Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2012; **20**:717–726
Published online 18 January 2012 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.1219

PAPER PRESENTED AT 26TH EU PVSEC, HAMBURG, GERMANY 2011

Performance ratio revisited: is PR > 90% realistic?

Nils H. Reich[1]*, Bjoern Mueller[1], Alfons Armbruster[1], Wilfried G. J. H. M. van Sark[2], Klaus Kiefer[1] and Christian Reise[1]

[1] Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, D-79110 Freiburg, Germany
[2] Science, Technology and Society, Utrecht University, Copernicus Institute, Budapestlaan 6, 3584 CD Utrecht, The Netherlands

ABSTRACT

In this study, we investigate the performance ratio (PR) of about 100 German photovoltaic system installations. Monitored PR is found to be systematically lower by ~2–4% when calculated with irradiation data obtained by pyranometers (henceforth denoted as PR_{Pyr}) as compared with irradiation amounts measured by reference cells (denoted as PR_{Si}). Annual PR_{Si} for the ~100 systems is found to be between ~70% and ~90% for the year 2010, with a median *PR* of ~84%. Next, simulations were performed to determine loss mechanisms of the top 10 performing systems, revealing a number of these loss mechanisms may still allow for some optimization. Despite the fact that we do not see such values from our monitoring data base up to now, we believe PR_{Si} values above 90% are realistic even today, using today's commercially available components, and should be expected more frequently in the future. This contribution may help in deepening our knowledge on both energy loss mechanisms and efficiency limits on the system level and standardization processes of system-related aspects. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS
performance ratio; PV yield

***Correspondence**
Nils H. Reich, Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstr. 2, D-79110 Freiburg, Germany.
E-mail: nils.reich@ise.fraunhofer.de

Received 31 May 2011; Accepted 5 September 2011

1. INTRODUCTION

Efficiencies of photovoltaic (PV) modules and other components of PV systems have increased continuously over the past decades. As a result, PV system performance has improved considerably. System performance is usually evaluated by the determination and analysis of the performance ratio (PR), which is described in detail in Section 2. Typical ranges of the PR rose from reportedly 50% to 75% in the late 1980s [1] and 70–80% in the 1990s [2,3] to >80% nowadays [4].

The much larger PR values of nowadays systems are illustrated in Figure 1, contrasted by system performances of years 1994/1997 as monitored within the German 1000-Roofs Programme. Clearly, along with increasing specific yields the average PR of systems greatly improved. However, similarly to the obvious efficiency limit of inverters and with efficiencies of system components (still) increasing, one may wonder how high could the PR of entire systems actually reach? To address this question, we first briefly introduce the PR definition. Next, we highlight the relevance of separately indicating whether irradiation is measured on-site by silicon reference cells or by pyranometers.

Following a brief description of monitoring installation setups used as data source for this study, we present today's ranges of the PR as monitored by the Fraunhofer ISE for German PV system installations. The 10 best performing systems showing highest annual PR in the year 2010 are then analyzed in-depth. After discussing the limit of the PR, we close with a brief summary of results and conclusions.

2. PERFORMANCE RATIO

2.1. Definition of PR

The PR is an internationally introduced measure for the degree of utilization of an entire PV system. It indicates the overall effect of losses on the PV system's rated output due to array temperature, incomplete utilization of the irradiation, and system component inefficiencies or failures. The PR is defined in IEC 61724 [5] as the ratio of final

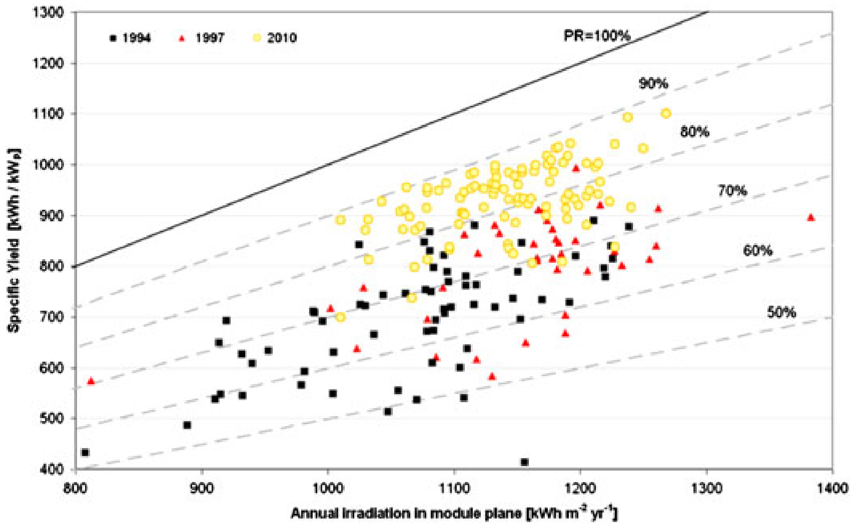

Figure 1. Monitored specific yield as a function of total plane-of-array irradiation of photovoltaic systems installed in years 1994, 1997, and 2010 with corresponding performance ratio contour lines. Data shown were acquired during the 1000-Roofs Programme in 1994/1997 and in 2010 by Fraunhofer ISE monitoring services. The shown data notably use on-site irradiation measured by exclusively mono-crystalline silicon reference cells (denoted PR_{Si}, see Section 2.2).

PV system yield (Y_f) to so-called reference yield (Y_r) and denoted R_P, see Equation (1).

$$R_P = \frac{Y_f}{Y_r} \tag{1}$$

with final yield Y_f defined by load efficiency (η_{Load}), energy recording interval (τ_r) of measured array power output (P_A), and rated power output (P_0), and the reference yield Y_r defined by total plane-of-array (POA) irradiance (G_{POA}) and reference irradiation (G_{ref}), see Equations (2) and (3).

$$Y_f = \eta_{Load}\tau_r \frac{\sum_{day} P_A}{P_0} \tag{2}$$

$$Y_r = \tau_r \frac{\sum_{day} G_{POA}}{G_{ref}} \tag{3}$$

As both Y_r and Y_f are referring to standard test conditions (STC), in more practical terms the performance ratio PR may be calculated as follows:

$$PR = E_{specific}/H_{specific} \cdot 100\% \tag{4}$$

$$E_{specific} = E_{feed\text{-}in}/P_{STC} \tag{5}$$

$$H_{specific} = H_{POA}/G_{STC} \tag{6}$$

with $E_{feed\text{-}in}$ the electricity fed into the grid, P_{STC} the rated direct current (DC) power of modules, H_{POA} the irradiation sum (energy) in the module plane, and G_{STC} the irradiation corresponding to STC irradiance intensity (1000 W/m^2).

The performance ratio is largely independent of particular radiation conditions, thus largely independent of the specific site and even of particular module orientations. The PR can therefore be used as a straightforward indicator to compare differently designed systems, equal system designs but erected at another location, or for the comparison of one and the same system over the years. However, there is a strong temperature dependence of the PR, which implies that in warm climates, PR will be lower as compared with cold climates. In this study, we therefore consider exclusively German PV system installations.

The versatility of the PR as an indicator comes along with the disadvantage of not always knowing, which peculiarities of the individual system are accounted for or not. The "AC Energy" may or may not include alternating current (AC) losses such as transformer and cabling losses, in larger systems perhaps mid-voltage transformer losses. Installed peak power is usually unknown, because of differing nameplate versus actual power output of modules. On the other hand, AC yield today is naturally measured by billing meters, because this is the reference point for any kind of feed-in tariff. As of today, the DC power is naturally defined by labeled STC power of modules, because this is what customers pay for. From this outset, it is clear that in practical terms the PR includes AC losses up to the feed-in-tariff billing meter and is stated with respect to labeled power output of modules (i.e., nominal PV capacity).

Last but not least, irradiation may be acquired by either a pyranometer or a crystalline silicon reference cell or even satellite images, which implies systematic differences, as evaluated and discussed in the next sub-section.

Prog. Photovolt: Res. Appl. 2012; **20**:717–726 © 2012 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

2.2. Distinguishing PR_{Pyr} and PR_{Si}

According to IEC 61724, both pyranometers and crystalline silicon reference cells are eligible for the measurement of on-site irradiation in PV monitoring systems. Both these devices, however, exhibit a variety of characteristics related to the two distinct physical effects exploited by each device. Pyranometers employ thermocouples, meaning incident radiation flux causes temperature differences of the thermocouples, in turn causing a voltage signal (Seebeck effect) that then can be measured using electronic circuitries. Silicon reference cells, on the other hand, rely upon the photovoltaic effect. A voltage drop at a shunt resistance measures the (quasi) short-circuited cell current directly, albeit also here cell temperature needs to be measured as to subsequently correct for temperature dependent short-circuit current. Pyranometers show response times of 5–30 s, whereas reference cells can accurately measure also very abrupt irradiance intensity changes. Similar to most PV modules, however, reference cells are encapsulated by polymers beyond a flat (low-iron) glazing. They are thus supposedly as sensitive to angular losses as the PV modules to be monitored. If the spectral response of the reference cell and the PV material monitored is equal, also the spectral mismatch cancels out. Pyranometers, on the other hand, exhibit virtually no spectral selectivity between ~300 nm and ~3 μm due to carbon-black coatings of the thermocouples. Furthermore, the field of view of pyranometers is 2πsr, because of the geometry of a dome (that is supposedly less susceptible to dirt accumulation, too). Hence, relatively little directional errors result (and supposedly less errors due to sensor soiling) when measuring irradiation using pyranometers. Large directional errors are especially high for reference cells in case of incident irradiance originating from predominantly large angles of incidence (AOI). The directional errors of pyranometers, in contrast, are as low as $\pm 0.5\%$ below 40° AOI and $\pm 1\%$ below 60° AOI. Daily errors for measured irradiation amounts using pyranometers are $<2\%$ [6], and annual drift is quoted to be as low as $<0.5\%$. These high accuracies (for notably "true" irradiation, without any spectral effects) come at the cost of significantly higher prices and the need for additional electronics that are required for amplifying signals ($\mu V/W\,m^{-2}$ output range) as compared with reference cells. Additionally, there is inevitable maintenance required for desiccant replacement advisable at least twice a year in humid climates. In order to pursue monitoring procedures conform to IEC 61724, however, replacement and/or recalibration of irradiance sensors is compulsory only every 2 years, so theoretically pyranometers do not impose additional maintenance burdens. From the practical perspective of data analysis, recalibration at least once a year seems highly desirable, irrespective of particular sensor type.

In conclusion, it is clear from the aforementioned that reference cells can have distinct advantages, if the monitoring goal is to test for general PV system functioning or the detection of inverter breakdowns only. Pyranometers allow for more accurate energy loss analyses, such as accounting for angular losses and spectral effects.

The use of both a reference cell and a pyranometer in a single system brings along the obvious benefit of measuring the relative influence of spectral effects and angular losses combined, if soiling of these two sensors is similar. However, in light of high pyranometer prices, most monitoring systems will be equipped with reference cells exclusively. To this end, a simplified model was developed and incorporated into our simulation routine that allows calculating the combined influence of angular losses and spectral effects, based upon irradiance data measured by only a reference cell. This correction routine takes into account solar zenith angles and clearness indices, but not (yet) reflection effects related to varying diffuse irradiance distribution(s) and varying spectral mismatch. A more detailed description will be made available in a forthcoming thesis (B. Müller, Fraunhofer ISE, Universität Kassel, unpublished dissertation).

The correction model was tested for 11 systems monitored by Fraunhofer ISE in the year 2010 with both a reference cell and pyranometers. The monitored PR is systematically lower by ~2–4% when calculated with irradiation data obtained by pyranometers (henceforth denoted as PR_{Pyr}) as compared with irradiation amounts measured by reference cells (denoted as PR_{Si}). The resulting accuracies of the correction routine are depicted in Figure 2.

The accuracy of the correction model may appear as only "fairly reasonable", regarding for example the absolute deviation for location 2, which is apparently as high as ~2% after the correction. However, it is worthwhile to recognize that this deviation is well within error margins of irradiance measurements, which currently are as large as 2%.

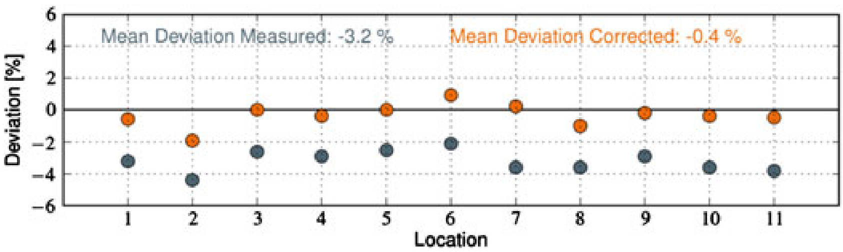

Figure 2. Comparison of annual irradiation deviations obtained by pyranometers and Si-sensors and resulting accuracies for a correction routine.

Considering the unfortunate but indeed possible case in which the pyranometer accuracy is at the positive edge of its calibration tolerance, whereas the reference cell is at the opposed end of the negative range, deviations of as large as 4% would still be within an "acceptable" margin. With the combined effects of angular and spectral mismatch losses also being ~4%, the obtained results shown in Figure 2 are thus encouraging in that they indicate typical differences between reference cell and pyranometer calibration tolerances to be well below the potential extremes of calibration tolerances.

2.3. PR measurement setup and uncertainty

Continuous performance monitoring in combination with adequate and prompt addressing of system problems is a prerequisite for sustained high energy yields of PV systems. Appropriate monitoring comprises at least the acquisition of in-plane irradiation and overall AC electricity generation. The only two alternatives for on-site irradiation measurement are satellite-based solar resource estimation [7] and the analysis of power output of nearby PV systems to estimate on-site irradiance by statistical correlation routines. However, both these alternatives come along with large "short-term uncertainties" and are related in particular to the accuracy of predicted direct and diffuse irradiation fractions. For the satellite approach, it is claimed in a recent comparison of models that "models converting satellite images into the different radiation components become increasingly performing and give often better estimations of the solar irradiance availability than ground measurements, if the (irradiance measurement) station is not situated in the near vicinity of the application" [8].

The quite large initial uncertainty of the satellite-imagery approach is reduced over time, as erroneous irradiance predictions cancel out [9]. If the early detection of system faults is the aim, however, on-site irradiation monitoring will allow for much higher certainty and better failure response times (with accuracies of irradiation measurement of ~2%, see aforementioned). In addition, the PR may be derived directly from the two basic values of plane-of-array irradiance and AC energy ($PR = Y_{AC}/G_{POA}$, see aforementioned), thus enabling the evaluation of short-term PR fluctuations, which is next to impossible if irradiance is not acquired on-site.

Monitoring systems offered by Fraunhofer ISE always employ at least one monocrystalline silicon reference cell. The systems tend to be large-scale installations: the 100 PV systems used as data source in this study, see Section 3 for more details, have a total installed capacity of 30 MWp. In a typical setup, the following data are measured each second and averaged into 5-min data record intervals (sensor types and typical precision in brackets):

- G_{POA} in-plane irradiation (reference cell, ±2%)
- T_{AIR} air temperature (Pt100 sensor, class A, $\pm(0.15°C + 0.002 \cdot |T|)$)
- T_{MOD} module temperature (Pt100 sensor, class B, $\pm(0.30°C + 0.005 \cdot |T|)$)
- Y_{AC} AC yield (billing meter pulses, ±0.5%)

Some systems include DC monitoring equipment. Here, the voltages and currents (I_{DC} and U_{DC}) on the DC-side of selected subsystems are recorded at individual strings or arrays of strings, together with the AC energy output of inverter(s) connected to these interconnected modules:

- I_{DC} DC current (shunt resistor, ±0.2%)
- U_{DC} DC voltage (voltage divider; ±0.5%)
- Y_{AC} AC yield (meter pulses, ±1.0%)

A few sites are also equipped with additional sensors such as pyranometers for horizontal or tilted irradiation and wind velocity sensors (anemometers).

Measured data are transferred to Fraunhofer ISE each night and undergo a system performance check. At this stage, warning messages may be issued to plant operators. Typical monitoring contracts also include monthly reports, and for a number of systems, data is made accessible on a daily basis on private or public web sites, for example, at www.solar-monitoring.de.

Each monitoring system undergoes a sound calibration routine during its initial installation on-site. Nevertheless, two main factors causing uncertainty of calculated PR cannot be circumvented, as they are caused by currently unavoidable irradiation measurement error and energy measurement error. The by far largest uncertainty is related to measurement of irradiation. This is not only due to the tolerance of sensor calibration of currently ±2% (see Section 2.2) but also related to the fact that, on top of calibration accuracy, over time soiling of sensors does occur. We measure soiling levels for all reference cells being replaced every 2 years. To this end, additional measurements before the actual recalibration are taken, that is, an additional calibration value is obtained prior to the appropriate cleaning procedure of sensors glass covers. Preliminary results indicate typical soiling levels in the −1% to –3% range. However, up to −5% and exceptionally higher deviations due to bird excrements were detected. Currently, three thesis projects are underway, each dealing with soiling issues and sensor drift-related aspects. Details will be reported in future publications.

The measurement error of overall electricity yield can be inferred from the individual billing meter. All monitoring systems use data obtained by utility billing meters, which may vary in accuracy from as low as ±0.1–0.2% for inspection equipment, over ±0.5–1% for typical industrial applications, and up to ±1–2% for electricity meters deployed in households. In addition, clamp-on DC ammeters and AC meters for monitoring the PR on the DC and AC sides of systems are used (for differentiating PR_{AC} and PR_{DC}) that have tolerances of ±1%.

All data are digitally recorded by voltage input signals or pulse counts by commercial data loggers, with overall

Prog. Photovolt: Res. Appl. 2012; **20**:717–726 © 2012 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

logger accuracy stated to be at least ±0.2%. Some further errors may be introduced for additional isolating amplifiers, implying ±0.5% potential deviations.

We expect the overall error of the PR to be typically below ±3%.

3. TODAY'S RANGE OF PERFORMANCE RATIO

3.1. Ascertaining data validity

In order to ensure the validity of performance data used for the analysis presented in this study, we performed a number of checks and exclusions of monitored systems. We rigorously excluded all systems employing module technologies such as bifacial modules or modules having a tubular shape, all systems that showed abrupt changes in the PR >2% absolute with no detectable system faults, and finally all systems that showed a drifting PR deviating ~3% or greater over the year as compared with simulation results. To this end, we compared the monitored DC-sides and AC-sides of the PR of each system with simulated data, using the measured irradiance intensity and module temperature time series as input for the simulation. Finally, 94 PV systems remain for a reliable assessment of realistic maximum PR.

3.2. PR results of some 100 systems

The performance ratio distribution of the 94 systems in 2010 that remain after the data check procedure (see previous section) is depicted in Figure 3(a). In addition to this "benchmark"-type distribution for the year 2010, the minima, maxima, and median PR values of these systems with respect to their installation year are shown in Figure 3(b) (calculated taking into account all monitored data of these systems since they were commissioned).

A number of qualitative insights can be gained from each of the shown PR distributions. For one, it can be observed in Figure 3(a) that only one-third of systems show $PR_{\mathrm{Si}} < 80\%$ and ~50% of systems in 2010 show PR_{Si} >83%. One-third even shows PR_{Si} >85%. However, from Figure 3(b) it can be discerned that also for systems commissioned as recently as in years 2006–2009, fairly low PR_{Si} lower than 80% is obtained, indicating that also recently systems were commissioned that are *not* optimized with regards to energy yield. One extreme example for this is a system design in which modules are placed in narrow

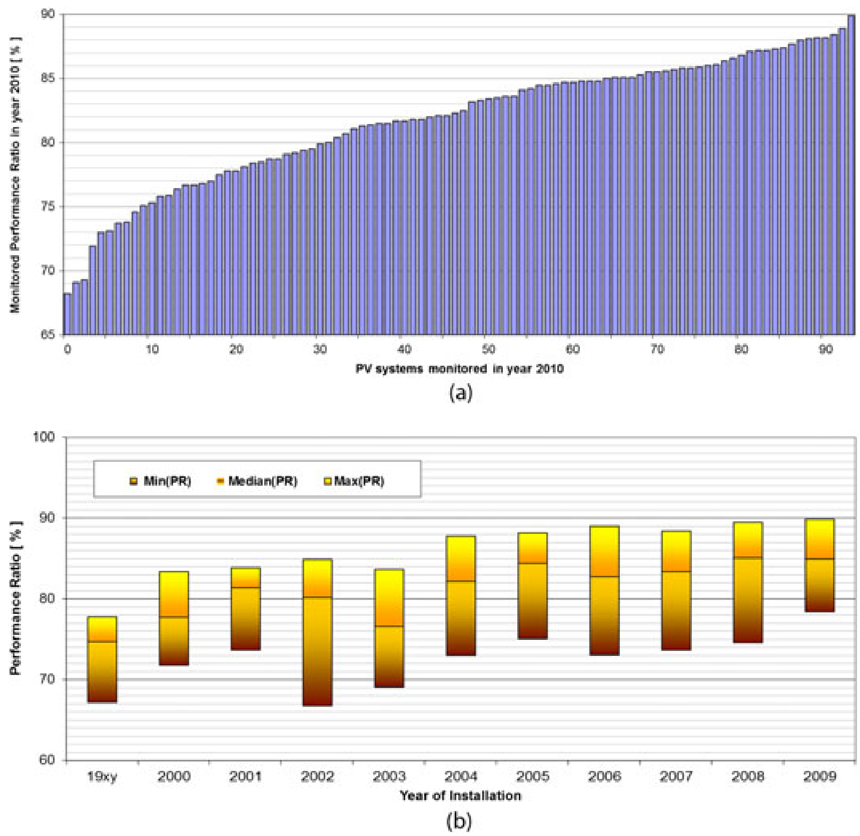

Figure 3. The performance ratio (PR) of 94 systems monitored by Fraunhofer ISE in 2010 with (a) showing the PR distribution as monitored in 2010 and (b) the ranges of monitored PR over time with respect to the installation year of each system.

distant rows, with relatively large tilt and mounted in "portrait" mode, that is, mounted as such that each cell string that has a bypass diode is equally row shaded. Energy losses of row shading are therefore not alleviated by the bypass diodes attached to cell strings. Together with inverters showing annual efficiencies close to 90%, it becomes obvious that such a system simply cannot have PR_{Si} 80%. From the perspective of project developers, who may want to realize as much installed PV capacity on a given roof, this design may perhaps be economically reasoned. But it is definitely not from the perspective of investors, who are naturally interested in yields rather than installed PV capacity being as high as possible.

Other examples of systems showing rather low PR values include overrated PV module capacity, deficiencies regarding the actual realization of systems in the field, long durations until replacements of defect inverters, and last but not least system component efficiencies that are below average rather than top-notch devices (which applies primarily to inverters).

4. ANALYSIS OF THE BEST PERFORMING SYSTEMS

4.1. Modeling as tool for detailing loss analysis

Monitoring data provides certainty about electricity yields, available irradiation, and (module) temperatures. However, not all loss mechanisms can be monitored, at least not with reasonable effort. Simulations may help in providing more insights here, because particular gains and losses can be differentiated for the several stages of PV electricity generation, starting with irradiation reaching the plane-of-array until electricity is fed into the grid.

For this study, we use the PV system simulation software "Zenit," developed at Fraunhofer ISE, for the modeling. As meteorological input data, we use monitored 5-min averages of plane-of-array irradiance (measured with a reference cell) and module temperature. On the basis of our experience from previous energy prediction studies [10] and uncertainty calculations [11–13], we estimate the overall standard uncertainty of this simulation to be ~2%.

Details of the simulation models incorporated in Zenit and specific assumptions are briefly summarized in the succeeding paragraphs, detailing in particular how shading loss and performance deviations at operating conditions other than STC are calculated. In addition, there are a number of detailed assumptions to be made. For transformer losses (if present) and module mismatch, we assume single loss factors of 1% and 0.8%, respectively. For cabling losses, we are often restricted to standard assumptions of fixed loss values of 1.5% for DC-wiring and 1% for AC wiring at maximum rated power. Spectral and reflection effects affect both the reference cell and the PV system and therefore are not relevant for the simulation itself. However, they are evaluated through the correction routine of the reference cell measurements (see Section 2.2). Soiling effects are also not considered in the simulation, which can be (partly) reasoned by the fact that all systems concerned in this study are located in Germany, implying frequent rainfall, which is likely to effectively clean both modules and reference cells. In addition, one may argue that similar soiling of sensors and modules occurs. However, more research is desirable as to enable us to account for these potential loss contributions in greater detail and higher certainty.

Shading losses can be distinguished into two different types. Horizon shading is caused by distant objects. These losses can therefore be considered equal for all modules of a particular site, and also irradiation measurement is affected by this type of shading. Nearby shading objects, however, may cause decisive yield reductions. Especially relevant is shade imposed by one module row upon the next row, because this system design is typical for all flat-roof and open-space PV systems. We denote this self-inflicted shade "row shading." Our assumptions for row shading took into account the direct and the diffuse irradiation component as well as lowered gains through less albedo contributions. Expected losses were based on calculations using the Meteonorm software (METEOTEST, Bern, Switzerland) and own adjustments with respect to module arrangement and interconnection.

Deviations between STC (that is, 1000 W/m² normal incident irradiation, 25°C temperature, AM 1.5 spectrum) and actual environmental conditions result in additional losses and gains. Empirical equations were used to model irradiance intensity-dependent module efficiency [14,15] and inverter performance as a function of inverter power output [16]. In addition, inverter dimensioning for each individual system was considered as to include inverter power limitations stated in datasheets. To account for the power decrease with increasing module temperature, we used the standard temperature coefficient of −0.4%/K for crystalline silicon modules, as each of the top 10 performing systems features crystalline silicon module technology.

4.2. Gains and losses observed for the top 10 systems

The monitored PR of the top 10 systems (as shown in Figure 3(a)) included five systems in which also some strings of the DC-side and the thereto connected inverter were measured. It is therefore possible to calculate a further differentiated performance ratio for AC-sides (PR_{AC}) and DC-sides (PR_{DC}) of the system by

$$PR = PR_{AC} \cdot PR_{DC} \tag{7}$$

The AC electricity counters to monitor the DC/AC performance ratio of these subsystems are, in most cases, mounted in close proximity to the feed-in-tariff billing meter, thus including AC-wiring losses. For the calculation of

Prog. Photovolt: Res. Appl. 2012; **20**:717–726 © 2012 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

overall PR losses (this is notably 1 − PR), we use exclusively the readings from billing meters.

The main characteristics of each system analyzed in detail are summarized in Table I. The monitored overall PR losses are compared with simulated ones in Figure 4. Note losses are indicated, that is, "one minus PR" is shown. For each system two bars are shown, with the left bar representing monitored PR losses and the right bar representing simulated PR losses. The bars for simulated PR losses are diverted into the various loss contributions distinguished in the simulation (cf. Section 4.1). The monitored PR distinguished into losses occurring on either the DC-side or the AC-side can of course, only be provided for those five systems, in which also the DC/AC sides were monitored.

Simulated overall PR loss corresponds well to monitored overall PR loss, see Figure 4, except for systems "E," "H," "I," and "J." In addition, for system "D," one can recognize a deviation of ~2% in losses attributed to the DC-sides and not the AC-sides of the system in simulated results as compared with monitored data. For all other systems, deviations are below ~1%, which is well below the ~2% accuracy underpinning currently incorporated models in the Zenit simulation software (see Section 4.1). In the following, we discuss the peculiarities of systems showing total loss deviations of monitored and simulated data, in an attempt to identify possible causes explaining observed differences.

System "E" shows ~2% deviation of monitored compared with simulated PR loss. The cause for this underperformance was identified to be related to nominal installed PV capacity versus actual installed capacity. The power output of modules at STC temperature does not reach the STC-labeled power output of these modules at 1000 W/m^2, as shown in Figure 5.

For the least performing systems "H," "I," and "J," we observed some energy losses due to system failures, in all cases presumably because of inverter black-outs. If these losses did not occur, one would actually obtain another order of best performing systems. Systems in Figure 4 are arranged such that monitored PR losses increase over numbers "A" through "J." In particular, the downtime loss of system "J" is remarkable in that it was caused by failure of a 0.5-MWp inverter compound.

Finally, for system "D" overall monitored PR loss and overall simulated PR loss agree well, but according to simulation results, inverter loss should be much smaller than monitored. Conversely, losses on the DC-side should be higher than monitored. The modules of this system are mounted onto a metal shed-roof structure. One can thus expect relatively high temperature losses, which is also reflected in the ~5% annual temperature loss simulated. However, considering the AC electricity meter tolerance of ~1%, this deviation appears reasonable. Nonetheless one would be interested in following up this finding, as to ascertain that inverters do live up to expectations raised through their datasheet performances. This could mean

Table I. Main characteristics of the 10 best performing systems shown in Figure 4.

	Installation site	Mounting tilt and type	Inverter type and capacity (kWp)
A	Flat building roof	15° fixed	2 × 500
B	Flat building roof	26° fixed	Decentral, 60
C	Flat building roof	25° fixed	Decentral, 400
D	Mounted on tilted metal roof	45° fixed	Decentral, 65
E	Open area	Single-axis tracking, horizontally mounted	5 × 340
F	Flat building roof	15° fixed	2 × 4
G	Detached house	30° fixed	2 × 4.5
H	Flat building roof	25° fixed	Decentral, 15 × 10
I	Flat building roof	25° fixed	Decentral, 400
J	Flat building roof	15° fixed	2 × 500

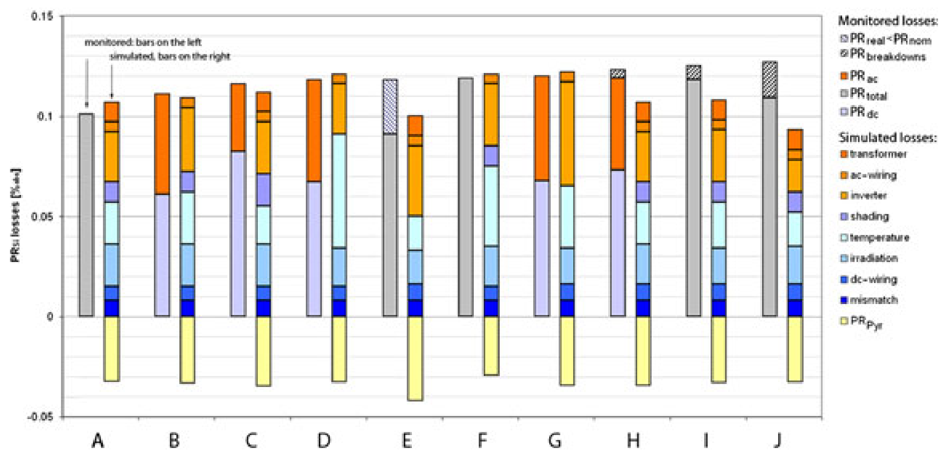

Figure 4. Detailed gains and losses for 10 systems observed and modeled. Explanation of single loss contributions are detailed in the text.

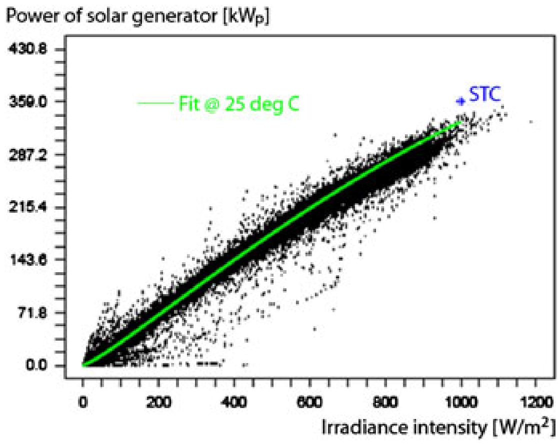

Figure 5. Solar generator power as a function of irradiance intensity (5-min averages) as monitored in 2010 for system "E" (Figure 4 and Table I). The fit that considered standard test conditions (STC) temperature only is well below STC rated power of modules, suggesting actually installed capacity is smaller than nominal installed capacity.

~2% gain in annual PV yield, effectively breaking the 90% line for PR_{Si}.

5. WHERE IS THE LIMIT?

It is clear from presented results that we have not (yet) monitored any $PR_{Si} > 90\%$ in a live system. The question remains: is 90% the limit? Although even the best performing system in this investigation does not reach $PR_{Si} > 90\%$, see Figure 4, this very Figure 4 may also show that the 90% line is not necessarily an upper limit of the PR. Different loss mechanisms may still allow for some optimization. A first approach would obviously be a combination of all smallest loss contributions, that is, the sum of the shortest section of each color of the depicted simulation bars. For example, when combining mismatch and cabling losses of system "F," irradiation level and temperature losses of system "E," inverter losses of system "J" into a fictive PV system, without shading and without transformer, one would end up with the PR a bit below, but close to 93%. This ideal selection of design features and components, however, is not realistic. For example, PV systems without any shading are typically mounted parallel to tilted roofs, leading to higher module temperatures as compared with tilted (and shaded) rows on flat roofs or in open areas. We will therefore recheck the most important loss mechanisms for their optimization potential in the following.

Ohmic losses, for both DC and AC cables, are only known for some systems simulated and shown in Figure 4. For other systems, we needed to assume the widely used approach of keeping cabling losses below 2.5% at full power. This leads to annual average losses of roughly 1.25%. Using greater wire diameters and/or optimized cabling concepts, ohmic losses may be reduced to 1.5–2.0% at full power. This would correspond to average losses of effectively 0.75–1.0% regarding the overall PR of systems.

Concerning module low light response, we see annual losses in the range of 2% in Figure 4. In the simulation, we used one standard c-Si parameter set for all systems under investigation, because for most of the modules in these 10 systems, module-specific parameters were not available. As a result of this assumption, no significant performance differences between module brands or types can be observed in Figure 4. Nevertheless, different module types will show varying low light characteristics. In a previous study, simulations based on measured low light response of 21 c-Si modules from different manufacturers revealed annual losses between 1% and 4%, with the majority of them between 2% and 3% [17]. Improvement of low light response is also related to cell processing and cell classification; it was suggested for c-Si technology to have at least a shunt resistance value of $>10\,\mathrm{k\Omega\,cm^2}$ as to avoid substantial low light efficiency decrease [16]. However, the room for improvement will be limited for this loss mechanism, 1.5% might be a first guess for a good module selection.

The lowest temperature loss is reported for system "E," a one-axis tracked system featuring long lines of single modules and rather large distances from ground and neighboring rows, perhaps the ideal case with respect to module ventilation. However, also some of the flat roof systems show temperature losses below 2%. More generally, one may argue that the temperature coefficient is a material constant. Hence, temperature losses could be addressed by switching to PV materials other than c-Si showing less temperature dependence, amongst which a-Si or CdTe thin films. However, the German top 10 performing PV systems as monitored by Fraunhofer ISE in the year 2010 all use c-Si solar cells. Also PV thermal hybrid modules [18] are rather exotic concepts not having entered the mainstream solar PV industry as of yet. We therefore do not assume any potential improvement with direct relation to the PV market of the next few years here. In fact, the same holds true for shading losses; good system designs with reasonable ground cover ratio limit shading losses to 1%. Besides inevitable shading close to sunrise and sunset, also shading due to diffuse irradiance will only be in a very limited range.

Finally, inverters may still offer some room for future improvement, despite today's devices showing annual losses below 2% in the simulation (see system "J"). This very good performance is confirmed by the best observed AC loss in system "C", being 3.4% including transformer and AC cable losses. Inverter prototypes with efficiencies reaching 99% were presented in [19], so devices with annual losses of 1.5% may become available fairly soon. It is worthwhile to note that the driving force beyond inverter development is related to prolonged inverter uptime, and energy loss implies component impairment.

Prog. Photovolt: Res. Appl. 2012; **20**:717–726 © 2012 John Wiley & Sons, Ltd.
DOI: 10.1002/pip

Summing up all previously noted improvements, an increase in PR between 1.25% and 2.5% seems feasible, the latter value only in the absence of shading. This would lead to PV systems showing PR greater than 91%, without shading losses even greater than 92%, under German climate conditions. Despite the fact that we do not see such values from our monitoring database up to now, we believe PR values above 90% are realistic even today, using today's commercially available components and should be expected more frequently in the future (i.e., at least within a couple of years).

6. SUMMARY AND CONCLUSIONS

In this study, we investigate the performance ratio (PR) of about 100 German PV system installations. The irradiation measurement technique is found to have a systematic influence on calculated PR values. Monitored PR is ~2–4% systematically lower when calculated with irradiation data obtained by pyranometers (henceforth denoted as PR_{Pyr}) as compared with irradiation amounts measured with reference cells (denoted as PR_{Si}).

Annual PR_{Si} for the ~100 systems for the year 2010 is found to be between ~70 and ~90% and shows a median PR of 84%. We therefore conclude that for the case of German PV systems, "good" performances are >84%. An analysis of the historical development of PRs over the past 10 years reveals, however, that also in recent years (2007 and 2008) system designs were realized that were *not* optimized with regards to energy yield. Such systems showed PR_{Si} as low as 75%, related primarily to row shading and bad inverter performance. This finding indicates the potential benefit of contract agreements between investors and developers that guarantee minimum performance ratios. On the other hand, systems using highly efficient components and designed appropriately, as well as realized on the ground with good workmanship, showed PR_{Si} very close to 90%. To identify potential improvements of loss mechanisms in even such highly performing systems, we then conducted energy loss simulations of the top 10 performing systems. All of these systems use crystalline silicon module technology. Very good agreement of simulation results with monitoring data was obtained, which proves that PV systems using crystalline silicon modules can be simulated with high accuracy using nowadays simulation methods.

The various loss mechanisms distinguished in the simulation included temperature, low light, wiring, and inverter losses. Loss heights of these simulated loss mechanisms show that even for highly performing systems, there is still room for some further optimization. Although we cannot yet report $PR_{Si} > 90\%$ for PV systems under German climate conditions up to now, we believe PR above 90% is realistic even today, using commercially available components and should be expected more frequently in the future.

REFERENCES

1. Decker B, Jahn U. Performance of 170 grid connected PV plants in Northern Germany—analysis of yields and optimization potentials. *Solar Energy* April-June, 1997; **59**(4–6) 127–133. *Selected Proceeding of ISES 1995: Solar World Congress. Part IV*. DOI: 10.1016/S0038-092X(96)00132-6
2. Erge T, Hoffmann VU, Kiefer K, Rössler E, Ringelhardt U, Teichmann T, Decker B, Grochowski J, Heilscher G, Schneider M, Blässer G, Ossenbrink H, Becker H, Vaaßen W, Gennening B, Rieß H, Sprau P. The German 1000-Roofs-PV Programme—a resume of the 5 years pioneer project for small grid-connected PV systems. *2nd World Conference on Photovoltaic Solar Energy Conversion*, Vienna, 1998; 2648–2651.
3. Reinders HME, van Dijk VAP, Wiemken E, Turkenburg WC. Technical and economic analysis of grid-connected PV systems by means of simulation. *Progress in Photovoltaics: Research and Applications* 1999; **7**(1): 71–82.
4. Ueda Y, K Kurokawa, K Kitamura, M Yokota, K Akanuma, H Sugihara. Performance analysis of various system configurations on grid-connected residential PV systems. *Solar Energy Materials & Solar Cells* 2009; **93**: 945–949.
5. IEC 61724. Photovoltaic system performance monitoring—guidelines for measurement, data exchange and analysis. Edition 1.0, 1998-04.
6. Kipp & Zonen Kipp & Zonen datasheets on the CMP pyranometer series. Available online at http://www.kippzonen.com [Accessed 31 May 2011].
7. Drews A, de Keizer AC, Beyer HG, Lorenz E, Betcke J, van Sark WGJHM, Heydenreich W, Wiemken E, Stettler S, Toggweiler P, Bofinger S, Schneider M, Heilscher G, Heinemann D. Monitoring and remote failure detection of grid-connected PV systems based on satellite observations. *Solar Energy* 2007; **81**: 548–564
8. Ineichen P. Five satellite products deriving beam and global irradiance validation on data from 23 ground stations. Scientific report, University of Geneva, 2011. Available online at http://www.cuepe.ch/html/biblio/detail_l.php?id=503&sr=&pr=&mjc=256 [accessed on 22 November 2011].
9. Lorenz E, Scheidsteger T, Hurka J, Heinemann D, Kurz C. Regional PV power prediction for improved grid integration. *Progress in Photovoltaics: Research and Applications* 2011; **19**. DOI: 10.1002/pip.1033
10. Müller B; Heydenreich W, Kiefer K, Reise C. More insights from the monitoring of real world PV power plants—a comparison of measured to predicted performance of PV systems. *24th European*

PhotovoltaicSolar Energy Conference and Exhibition, Hamburg, Germany, 2009; 3888–3892.

11. Dittmann S, Friesen G, Williams S, Betts T, Gottschalg R, Beyer HG, Guérin de Montgareuil A, Van Der Borg N, Burgers AR, Huld T, Müller B, Reise C, Kurnik J, Topic M, Zdanowicz T, Fabero F. Results of the 3 rd modelling round robin within the European project "PERFORMANCE"—comparison of module energy rating methods. *25th European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, Spain, 2010; 4333–4338.
12. Friesen G, Dittmann S, Williams S, Gottschalg R, Beyer HG, Guérin de Montgareuil A, Van Der Borg NJCM, Burgers AR, Kenny RP, Huld T, Müller B, Reise C, Kurnik J, Topic M. Intercomparison of different energy prediction methods within the European project "PERFORMANCE"—results on the 2nd round robin. *24th European Photovoltaic Solar Energy Conference and Exhibition*, Hamburg, Germany, 2009; 3189–3197.
13. Strobel, M, Betts T, Friesen G, Beyer H, Gottschalg R. Uncertainty in photovoltaic performance parameters—dependence on location and material. *Solar Energy Materials and Solar Cells* 2009 **93**: 1124–1128.
14. Heydenreich W, Müller B Reise C. Describing the world with three parameters: a new approach to PV module power modelling. *23rd European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, Spain, 2008 2786–2789.
15. Reich NH, van Sark WGJHM, Alsema EA, Lof RW, Schropp REI, Sinke WC, Turkenburg WC. Crystalline silicon cell performance at low light intensities. *Solar Energy Materials and Solar Cells* 2009; **93**: 1471–1481. DOI: 10.1016/j.solmat.2009.03.018
16. Schmidt H, Sauer D. Wechselrichter-wirkungsgrade—praxisgerechte modellierung und abschätzung. *Sonnenenergie* 1996; **4**: 43–47.
17. Müller B, Kräling U, Heydenreich W, Reise C, Kiefer K. Simulation of irradiation and temperature dependent efficiency of thin film and crystalline silicon modules based on different parameterization. *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition*, Valencia, Spain, 2010; 4240–4243.
18. Zondag HA. Flat-plate PV-thermal collectors and systems: a review. *Renewable and Sustainable Energy Reviews* 2008; **12**: 891–959.
19. Wilhelm C, Kranzer D, Burger B. Highly compact and high efficient solar inverter with silicon carbide transistors. *25th European Photovoltaic Solar Energy Conference and Exhibition/5th World Conference on Photovoltaic Energy Conversion*, Valencia, Spain, 2010; 4442–4447.