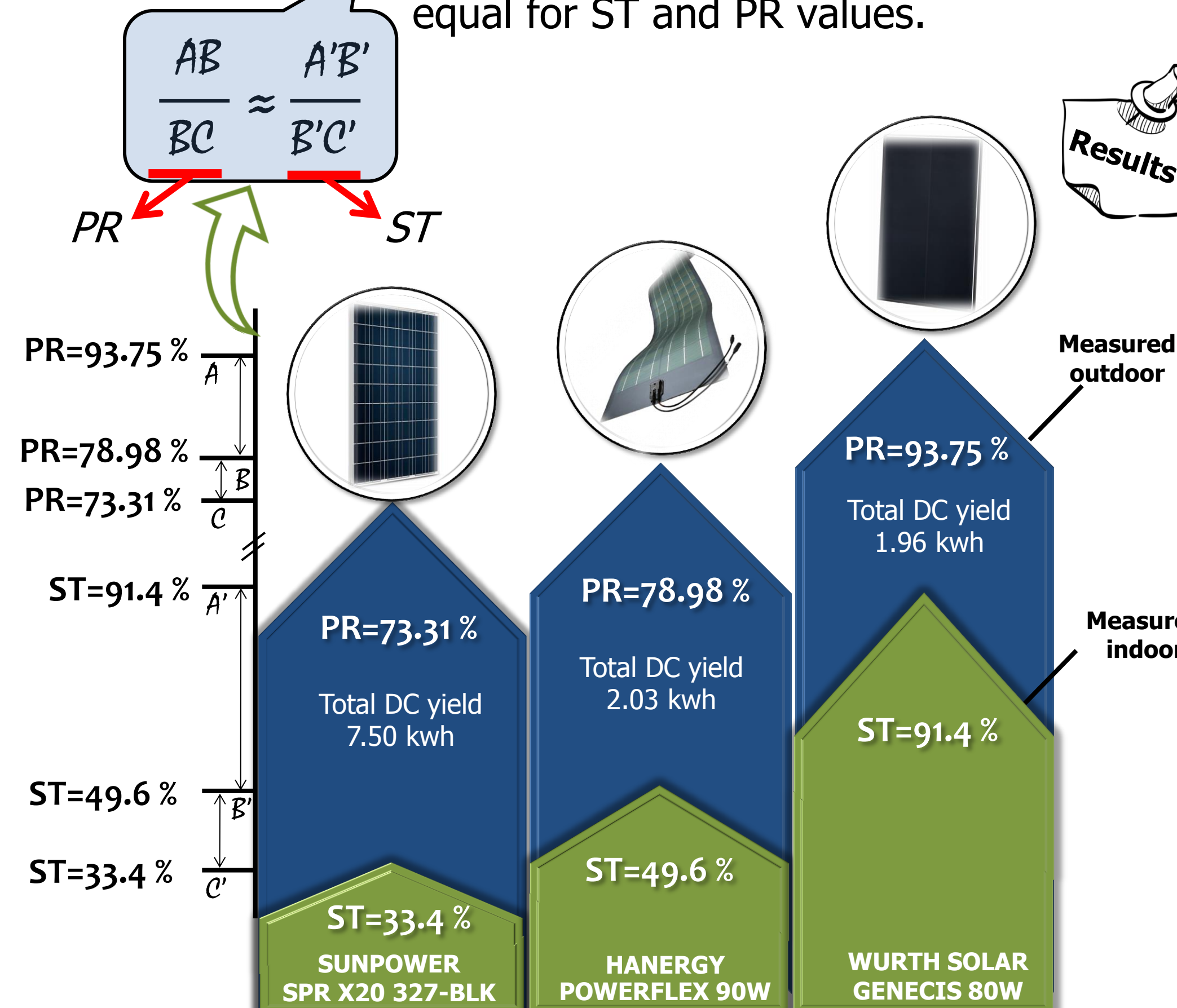
- ST values from indoors experiments using Large Area Solar Simulator.
- Indoor measurements setup.



- PR values from outdoor experiments by long-term monitoring.
- Outdoor measurements location: Delft, the Netherlands. 52.00° N 4.21° E.



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



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:

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

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

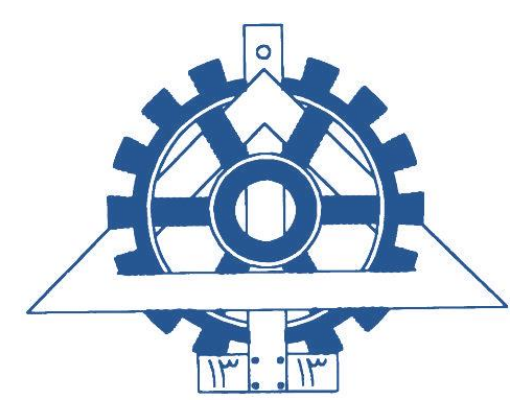
- It was mathematically proven that the **ST** of a PV module can be modeled by the function of $g/(n+1)$.
- It is suggested to add **ST** on PV modules datasheet as a benchmark to distinguish PV modules regarding shading tolerability.

Acknowledgment

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- [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.
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Note: Results of this research has been published in IEEE Journal of Photovoltaics, vol 7, no 5, pp. 1390-1399, Sep. 2017.



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Disclaimer: Results presented in this work strictly concern the individual photovoltaic modules available and tested in the PV Laboratory of the Photovoltaic Materials and Devices Group of TU Delft. The performance of such modules might not reflect that of similar or updated modules from the same brand and/or under different circumstances.

