

FACTORS AFFECTING THE PERFORMANCE OF DIFFERENT THIN-FILM PV TECHNOLOGIES AND THEIR IMPACT ON THE ENERGY YIELD

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ABSTRACT: This paper reports the results of high-precision energy yield measurements of different PV module technologies performed at the headquarters of TÜV Rheinland, Cologne, from May 2010 through April 2011. The investigations refer to 12 specimens each subjected to a separate electronic load for automated MPP tracking and V/I-curve measurements. Modules based on CdTe, CI(G)S, a-Si, a-Si/ μ -Si, a-Si/a-Si and c-Si (mono and poly) semiconductors were analyzed and compared in a ranking with regard to the achieved specific energy yield. We consider the individual reasons for differences in performance, such as low irradiance behaviour, temperature coefficients, spectral irradiance effects and meta-instabilities of nominal power output, and describe the challenges in gathering high resolution measurement data.

Keywords: PV module, energy yield, performance, characterization, thin-film technologies, low irradiance behaviour, temperature dependencies, spectral response, efficiency

1 INTRODUCTION

The assessment of PV module performance is typically based on the nominal output power that is commonly related to standard test conditions (STC).

Care must be taken when using P_{max} as the only parameter for energy yield assessments under actual outdoor conditions because effects like low irradiance behaviour, temperature dependence and the variability of solar spectrum as well as non-stabilities of several PV module technologies are neglected.

The most important factors influencing the results of energy yield measurements on different modules are the following:

- Temperature coefficient T_C of $P_{Max}(\gamma)$ and its dependency on irradiance G
- Low irradiance behaviour $\eta(G)$ and its dependency on module temperature T_M
- Matching of the quantum efficiency with daily and seasonal changes in the solar spectrum at the test-site location, including potential current mismatch effects of tandem technologies
- Weighted average module temperature $\overline{T_M}(G)$
- Angle dependencies, soil resisting, module circuitry
- Long-term stability of module parameters (e.g. R_S , R_P) and performance (e.g. degradation, annealing)

To measure these rather small differences between the specimens and to evaluate their impact on the energy yields we require high-precision outdoor measurements with preferably small measurement uncertainties, not yet available from any common simulation software. The aim is to obtain a suitable comparison of different module technologies and module designs in order to determine their advantages and weaknesses and, last but not least, to find an optimal location for the installation of each module type.

To this end TÜV Rheinland operates a state-of-the-art outdoor test site for high precision energy yield measurements of PV modules. During an initial measurement period from 01-05-2010 through 30-04-2011 we were able to gather and analyze extensive data. This paper presents some of our results.

2 MODULE SPECIMENS AND OUTDOOR MEASUREMENT TECHNOLOGY

In order to carry out a technology-specific analysis and comparison we have selected 12 different types of PV modules: two crystalline modules (mono- and poly-crystalline silicon to compare with thin-film specimens), three CI(G)S modules (CIS and CIGS), one CdTe module and six amorphous silicon modules (a-Si; a-Si/a-Si, a-Si/ μ -Si). Before the start of energy yield measurements all specimens were stabilized according to the $\pm 2\%$ P_{Max} criteria of IEC 61646.

Following detailed initial measurements in the PV test laboratory of TÜV Rheinland, all modules were exposed on a fixed mounting system tilted at an angle of 35° and facing south, as shown in Figure 1.



Figure 1: Photo of the outdoor test field for energy yield measurements of ten thin-film and two crystalline PV modules

Each module is connected to a separate electronic load by four-wire sensing. Weather data such as module temperature, irradiance (in-plane, horizontal and diffuse) and P_{Mpp} are measured every 30 seconds. The spectral irradiance is measured with two radio spectrometers in a wavelength range of 300 nm to 1600 nm. The I/V curve is measured by the 12 electronic loads at time intervals of 30 minutes. The data collection of the modules and measurement instruments began at irradiance levels

above 15 W/m² simultaneously for all specimens. The module test field is located on the top of an office building of TÜV Rheinland free of any shading.

3 SEASONAL WEATHER CONDITIONS IN COLOGNE

To evaluate technology specific effects when measuring the energy yield, the seasonal changes of the weather conditions and the technology-specific characteristics must be known for the region of the particular test site.

Figure 2 shows the analysis of the one-year weather data with the given distribution of solar insolation for Cologne, as measured with a pyrometer in module plane.

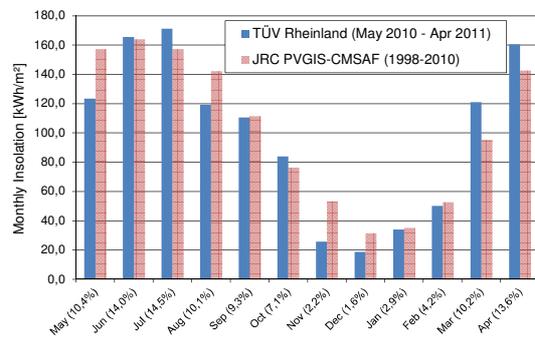


Figure 2: Distribution of monthly in-plane insolation at the outdoor test site in Cologne compared with the average insolation from 1998 to 2010 data

The data recorded at the test site reveal that the three winter months with a cumulative annual insolation of 2.2% (Nov), 1.6% (Dec) and 2.9% (Jan) played a minor role in the given energy yield analysis. The significant insolation occurred in the three summer months: The total insolation for June, July and August was 38.6%, while the following seven months, from September to March, had a total insolation of 37.5%. Moreover, exceptional insolation levels for the spring of 2011 were recorded in March and April. The total cumulative insolation for the entire year was 1183 kWh/m².

Besides the annual available solar insolation energy, the distribution of the solar spectrum varies significantly in the course of a single day and over the entire year due to changes in the air mass and in the composition of the atmosphere. Since each module technology has a different spectral response (Fig. 8), this variation influences the energy yield of the modules. For cloudy days with a high level of diffuse solar insolation, the daily and seasonal differences are very small and the spectrum shows a blue shift. Over the course of a cloudless day the solar spectrum typically exhibits a blue shift in the early morning, a red shift at midday and a blue shift again in the late afternoon, as measured in module plane. Regarding the dependence on seasonal changes, the site of installation plays a major role. Figure 3 shows four representative spectral measurements illustrating the variation of the spectral distribution of solar insolation for sunny days as measured at the test site in Cologne during different seasons.

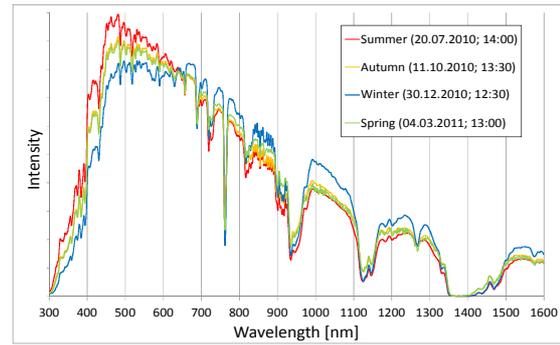


Figure 3: Seasonal variation of solar spectrum, measured in the module plane – The integrated area for four representative cloudless days in Cologne is normalized.

The measurements show large differences between the several seasons. To evaluate the spectral shift we compared the data according to IEC 60904-9 with the AM1.5 spectrum of IEC 60904-3 (Table 1).

Table 1: Classification of solar spectrum according to IEC 60904-9

| Interval | 400 - 500 [nm] | 500 - 600 [nm] | 600 - 700 [nm] | 700 - 800 [nm] | 800 - 900 [nm] | 900 - 1100 [nm] |
|----------|----------------|----------------|----------------|----------------|----------------|-----------------|
| Summer | 1.12 | 1.07 | 1.00 | 0.95 | 0.90 | 0.90 |
| Autumn | 1.01 | 1.03 | 1.00 | 0.98 | 0.94 | 1.01 |
| Winter | 0.86 | 0.96 | 1.01 | 1.05 | 1.05 | 1.12 |
| Spring | 0.99 | 1.01 | 1.00 | 1.00 | 1.00 | 0.99 |

The classification of all four measurements matches the requirements of a class A spectrum despite the large differences in the composition of the intensities. Compared with the spectrum of the IEC standard, the months of October and March showed minimal discrepancies for the six defined wavelength intervals. For the winter months, a red shift of the solar spectrum with an intensity of about -15% at the wavelengths of 400 – 500 nm and of about +15% at 900 – 1100 nm was observed, and vice versa for the summer months.

When simultaneously measuring a high number of different specimens, with no appropriate tracker system available, we suggest measuring P_{Max} at STC conditions during the spring and autumn months to obtain an almost ideal AM1.5 spectrum. This keeps the spectral and current mismatch errors as low as possible. Additionally, we recommend calibrating the spectrometer at short time intervals and attending to its uncertainty of measurement.

4 RESULTS OF THE OUTDOOR MEASUREMENTS AND TECHNOLOGY-SPECIFIC CHARACTERISTICS

4.1 Specific energy yield and ranking

To compare the energy yield of different specimens with different nominal power values it is necessary to normalize the measured energy yield [Wh] with the nominal output power at STC [W_p]. While this paper will not discuss in detail the challenges faced in determining the correct P_{Max} value, it must be stated that P_{Max} influences the specific energy yield [Wh/W_p] in an extremely negative way [7]. Factors such as the history and conditioning of the modules prior to measuring play an important role for thin-film modules, as do good measurement conditions (solar spectrum, module

temperature, irradiance, etc.). The P_{Max} measurements of this study were performed indoors (using a flasher with reference cell) as well as outdoors (pyranometer, nearly AM1.5 spectrum) and the results are compared in Fig. 4.

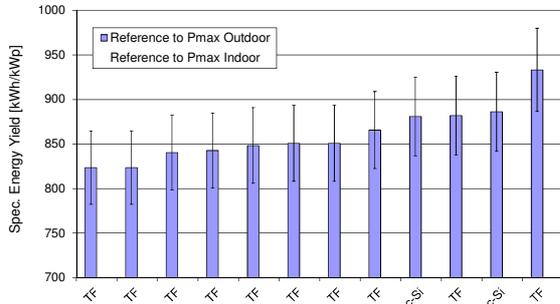


Figure 4: Ranking of energy yield measurements of 12 modules of different technologies performed at TÜV Rheinland, Cologne, in the period 01.05.2010 – 30.04.2011. Values with ineffective P_{MPP} -tracking have been deleted.

The annual energy yields analysed from the data of one-year 30s P_{MPP} values show a difference of 11.8% between the first and the last specimens. The two crystalline modules reached positions two and four. Applying the outdoor P_{Max} value for normalizing the energy yield was identified as the best method because of short-time instability effects of several thin-film modules and the spectral mismatch effects in measurements with the indoor flasher. The error bars calculated at $\pm 5\%$ are mainly due to the P_{Max} uncertainty and must be considered when interpreting the results.

4.2 Temperature dependence and low irradiance behaviour

In order to explain the significant differences in the performance of different PV module types we must take a closer look at characteristics like temperature dependence, low irradiance behaviour, spectral response and the non-stability of module performance.

Laboratory and outdoor measurements have shown substantial differences in the temperature and low irradiance behaviour of the different technologies. Temperature coefficients as well as the average module temperature vary. The temperature dependence has been discussed in previous papers [1], [8]. The results showed higher values of γ (T_C of P_{Max}) for CI(G)S and c-Si based technologies (-0.31 to -0.48%/K), whereas a-Si and CdTe based technologies (-0.16 to -0.35%/K) seem to be advantageous. The differences of γ within one technology are rather high. In hot summer months with relatively high average module temperatures we observed advantages for specimens with low γ values.

Indoor measurements of the low irradiance behaviour also resulted in large differences for the several specimens [1]. These measurements could be reproduced in an almost similar constellation at outdoor conditions (Fig. 5). We found the best way to analyze the low irradiance behaviour without parasitic effects like spectral shifts or angle dependence to be the self-reference method via I_{SC} , which uses the PV module itself as the irradiance detector. The linearity of I_{SC} was established for all specimens under indoor conditions for irradiance >100 W/m². The best results were obtained by

several a-Si modules, the CdTe module and the c-Si based modules. The analysis of the CI(G)S specimens indicates room for improvement. Like the temperature behaviour, the low irradiance behaviour showed significant differences within a given technology.

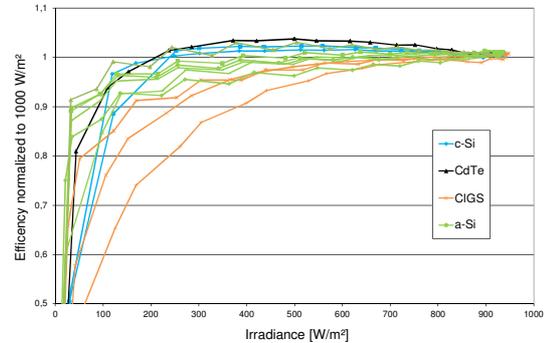


Figure 5: Low irradiance behaviour of different thin-film modules, using self-reference method, 10.10.2010

These performance differences of certain thin-film modules clearly influence the energy yield for different irradiance levels, as shown in Fig. 6. The module showing a good low irradiance performance (turquoise segments) generates significantly more electrical energy from its total yield at low irradiance (< 400 W/m²) than the module with moderate low irradiance behaviour (purple segments), which produces more energy at high irradiance levels. The total of all irradiance levels is equal to 100%.

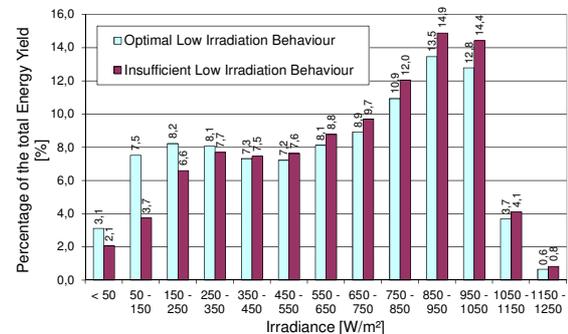


Figure 6: Comparison of the energy yield generation of two modules with different low irradiance behaviour with respect to different irradiance levels

4.3 Spectral response and non-stability of performance

To evaluate the influence of changes in the composition of the solar spectrum (as discussed in chapter 3), the spectral response of the different specimens must be known. TÜV Rheinland therefore purchased and configured a unique measurement station to determine the spectral response (SR) on a module basis. The system allows non-destructive measurements of single- and multi-junction modules in a wavelength range between 300 nm to 1200 nm and in wavelength intervals of 1 nm (Fig. 7).



Figure 7: Non-destructive spectral response measurement station at TÜV Rheinland, Cologne

Using this high-tech equipment it was possible to measure the spectral response of each specimen. As expected, the results showed significant differences between the different single-junction and multi-junction PV module technologies. A SR comparison of selected single-junction specimens is shown in Figure 8. The a-Si module (red curve) has its spectral response in the narrow band of about 300 nm to 800 nm. CIS (yellow) and CdTe (green) show similar curves with SR values from 350 nm to 900 nm. The SR curve of a CIGS module (blue) falls into the same range as those of c-Si modules (pink, black), but for some CIGS modules (brown) the SR data attain values higher than 1200 nm. Due to this situation, the classification of IEC 60904-9 (up to 1100 nm) may be insufficient for some module flasher combinations.

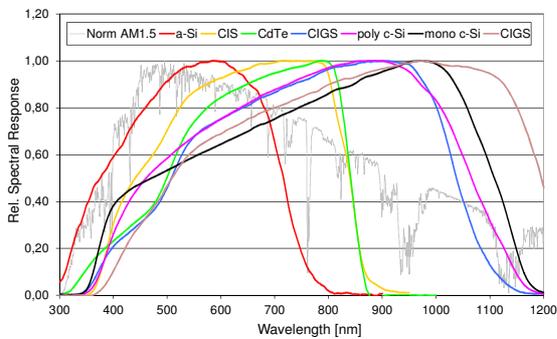


Figure 8: Normalized spectral response graphs of different single-junction technologies compared with the IEC 60904-3 AM1.5 spectrum

To analyse the effects of changes of the solar spectrum on the performance of the modules, the influences of temperature and irradiance must be negated by using one of the correction procedures of IEC 60891. For the present investigations all required parameters were determined in the laboratory. The 30 minute I/V curve data was filtered in a wavelength range of 400 – 1200 W/m², module temperatures of 20 – 60°C, between 11:00 and 15:00 and with a fluctuation of less than 5% of the irradiance before and after the measurement. The large filtering range is necessary to obtain enough filter results in the winter months. Following the filtering, the I/V data was corrected via IEC60891 Proc.2 to 800 W/m² and 40 °C in order to find a compromise for leaving correction errors as small as possible. Figure 9 shows the results for two representative samples.

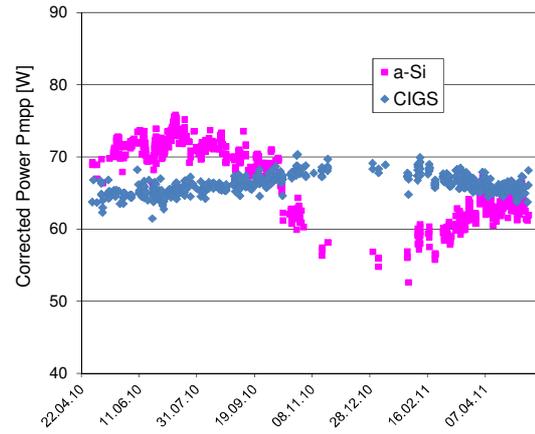


Figure 9: Seasonal variation of filtered and corrected module power at 800 W/m² and 40°C – example of a-Si and CIGS specimens with different nominal power

The temperature and low irradiance effects are irrelevant because of the correction of module power (800 W/m², 40°C). The seasonal variation in the output power is due to degradation processes, performance instability and the spectral shift of the solar spectrum. The largest seasonal change was detected for the a-Si specimen (pink). This may be explained by the seasonal variation of the solar spectrum (Fig. 3) and by the SR of a-Si (Fig. 8 red curve). While other technologies can handle each wavelength (some wavelengths better, some less well), the a-Si specimen is very sensitive when shifting up to approx. 15% from short wavelengths (400 – 500 nm, which a-Si can handle) to long wavelengths (900 – 1100 nm, which a-Si cannot utilise). All a-Si tandem modules perform similarly to the single-junction a-Si specimen, possibly because of the limiting top layer and the subsequent current mismatch in combination with degradation and annealing effects. The performance change of CIGS (blue curve in Fig. 8) and c-Si contrasts with that of a-Si for all tested specimens and is less pronounced. CIS shows almost no seasonal variation in output power, while the CdTe is similar to a-Si, but also less pronounced.

4.4 Performance ratio (PR) and measured operative efficiency

To evaluate the impact of low irradiance behaviour in combination with spectral adaptation under actual outdoor weather conditions, the Performance Ratio (PR) can be a good indicator to see which of these effects is dominant (Fig. 10).

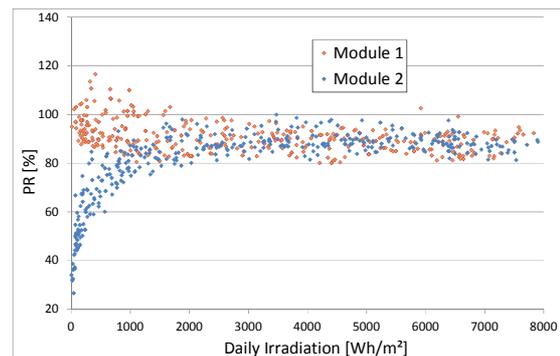


Figure 10 Dependence of PR on daily irradiation -

comparison of two different thin-film module types

Cloudy days with small total irradiation bring low temperatures, a blue shift in the spectrum and low irradiance levels. For all modules the PR gets smaller within the total irradiation of the day because of high module temperatures and the negative effect of the T_C . The slope depends on the value of the T_C . For most of the modules the low irradiance on cloudy days has a negative effect on the PR, but some modules can withstand or even compensate for these efficiency losses thanks to the blue shift of the solar spectrum. A-Si modules with good low irradiance behaviour can increase their slope for cloudy days ($H < 2000 \text{ Wh/m}^2$), as shown in Fig. 9 (red curve). A-Si modules with tandem technology must be inspected individually because of possible current mismatch losses. Modules with insufficient low irradiance behaviour in combination with small spectral response at low wavelengths significantly lose PR (Fig. 9 blue) on cloudy days.

To get an outline of the change of the module performance, the operational efficiency was calculated for all specimens and for each month of the year (Fig. 11).

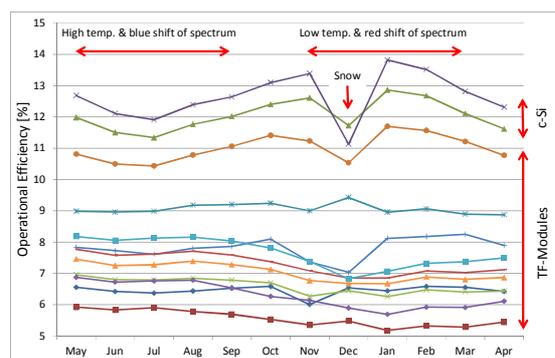


Figure 11 Seasonal variations of the measured efficiency of 12 different module types

In December heavy snow fall in Cologne partly covered the modules and some of the sensors. The data must therefore be disregarded.

The measured efficiencies range between 11% and 14% for the c-Si specimen and between 5% to 12% for the thin-film modules. The best value of all tested thin-film modules was attained by a CIGS module. The c-Si modules and CI(G)S modules show a maximum of efficiency in winter because of low temperatures and the red shift in the spectrum, and a minimum during the summer because of high temperatures and the blue shift in the solar spectrum. The a-Si modules behave differently because of degradation effects and low irradiance in winter. The annealing of the a-Si specimen begins in spring. Analysis of the total degradation of the modules requires preconditioning in the laboratory with the light-soaking test site, in order to obtain stable power values for final flasher measurements.

5 CONCLUSIONS

The analysis of the single-year high-precision outdoor data of from twelve different PV modules yielded the following results:

The significant factors influencing the energy yield of

different thin-film module types are low irradiance behaviour, temperature dependence and spectral matching with the solar spectrum and its changes in the course of a day and a year, respectively.

With respect to the low irradiance behaviour, the CdTe, the c-Si and some of the a-Si specimens showed good performance. The tested CI(G)S specimen left some room for improvement. Advantages of the temperature dependence of the CdTe and some a-Si specimens were detected. The a-Si specimen showed performance gains in summer because of annealing and the blue shift in the solar spectrum. The c-Si and CI(G)S specimens showed performance gains in winter because of high T_C s and the red shift in the solar spectrum.

The ranking of the specific energy yield showed significant differences of 11.8%. Rankings 1 to 4 were attained by the modules with the best low irradiance behaviour, rankings 2 and 4 by the c-Si specimens. The measurement uncertainty in the specific energy yield ranking was $\pm 5\%$ owing to the uncertainty in determining the nominal power, P_{max} ; this uncertainty must be further reduced.

The best efficiency curves of tested thin-film modules were achieved by CI(G)S.

The results of temperature and low irradiance behaviour correlate with the results of the energy yield ranking.

The results of the efficiency and performance analysis correlate with changing seasonal weather conditions, with respect namely to ambient temperatures, irradiance levels and spectral shifts.

6 ACKNOWLEDGEMENTS

This work has been supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the framework of Contract No. 0325070A, and by the participating manufacturers.

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