PROPAGATION OF MEASUREMENT UNCERTAINTIES INTO KWH PREDICTION

Christian Reise
Daniela Dirnberger
Björn Müller

Fraunhofer Institute for
Solar Energy Systems ISE
Freiburg, Germany

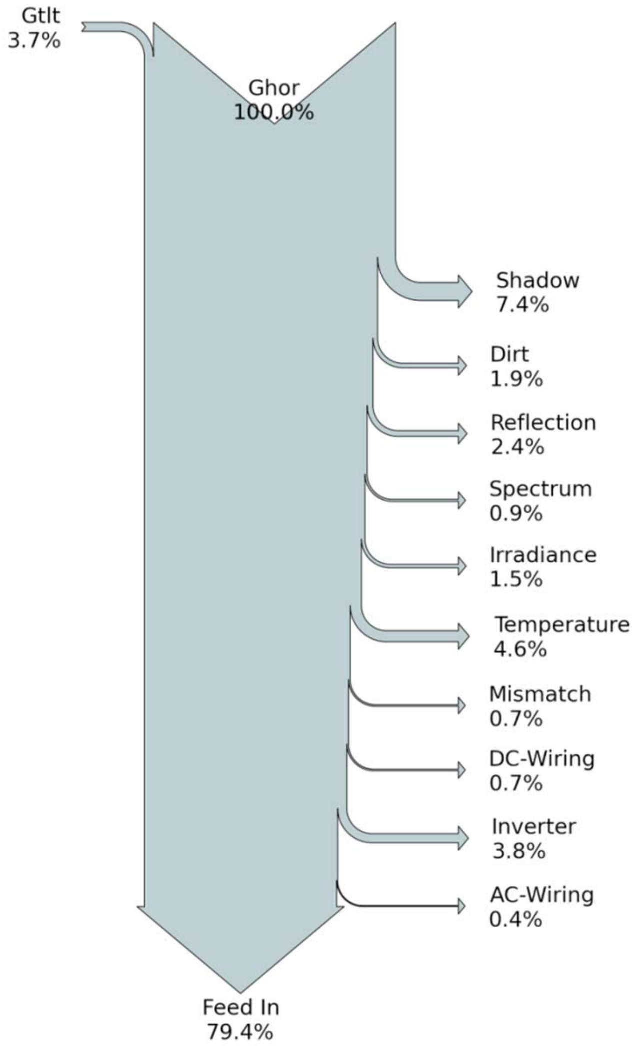
Energy Rating and
Module Performance Workshop
Lugano 2017

Fraunhofer
ISE

Agenda

- PV Module Energy Rating
- A Set of Samples
- Uncertainty of Energy Rating Input Values
- Results: Module Ranking and Uncertainties
- Conclusions

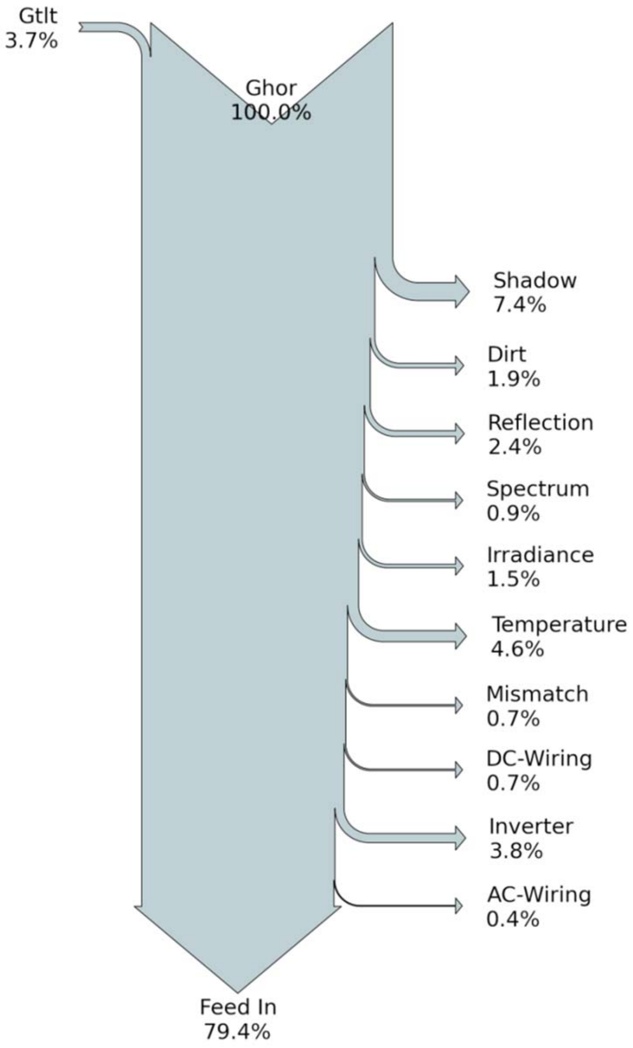
Calculation steps of a yield assessment



Calculation steps of a yield assessment
Energy Rating (ER)

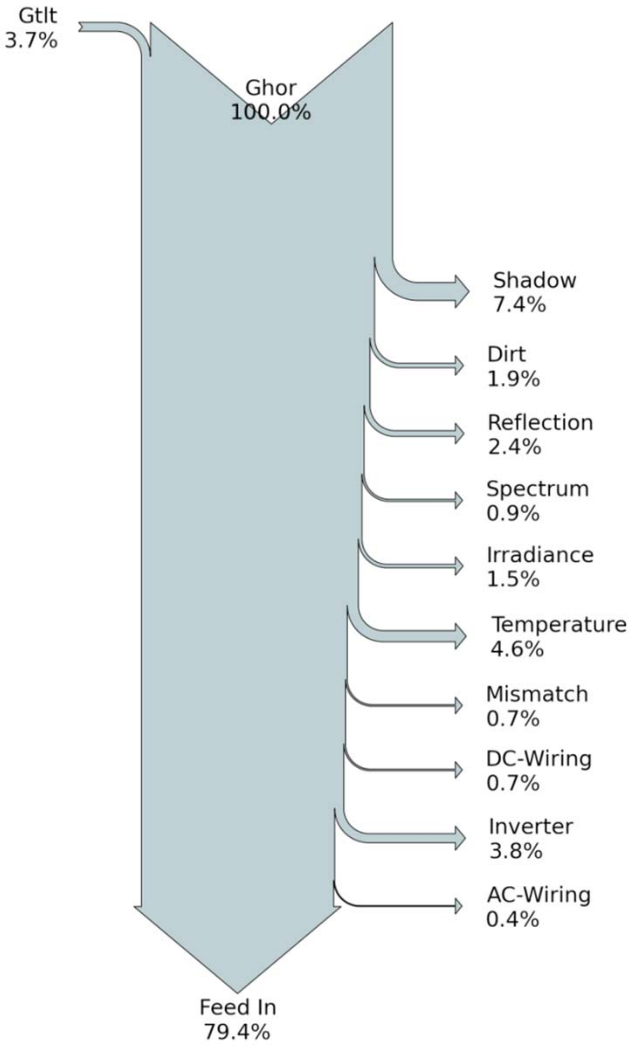
- Reflection losses
- Spectral effects

- Dependency on irradiance level
- Dependency on temperature



Calculation steps of a yield assessment
Performance Ratio (PR)

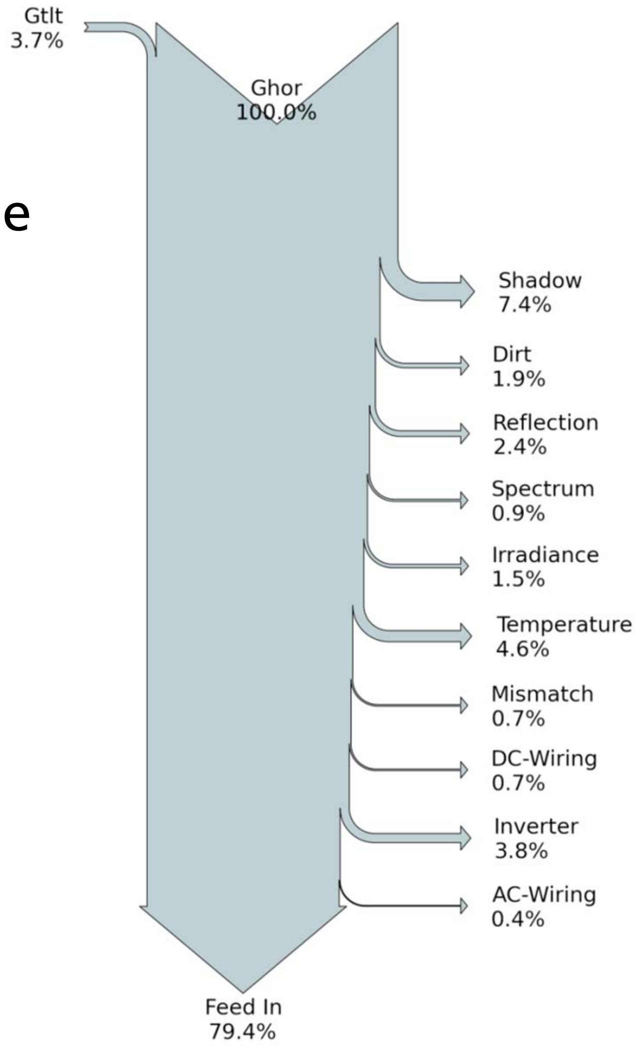
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses



Calculation steps of a yield assessment

Typical initial yield

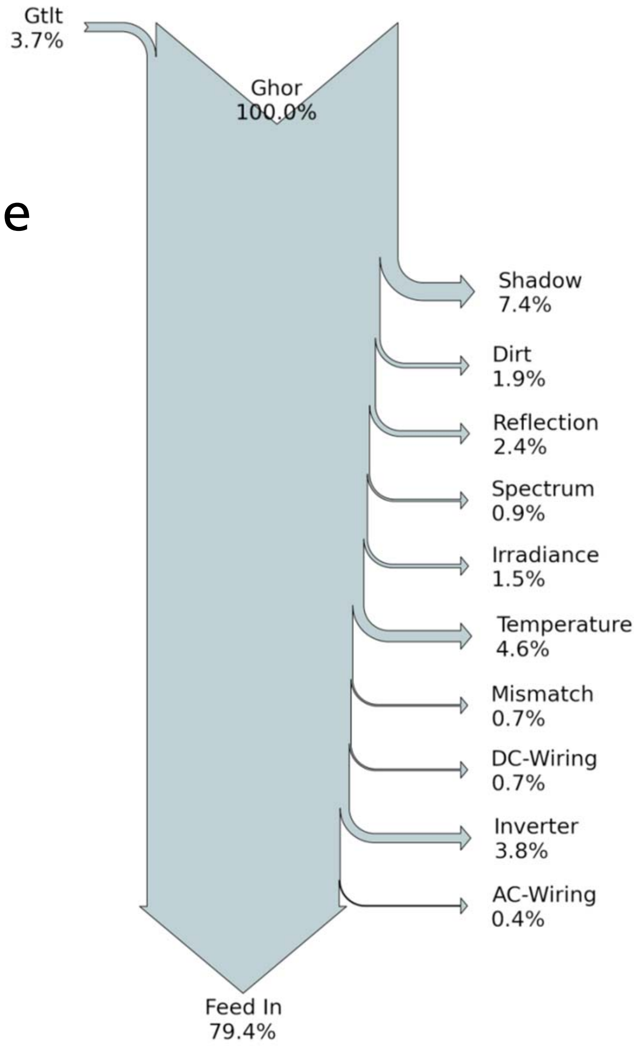
- Horizontal irradiation (history)
-
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
-
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
-



Calculation steps of a yield assessment

Long term yield

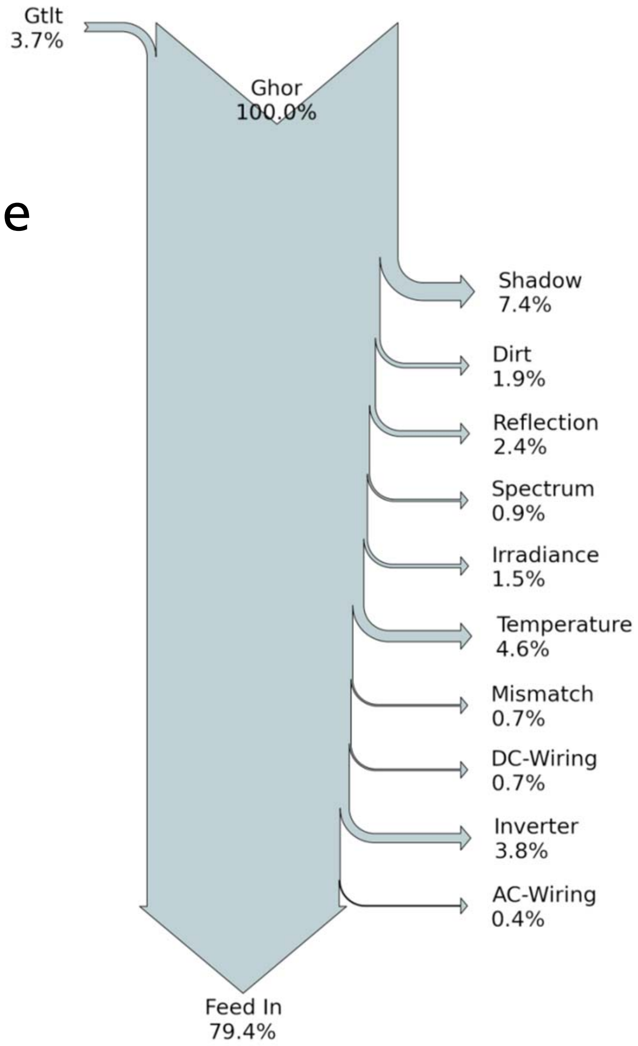
- Horizontal irradiation (history)
- Horizontal irradiation (future)
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
-
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
- System degradation



Calculation steps of a yield assessment

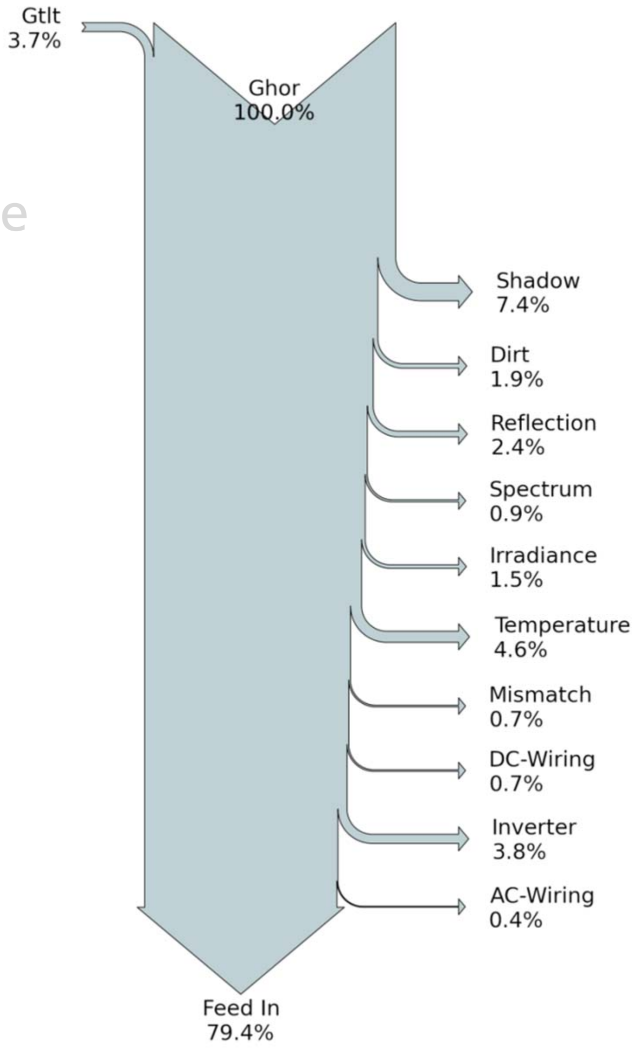
Actual long term yield

- Horizontal irradiation (history)
- Horizontal irradiation (future)
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
- Product specifications vs. actual properties
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
- System degradation



Calculation steps of a yield assessment
PV Module Energy Rating

- Horizontal irradiation (history)
- Horizontal irradiation (future)
- Diffuse fraction & conversion into module plane
- Partial shading (& inverter behavior)
- Soiling losses
- Reflection losses
- Spectral effects
- Product specifications vs. actual properties
- Dependency on irradiance level
- Dependency on temperature
- Mismatch losses
- DC + AC cable losses
- Inverter efficiency and limitations
- Transformer losses
- System degradation



PV Module Energy Rating

Formulae

- DC Yield:

$$Y_{\mathrm{DC}} = \sum\nolimits_{i=1}^{N} G_{\mathrm{POA},i}\, \eta_{\mathrm{STC}}\, A_{\mathrm{module}}\, f_i(\mathrm{AOI},\ \mathrm{spectrum}, \mathrm{T},\ \mathrm{module\ characteristics})$$

PV Module Energy Rating
Formulae

- DC Yield:

$$
\begin{aligned}
Y_{\mathrm{DC}} &= \sum_{i=1}^{N} G_{\mathrm{POA},i}\,\eta_{\mathrm{STC}}\,A_{\mathrm{module}}\,f_i(\mathrm{AOI},\ \mathrm{spectrum}, \mathrm{T},\ \mathrm{module\ characteristics}) \\
&= H_{\mathrm{POA}}\,\eta_{\mathrm{STC}}\,A_{\mathrm{module}}\,f_{\mathrm{AOI}}\,f_{\mathrm{spectral}}\,f_G\,f_{\mathrm{T}}
\end{aligned}
$$

PV Module Energy Rating
Formulae

- DC Yield:

$$Y_{\mathrm{DC}} = \sum_{i=1}^{N} G_{\mathrm{POA},i}\, \eta_{\mathrm{STC}}\, A_{\mathrm{module}}\, f_i(\mathrm{AOI},\ \mathrm{spectrum}, \mathrm{T},\ \mathrm{module\ characteristics})$$

$$= H_{\mathrm{POA}}\, \eta_{\mathrm{STC}}\, A_{\mathrm{module}}\, f_{\mathrm{AOI}}\, f_{\mathrm{spectral}}\, f_G\, f_{\mathrm{T}}$$

- Module Performance Ratio (MPR):

$$MPR_{\mathrm{nominal}} = \frac{Y_{\mathrm{DC,nominal}} \Big/ P_{\mathrm{STC,nominal}}}{H_{\mathrm{POA}} \Big/ \frac{1\mathrm{kW}}{\mathrm{m}^2}} = f_{\mathrm{AOI}}\, f_{\mathrm{spectral}}\, f_G\, f_{\mathrm{T}}$$

PV Module Energy Rating
Formulae

- DC Yield:

$$Y_{\mathrm{DC}} = \sum_{i=1}^{N} G_{\mathrm{POA},i}\,\eta_{\mathrm{STC}}\,A_{\mathrm{module}}\,f_i(\mathrm{AOI},\ \mathrm{spectrum},\mathrm{T},\ \mathrm{module\ characteristics})$$

$$= H_{\mathrm{POA}}\,\eta_{\mathrm{STC}}\,A_{\mathrm{module}}\,f_{\mathrm{AOI}}\,f_{\mathrm{spectral}}\,f_{G}\,f_{\mathrm{T}}$$

- Module Performance Ratio (MPR):

$$MPR_{\mathrm{nominal}} = \frac{Y_{\mathrm{DC,nominal}} \big/ P_{\mathrm{STC,nominal}}}{H_{\mathrm{POA}} \big/ \frac{1\mathrm{kW}}{\mathrm{m}^2}} = f_{\mathrm{AOI}}\,f_{\mathrm{spectral}}\,f_{G}\,f_{\mathrm{T}}$$

$$MPR = \frac{\eta_{\mathrm{STC,measured}}}{\eta_{\mathrm{STC,nominal}}} f_{\mathrm{AOI}}\,f_{\mathrm{spectral}}\,f_{G}\,f_{\mathrm{T}}$$

PV Module Energy Rating
Uncertainties

- Module Performance Ratio (MPR):

$$\mathrm{u}_{MPR_{\mathrm{nominal}}} = \sqrt{\mathrm{u}_{f_{\mathrm{AOI}}}{}^2 + \mathrm{u}_{f_{\mathrm{spectral}}}{}^2 + \mathrm{u}_{f_G}{}^2 + \mathrm{u}_{f_{\mathrm{T}}}{}^2}$$

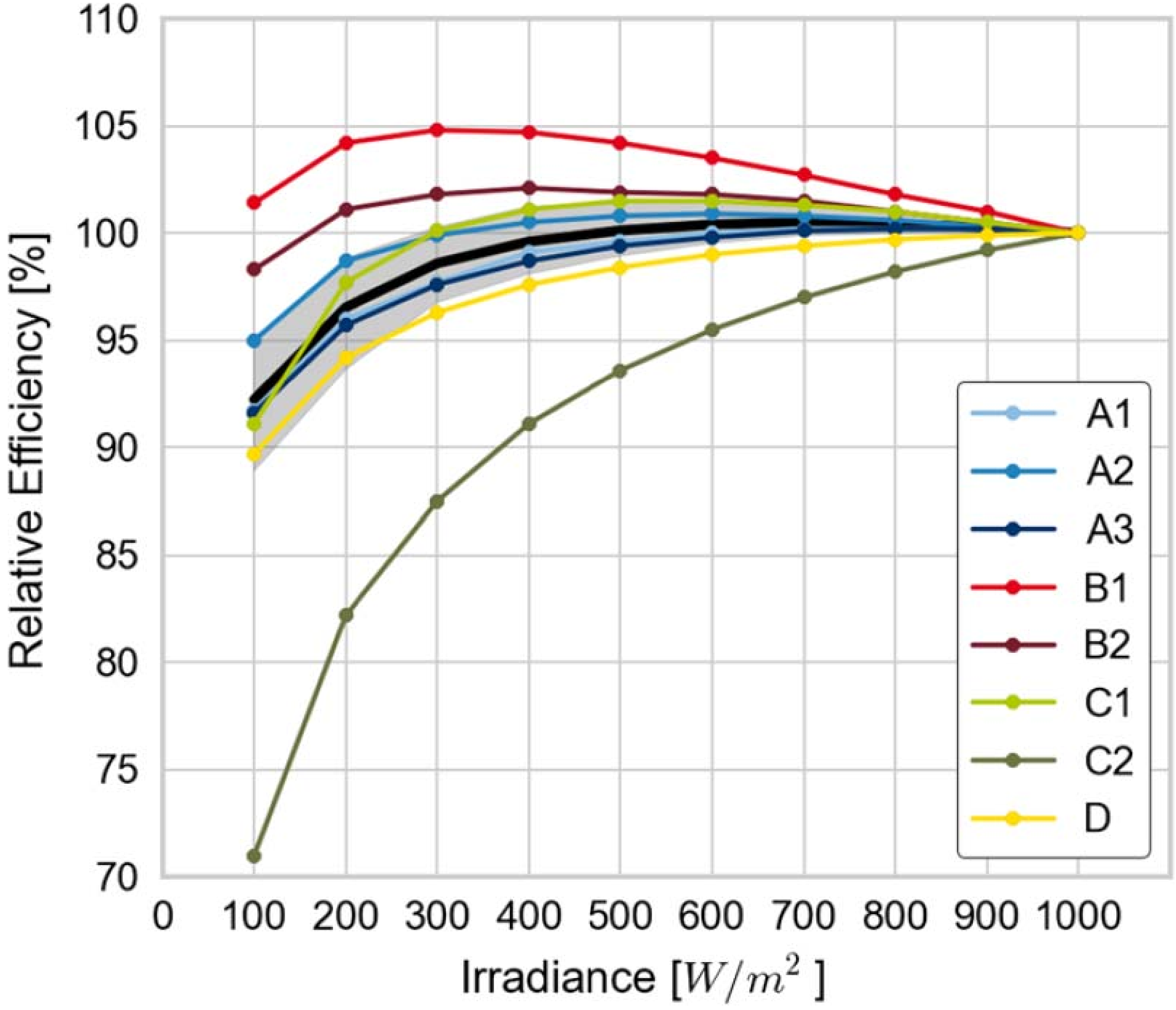
$$\mathrm{u}_{\mathrm{MPR}} = \sqrt{\mathrm{u}_{P_{\mathrm{STC,measured}}}{}^2 + \mathrm{u}_{f_{\mathrm{AOI}}}{}^2 + \mathrm{u}_{f_{\mathrm{spectral}}}{}^2 + \mathrm{u}_{f_G}{}^2 + \mathrm{u}_{f_{\mathrm{T}}}{}^2}$$

A Set of Samples
List of modules

	ID	cell techn.	efficiency	meas. – nom. eff.
■	A1	c-Si	14.7 %	–1.6 %
■	A2	c-Si	16.3 %	+1.1 %
■	A3	c-Si (high eff.)	17.1 %	+0.0 %
■	B1	CdTe	10.3 %	–1.3 %
■	B2	CdTe	12.2 %	+1.1 %
■	C1	CIGS	11.9 %	+4.3 %
■	C2	CIGS	12.4 %	–5.0 %
■	D	a-Si	5.9 %	–6.7 %

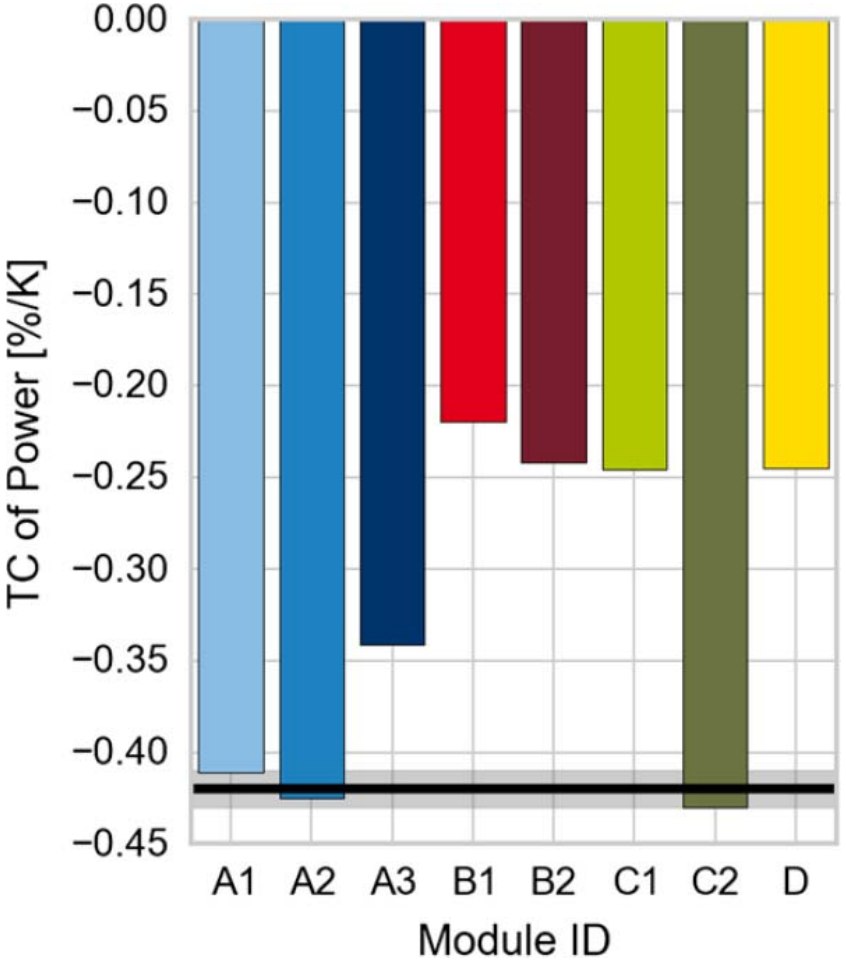
A Set of Samples

Dependency on irradiance level



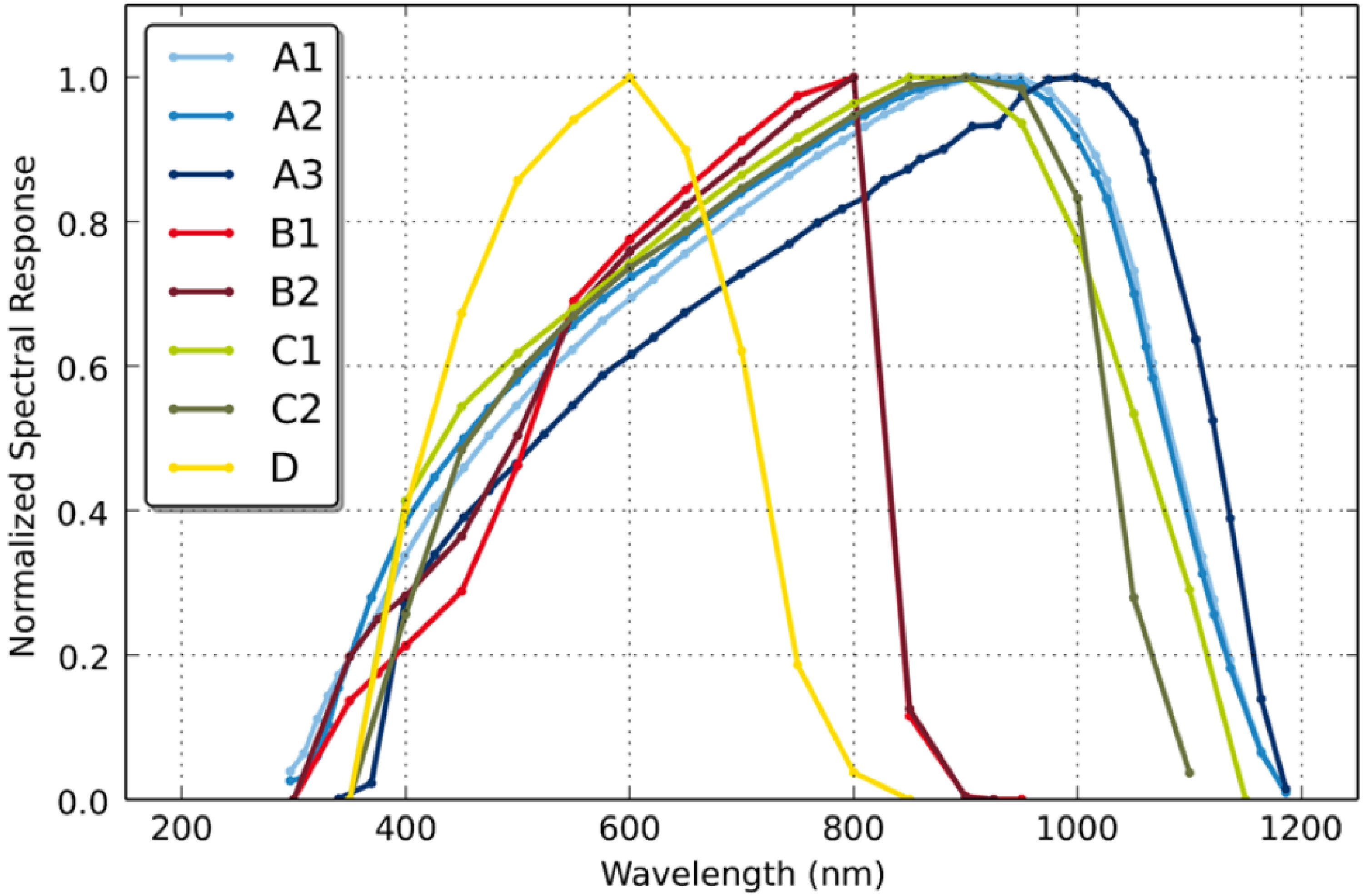
A Set of Samples

Dependency on module temperature



A Set of Samples

Spectral response



A Set of Samples

List of sites

	ID	Site	Hor. Irrad. *kWh/m²*	Avg. Temperature °C
🟩	1	Norwich, UK	978	10.3
🟩	2	Breisach, Germany	1216	9.8
🟩	3	Rafah, Egypt	1876	20.7

Uncertainty of ER Input Values

How to obtain the “u” values ?

- Uncertainty of Module Performance Ratio (MPR):

$$\mathrm{u}_{MPR_{\mathrm{nominal}}} = \sqrt{\mathrm{u}_{f_{\mathrm{AOI}}}{}^{2} + \mathrm{u}_{f_{\mathrm{spectral}}}{}^{2} + \mathrm{u}_{f_{G}}{}^{2} + \mathrm{u}_{f_{\mathrm{T}}}{}^{2}}$$

$$\mathrm{u}_{\mathrm{MPR}} = \sqrt{\mathrm{u}_{P_{\mathrm{STC,measured}}}{}^{2} + \mathrm{u}_{f_{\mathrm{AOI}}}{}^{2} + \mathrm{u}_{f_{\mathrm{spectral}}}{}^{2} + \mathrm{u}_{f_{G}}{}^{2} + \mathrm{u}_{f_{\mathrm{T}}}{}^{2}}$$

Uncertainty of ER Input Values

The “u” values

	A1	A2	A3	B1	B2	C1	C2	D
England								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.7	0.7	0.7	1.4	1.4	1.4	1.4	0.7
u_{f_T} [%]	0.1	0.1	0.1	0.0	0.0	0.0	0.1	0.0
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	1.5	1.6	2.2	2.2	2.0	2.0	2.2
u_{MPR} [%]	1.9	1.9	2.0	3.0	3.0	2.7	2.7	2.6
Southern Germany								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.6	0.6	0.6	1.1	1.1	1.1	1.1	0.6
u_{f_T} [%]	0.2	0.3	0.2	0.1	0.1	0.1	0.3	0.1
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	1.5	1.5	2.0	2.0	1.8	1.8	2.1
u_{MPR} [%]	1.8	1.8	2.0	2.8	2.8	2.6	2.6	2.6
Egypt								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.4	0.4	0.4	0.8	0.8	0.8	0.8	0.4
u_{f_T} [%]	0.8	0.8	0.6	0.4	0.4	0.4	0.8	0.4
$u_{MPR,\mathrm{nominal}}$ [%]	1.6	1.6	1.6	1.9	1.9	1.7	1.8	2.1
u_{MPR} [%]	1.9	1.9	2.0	2.8	2.8	2.5	2.6	2.6

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

Uncertainty of ER Input Values

Module power @ STC

	A1	A2	A3	B1	B2	C1	C2	D
England								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
u_{f_spectral} [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.7	0.7	0.7	1.4	1.4	1.4	1.4	0.7
u_{f_T} [%]	0.1	0.1						0.0
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	1.5						2.2
u_{MPR} [%]								2.6
Southern Germany								
u_{f_AOI} [%]	1.0	1.0						1.0
u_{f_spectral} [%]	0.9	0.9						1.8
u_{f_G} [%]	0.6	0.6						0.6
u_{f_T} [%]	0.2	0.3						0.1
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	1.5						2.1
u_{MPR} [%]	1.8	1.8						2.6
Egypt								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
u_{f_spectral} [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.4	0.4	0.4	0.8	0.8	0.8	0.8	0.4
u_{f_T} [%]	0.8	0.8	0.6	0.4	0.4	0.4	0.8	0.4
$u_{MPR,\mathrm{nominal}}$ [%]	1.6	1.6	1.6	1.9	1.9	1.7	1.8	2.1
u_{MPR} [%]	1.9	1.9	2.0	2.8	2.8	2.5	2.6	2.6

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

STC power measurement uncertainties derived from research on the uncertainty budget of Fraunhofer ISE's CalLab PV Modules

(depends on cell technology)

Uncertainty of ER Input Values
Angle of incidence (AOI)

	A1	A2	A3	B1	B2	C1	C2	D
England								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
u_{f_spectral} [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.7	0.7	0.7	1.4	1.4	1.4	1.4	0.7
u_{f_T} [%]	0.1	0.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.2
u_{MPR} [%]	1.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6
Southern Germany								
u_{f_AOI} [%]	1.0	1.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.0
u_{f_spectral} [%]	0.9	0.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.8
u_{f_G} [%]	0.6	0.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.6
u_{f_T} [%]	0.2	0.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.1
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	1.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.1
u_{MPR} [%]	1.8	1.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6
Egypt								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
u_{f_spectral} [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.4	0.4	0.4	0.8	0.8	0.8	0.8	0.4
u_{f_T} [%]	0.8	0.8	0.6	0.4	0.4	0.4	0.8	0.4
$u_{MPR,\mathrm{nominal}}$ [%]	1.6	1.6	1.6	1.9	1.9	1.7	1.8	2.1
u_{MPR} [%]	1.9	1.9	2.0	2.8	2.8	2.5	2.6	2.6

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

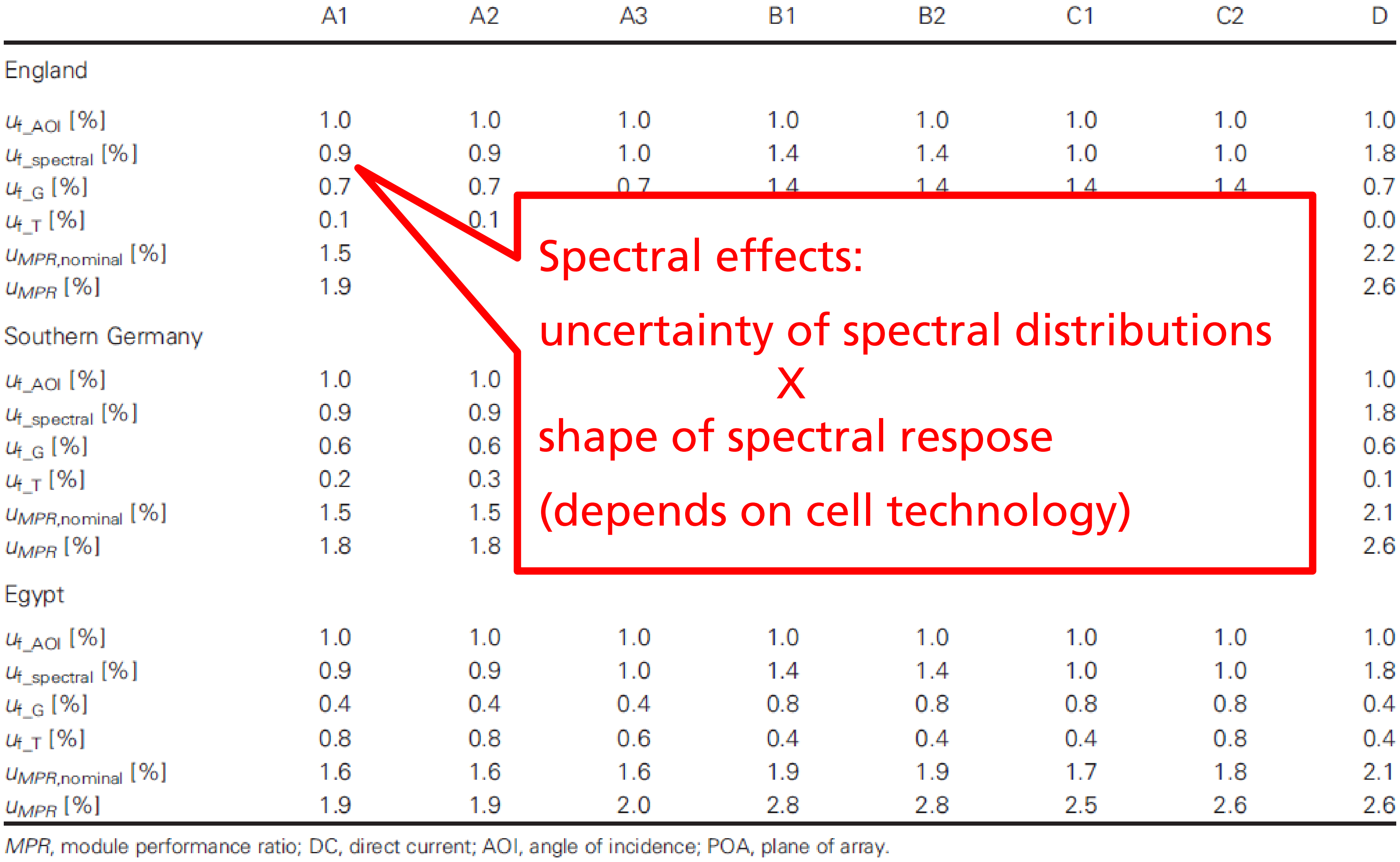
AOI effect uncertainty:

1% everywhere

(further reserach necessary)

Uncertainty of ER Input Values

Spectral response



	A1	A2	A3	B1	B2	C1	C2	D
England								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
u_{f_spectral} [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.7	0.7	0.7	1.4	1.4	1.4	1.4	0.7
u_{f_T} [%]	0.1	0.1						0.0
$u_{MPR,\mathrm{nominal}}$ [%]	1.5							2.2
u_{MPR} [%]	1.9							2.6
Southern Germany								
u_{f_AOI} [%]	1.0	1.0						1.0
u_{f_spectral} [%]	0.9	0.9						1.8
u_{f_G} [%]	0.6	0.6						0.6
u_{f_T} [%]	0.2	0.3						0.1
$u_{MPR,\mathrm{nominal}}$ [%]	1.5	1.5						2.1
u_{MPR} [%]	1.8	1.8						2.6
Egypt								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
u_{f_spectral} [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.4	0.4	0.4	0.8	0.8	0.8	0.8	0.4
u_{f_T} [%]	0.8	0.8	0.6	0.4	0.4	0.4	0.8	0.4
$u_{MPR,\mathrm{nominal}}$ [%]	1.6	1.6	1.6	1.9	1.9	1.7	1.8	2.1
u_{MPR} [%]	1.9	1.9	2.0	2.8	2.8	2.5	2.6	2.6

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

Spectral effects:

uncertainty of spectral distributions

X

shape of spectral respose

(depends on cell technology)

Uncertainty of ER Input Values

Dependency on irradiance level

	A1	A2	A3	B1	B2	C1	C2	D
England								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.7	0.7	0.7	1.4	1.4	1.4	1.4	0.7
u_{f_T} [%]	0.1	0.1						0.0
$u_{MPR,nominal}$ [%]	1.5							2.2
u_{MPR} [%]	1.9							2.6
Southern Germany								
u_{f_AOI} [%]	1.0	1.0						1.0
$u_{f\_spectral}$ [%]	0.9	0.9						1.8
u_{f_G} [%]	0.6	0.6						0.6
u_{f_T} [%]	0.2	0.3						0.1
$u_{MPR,nominal}$ [%]	1.5	1.5						2.1
u_{MPR} [%]	1.8	1.8						2.6
Egypt								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.4	0.4	0.4	0.8	0.8	0.8	0.8	0.4
u_{f_T} [%]	0.8	0.8	0.6	0.4	0.4	0.4	0.8	0.4
$u_{MPR,nominal}$ [%]	1.6	1.6	1.6	1.9	1.9	1.7	1.8	2.1
u_{MPR} [%]	1.9	1.9	2.0	2.8	2.8	2.5	2.6	2.6

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

Low light response:

assessment of meas. uncertainty at 600 W/m² and 200 W/m²

(depends on cell technology and site)

Uncertainty of ER Input Values

Dependency on module temperature

	A1	A2	A3	B1	B2	C1	C2	D
England								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.7	0.7	0.7	1.4	1.4	1.4	1.4	0.7
u_{f_T} [%]	0.1	0.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0
$u_{MPR,nominal}$ [%]	1.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.2
u_{MPR} [%]	1.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6
Southern Germany								
u_{f_AOI} [%]	1.0	1.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1.8
u_{f_G} [%]	0.6	0.6	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.6
u_{f_T} [%]	0.2	0.3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.1
$u_{MPR,nominal}$ [%]	1.5	1.5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.1
u_{MPR} [%]	1.8	1.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.6
Egypt								
u_{f_AOI} [%]	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
$u_{f\_spectral}$ [%]	0.9	0.9	1.0	1.4	1.4	1.0	1.0	1.8
u_{f_G} [%]	0.4	0.4	0.4	0.8	0.8	0.8	0.8	0.4
u_{f_T} [%]	0.8	0.8	0.6	0.4	0.4	0.4	0.8	0.4
$u_{MPR,nominal}$ [%]	1.6	1.6	1.6	1.9	1.9	1.7	1.8	2.1
u_{MPR} [%]	1.9	1.9	2.0	2.8	2.8	2.5	2.6	2.6

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

Temperture effects:

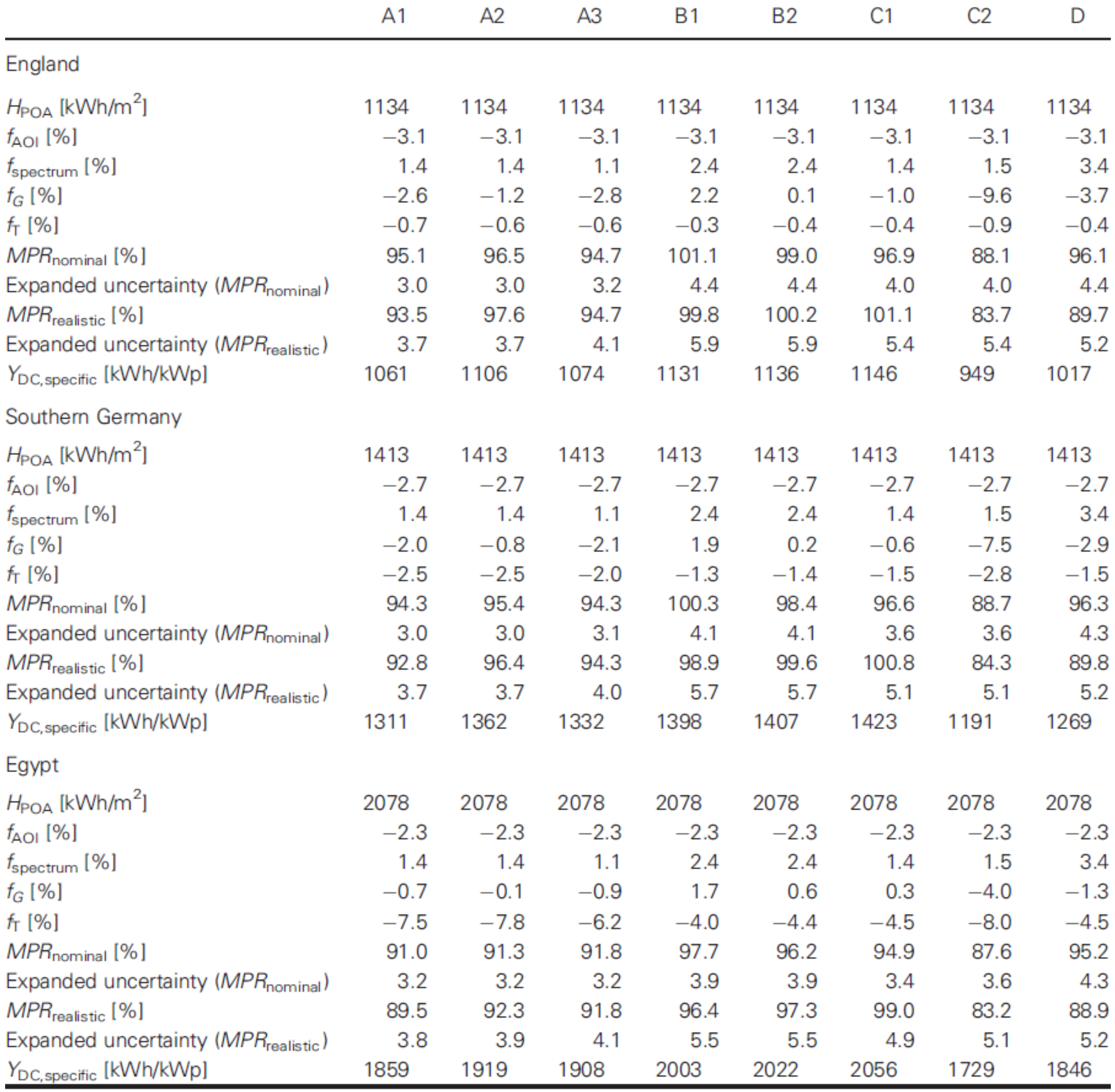
uncertainty Tk_{Pstc} = 10%

X

distribution of module temperature

(depends on cell technology and site)

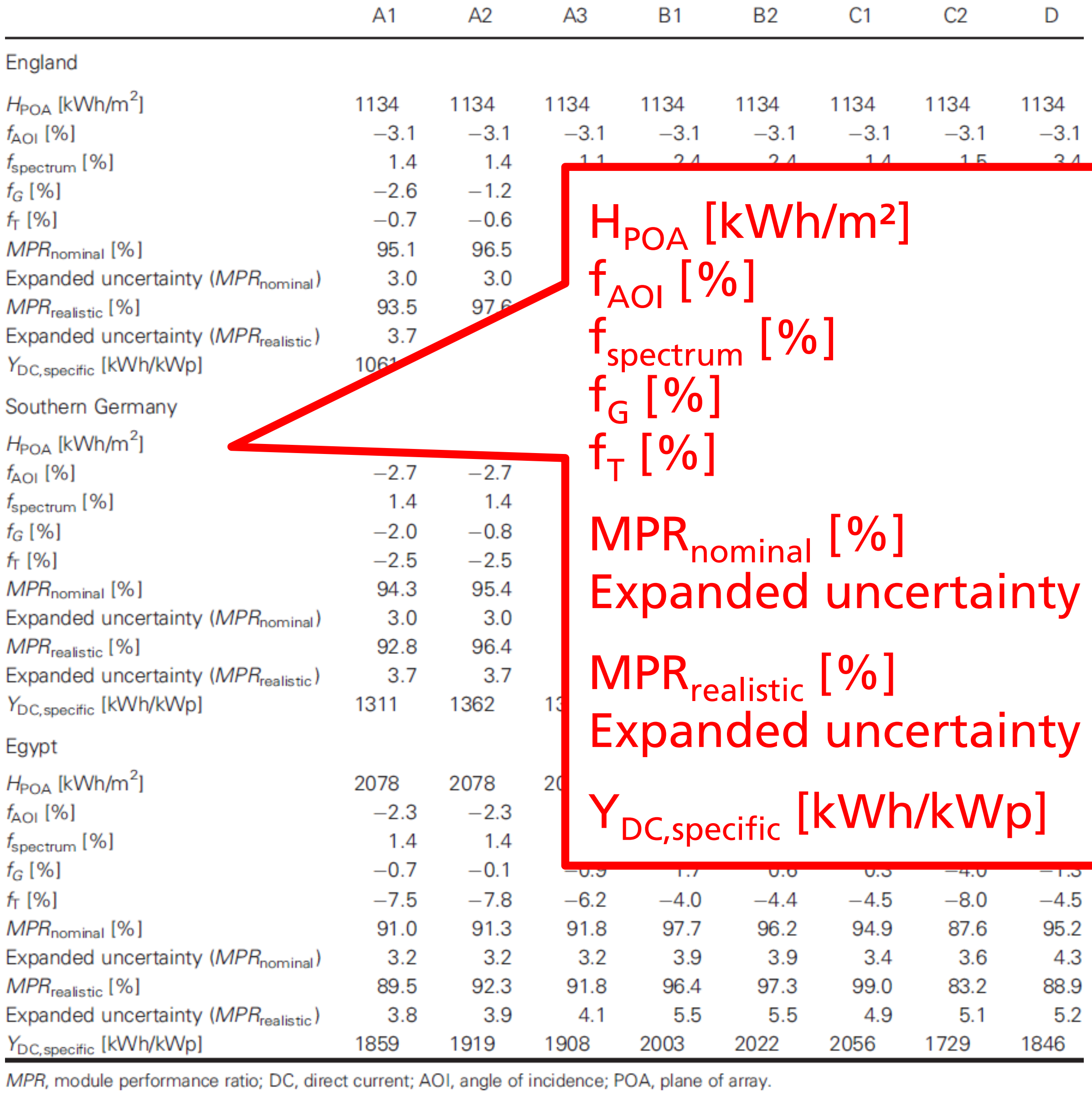
Results: Module Energy Rating and Uncertainties



	A1	A2	A3	B1	B2	C1	C2	D
England								
H_{POA} [kWh/m^2]	1134	1134	1134	1134	1134	1134	1134	1134
f_{AOI} [%]	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1
$f_{spectrum}$ [%]	1.4	1.4	1.1	2.4	2.4	1.4	1.5	3.4
f_G [%]	−2.6	−1.2	−2.8	2.2	0.1	−1.0	−9.6	−3.7
f_T [%]	−0.7	−0.6	−0.6	−0.3	−0.4	−0.4	−0.9	−0.4
$MPR_{nominal}$ [%]	95.1	96.5	94.7	101.1	99.0	96.9	88.1	96.1
Expanded uncertainty ($MPR_{nominal}$)	3.0	3.0	3.2	4.4	4.4	4.0	4.0	4.4
$MPR_{realistic}$ [%]	93.5	97.6	94.7	99.8	100.2	101.1	83.7	89.7
Expanded uncertainty ($MPR_{realistic}$)	3.7	3.7	4.1	5.9	5.9	5.4	5.4	5.2
$Y_{DC,specific}$ [kWh/kWp]	1061	1106	1074	1131	1136	1146	949	1017
Southern Germany								
H_{POA} [kWh/m^2]	1413	1413	1413	1413	1413	1413	1413	1413
f_{AOI} [%]	−2.7	−2.7	−2.7	−2.7	−2.7	−2.7	−2.7	−2.7
$f_{spectrum}$ [%]	1.4	1.4	1.1	2.4	2.4	1.4	1.5	3.4
f_G [%]	−2.0	−0.8	−2.1	1.9	0.2	−0.6	−7.5	−2.9
f_T [%]	−2.5	−2.5	−2.0	−1.3	−1.4	−1.5	−2.8	−1.5
$MPR_{nominal}$ [%]	94.3	95.4	94.3	100.3	98.4	96.6	88.7	96.3
Expanded uncertainty ($MPR_{nominal}$)	3.0	3.0	3.1	4.1	4.1	3.6	3.6	4.3
$MPR_{realistic}$ [%]	92.8	96.4	94.3	98.9	99.6	100.8	84.3	89.8
Expanded uncertainty ($MPR_{realistic}$)	3.7	3.7	4.0	5.7	5.7	5.1	5.1	5.2
$Y_{DC,specific}$ [kWh/kWp]	1311	1362	1332	1398	1407	1423	1191	1269
Egypt								
H_{POA} [kWh/m^2]	2078	2078	2078	2078	2078	2078	2078	2078
f_{AOI} [%]	−2.3	−2.3	−2.3	−2.3	−2.3	−2.3	−2.3	−2.3
$f_{spectrum}$ [%]	1.4	1.4	1.1	2.4	2.4	1.4	1.5	3.4
f_G [%]	−0.7	−0.1	−0.9	1.7	0.6	0.3	−4.0	−1.3
f_T [%]	−7.5	−7.8	−6.2	−4.0	−4.4	−4.5	−8.0	−4.5
$MPR_{nominal}$ [%]	91.0	91.3	91.8	97.7	96.2	94.9	87.6	95.2
Expanded uncertainty ($MPR_{nominal}$)	3.2	3.2	3.2	3.9	3.9	3.4	3.6	4.3
$MPR_{realistic}$ [%]	89.5	92.3	91.8	96.4	97.3	99.0	83.2	88.9
Expanded uncertainty ($MPR_{realistic}$)	3.8	3.9	4.1	5.5	5.5	4.9	5.1	5.2
$Y_{DC,specific}$ [kWh/kWp]	1859	1919	1908	2003	2022	2056	1729	1846

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

Results: Module Energy Rating and Uncertainties



	A1	A2	A3	B1	B2	C1	C2	D
England								
H_{POA} [kWh/m^2]	1134	1134	1134	1134	1134	1134	1134	1134
f_{AOI} [%]	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1	−3.1
$f_{spectrum}$ [%]	1.4	1.4						
f_G [%]	−2.6	−1.2						
f_T [%]	−0.7	−0.6						
$MPR_{nominal}$ [%]	95.1	96.5						
Expanded uncertainty ($MPR_{nominal}$)	3.0	3.0						
$MPR_{realistic}$ [%]	93.5	97.6						
Expanded uncertainty ($MPR_{realistic}$)	3.7							
$Y_{DC,specific}$ [kWh/kWp]	1061							
Southern Germany								
H_{POA} [kWh/m^2]								
f_{AOI} [%]	−2.7	−2.7						
$f_{spectrum}$ [%]	1.4	1.4						
f_G [%]	−2.0	−0.8						
f_T [%]	−2.5	−2.5						
$MPR_{nominal}$ [%]	94.3	95.4						
Expanded uncertainty ($MPR_{nominal}$)	3.0	3.0						
$MPR_{realistic}$ [%]	92.8	96.4						
Expanded uncertainty ($MPR_{realistic}$)	3.7	3.7						
$Y_{DC,specific}$ [kWh/kWp]	1311	1362						
Egypt								
H_{POA} [kWh/m^2]	2078	2078						
f_{AOI} [%]	−2.3	−2.3						
$f_{spectrum}$ [%]	1.4	1.4						
f_G [%]	−0.7	−0.1						
f_T [%]	−7.5	−7.8	−6.2	−4.0	−4.4	−4.5	−8.0	−4.5
$MPR_{nominal}$ [%]	91.0	91.3	91.8	97.7	96.2	94.9	87.6	95.2
Expanded uncertainty ($MPR_{nominal}$)	3.2	3.2	3.2	3.9	3.9	3.4	3.6	4.3
$MPR_{realistic}$ [%]	89.5	92.3	91.8	96.4	97.3	99.0	83.2	88.9
Expanded uncertainty ($MPR_{realistic}$)	3.8	3.9	4.1	5.5	5.5	4.9	5.1	5.2
$Y_{DC,specific}$ [kWh/kWp]	1859	1919	1908	2003	2022	2056	1729	1846

MPR, module performance ratio; DC, direct current; AOI, angle of incidence; POA, plane of array.

H_{POA} [kWh/m²]
f_{AOI} [%]
$f_{spectrum}$ [%]
f_G [%]
f_T [%]

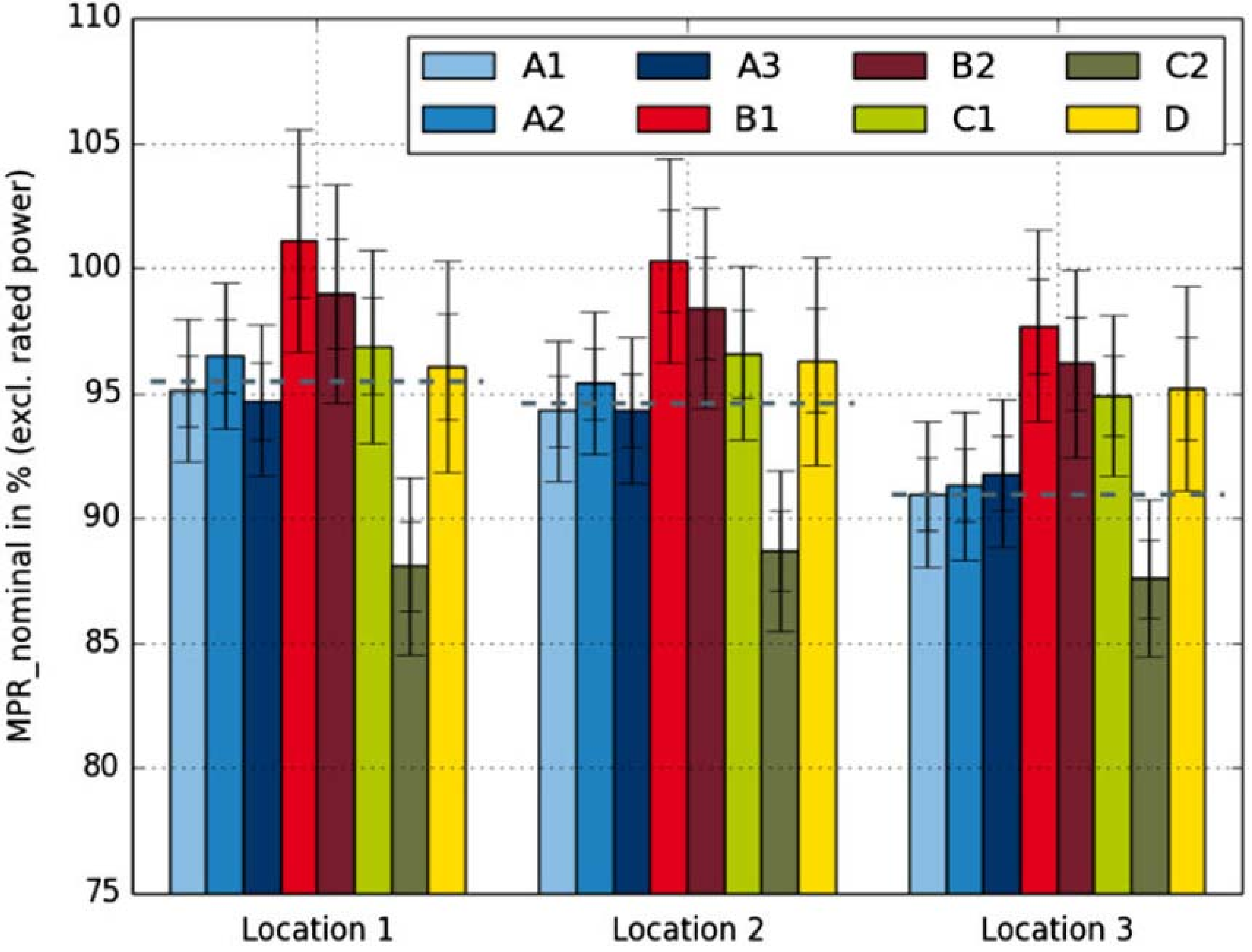
$MPR_{nominal}$ [%]
Expanded uncertainty

$MPR_{realistic}$ [%]
Expanded uncertainty

$Y_{DC,specific}$ [kWh/kWp]

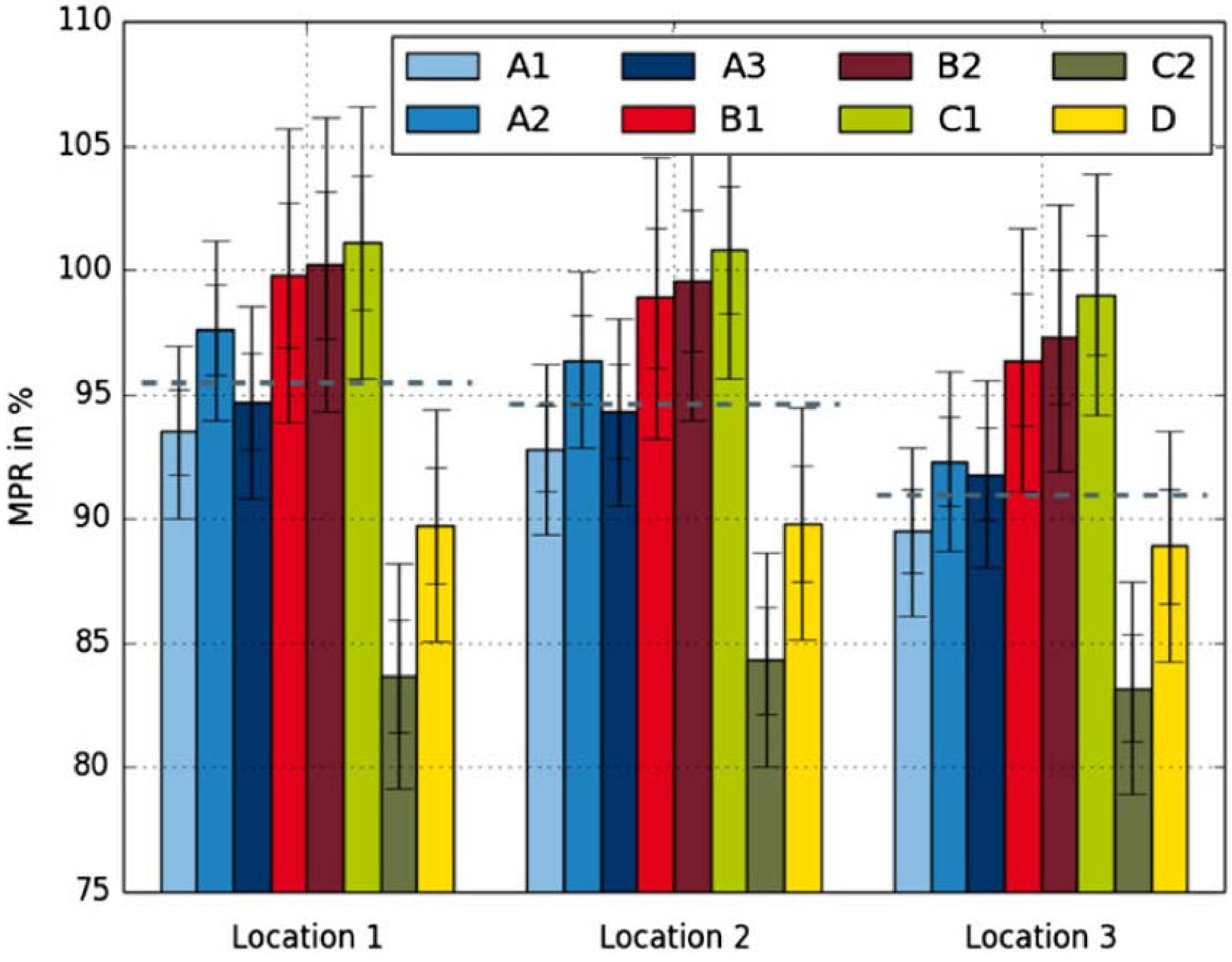
Results: Module Ranking and Uncertainties

Nominal Module Performance Ratio



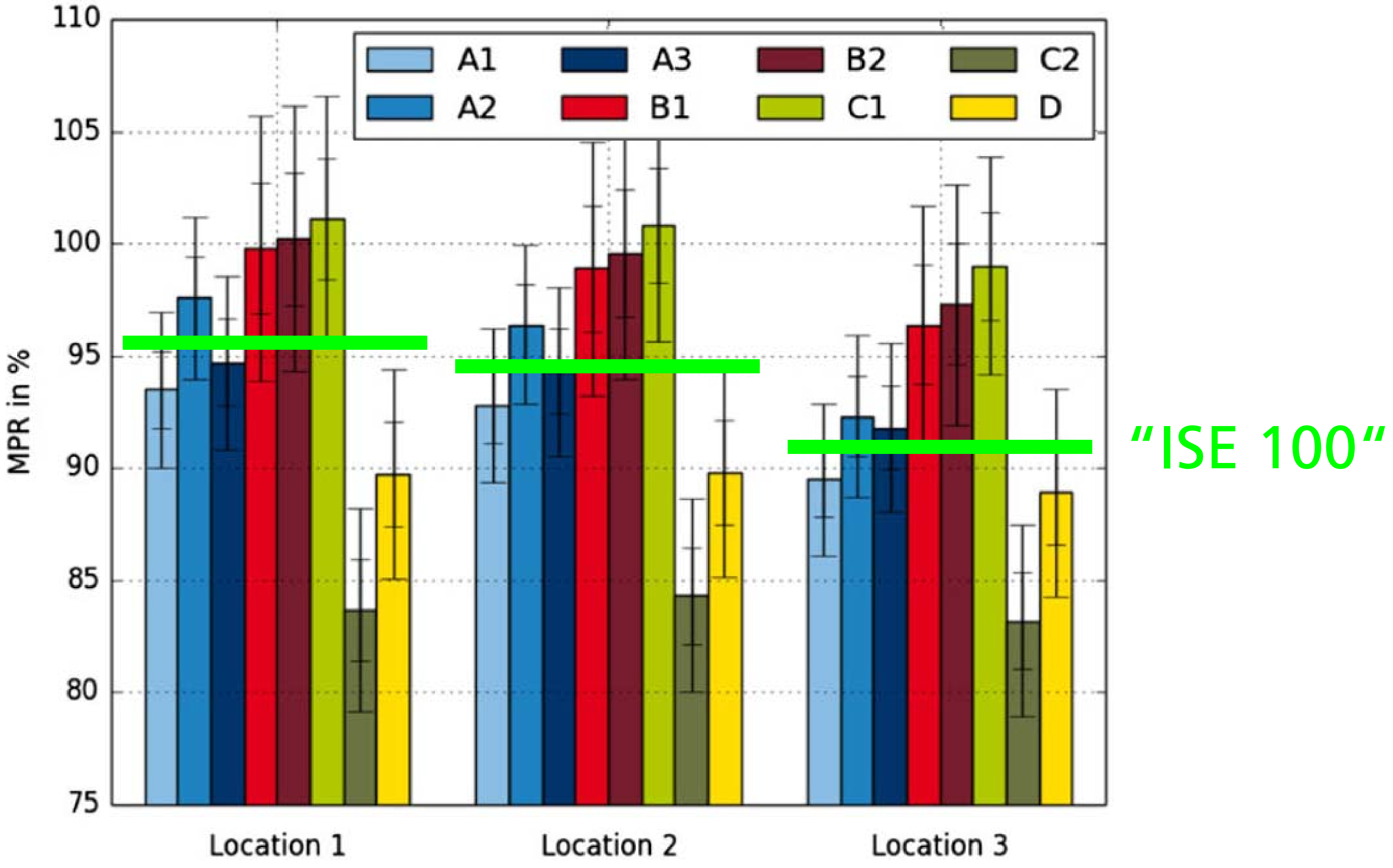
Results: Module Ranking and Uncertainties

Actual Module Performance Ratio



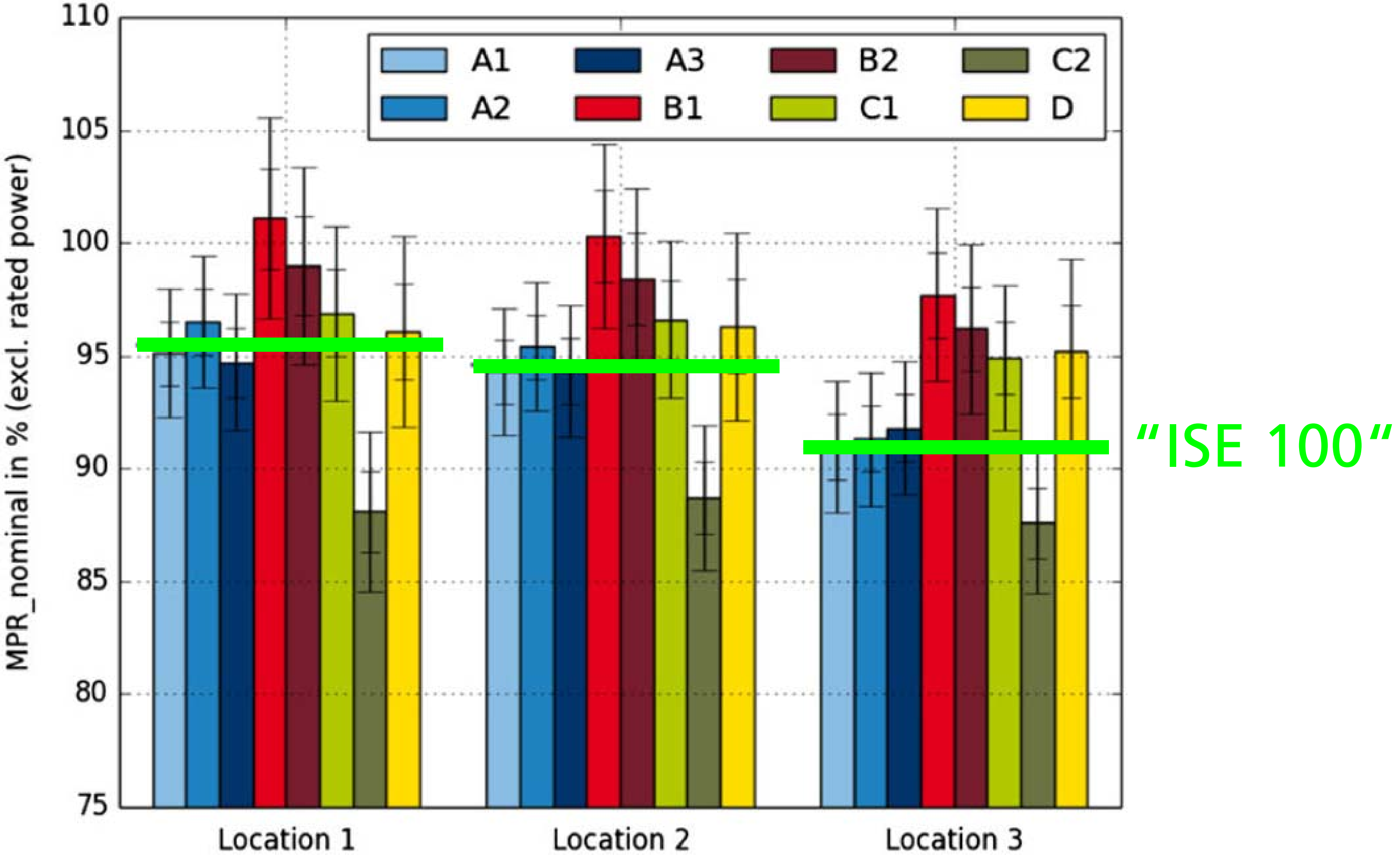
Results: Module Ranking and Uncertainties

Actual Module Performance Ratio



Results: Module Ranking and Uncertainties

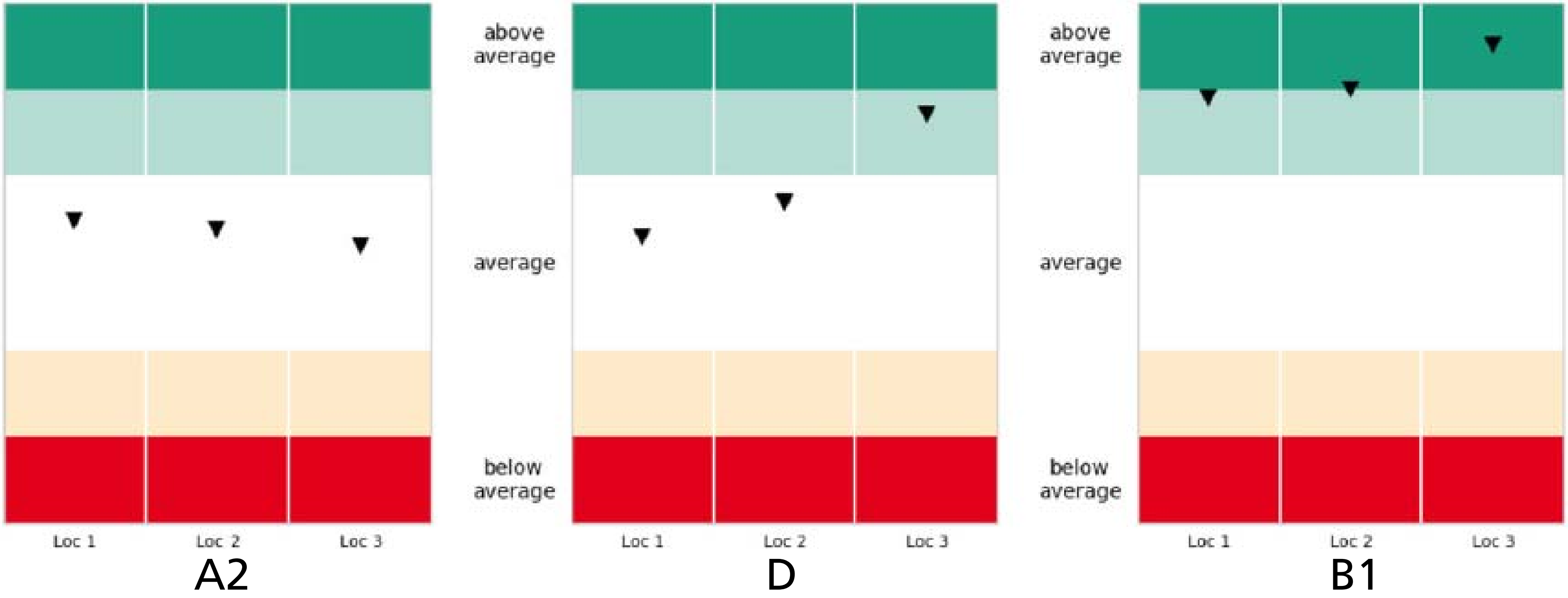
Nominal Module Performance Ratio



Results: Module Ranking and Uncertainties

Module Ranking

Using the “z-score”: $z = (\mathrm{MPR} - \mathrm{MPR}_{ref}) / u_{\mathrm{MPR}}$



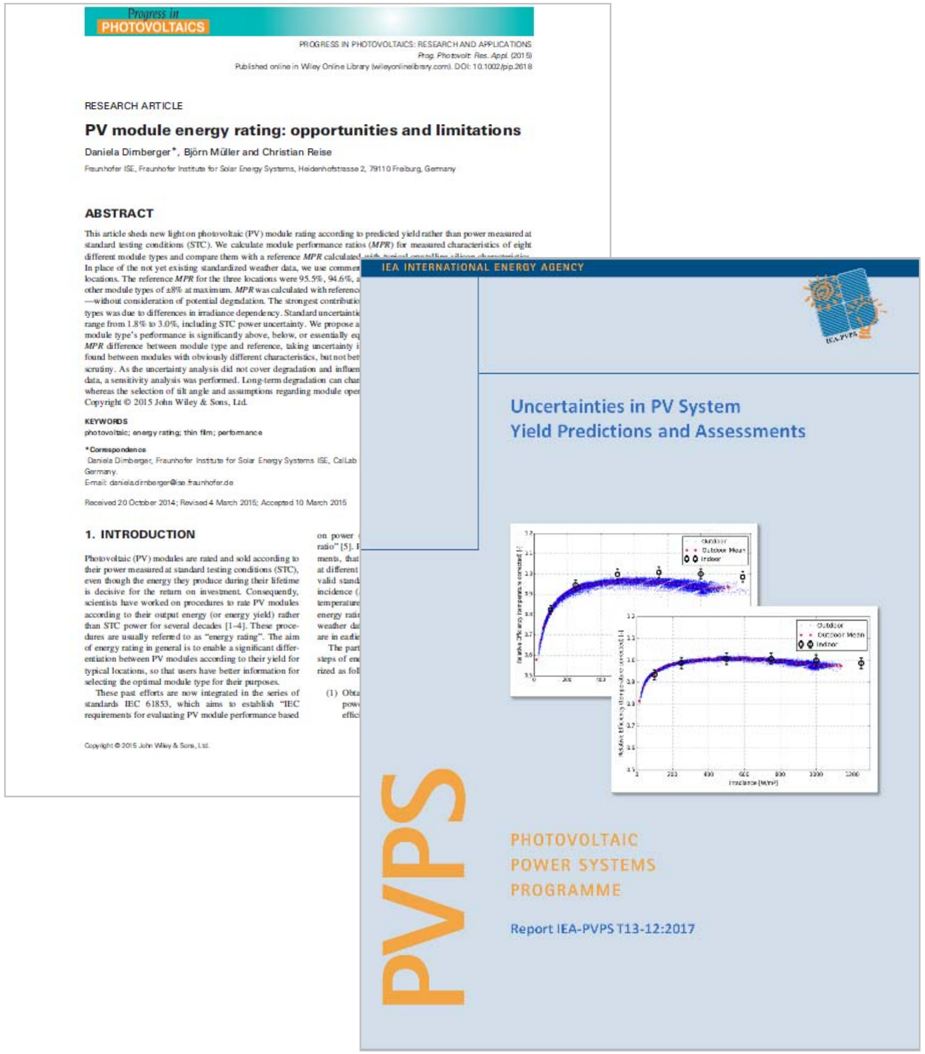
Conclusions

- Even simple assumptions on individual measurement uncertainties lead to overall module performance ratio uncertainties varying with module type and climatic region
- Typical module performance ratio uncertainties may be greater than the actual differences in module performance ratio
- A reference to the current state of the art (e.g. the most recent 100 module characterizations) and to MPR uncertainty (using the z-score) may help to keep uncertainties in mind

References

- D. Dirnberger, B. Müller, Ch. Reise:
  *PV module energy rating:
  opportunities and limitations.*
  Prog. Photovolt: Res. Appl. (2015)

- IEA PVPS Task 13
  Ch. Reise, B. Farnung (Eds.):
  *Uncertainties in PV System Yield
  Predictions and Assessments.*
  Report IEA-PVPS T13-??:2017,
  to be published in 2017



PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2015)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2618

RESEARCH ARTICLE

PV module energy rating: opportunities and limitations

Daniela Dirnberger*, Björn Müller and Christian Reise

Fraunhofer ISE, Fraunhofer Institute for Solar Energy Systems, Heidenhofstrasse 2, 79110 Freiburg, Germany

ABSTRACT

This article sheds new light on photovoltaic (PV) module rating according to predicted yield rather than power measured at
standard testing conditions (STC). We calculate module performance ratios (*MPR*) for measured characteristics of eight
different module types and compare them with a reference *MPR* calculated
In place of the not yet existing standardized weather data, we use commer
locations. The reference *MPR* for the three locations were 95.5%, 94.6%, a
other module types of ±8% at maximum. *MPR* was calculated with referenc
—without consideration of potential degradation. The strongest contributio
types was due to differences in irradiance dependency. Standard uncertaintie
range from 1.8% to 3.0%, including STC power uncertainty. We propose a
module type's performance is significantly above, below, or essentially eq
MPR difference between module type and reference, taking uncertainty i
found between modules with obviously different characteristics, but not bet
scrutiny. As the uncertainty analysis did not cover degradation and influen
data, a sensitivity analysis was performed. Long-term degradation can chan
whereas the selection of tilt angle and assumptions regarding module oper
Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS
photovoltaic; energy rating; thin film; performance

*Correspondence
Daniela Dirnberger, Fraunhofer Institute for Solar Energy Systems ISE, CalLab
Germany.
E-mail: daniela.dirnberger@ise.fraunhofer.de

Received 20 October 2014; Revised 4 March 2015; Accepted 10 March 2015

1. INTRODUCTION

Photovoltaic (PV) modules are rated and sold according to their power measured at standard testing conditions (STC), even though the energy they produce during their lifetime is decisive for the return on investment. Consequently, scientists have worked on procedures to rate PV modules according to their output energy (or energy yield) rather than STC power for several decades [1–4]. These procedures are usually referred to as "energy rating". The aim of energy rating in general is to enable a significant differentiation between PV modules according to their yield for typical locations, so that users have better information for selecting the optimal module type for their purposes.

These past efforts are now integrated in the series of standards IEC 61853, which aims to establish "IEC requirements for evaluating PV module performance based

on power
ratio" [5].
ments, that
at different
valid stand
incidence
temperature
energy rati
weather da
are in earlie

The part
steps of en
rized as fol

(1) Obta
pow
effici

Copyright © 2015 John Wiley & Sons, Ltd.

IEA INTERNATIONAL ENERGY AGENCY

Uncertainties in PV System
Yield Predictions and Assessments

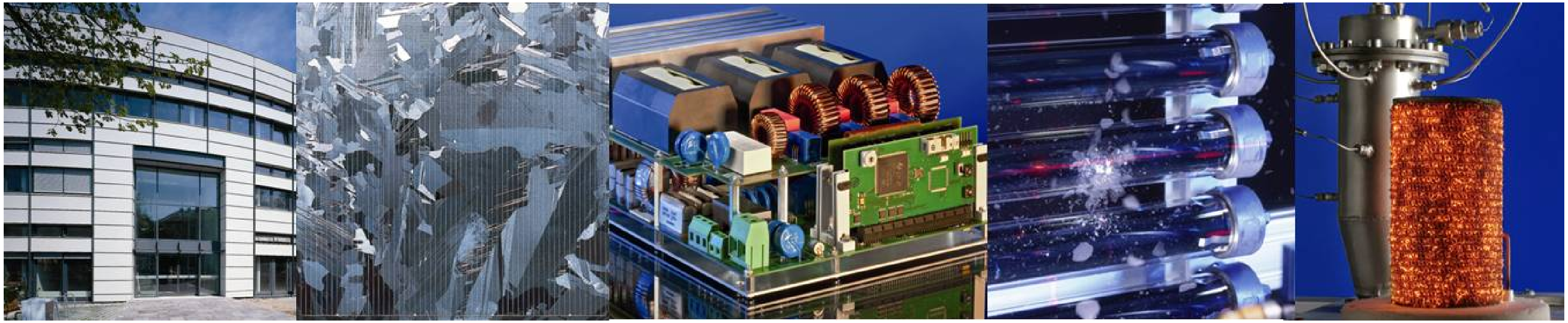
PVPS

PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME

Report IEA-PVPS T13-12:2017

Fraunhofer
ISE

Thank you for your attention!



Fraunhofer Institute for Solar Energy Systems ISE

Dr. Christian Reise

christian.reise@ise.fraunhofer.de
ertragsgutachten@ise.fraunhofer.de