Understanding the energy yield of photovoltaic modules in different climates by linear performance loss analysis of the module performance ratio

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Abstract: The energy yield of 15 different photovoltaic module technologies is measured during one year of operation at four locations (Germany, Italy, India, Arizona) corresponding to four different climate zones. The data are analysed in terms of a linear performance loss analysis for the module performance ratio (MPR) taking into account the influence of module temperature, low irradiance conditions, spectral and angular effects and soiling. This analysis is based on an independent characterisation of the modules in the laboratory combined with site specific data accumulated during operation. The model predicts trends of the measured MPR due to different module technologies and different locations.

1 Introduction

During the last six years from 2010 to 2015 a sum of $809 billion has been invested in photovoltaic (PV) systems [1]. A large part of this investment is given by the price of PV modules which, in turn, is determined by their output power rated at standard test conditions (STC) [2, 3], i.e. at an irradiance of 1000 W/m², a module temperature of 25°C and a spectral irradiance according to international electrochemical commission (IEC) 60904-3 [4]. However, the return on investment is determined by the energy yield of the module at physical outdoor conditions that depend on the module location, include daily and seasonal variations, and are in general substantially different from the STC. Therefore, the energy yield of a module cannot be predicted simply by multiplying the time averaged insolation of a specific location with the rated module output power according to STC. Instead, a factor, the module performance ratio (MPR), usually significantly smaller than unity, is used to describe this discrepancy. The MPR of a module depends on the module technology, its mounting situation, and the location. The location implies characteristic variations of irradiance, module temperature and spectral distribution of sunlight, all occurring on seasonal and daily basis. These aspects lead to high uncertainties and differences in the energy yield prediction of PV modules of different technologies.

This paper investigates the energy yield in terms of the MPR for 15 different solar module technologies at four different locations over the course of one year. In contrast to earlier studies [5] we performed an extensive electrical characterisation of all samples in our laboratory prior to the outdoor exposure. Furthermore, nominally identical (i.e., same nameplate rated power) PV modules were installed at all locations. Also the measuring system is equal at each test site including continuous spectral irradiance measurements in the plane of the arrays which availability is limited in previous studies [6, 7]. The present experimental approach allows us to investigate the dependence of the MPR on specific module technologies and locations. We use a linearised model to explain the MPR in terms of module performance differences MPR resulting from the external factors module temperature, low irradiance behaviour, spectral and angular effects as well as soiling. This linear performance loss analysis (LPLA) combines physical parameters of the different PV modules that have been measured independently with the site specific external conditions. The measured MPR at the four locations for the respective 15 modules is well described by the model.

2 PV module samples and outdoor test sites

We have investigated 15 different PV module types for each of the four locations. All tested samples have been manufactured in 2013 and were brand new before testing. Thin-film PV modules based on CdTe, copper indium gallium selenide (CIGS) and amorphous silicon are part of the test as well as crystalline silicon PV modules as listed in Table 1.

The crystalline PV module types are mono-crystalline silicon with heterojunction technology (HJT), back contacted mono-crystalline silicon with n-type basis cells and three conventional polycrystalline silicon samples. The three polycrystalline silicon samples are identical in construction except for the front-glass. The three different front-glass types are rolled glass without coating (Albarino T), rolled glass with anti-reflection (AR) coating (Albarino T AR3) and deep structured glass (Albarino P). The samples were characterised in the laboratory by means of a class AAA [8] pulsed solar simulator to determine the low irradiance behaviour and the temperature coefficients according to [9]. The angular response was measured with an approach introduced in [10]. The spectral response was measured with a set-up developed by the national institute of advanced industrial science and technology (AIST) [11] in 5 nm step-size. Due to the large number of modules preconditioning was not possible and the laboratory tests for the efficiency turned out to be of limited value. Therefore, we have decided to use the nameplate efficiency as a reference where needed. An investigation of the same data set focuses on the stability of the modules using on-site determination of the STC.
efficiency as a reference is under way [12]. Note also that one module (a-Si 1, Cologne) was broken during the time of the experiment such that in the following we are referring to only 59 modules.

To generate precise outdoor data sets four test sites were established as shown in Table 2. The four outdoor test sites (Cologne, Germany; Ancona, Italy; Tempe, Arizona; Chennai, India) cover a wide range of characteristic climate conditions. The geographical performance variation of PV module technologies as thin-film can be significantly different to c-Si as described in [13].

Each test site was equipped with identical samples and a measuring system developed by TÜV Rheinland Energy. The PV modules are mounted facing south and tilted. The modules are open rack mounted without thermal insulation and 10 cm apart from each other. Each module is equipped with its own electronic load which allows time synchronous measurements. The 4-wire contacting (cable length 10 m, resistance 0.057 Ω) for independent current and voltage measurement starts directly at the connector of the PV modules. The electronic loads perform the maximum power (BoM) tracking in 30 s intervals. The average of two Pt100 temperature sensors is used to measure the back of module temperature \( T_{\text{BoM}} \) of each sample.

The irradiance \( G_{\text{PoA}} \) in the plane of the array is measured by a ventilated pyranometer with a standard uncertainty of \( u = \pm 0.765\% \). The spectral irradiance is measured by a spectroradiometer in the range of 300–1600 nm with a sampling frequency of 1 min. The whole equipment and sensors are calibrated in-house once a year and the maintenance work is done by local partners.

### 3 General approach

The energy yield \( Y \) is usually normalised to the output power \( P_{\text{STC}} \) of the module under STC (yielding units of kWh/kWp) and reads

\[
Y = \int P_{\text{Max}} \, dt / P_{\text{STC}} \quad \text{where} \quad P_{\text{Max}} \quad \text{denotes the maximum power output}\text{ of the module. The MPR relates the energy yield to the measured irradiance in the plane of the array} \ G_{\text{PoA}} \text{normalised to the irradiance} \ G_{\text{STC}} \text{at STC via}
\]

\[
\text{MPR} = \frac{Y}{\int G_{\text{PoA}} \, dt / G_{\text{STC}}} = \frac{\int P_{\text{Max}} \, dt \ G_{\text{STC}}}{\int G_{\text{PoA}} \, dt \ G_{\text{STC}}} = \frac{\hat{\eta}_{\text{T}}}{\eta_{\text{STC}}} \tag{1}
\]

Thus, the MPR can be also seen as the ratio between the time averaged module efficiency \( \hat{\eta}_{\text{T}} \) at a specific location and the nominal efficiency \( \eta_{\text{STC}} = P_{\text{STC}} / G_{\text{STC}} \) at STC. The MPR is suitable to compare PV modules of different nominal power. Furthermore, the MPR is independent of the amount of solar radiation energy that arrives in the plane of the PV modules. The in-plane irradiance is the most important environmental factor influencing the energy yield but already well known for different geographical positions and can be easily estimated by software tools for different mounting directions. The difference of the measured MPR to the value of unity, i.e. an energy yield that corresponds to the module efficiency under STC, results from various other loss mechanisms which are the topic of interest in this study.

In the following we factorise the functional dependence of the output power \( P_{\text{Max}} \) on the external variables irradiance \( G_{\text{PoA}}, \) module temperature \( T_{\text{BoM}}, \) angle of incidence (AoI), spectral mismatch factor MMF, and the soiling parameter \( s \) according to

\[
P_{\text{Max}}(G_{\text{PoA}}, T_{\text{BoM}}, \text{AoI}, \text{MMF}, s) = P_{\text{STC}} (\delta(T_{\text{BoM}}))p(G_{\text{PoA}})p(\text{AoI})p(\text{MMF})p(s) G_{\text{PoA}} / G_{\text{STC}}. \tag{2}
\]

In (2) each effect is accounted for by a specific dimensionless performance factor \( p(x) \). To obtain a linear form we expand (2) linearly in the performance losses \( \delta p(x) = 1 - p(x) \) to arrive at (see (3) and (4)). Note that in (3) non-linear combinations of losses of the form \( \delta p(x) \delta p(y) \) are neglected. This approximation is necessary to achieve an additive form for the various losses. With (3) the time averaged module efficiency \( \hat{\eta}_{\text{T}} \) reads (see (4)). Finally, the MPR reads

\[
\text{MPR} = \frac{\hat{\eta}_{\text{T}}}{\eta_{\text{STC}}} = 1 + \sum \Delta \text{MPR}_x
\]

\[
= 1 - \sum \left( \frac{\int \delta p(x) G_{\text{PoA}} \, dt}{\int G_{\text{PoA}} \, dt} \right)
\]

The mechanisms corresponding to loss terms AMPR for different climates from the PV module characteristics measured in the laboratory and the measured meteorological data can be separated. Loss mechanisms which influence the MPR of electrically stable

### Table 2 Test site specifications: geographical data, tilt angles of the modules, measured in plane solar irradiance during the test period, share of low irradiance contribution, average ambient temperature, and annual precipitation. The reference time for averaging the temperature and for calculating the percentage of low irradiance is defined by the time where irradiance is larger than 15 W/m²

| Location         | Latitude (Germany) | Longitude | Tilt angle | Annual in-plane solar irradiation (kWh/m²) | Low irradiance contribution (<200 W/m²), % | Average ambient temperature (>15 W/m²), °C | Average annual amount of precipitation, mm |
|------------------|-------------------|-----------|------------|-------------------------------------------|------------------------------------------|-------------------------------------------|------------------------------------------|
| Cologne (Germany)| 50.922813         | 6.991705  | 35°        | 1195                                      | 19                                       | 15.2                                      | 774                                      |
| Ancona (Italy)   | 43.474195         | 13.074653 | 35°        | 1156                                      | 12                                       | 18.1                                      | 757                                      |
| Chennai (India)  | 12.984217         | 79.987987 | 15°        | 1861                                      | 9                                        | 30.3                                      | 1197                                     |
| Tempe (USA)      | 33.42404          | -111.910036 | 33.5°     | 2360                                      | 5                                        | 27.4                                      | 219                                      |

\[
P_{\text{Max}}(G_{\text{PoA}}, T_{\text{BoM}}, \text{AoI}, \text{MMF})
\]

\[
= P_{\text{STC}} [1 - \delta p(T_{\text{BoM}}) - \delta p(G_{\text{PoA}}) - \delta p(\text{AoI}) - \delta p(\text{MMF}) - \delta p(s)] G_{\text{PoA}} / G_{\text{STC}}. \tag{3}
\]

\[
\hat{\eta}_{\text{T}} = \frac{\int P_{\text{Max}}(G_{\text{PoA}}, T_{\text{BoM}}) \, dt}{\int G_{\text{PoA}} \, dt}
\]

\[
= P_{\text{STC}} \left[ 1 - \frac{\int [\delta p(T_{\text{BoM}}) + \delta p(G_{\text{PoA}}) + \delta p(\text{AoI}) + \delta p(\text{MMF}) + \delta p(s)] G_{\text{PoA}} \, dt}{\int G_{\text{PoA}} \, dt} \right] \tag{4}
\]

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PV modules are temperature ($\Delta \text{MPR}_{\text{TEMP}}$), low irradiance ($\Delta \text{MPR}_{\text{LIRR}}$), spectral effects ($\Delta \text{MPR}_{\text{MMF}}$), angular losses ($\Delta \text{MPR}_{\text{AOI}}$) and soiling ($\Delta \text{MPR}_{\text{SOIL}}$). Thus, (5) becomes

$$\text{MPR}_{\text{calc}} = 1 + \Delta \text{MPR}_{\text{TEMP}} + \Delta \text{MPR}_{\text{LIRR}} + \Delta \text{MPR}_{\text{MMF}} + \Delta \text{MPR}_{\text{AOI}} + \Delta \text{MPR}_{\text{SOIL}}. \quad (6)$$

Note that the definition of the loss terms $\Delta \text{MPR}$ in (6) implies that losses are identified by negative numbers and gains by positive numbers. Compared (5) with (6) shows that each loss term $\Delta \text{MPR}_x$ can be computed from the irradiance weighted average of the specific performance loss term $\delta p(x)$. Note further that in this study, we have omitted the influence of metastabilities or degradation which will add further losses (or gains) especially for thin-film modules. However, the overall conclusions from this work remain valid though the analysis of metastabilities adds some refinement as will be shown elsewhere [12].

### 4 Factors influencing the energy yield of PV modules

The MPR parameter provides an estimation of how well the PV module performs under real conditions in a certain climate compared to continual operation at STC efficiency. The MPR reveals test site specific performance differences for various samples. In Fig. 1, the results of 15 test modules for different test locations are shown using as basis the nominal (nameplate) output power $P_{\text{STC}}$ as stated by the manufacturer. The difference in the energy yield between the best and worst performing PV module is 23% in India, 21% in Arizona, 14% in Germany and 12% in Italy. MPR variations due to climatic impact are most pronounced between Germany and India with typically 5–7%, but up to 14% has been observed for CIGS module type. The differences between the PV module types are thus higher than the extended measurement uncertainty, which lies in the range of $\pm 5.4\%$.

#### 4.1 Module temperature

The temperature coefficients $\gamma$ for the maximum output power $P_{\text{Max}}$ has been determined for all individual modules in the laboratory. Table 3 compares the temperature coefficients $\gamma$ taken from the datasheet with the average value measured in the laboratory showing considerable deviations (>10%) between our laboratory measurements and the label values. In contrast, the spread within four respective laboratory values is less than $\pm 6\%$ for all nominally identical modules (except for a-Si 2 [±9%], CdTe 2 and 3 [±8%]).

| PV module type | $\gamma_D$ datasheet, %/K | $\gamma_M$ measured, %/K | Spread min/max, % | Difference $\gamma_D - \gamma_M$, % |
|---------------|--------------------------|---------------------------|-------------------|-----------------------------------|
| c-Si 1        | −0.43                    | −0.43                     | −1.73 to 0.58     | 0.00                              |
| c-Si 2        | −0.43                    | −0.42                     | −1.78 to 2.96     | 2.38                              |
| c-Si 3        | −0.43                    | −0.43                     | −2.92 to 1.75     | 0.00                              |
| c-Si 4        | −0.29                    | −0.35                     | −5.71 to 2.86     | −17.14                            |
| c-Si 5        | −0.38                    | −0.36                     | −2.07 to 0.69     | 5.56                              |
| CIGS 1        | −0.39                    | −0.42                     | −0.70 to 2.10     | −7.14                             |
| CIGS 2        | −0.38                    | −0.40                     | −0.90 to 9.09     | −5.00                             |
| CIGS 3        | −0.36                    | −0.37                     | −1.30 to 2.60     | −2.70                             |
| CIGS 4        | −0.31                    | −0.35                     | −4.14 to 2.96     | −11.43                            |
| a-Si 1        | −0.27                    | −0.36                     | −2.50 to 2.50     | −25.00                            |
| a-Si 2        | −0.30                    | −0.39                     | −0.68 to 2.04     | −23.08                            |
| a-Si 3        | −0.20                    | −0.26                     | −5.71 to 5.71     | −23.08                            |
| CdTe 1        | −0.27                    | −0.29                     | −3.45 to 3.45     | −6.90                             |
| CdTe 2        | −0.27                    | −0.29                     | −7.83 to 6.09     | −6.90                             |
| CdTe 3        | −0.25                    | −0.23                     | −7.53 to 5.38     | 8.70                              |

Note that the definition of the loss terms $\Delta \text{MPR}$ in (6) implies that losses are identified by negative numbers and gains by positive numbers. Compared (5) with (6) shows that each loss term $\Delta \text{MPR}_x$ can be computed from the irradiance weighted average of the specific performance loss term $\delta p(x)$. Note further that in this study, we have omitted the influence of metastabilities or degradation which will add further losses (or gains) especially for thin-film modules. However, the overall conclusions from this work remain valid though the analysis of metastabilities adds some refinement as will be shown elsewhere [12].

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Fig. 1 Annual MPR ($\text{MPR}_{\text{Label}}$) for 15 different PV modules in four different climates referenced to $P_{\text{Max},\text{Label}}$, time period: 08.01.2014–07.01.2015 Tempe and Ancona, 08.03.2014–07.03.2015 Chennai and 19.03.2014–18.03.2015 Cologne. Note that the a-Si 1 module in Cologne was broken during operation and is not considered.
With the experimentally determined temperature coefficient $\gamma$ the performance loss term $\delta p(T_{BoM})$ related to the module temperature $T_{BoM}$ reads

$$\delta p(T_{BoM}) = \gamma(T_{BoM} - 25^\circ C).$$  \hfill (7)

With (5) we obtain

$$\Delta MPR_{Temp} = \gamma \left( \int_T T_{BoM} G_{PoA} \, dt / \int_T G_{PoA} \, dt - 25^\circ C \right).$$  \hfill (8)

Thus, the temperature related MPR difference $\Delta MPR_{Temp} = \gamma(T_{BoM} - 25^\circ C)$ is calculated from the site and module specific irradiance weighted average module temperature

$$T_{BoM,G} = \int_T T_{BoM} G_{PoA} \, dt / \int_T G_{PoA} \, dt.$$  \hfill (9)

Fig. 2 shows the measured temperature coefficients $\gamma$ of $P_{Max}$ and the corresponding weighted average module temperatures $T_{BoM,G}$ of each sample. The temperature $T_{BoM,G}$ is in the range of 30.0–33.7°C in Cologne, 33.1–38.0°C in Ancona, 45.8–49.2°C in Chennai and 44.0–49.0°C in Tempe. The performance differences $\Delta MPR_{Temp} = \gamma(T_{BoM} - 25^\circ C)$ due to temperature effects are illustrated by isolines. For the moderate climates, we find $\Delta MPR_{Temp}$ in the range of $-1.2\%$ (CdTe 3) to $-3.7\%$ (CIGS 1, Cologne) and $-2.6\%$ (a-Si 3) to $-5.3\%$ (CIGS 1, Ancona). In the hotter climates, the performance differences are more significant. We find ranges from $-5.3\%$ (CdTe 3) to $-9.6\%$ (c-Si 1, Chennai) and $-5.1\%$ (CdTe 3) to $-10.6\%$ (CIGS 1, Tempe). Thus, different temperature coefficients $\gamma$ and operating temperatures lead to moderate ($\sim2.5\%$) performance differences in moderate climates and to significant ones ($\sim5.5\%$) in hot climates.

### 4.2 Low irradiance behaviour

The losses due to non-linear PV module performance in dependence on irradiance ($\Delta MPR_{IRR}$) are calculated similar to the temperature effects. In a first step, the low irradiance behaviour is determined in the lab according to

$$p(G_{Meas}) = \frac{P_{Max,Meas} G_{STC}}{P_{Max,STC} G_{Meas}}.$$  \hfill (10)

The results of those measurements (averaged for each technology) are shown in Fig. 3 for illustration, more details can be found in [14]. Note that not all modules exhibit their maximum relative performance $p(G_{Meas})$ at $G_{STC} = 1000$ W/m². A decrease of the performance towards higher irradiance usually results from resistive effects (external or internal series resistance) whereas a decrease towards low irradiation results from parallel shunts or secondary diode behaviour.

In a next step, the performance difference $\Delta MPR_{IRR}$ due to low irradiance is calculated using the site specific measured irradiance data according to

$$\Delta MPR_{IRR} = \left( \frac{\int T_{BoM} G_{PoA} \, dt}{\int G_{PoA} \, dt} \right) - 1.$$  \hfill (11)

Table 4 displays for each site the largest gain and the largest loss due to irradiance effects. Notably, CIGS modules have large losses due to the poor low-irradiance performance. In contrast, CdTe modules exhibit gains ($\Delta MPR_{IRR} > 0$) for all locations (highest in Cologne because of the highest overall share of low irradiances and in Chennai because of the high energy delivered at medium irradiances where the relative performance of the CdTe is also above 100%).

### Table 4 Minimal and maximal relative yield losses due to non-linear efficiency for four test sites

| Location | Sample type | $\Delta MPR_{IRR}$ (max. gain), % | $\Delta MPR_{IRR}$ (max. loss), % |
|----------|-------------|----------------------------------|----------------------------------|
| Ancona   | CdTe 2      | 0.33                             | -3.21                            |
| Tempe    | CdTe 1      | 0.26                             | -1.82                            |
| Chennai  | CdTe 1      | 0.63                             | -2.86                            |
| Cologne  | CdTe 2      | 1.13                             | -3.63                            |
where $SR_{Mod}(\lambda)$ denotes the spectral response of the module measured over the wavelength $\lambda$ of the incident light. The ratio between the irradiances $G_{STC}$ and $G_{PoA}$ can be expressed via

$$\frac{G_{STC}}{G_{PoA}} = \frac{\int E_{STC}(\lambda) \, d\lambda}{\int E_{Sun}(\lambda) \, d\lambda}.$$  

(13)

Therefore, the performance factor $p(MMF)$ corresponds to the spectral mismatch factor MMF as defined in IEC 60904-7 [15]

$$p(MMF) = MMF = \frac{\int E_{Sun}(\lambda) \cdot SR_{Mod}(\lambda) \, d\lambda}{\int E_{STC}(\lambda) \cdot SR_{Mod}(\lambda) \, d\lambda} \times \frac{\int E_{STC}(\lambda) \cdot SR_{Det}(\lambda) \, d\lambda}{\int E_{Sun}(\lambda) \cdot SR_{Det}(\lambda) \, d\lambda},$$

(14)

provided that the spectral response $SR_{Det}(\lambda)$ of the detector is spectrally flat in the relevant range of wavelengths. From the definition of the performance loss terms in (6), we finally find (see (15)) where $E_{Sun}(\lambda)$ denotes the temporal average of the incident solar power distribution.

As input parameters served the measured spectral response [16] of the samples as shown in Fig. 4, the spectral response of the pyranometer and the AM1.5 reference spectral irradiance as well as the average measured spectral irradiance $E_{\lambda}$ of the different test sites as shown in Fig. 5. Note that for the tandem modules we have used the spectral response of the limiting (top) junction only as a first-order approach. In principle a more detailed analysis would be necessary, e.g. along the lines of [17]. However, such an extended approach is outside of the scope of this paper.

The cumulative effect of solar spectral influence on energy production of single junction devices is shown in Table 5. The annual influence of changing solar spectrum is relatively small for crystalline silicon and CIGS samples [18]. The highest influence of solar spectral irradiance on PV module yield could be found in Chennai with maximal gains of 1.6% for c-Si, 2.8% for CIGS and 5.3% for CdTe.

### 4.4 Angular response

The measurement of the angular response of PV modules is not internationally harmonised. For this purpose, we have measured the variation in angular response of various glass types that are used as front cover in c-Si PV modules as shown in Fig. 6. For each glass type we obtain the performance factor

$$p(AoI) = \frac{P_{Max}(AoI)}{P_{Max,STC}}.$$  

(16)

Note that the actual value of $p(AoI)$ depends on the angular distribution of the incidence light during the measurement of the reference value $P_{Max,STC}$. For the data in Fig. 6 we have assumed that the AoI for the reference measurement is 0° implying that also diffusive part of the incident spectrum stems from normal incidence. This is usually the case for reference measurements in the laboratory but not for reference measurements under outdoor conditions.

The total radiation incident on a tilted plane consists of the direct radiation, the diffuse radiation and the reflected radiation from the ground [19]. The amount of direct radiation is calculated from the cosine corrected direct normal irradiance data measured with a tracked pyrheliometer. To estimate the ratio of diffuse solar radiation an isotropic distribution of diffuse sky radiation over the

![Fig. 4 Normalised spectral response curves of tested module types](image)

![Fig. 5 Thermopile pyranometer, AM1.5G standard spectrum and peak normalised annual average spectrum of four test sites](image)

4.3 Spectral response

The performance factor $p(MMF)$ due to differences in the spectral power distribution $E_{Sun}(\lambda)$ at different locations and times as compared to the power distribution $E_{STC}(\lambda)$ under standard test conditions is given by

$$p(MMF) = \frac{\int E_{Sun}(\lambda) \cdot SR_{Mod}(\lambda) \, d\lambda \times G_{STC}}{\int E_{STC}(\lambda) \cdot SR_{Mod}(\lambda) \, d\lambda \times G_{PoA}}.$$  

(12)

The cumulative effect of solar spectral influence on energy production of single junction devices is shown in Table 5. The annual influence of changing solar spectrum is relatively small for crystalline silicon and CIGS samples [18]. The highest influence of solar spectral irradiance on PV module yield could be found in Chennai with maximal gains of 1.6% for c-Si, 2.8% for CIGS and 5.3% for CdTe.
horizontal sky dome is assumed. The data for the different test sites is shown in Fig. 7.

The percentage \( f_{\Delta A_oI}(A_oI) \) of insolation within an interval \( \Delta A_oI \) of the AoI reads

\[
f_{\Delta A_oI}(A_oI) = \frac{\int f_{G_{P\alpha\lambda}}(\Delta A_oI) \, d\tau}{\int f_{G_{P\alpha\lambda}} \, d\tau}.
\] (17)

The module performance difference \( \Delta MPR_{A_oI} \) due to angular effects is defined by

\[
\Delta MPR_{A_oI} = \left( \frac{\int p(A_oI)f_{\Delta A_oI}(A_oI) \, d\tau}{\int f_{G_{P\alpha\lambda}} \, d\tau} \right) - 1.
\] (18)

Practically, we have calculated \( \Delta MPR_{A_oI} \) via

\[
\Delta MPR_{A_oI} = \sum_{\Delta A_oI} [p(A_oI)f_{\Delta A_oI}(A_oI)] - 1
\]

That is by summarising the module specific data of Fig. 6 weighted with their site specific frequency shown in Fig. 7. The ranges of relative energy yield losses due to angular effects are shown in Table 6. Compared to the standard glass a gain of up to 0.7% was achieved by the anti-reflective coating and a gain of up to 1.8% by the texturing for the Cologne site. Note that these improvements only result from the improved shallow angle light acceptance of AR coated and textured glass and do not contain the overall effect of reduced reflectance which is accounted for already by the efficiency under STC.

4.5 Soiling

The influence of soiling (\( \Delta MPR_{SOIL} \)) strongly depends on the rainfall frequency which can vary significantly for different periods under observation. The annual MPR losses due to soiling for the given test period were calculated by comparing the signal of a regularly cleaned reference cell and a soiled one assuming identical soiling rates for the tested PV modules. The site specific performance differences \( \Delta MPR_{SOIL} \) are −3.7\% in Tempe (despite of the higher tilt angle as compared to Chennai), −2.1\% in Chennai and less than −0.5\% in Ancona and Cologne. Note these results refer to flat glass only. Soiling rates of structured glass can be significantly higher [20].

4.6 Discussion

Fig. 8 displays the summary of our investigations in terms of the five different performance differences \( \Delta MPR \) for all 59 modules at the four locations. The influence of temperature on the energy yield is in the range of −1.2 up to −10.6\% depending on the operating temperature and the temperature coefficient \( \gamma \). The module temperature related difference \( \Delta MPR_{Temp} \) has clearly the strongest impact at the hot locations Tempe and Chennai. Here also the lower temperature coefficients \( \gamma \) of the CdTe and some a-Si modules have their strongest influence on the mitigation of temperature related MPR losses as discussed already above. Note also that differences in the average energy weighted operating temperature of up to 5.0°C were observed for samples with different module design (cf. Fig. 2).

Low irradiance losses are most pronounced for CIGS and the a-Si/μc-Si tandems (a-Si 1 and 2) combined with the test sites in Cologne, Ancona and partly Chennai. In contrast, \( \Delta MPR_{LIRR} \) is virtually zero or even positive for the c-Si and CdTe modules at these three sites. Due to the overall high irradiance in Tempe the effect of low irradiance is small on any module type.
higher in reality as compared to the norm. This is also the reason with respect to the standard AM1.5G spectrum. Therefore the relative spread of the ΔMPR
value of nameplate output power is positive for most of the modules and locations. This is because the performance difference ΔMPRcalc due to spectral effects is positive for most of the modules and locations. This is because the illumination weighted averaged spectra $E_{\text{sun}}(\lambda)$ in Cologne, Tempe and Chennai (as shown in Fig. 5) are blue shifted with respect to the standard AM1.5G spectrum. Therefore the relative share of the wavelength range $\lambda = 400$, ..., 600 nm is slightly higher in reality as compared to the norm. This is also the reason why the spectral gain is the highest for the wide gap CdTe modules. The spread of the ΔMPRcalc values for the thin-film Si tandems is due to different matching conditions for the different devices.

The performance difference ΔMPRcalc caused by the AoI is site specific with values for standard float glass the lowest for Tempe (Arizona) with −2.0% and the highest for Cologne (Germany) with −3.5%. The soiling losses are also site specific with a highest value of ΔMPRsol = −3.7% in Tempe and the lowest values in Cologne and Ancona.

Fig. 9 displays the calculated MPRcalc, according to (6) plotted versus the value MPRLabel measured during one year using the nameplate output power $P_{\text{STC}}$ as a reference. It is seen that the overall trend of the measured data is reproduced by the calculated ones within a margin of ±5%. The reason for the relative large error margin primarily lies in the uncertainty of the nameplate output power of the modules. However, comparing the predictions of our model for the specific modules shows that we are able to describe the performance differences between Cologne, Ancona, and the two hot locations (Tempe Chennai) reasonably well (±2%) if one allows for an offset caused by the uncertainty of the nameplate values. The data for Tempe and Chennai are anti-correlated for some samples but are still in the range of ±2%. The overall higher MPR of CdTe modules compared to other technologies at both hot locations is also reproduced by our model. The CIGS data (2–4) are also well described, whereas sample CIGS 1 has obviously degraded with MPRLabel < 80% (data points not seen in Fig. 9). The highest scatter in the data stems from the Si thin films. However, the high performance of the a-Si/a-Si tandem at both hot locations is well predicted.

5 Summary
We have presented a comprehensive study of the module performance of 15 different module types at four different locations during one year of operation. A significant performance spread of up to 23% difference in the MPR was observed for PV modules of different technology at the four locations. We have evaluated our data in terms of a LPLA taking into account the influence of module temperature, low irradiance conditions, spectral and angular effects and soiling. With this approach the MPR of PV modules can be forecasted for different climates, using measured environmental data and performance data measured under laboratory conditions. A prediction within a deviation of about ±2% is possible for most of the modules when allowing for an offset due to uncertainty in the nameplate performance. However, more detailed analysis of the field data appears necessary, especially to understand the consequences of metastabilities of thin-film modules both on the initial efficiency and on the module performance.

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