Understanding the energy yield of PV modules

Module yield | Varying climatic conditions across markets and the individual characteristics of PV technologies undermine accurate predictions of module energy yield using conventional methods. Markus Schweiger, Werner Herrmann, Christos Monokroussos and Uwe Rau describe how a calculation of module performance ratio can be used to accurately assess the efficiency of different PV module technologies in different climates and thus the likely return on investment from a project

Between 2004 and 2016 a sum of US$1,161 billion was invested in PV systems [1], and there is currently approximately 200GW of PV capacity installed worldwide. By 2050 a globally installed PV capacity of around 4.6TWp is expected; this in turn implies a global investment market of some US$225 billion per year on average through 2050 [2].

A major part of this investment is represented by the price of PV modules, which is determined by their output power rated at standard test conditions (STC), specifically an irradiance of 1,000W/m^2, a module temperature of 25°C and a spectral irradiance according to IEC 60904-3. Real outdoor operating conditions, however, are in general considerably different from STC conditions, as demonstrated in Figures 1 and 2 for optimal mounting conditions. The relevant standards for specifying the energy rating of PV modules are IEC 61853 parts 1 to 4, but not all parts have been published yet [3,4]. The energy yield estimation for various PV module technologies, using simulation tools, exhibits high uncertainties as a result of the limited availability of sufficient PV module performance data.

It is therefore essential to have a detailed understanding of all the factors that impact on the energy yield performance of PV modules. Such knowledge will provide a scientific basis for making accurate yield estimates for different technologies and for optimising energy yield performance for different climates. For the upcoming multi-GW installations of 125GW/year on average, each percentage of uncertainty results in significant investment uncertainty with regard to capital expenditures.

Energy yield performance as a key factor for the return on a PV investment

Consider a PV power plant with 100MWp nominal power (for STC) at a location with a moderate specific energy yield of 1,500kWh/kWp and a levelised cost of electricity (LCOE) of US$100/MWh; this means US$150,000 extra revenue for each per cent of additional energy yield and year of operation (if emerging interest earnings are neglected). This would essentially mean US$3.75 million more revenue per 1% increase in energy yield after 25 years of operation. Furthermore, assuming a new market of around 4.4TWp as mentioned earlier, and while keeping the specific energy yield, lifetime and LCOE constant, the result is an astonishing US$165 billion surplus in revenue per 1% of energy yield, which could be achieved by choosing capable PV modules. Besides the chance for investors to maximise their net profit by considering the energy yield performance, this relation also bears a certain investment risk for the PV industry if the long-term performance is lower than expected, and if investors are not able to accurately calculate the expected income.

Figure 1. The test sites operated by TÜV Rheinland for PV module characterisation and energy yield measurements (clockwise from left): Cologne (Germany, moderate climate), Tempe (Arizona, dry continental climate), Chennai (India, tropic climate), Thuwal (Saudi Arabia, dry desert climate with sand deposition) and Ancona (Italy, Mediterranean climate).

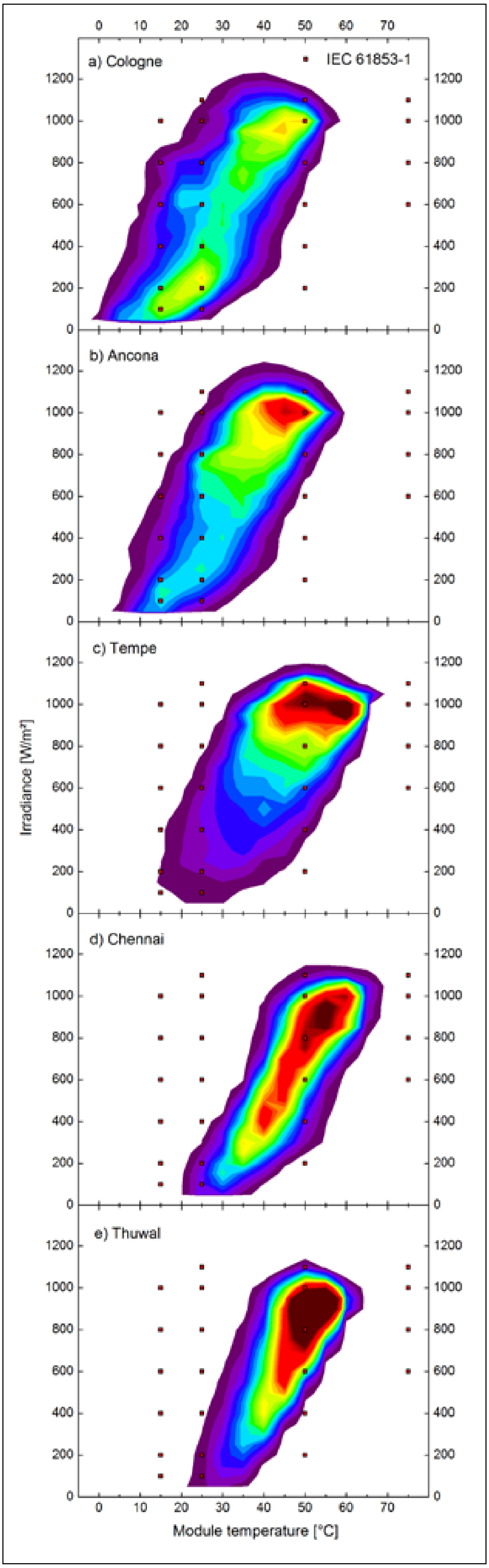


Figure 2. Generated electrical energy of a crystalline PV module in five different climates as a function of module temperature and irradiance on an annual basis, compared with the measuring conditions of IEC 61853-1 energy rating matrix (red dots). Colour range: 0.1–2.6%; colour increment: 0.1%

From absolute yield to specific yield to module performance ratio

The energy yield of PV modules deployed in different climates is a complex topic involving interdisciplinary knowledge of cell physics, module properties and meteorological aspects. To find a pathway to the underlying correlations, some general definitions therefore need to be discussed first.

The absolute energy yield (EY) of PV modules is defined in watt hours (Wh). Because of the different efficiencies and designs of PV modules, it makes sense to calculate the specific energy yield in watt hours per watt peak (kWh/kWp), by dividing EY by the nominal power P_{STC}; this allows a comparison of the energy yield performances of different types of PV module. Besides P_{STC} the second factor dominating energy yield is solar irradiation (H); this strongly depends on geographic location, local mounting conditions of the PV power plant and annual fluctuations. When choosing a pyranometer as a reference irradiance sensor, H is almost independent of environment-related impact factors, such as angle of incidence, spectral shifts or temperature. Thus, to compare and elaborate only technology-driven performance factors, the module performance ratio (MPR) is the best-practice method and can be calculated as:

$$MPR = \frac{EY}{P_{STC}} \cdot \frac{1{,}000\,\mathrm{W/m^2}}{H}$$

The MPR is suitable for investigating the efficiency of PV modules in different climates compared with STC efficiency, as well as for comparing different technologies and climates. As the local weather conditions cannot be changed (unlike the global climate), differences with respect to technological origin are of special interest for optimising PV module performance and for selecting suitable products for a certain climate. The amount by which the value of MPR differs from unity represents the losses in real outdoor operating conditions compared with STC efficiency. The MPR facilitates a relative comparison in percentage terms between different technologies and climates; it includes all the offset relevant influences on energy yield performance due to inaccurate nominal power, temperature losses, non-linear module performance depending on irradiance *G* (low-irradiance behaviour) and spectral effects, as well as the losses due to soiling and angular behaviour (as illustrated in Figure 3). The MPR is identical to the performance ratio (PR), commonly used for PV systems, when system losses, such as wiring, module mismatch or invertor losses, are not considered. Uncertainties of less than ±1% can be achieved when choosing P_{STC} as stated by the manufacturers as a constant basis for MPR calculations.

Underlying database and investigations performed

Since 2013 the performance of 15 different PV module types within the nationally founded 'PVKlima' R&D project has

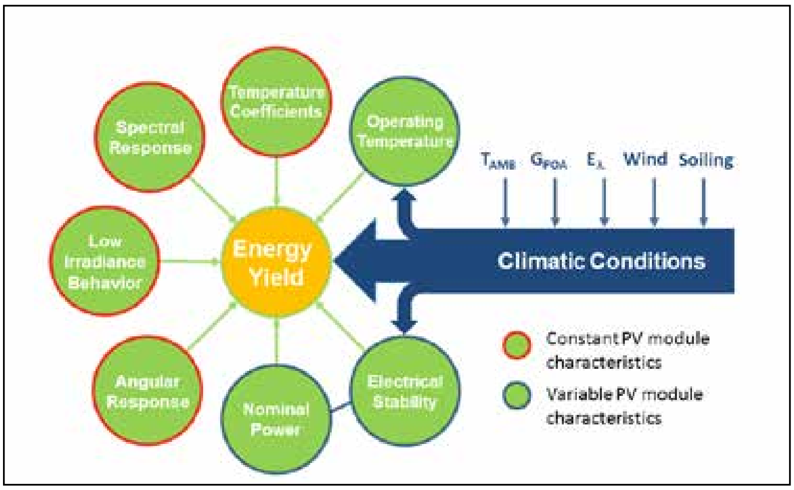


Figure 3. Factors influencing the energy yield of PV modules

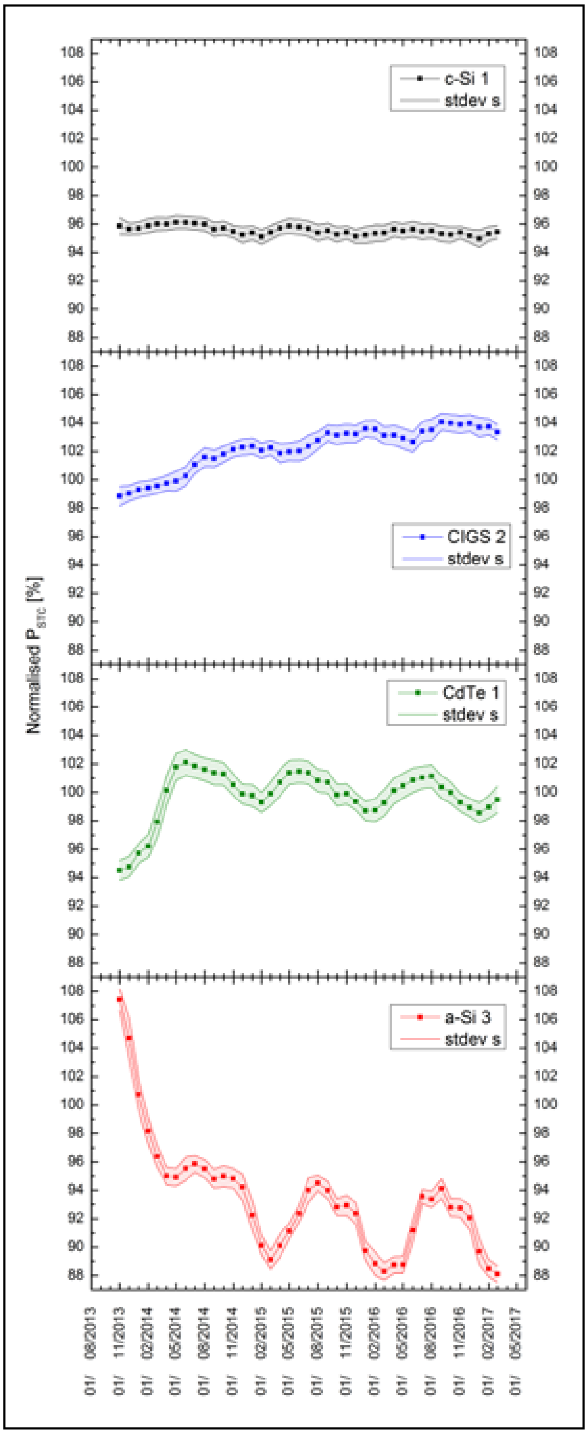


Figure 4. Monthly averages of STC-corrected nominal power for four PV module types, normalised to stated nominal power, for the Ancona test site in Italy (uncertainty: ±2.5%)

been undergoing systematic analysis. The tested modules were:

- Five different crystalline silicon (c-Si) module types from three different manufacturers.
- Four $Cu(In,Ga)Se_2$ (CIGS) modules from four different manufacturers.
- Three cadmium telluride (CdTe) module types from two different manufacturers.
- Three amorphous silicon (a Si tandem) module variants from three different manufacturers.

The five different c-Si module types comprise three polycrystalline and one monocrystalline PV modules with heterojunction cells, and one monocrystalline module with back-contacted n-type cells. The polycrystalline samples are equipped with different front glasses: one sample with standard float glass, one with an anti-reflection coating and one with deeply structured glass.

Comprehensive tests with regard to energy rating and energy yield were performed in the laboratory and outdoors; five test sites, each in a different climate zone, were therefore constructed (see Fig. 1). The annual in-plane global solar irradiation was 2,386kWh/m² in Saudi Arabia, 2,360kWh/m² in Arizona, 1,860kWh/m² in India, 1,556kWh/m² in Italy and 1,195kWh/m² in Germany. These test sites allow the generation of the PV module and environmental data sets needed to understand the real-world performance and long-term reliability of PV modules. Thus it was possible to generate an understanding (that so far is unique) of PV module performance under real operating conditions in different climates.

Nominal power at STC and monitoring of electrical stability

To understand the energy yield of PV modules, it is necessary to first begin with the most challenging aspect from the metrology point of view: the determination of STC power and the monitoring of its stability during outdoor operation.

To get a deeper insight into the various seasonal effects on module performance, an elaborate current–voltage (*I–V*) curve analysis was employed. After the *I–V* curves of all samples were measured using a sampling rate of 10 minutes, corrections of temperature and irradiance according to IEC 60891 [5] were applied, in combination with a spectral mismatch correction obtained from measured spectral irradiance data according to IEC 60904-7 [6]. These corrections are necessary in order to create constant operating conditions for time series analysis which would not otherwise be achieved outdoors.

Figure 4 shows the monthly average STC power for four samples representing four technologies. The test site in Italy is used as a model case for the discussion of some fundamental PV module performance characteristics.

With the application of this correction method, all environmental influences are accounted for and can be directly compared. The method allows the influence of temperature and spectral irradiance on fill factor *FF*, short-circuit current I_{sc}, open-circuit voltage V_{oc} and P_{STC} to be analysed independently of each other.

Starting with c-Si, mostly stable P_{STC} power values were found within more than three years of outdoor exposure for all climates. Typical long-term average degradation rates of less than –0.5% per year can be confirmed. For heterojunction PV modules, higher rates of about –1.0% per year were observed, mainly related to a decrease in V_{oc}. The c-Si 1 sample shown in Figure 4 exhibits an approximately 4% lower value than the P_{STC} stated on the label. It is noted that the stated results are subject to a measurement uncertainty of ±2.5%, which should be borne in mind when interpreting the results.

"The most important pieces of information for investors are the results based on the pure STC power as stated and sold by the manufacturers"

The nominal power of CIGS PV modules revealed significant performance changes due to metastable cell processes; the consolidation phase of these processes can take longer than a year. Changes in power are related in equal proportions to *FF* and V_{oc}. The depicted CIGS 2 sample in Figure 4 exhibited an increasing P_{STC} of around +4% compared with the label specification. Some of the other PV module types resulted in more than a –10% deviation from the label value after three years of operation; this depends on the manufacturer and not just on the technology.

The tested CdTe PV modules also revealed metastable processes that significantly affected P_{STC}. After an initial performance increase of up to 8%, which takes several months (depending on local temperature conditions), the nominal power exhibits annealing processes between summer and winter, leading to a P_{STC} oscillation with an amplitude of approximately ±2%; this oscillation disappears in hot climates, such as those found in Tempe or Chennai. The annealing

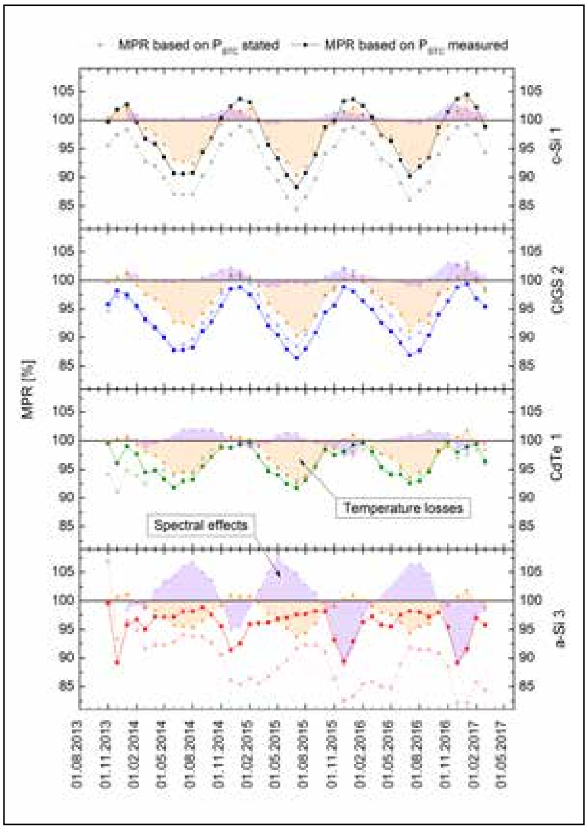


Figure 5. Monthly module performance ratio based on stated P_{STC} for four PV module types, compared with the MPR based on monthly measured P_{STC}, for the Ancona test site in Italy. A deviation from 100% means yield losses or gains; the temperature (orange) and spectral effect (purple) contributions are indicated

process is assumed to achieve a constant state in these hot locations for the whole year. Changes in power are related mainly to *FF*. The average stabilised P_{STC} of the CdTe 1 sample shown in Figure 4 fits quite well with the stated P_{STC} values after three years of operation; however, PV module types with more than a –10% deviation from the label value after three years of operation were also found.

The performance of a-Si PV modules revealed the well-known (but not fully understood) Staebler–Wronski effect, with initial stabilisation of around –10% to –15%, depending on module type. As in the case of CdTe, the performance reveals a summer and winter oscillation of about ±3%, which could also be observed for hot climates. The time constants of these effects are again temperature driven and mainly related to *FF*. The average stabilised P_{STC} of the depicted a-Si 3 sample is about –9% lower than that stated by the manufacturer. Long-term degradation rates are superimposed onto these metastable effects. One module type completely failed the long-term test; two out of four samples ceased operation after just a few months of operation.

It remains unanswered here whether or not the technology-specific stabilisation procedures stated in the new IEC 61215 [7] series of standards are suitable in order to achieve reliable, stabilised P_{STC} values. All the results on stability can be reviewed in Schweiger et al. [8]. Now that the P_{STC} values of all PV modules have been verified, the discussion about climate-related influences can continue.

Origin of climate-related performance differences for PV module technologies and major findings

As mentioned above, PV modules have different low-irradiance behaviours, different temperature coefficients, different operating temperatures, different spectral and angular behaviours and also different soiling behaviours when different front glasses are used. These factors, combined with site-specific climate conditions, result in significant performance differences on the basis of the nominal power measured at STC. As pointed out, the nominal power can deviate significantly up or down from the stated values as a result of binning policies, measuring inaccuracies (±2% in the laboratory) or stability issues, such as light-induced degradation (LID), potential-induced degradation (PID), or metastabilities for thin film.

Given the impact on investment of just one percentage point difference in energy yield performance, the most important pieces of information for investors are the results based on the pure STC power as stated and sold by the manufacturers. Within this project, a significant difference in the energy yield performance was observed between the best- and worst-performing PV module types: up to 23% in India, 21% in Arizona, 14% in Germany and 12% in Italy. After compensating the effects related to nominal power mismatch discussed earlier, an annual difference in yield of 16% in India, 19% in Arizona, 8% in Germany and 9% in Italy remained; the results for Saudi Arabia are still under investigation.

For comparable standard crystalline only, the latest investigation of 24 c-Si samples indicates a technological-origin-related difference of at least 5% (implying again correct and stable nominal power values). This value increases greatly for certain PV modules incorporating special technologies affecting energy yield performance, such as in the case of bifacial PV modules or some thin-film technologies.

Seasonal performance behaviour under investigation

To investigate the origin of the above-mentioned significant differences in annual yield results, an evaluation of short-term MPR values provides a first impression of the physical background. It is a fast and easy way to obtain insights into module performance, which is also the reason why it is used most frequently as a monitoring solution for PV systems, needing just one reference irradiance sensor. The potential, however, is limited, since all influencing factors are superimposed onto just a single value.

For the MPR calculation, the maximum power point was tracked with a sampling frequency of 30s, and a ventilated pyranometer served as a reference irradiance sensor. Figure 5 shows the monthly average MPR values of representative samples in Italy based on stated P_{STC}, together with the compensated MPR based on measured P_{STC}, as well as temperature losses and spectral irradiance influences. This plot is used again as the model case for the discussion of some fundamental performance characteristics of different PV module technologies.

As discussed earlier, the performance of c-Si PV modules (black dots, Figure 5) is mostly stable. Nevertheless, the plot of monthly MPR values for c-Si shows the strongest oscillations by season, with maximal MPR values in winter; the reason for this is the high relative temperature coefficient γ, with typical values of –0.35%/K for high-efficiency modules and –0.42%/K for standard cells. The maximum in winter can be reduced for modules of each technology with poor low-irradiance behaviour due to the lower average irradiances on winter days. The influences of spectral effects on c-Si are low. An offset of the MPR curves can occur in the case of PV modules with inaccurately stated nominal power on the label or datasheet.

Almost the same performance behaviour can be observed for CIGS samples (blue dots, Figure 5); the spectral response signals and temperature behaviour are comparable to those for c-Si. The oscillations between summer and winter can be slightly lower for the samples with better temperature behaviour or poor low-irradiance behaviour. Any potential gains due to a better temperature coefficient can be lost again, however, as a result of higher average operating temperatures. The CIGS 2 module shown in Figure 5 indicates the effect of an increasing P_{STC} over the years due to metastable behaviour, as demonstrated earlier, which can be either positive or negative for PV modules of this type.

CdTe samples (green dots, Fig. 5) show less oscillation by season, but still exhibit maximum MPR values during the winter months. The reasons for the lower amplitudes can be found in the significantly lower temperature coefficient γ of typically –0.29%/K, and in the spectral gains in summer. The difference between summer and winter is further reduced because of the metastable behaviour, as shown earlier.

In the case of a-Si samples (red dots, Fig. 5), the MPR values during the first few months are dominated by Staebler–Wronski degradation, followed by temperature annealing observed in the summer months. Compared with c-Si, small oscillations between summer and winter are achieved. In contrast to all other cell technologies, the maximum MPR values are reached in summer; the reason is a combination of small temperature losses, again due to low temperature coefficients γ (typically in the range of –0.26%/K to –0.39%/K, depending on manufacturer), gains due to thermal annealing, and significant spectral gains in summer. For some samples, high losses due to poor low-irradiance behaviour in winter were observed. It is noted that the performance of some a-Si samples did not reach a stable level after more than a year of outdoor exposure.

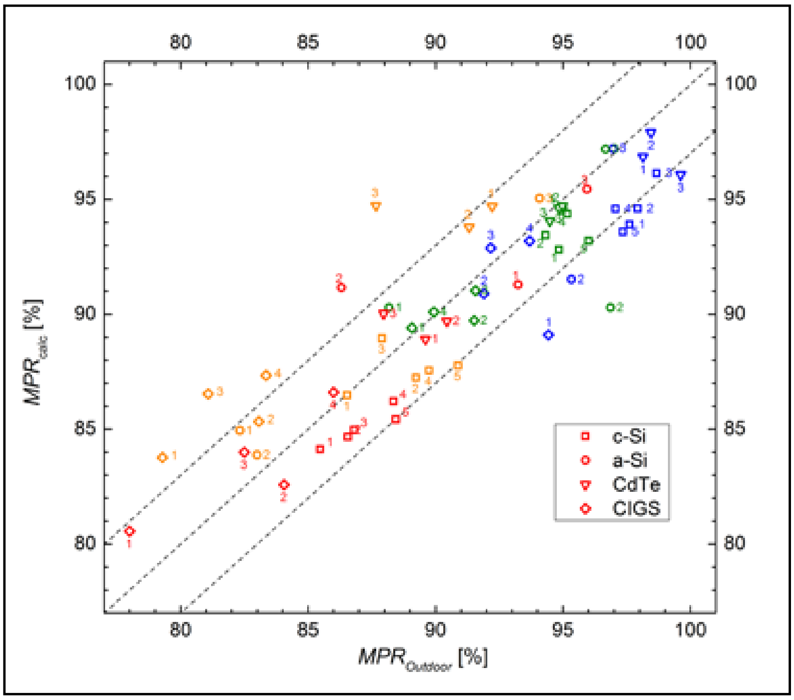


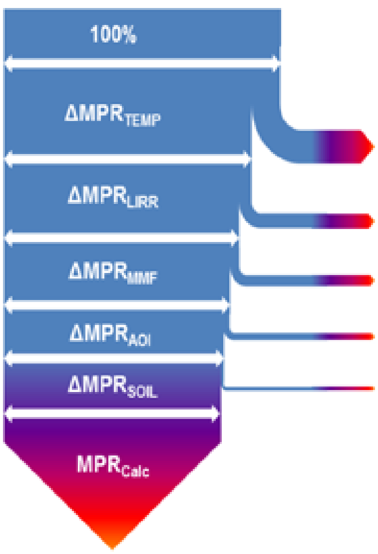
Figure 6. Module performance ratio MPR_{Calc}, calculated using weather data and indoor measurements, plotted versus the measured $MPR_{Outdoor}$ based on energy-weighted average outdoor power (blue: Cologne; green: Ancona; red: Tempe; orange: Chennai)

Energy rating of PV modules using linear performance loss analysis

A linear performance loss analysis (LPLA), as described in Schweiger et al. [9], can be used to quickly, accurately and inexpensively predict the MPR of PV modules for different climates. Simple reference environmental data sets and energy rating data, in accordance with the IEC 61853 series, measured in the laboratory serve as input data. An energy yield prediction based on calculated MPR_{Calc}, with a deviation of ±3% from measured $MPR_{Outdoor}$ values, can be achieved, as illustrated in Figure 6; this deviation is assumed to be mainly due to the influence of P_{STC} measuring uncertainties on the $MPR_{Outdoor}$ results. The approach takes into account all the relevant factors that have an impact on energy yield, such as module temperature, low-irradiance conditions, and spectral and angular effects, as well as soiling.

The approach also allows a quantification and comparison of the various influencing factors for different PV module technologies and for different climates, as illustrated in Figure 7. The energy yield of PV modules is affected by five individual loss factors; the mechanisms correspond

Figure 7. Quantified loss mechanisms influencing the MPR of PV module types c-Si 1, CdTe 1 and CIGS 2 in different climates on an annual basis



	c-Si 1				CdTe 1				CIGS 2			
	Cologne	Ancona	Tempe	Chennai	Cologne	Ancona	Tempe	Chennai	Cologne	Ancona	Tempe	Chennai
ΔMPR_{TEMP}	-2.3%	-3.9%	-8.9%	-9.6%	-1.5%	-3.5%	-6.7%	-6.2%	-2.9%	-4.5%	-8.8%	-9.1%
ΔMPR_{LIRR}	-1.2%	-0.8%	-0.4%	-0.5%	0.0%	+0.2%	+0.3%	+0.6%	-3.6%	-3.1%	-1.8%	-2.4%
ΔMPR_{MMF}	+1.3%	+0.5%	-0.8%	+1.6%	+2.3%	+0.9%	+1.1%	+5.3%	+1.4%	+0.3%	-1.1%	+1.8%
ΔMPR_{AOI}	-3.5%	-2.4%	-2.0%	-2.9%	-3.5%	-2.4%	-2.0%	-2.9%	-3.5%	-2.4%	-2.0%	-2.9%
ΔMPR_{SOIL}	-0.5%	-0.5%	-3.7%	-2.1%	-0.5%	-0.5%	-3.7%	-2.1%	-0.5%	-0.5%	-3.7%	-2.1%
	-6.2%	-7.2%	-15.9%	-13.5%	-3.1%	-5.4%	-11.1%	-5.3%	-9.1%	-10.3%	-17.4%	-14.7%
MPR_{Calc}	**93.9%**	**92.8%**	**84.1%**	**86.5%**	**96.9%**	**94.6%**	**88.9%**	**94.7%**	**90.9%**	**89.7%**	**82.6%**	**85.3%**

to loss terms ΔMPR for different climates, which can be singled out. The loss mechanisms which influence the MPR of electrically stable PV modules are: temperature (ΔMPR_{TEMP}), low irradiance (ΔMPR_{LIRR}), spectral effects (ΔMPR_{MMF}), angular losses (ΔMPR_{AOI}) and soiling (ΔMPR_{SOIL}).

The losses due to soiling and angular effects are almost constant for PV modules with standard untreated front glass. Soiling losses (ΔMPR_{SOIL}) are highest in Arizona, although higher soiling rates can be expected in Saudi Arabia. The soiling rate is highly dependent on the period under consideration, and long-term averages are needed.

The losses due to angular effects (ΔMPR_{AOI}) are highest, compared with overall available energy, in Cologne, with up to –3.5%. In addition to the advantages gained in light transmission, lower angular losses can be achieved with deeply structured glass (–2.8%) or an anti-reflection coating (–1.6%). For deeply structured glass, however, higher soiling rates must be considered.

Relative losses due to low-irradiance behaviour (ΔMPR_{LIRR}) are also highest in Cologne, with up to –3.6%. The low-irradiance behaviour for constant spectral irradiance conditions is technology driven, but also depends on the individual manufacturers. The behaviour is dominated by wafer recombination losses, and module internal serial and parallel resistance in combination with operating voltage and current. The performance between different manufacturers may vary significantly. A satisfactory low-irradiance behaviour for constant spectral irradiance conditions means an efficiency drop of less than –5% at 100W/m^2 relative to STC; this can easily be tested in the laboratory.

Losses due to temperature (ΔMPR_{TEMP}) are highest for c-Si, with up to –9.6% in Chennai. Better values can be achieved with thin film when the advantages due to low temperature coefficients are not lost because of higher operating temperatures.

The influence of spectral irradiance (ΔMPR_{MMF}) on c-Si is low on an annual basis. The highest impact on energy yield can be found for CdTe (up to +5.3% in Chennai) and a-Si.

For other mounting conditions with orientations that differ from optimal or those with reduced ventilation, as in the case of building-integrated PV (BIPV), other loss factors must be assumed.

Conclusions

Because of cost and time pressure, consideration of the energy yield performance of PV systems is often of secondary importance when constructing PV plants. Optimisation of the yield is necessary, however, for successful investment. Significant differences were observed in the energy yield of PV modules available on the market – up to 23%, depending on power rating, technology and climate.

The results have shown that a combination of indoor tests and reference climate datasets is sufficient for estimating, within ±3%, and comparing the energy yield performance of different PV module technologies. The long-term stability of electrical power, however, must still be tested in the field.

The ultimate owner of the PV power plant should consider a well-defined module performance ratio before making an investment decision. The competitiveness of solar projects can be enhanced by PV modules with reliable long-term performance and optimal energy yield performance suited to the climate of the installation location.

Acknowledgement

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