Quantitative Evaluation of the Shading Resilience of PV Modules

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4BO.2.6

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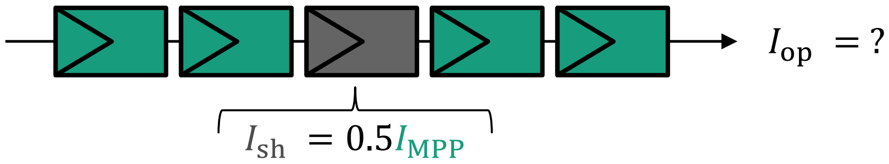
Shading of Serial Interconnected Solar Cells

Bypass Diodes and the *I-V* curve

- Shading of serial interconnected solar cells



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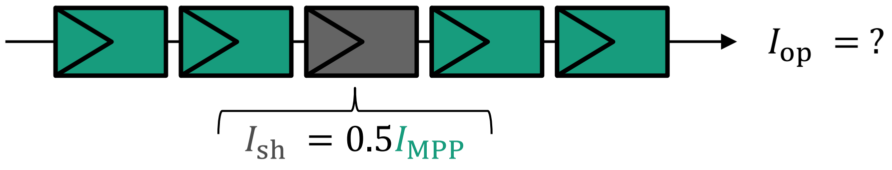
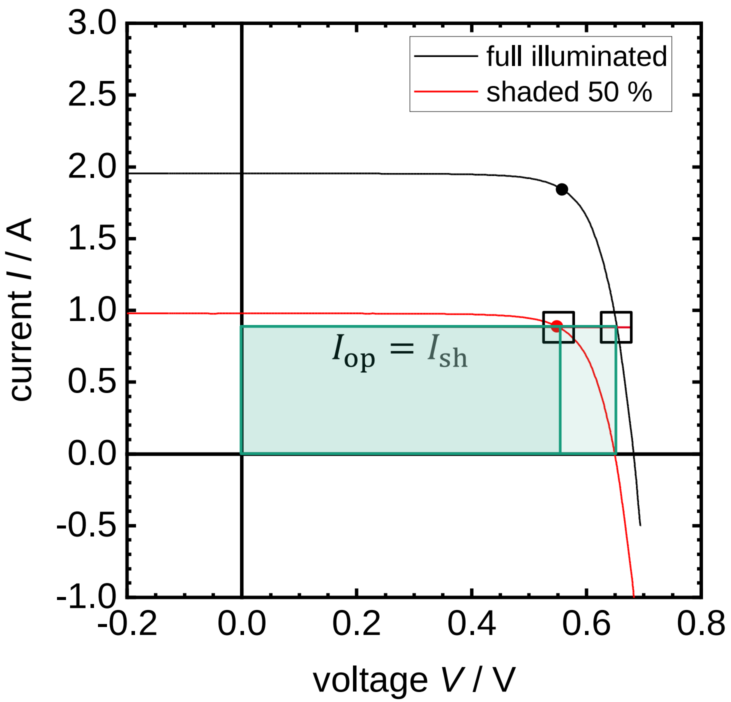


- $I_{op} = I_{sh}$ ➔ (reduced) power generation in both solar cells



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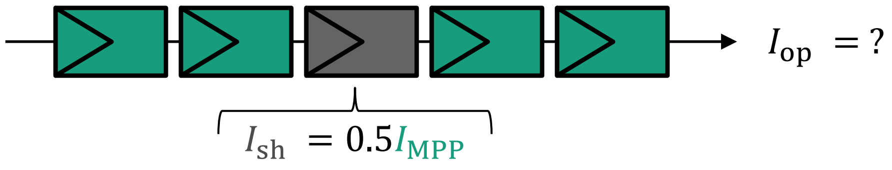
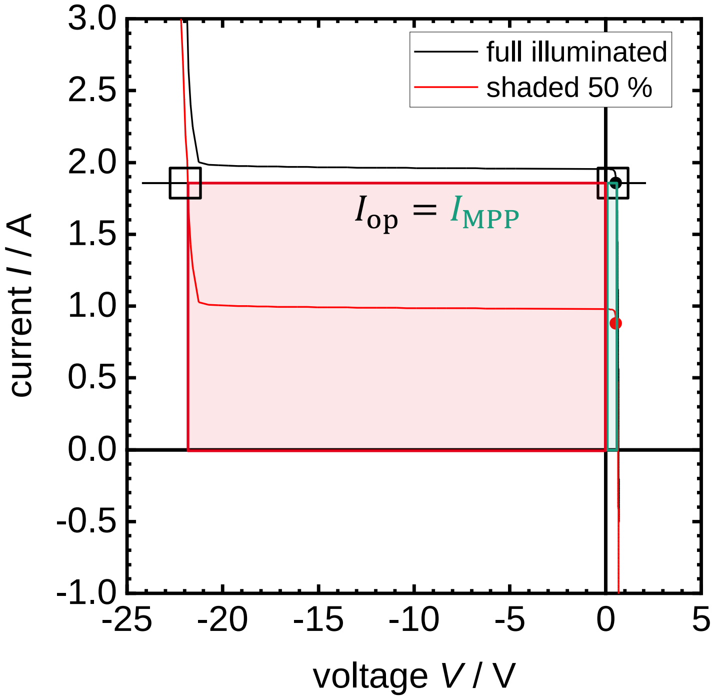


- $I_{op} = I_{sh}$ ➔ (reduced) power generation in both solar cells
- $I_{op} = I_{MPP}$ ➔ power dissipation in shaded solar cell

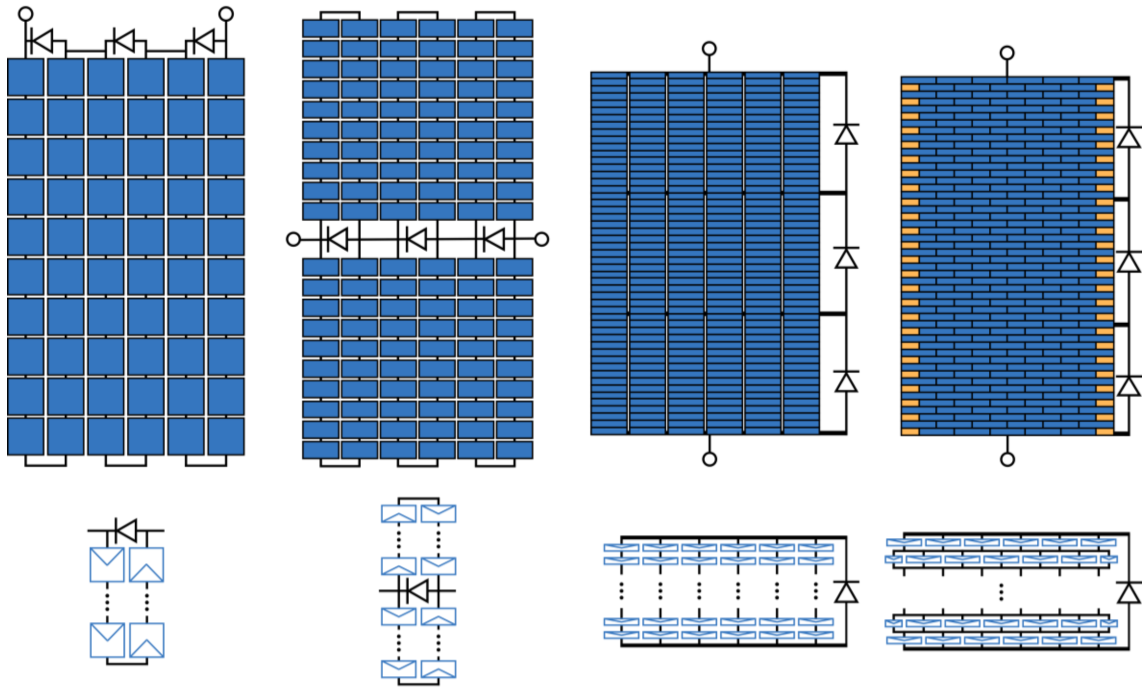


- Problem: current mismatch between solar cells
- State of the art measure:
  - Implementation of bypass diodes

Reduction of Shading Losses
Adapted Solar Module Topologies

- Investigated solar module topologies
  - Conventional full cell
  - Butterfly half cell
  - Shingle string
  - Shingle matrix [1]
- LTspice shading simulations [2,3]

Conventional	Butterfly	Shingle String	Shingle Matrix
full sized solar cells 60 Pcs	half-cut solar cells 120 Pcs.	1/5th shingle solar cells 300 Pcs.	1/5th shingle solar cells 300 Pcs.



[2,3]

[1] A. Mondon *et al.*, 2018
[2] N. Klasen *et al.*, submitted to IEEE Journal of Photovoltaics, 2021
[3] N. Klasen *et al.*, accepted Progress in Photovoltaics, 2021

Reduction of Shading Losses
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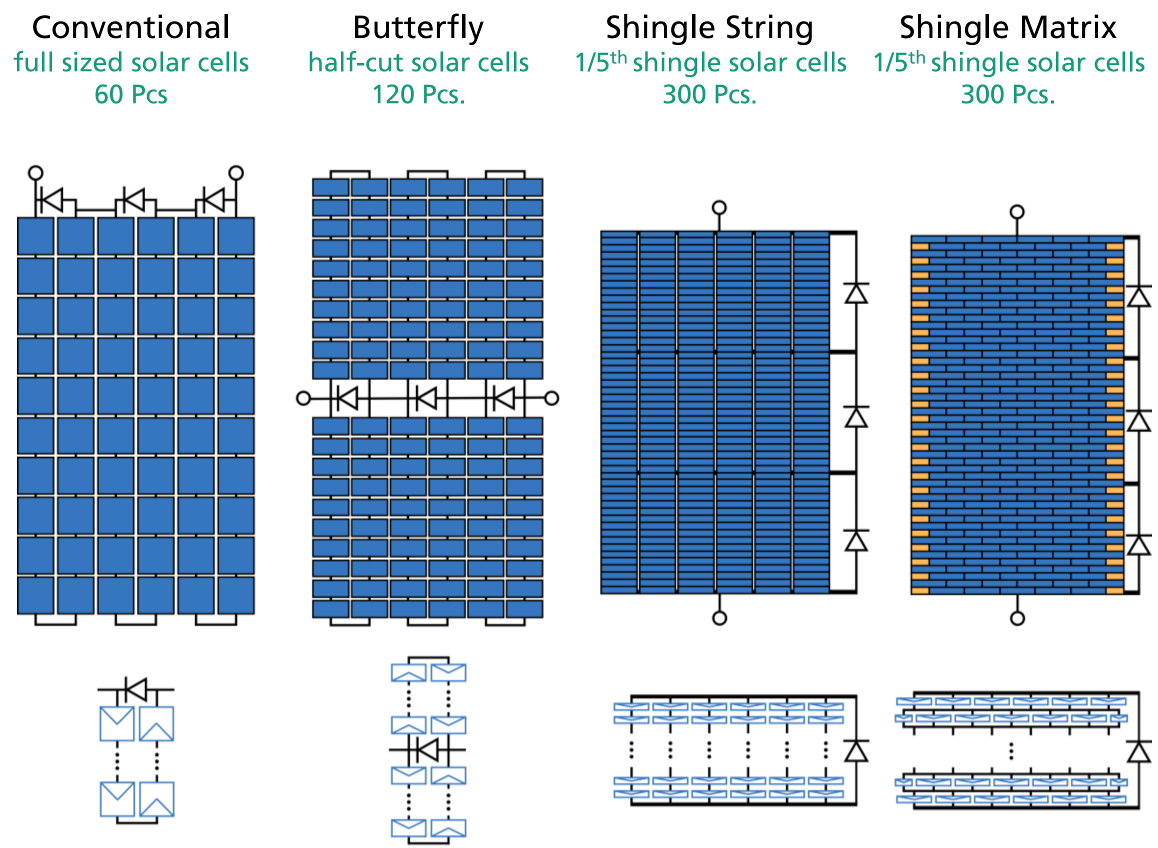
- Investigated solar module topologies
  - Conventional full cell
  - Butterfly half cell
  - Shingle string
  - Shingle matrix [1]
- LTspice shading simulations [2,3]
  - Module topologies ✔
  - *I-V* data: extended two-diode model [4] ✔
  - Shading scenarios
  - Criterion for comparison



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[4] H. S. Rauschenbach, *Solar cell array design handbook*, 1980

Shading Scenarios
Rectangular and Random Shading

- Shading is arbitrary
  - **Rectangular:** Poles, antennae, chimneys, other PV modules, …
  - **Random:** Leaves, bird droppings, branches / trees, …

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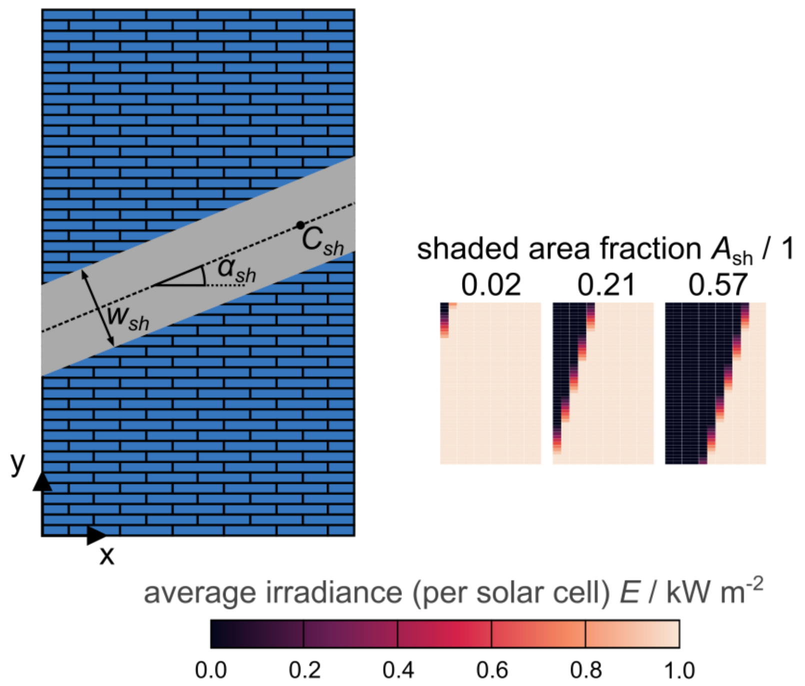
- **Rectangular shading**
  - 4 parameters $(w_{\mathrm{sh}}, \alpha_{\mathrm{sh}}, C_{\mathrm{sh}}(x, y))$
  - Evaluation of A_{sh} from parameters
  - Scenarios: 2000 combinations, Latin Hypercube Sampling [1,2]

$$A_{sh} = \frac{A}{A_0}$$



A / m^2: shaded area

A_0 / m^2: module area

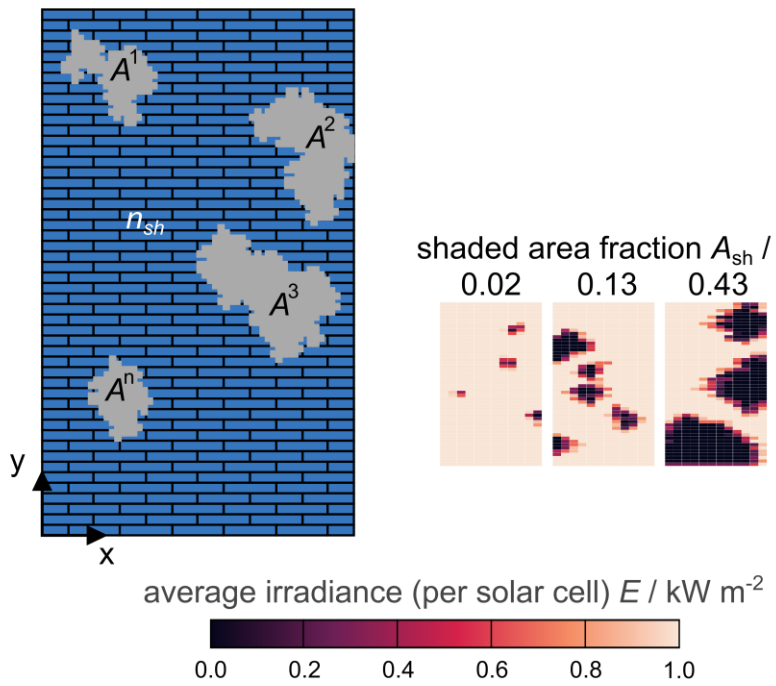
[1] M. D. Mckay *et al.*,1979, doi: 10.2307/1268522.
[2] J. C. Helton and F. J. Davis, 2003, doi: 10.1016/s0951-8320(03)00058-9.

Shading Scenarios
Rectangular and Random Shading

- Shading is arbitrary
  - **Rectangular:** Poles, antennae, chimneys, other PV modules, …
  - **Random:** Leaves, bird droppings, branches / trees, …

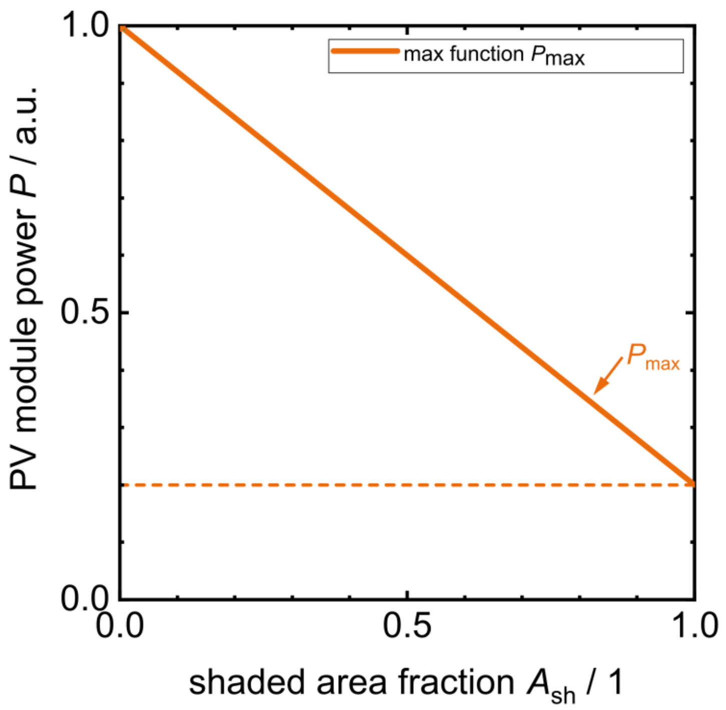
- **Random shading**
  - 2 parameters $(A_{\mathrm{sh}}, n_{\mathrm{sh}})$
  - $25x25$ pixel per shingle solar cell
  - $n_{\mathrm{sh}} = 10$
  - **Scenarios:** 1250 equidistant steps in A_{sh} from 0 to 1

- All scenarios are transferable between topologies

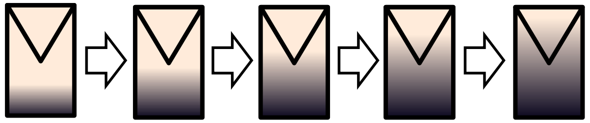


Criterion for Comparison
Shading Resilience *SR*

- Limit functions
  - Assumption: electrically ideal interconnection
  - $P \propto I \propto A$ ➔ $P_{\mathrm{max}} = P_0(1 - A_{\mathrm{sh}})$



$E_{\mathrm{sh}} = 0.2\ \mathrm{kW/m^2}$ [1]



P / W: power
I / A: current
A / m^2: area
E / $\mathrm{kW\ m^{-2}}$: irradiation

[1] M. A. Sattler and S. Sharpies, “FIELD MEASUREMENTS OF THE TRANSMISSION OF SOLAR RADIATION THROUGH TREES”, 1988

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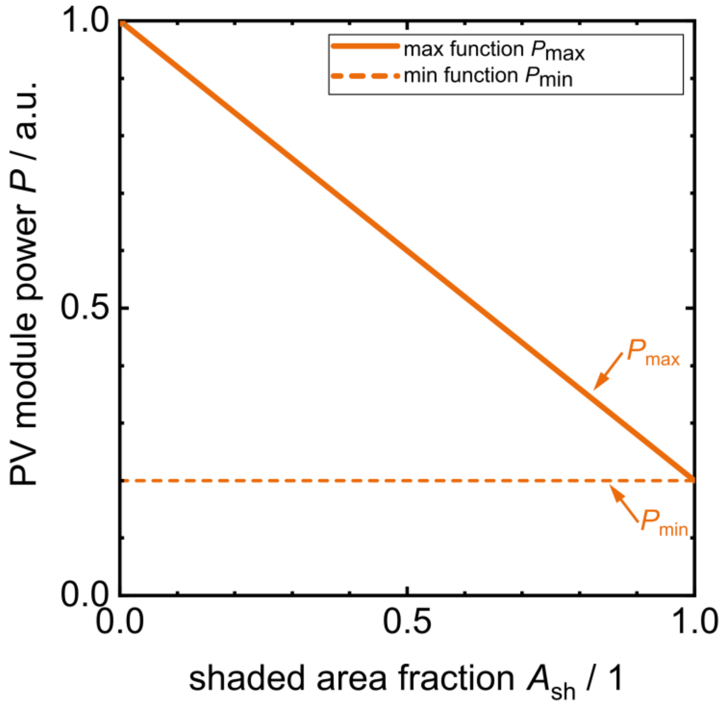
  - $P \propto I \propto E_{\mathrm{sh}} \rightarrow P_{\min} = P(A_{\mathrm{sh}} = 1) = P_0 E_{\mathrm{sh}}$



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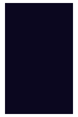

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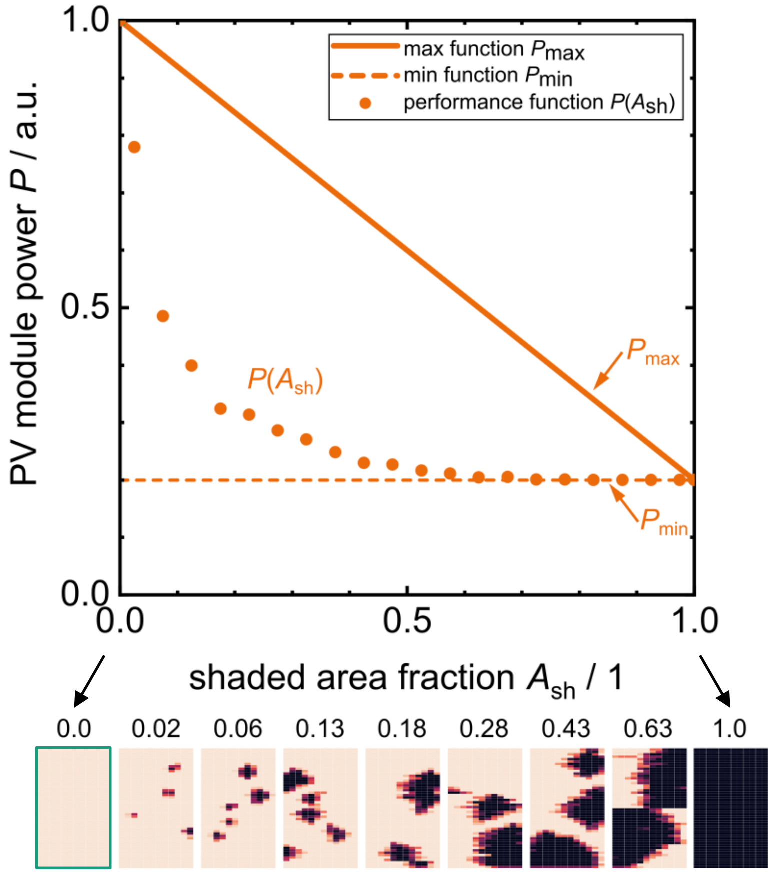
- Performance function $P(A_{\mathrm{sh}})$
  - Obtain by LTpsice simulations



Solar module

P / W: power
I / A: current
A / m^2: area
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Criterion for Comparison
Shading Resilience *SR*

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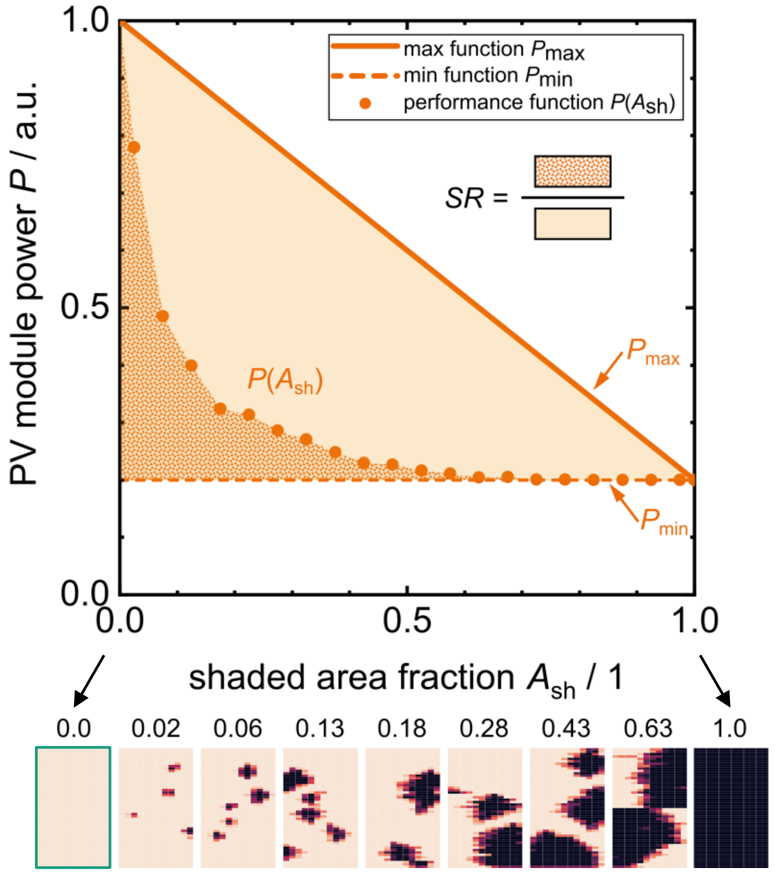
  - Assumption: electrically ideal interconnection
  - $P \propto I \propto A$ ➔ $P_{\max} = P_0(1 - A_{sh})$
  - $P \propto I \propto E_{sh}$ ➔ $P_{\min} = P(A_{sh} = 1) = P_0 E_{sh}$

- Performance function $P(A_{sh})$
  - Obtain by LTpsice simulations

- **Shading resilience *SR*** = „how close is a topology to the ideal shading behavior?“
  - Integration from $A_{sh} = 0$ to 1

$$SR = \frac{2}{(1-\hat{\imath})P_0} \int_0^1 P(A_{sh})\, dA_{sh} - \frac{2\hat{\imath}}{1-\hat{\imath}} \quad [1] \qquad \hat{\imath} = \frac{E_{sh}}{E_0}$$



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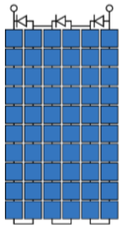
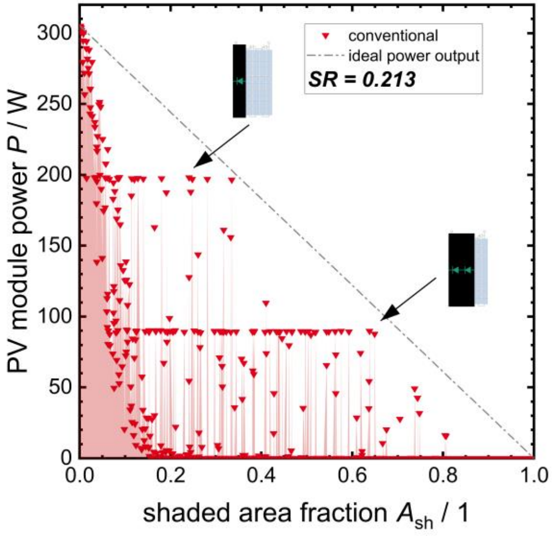
[1] N. Klasen *et al.*, submitted to IEEE Journal of Photovoltaics, 2021

Results
Rectangular Shading

Topology	Shading Resilience SR Rectangular	Random
Conventional	0.213	
Butterfly		
Shingle string		
Shingle matrix		



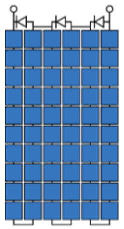


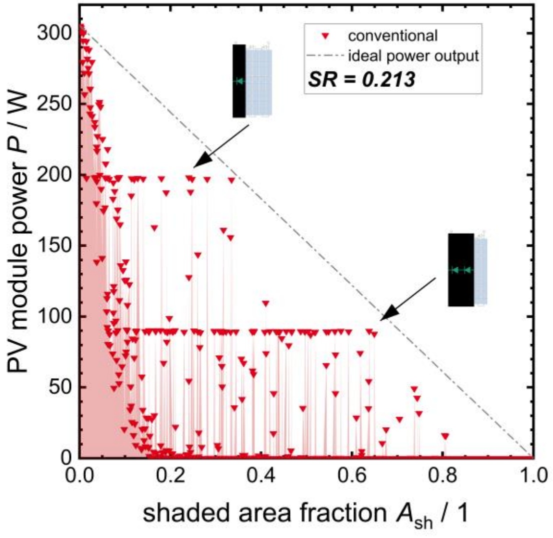
- Horizontal lines:
  - Conductive bypass diode at shaded module part
  - Remaining part of module unshaded

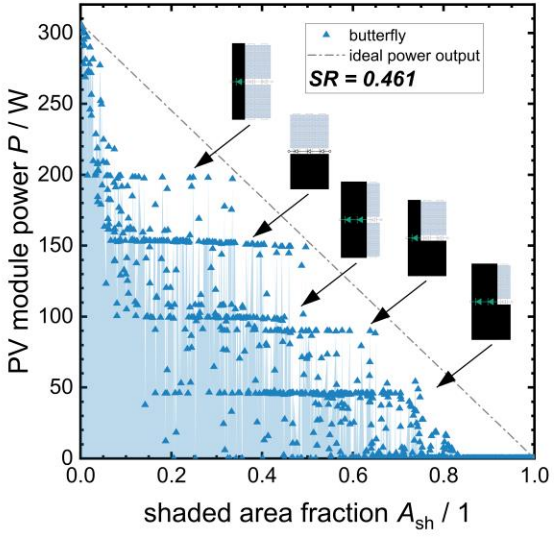
Results

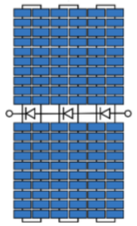
Rectangular Shading

Topology	Shading Resilience SR Rectangular	Shading Resilience SR Random
Conventional	0.213	
Butterfly	0.461	
Shingle string		
Shingle matrix		







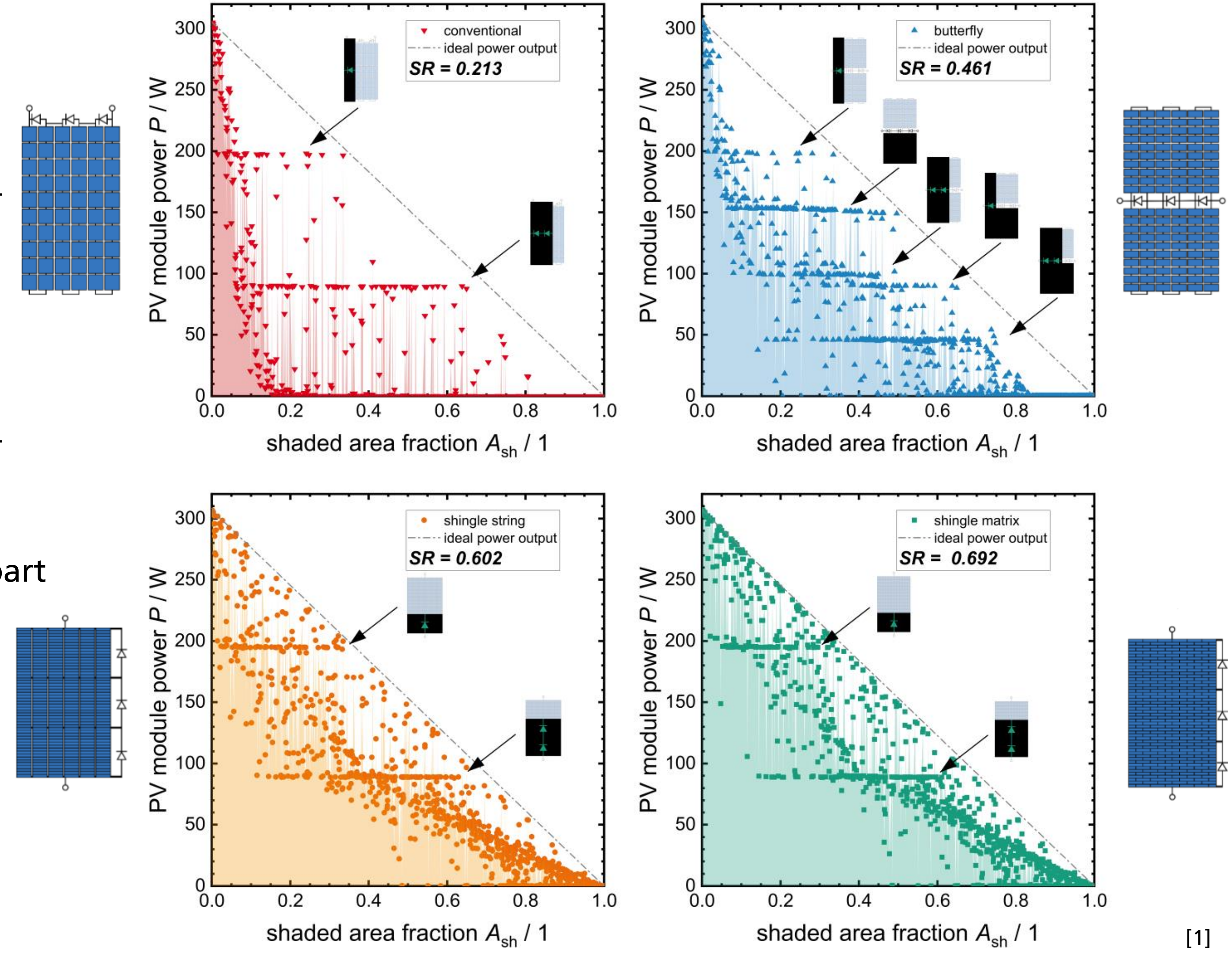


- Horizontal lines:
  - Conductive bypass diode at shaded module part
  - Remaining part of module unshaded

Results
Rectangular Shading

Topology	Shading Resilience SR Rectangular	Shading Resilience SR Random
Conventional	0.213	
Butterfly	0.461	
Shingle string	0.602	
Shingle matrix	0.692	

- Horizontal lines:
  - Conductive bypass diode at shaded module part
  - Remaining part of module unshaded
- Shingle solar modules
  - Produce power output up to $A_{\mathrm{sh}} = 1$
  - Many data points close to P_{max}



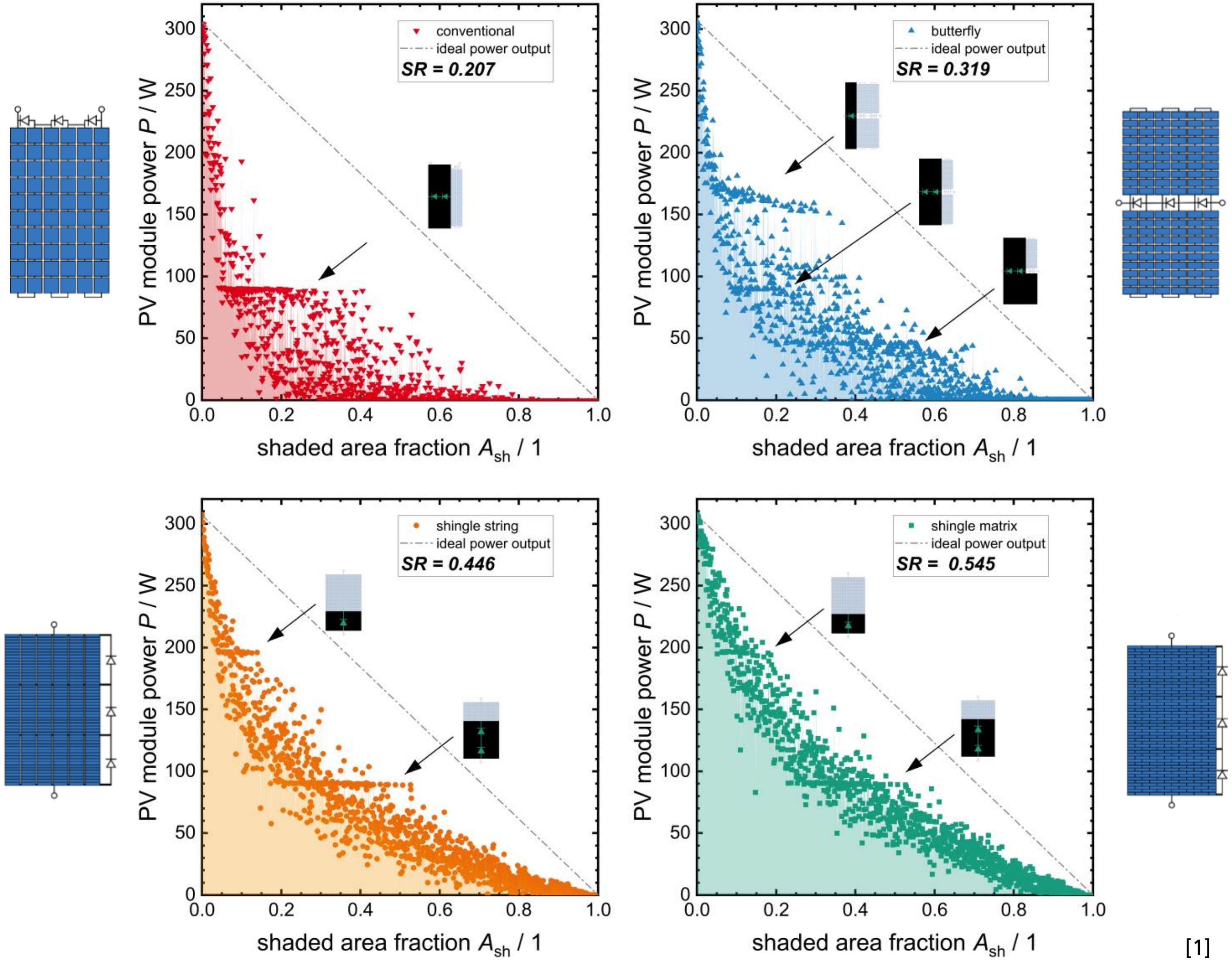
[1]

[1] N. Klasen *et al.*, submitted to IEEE Journal of Photovoltaics, 2021

Results
Random Shading

Topology	Shading Resilience SR Rectangular	Random
Conventional	0.213	0.207
Butterfly	0.461	0.319
Shingle string	0.602	0.409
Shingle matrix	0.692	0.554

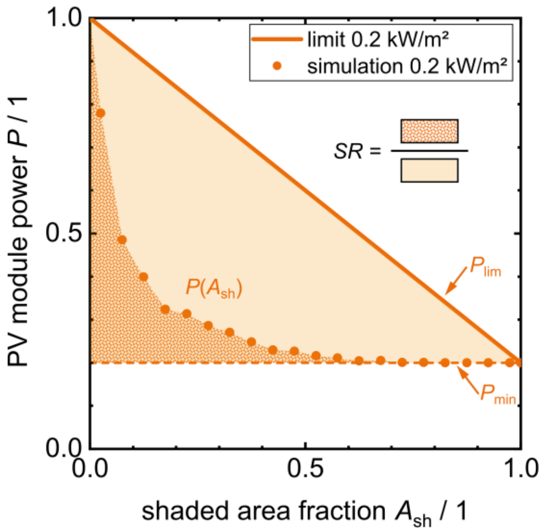
- Lower SR in random scenarios for all topologies
  - Less data points close to $P_{\max}$
  - Reduced MPP currents [2]
  - Less distinct horizontal „diode"-lines
  - Overall reduced SR
- Reason: Distribution of shading on entire module surface

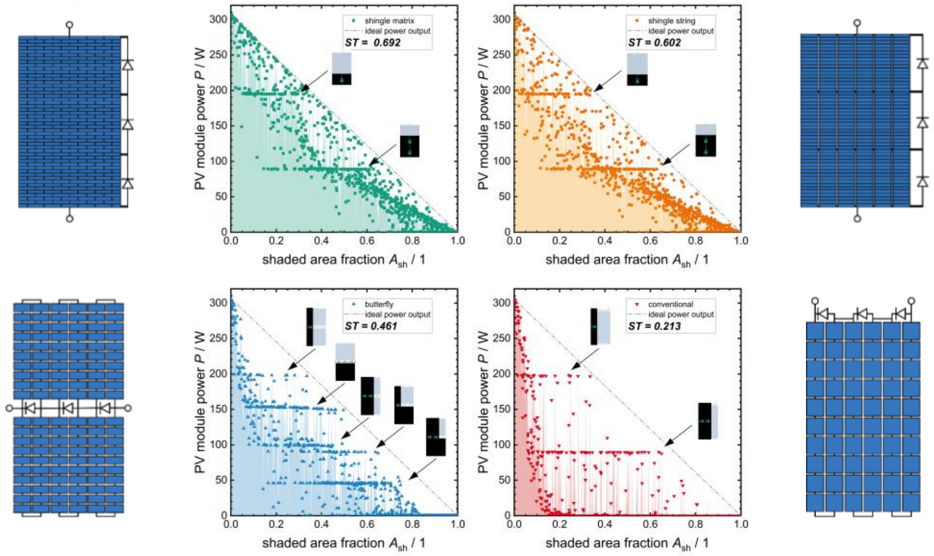


[1]

[1] N. Klasen *et al.*, submitted to IEEE Journal of Photovoltaics, 2021
[2] Conference Proceedings

Summary





- Definition of the **Shading Resilience** ***SR***:
  - Valid for arbitrary shading
  - Applicable on arbitrary module topologies
  - **Summarizes response to shading in one value**

- Investigation of **four module topologies**:
  - Shingle PV modules yield **up to 3.5 times more energy** compared to the conventional reference.

Thank You for Your Attention!

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