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FIRST RESULTS FROM A HIGH PRECISION INDOOR & OUTDOOR PV MODULE MONITORING CAMPAIGN

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ABSTRACT: To aid the design and parameterization of risk models used in insurance solutions for the PV industry, we introduced an innovative combination of repeated laboratory measurements and ongoing test field monitoring. This approach aims at the relationship between the real life experience and the STC based performance warranties. Each four samples of ten different module brands and types have been exposed for five years now. In this contribution, we compare the results of indoor module characterization to module parameters derived from outdoor operation, where IV curves are acquired in regular intervals. Dependent on the time scale, this comparison needs different approaches. When looking at the major influences on a PV module's long term yield, a clear ranking is visible after 5 years of exposition. Deviations from rated values as given in the data sheet have the biggest influence on long-term yield, followed by initial degradation. Differences in cell and module technology are next in the ranking: low light behaviour, angular response and spectral response may help some products to perform better than others. Finally, long term degradation may cause different life time yields, as this (typically small) effect will increase differences in module characteristics with time. In this experiment, degradation rates between 0% and 1% per year have been deduced.
Keywords: Calibration, Characterisation, Energy Performance, Monitoring, Degradation

1 MOTIVATION

The fast pace of photovoltaic expansion over the last years was driven by a continuous global investment around US$ 150 billion per year [1], a drastic cost decrease [2], and ramping up of production and installation capacity. To keep the investment volume high and manage the risk accumulation, a thorough analysis is essential. Despite cost improvements, PV modules still represent the major share of initial investment.

Insurance solutions represent an important part of the industry wide risk management by offering risk transfer solutions based on a risk-adequate premium [8]. The premium can partially be evaluated by historical data but needs a sophisticated risk model matching the PV characteristics in the future. The measurements described in this paper were commissioned to improve the reliability of the risk model and the input parameters specific for each PV module variant. This includes the valuation of the existing insurance portfolio as well as the underwriting of upcoming insurance policies.

There are many publications on the technical reliability, durability, and failure modes of photovoltaic modules available [3], [5]-[7]. However, it is nearly impossible to determine absolute failure rates or degradation numbers for a specific selection of module types. Most results are just presented on an average basis in an anonymized form without spread or distribution shapes. This is due to the high effort and the long time needed.

There are also attempts to derive module failure rates from the warranty accruals in the annual reports [9], [10]. However, the consumption of warranty reserves is not split up into module types or production years. While the revenue of the manufacturers was growing rapidly, the older modules are under-represented in the reported numbers. Modules rejected on delivery will not be accounted as warranty claims because they can be re-flashed, repaired, or down-rated in most cases and sold in a second attempt.

The insurance solutions offered to cover performance warranties require a proper product qualification according to IEC-61215/61730 [4] and a solid quality culture in the production facilities. Additional checks for UV resistance, junction box design, PID, LID/LeTID, as well as enhanced climate stress complement the technical prerequisites. A purchaser should be able to trace back his delivery to the matching certifications. A further question that should be addressed is the discovery of open qualification gaps and unwanted production excursions to minimize design errors and systematic wrongdoing. Over the long period of 25 years, small findings in the early years can develop to significant problems over the desired lifetime. It is desired to gain more knowledge about the significant drivers.

The risk model and risk parameter estimation are the vital know-how of the reinsurer Munich Re. This way, the commercial side of the PV business is bridged with the technical characteristics. Insurance is the protection against something random and unforeseeable. Thus, it is essential to distinguish between sporadic events and systematic clustering. The characterization of PV modules in this study shall reveal possible problem areas in the underlying design of different PV module technologies.

Nine small groups of five identical PV modules were chosen for detailed characterization. This way, it shall be possible to determine the intra-group and inter-group specifics, compare the findings with the literature, and match the results with datasheets, warranty claims, bill of materials as well as production environment. The variability across module types hints at the diversity across the market players and the maturity of specific problem areas. The focus of this paper is on crystalline PV and does not show the results for CIGS and µ-Si devices.

An innovative combination of repeated laboratory measurements and ongoing test field monitoring was chosen to identify how the outdoor behaviour correlates to flasher values at standard test conditions (STC). This approach aims at the relationship between the real life experience and the STC based performance warranties. An important influence for the warranty credibility are the initial conditions of the modules, especially the stabilized power after LID in relation to the nameplate values. The calibration quality of factory flashers is important, because many linear performance warranties start already at 97% of nominal power. It is also interesting whether manufacturers influence the binning strategy depending on the purchase order. Thus, some modules were received directly from manufacturers and others got purchased via a distributor.

2 TEST PROCEDURES

In order to establish the link between STC based module qualification and long term "real life" module operation, both indoor and outdoor measurements need to be performed with a continuously high accuracy. Fraunhofer ISE's CalLab PV Modules is a renowned institution in the field of PV module characterization.

By using primary calibrated reference standards form the Physikalisch Technische Bundesanstalt (PTB), measurements can be traced back to international reference standards. All measuring equipment and measurement procedures are subject to a comprehensive quality management system. The reliability of the results is guaranteed by regular comparisons with other internationally recognized laboratories. The entire CalLab PV Modules is accredited under ISO/IEC 17025.

2.1 Indoor measurements

For each module type, a detailed initial characterization sequence was performed.
Table 1 shows which tests each module was put through in detail. After the initial characterization, the modules were deployed on the outdoor test site. In order to track changes in the modules' behaviour, every six months remeasurements are performed. The related test sequence per module is summarized in Table 2.

The I-V curve measurement at STC is conducted with a class AAA sun simulator according to IEC 60904-9. During the measurement, deviations from STC are smaller than ±5 W/m² respectively ±1 K. To determine the irradiance dependence (the performance at low irradiance), I-V curves are measured at 100 W/m², 250 W/m², 500 W/m², 750 W/m², 1000 W/m², and 1250 W/m² at a temperature of 25 °C. The temperature dependency of a PV module is determined by measuring I-V curves in the range of 25 °C to 75 °C at an irradiance of 1000 W/m². The measurements are carried out in temperature intervals of 1 K. The spatial inhomogeneity of the temperature across the PV module is less than 2 K. These procedures deliver the irradiance and temperature dependency of Isc, Impp, Pmpp, Vmpp, Voc, and FF.

Table 1: Initial characterization.

Test	Standard	# of samples
Visual inspection	IEC 61215-1	4
Wet leakage test	IEC 61215-1	4
STC power	IEC 60904-1	5
Irradiance dependency	IEC 60904-1	5
Temperature coefficient	IEC 60891	2
Spectral response	IEC 60904-8	1
Angular response	IEC 61853-2	1
EL image	n/a	5
Infrared image	n/a	1
Raman Spectroscopy	n/a	1

Table 2: Periodic indoor characterization.

Test	Standard	# of samples
Visual inspection	IEC 61215-1	4
Wet leakage test	IEC 61215-1	4
STC power	IEC 60904-1	5
Irradiance dependency	IEC 60904-1	1
EL image	n/a	5
Infrared image	n/a	1
Raman Spectroscopy	n/a	1

2.2 Outdoor measurements

Fraunhofer ISE operates numerous outdoor test sites under different climatic conditions. While some of them rather remind of outdoor laboratories, the test facility designed here should offer comparable (ideally identical) outdoor operating conditions for all modules under test, and these operating conditions should be very close to those of real PV power plants.

The test installation is situated on a warehouse roof close to the city of Freiburg. There is no public access to the site or the roof, so external influence on the test samples is minimized. Each 4 samples of 9 different module brands and types are mounted on a standard rooftop racking system (Figure 1). In this way, the module operating conditions are similar to those of standard commercial roof top PV power plants. A difference to commercial systems is an increased row-to-row distance in order to minimize mutual shading between the module rows.

Figure 1: View of the test field. Each of the 4 rows carries 9 modules under test. The leftmost modules are additional reference modules provided by Fraunhofer ISE.

The individual modules are operated at their MPP by means of programmable electronic loads. For all modules, IV curves are recorded simultaneously in intervals of 5 minutes. In-plane irradiance and back-of-module temperatures are monitored at the same time, while all other relevant meteorological parameters like ambient temperature, relative humidity and wind speed are recorded as one-minute averages.

The IV curve data is subject to different quality checks and filter procedures, before a number of characteristic values (Isc, Voc, Impp, Vmpp, FF, Rs) are calculated for each validated measurement.

3 MODULES UNDER TEST

Module types were selected based on existing insurance policies and upcoming products eligible for future insurance policies. Initially, the manufacturers were asked to provide samples directly. In a second step, further module types got purchased from the market. In a third step, some modules with the latest PERC and half-cell technology were added. The modules have 60 to 72 cells, packaged in glass-backsheet or glass-glass, and with or without frame. The specific manufacturers will not be disclosed in this contribution. However, the colour code defined in Table 3 is used consistently to identify the different technologies throughout the paper.

Fraunhofer ISE provided an additional set of monocrystalline silicon PV modules in glass-glass packaging. Modules of the same type are in use as stable reference devices at several Fraunhofer ISE test sites and serve for additional tests on the stability and comparability of the data acquisition and processing chain. As these modules were deliberately produced as test devices, they do not bear a label, and there are no rated values of STC power or Tk of power.

From all module types, each 4 samples are operated at the outdoor facility, while module #5 is kept in dark storage. This module serves as reference during the regular indoor measurements.

Table 4 gives the laboratory results of the initial and the 2nd measurement and compares these values to rated values. Most module types are on the lower end or do not meet the stated power tolerances even with the initial measurement. Initial degradation (LID) may be deduced from the difference of both measurements. However, the influence of 6 months of outdoor exposure (from September 2013 to March 2014) adds to the LID.

Rated values of Tk are compared to laboratory measurements in Table 5. Here, roughly half of the module types show better (lower) Tk values than stated in the data sheet.

4 COMPARISON OF INDOOR TO OUTDOOR RESULTS

Outdoor module characterization shall bridge the gap between STC data determined in the laboratory and the life time yield of a PV module. However, a comparison of both types of measurements is a sophisticated task. While there are quite controlled and repeatable conditions when working indoor, outdoor ambient conditions vary throughout day and year, so filtering and data translations become necessary.

Table 3: List of modules under test, sorted according to cell technology and rated power. The colours are used to distinguish the module types in Figures 3, 5, 7, and 9.

#	Technology	Rated power	Tolerance	Colour code
0	mono-Si			
1	poly-Si	255 W	-0/+5 W	
2	poly-Si	255 W	-0/+3 %	
3	poly-Si	250 W	-0/+5 W	
4	poly-Si	240 W	-0/+5 W	
5	mono-Si	260 W	-0/+5 W	
6	mono-Si	245 W	-3/+3 %	
7	mono-Si	235 W	-0/+5 W	
8	a-Si / c-Si	300 W	-0/+3 %	
9	a-Si / c-Si	240 W	-0/+3 %	

Table 4: Comparison of rated power to actual power as determined during the initial characterization (in out-of-box condition) and as determined after 6 months of outdoor exposition. The difference between both measurements may be used as a rough estimation of light induced degradation (LID). All values are averages over 4 test samples.

#	Technology	Rated power	Actual power M0	Actual power M6
0	mono-Si		225.4 W	226.7 W
1	poly-Si	255 W	253.8 W	251.6 W
2	poly-Si	255 W	255.6 W	254.7 W
3	poly-Si	250 W	248.5 W	244.8 W
4	poly-Si	240 W	238.3 W	237.0 W
5	mono-Si	260 W	255.4 W	256.5 W
6	mono-Si	245 W	235.0 W	234.6 W
7	mono-Si	235 W	240.8 W	241.1 W
8	a-Si / c-Si	300 W	295.7 W	296.0 W
9	a-Si / c-Si	240 W	225.8 W	221.3 W

Table 5: Temperature coefficients of module power. Rated values are compared to the results of the initial characterization.

#	Technology	Rated Tk(power)	Actual Tk(power)
0	mono-Si		-0.437 %/K
1	poly-Si	-0.400 %/K	-0.431 %/K
2	poly-Si	-0.409 %/K	-0.426 %/K
3	poly-Si	-0.450 %/K	-0.426 %/K
4	poly-Si	-0.469 %/K	-0.419 %/K
5	mono-Si	-0.420 %/K	-0.443 %/K
6	mono-Si	-0.450 %/K	-0.470 %/K
7	mono-Si	-0.469 %/K	-0.440 %/K
8	a-Si / c-Si	-0.350 %/K	-0.356 %/K
9	a-Si / c-Si	-0.390 %/K	-0.398 %/K

For the first level of module characterization and indoor-outdoor comparison, the (relative) efficiency over irradiance is used. For that purpose, measured values of Pmpp are normalized both with respect to irradiance at STC and nominal module power. Thus, the relative performance of one module at different irradiation levels as well as different modules against each other may be compared. The main influencing effects are treated as follows:

- Module temperature is corrected to STC (25 °C) using the temperature coefficient of power as determined in the laboratory.
- A filter is applied to consider incidence angles in a range where module response is relatively close to the ideal cosine behaviour.
- Spectral effects are eliminated by determining the effective irradiance from Isc: Geff = k Isc, where k is determined from the indoor STC measurement under standard spectral conditions.

The resulting data is binned into bins of 25 W/m² width, and a mean value is calculated for each bin. Since this representation does not allow for an analysis over time, each measurement period of 6 months is lumped together and assessed separately. Indoor data hence are the averages of the measurements before and after that period. For a single module, results are shown exemplarily in Figure 2. Here, the indoor measurements (including error bars) are plotted as well. Indoor and outdoor data show only minor deviations that generally lie within the measurement uncertainty.

The same procedure was applied to all module types; the result is shown in Figure 3. Again, all data are normalized to an efficiency of 1 at 1000 W/m². All modules show higher efficiencies at irradiance levels between 400 W/m² and 1000 W/m². Below 400 W/m², 4 module types show a particularly low efficiency, while the others still reach 90% of STC efficiency even down to 50 W/m².

5 SEASONAL AND LONG TERM BEHAVIOUR

To investigate the long term behaviour of PV modules, the self-reference of effective irradiance to Isc is not possible any more, as long term changes in Isc would be masked by this approach. Therefore, a more complex filtering and correction procedure is applied:

- Each IV curve is translated to the closest of the following selected conditions: 250, 500, 750 and 1000 W/m² at 25°C. These are chosen to match the laboratory conditions in temperature and level of irradiance. The necessary parameters to perform curve translation are determined from laboratory measurements.
- Curve translation is performed according to IEC 60891 Ed. 2, procedure 1.
- The data is filtered to include only points with irradiance values that are within ±50 W/m² of the target irradiances.
- Monthly mean values of relevant parameters such as maximum power (Pmax), open circuit voltage (Voc), short circuit current (Isc), fill factor (FF) and series resistance (Rs) are calculated, provided that after statistical removal of outliers at least 10 data points are left.

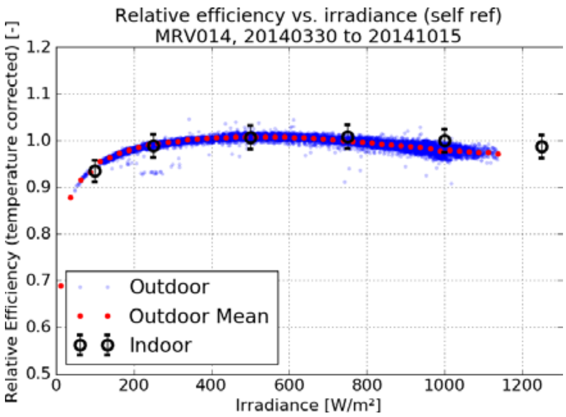

Figure 2: Exemplary comparison of outdoor to indoor measurement results for a period of 6 months. Blue dots denote normalized efficiency values for each 5 min interval, red dots are averages in bins of 25 W/m², black circles and error bars denote indoor measurements (averaged from both measurements before and after the 6 months period).

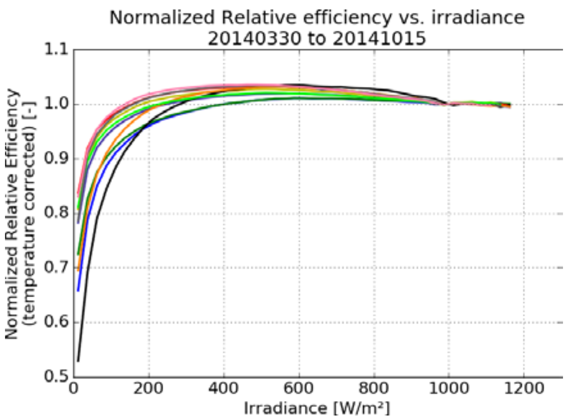

Figure 3: Dependency of module efficiency on irradiance for all module types as derived from outdoor measurements over a 6 months period. Each curve gives the mean value of the 4 test samples. The key to colour codes of the module types is given in Table 3.

To assess module stability over time, the behaviour of key parameters is investigated under the conditions defined above. Again, we show exemplarily results for a single module first. Figure 4 depicts the temporal development of Isc, Voc, and Pmpp. Compared to Figure 2, there is more scattering visible with single values due to higher uncertainty in the translation procedures and due to remaining spectral effects.

To compare the long term behaviour of all module types, plots of translated Pmpp were generated as well for each module and each of the 4 irradiation levels. Plotted data were normalized to the corresponding first valid monthly mean value. Figure 5 shows the plot for all module types at 750 W/m². After 5 years of outdoor exposure (from September 2013 to September 2018), some modules show no change in performance, while others lost up to 5% of power. This corresponds to degradation rates between 0 %/a and 1 %/a.

These findings are specific for a given module type. The variance between the 4 samples of one module type is much smaller than between different module types, as Figure 6 shows for one example.

Initial degradation (LID) is not visible in these plots, mainly due to scaling, but also due to a late start of data acquisition in some cases. A table with observed changes from the beginning to the end of the first period of 6 months is given in Section 3.

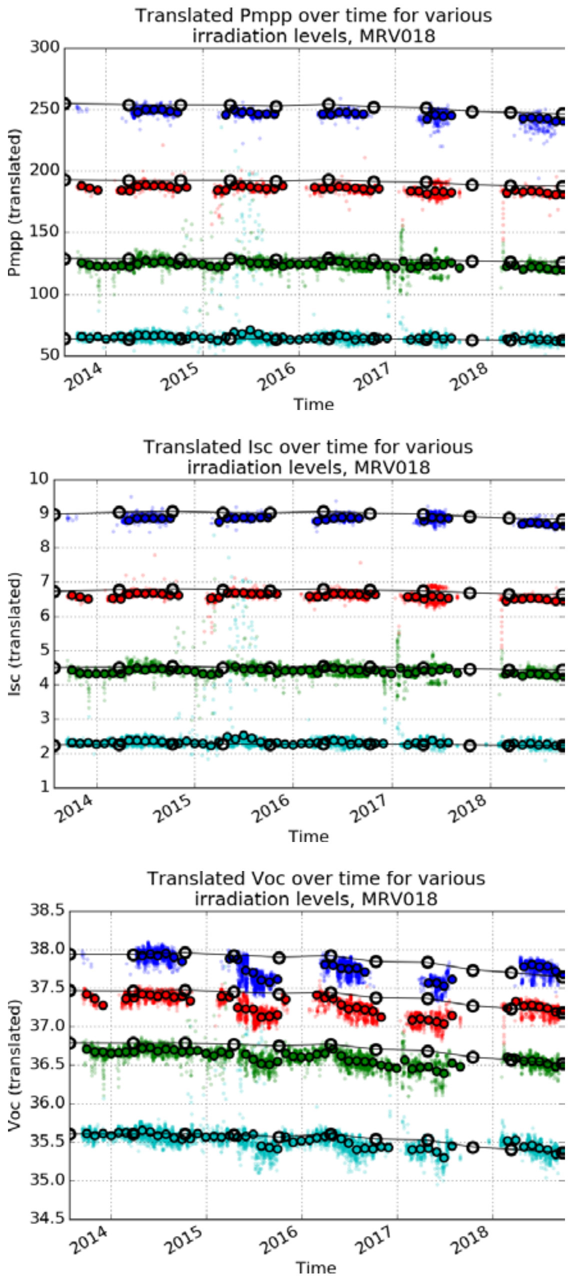

Figure 4: Example for the development of characteristic module parameters over time. The coloured dots present Pmpp, Isc, and Voc for 4 bins (1000 W/m², 750 W/m², 500 W/m², 250 W/m²) as explained in the main text. The black circles denote the results of the indoor measurements.

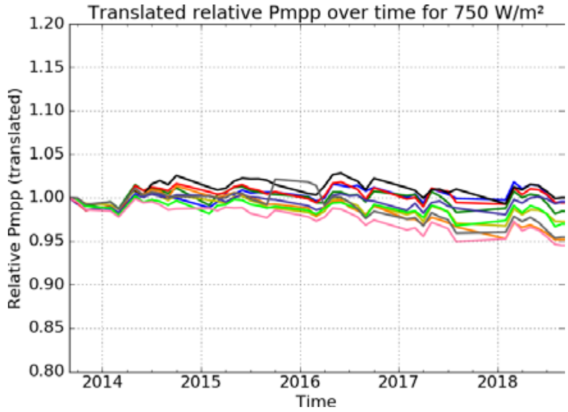

Figure 5: Development of Pmpp in the 750/m² bin for all module types over time. The plot shows Pmpp normalized to the initial value. Each curve represents the mean value of the 4 test samples.

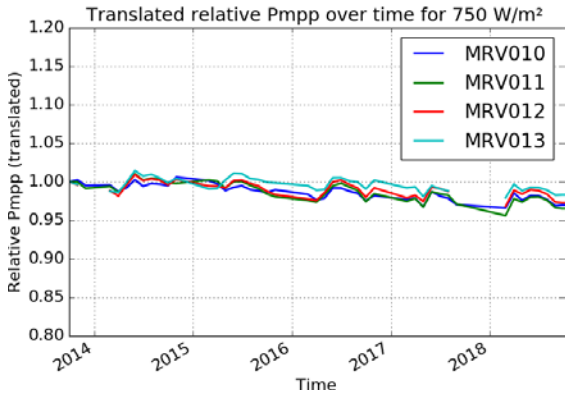

Figure 6: Exemplary comparison of the 4 test samples of one module type. As in Figure 5, the development of Pmpp in the 750 W/m² bin over time is shown.

In a final step, we proceed from module characterization in terms of key values like Isc or Pmpp towards their long term yield. As the development over a certain time is of interest, the cumulative specific yield is used as measure here. Specific yield values (reported in kWh/kWp) may be related to module power as stated in the data sheet, to module power according to the initial characterization, or to module power according to the second characterization, which is closer to a stabilized value. Within this contribution, we refer module yield to the data sheet specifications, as rated power is still determining module prices.

For the 4 years period from October 2014 to September 2018, cumulative specific yield is shown for all module types in Figure 7 and for the 4 samples on one module type in Figure 8. For the site of Freiburg, typically yields of more than 1000 kWh/kWp would be expected. In our case, this margin is not reached by most module types. One reason are the interruptions of outdoor exposure during the laboratory measurements, taking around 10 days each time. Another reason is the necessary data filtering in order to achieve a fair comparison. As soon as one module sample out of the whole batch is not measured correctly, this period of time is excluded from the evaluation. This lead to a rather large gap in fall and winter 2017, as several IV curve tracers suffered from uncorrelated individual technical problems.

Obviously, there are clear differences in annual yield between the different module types under investigation (Figure 7), while the 4 test samples of one type stay close together (Figure 8). If the ratio between the different yield curves would be constant on an annual basis, this may be explained with constant offsets of actual power from rated power (due to offsets from specifications and to LID). If seasonal changes could be observed in this ratio, effects of operating temperature, angle of incidence and of solar spectrum differentiate one module type from another. Low-light behaviour, in turn, is partially seasonal and partially random. Finally, if the ratio between the cumulative yield curves changes over the years, long term degradation of module power plays a role.

All these effects may be seen in Figure 9, where the module with the highest specific yield is taken as the baseline for a comparison of cumulative yield.

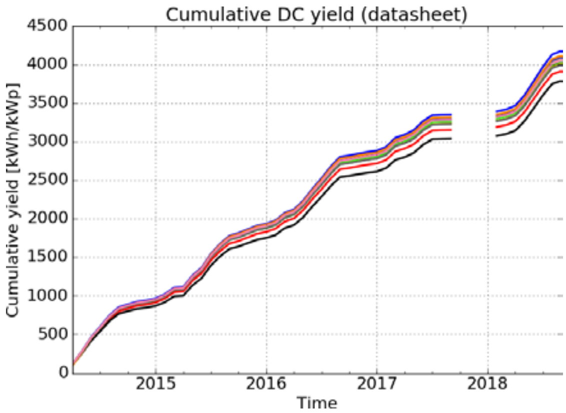

Figure 7: Cumulative specific yield (related to data sheet specifications) for each module type. Each curve represents the mean value of the 4 test samples. There are several months in spring and fall with almost no yield in this plot. These are the times when the modules were dismounted for laboratory characterization. The large gap at the end of 2017 results from measurement problems with individual modules, thus preventing a fair comparison of all module types for this period.

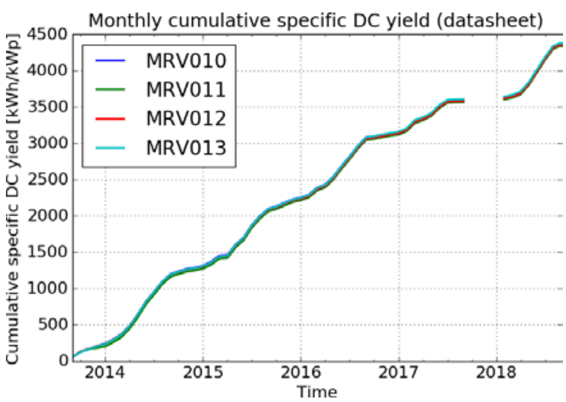

Figure 8: Exemplary comparison of the 4 test samples of one module type. As in Figure 7, the cumulative specific yield (related to data sheet specifications) is shown.

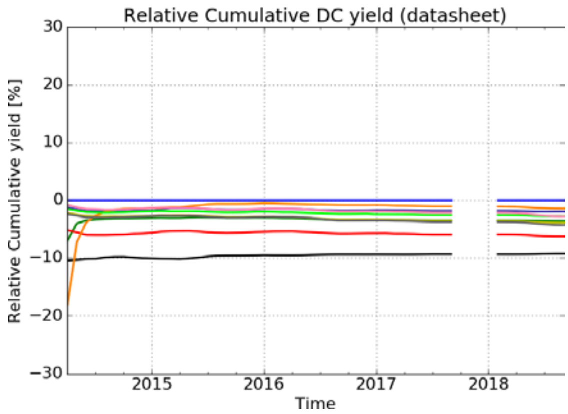

Figure 9: Relative cumulative specific yield (related to data sheet specifications) for each module type. Each curve represents the mean value of the 4 test samples. This plot relates the cumulative specific yield of each module type to the cumulative specific yield of the best performing module type. When lines are not parallel in this presentation, modules change their behaviour over time.

6 RESULTS OF TECHNICAL INVESTIGATIONS

Regarding the changes in power output (and Isc, Voc, and FF) over time, a clear ranking of the major influences is visible after the first 5 years of exposition:

A deviation from rated values as given in the data sheet has the biggest influence on long term yield of a specific module. If there is 3% less STC power right at the beginning of a module's life time, the overall output will be proportionally lower as well.

Initial degradation (also called light induced degradation) has a similar, but in this study slightly smaller effect. Each percent of module power lost in the first weeks of operation will be lost for the full life time of the product.

Then, differences in cell and module technology are next in the ranking: low light behaviour, angular response and spectral response may help some products to perform better than others. The difference in performance might change with the seasons, dependent on the varying influence of these effects.

Finally, long term degradation may cause different life time yields, as this (typically small) effect will increase differences in module characteristics with time. From Figure 5, degradation rates between 0 %/a and 1 %/a may be deduced.

For most module types, the variation between the four test samples was much smaller than between the different types. Thus, our investigations allow for a meaningful comparison of different module types. A generalization to PV technologies is not possible, since our sample of module types may not be representative for the PV market. However, the study allowed collecting valuable input parameters for improved risk assessment.

7 RISK ASSESSMENT

Based on the results, it is possible to evaluate the existing risk portfolio aggregating all warranty insurance policies with better accuracy. The risk of error inherited from the reliability and durability modelling can be reduced. The assessment of individual module types as well as the correlation across the brands can now be based on real life data which is directly related to the insured warranties.

The weaknesses identified in this study are a basis for improved product qualification and especially monitoring of factory flasher operations and calibration. No additional requirements for qualification testing were identified beyond the list mentioned in chapter 1.

While the performance warranty promises are getting more and more ambitious, the underwriting of future insurance policies needs to consider the achievement of an ever tougher production stability, and a proper alignment of tolerances in the specifications. The findings show that solar projects should always do a precise power verification of their shipments to have a proof in case of warranty claims that their modules initially performed well and no over-rated modules were accepted.

The fast dynamics in the PV industry bringing up new production methods, cell designs, and encapsulation materials, requires transferring the findings from the reviewed modules, being produced some years ago, to the current state-of-the-art setup. Some weaknesses identified in older modules might be solved nowadays while other issues are introduced.

Beyond the results shown in this paper, the study also revealed that modules based on thin-film or hybrid technologies are more difficult to assess because they do not achieve the homogeneity and conformity as currently observed in c-Si production batches.

OUTLOOK

The data acquired during the (ongoing) measurement campaign still offers great opportunities to learn more about long term PV module behaviour and the predictability of module operation.

As far as we can state up to now, there is no or only a marginal correlation between conspicuous features seen during the optical inspection or the electroluminescence imaging and a module's 5-years yield. Anyhow, these features deliver hints on production quality. Whether such results from the initial characterization may also correlate with differences in life time yield will be topic of another contribution.

In a similar way, results from the Raman spectroscopy of the encapsulants, carried out in regular intervals for each module type, may be correlated to long term behaviour in a later contribution.

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