DEGRADATION IN PV POWER PLANTS: THEORY AND PRACTICE

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ABSTRACT: Our contribution is based exclusively on data from PV power plants in Germany that have been measured in detail. The comprehensive evaluations and statements are based on 44 plants, each with a rated power between 500 kWp and 1500 kWp and an operating life of almost 10 years. The main conclusion of this study is that almost all observed yield degradation effects are repairable or reversible, like inverter failures or soiling of the PV modules. But these effects lead to a negative trend in the Performance Ratio. PV Modules are taken from the field after 10 years of operation. The measurements show very small power deviations from the initial values. Furthermore, due to a positive trend of irradiance in plane of array no decreasing trend in annual energy yields is observed. The most frequent causes of larger fluctuations are inverter failures and inverter malfunctions. The sensors for measuring solar irradiation are very stable throughout the entire measurement period and the soiling of the sensors is very low. The results further support the thesis that beside climatological and site specific influences also operation and maintenance strategies have a significant influence on observed performance loss rates of commercially operated PV systems.
Keywords: Quality Assurance, PV Power Plants, Long-term Data Analysis, Performance Ratio, Degradation

1 INTRODUCTION

The following evaluations and statements are based on the many years of operating experience of 44 PV power plants in Germany. These are large roof-mounted systems in the power range from 500 to 1500 kWp which were installed on the roofs of the central warehouses of ALDI Süd and ALDI Nord as part of a DCM AG fund.

Figure 1: The PV power plant at the Altenstadt site in Bavaria has been in operation since 2006.

For all the PV power plants investigated, there are

- A yield report and an independent final acceptance test.
- Precise module measurements of a selected sample of modules in the calibration laboratory of Fraunhofer ISE
- Continuous independent monitoring data with over 99.5 % availability
- Regular and traceable calibrations of the irradiation sensors

2 OVERAL TREND ANALYSIS

The results of the analysis are summarized in Figure 2, which shows the long-term trend of the irradiance in plane of array (GPOA), performance ratio (PR) and energy yield in comparison to the initially measured values for the first full year of operation.

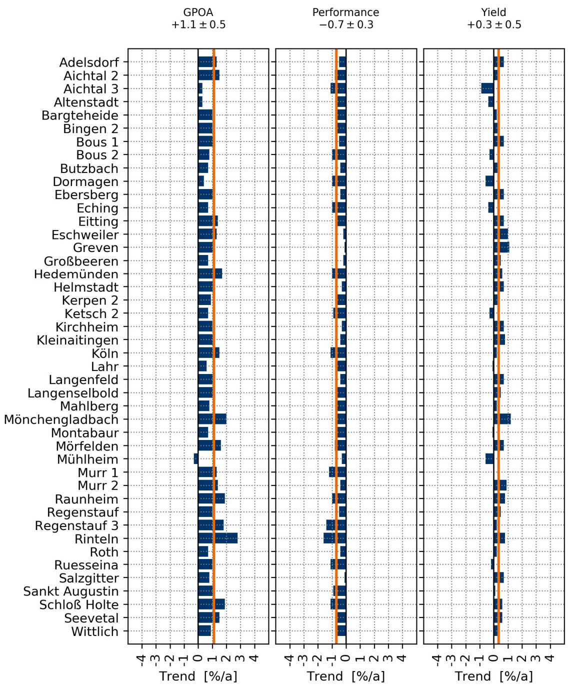

Figure 2: Trend analysis for the 44 PV power plants. The vertical red line is the mean value of the annual rates of change over all plants and all operating years.

The average annual performance loss rate for the whole portfolio is -0.7 % with a standard deviation of +/- 0.3 %. There are only a few outliers with a rate of change below -1.0 % at the Aichtal, Hedemünden, Murr, Regenstauf and Rinteln sites. On the other hand, the change rates at the Eschweiler, Greven, Großbeeren, Mühlheim and Salzgitter sites are above -0.3 %.

The reasons for the fluctuations in the performance ratio are determined in detail in all examples. The most frequent causes of the larger fluctuations are inverter failures and inverter malfunctions. The sensors for measuring solar irradiation are very stable throughout the entire measurement period and the degree of contamination of the sensors is very low.

It is worth mentioning that in the period under consideration the average solar irradiance increased very sharply by 1.1 % per year compared to the initial value. As a result, yields increased by an average of 0.3 %.

All PR's given in this article refer to irradiation values measured with reference cells. The deviation in comparison to pyranometers measurement is explained in [2, 3]. Possible reasons for increasing irradiation are also discussed in [1].

3 PERFORMANCE RATIO OVER THE YEARS

The first generation of the PV power plants studied were built in 2006 and 2007. Continuous high-resolution monitoring data has been available from these power plants since 2008/2009 for about 10/11 years.

Location	Pnom kWp	PR %	Spread %	year1/2018 %	loss/year %
Ebersberg	497	82.6	4.0	-1.4	-0.14
Roth	1045	83.9	2.2	-1.6	-0.16
Mahlberg	1252	82.4	3.5	-1.8	-0.18
Regen-stauf	763	79.7	5.9	-3.9	-0.35
Salzgitter	530	84.0	2.6	-4.2	-0.42
Adelsdorf	1553	84.5	2.0	-5.9	-0.54
Altenstadt	1512	80.4	3.8	-9.4	-0.78
Montbaur	1012	82.3	3.4	-8.6	-0.79
Bous	453	81.2	3.0	-7.8	-0.97
Kleinai-ting	1079	82.6	3.5	-10.7	-1.07
Rinteln	826	80.7	5.1	-17.2	-1.72
	10522	**82.2**	**3.5**	**-6.6**	**-0.65**

Table I: The overview shows the PR results of the first generation of the described PV power plants.

Over the operating period of 11 years, these PV power plants achieved a Performance Ratio of 82 % on average, with a standard deviation from the mean of 3.5 %.

At the Salzgitter, Roth and Adelsdorf sites, the highest values for the Performance Ratio (84.0, 83.9 and 84.5 %) and the lowest standard deviations (2.6, 2.2 and 2.0) were determined. The largest fluctuations from year to year are recorded in Regenstauf and Rinteln (5.9 % and 5.1 %). The most frequent reasons of the larger fluctuations are inverter failures and inverter malfunctions.

Table I shows not only the mean value and the variance of the performance ratio, but also the comparative values for the first year of operation in relation to the last year of operation, in 2018. In the last column, the rate of change per year was calculated. Figure 3 illustrates the long-term behaviour of the power plant at the Roth site, while Figure 4 shows Rinteln's long-term behaviour.

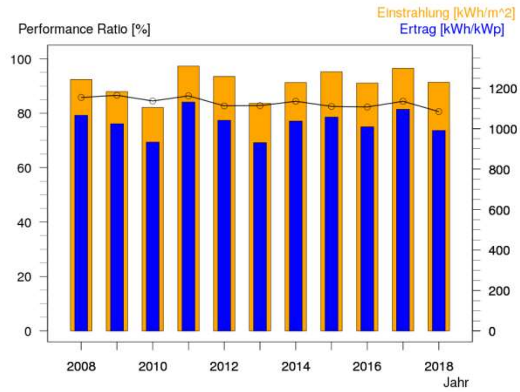

Figure 3: Development of the annual values of solar irradiation, yield and performance ratio of the PV power plant at the Roth site over the first 11 years of operation.

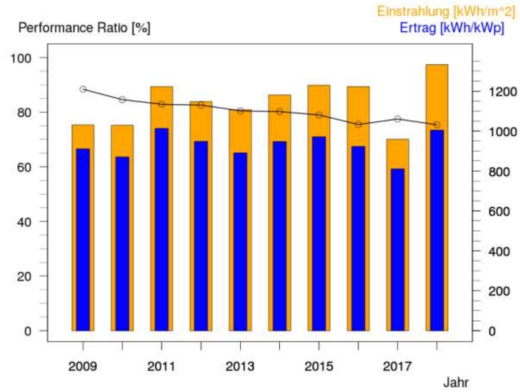

Figure 4: Development of the annual values of solar irradiation, yield and performance ratio for the Rinteln site.

At the power plant in Roth, there are only very slight fluctuations in the performance ratio and only a very small change of -1.6 % over the years of operation compared with the initial value. The system has been running almost without failures.

In Rinteln a clear and steady decline of 17 % of the Performance Ratio can be seen. Repeated failures of inverters and fuses were the main reason for the negative trend in the Performance Ratio. Therefore in spring of 2019 an extensive maintenance of the system and cleaning of the PV Modules was carried out. The performance now shows an increase of 5% compared to the previous year.

For the third generation of PV power plants listed in Table II, all elements of quality assurance have been further optimized. Therefore the projects designed and implemented between 2009 and 2011 achieved an average Performance Ratio of almost 88 % in the period under review.

For most of these power plants, module manufacturers have already supplied modules with clearly positive output tolerances compared with the nominal output values. For inverters, the new generation of three-phase decentralized inverters was introduced, which already showed significantly higher efficiencies than their predecessors. These new power plants show only a small spread of the annual values over the entire operating period, which is well below 3 %. However, if major deviations occur, it is also mainly caused by inverter failures. Looking at Table II, it is noticeable that some PV power plants achieve a Performance Ratio of around 90 %.

Location	Pnom kWp	PR %	Spread %	year1/ 2018 %	loss/ year %
Eschweiler	999	90.2	1.9	1.7	0.17
Mülheim	984	85.9	2.2	-0.3	-0.05
Kircheim	1001	88.8	1.6	-0.8	-0.09
Murr	293	86.1	1.5	-1.2	-0.13
Greven	999	90.6	1.2	-1.2	-0.15
Dormagen	1003	90.0	3.7	-2.7	-0.33
Großbeeren	910	88.3	1.8	-2.9	-0.37
Butzbach	1002	91.4	1.6	-2.9	-0.37
Langense-bol	988	86.4	1.8	-4.2	-0.52
Raunheim	999	89.6	2.4	-4.2	-0.59
Kerpen	542	87.1	2.7	-5.5	-0.61
Lahr	595	87.1	1.8	-5.3	-0.66
Eching	829	86.5	2.8	-5.7	-0.71
StAugustin	999	88.5	3.0	-6.8	-0.75
Sevetal	555	88.4	2.5	-6.3	-0.89
Köln	713	87.5	3.1	-7.3	-0.91
Ketsch	595	89.0	2.8	-8.3	-1.03
Bargtheide	998	86.8	2.6	-8.1	-1.16
Aichtal	553	81.3	3.2	-9.8	-1.23
	14558	**87.7**	**2.4**	**-4.6**	**-0.59**

Table II: The overview shows the technology and the results of the third generation of the PV power plants described.

As an example, we have examined the Eschweiler power plant in detail, which remained at a very high performance level throughout the entire operating period. For this example, the annual results are summarised in Figure 5 and Table III.

In 2018, the solar irradiation and therefore also the module temperatures were about 10 percent above the long-term average compared to other years. This year with the extremely high irradiation values for Germany had an overall influence on the performance ratio. Until the middle of the first year of operation, one of the two central inverters had malfunctions that led to the lower performance in the year 2010.

During the entire measurement period, the calibration values of the irradiance sensors were almost the same and the soiling was less than 0.3 percent (see Table IV). A complete cleaning of the solar modules was last carried out in June 2016.

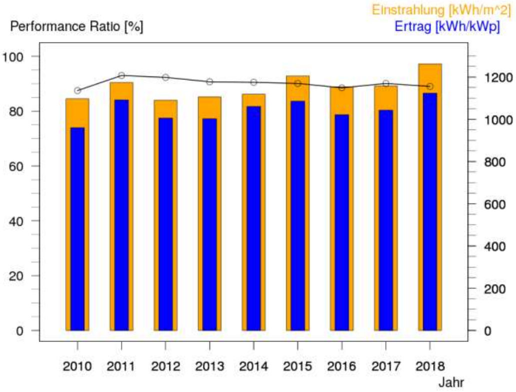

Figure 5: Development of the annual values of solar irradiation, yield and Performance Ratio for the Eschweiler-site.

Year	Data %	G_{Module} kWh/m²	Yield kWh/kWp	PR %	Tamb °C
2010	99.7	1097	959.9	87.5	10.0
2011	99.8	1174	1091.3	93.0	11.8
2012	98.9	1090	1005.8	92.3	11.1
2013	98.9	1105	1002.5	90.7	10.7
2014	99.6	1119	1060.4	90.5	12.4
2015	99.8	1205	1085.7	90.1	11.8
2016	99.8	1154	1021.6	88.5	11.5
2017	99.9	1158	1042.9	90.1	11.9
2018	99.9	1262	1123.2	89.0	12.6
	99.6	**1152**	**1043.8**	**90.2**	**11.5**

Table III: All important data for the evaluation are summarised for the Eschweiler site.

year	C_values	Delta_C	Soiling
2010	53.8 mV		
2013	53.4 mV	-0.4%	0.3%
2013	54.4 mV		
2017	54.3 mV	-0.1%	0.2%
2017	52.4 mV		
2018	52.8 mV	-0.4%	0.2%

Table IV: Historical data of the calibration of the irradiation sensor at Eschweiler. C_value is the calibration value in mV, Delta_C is the difference between initial calibration value and recalibration value, soiling is the difference between the value before and after cleaning of the sensor.

Also at the PV power plant in Butzbach the Performance Ratio is more than 90 % over the entire period of operation. The low PR in 2016 is caused by inverter failures. End of 2018 an extensive maintenance of the system and cleaning of the PV Modules was carried out. The performance ratio in 2019 is at the same level as in the first year of operation.

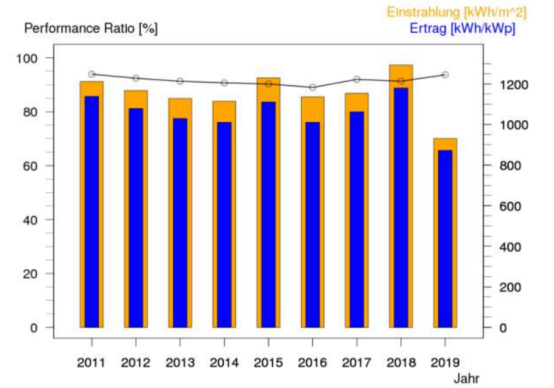

Figure 6: The figure shows the annual Performance Ratio of the PV power plant in Butzbach over the years of operation.

4 PERFORMANCE CHECK OF PV MODULES

In November 2018, 10 modules were removed from one string at the Dormagen plant in order to analyse possible degradation phenomena after 9 years of operation. The results in Figure 7 show that the performance values are only about one percent below the initial value.

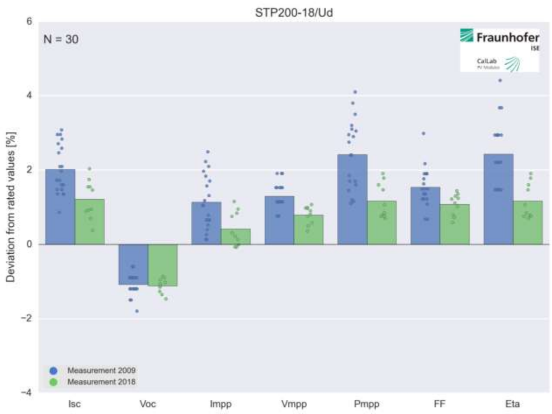

Figure 7: The figure shows a comparison of the laboratory analyses before the solar modules were installed in the field and after 9 years of operation.

At that time the tests were carried out before the initial degradation. If one assumes that the solar modules were still subject to initial degradation after installation in the field, then degradation would hardly have occurred.

Of course, such comparisons must also include the question of the reproducibility of laboratory measurements. In our calibration laboratory we can prove a reproducibility of maximum 0.5 % for measurements done in the last 10 years.

Within the scope of the degradation analyses, further random samples from other manufacturers were carried out. Table V summarizes the results of 10 modules per manufacturer from different sites. Overall, the deviations compared to the initial measurements are clearly below the reproducibility and absolute measurement uncertainty. The first analyses show that the solar modules used have a high quality standard and show no remarkable degradation.

Location	PV Modules	Delta	Year	p/year
Dormagen	Suntech 200	-1.50%	8	-0.19%
Hedemünden	Tenesol 200	-2.40%	10	-0.24%
Kerpen	Solara 220	-1.20%	9	-0.13%
Bingen	Kyocera 205	-0.80%	10	-0.08%
Aichtal	Kyocera 200	-0.70%	8	-0.09%
Altenstadt	SMD 200	-1.00%	12	-0.08%

Table V: Results of the re-measurement of PV modules from the field showing the mean annual degradation p/year

At the system level, as well, the annual performance losses are quite low (see Table VI). Table VI also shows that module degradation contributes only slightly to performance loss rates and that most of the performance losses may be reversible.

Location	years	PRloss/year	p/year
Dormagen	8	-0.30%	-0.19%
Hedemünden	10	-0.50%	-0.24%
Kerpen	9	-0.50%	-0.13%
Bingen	10	-0.40%	-0.08%
Aichtal	8	-0.67%	-0.09%
Altenstadt	12	-0.60%	-0.08%
Average	9.5	-0.50%	-0.14%

Table VI: Comparison of performance ratio losses per year and module degradation per year for randomly selected locations

In 2018 extensive maintenance and cleaning work was also carried out at several other sites. The Performance Ratio of these plants could be significantly increased again.

5 SUMMARY

The following summary refers to 44 large PV power plants on industrial roofs in Germany with 38 megawatts of installed capacity, with 200,000 solar modules, with 70 central inverters and 800 decentral inverters.

Figure 8: The PV power plant at the Regenstauf site was built in 2007.

Performance Ratio

The projects designed and implemented between 2009 and 2011 achieved an average Performance Ratio of almost 88%. PV module manufacturers have supplied modules with clearly positive output tolerances and inverters showed significantly high efficiencies. The average performance loss rate for the portfolio is -0.7 %.

Energy Yield

The expected Yields for the entire portfolio were far exceeded. Despite the observed performance loss rate, the yields increased over time by an average of 0.3 % per year, due to an increase in solar radiation by 1.1% per year.

Inverters

Inverter failures were the main cause of the large fluctuations in the Performance Ratio of the plants. Central inverters are less frequently affected by malfunctions than decentral inverters, but failures in the central concept have a greater impact on the overall performance of the PV power plant. For plants distributed throughout Germany, immediate troubleshooting is not always economical. In the case of central inverters, the availability of the manufacturer for trouble shooting is very important. With an increasing number of inverter failures over time, it can be concluded that these failures are one of the main drivers for the observed performance loss rates.

PV Modules

Since the commissioning of the first power plants in the year 2007, less than 0.25% of the modules had to be replaced due to defects. One type of module used in the plants shows snail trails. Measurements in the laboratory, however, have so far shown if at all only very low degradation effects. The contribution of module degradation to performance loss rates seems to be very low.

Soiling

At almost all locations, slight soiling of the solar modules can be seen at the edges of the modules. The outer cell row towards the frame is also partially affected. Only a few projects show heavily soiled solar modules, mostly caused by bird droppings. Long-term soiling effects seem to be a driver of observed performance loss rates even in climates with generally regular rainfalls like in Germany. This may at least in part also be attributed to climate change effects with longer dry periods (as observed e.g. in 2018).

Installation

Fuses and plug connections have occasionally had to be replaced. The cable ties used were replaced in many systems after the first 3 years as part of regular maintenance.

Quality Assurance and Monitoring

Comprehensive Quality Assurance reduces technical risks of component and system failure and validates performance with a high degree of certainty. Reliable measurement technology with well-maintained and precise irradiation sensors is the basic requirement for reliable error and degradation analyses.

6 CONCLUSION AND OUTLOOK

"We found median degradation for x-Si technologies in the 0.5-0.6%/year range with the mean in the 0.8-0.9%/year range" is the core statement of one of the most comprehensive and most cited papers on degradation effects of PV power plants [4]. At a first look our results on observed performance loss rates fit into this statement.

However, we found that almost all of this observed performance loss is reversible. Inverter failures or soiling of the PV modules have a much more negative effect on performance loss rates than degradation of PV modules. A sample of PV Modules taken out from the PV Power Plants after 10 years of operation showed very small power deviations from the initial values and the modules seem to be very stable and reliable.

The calculation of performance loss rates excluding down times, failures or periods of high soiling losses seems to be impossible for commercially operated PV power plants given the number of possibly affected inverters and PV modules in relation to only one or a few measurements of the power feed into the grid. Furthermore, the calculation of such performance loss rates seems to be not relevant for the commercial operation of PV systems. More interesting for commercial operation of PV systems is the question to which extend observed performance loss rates can be influenced by O&M efforts and expenses.

The previous work on the scientific analysis of degradation effects will be intensified within the framework of a planned research project. In the future, inverter failures are to be rectified even more quickly. Automated error detection mechanisms should also enable errors to be detected earlier. The maintenance concept is to be optimized with regard to economy and efficiency. The focus here is above all on more intensive infrared measurements and cleaning of the PV modules.

REFERENCES

[1] Müller B, Wild M, Driesse A, Behrens K (2014) Rethinking solar resource assessments in the context of global dimming and brightening. Solar Energy 99:272–282. doi:10.1016/j.solener.2013.11.013

[2] Müller B, Hardt L, Armbruster A, Kiefer K, Reise C (2015) Yield predictions for photovoltaic power plants: empirical validation, recent advances and remaining uncertainties. Prog. Photovolt: Res. Appl. 24(4):570–583. doi:10.1002/pip.2616

[3] Reich NH, Müller B, Armbruster A, van Sark, Wilfried G. J. H. M., Kiefer K, Reise C (2012) Performance Ratio revisited: is PR > 90% realistic? Prog. Photovolt: Res. Appl. 20(6):717–726. doi:10.1002/pip.1219

[4] Jordan, D.; Kurtz, S.; VanSant, K.; Newmiller, J. (2016): Compendium of photovoltaic degradation rates. In: Progress in Photovoltaics: Research and Applications (24), S. 978–989. DOI: 10.1002/pip.2744.