Comprehensive Evaluation of IEC Measurement Procedures for Bifacial Solar Cells and Modules

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37th EU PVSEC

September 09, 2020

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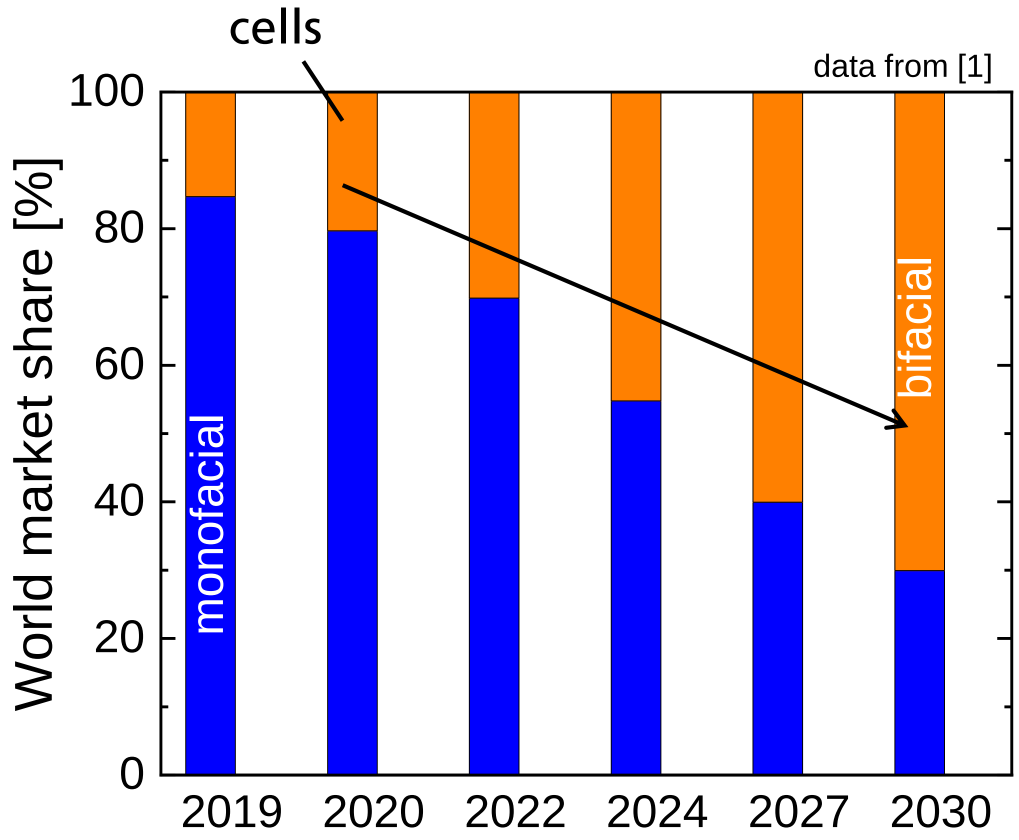
Measurement of Bifacial Silicon Solar Cells and Modules
Motivation

- Bifacial solar cells and modules become more and more important



[1] ITRPV, 11th Edition (2020).

Measurement of Bifacial Silicon Solar Cells and Modules
Motivation

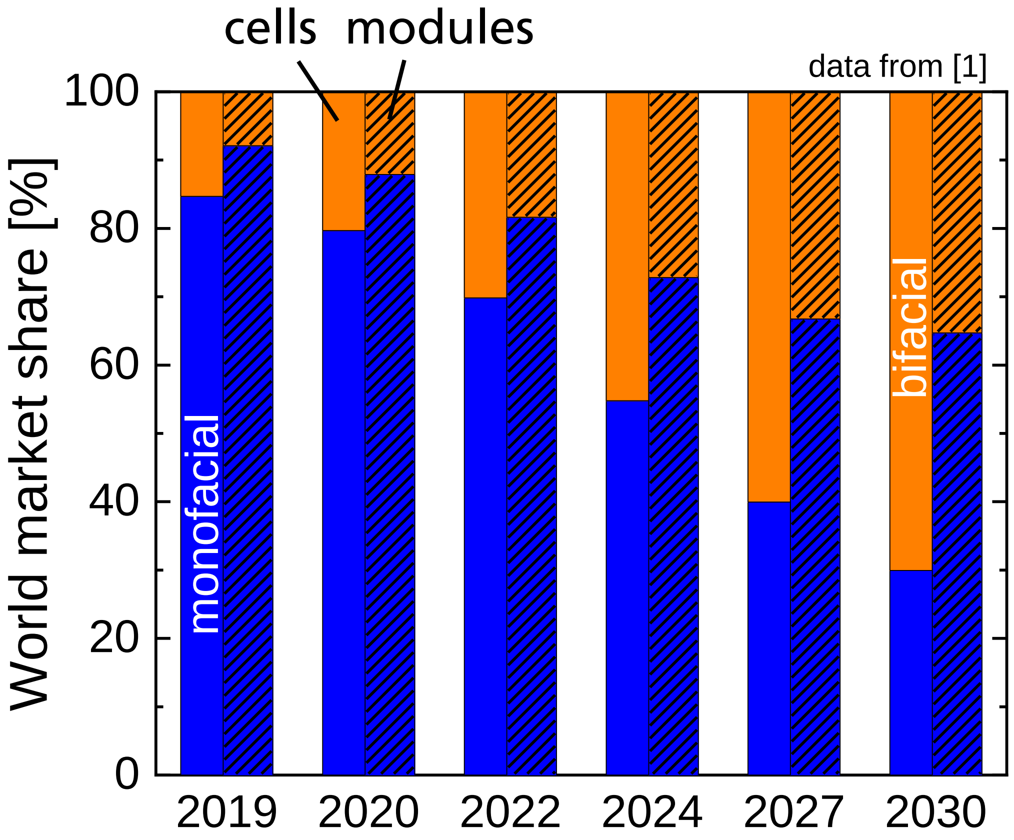
- Bifacial solar cells and modules become more and more important
- Strongest hindrance for market introduction [2]: Missing standardized characterization of bifacial performance

→ IEC technical specification (TS) 60904-1-2 [3]

  - Comparability to monofacial devices
  - Comparability among bifacial devices

→ Two different methods for indoor measurement of bifacial devices proposed

▶ **In this study: Comparison of measurement methods and input parameters**



[1] ITRPV, 11th Edition (2020).
[2] R. Kopecek, Photovoltaics International 26 (2014): 32.
[3] IEC 60904-1-2, Technical Specification, 2019.

AGENDA

- Introduction to IEC TS 60904-1-2
- Amendment Proposal 1
  - Motivation and Derivation
  - Evaluation: Partial Rear Shading
- Amendment Proposal 2
  - Motivation and Derivation
  - Evaluation: Low-Light Conditions
- Summary

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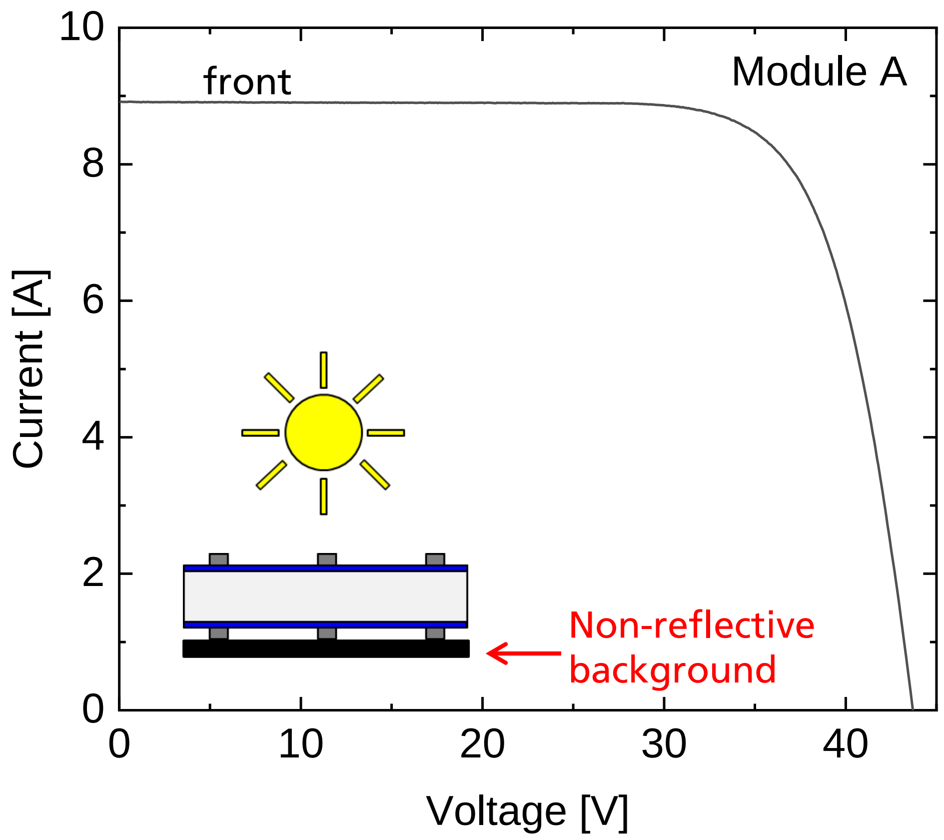
IEC Technical Specification 60904-1-2
Measurement Procedure

Measurement at **Standard Testing Conditions** (1000 W/m², 25°C, AM1.5g) from front

- Short-circuit currents $I_{sc,front}$
- Maximum power $P_{mpp,front}$

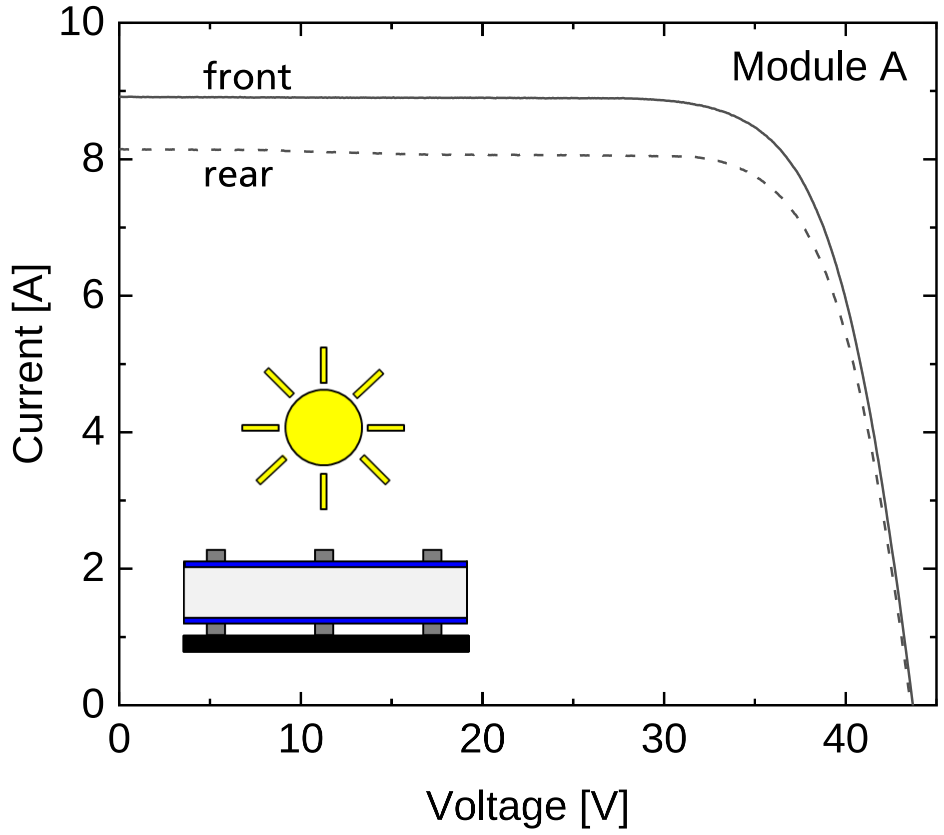


IEC Technical Specification 60904-1-2

Measurement Procedure

Measurement at Standard Testing Conditions (1000 W/m², 25°C, AM1.5g) from front and rear

- Short-circuit currents $I^{STC}_{sc,front}$, $I^{STC}_{sc,rear}$
- Maximum power $P^{STC}_{mpp,front}$, $P^{STC}_{mpp,rear}$



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IEC Technical Specification 60904-1-2
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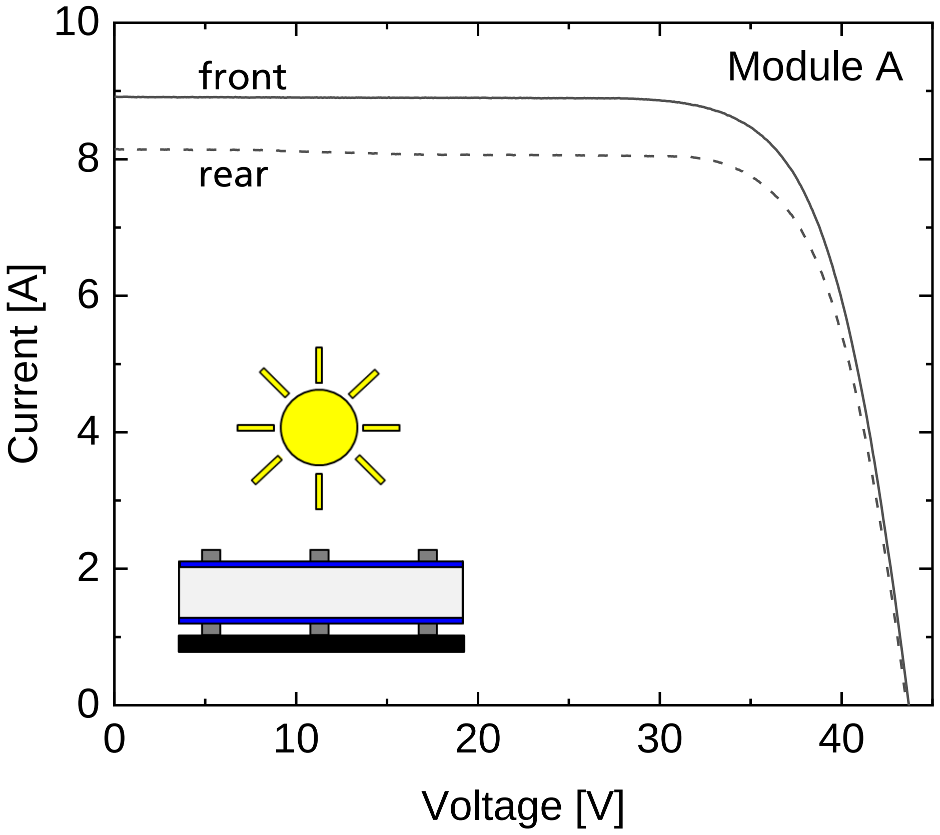
⟶ **Bifaciality coefficients:** [3]

- I_{sc} bifaciality: $\phi_{Isc}^{STC} = \frac{I_{sc,rear}^{STC}}{I_{sc,front}^{STC}}$
- P_{mpp} bifaciality: $\phi_{Pmpp}^{STC} = \frac{P_{mpp,rear}^{STC}}{P_{mpp,front}^{STC}}$



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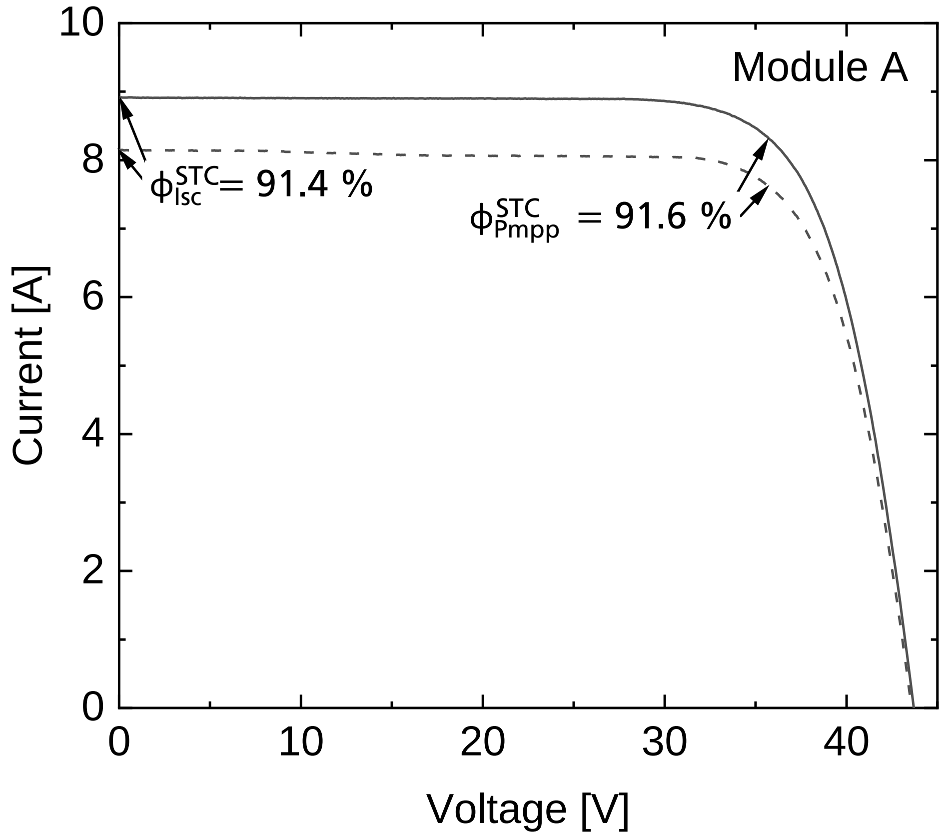

[3] IEC 60904-1-2, Technical Specification, 2019.

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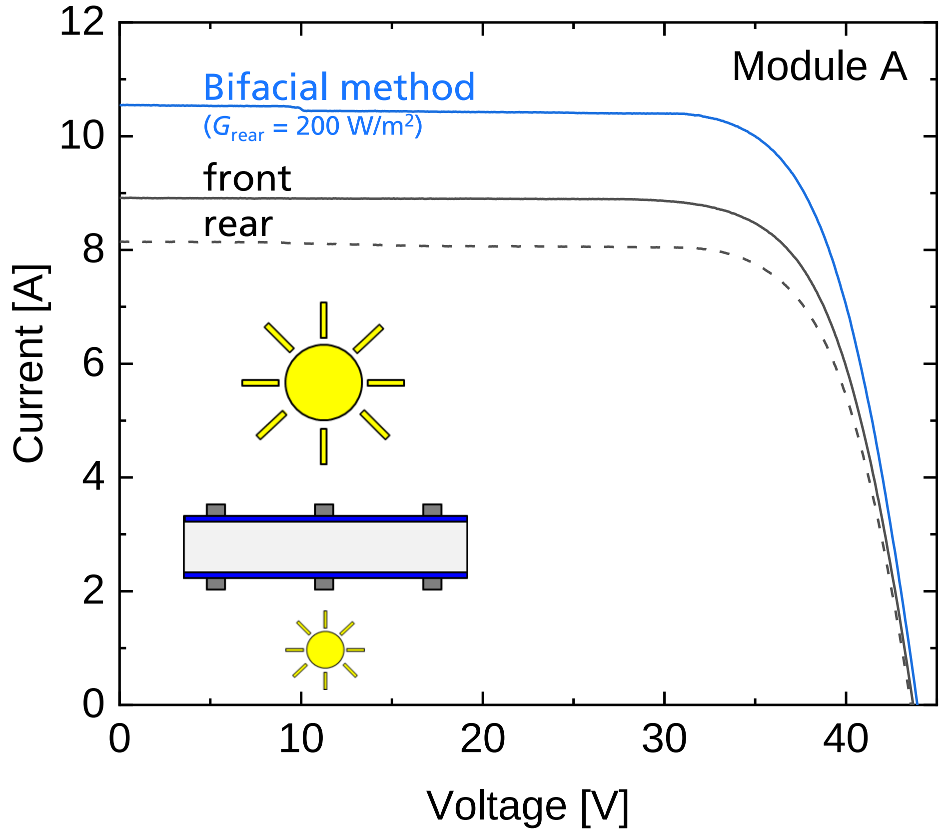
IEC Technical Specification 60904-1-2
Measurement Procedure

Two different methods for indoor measurements [3]

- **Both-sided illumination (*Bifacial method*):**

  Front irradiance: $G_{front} = 1000\ \mathrm{Wm}^{-2}$

  Rear irradiance: $G_{rear} = 100$ to $200\ \mathrm{Wm}^{-2}$



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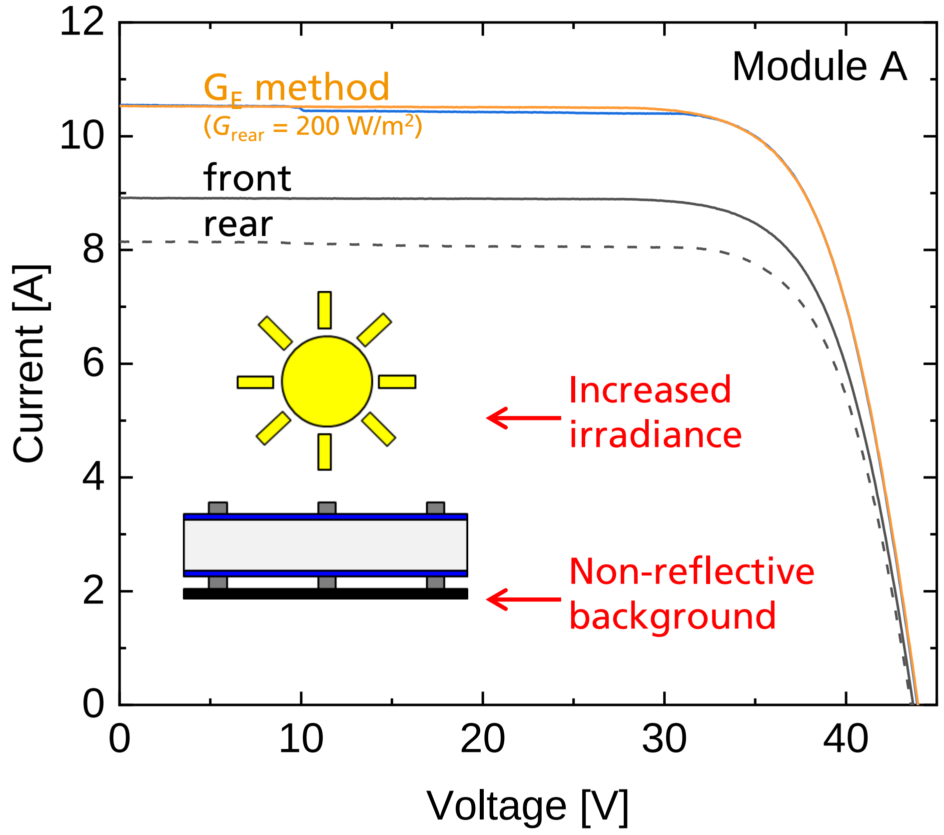
- **Single-sided illumination**
  (*equivalent irradiance (G_E) method*):

  Front irradiance: $G_E = 1000\ \mathrm{Wm}^{-2} + \phi \cdot G_{rear}$

  compensated rear contribution

  $\min(\phi_{Isc}^{STC}, \phi_{Pmpp}^{STC})$



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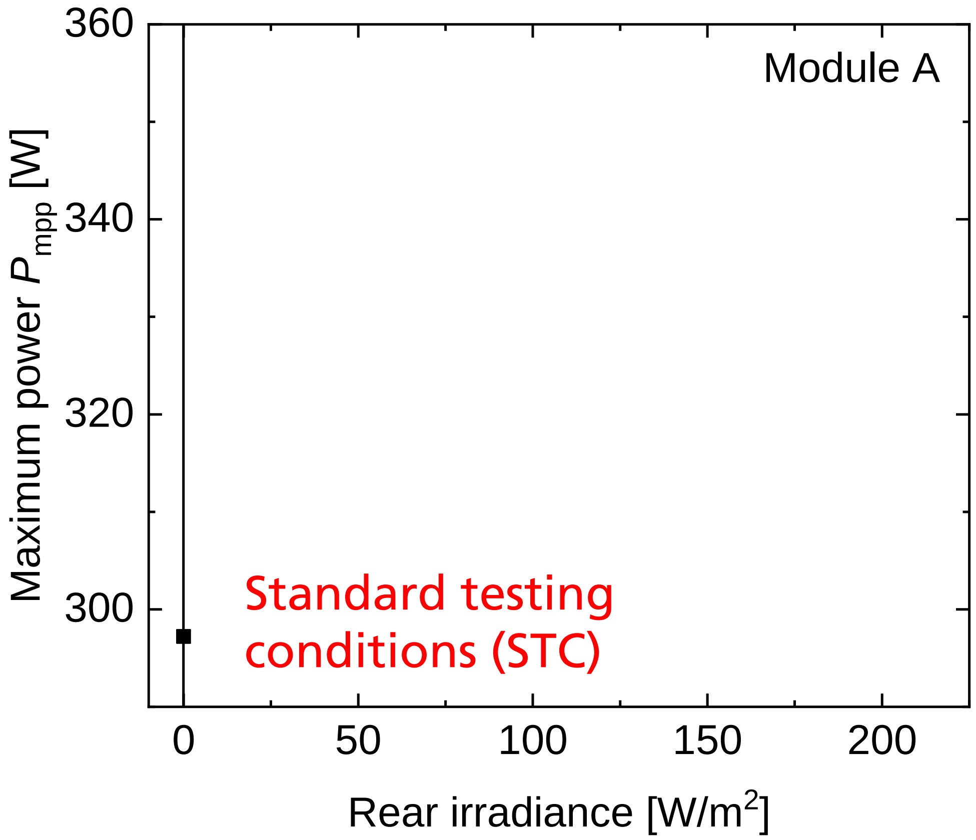
→ Measurement of P_{mpp} as function of G_{rear} additional to STC



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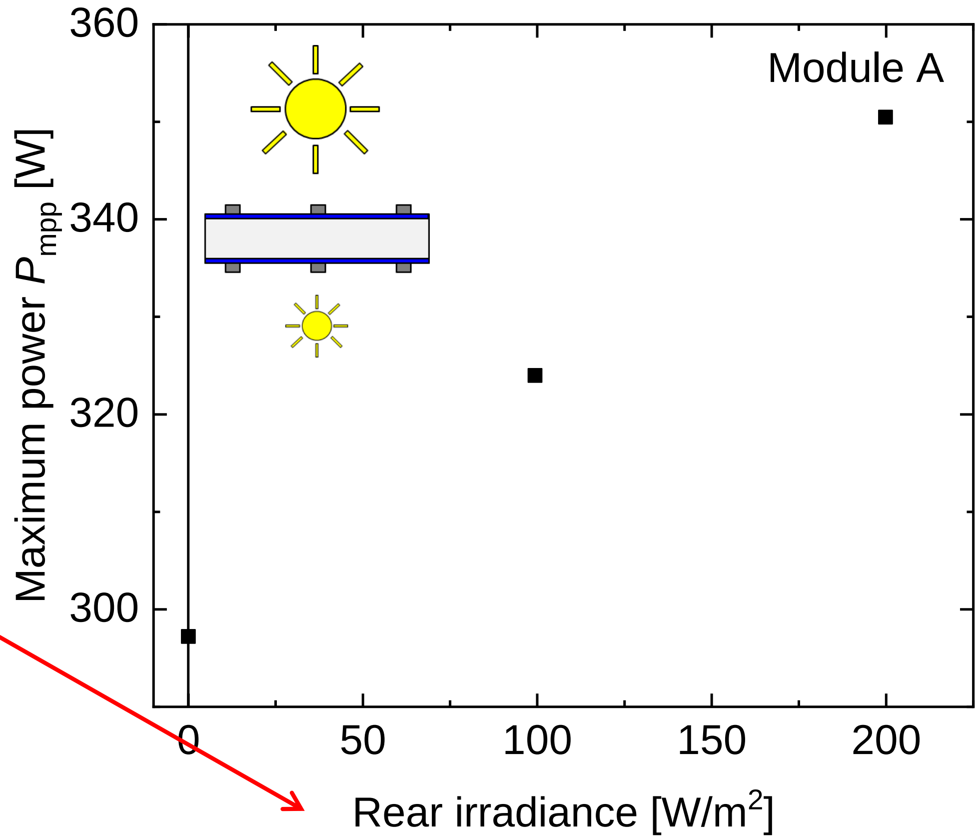

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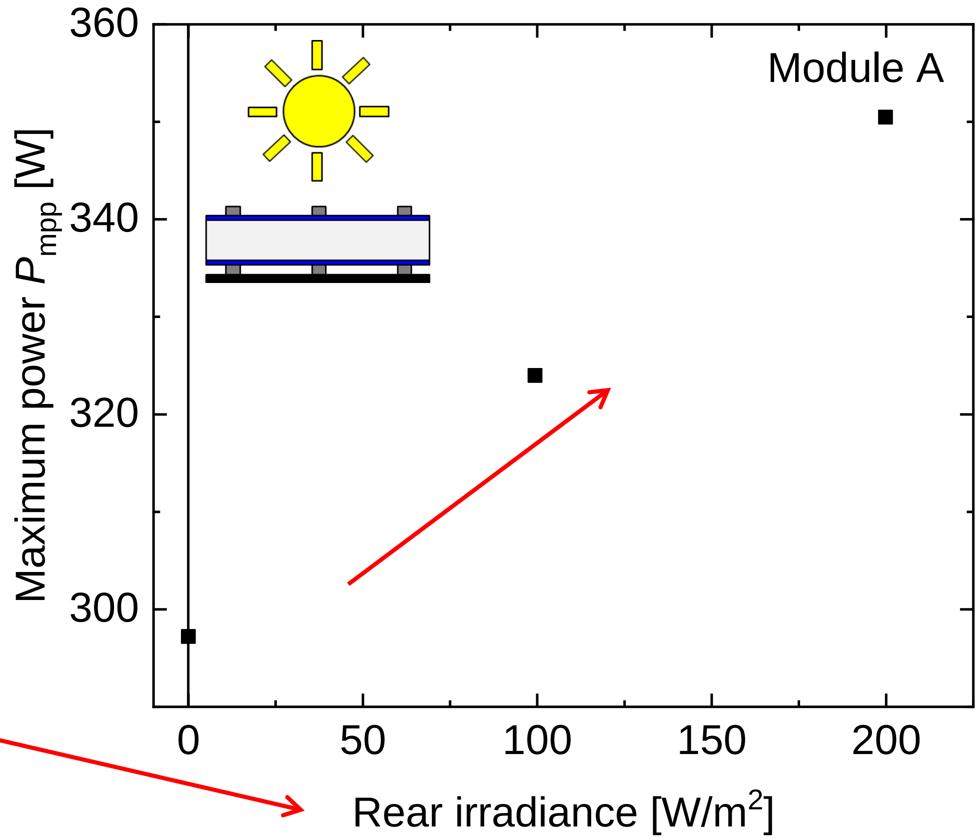
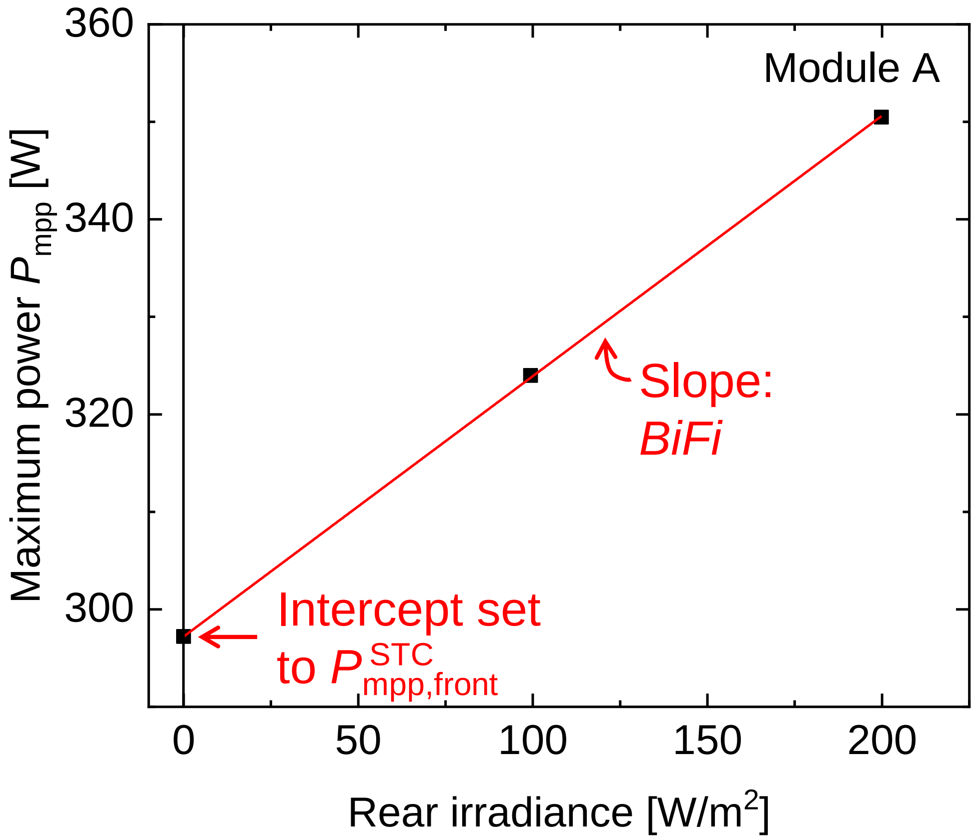


IEC Technical Specification 60904-1-2

Standardized Evaluation

Standardized parameters to quantify bifacial performance

- *BiFi:* Measure for power gain by additional rear irradiance in W/(W/m²)



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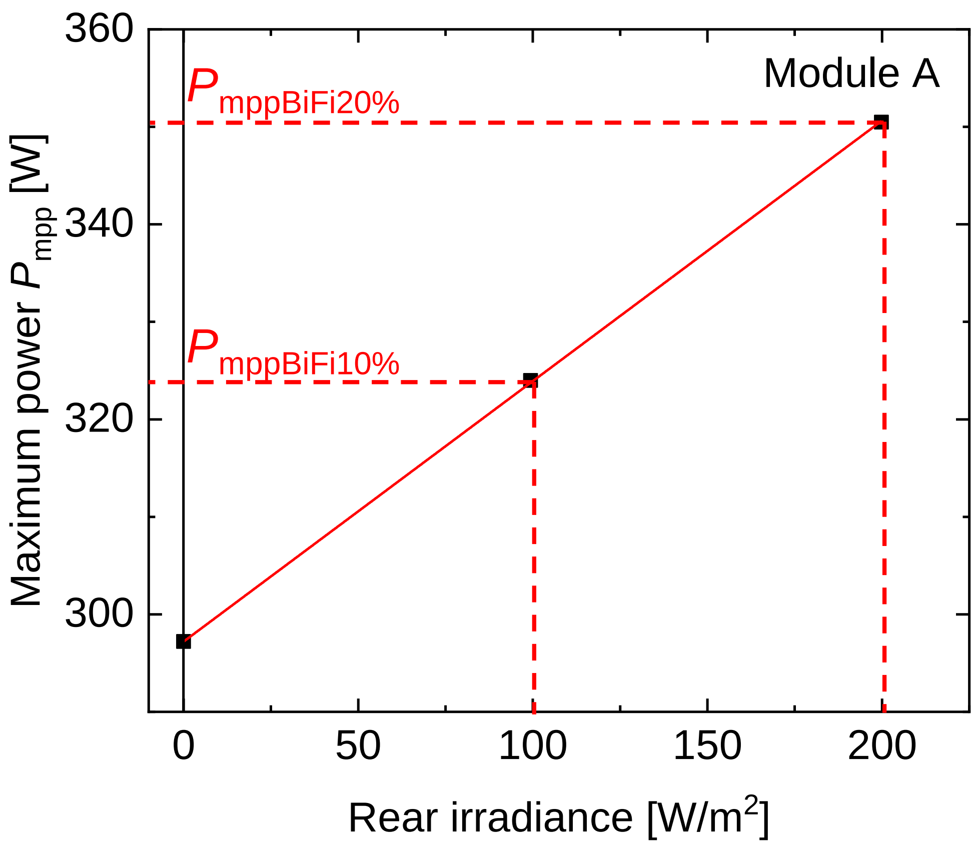
IEC Technical Specification 60904-1-2
Standardized Evaluation

Standardized parameters to quantify bifacial performance

- *BiFi:* Measure for power gain by additional rear irradiance in W/(W/m²)
- $P_{mppBiFi10\%}$: Interpolated power at standardized rear irradiance of 100 W/m²
- $P_{mppBiFi20\%}$: Interpolated power at standardized rear irradiance of 200 W/m²



IEC Technical Specification 60904-1-2
Low-Light Conditions

Methods applicable in similar way:

"The same approach may be applied to assess the low-light behaviour of bifacial PV devices" [3]

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- **Single-sided illumination** (G_E *method*):

  Front irradiance: $G_{\text{E}} = G_{\text{front}} + \phi \cdot G_{\text{rear}}$

  $\min(\phi_{\text{Isc}}^{\text{STC}}, \phi_{\text{Pmpp}}^{\text{STC}})$

No other bifaciality coefficients specified in 60904-1-2

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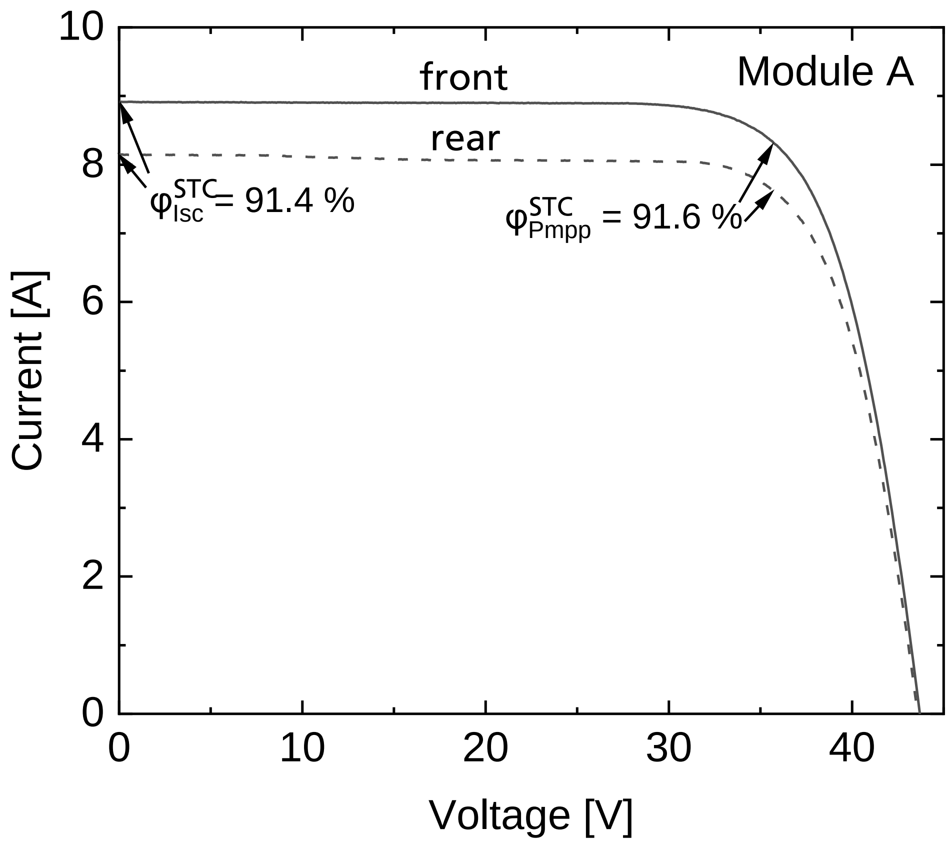

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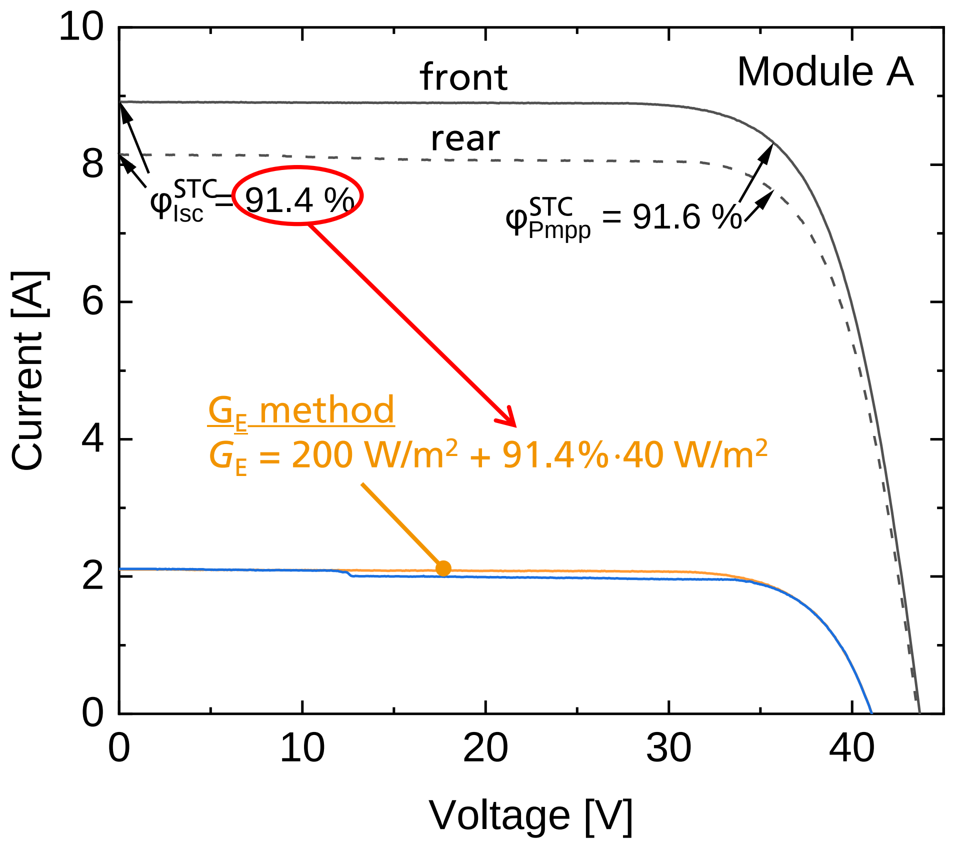

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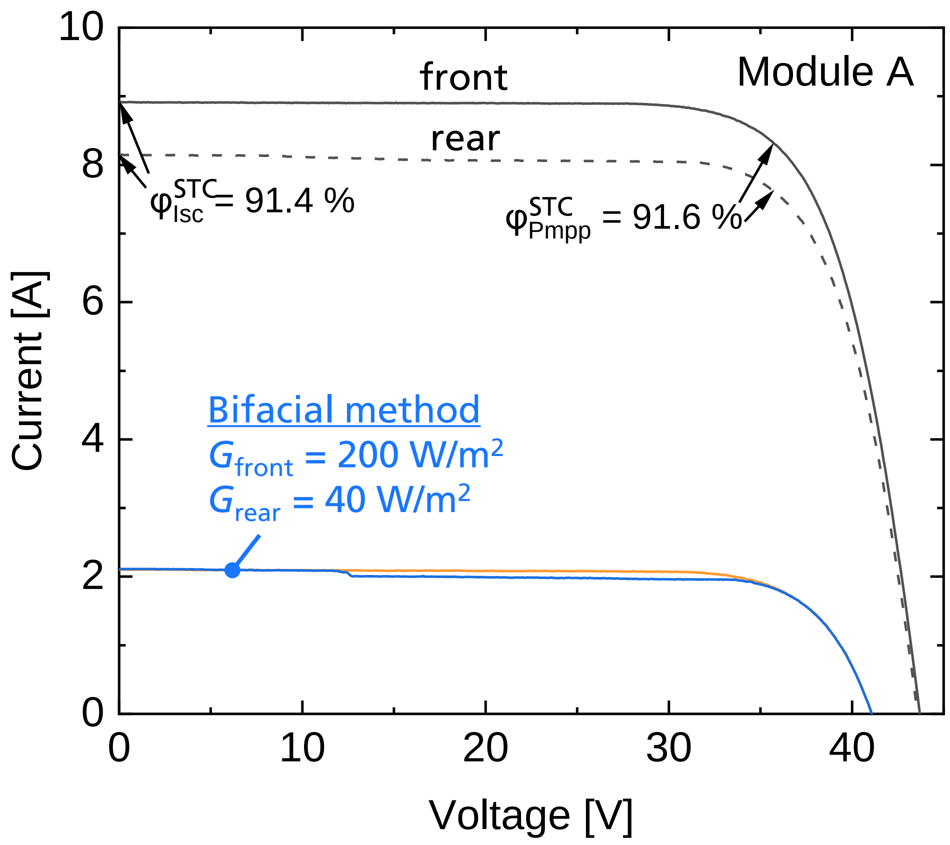

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Partial Rear Shading
Bifacial Modules Under Test

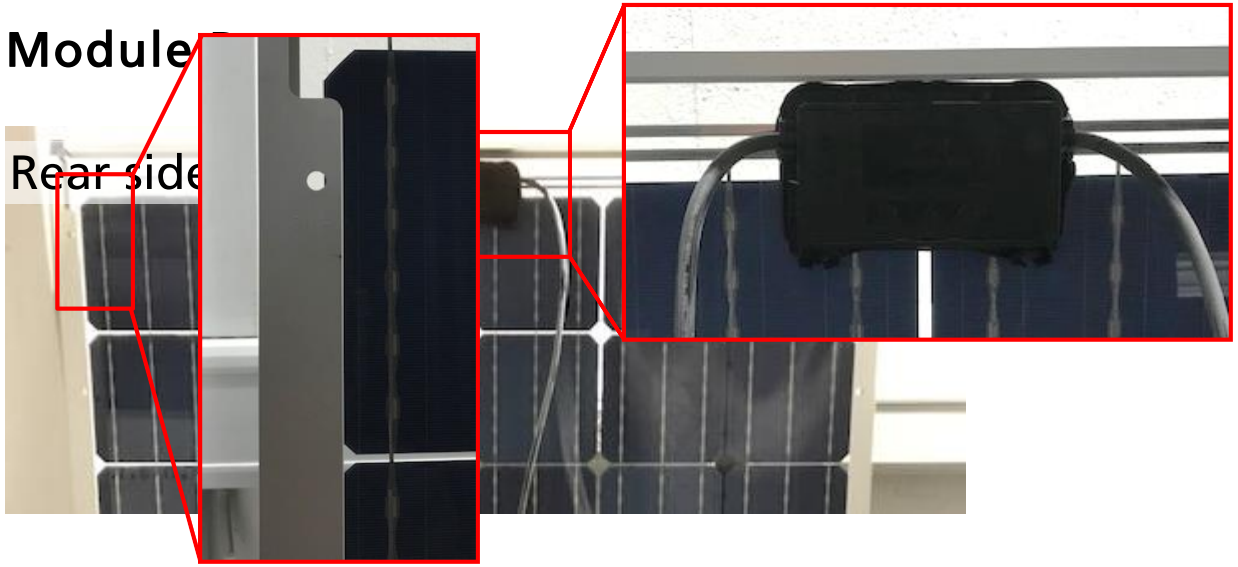
Module A

Optimized for bifacial application:

- Flat junction box
- Slim module frame

→ Only slight partial rear shading

Module B



Non-optimized for bifacial application:

- Overlapping junction box
- Wide module frame

→ Significant rear shading

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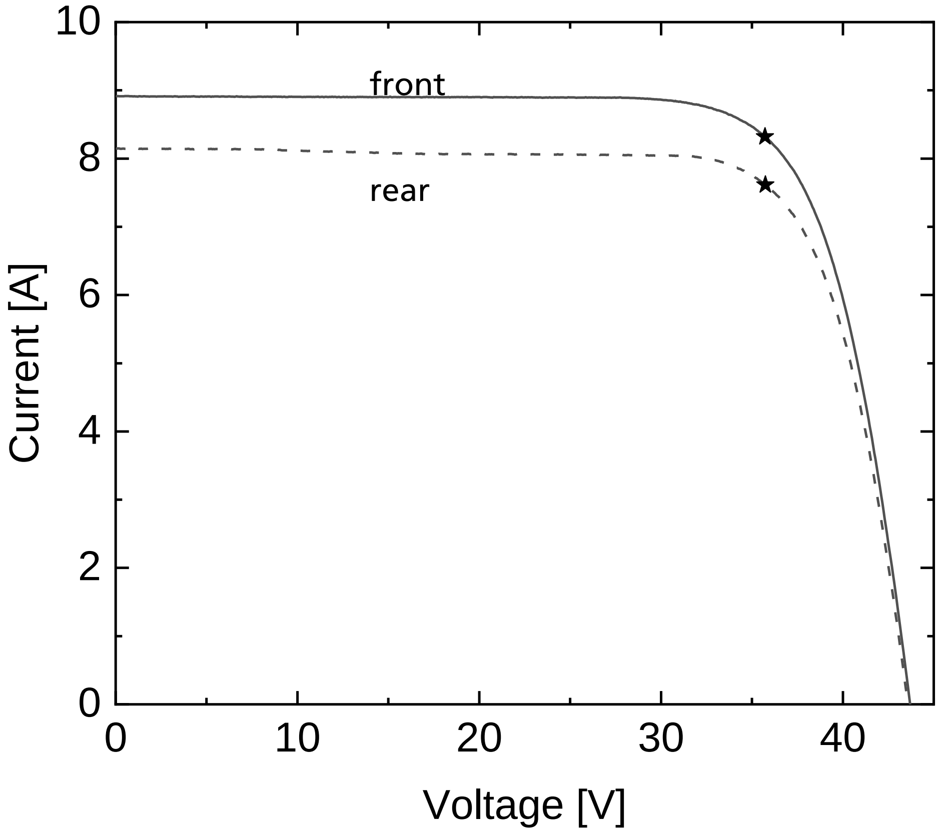
Partial Rear Shading
Bifacial Modules Under Test

Module A: Optimized for bifacial applications

- No conspicuous features in *I-V* curves

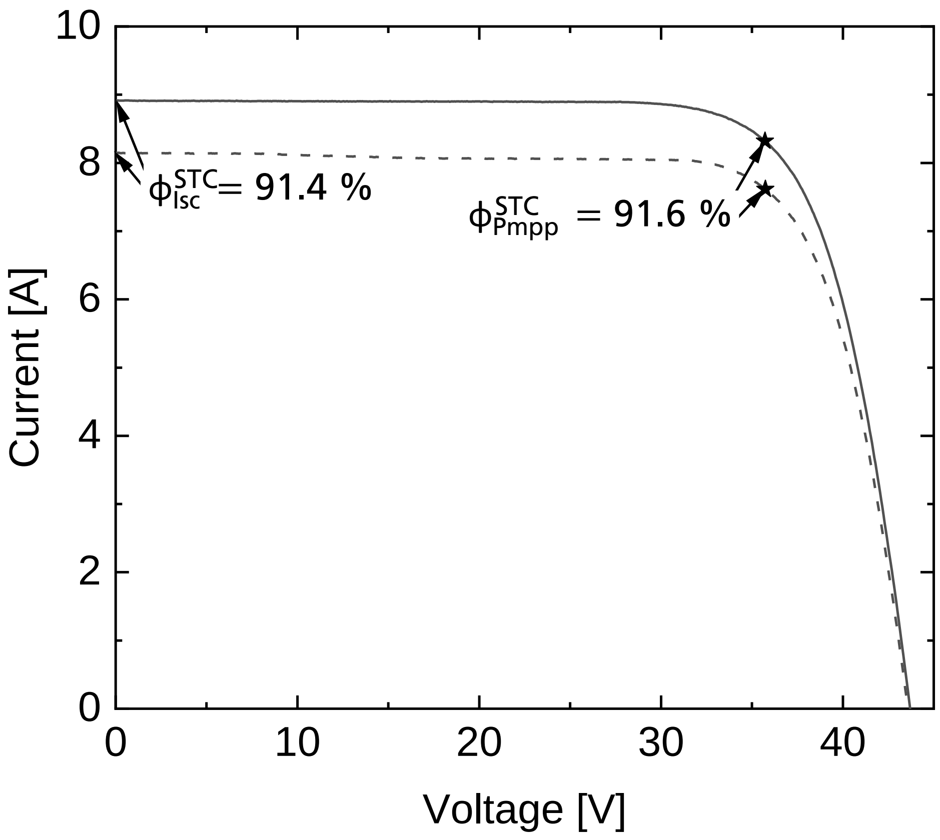


Partial Rear Shading

Bifacial Modules Under Test

Module A: Optimized for bifacial applications

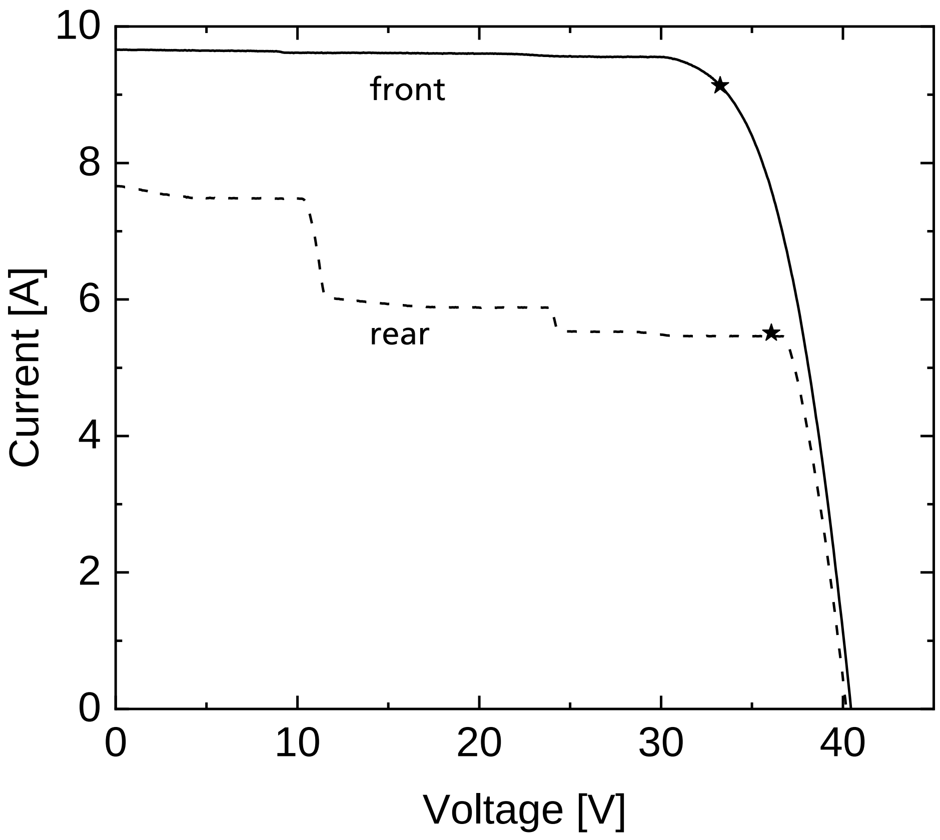
- No conspicuous features in *I-V* curves
- Bifaciality coefficients approximately similar



Partial Rear Shading
Bifacial Modules Under Test

Module B: With partial rear shading

- Kinks in rear *I-V* curve due to bypassing of strings by bypass diodes



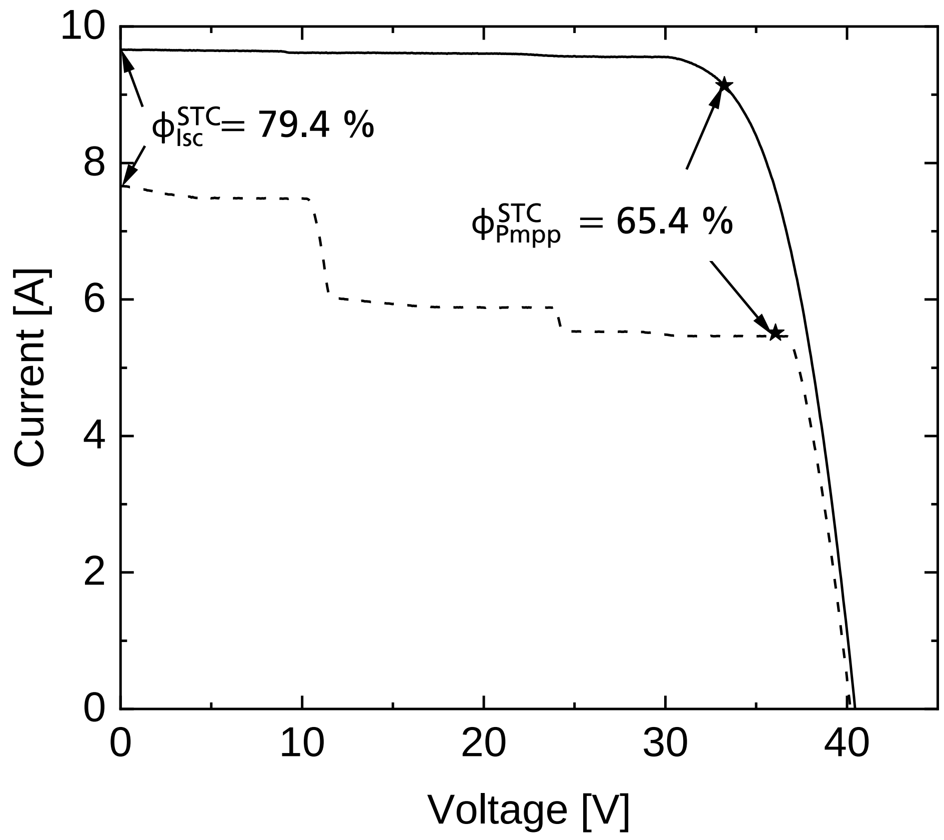
Partial Rear Shading
Bifacial Modules Under Test

Module B: With partial rear shading

- Kinks in rear *I-V* curve due to bypassing of strings by bypass diodes
- Large difference in bifaciality factors ϕ_{Isc} and ϕ_{Pmpp} as input parameters for G_E

→ To counter this issue, minimum criterion has originally been introduced to IEC TS 60904-1-2

$$\phi = \min(\phi_{Isc}, \phi_{Pmpp})$$



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Amendment Proposal 1
Omission of Minimum Criterion

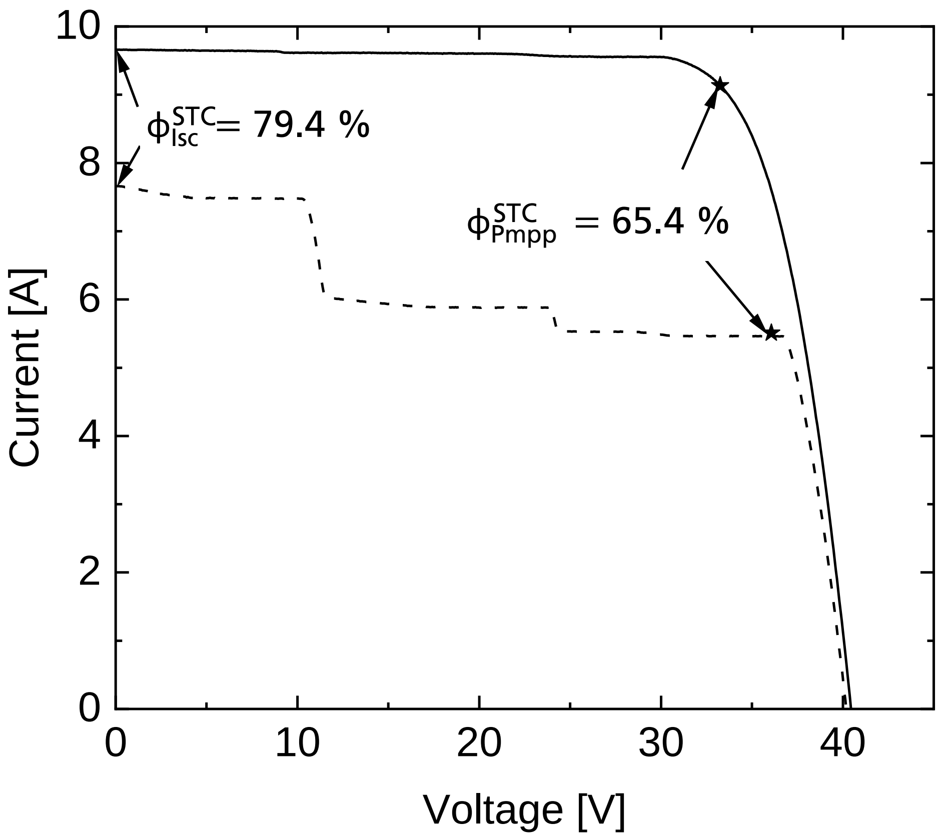
Amendment Proposal (1):
Omission of minimum criterion

- For all bifacial cells and modules:

$$\phi = \phi_{Isc}$$

- Physically more meaningful weight for rear irradiance:

$I_{sc} = \text{const} \cdot G$ for linear solar cells



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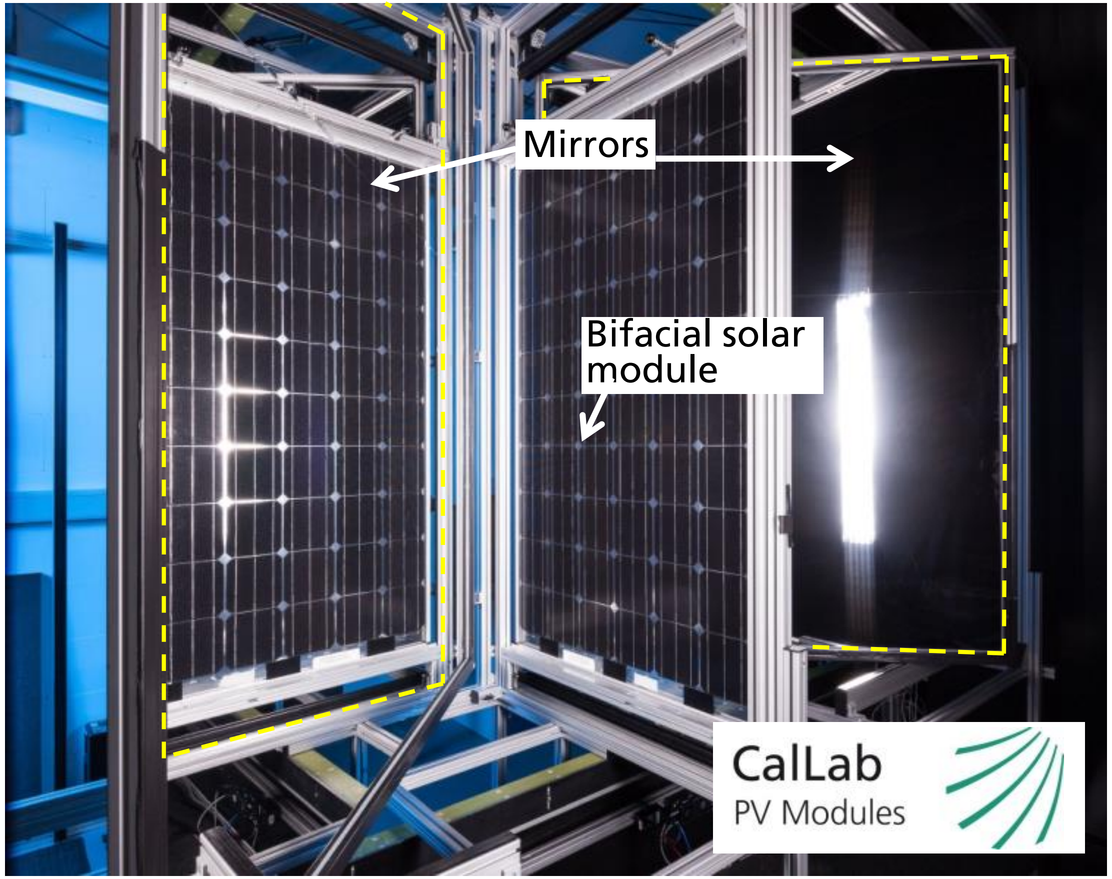
Partial Rear Shading

Comparison of Bifacial and G_E Method

- *I-V* measurement of modules A and B with bifacial method and G_E method using two-mirror setup*
- Measurement of P_{mpp} as function of G_{rear}



*Further details: A. Schmid, 32nd EUPVSEC, 2016.

Partial Rear Shading

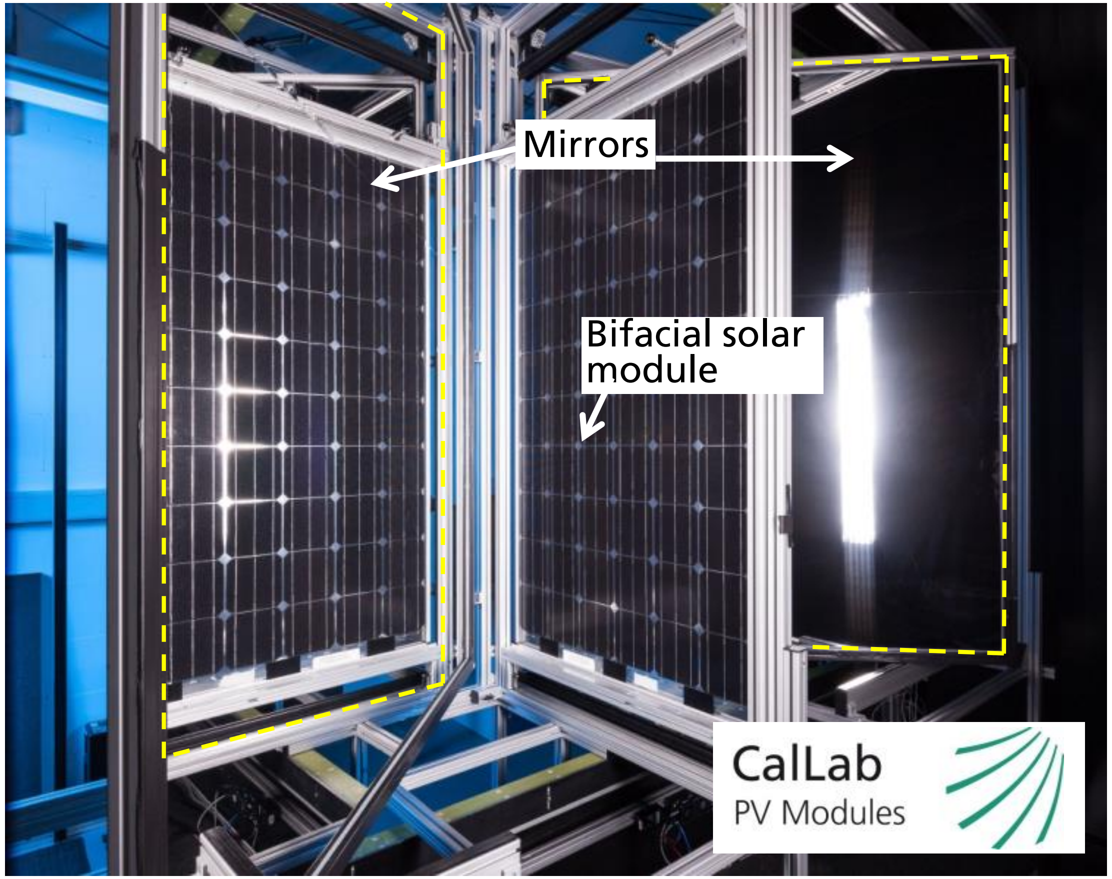
Comparison of Bifacial and G_E Method

- *I-V* measurement of modules A and B with bifacial method and G_E method using two-mirror setup*
- Measurement of P_{mpp} as function of G_{rear}

→ Evaluation of bifaciality coefficients as input for G_E method:

IEC TS 60904-1-2: $\phi = \min(\phi_{Isc}^{STC}, \phi_{Pmpp}^{STC})$

This study: $\phi = \phi_{Isc}^{G_{front}}$



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Comparison of Bifacial and G_E Method

Module A: Optimized for bifacial applications

- **Both-sided illumination (*Bifacial method*):**

  Front irradiance: G_{front} = 1000 W/m²

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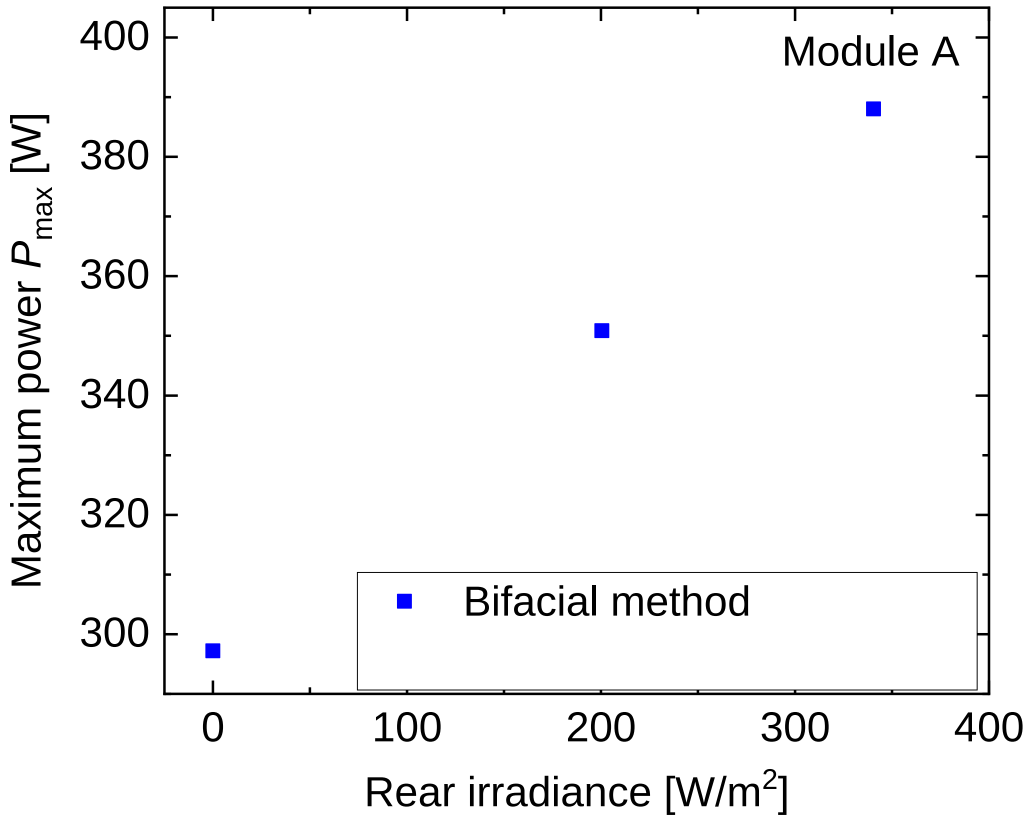

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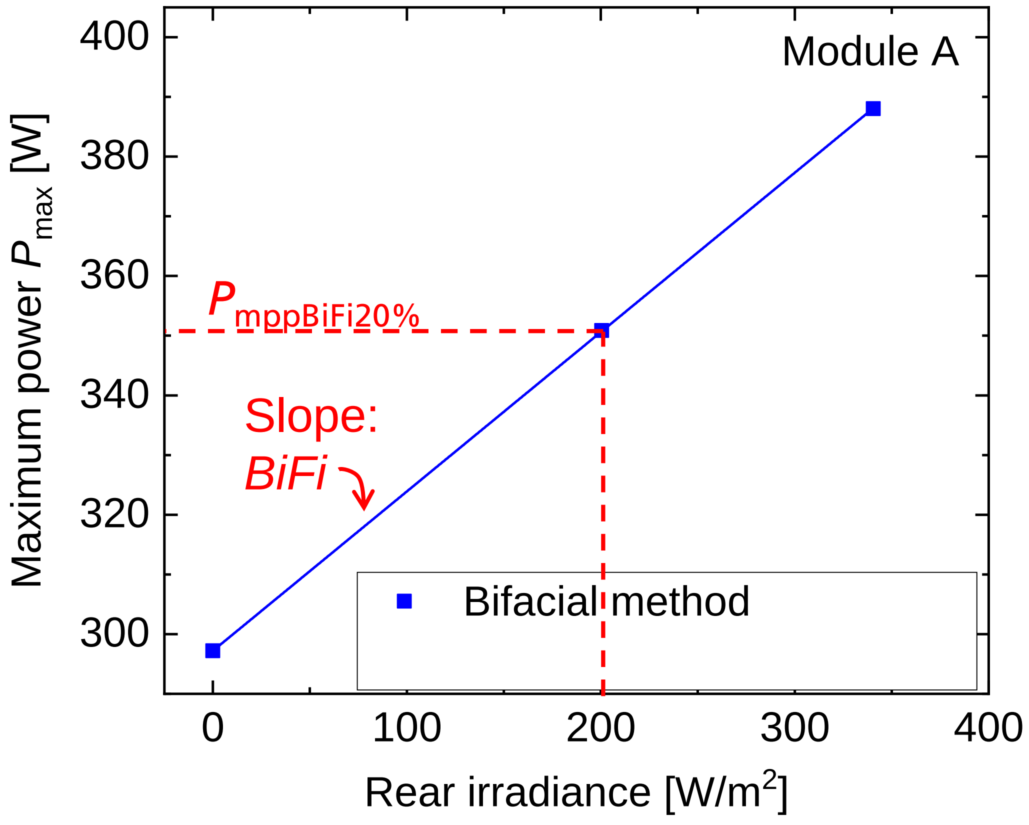

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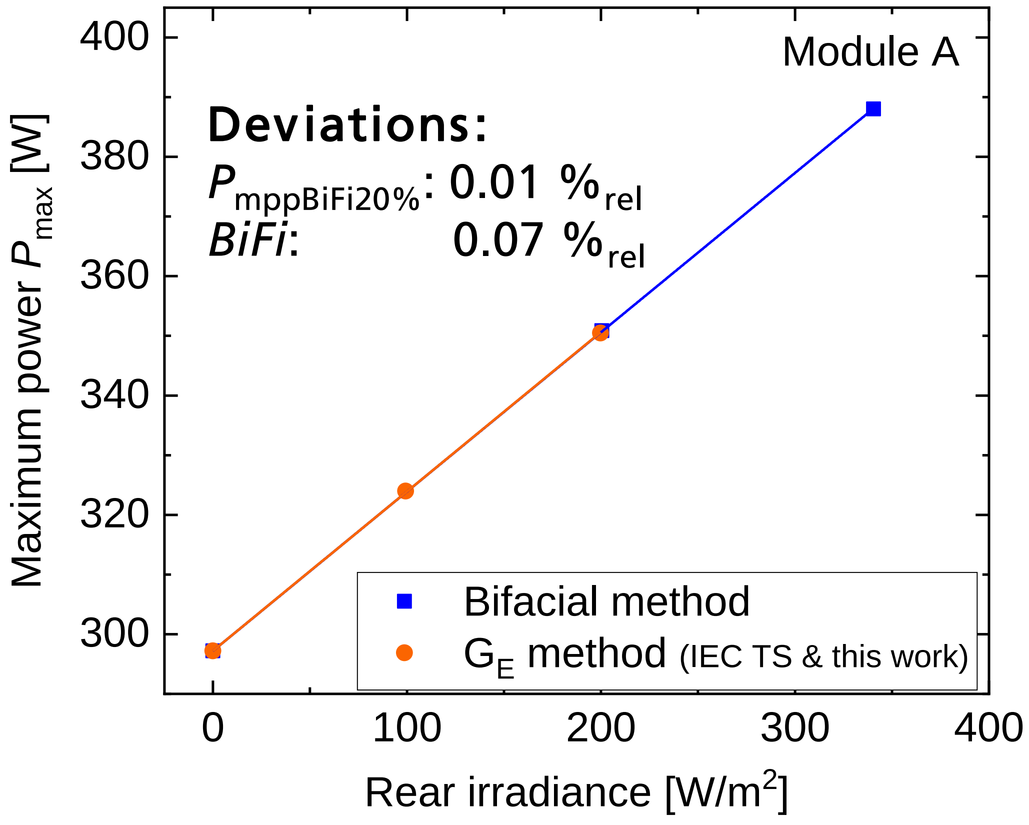
- **Single-sided illumination (*G_E method*):**

  Front irradiance: $G_E = G_{front} + \phi \cdot G_{rear}$

  IEC TS: ϕ_{Isc}
  This study: ϕ_{Isc}



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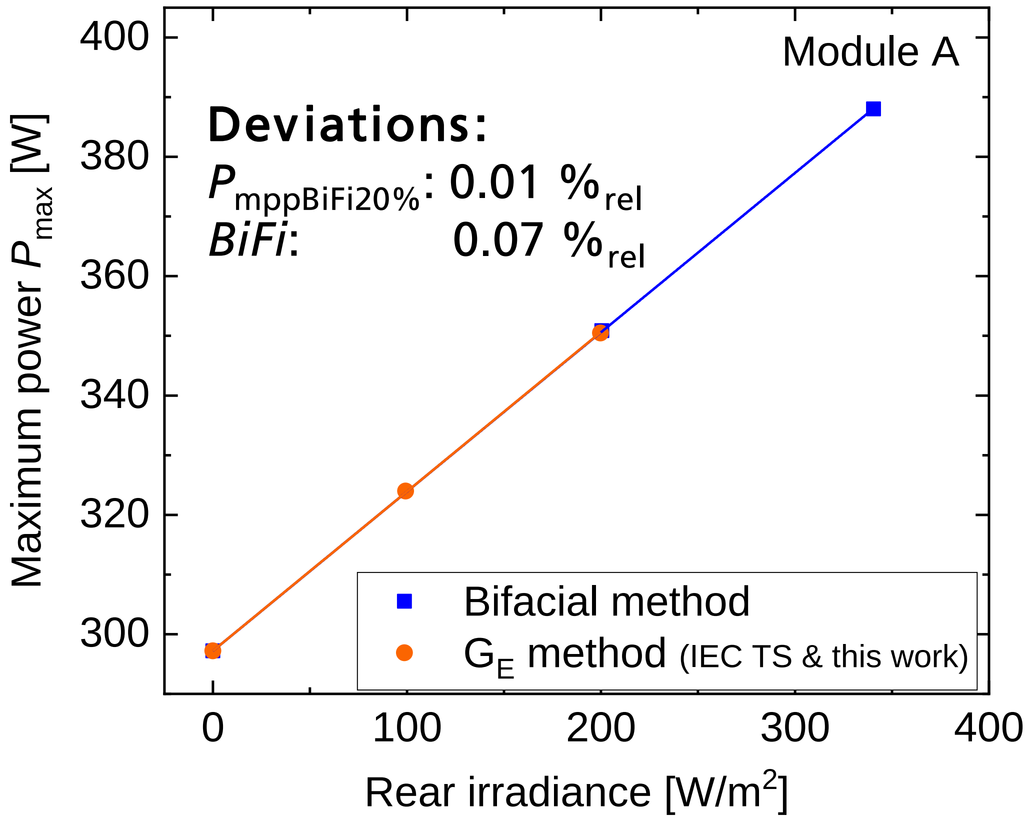
- **Single-sided illumination (*G_E method*):**

  Front irradiance: $G_E = G_{front} + \phi \cdot G_{rear}$

→ Good accordance between both methods for approaches of IEC TS 60904-1-2 and this study



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Partial Rear Shading
Comparison of Bifacial and G_E Method

Module B: With partial rear shading

- **Both-sided illumination** (*Bifacial method*):

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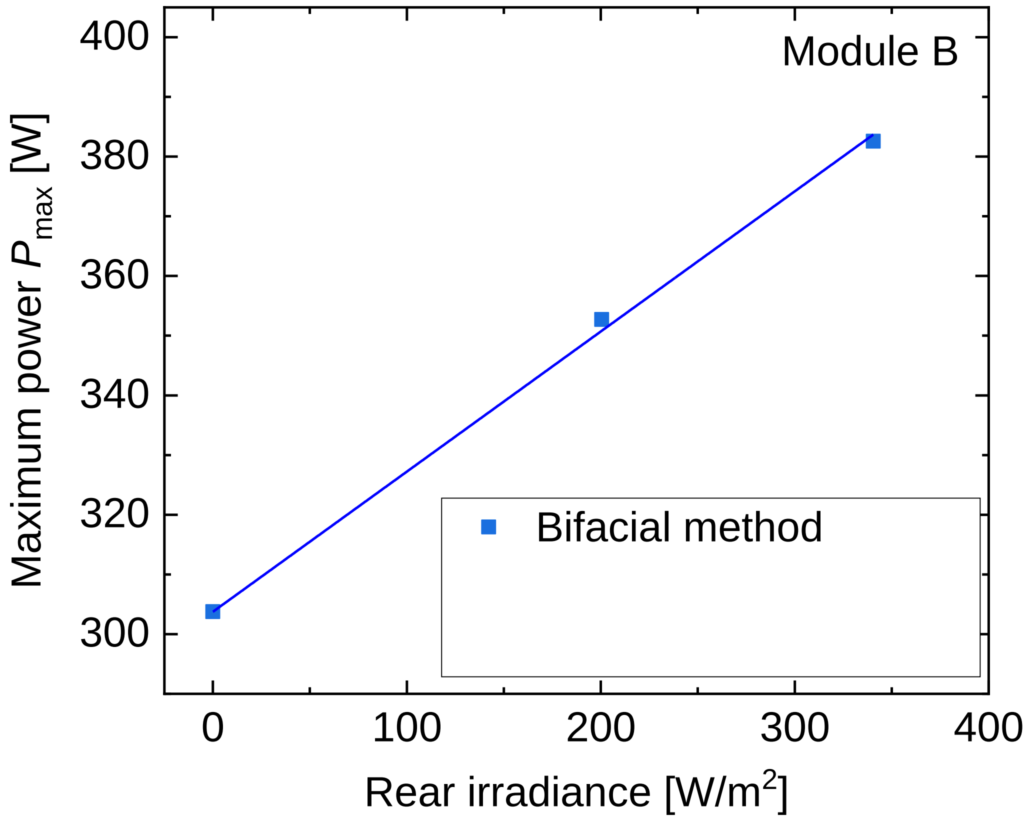
  Rear irradiance: G_{rear} = 100 to 300 W/m²



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Partial Rear Shading
Comparison of Bifacial and G_E Method

Module B: With partial rear shading

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- **Single-sided illumination (*G_E method*):**

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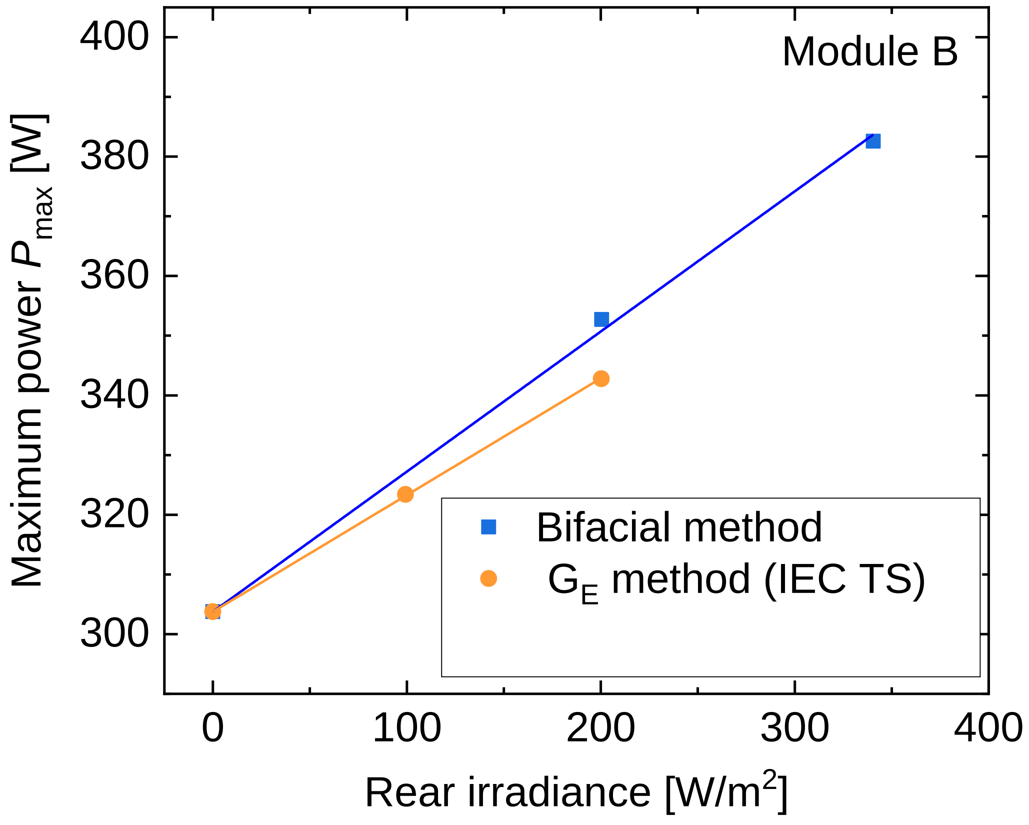
IEC TS: ϕ_{Pmpp}
This study: ϕ_{Isc}



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Partial Rear Shading

Comparison of Bifacial and G_E Method

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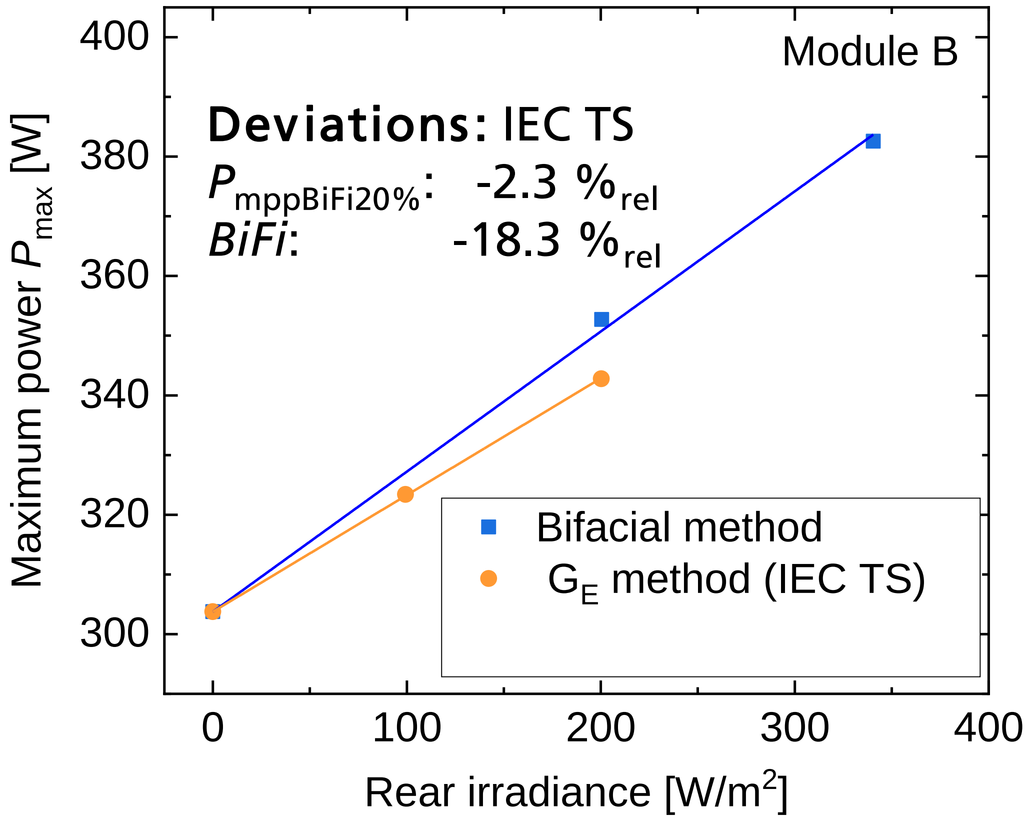
- **Single-sided illumination (*G_E method*):**

  Front irradiance: $G_E = G_{front} + \phi \cdot G_{rear}$

→ IEC TS 60904-1-2: G_E and P_{mpp} underestimated



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Partial Rear Shading

Comparison of Bifacial and G_E Method

Module B: With partial rear shading

- **Both-sided illumination (*Bifacial method*):**

  Front irradiance: $G_{front} = 1000$ W/m²

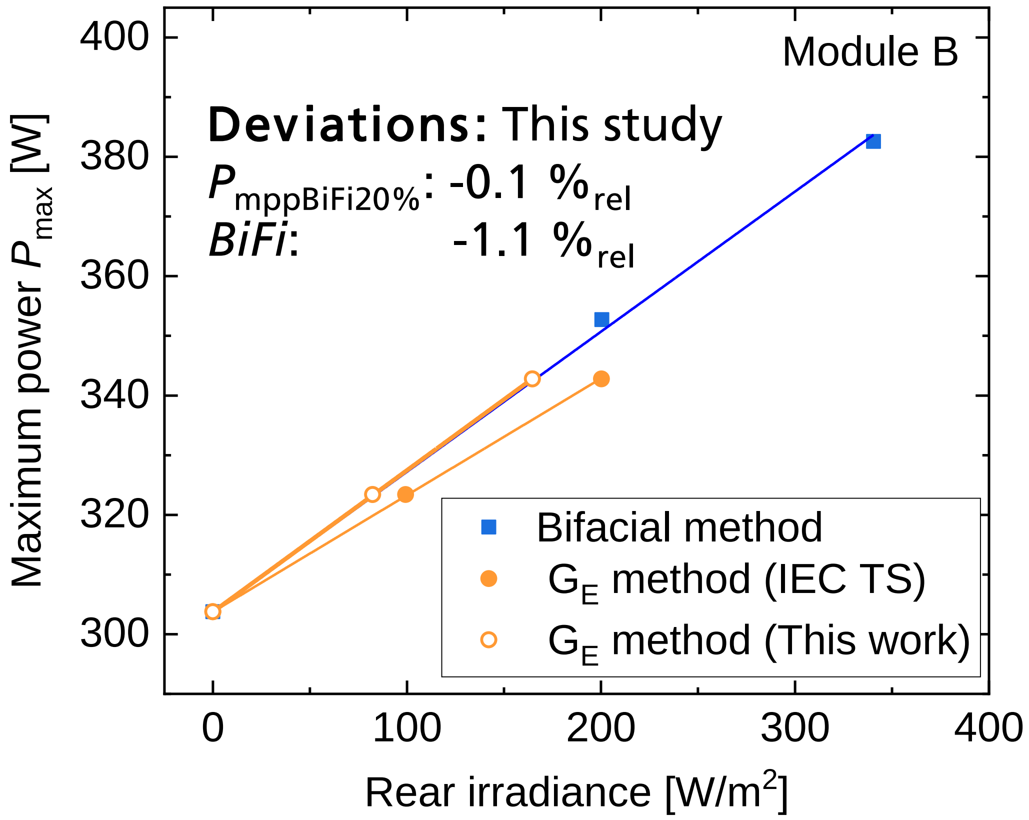
  Rear irradiance: $G_{rear} = 100$ to 300 W/m²

- **Single-sided illumination (*G_E method*):**

  Front irradiance: $G_E = G_{front} + \phi \cdot G_{rear}$

→ IEC TS 60904-1-2: G_E and P_{mpp} underestimated

→ This study: Agreement significantly improved



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Partial Rear Shading

Comparison of Bifacial and G_E Method

Module B: With partial rear shading

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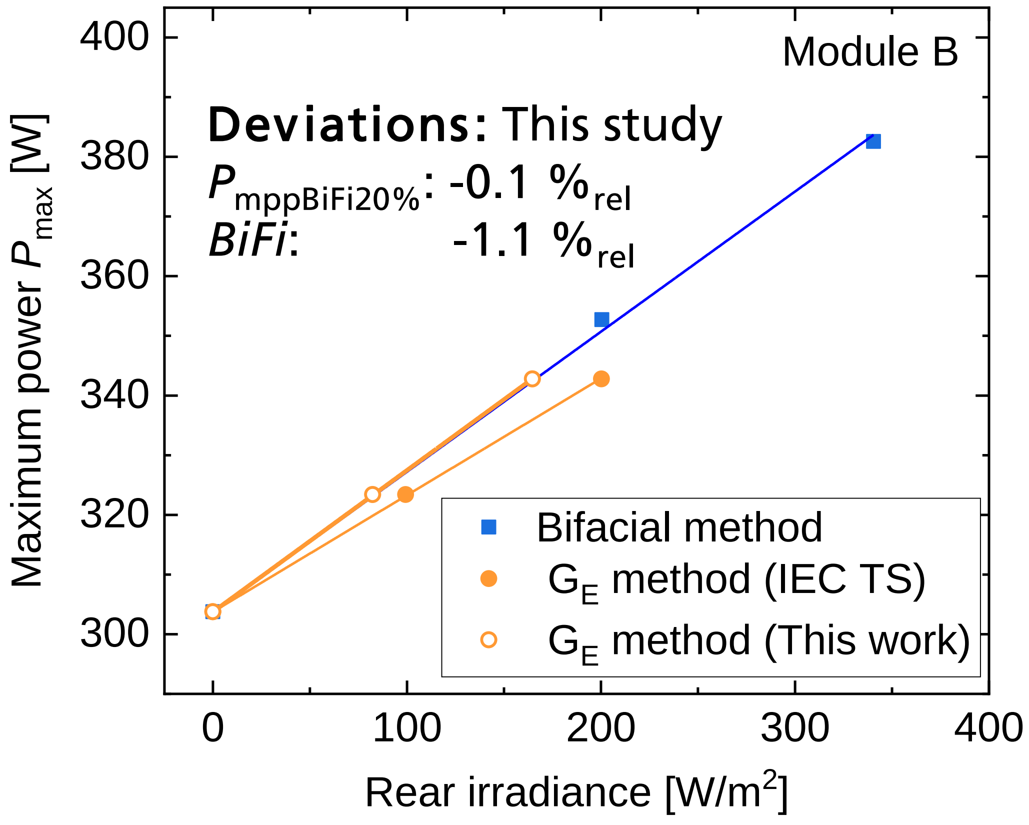
More systematic investigation of impact of partial rear shading



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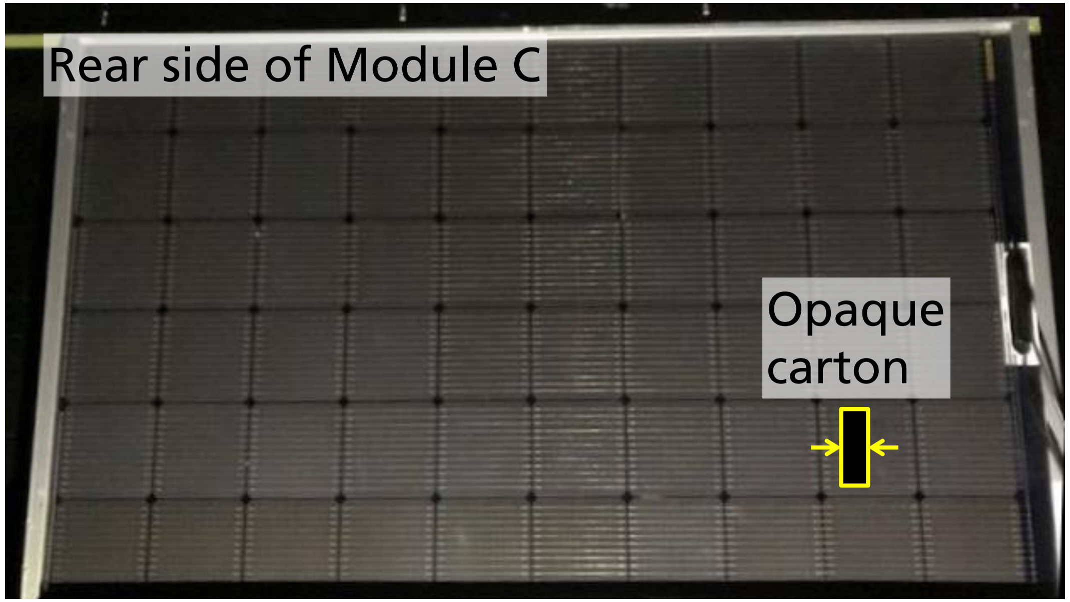
Partial Rear Shading
Systematic Variation of Shading

- Two different modules with different ϕ_{Isc}
  - 84 % (Module C)
  - 56 % (Module D)
- Coverage of rear by black opaque carton
  - One solar cell in string already affected by built-in shading
- Systematic variation of shading percentage
  - None, 20%, 30%, 40% of cell area



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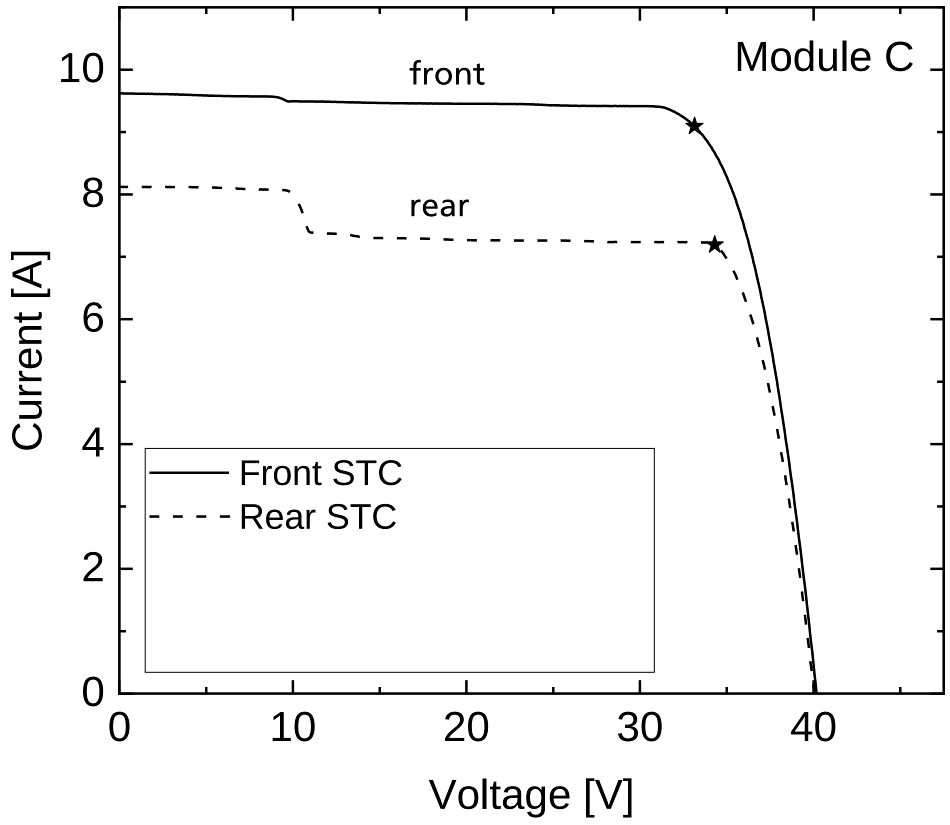
Partial Rear Shading

Systematic Variation of Shading

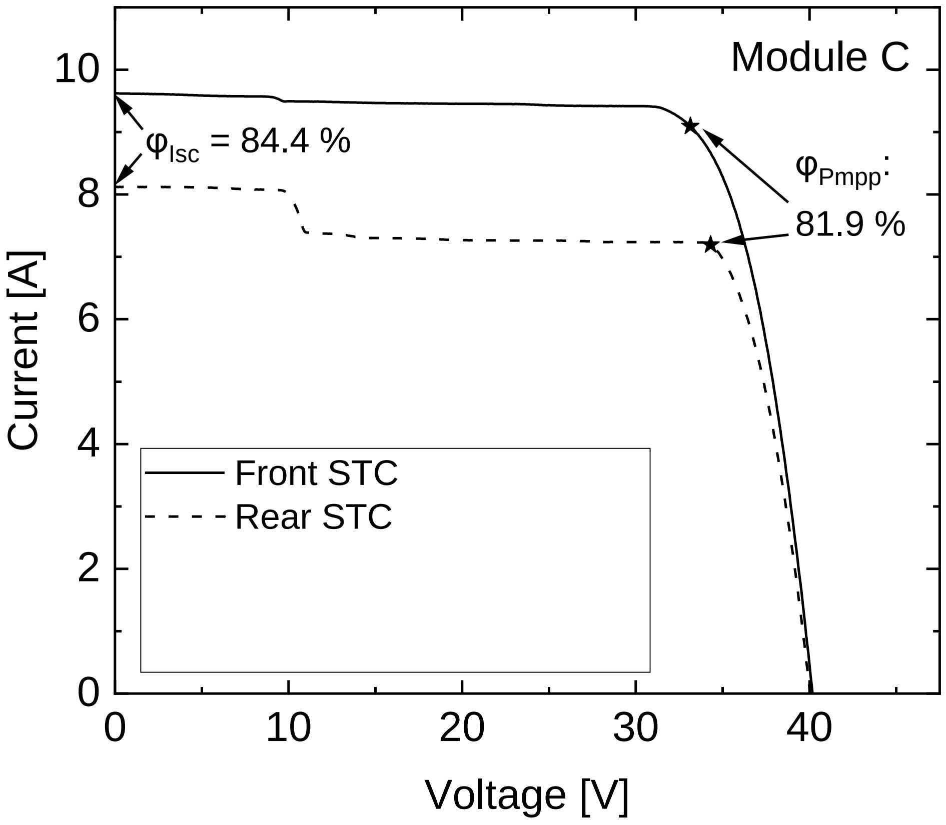
- *I-V* measurement of front and rear at STC for different rear shading fractions



Partial Rear Shading

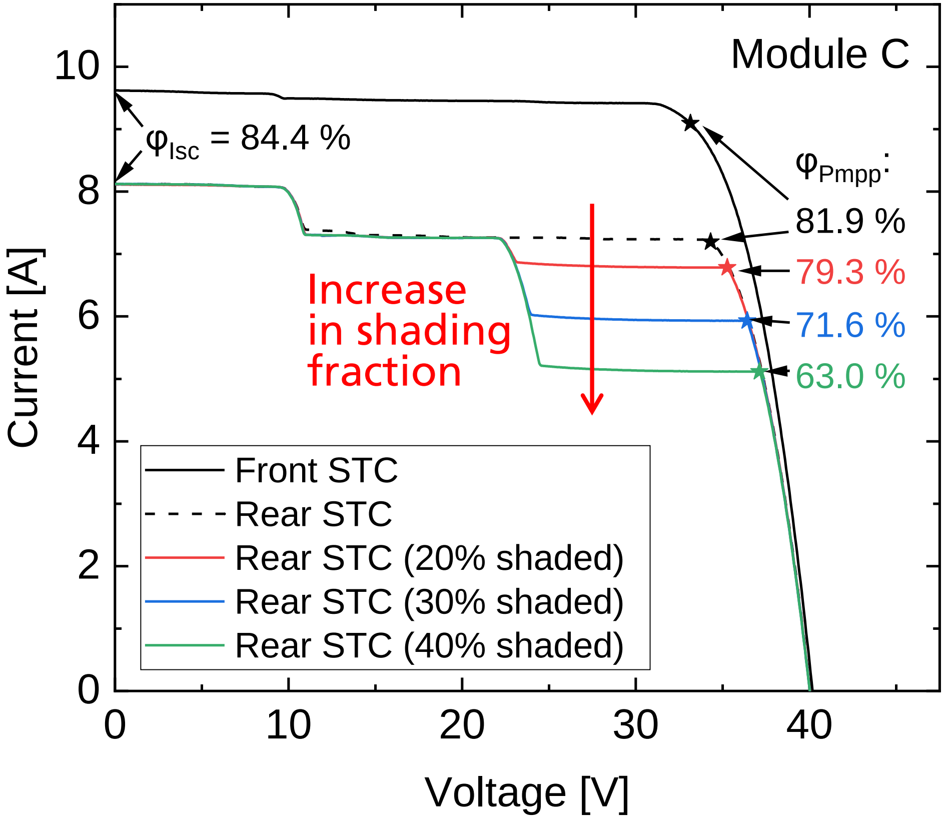
Systematic Variation of Shading

- *I-V* measurement of front and rear at STC for different rear shading fractions
- Difference in ϕ_{Isc} and ϕ_{Pmpp} due to built-in rear shading



Partial Rear Shading
Systematic Variation of Shading

- *I-V* measurement of front and rear at STC for different rear shading fractions
- Difference in ϕ_{Isc} and ϕ_{Pmpp} due to built-in rear shading
- Further reduction of rear *I-V* curve near mpp by additional shading



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Partial Rear Shading

Systematic Variation of Shading

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- Difference in ϕ_{Isc} and ϕ_{Pmpp} due to built-in rear shading
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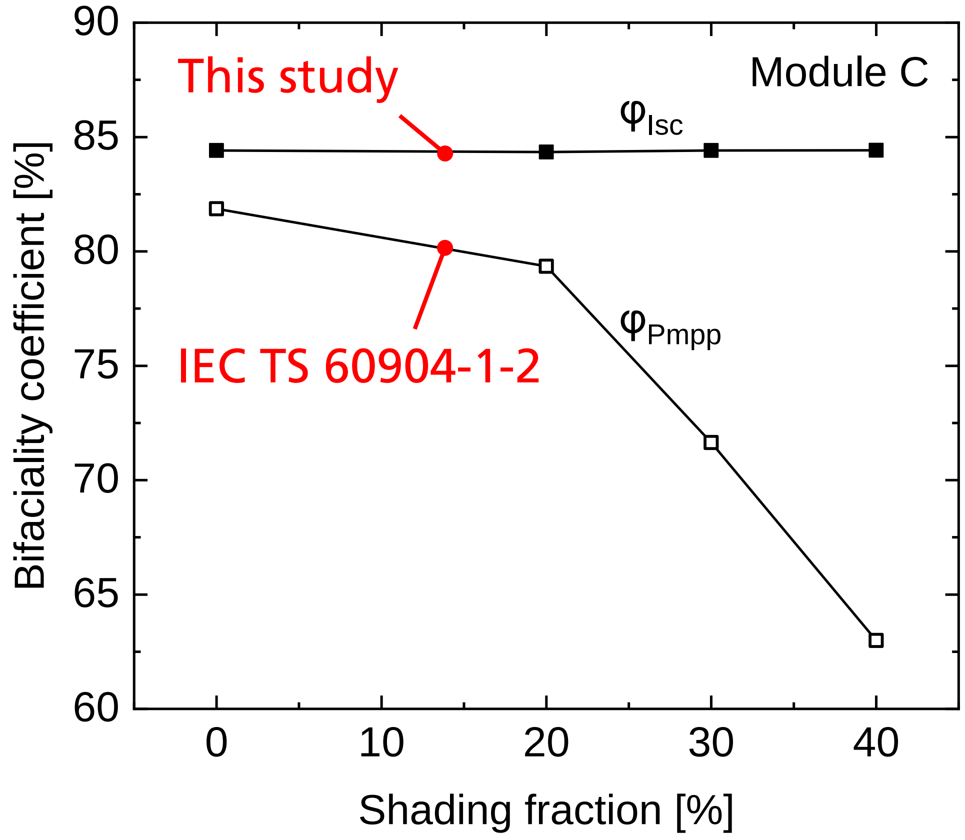
→ Reduction of ϕ_{Pmpp}, consistency of ϕ_{Isc}

How does this affect the G_E methods?



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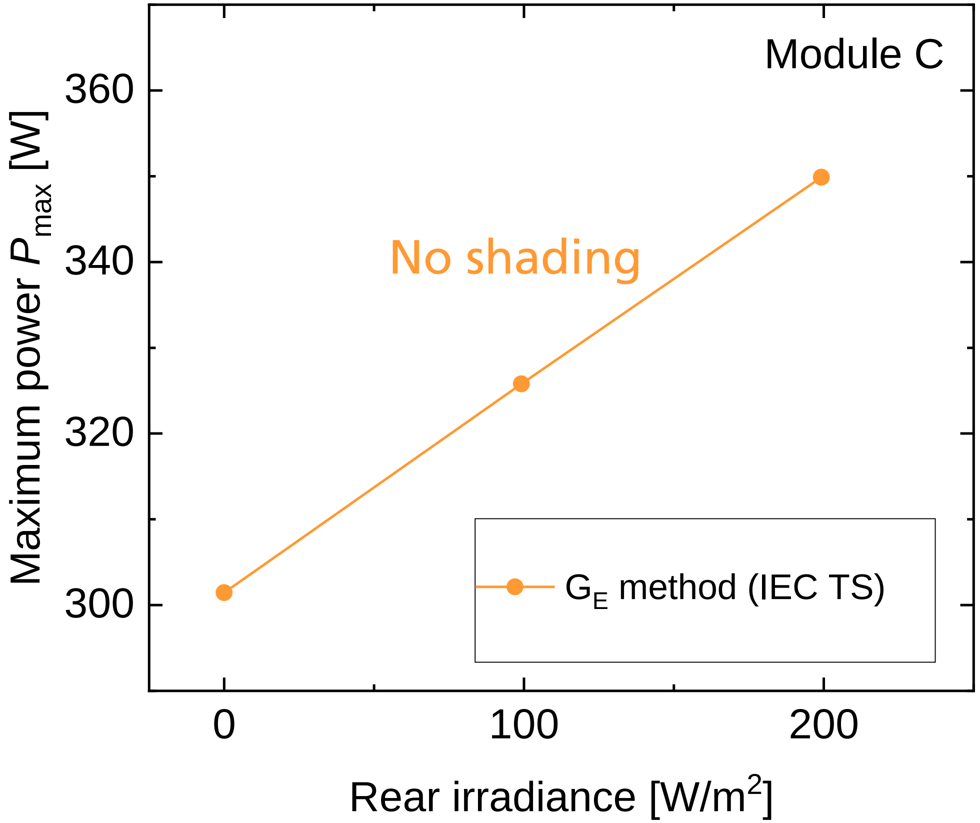
Partial Rear Shading

Systematic Variation of Shading

Single-sided illumination (*G_E method*):

- IEC TS: Strongly affected by shading due to minimum criterion



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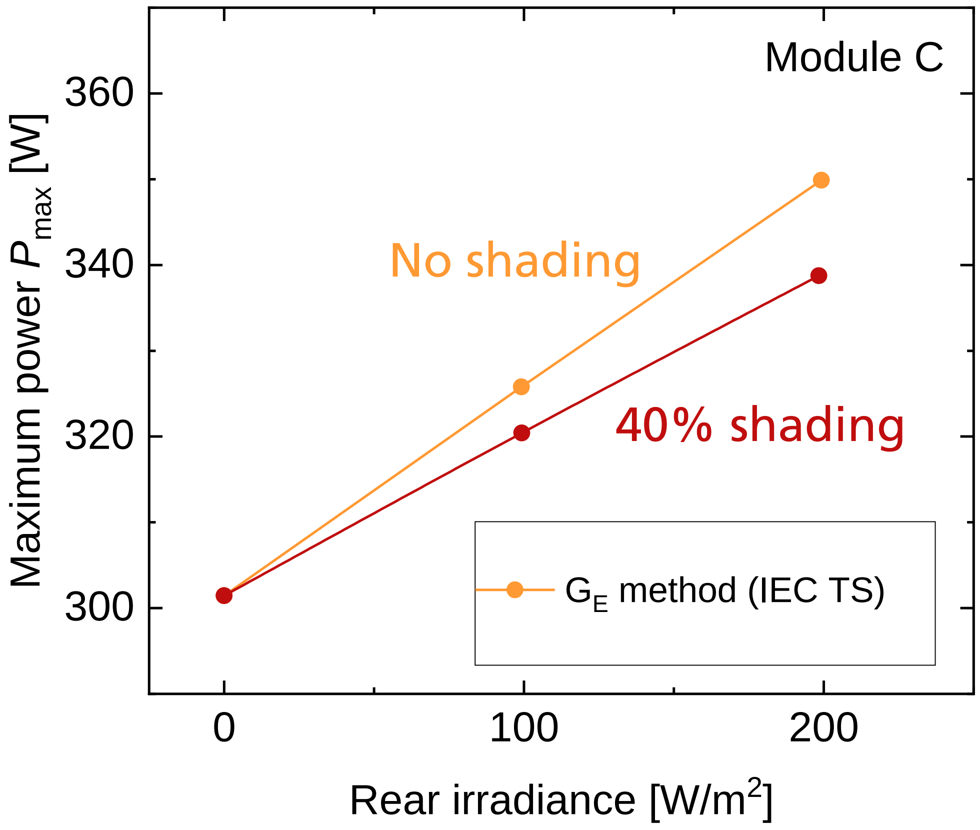

Partial Rear Shading
Systematic Variation of Shading

Single-sided illumination (*G_E method*):

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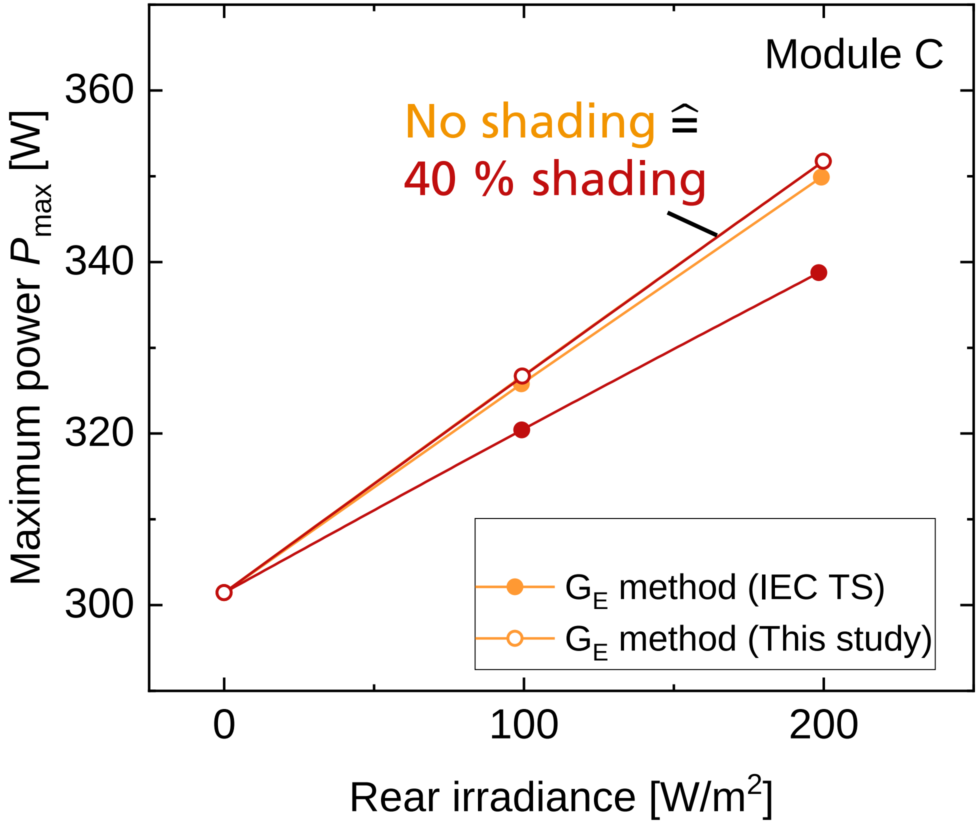
- This study: Not affected by shading due to constancy of ϕ_{Isc}



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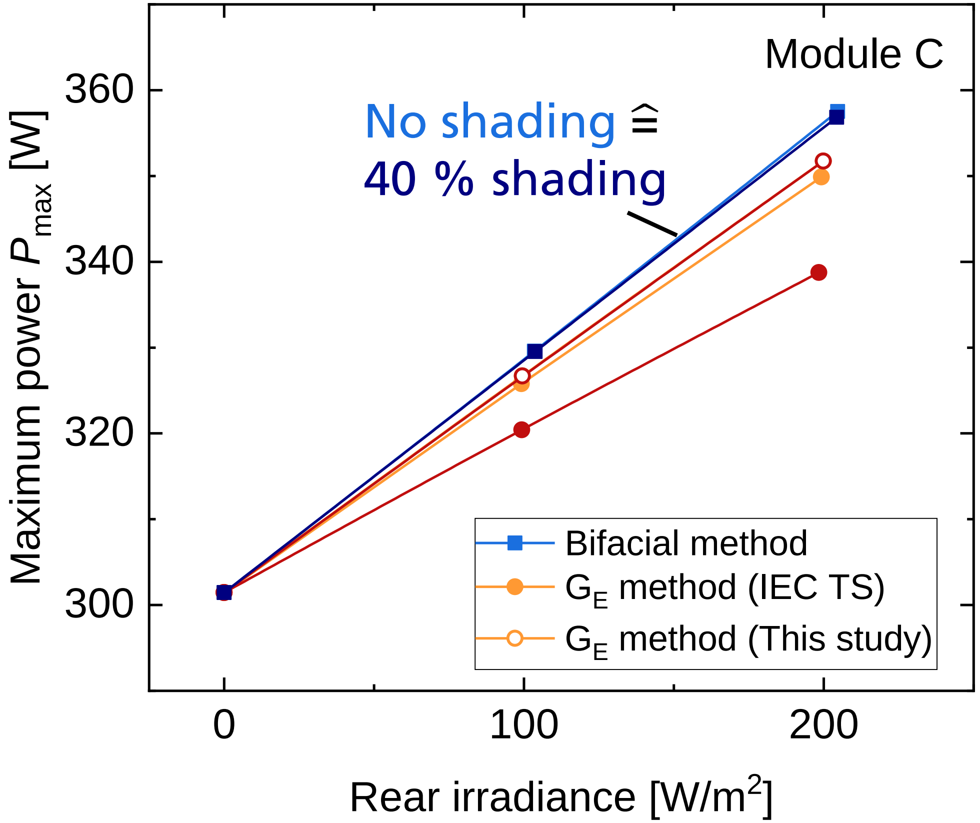
Both-sided illumination (*Bifacial method*):

- mpp not affected by shading for realistic measurement and shading scenarios
- Rear kinks superimposed by much larger front contribution



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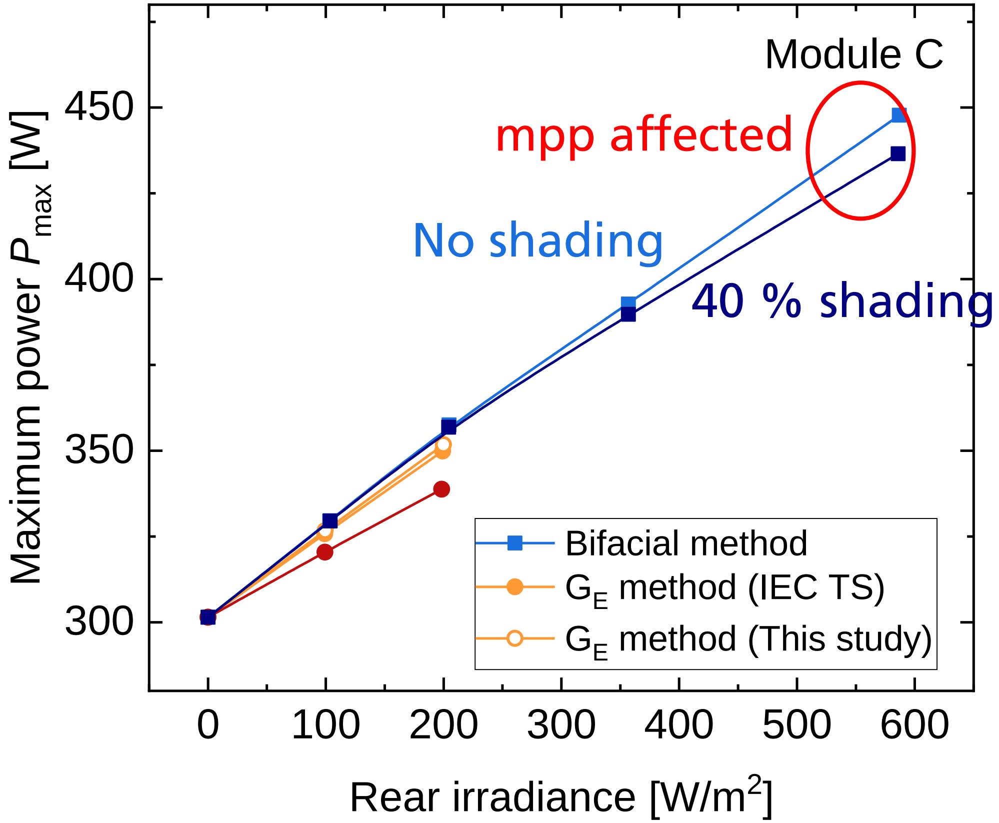

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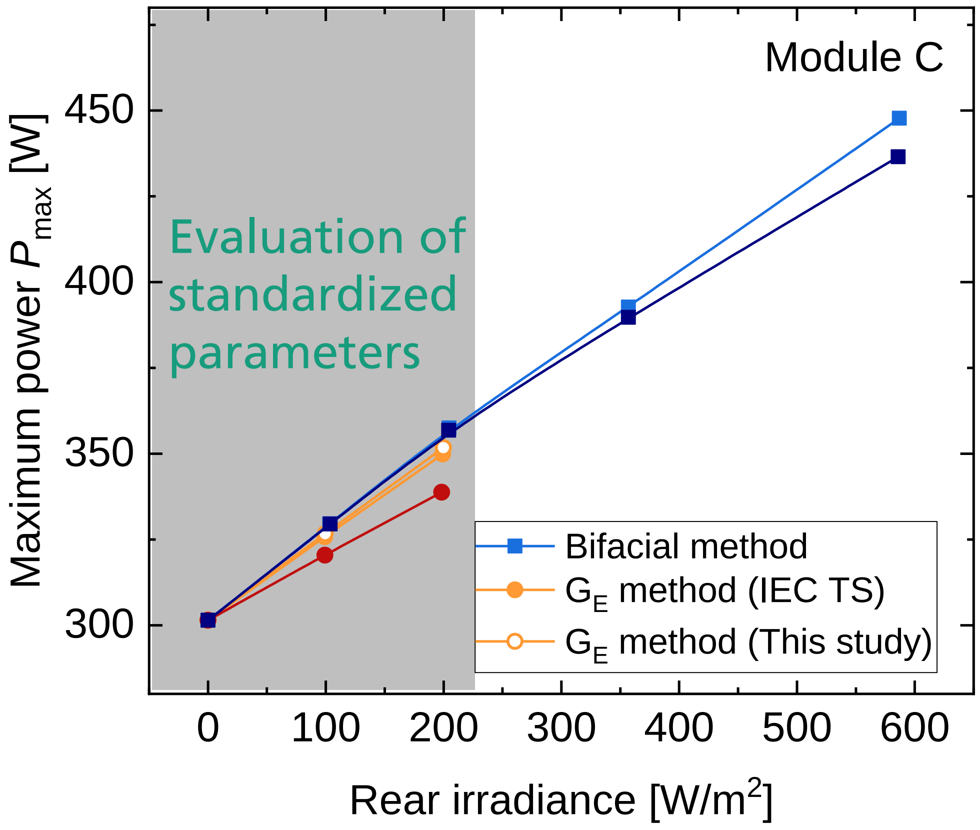

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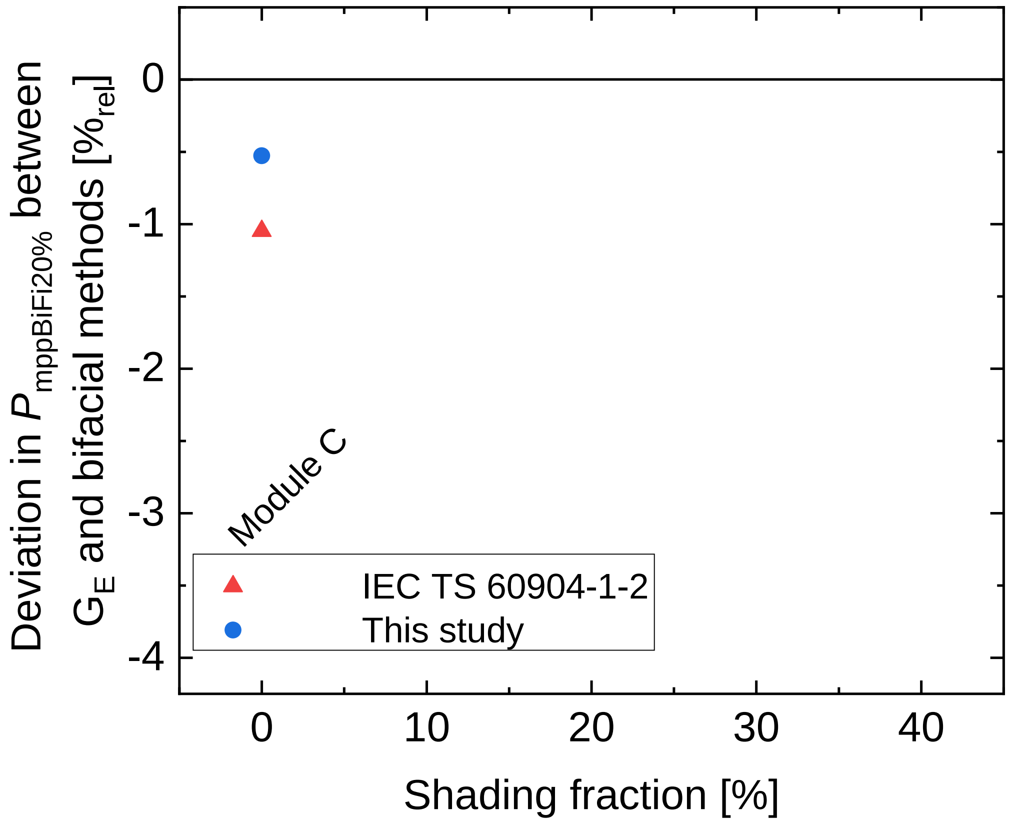
Partial Rear Shading
Systematic Variation of Shading

Difference between bifacial method and G_E methods



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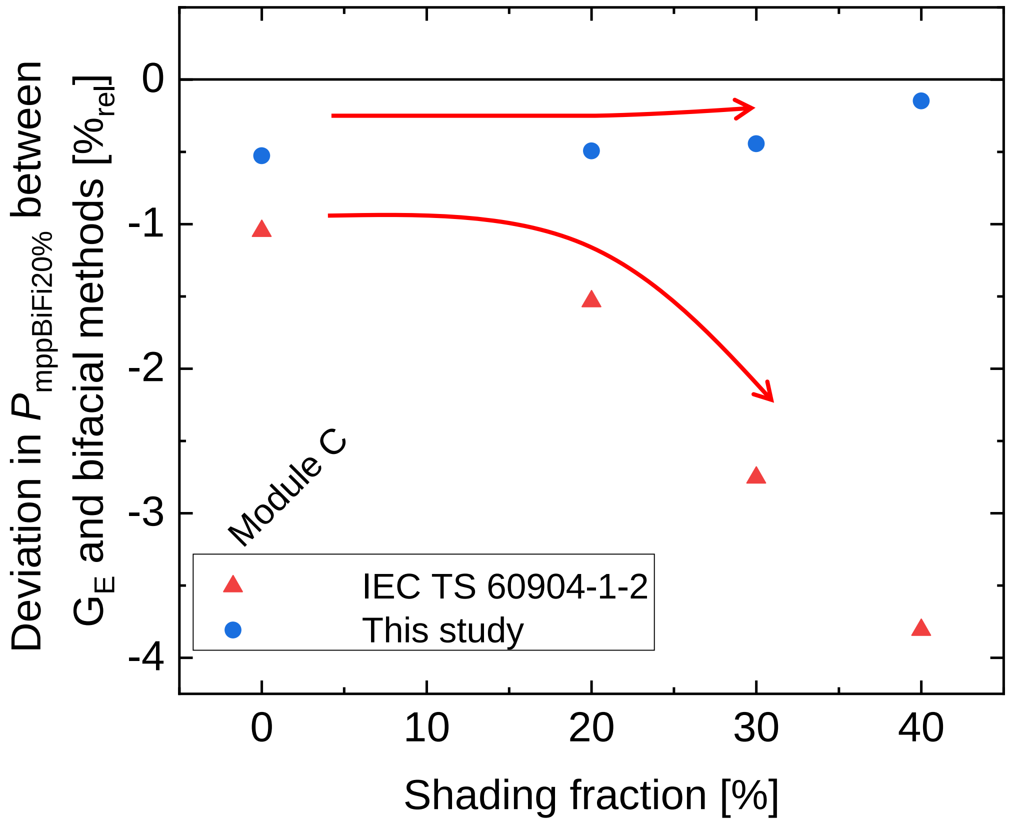
Partial Rear Shading
Systematic Variation of Shading

Difference between bifacial method and G_E methods

- IEC TS: Difference between methods increasing with increasing rear shading fraction
- This study: Improved agreement between bifacial and G_E methods



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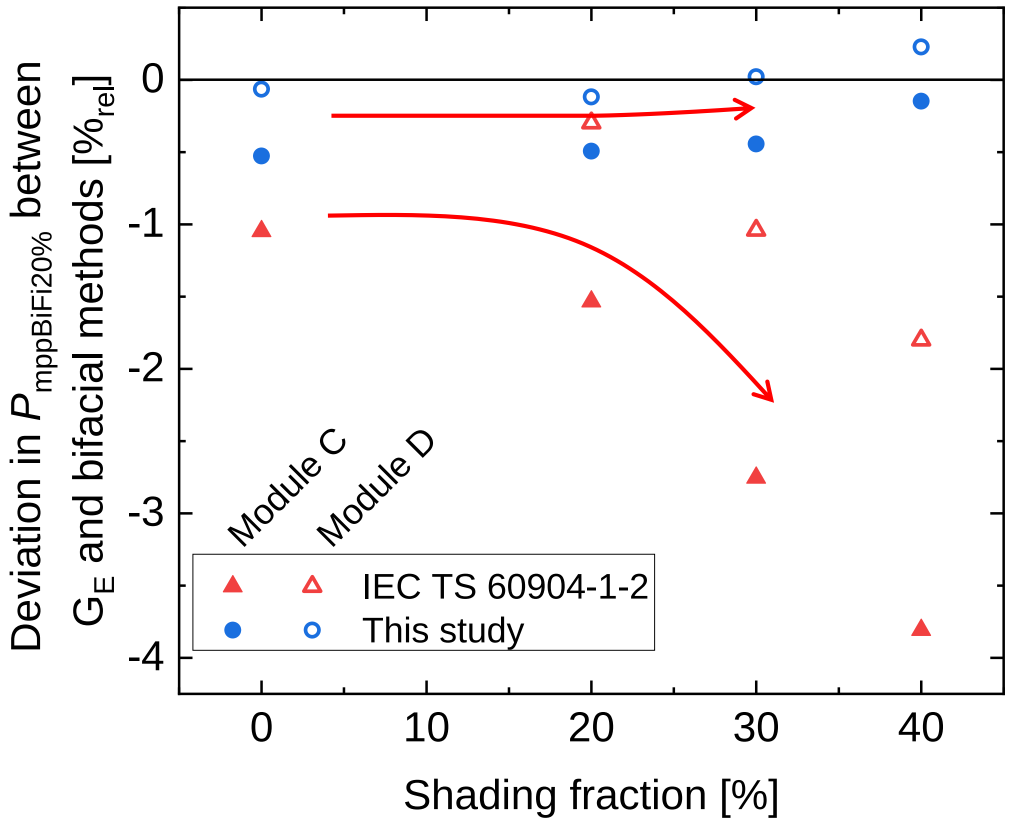
Application of G_E method using ϕ_{Isc} essential to correctly consider partial rear shading

For evaluation of parameter *BiFi* please see proceedings paper



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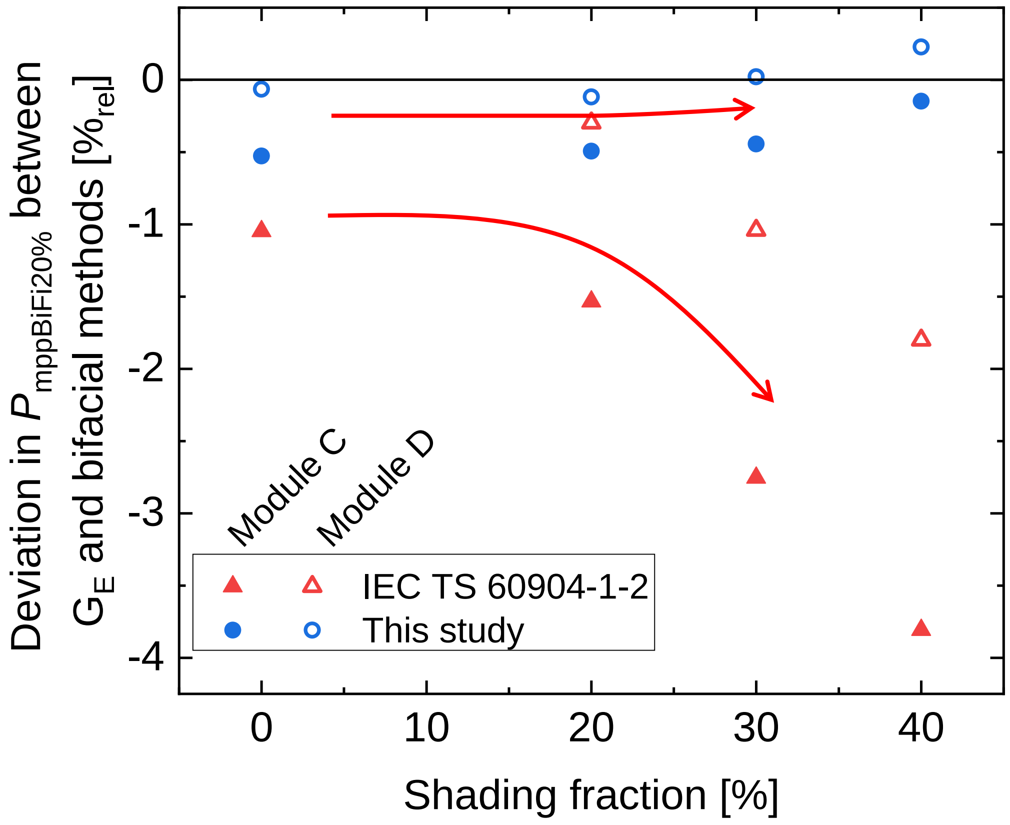
Criterion for applicability of G_E method using ϕ_{Isc} in proceedings paper



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AGENDA

- Introduction to IEC TS 60904-1-2
- Amendment Proposal 1
  - Motivation and Derivation
  - Evaluation: Partial Rear Shading
- Amendment Proposal 2
  - Motivation and Derivation
  - Evaluation: Low-Light Conditions
- Summary

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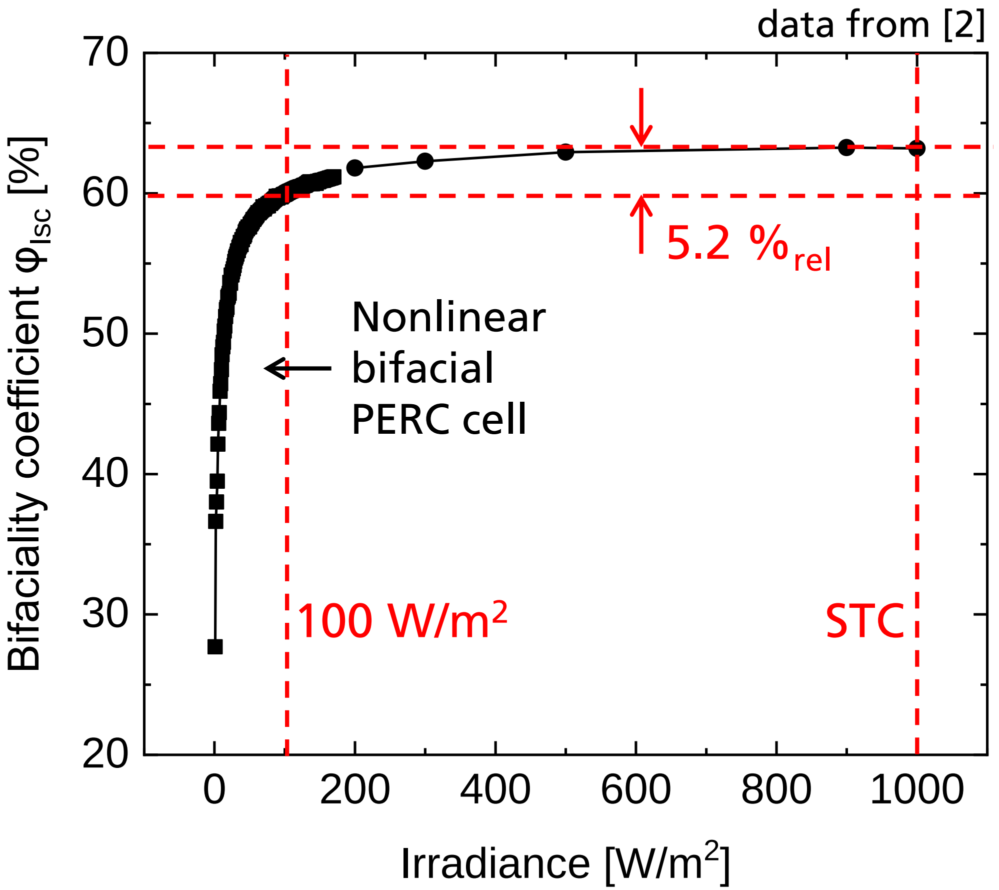
Amendment Proposal 2

Generalized Bifaciality Coefficients

Nonlinear bifacial solar cell

- Front and rear I_{sc} and P_{mpp} depend differently on irradiance

→ Bifaciality coefficients also depend on irradiance [1,2]



[1] B. Müller, 5th bifiPV workshop, Denver, 2018.
[2] M. Rauer, 36th EUPVSEC, Marseille, 2019.

Amendment Proposal 2
Generalized Bifaciality Coefficients

Nonlinear bifacial solar cell

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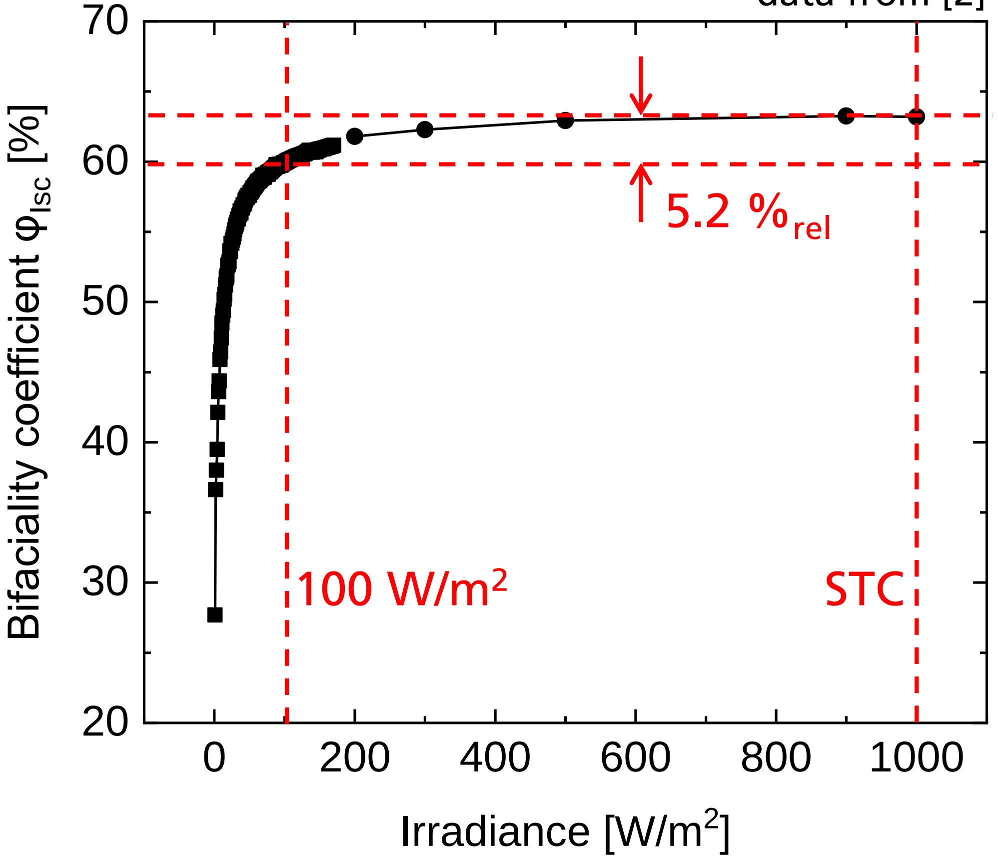
⟶ Bifaciality coefficients also depend on irradiance [1,2]

Generalized bifaciality coefficients

Evaluation of ϕ_{Isc} at irradiance of measurement

- I_{sc} bifaciality: $\phi_{Isc}^{G} = \dfrac{I_{sc,rear}(G)}{I_{sc,front}(G)}$

data from [2]



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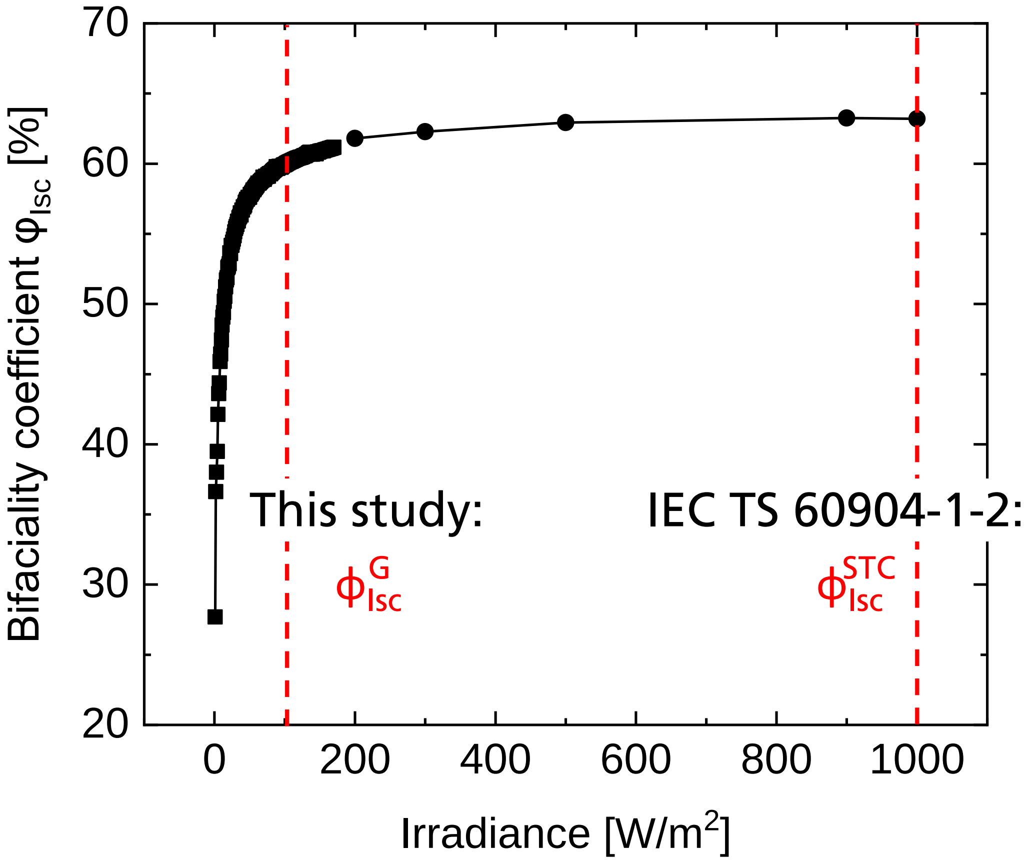
Amendment Proposal 2
Generalized Bifaciality Coefficients

Amendment Proposal (2):
Application of generalized bifaciality coefficients evaluated at irradiance of measurement

- Amendment only for low-light conditions
- Similar to IEC TS for measurements at STC



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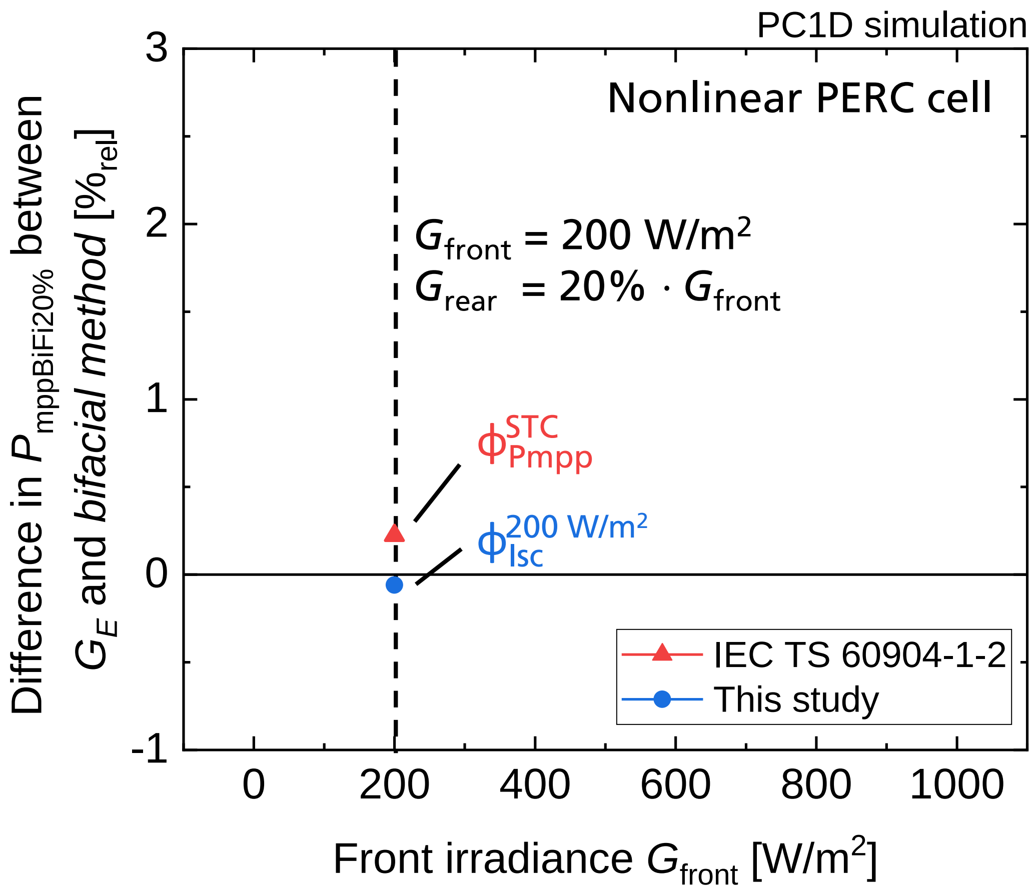
Low-Light Performance of Nonlinear Bifacial Solar Device
Results

- Simulation of different bifacial PERC solar cells by PC1D [1]
- Difference in $P_{mppBiFi20\%}$ between G_E method and bifacial method determined for different front irradiance levels



[1] M. Rauer, 36th EUPVSEC, Marseille, 2019.

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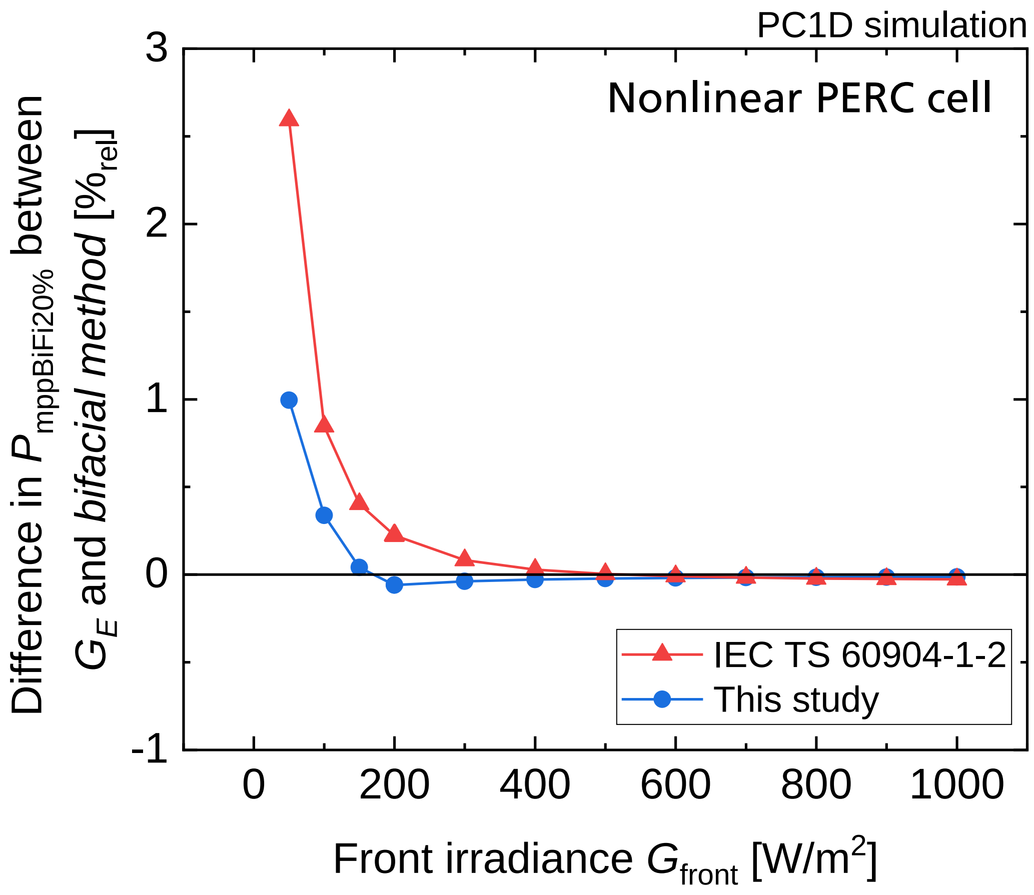
→ IEC TS: G_E method overestimates power of bifacial device in low-light conditions

→ This study: Overestimation significantly less strong by generalized bifaciality coefficients

▶ Application of ϕ_{Isc} evaluated at G_{front} leads to better agreement between two methods in low-light conditions



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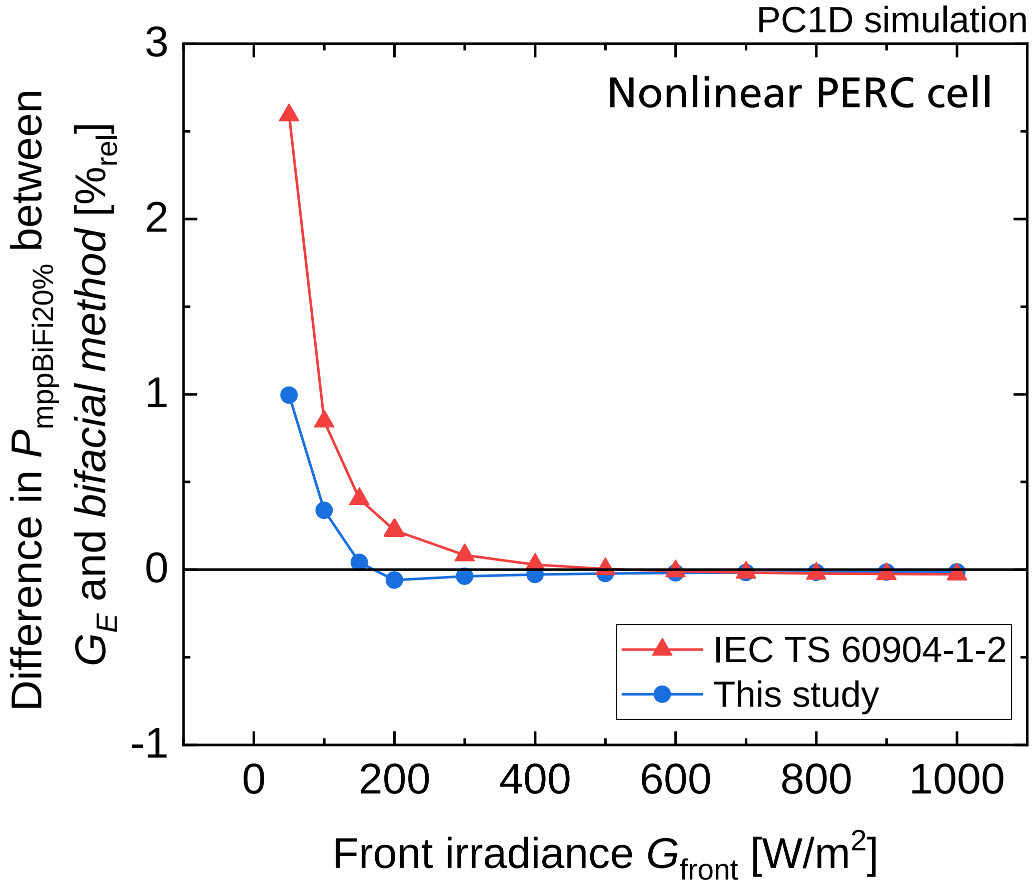
For evaluation of parameter *BiFi* please see proceedings paper

For evaluation of linear PERC solar cell please see proceedings paper



Amendment Proposals
Summary

	IEC TS 60904-1-2	This study
Bifaciality coefficients	$\phi_{Isc}^{STC} = \frac{I_{sc,rear}^{STC}}{I_{sc,front}^{STC}}$ $\phi_{Pmpp}^{STC} = \frac{P_{mpp,rear}^{STC}}{P_{mpp,front}^{STC}}$	$\phi_{Isc}^{G} = \frac{I_{sc,rear}(G)}{I_{sc,front}(G)}$
Application of coefficients	$\phi = \min(\phi_{Isc}^{STC}, \phi_{Pmpp}^{STC})$	$\phi = \phi_{Isc}^{G}$

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Summary

- Comprehensive comparison of bifacial method and G_E method as proposed by IEC TS 60904-1-2
- Analysis of bifaciality coefficients ϕ_{Isc} and ϕ_{Pmpp} as input parameters for calculation of G_E

Proposal of amendments to IEC TS 60904-1-2:

- Application of ϕ_{Isc} only for calculation of G_E and omission of minimum criterion
- Evaluation of bifaciality coefficients at the front irradiance of measurement

Evaluation of amendments: Partial rear shading and low-light conditions

- <u>IEC TS 60904-1-2</u>: Significant deviations between bifacial and G_E methods
- <u>This study</u>: Considerably improved agreement between methods

→ Recommendation to apply amendments proposed in this study

CalLab PV Cells
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Thank you very much for your attention!

Michael Rauer

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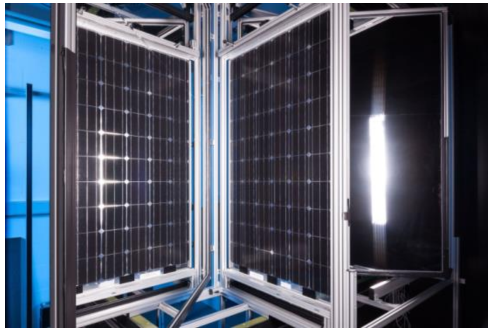
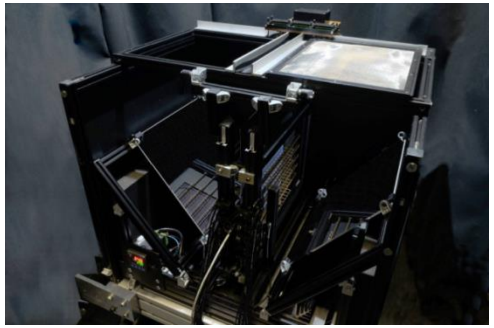
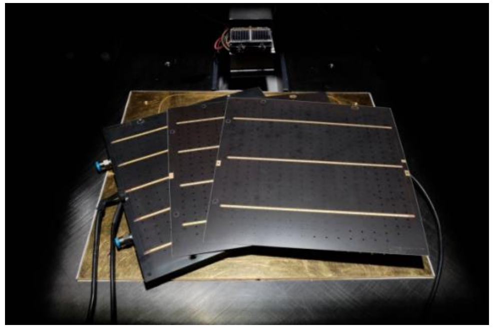
www.ise.fraunhofer.de







This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme within the project "**PV-Enerate**" (number 16ENG02).

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

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Thank you very much for your attention!

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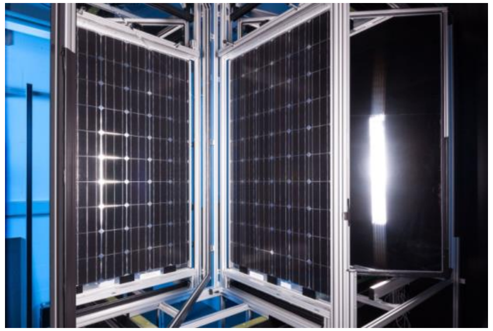
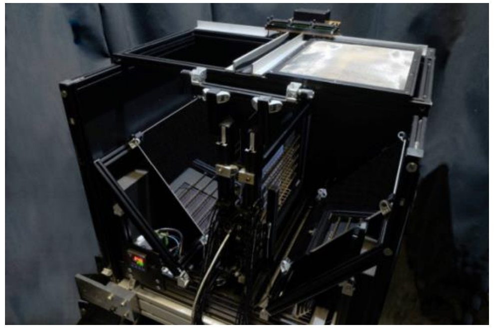
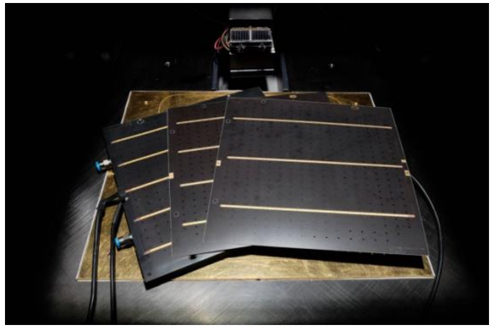
CalLab PV Modules







- Fraunhofer ISE CalLab PV Cells & CalLab PV Modules

→ Calibration services for research and industry
→ Measurements of all kinds of solar cells (single/multi junction)
→ Accredited as ISO 17025 DAkkS laboratory