Modeling Method for Rear-face Spectral Irradiance at Standard Test Condition and Its Application to Power Rating of Bifacial PV Module

标准测试条件下背面光谱辐照度的建模方法及其在双面光伏组件功率标定中的应用

11th PVPMC, 4th – 5th Dec. 2018, Weihai, China

Q. Gao[1], C. Monokroussos[1], X. Y. Zhang[1], E. Lee[1], Y.H. Wang[1], C. Zou[1],
L. Rimmelspacher[2], J. Bonilla Castro[2], M. Schweiger[2] and W. Herrmann[2]

[1] TÜV Rheinland (Shanghai) Co., Ltd., No.177, Lane 777, West Guangzhong, 200072, Shanghai, P.R. China

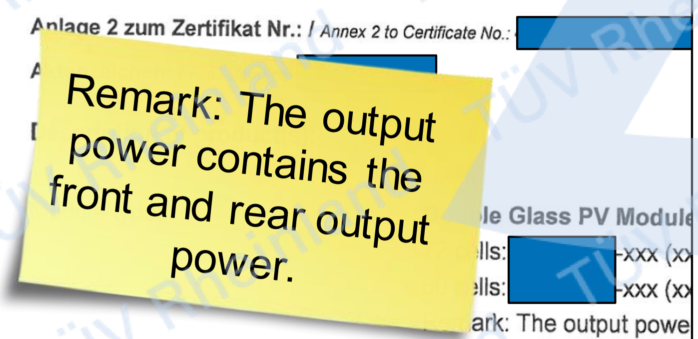
[2] TÜV Rheinland Energy GmbH, Am Grauen Stein, 51105, Cologne, Germany

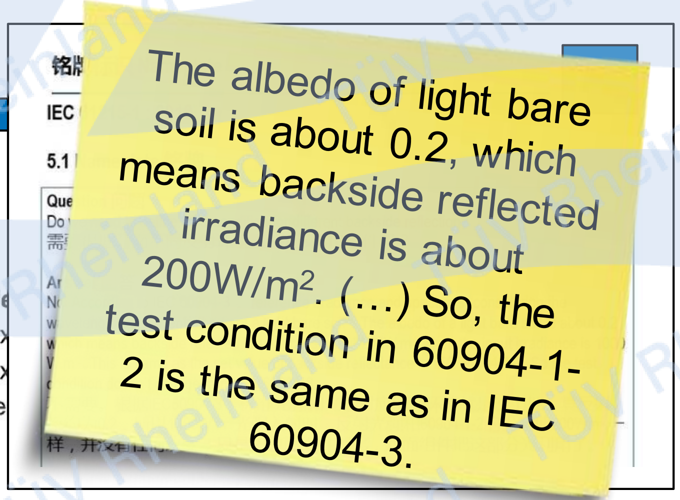
Outline

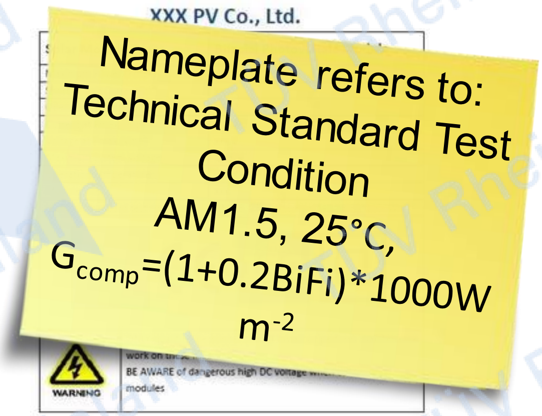
- Introduction and Motivation 研究背景
- Standard and Literature Review 双面光伏器件测试标准回顾
- Modelling Approach and Simulation Results 双面组件光谱辐照度建模方法与模拟结果
- Comparison with Outdoor Measurements 户外测试结果验证
- Definition of Bifacial Standard Test Conditions (BSTC) 双面标准测试条件
- Application to Power Rating BSTC在双面光伏组件标定中的应用
- Summary and Conclusions 总结

Introduction and Motivation 研究背景

- Sales price of PV modules is based on STC measurements
  光伏组件在标准测试条件下的标定功率直接影响其定价基准
- Bifacial modules have higher performance (PR>100%) than monofacial, due to the contribution of rear face irradiance
  由于背面辐照度增益，双面光伏组件性能比往往大于100%
- PV-modules with unclear rating conditions were seen in the market
  在光伏市场中，双面光伏组件的标定条件依然不明确







Introduction and Motivation 研究背景

- Sales price of PV modules is based on STC measurements
  光伏组件在标准测试条件下的标定功率直接影响其定价基准
- Bifacial modules have higher performance (PR>100%) than monofacial, due to the contribution of rear face irradiance
  由于背面辐照度增益，双面光伏组件性能比往往大于100%
- PV-modules with unclear rating conditions were seen in the market
  在光伏市场中，双面光伏组件的标定条件依然不明确

? Do we need a supplementary rating test condition for bifacial module performance?
对于双面光伏组件性能测试，我们是否需要一个补充测试条件？

Extension of STC needed? STC的延伸条件是否必要？

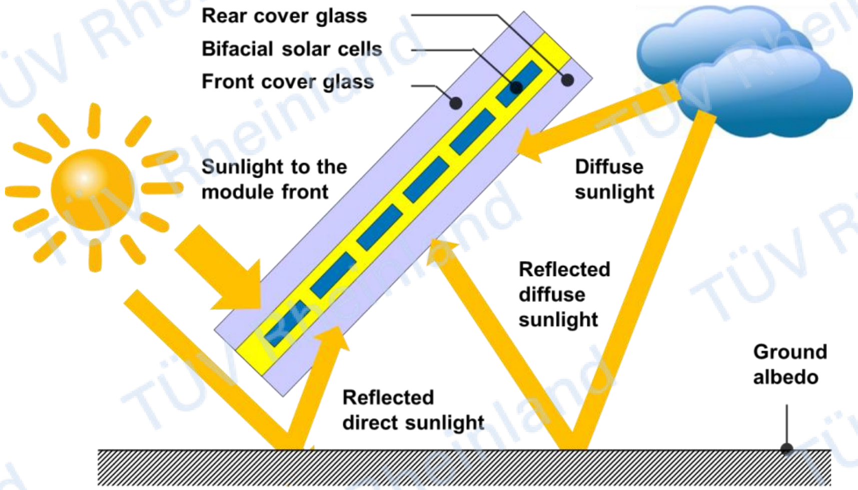
- **Fielded bifacial PV modules**

  ⇒ Field parameters greatly affected by rear side irradiance, G_R
  双面光伏组件的发电能力极大地受到背面辐照度的影响

  ⇒ Commercial bifacial module types vary in terms of bifaciality (60-90%)
  不同种类双面组件的双面率亦有所不同

- **Consumer view:** Additional power labelling to differentiate products is necessary
  从用户的角度看，额外的功率标签非常必要
- **Reference G_R value for BSTC?** BSTC中背面参考辐照度应为？
- **Ray-tracing simulations**: 光线追踪法测试结果？

  ⇒ Rear side irradiance lies in the range 120-135 W/m² for parameters given in the table using *Radiance* software
  如右表中条件，组件背面辐照度在120-135 W/m²。

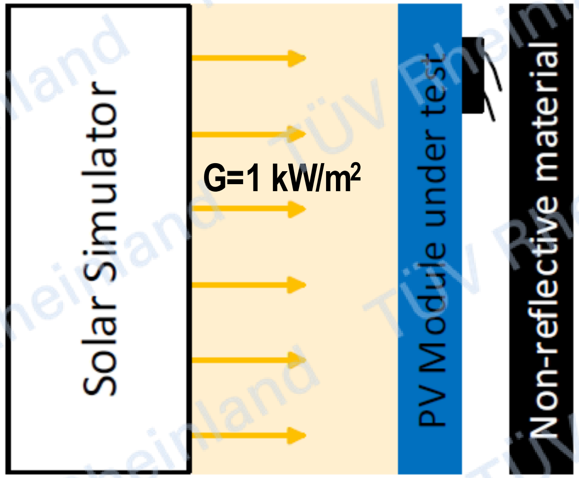


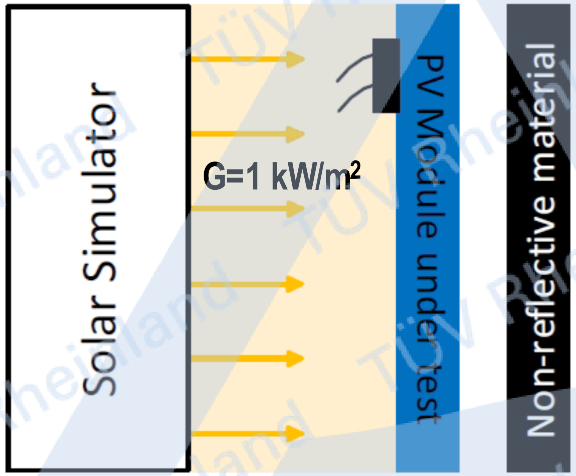
Field parameter	Bifacial reference conditions
Albedo	0.21 (light soil)
Height above ground	1 m
Inclination angle	37°
Front side irradiance	1000 W/m²

Reference:
C. Deline et al., Assessment of Bifacial Photovoltaic Module Power Rating Methodologies - Inside and Out, IEEE Journal of Photovoltaics Vol. 7, No. 2 (2017)

IEC 60904-1-2: Test Method for IV Measurement of Bifacial PV-Modules

IEC 60904-1-2: 双面光伏组件I-V曲线测试方法

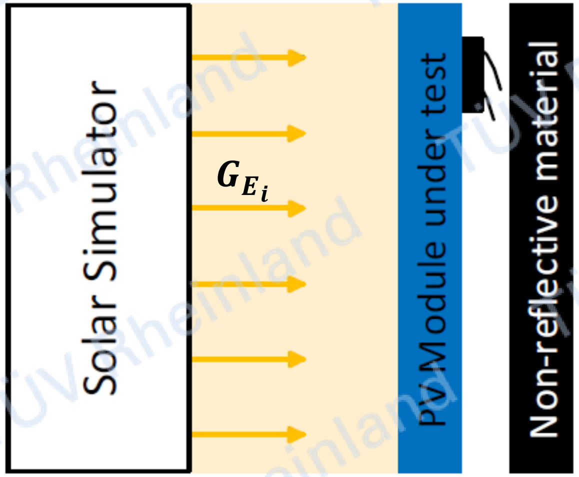




$$\varphi_{Isc} = \frac{Isc_r}{Isc_f}$$

$$\varphi_{Voc} = \frac{Voc_r}{Voc_f}$$

$$\varphi_{Pmax} = \frac{Pmax_r}{Pmax_f}$$

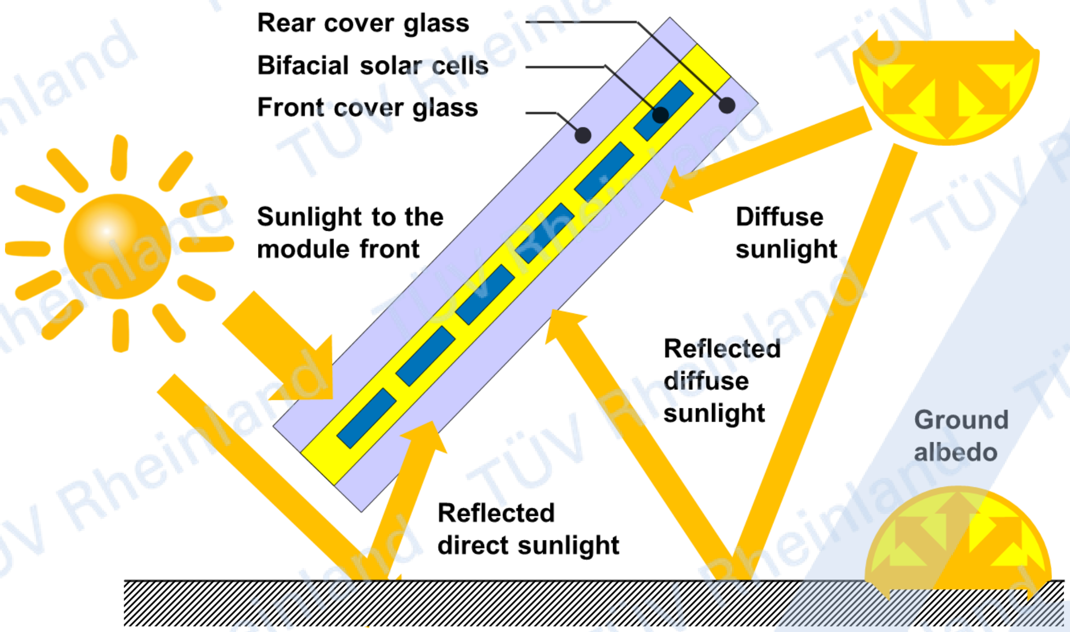


G_{E_i} = 1000 W/m² + $\varphi * G_{R_i}$

$\boldsymbol{\varphi} = Min\ (\boldsymbol{\varphi Isc}, \boldsymbol{\varphi Pmax})$

IEC 60904-1-2 CD G_{R_1} = 100 W/m² G_{R_2} = 200 W/m² G_{R_3} = xxx W/m²

Modelling Approach 建模方法



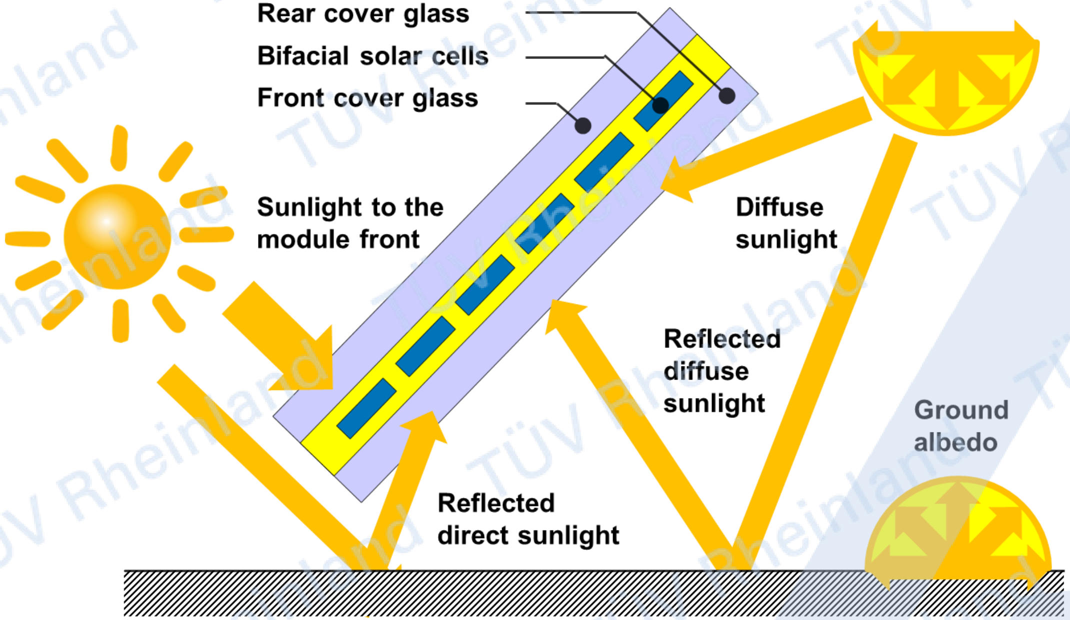
$$E_{s\lambda} = \cos\theta \cdot E_{bn\lambda} + R_d \cdot E_{d\lambda} + \rho_{g\lambda} \cdot R_r \cdot E_\lambda$$

$E_{s\lambda}$	$\cos\theta \cdot E_{bn\lambda}$	$R_d \cdot E_{d\lambda}$	$\rho_{g\lambda} \cdot R_r \cdot E_\lambda$
Global Tilted Irradiance 倾斜面全局辐照度	Direct Beam Component 直射部分	Diffuse Beam Component 散射部分	Albedo Component 反射部分

Field parameter	Bifacial reference condition
Beam & Circumsolar Irradiance	- As defined in IEC 60904-3
Diffuse Irradiance	- As defined in IEC 60904-3 - Isotropic diffuse 各向同性散射
Ground Albedo	- Lambertian diffuse reflector 朗伯特散射面 - Light sandy soil with spectral albedo as given in SMARTS v. 2.9.5 SMARTS中细砂土光谱反射率
Air Mass	1.5
Inclination angle	37°
Front side irradiance	1000 W/m^2
Shading	No near shading 无周边遮挡
PV-array design	Single row, >10 modules 单排阵列，每排组件数量大于10

Reference:
C. Guyemard et al., "SMARTS2: A simple model of the atmospheric radiative transfer of Sunshine: Algorithms and performance assessment", FSEC-PF-270-95 (1995)

Modelling Approach 建模方法



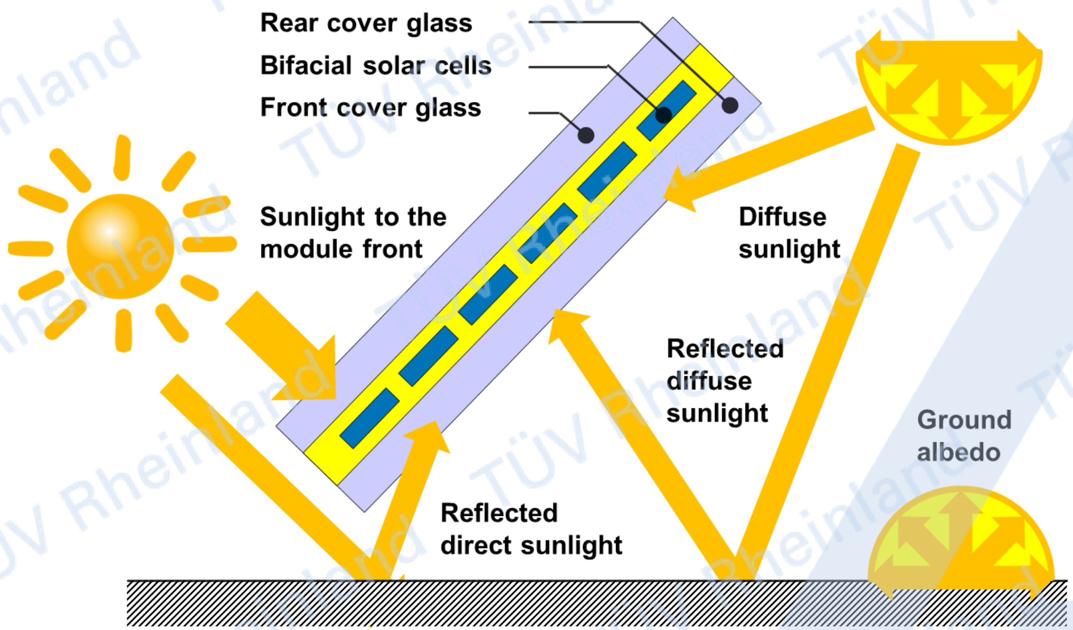
$$E_{s\lambda} = R_d \cdot E_{d\lambda} + \rho_{g\lambda} \cdot R_{bn\lambda} \cdot E_{bn\lambda} + \rho_{g\lambda} \cdot R_d \cdot E_{d\lambda}$$

$E_{s\lambda}$	$R_d \cdot E_{d\lambda}$	$\rho_{g\lambda} \cdot R_{bn\lambda} \cdot E_{bn\lambda}$	$\rho_{g\lambda} \cdot R_d \cdot E_{d\lambda}$
Rear Face Tilted Irradiance 背面辐照度	Diffuse Beam Component 散射部分	Albedo Direct Beam Component 直射光反射	Albedo Diffuse Beam Component 散射光反射

Field parameter	Bifacial reference condition
Beam & Circumsolar Irradiance	- As defined in IEC 60904-3
Diffuse Irradiance	- As defined in IEC 60904-3 - Isotropic diffuse 各向同性散射
Ground Albedo	- Lambertian diffuse reflector 朗伯特散射面 - Light sandy soil with spectral albedo as given in SMARTS v. 2.9.5 SMARTS中细砂土光谱反射率
Air Mass	1.5
Inclination angle	37°
Front side irradiance	1000 W/m²
Shading	No near shading 无周边遮挡
PV-array design	Single row, >10 modules 单排阵列，每排组件数量大于10
Height above ground	**1 m**
Module Transmittance	**- Spectral Transmittance of Glass/EVA/Glass, Glass/POE/Glass structures 不同封装结构透射率 - Solar Cell Transmittance 太阳电池透射率 - Angular response of bifacial modules 角度响应**

Reference:
C. Guyemard et al., “SMARTS2: A simple model of the atmospheric radiative transfer of Sunshine: Algorithms and performance assessment”, FSEC-PF-270-95 (1995)

Modelling Approach 建模方法



$$E_{s\lambda} = R_d \cdot E_{d\lambda} + \rho_{g\lambda} \cdot R_{bn\lambda} \cdot E_{bn\lambda} + \rho_{g\lambda} \cdot R_d \cdot E_{d\lambda}$$

$E_{s\lambda}$, $E_{bn\lambda}$, $E_{d\lambda}$, E_{λ} : Spectral irradiance components

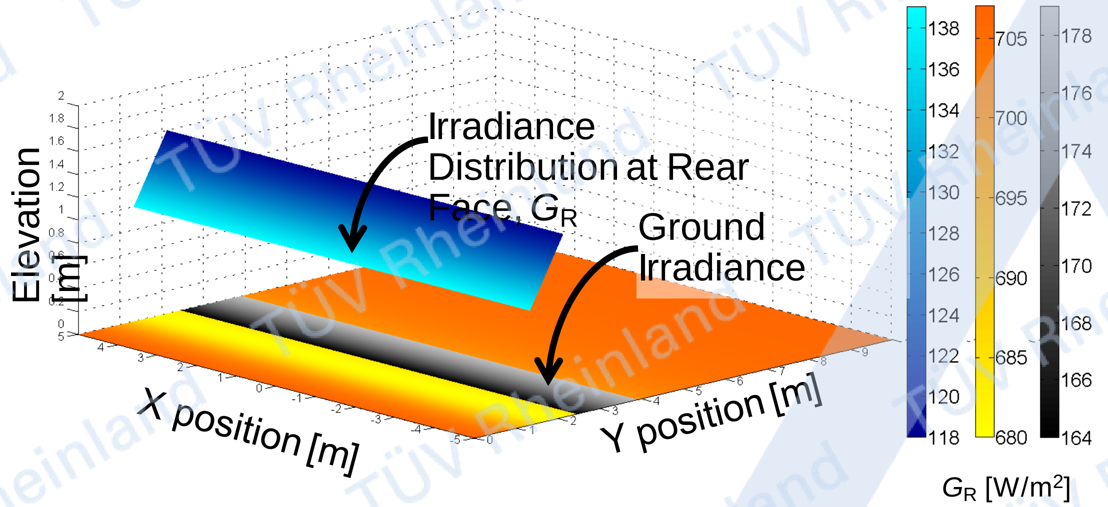
$R_{bn\lambda}$, R_d, R_r : Angular and field of view components

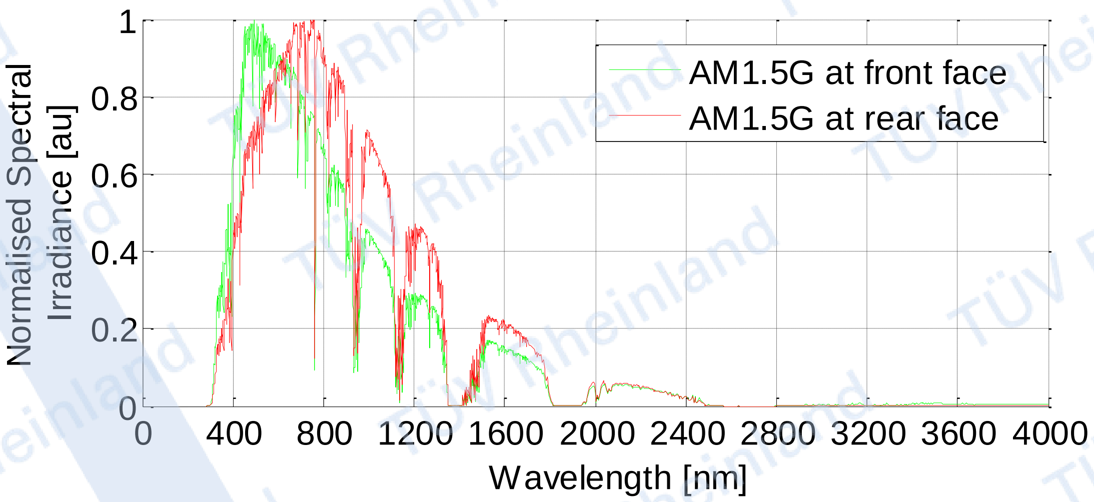
$\rho_{g\lambda}$: Spectral albedo

Field parameter	Bifacial reference condition
Beam & Circumsolar Irradiance	- As defined in IEC 60904-3
Diffuse Irradiance	- As defined in IEC 60904-3 - Isotropic diffuse 各向同性散射
Ground Albedo	- Lambertian diffuse reflector 朗伯特散射面 - Light sandy soil with spectral albedo as given in SMARTS v. 2.9.5 SMARTS中细砂土光谱反射率
Air Mass	1.5
Inclination angle	37°
Front side irradiance	1000 W/m^2
Shading	No near shading 无周边遮挡
PV-array design	Single row, >10 modules 单排阵列，每排组件数量大于10
Height above ground	**1 m**
Module Transmittance	**- Spectral Transmittance of Glass/EVA/Glass, Glass/POE/Glass structures 不同封装结构透射率** **- Solar Cell Transmittance 太阳电池透射率** **- Angular response of bifacial modules 角度响应**

Reference:
C. Guyemard et al., “SMARTS2: A simple model of the atmospheric radiative transfer of Sunshine: Algorithms and performance assessment”, FSEC-PF-270-95 (1995)

AM1.5G Spectral Irradiance at Rear Face 对应于AM1.5G的背面光谱





- Accounting for the methodology used in **SMARTS2**, a physics-based model was created, which can compute **radiation** distributions **on tilted surfaces** and their **spectrum**.

  该物理模型参考SMARTS2的光谱计算方法，可以用于计算倾斜面的光谱辐照度。

- It is shown that **rear face irradiance** distribution for PV-modules deployed in a single row at **1 m** above ground at conditions as defined in AM1.5G is **strongly non-uniform**.

  ⇒ **Landscape mounting configuration** is **beneficial** for bifacial modules.

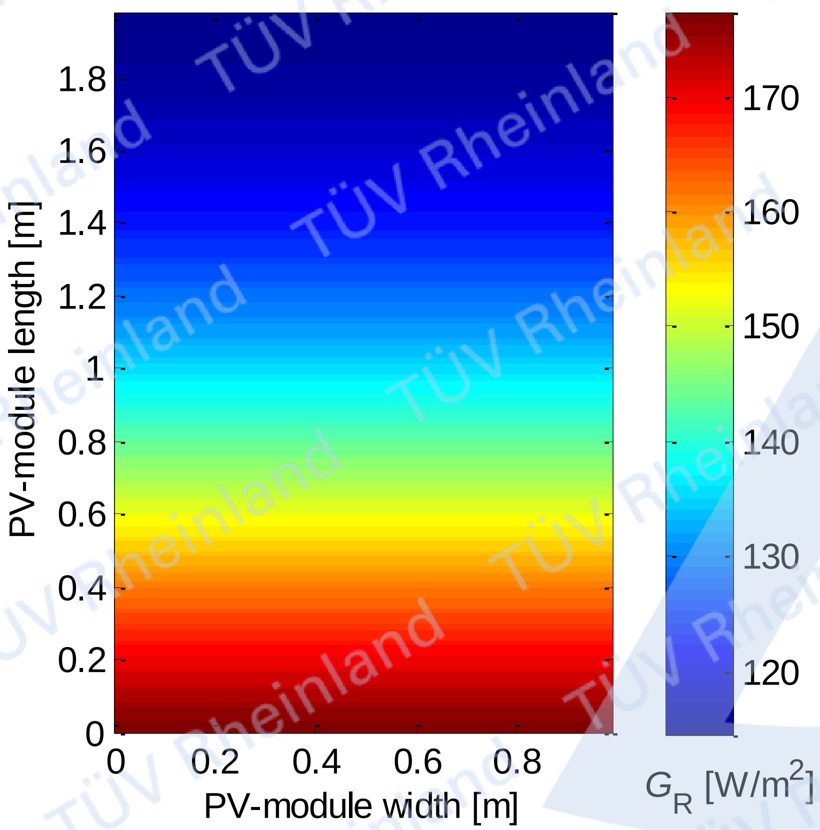
  1m安装高度的光伏组件背面光谱辐照度在组件上分布不均，横向安装方式更为有益。

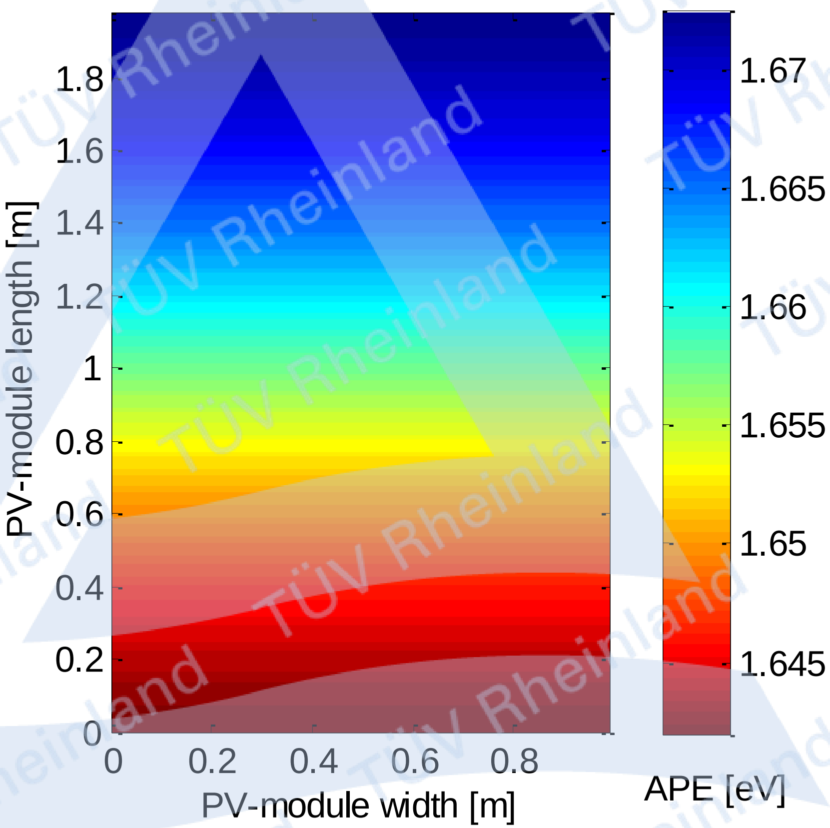
- The **spectral** distribution of the **irradiance** at rear face is **red-shifted** due to spectral albedo effects.

  相比于正面光谱，背面光谱有一定红移，所以功率标定中正反面失配系数不同。

TÜVRheinland® Precisely Right.

Non-Uniformity of Irradiance and Average Photon Energy
背面辐照度与平均光子能量不均匀度分布





- The **rear face irradiance, G_R** lies in the range of **110-180 W/m^2**.

  ⇒ Top-row: 110-145W/m^2

  ⇒ Bottom-row: 145-180W/m^2

  背面辐照度在**110-180 W/m²**范围内：
  顶部阵列110-145W/m²
  底部阵列145-180W/m²

- The **average photon energy** (300-1200nm) varies within **1.64-1.68eV** (<1.80eV of front face).

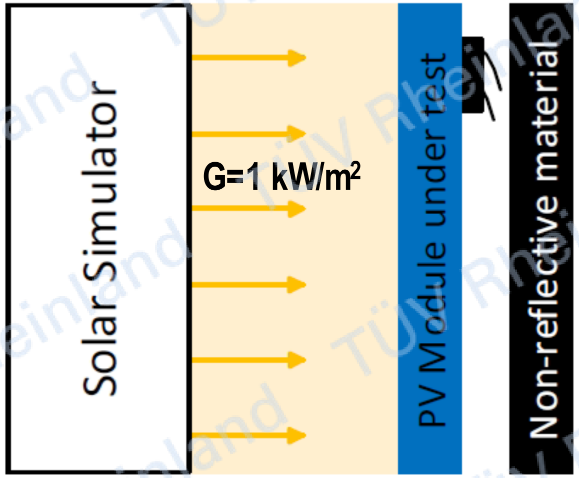
  在300-1200nm范围内的平均光子能量为**1.64-1.68eV**。

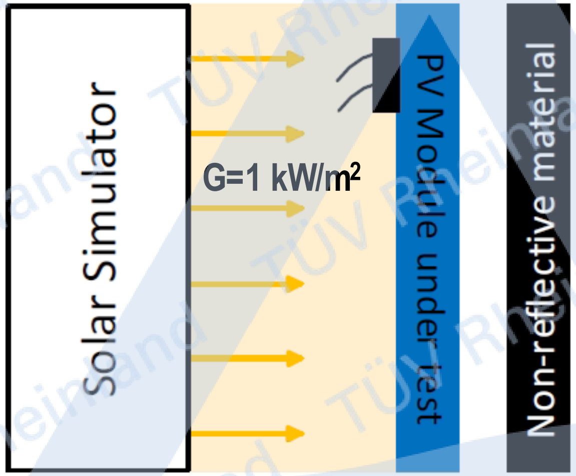
Example: **2m x 1m sized, frameless PV-module** deployed in **portrait configuration** at **1 m** above ground at conditions as defined in AM1.5G.

2m x 1m无边框双面组件在安装高度，正面光谱辐照度AM1.5G时的背面辐照度与平均光子能量分布。

IEC 60904-1-2: Test Method for IV Measurement of Bifacial PV-Modules

IEC 60904-1-2: 双面光伏组件I-V曲线测试方法

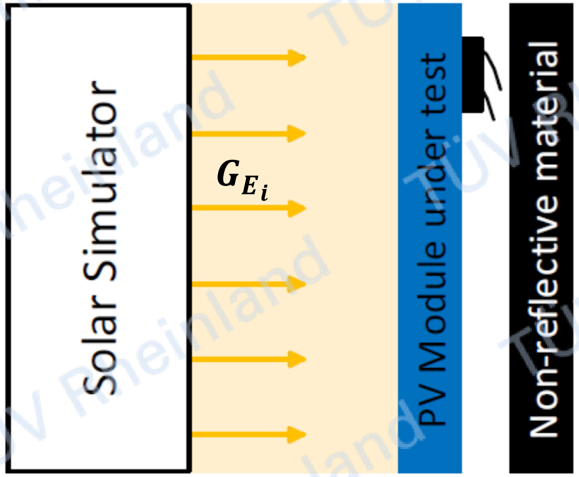




$$\varphi_{Isc} = \frac{Isc_r}{Isc_f}$$

$$\varphi_{Voc} = \frac{Voc_r}{Voc_f}$$

$$\varphi_{Pmax} = \frac{Pmax_r}{Pmax_f}$$



G_{E_i} = 1000 W/m² + $\varphi * G_{R_i}$

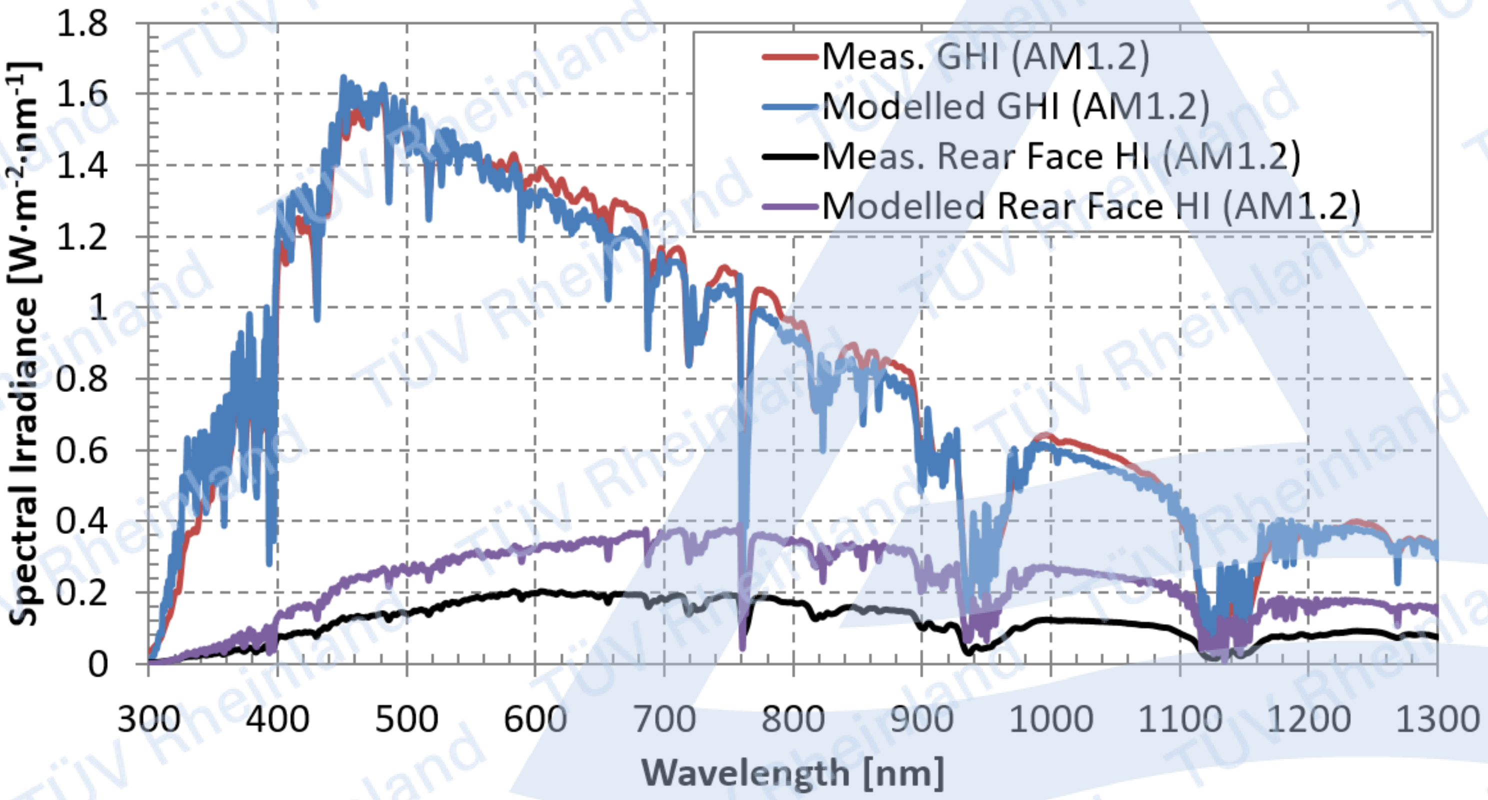
$\boldsymbol{\varphi} = Min\ (\boldsymbol{\varphi Isc}, \boldsymbol{\varphi Pmax})$

IEC 60904-1-2 CD	G_{R_1} = 100 W/m²	G_{R_2} = 200 W/m²	G_{R_3} = xxx W/m²
2PfG 2645/11.17	G_{R_1} = 100 W/m²	G_{R_2} = 200 W/m²	G_{R_3} = **135 W/m²**

- Front irradiance: 1000 W/m²
- Rear irradiance: 135 W/m²
- Equivalent irradiance: 1000 + φ·135 W/m²
- Module temperature: 25° C
- Spectral irradiance: AM1.5G

[1] 2PfG 2645/11.17: Supplementary Power Rating of Bifacial Photovoltaic (PV) Modules

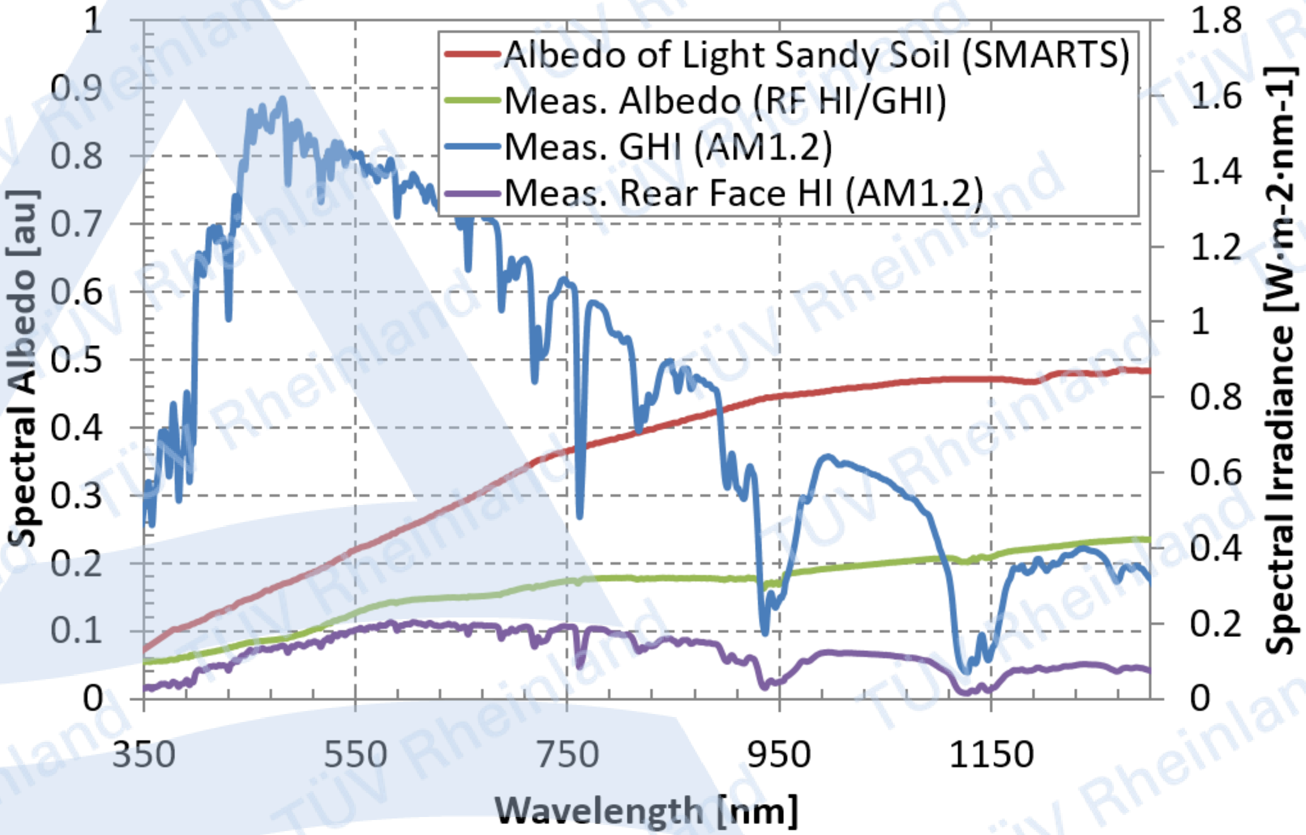
Comparison with Outdoor Measurements: Rear Face Horizontal Irradiance
水平面背面光谱辐照度模拟结果与户外实测值对比



<u>Measurement Conditions</u>
Site: Cologne
Date: 15/08/2018
Time: 13:00, Solar Noon
Air Mass: AM1.2
Sky Condition: Clear Skies
Height: 1.5m

<u>Model Parameters</u>
Air Mass: AM1.2
GHI: SMARTS (2.9.5)
DNI: SMARTS (2.9.5)
Albedo: Light Sandy Soil
Height: 1.5m

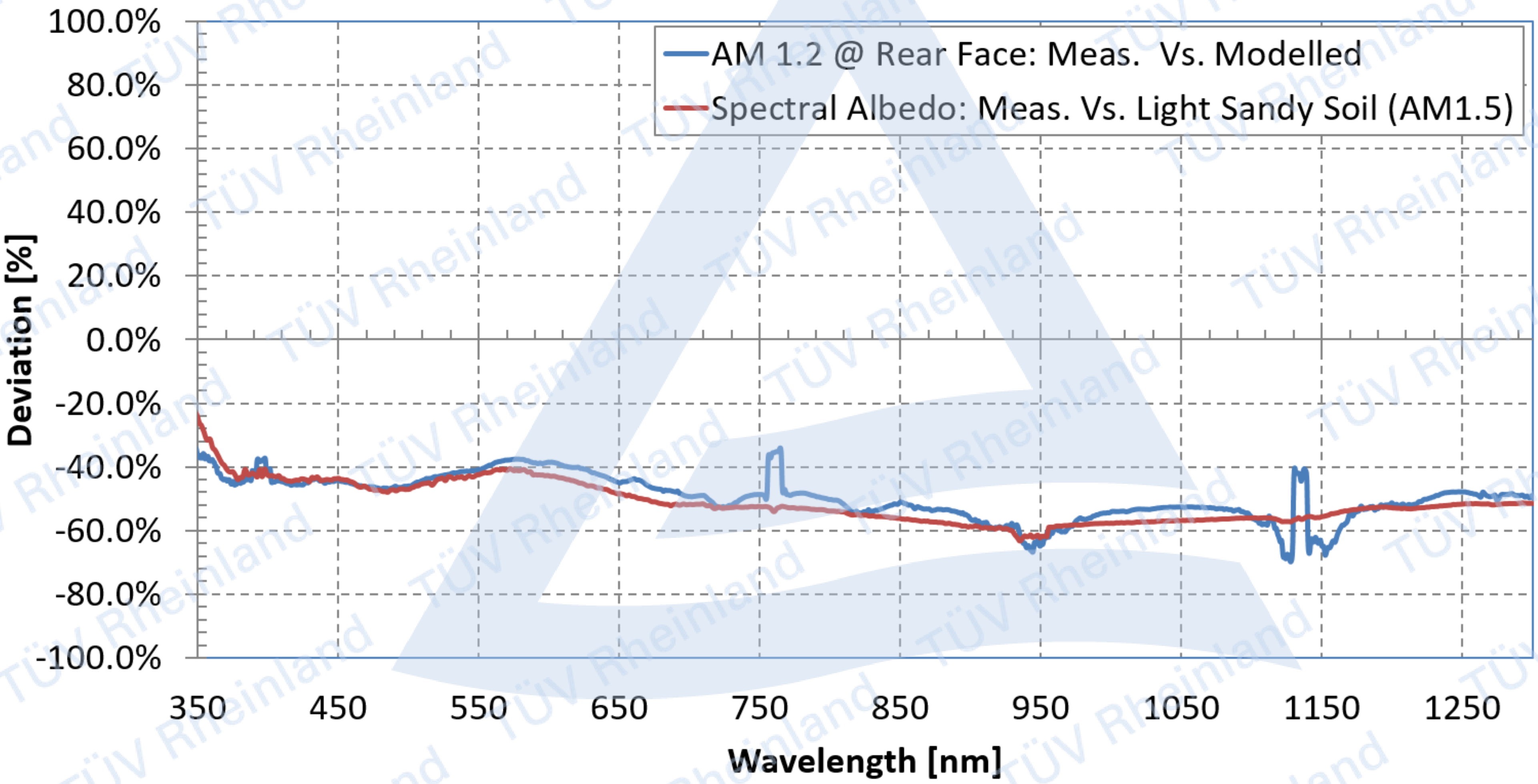
Comparison with Outdoor Measurements: Rear Face Horizontal Irradiance
水平面背面光谱辐照度模拟结果与户外实测值对比



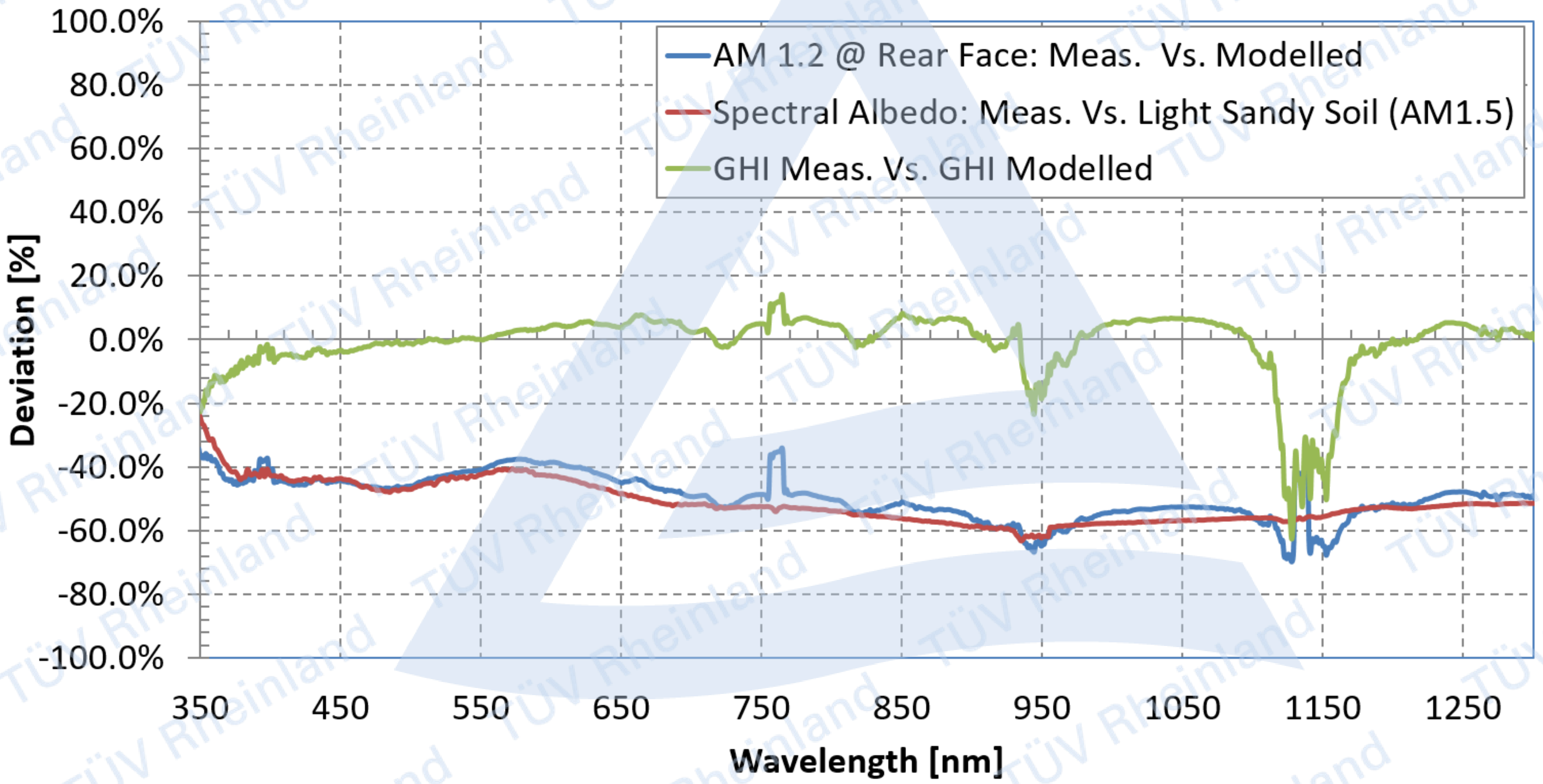
The Spectral Albedo was measured with a **spectroradiometer** and **two pyranometers** (Rear Face HI_λ/GHI_λ).

光谱反射率由一台光谱仪与两台辐照计测量。

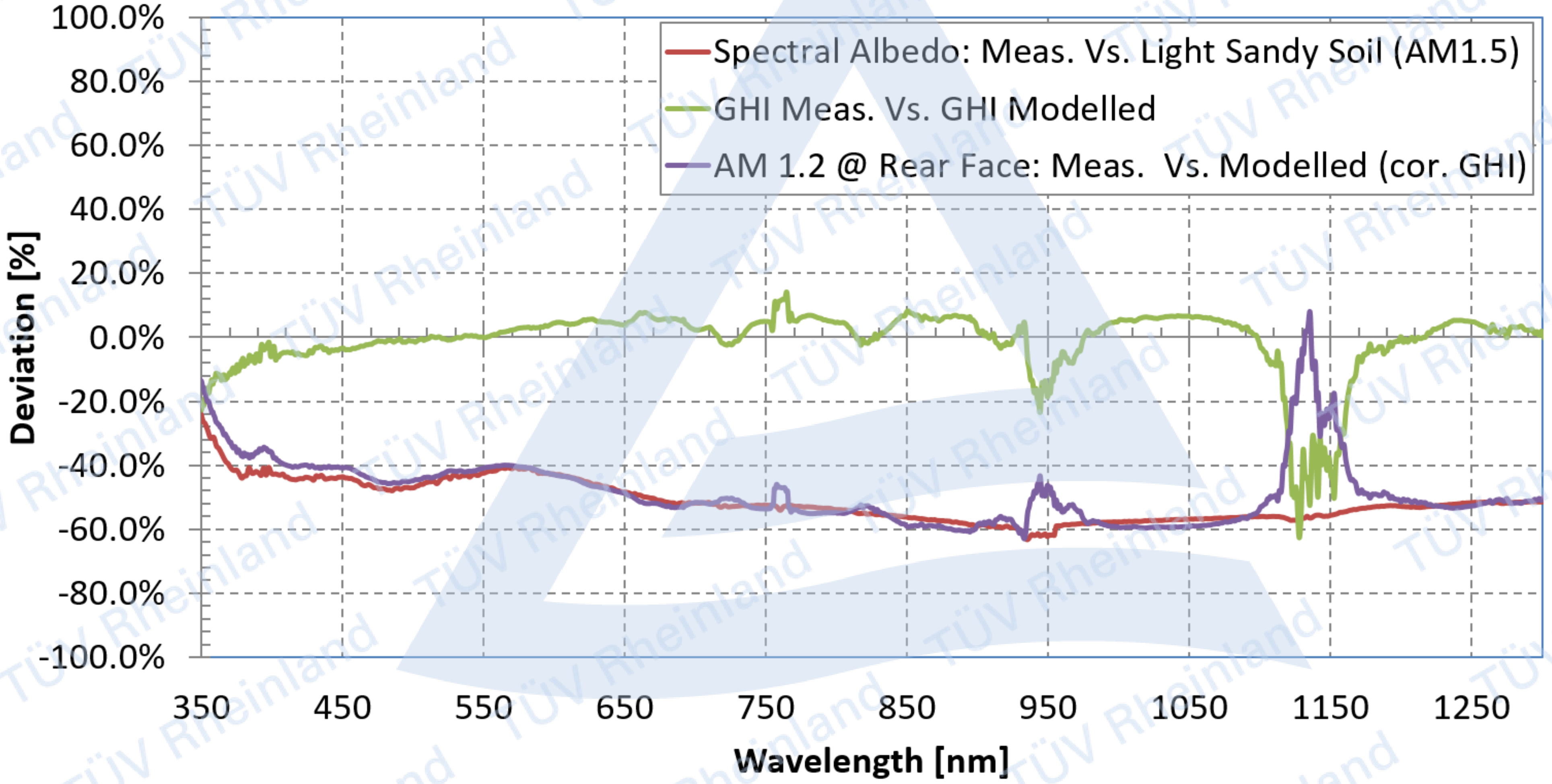
Comparison with Outdoor Measurements: Rear Face Horizontal Irradiance
水平面背面光谱辐照度模拟结果与户外实测值对比



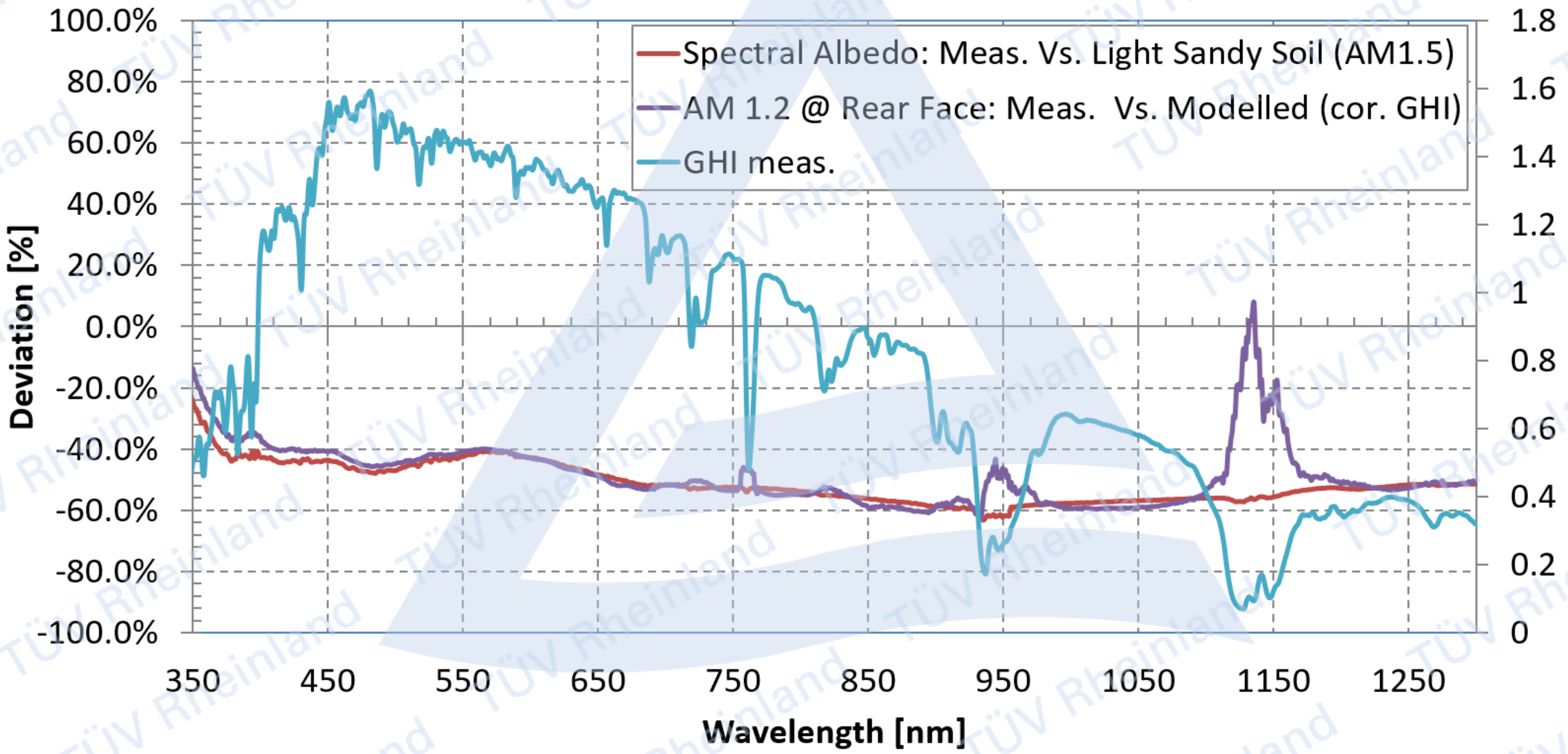
Comparison with Outdoor Measurements: Rear Face Horizontal Irradiance
水平面背面光谱辐照度模拟结果与户外实测值对比



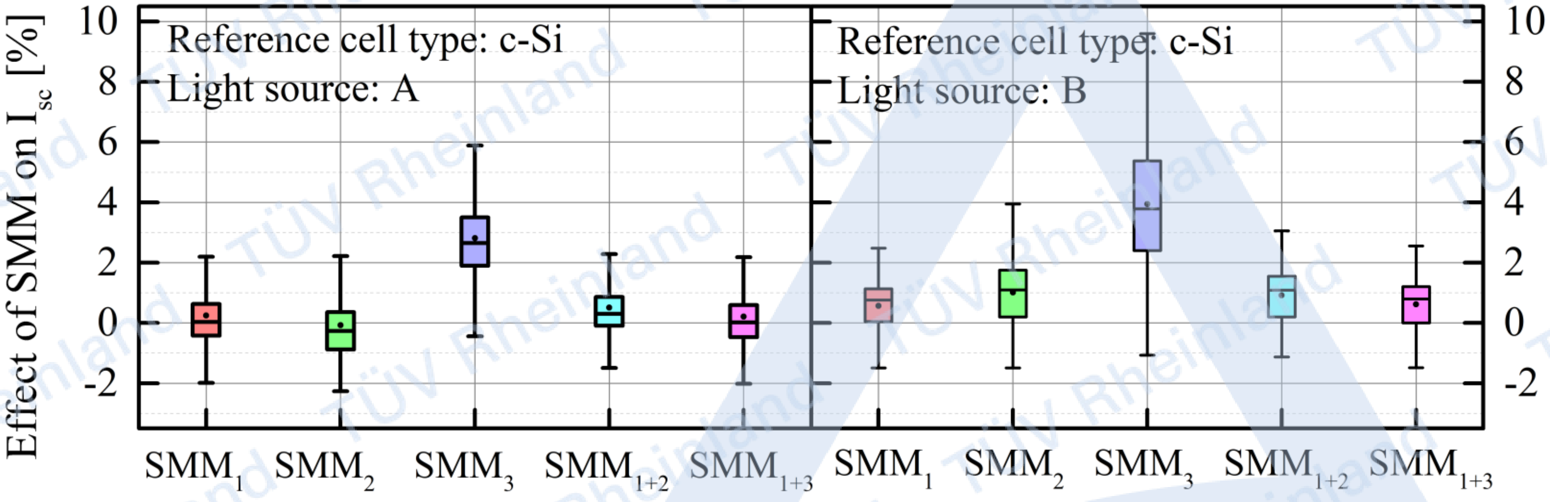
Comparison with Outdoor Measurements: Rear Face Horizontal Irradiance
水平面背面光谱辐照度模拟结果与户外实测值对比



Comparison with Outdoor Measurements: Rear Face Horizontal Irradiance
水平面背面光谱辐照度模拟结果与户外实测值对比



Significance of Rear Face Spectral Irradiance for Bifacial Module Rating
背面光谱分布对双面光伏组件标定的影响



Sample	Type	Qty
DUTs:(encapsulated) SR_{front} + SR_{rear} Bifaciality, φ	Bifacial c-Si PV (PERC, HJT, PERT)	20
Reference Cell *SR*	c-Si	8
Solar Simulator Spectra	A	14
	B	3

SMM_1: SR_{front} and AM1.5G

SMM_2: SR_{rear} and AM1.5G

SMM_3: SR_{rear} and AM1.5R

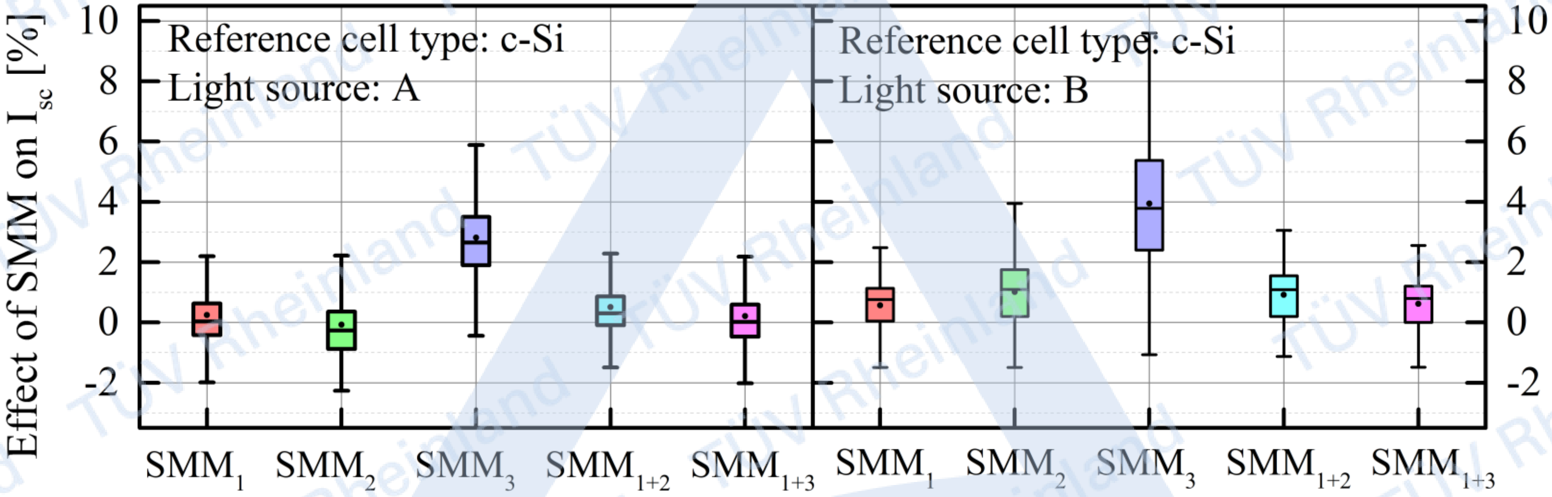
SMM_{1+2}:

$$\frac{\frac{1000}{SMM_1}+\varphi\frac{135}{SMM_2}}{1000+135\cdot\varphi}$$

SMM_{1+3}:

$$\frac{\frac{1000}{SMM_1}+\varphi\frac{135}{SMM_3}}{1000+135\cdot\varphi}$$

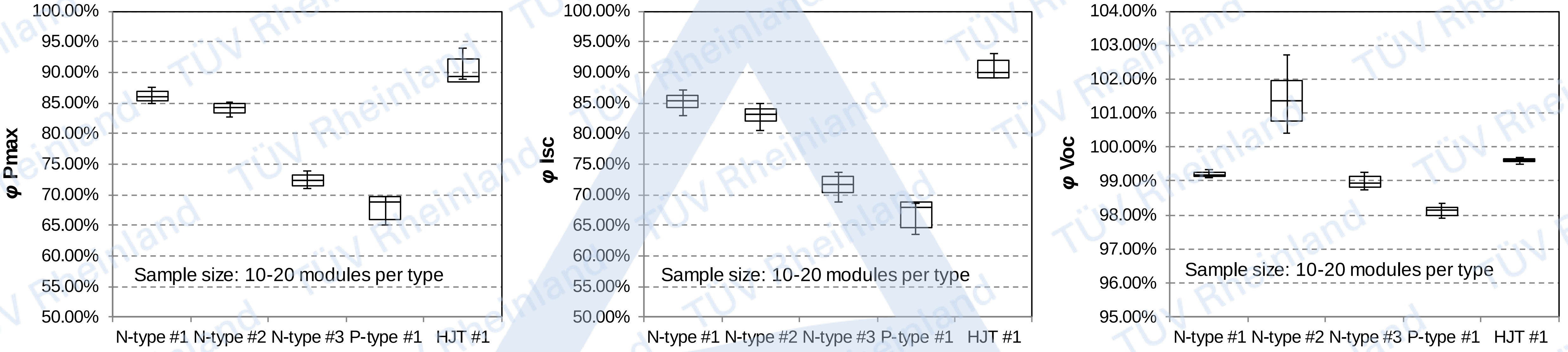
Significance of Rear Face Spectral Irradiance for Bifacial Module Rating
背面光谱分布对双面光伏组件标定的影响



- The **rear face spectral mismatch** strongly **depends** on the reference spectrum choice (**AM1.5G** or **AM1.5R**)
  背面光谱失配系数依赖于参考光谱选择。
- The **weighted spectral mismatch** is **not significantly affected** by the rear face spectral distribution choice (**AM1.5G** or **AM1.5R**)
  加权光谱失配系数受参考光谱影响不大。

⇒ Practically **AM1.5G** can be used for **both sides** without significant error
AM1.5G可以应用于实际双面光谱失配系数的计算。

Bifaciality Coefficients Dispersion seen in Production
双面率在实际产线中的分布



- The **variation** of **bifaciality coefficients,** ***φ***, was evaluated by measuring a series of modules in **production (10-20 modules per type**).
- **Bifaciality** depends strongly on **technology.** Coefficients may vary from **60%** to **90%**
- **Bifaciality coefficients** may **vary** from **±2.0%** to **±5.0%** (k=2) in production for as-produced modules of the same family.

⇒ BSTC tolerance shall account this variation to comply with supplementary label verification in accordance with gate #1 requirements.

Verification of BSTC Values on the Label (Gate #1)
标签中BSTC相关数值的验证准则

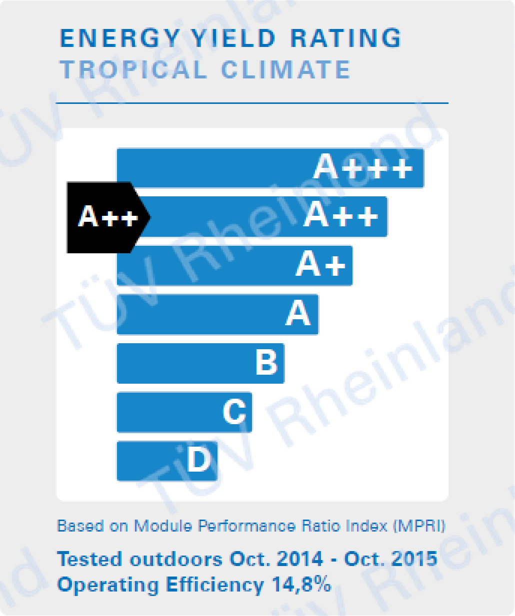
P_{max} (BSTC)	• Stabilized P_{max} of each sample with consideration of plus-uncertainty ≥ Nominal Power with consideration of minus-tolerance
$\overline{P_{max}}$ (BSTC)	• Average of stabilized P_{max} values of all samples with consideration of plus-uncertainty ≥ Nominal Power
V_{oc} (BSTC)	• Stabilized V_{oc} with consideration of plus-uncertainty ≤ nominal value on type label with consideration of plus-tolerance
I_{sc} (BSTC)	• Stabilized I_{sc} with consideration of plus-uncertainty ≤ nominal value on type label with consideration of plus-tolerance
P_{max} (BSTC) for minimum power class	• Stabilized P_{max} with consideration of minus-uncertainty ≤ Nominal Power with consideration of plus-tolerance

Conclusions 结论

- Power **labelling** of **bifacial** PV modules is an **urgent** matter. Sufficient **knowledge** is **available** to define bifacial reference conditions.
  双面光伏组件的功率标签十分必要，现有理论已足够定义双面测试标准状况
- **Bifacial Standard Test Condition (BSTC)** has been proposed based on **IEC 60904-1-2 CDTS** and **IEC 60904-3**, which intends to provide **supplementary** information on the label:
  双面标准测试条件（BSTC）的制定基于IEC 60904-1-2 CDTS和IEC 60904-3，可用于在标签上提供补充信息：

Bifacial Standard Test Conditions (BSTC) :

- Front irradiance: 1000 W/m²
- Rear irradiance: 135 W/m²
- Equivalent irradiance: $1000 + \varphi \cdot 135$ W/m²
- Spectral irradiance: AM1.5G
- Module temperature: 25° C



- **BSTC** is a **simple indicator**, which is **unsuitable for EY predictions**.
  BSTC只是一个测试条件，不能应用于发电量预测。
- **Energy rating standard** according to **IEC 61853** should be extended for **bifacial** applications.
  基于IEC 61853的功率标定标准可被拓展到双面光伏组件中。

Acknowledgements

- Mr. Yabin Li, Mr. Fan Wang and Dr. Jason Nee from Yingli Solar
- Mr. Thomas Guo and Dr. Jin Hao from Jinko Solar
- Dr. Thomas R. Betts from Loughborough University, UK

for the helpful discussions and data contribution.

Acknowledgements

Participators

Thank you for your attention !

TÜVRheinland®
Precisely Right.