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RESEARCH ARTICLE

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Statistical analysis of 12 years of standardized accelerated aging in photovoltaic-module certification tests

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Abstract

Accelerated aging tests according to international standards (IEC 61215 and IEC 61730) have been used for many years to investigate photovoltaic (PV) module reliability. In this publication, we share a thorough analysis of the tests that were acquired over a time span of 12 years across a wide range of technologies and module generations. The results can serve as a valuable reference to evaluate the reliability of module types and prototypes beyond the use of standardized pass/fail criteria. Furthermore, this work can contribute to ongoing revisions of these standards. In more technical depth, we share the failure rates of different accelerated aging tests. We further discuss trends that are apparent over the investigated decade and reveal which test sequences have become the most relevant to differentiate different PV module types in terms of reliability.

KEYWORDS
accelerated aging, certification, PV modules, reliability, standardization

1 | INTRODUCTION

Photovoltaic (PV) module reliability is a major factor for PV module sustainability and bankability.[1] The reliability is typically verified by accelerated aging tests as defined in the certification standards IEC 61730[2] and IEC 61215.[3] While IEC 61730 focuses on electrical safety, IEC 61215 represents the most important reference for performance and quality. Because the PV module market is very dynamic, constant improvement and adaptation of available standards is necessary. Furthermore, new standards and test specifications are created for the detection of new failure modes, which are observed as new technologies on cell and module level appear on the market. Consequently, test procedures are improved by standardization committees in the form of revised standards with time.

Practically every new technology on cell and on module level is being tested by accelerated aging tests according to or at least based on IEC 61730 and IEC 61215. This underlines the importance to understand these tests and the obtained results in order to correctly evaluate the reliability of new technologies. Despite the certification of practically every PV module type on the market, an astonishingly high fraction of modules on the field are subject to failures.[4,5] This could be rooted in either (a) an overestimation of the expressiveness of certification test results, that is, the misconception that a pass of the test criteria attest the absence of major power degradation over the whole module lifetime, which could lead to insufficient further lifetime tests. On the other hand, (b) the adaptation of test procedures tends to lag behind the introduction of new technological trends. The mere pass of certification tests is not necessarily sufficient to guarantee the reliability of a PV module type over the promised lifetime.

Since 2006, PV modules have been tested in the accredited (ISO 17025) TestLab PV modules at Fraunhofer ISE. The most important procedures for the tests are specified in IEC 61215 and IEC 61730, whose major pass/fail criteria concern stability of power and safety characteristics upon several stress treatments; that is, the power loss must be less than 5% plus measurement uncertainty. Because the measurement uncertainty is applied for the benefit of the customer, the low uncertainty of only 1.1% at the CalLab PV Modules of Fraunhofer ISE leads to a relatively high failure rate compared with other labs.[6] Furthermore, the modules' electrical insulation properties at dry and wet conditions must continuously lie above minimum requirements and visible changes through accelerated aging shall not indicate safety risks and are evaluated upon clear criteria. A more detailed description can be found elsewhere.[2,3]

Statistics of standardized accelerated aging tests on PV modules have been published a decade ago from a smaller dataset.[7] In this publication, we share a thorough analysis of the results of standardized accelerated aging tests that were acquired over 12 years from 2008 to 2019 across a wide technologies and module generations. The results can serve as a valuable reference to evaluate the reliability of module types and prototypes beyond the use of standardized pass/fail criteria. Furthermore, we discuss the effect of the 2016 revisions of both standards as well as general trends that we observed over the years. The question if the general quality of PV modules has improved over time is discussed and possibilities for the underlying reasons are given.

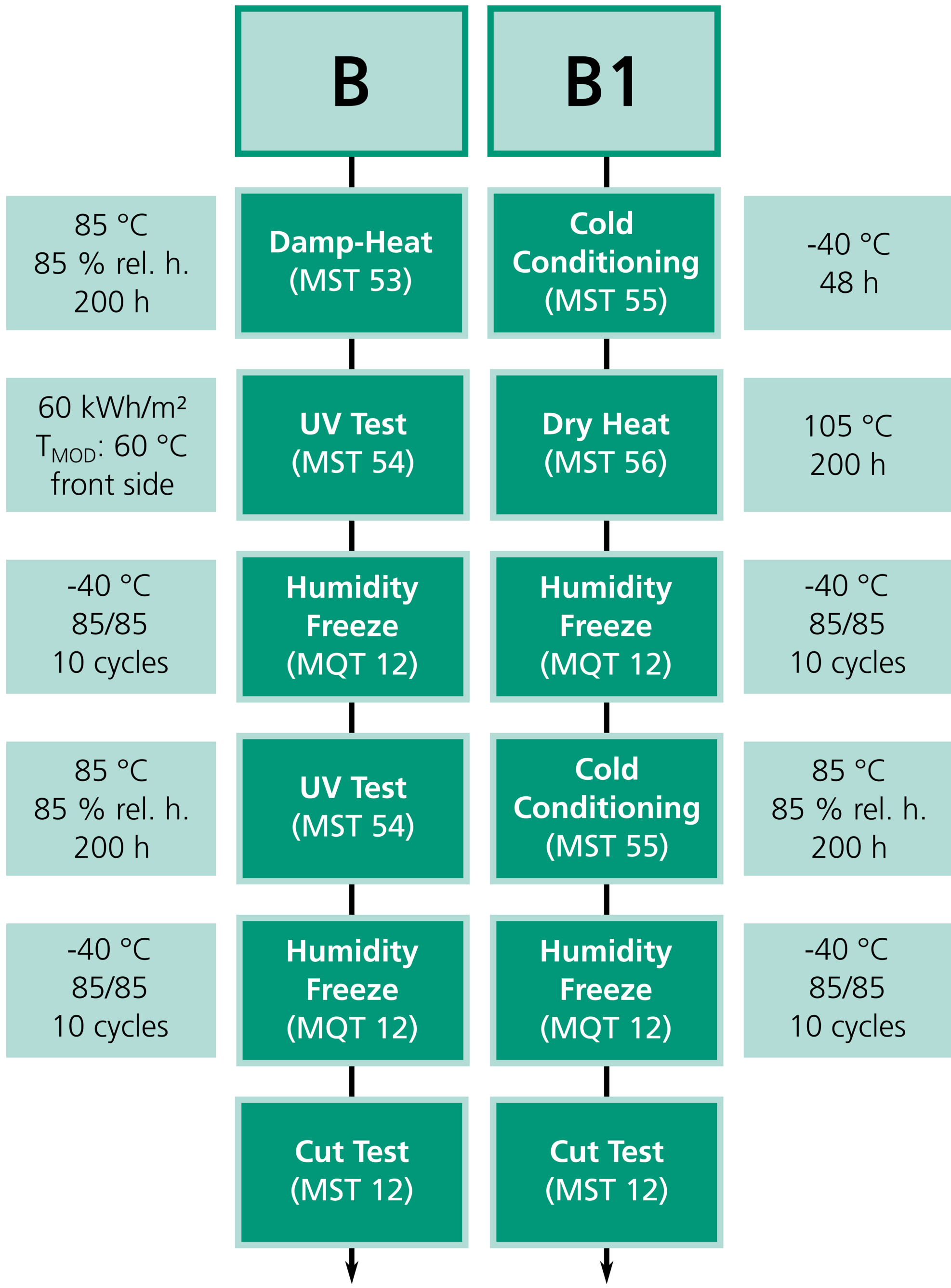

FIGURE 1 Test scheme as summary of combined Sequences B and B1 from IEC 61730-2016

In more technical depth, we share the failure rates of different accelerated aging sequences taken from these standards and discuss the weaknesses and specific failure modes that the respective tests address. We further discuss trends that are apparent over the investigated decade and reveal which test sequences provoke the greatest failures within the test program and which tests are passed by almost all module types in certification testing.

2 | EXPERIMENTAL

For the certification testing according to IEC 61730 and 61215, a set of modules of the respective design must be exposed to several test sequences, each of which contain one more stress tests that are accompanied by characterization measurements like IV characteristics, visual inspection, and electrical insulation. The test sequences are referred to with letters such as IEC 61215 sequence A, B, or C. In the following work, we refer to this nomenclature only for multistress sequences (two or more stress tests done sequentially). For stress sequences with only single tests, we directly refer to abbreviations of the respective test—for example, DH1000 for a damp-heat 1000-h exposure at 85°C, 85% rel. hum. TC200 specifies 200 cycles of thermal cycling between −40/+85°C. Sequence C is a sequential test of UV irradiation, thermal cycling, and humidity-freeze. Sequences B and B1 are sequential tests as described in Figure 1. Table 1 provides an overview of all discussed stress tests respectively test sequences together with the abbreviations used in this evaluation.

According to the respective standards, Sequences B and B1 are carried out on one module. DH1000, TC200, and Sequence C tests are performed on two modules each. The mechanical load (ML) test is performed on one module after the DH1000 test.

The statistical analysis was done using python version 3.8 and the pandas package version 1.1.[8]

TABLE 1 Discussed reliability test sequences

Abbreviation	Test sequence
Sequence C	Sequence C, IEC 61215-2
DH1000	MQT 13, IEC 61215-2
ML	MQT 16, IEC 61215-2
Sequence B	Sequence B, IEC 61730-2
Sequence B1	Sequence B1, IEC 61730-2
TC200	MQT 11, IEC 61215-2

TABLE 2 Discussed characterization tests

Abbreviation	Characterization test
Dry insulation test	MST 16, IEC 61730-2
Visual inspection	MQT 01, IEC 61215-2
Wet leakage	MQT 15, IEC 61215-2

2.1 | Data set

This publication discusses data from accelerated aging tests and characterization tests of PV modules acquired over a time span of 12 years (2008–2019). This accounts for a total of 4653 modules, representing 756 different module types/products from 95 different manufacturers, mainly from Europe and Asia. This analysis excludes thin-film technologies and focuses on crystalline silicon PV (c-Si). The distribution of mono- and poly-Si over the discussed time frame is shown in Figure 2. While the majority of modules rely on poly-Si cells, recent years have seen a rise of mono-Si technology, which corresponds well with other observations of the PV market.[1,9]

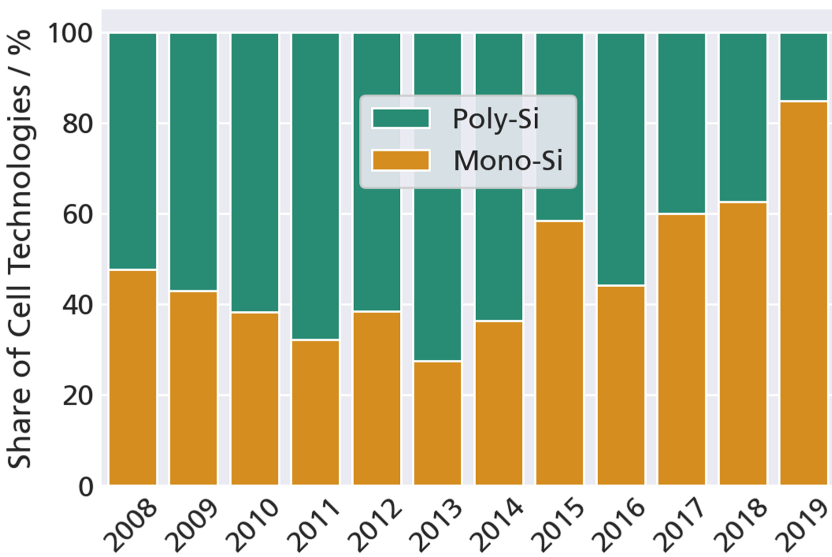

FIGURE 2 Share of mono and poly cells in tested modules

3 | RESULTS

3.1 | Old versus new standard

In 2016, a rework of both relevant international standards (IEC 61215 and IEC 61730) was published as a reaction to experiences in accelerated testing and the progressing technologies, especially on cell and connection level. It introduced several alterations to the test procedures and evaluation. The main differences in the context of this publication include (a) the introduction of two new test sequences with combined stress factors; (b) a more thorough initial characterization and longer stabilization (Gate 1) including the verification of label values; (c) changes in the current injection profile the TC200 test; (d) adaptions of the parameters in the ML test: a defined load is applied three times subsequently in the new version of the standard, whereas the old standard allowed to increase the load to 5400 Pa only in the last test cycle; and finally, (e) the applicability of the pass/fail criteria of 5% power loss over complete test sequences instead of individual tests. The latter point was relevant, for example, in the case of the DH1000 test followed by ML: While the 2005 version of IEC 61215 required a power (P_{MPP}) degradation of less than 5% for the individual tests, respectively, and 8% over both tests, the 2016 version applies the criterion of less than 5% after the whole sequence. We will therefore consistently apply the 5% criterion throughout this paper for better comparison.

Figure 3 shows the distribution of the P_{MPP} degradation after three different accelerated aging tests, which were performed according to the old (pre-2016) and new (post-2016) versions of the IEC standard. In all three cases, the distribution of power degradation is relatively similar for modules tested according to the two standards. The largest difference between standards can be observed for the DH1000 test, where the median P_{MPP} degradation is −0.04% and −1.33% for old and new standard, respectively, although the test procedure was not altered in the 2016 revision except for a longer stabilization before the test. This suggests that technological changes in the cell and module could be responsible for this trend. Another remarkable result is that no effect of the current injection during the heating phase of the TC200 test can be observed from the comparison in Figure 3. For the ML test, only tests with a maximum load of 5400 Pa were considered in this comparison. No clear trend can be observed. However, it has to be remarked that the last years have seen technological trends, such as larger modules (>180 cm) and thinner frames, so that it cannot be resolved to what extend the power loss is caused by the revised ML test procedure. These latter aspects are subject of ongoing investigations.

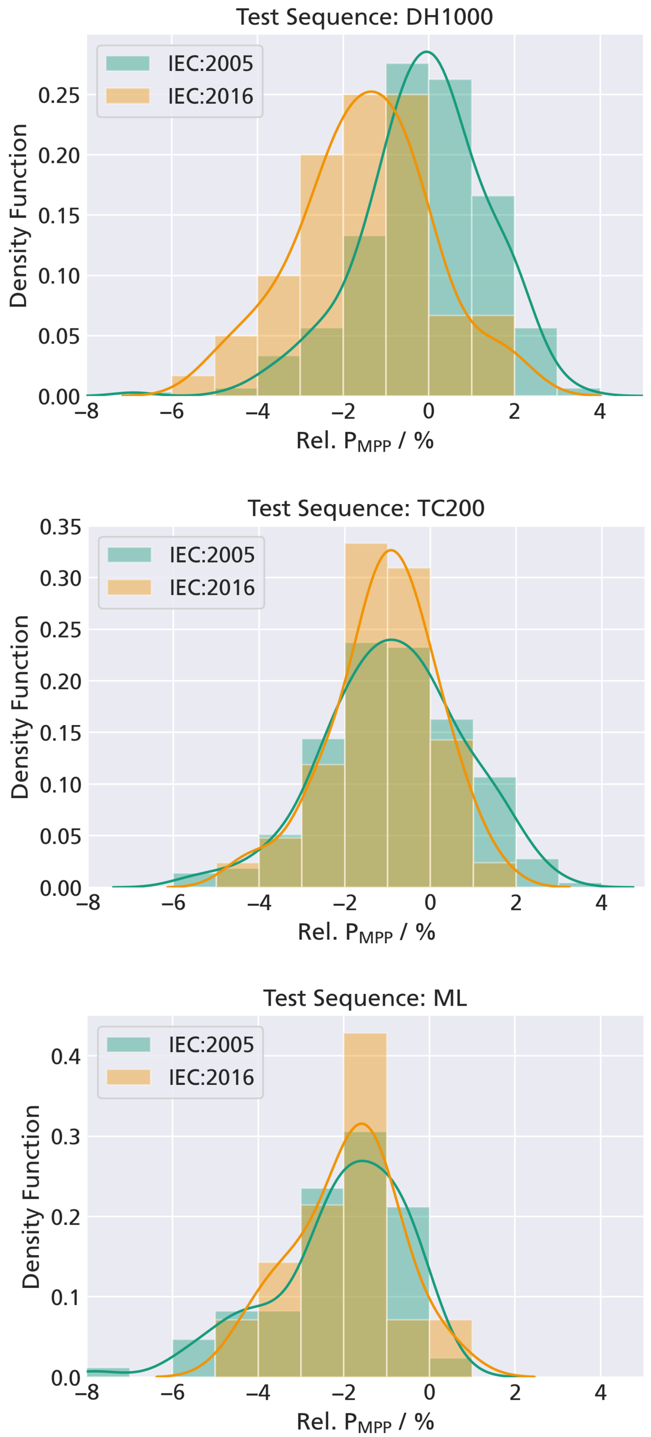

FIGURE 3 Comparison of aging tests according to IEC 61215:2005 ("old standard") and IEC 61215:2016 ("new standard")

3.2 | Standard test overview

Over the investigated time span, a large number of modules was subjected to different standardized aging tests and power measurements at standard conditions were conducted before and after, according to IEC 61215-2 MQT02. The distribution of the relative differences between the respective MPP powers is shown in Figure 4. Additionally, for each stress test, the power degradation is correlated to the IV curve parameters (I_{SC}, V_{OC}, FF). The colored area around the respective regression lines represents the 90% confidence interval.

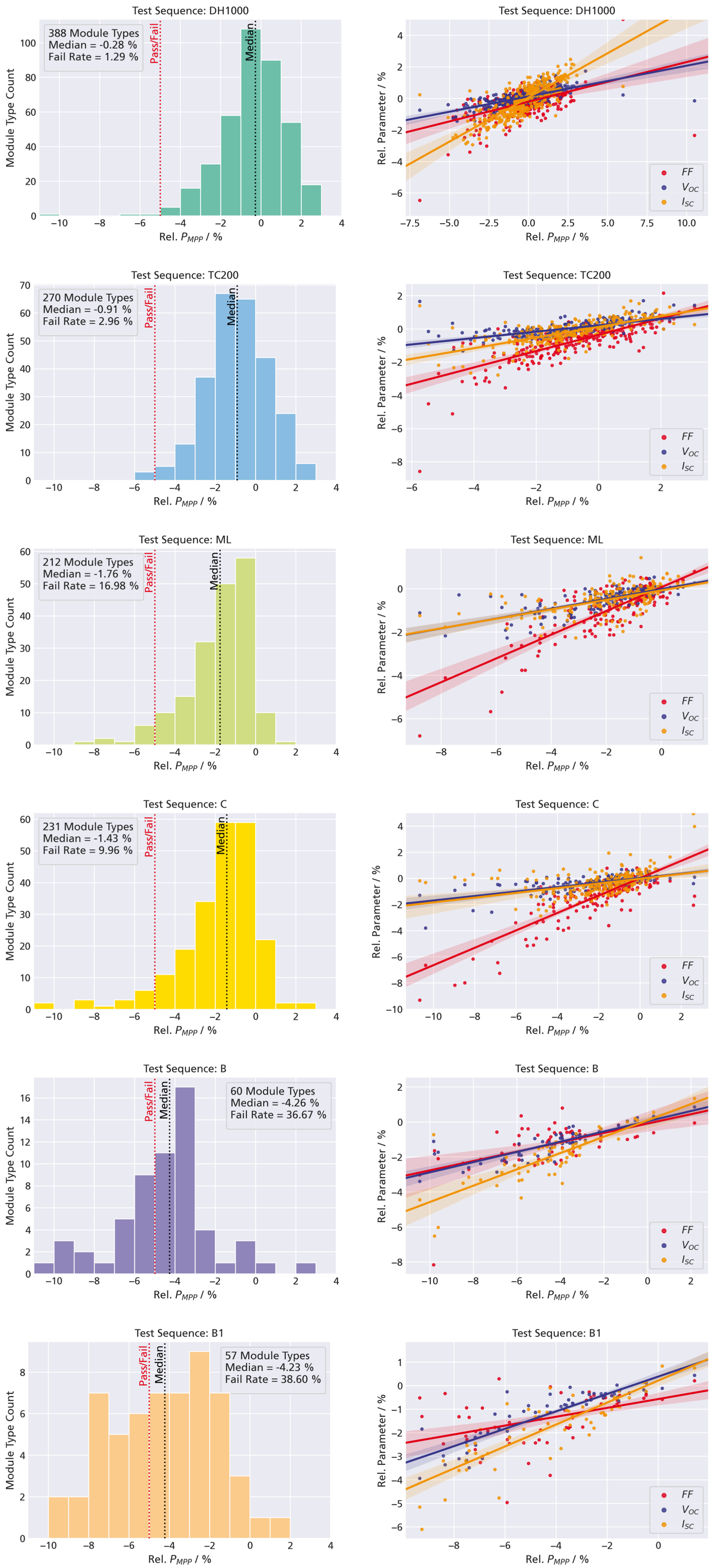

FIGURE 4 Left: Distribution of power degradation after accelerated aging tests. Right: Correlation of the power degradation with different IV curve parameters. In module certification, the indicated pass/fail criterion for Sequences B and B1 is not applied according to IEC 61730-2-2016; the pass/fail rate is only given to allow a comparison

In case of DH1000, 788 different modules corresponding to 388 module types were tested (Figure 4, top). Out of the IV characteristics, the I_{SC} shows the best correlation with the P_{MPP} degradation, which can be explained by the discoloration of the encapsulant as a common failure mechanism that is driven by high temperatures and humidity ingress into the module. Another typical failure mechanism caused by DH is an *FF*-reduction due to the corrosion of cells and connectors,[10] which is also observed, but significantly weaker because (a) this failure usually requires more than 1000 h of aging time and (b) it often appears in conjunction with the aforementioned encapsulant discoloration.

The strikingly low median relative degradation of −0.28% and a fail rate (below −5%) of only 1.29% can be explained by different reasons: First, this aging test is among the most well known for PV modules,[11] and it can therefore be assumed that most module types for which certification is attempted have already gone through the DH1000 test during the development process. As will be shown, a decreasing failure rate over the last years (see Figure 8) confirms this assumption. Second, a high number (13.9%) of modules show a positive change of P_{MPP} after DH1000. In recent years, the introduction of new cell technologies such as PERC has increased the relevance of so-called meta-stable states that affect the module performance, which can be caused, for example, by light and temperature, such as LID,[12] LeTID,[13,14] and others.[15] A detailed discussion of such effects exceeds the scope of this work, but due to the light soaking in the initial "gate 1" stage before the aging test, modules might reside in such a meta-stable state before the aging and can change its meta-stable state due to the elevated temperature applied during the aging test. This additional effect can lead to the apparent "performance gain" after aging tests such as DH1000 and TC200 (Figure 4).[16]

The TC200 test shows a similar relative performance distribution as DH1000. With an overall failure rate of only 2.96%, it seems likely that the same reasons apply as for the DH1000 test. The strong correlation between power degradation and *FF* decline points to an increased series resistances as a consequence of the thermomechanical stress on the cell connectors as a main driving factor.[17] Considering only those modules with a positive power deviation after TC200 (Figure 5), this negative *FF* effect is still observable, which supports the assumption that a second, independent mechanism, such as the discussed meta-stability, is responsible for the increase in P_{MPP}.

The absence in elevated temperatures of the ML test coincides with a strongly reduced fraction of modules with a positive power deviation after the aging test, further supporting the assumption that the positive power deviation is partly caused by elevated temperature. Similar to TC200, the power degradation correlates with a decrease in *FF*, pointing to a negative influence of the cell connection as major issue. Compared with DH1000 and TC200 tests, the ML failure rate of 17.5% is significantly higher.

The following diagrams in Figure 4 depict test sequences that combine different stress tests. The so-called Sequence C is part of the PV module certification already since the 2005 version of the IEC 61215 standard and combines a UV preconditioning with an irradiation of 15 kWh/m^2, a TC50 test (50 cycles −40/+85°C) and 10 humidity freeze cycles (HF10). The individual tests are rather short and represent a small amount of environmental stress or example, a UV irradiation 15 kWh/m^2 only corresponds to approximately three summer months in a typical moderate climate, neglecting temperature effects.[18] However, a failure rate of 10%, most likely due to the combination of several aging factors, attests a high relevance of this sequence.

Additionally to the well-known standardized tests, IEC 61730:2016 introduced the combined stress test Sequences "B" and "B1." These interesting sequences also combine a variety of tests sequentially but are significantly longer than sequence C. While Sequence B focuses mainly on the effect of humidity and UV irradiation, Sequence B1 combines different temperature and humidity stress factors.

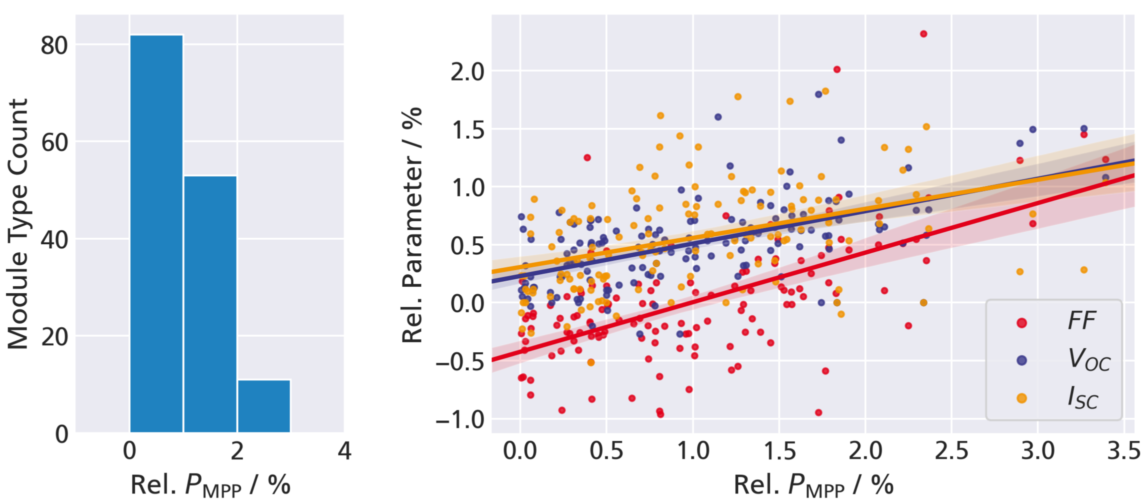

FIGURE 5 Analysis of modules with positive power deviation after TC200. Left: Distribution of relative P_{MPP} degradation; right: correlation of the power degradation with different IV curve parameters

The distributions of relative power degradation of Sequences B and B1 show a significantly lower median around −4.5% and a much stronger degradation compared with the aforementioned aging tests and sequences according to IEC 61215-2. Because both sequences are not part of IEC 61215 but of the mandatory safety standard IEC 61730, which focuses more on module safety than performance, the 5% pass/fail criterion for P_{MPP} degradation is not applied for certification, except for an intact IV curve without kinks. It can, however, still be used to benchmark different module types in terms of reliability. In this case, an imaginary failure rate of around one third shows that these sequences are especially relevant and can be in many cases more helpful to identify less reliable module types than test sequences from IEC 61215. The correlation with IV characteristics is strongest for I_{SC}, but no clear single degradation mechanism can be deduced for any of the two sequences due to the different stress factors applied during the tests.

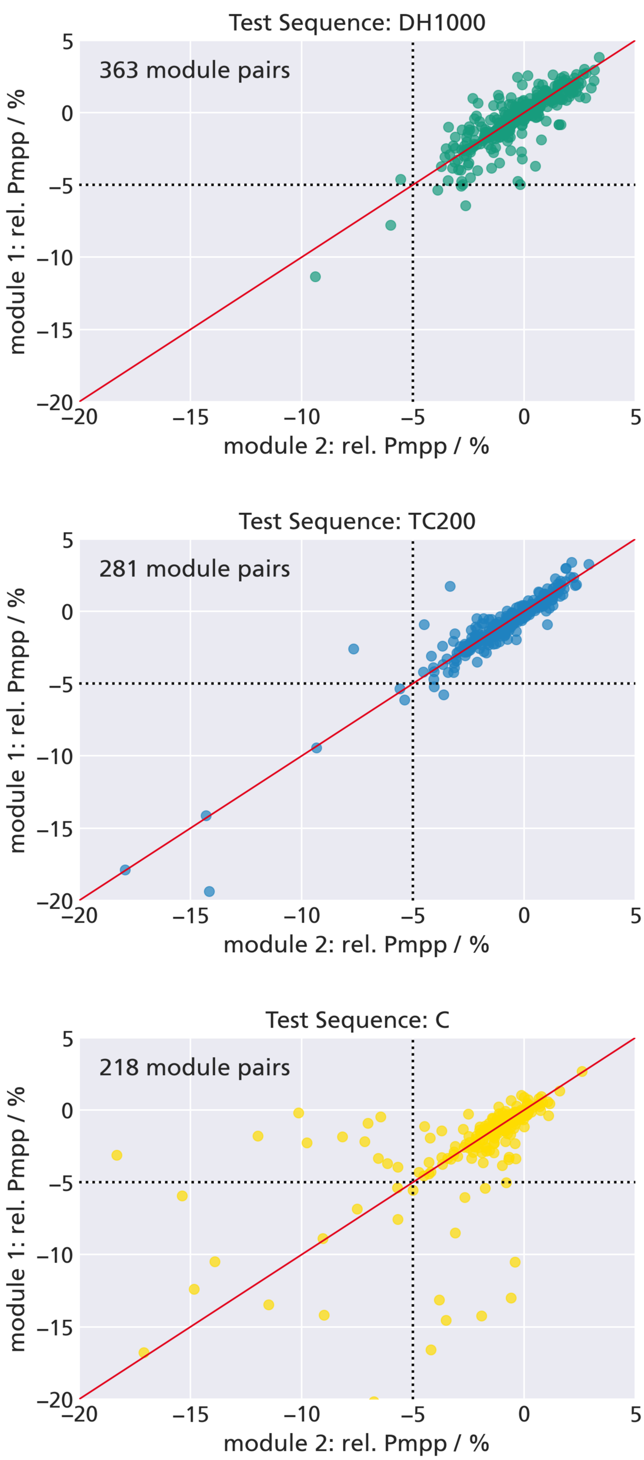

FIGURE 6 Correlation between two modules of the same type in accelerated aging tests

3.3 | Reproducibility of aging tests

The quantity of modules for each test sequence is a frequently considered topic in the certification committee. The aging tests DH1000, TC200, and Sequence C are each carried out on two modules of the same type, respectively. Other tests e.g. hot-spot, ML, as well as Sequence B and B1 are typically performed only on one sample. A visualization of the statistical difference between the two tested modules is shown for 363 module pairs for the DH1000 test (Figure 6, top). Out of these, 2.5% of the pairs (i.e., module types) failed the test criteria of 5% P_{MPP} degradation. (Note: The difference to the previously presented failure rate of 1.29% [Figure 4] stems from the consideration of module type averages in that figure.) The median deviation of two modules after DH is 1.26% and the deviation of 95% of all module types lies below 2.37% (Table 3). Out of the failed module types, in most cases (77%), only one module failed the criteria. The TC200 test gives a similar picture, where out of 281 module pairs, 4.6% pairs fail, of which 46.0% only show one module below the pass/fail limit. One reason for this seemingly high fraction of cases, where one module of a pair lies above the pass/fail limit and one below is the low absolute number of failed module pairs. On the other hand, this sequence is a combination of three individual tests that could add up, out of which in particular the UV test exhibits possible error sources such as differences in irradiance and module temperature. However, most module pairs (98.5%) lie together, either above or below the pass/fail threshold.

For Sequence C, in 17.4% out of 218 module pairs, at least one module failed the criteria. In 57.9% of these, only one module failed.

TABLE 3 Mean deviation and 95th percentile of the relative power degradation of two modules of the same type after aging tests

	Mean deviation (%)	95th percentile (%)
DH1000	1.26	2.37
TC200	1.09	1.32
Sequence C	1.76	9.98

3.4 | Failure rates

Figure 7 summarizes the failure rates of different accelerated aging tests and sequences, as discussed above. In contrast to the data shown in Figure 4, these data include fails due to power degradation as well as insulation tests and visual inspections. In case of Sequences B and B1, the 5% power criterion was applied, although it is not required by the standard. Figure 8 further breaks down these data and illustrates the development of failure rates of various tests over the years.

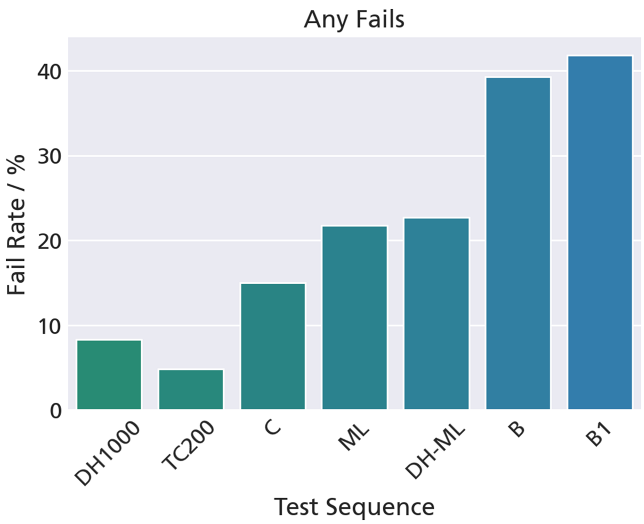

FIGURE 7 Failure rate for different aging sequences. Criteria: P_{MPP} degradation, visual inspection, insulation, and wet leakage test

The failure rates of DH1000, TC200, and Sequence C show a decreasing trend over the years. Since these tests are among the most common and well-known accelerated aging tests, this could be due to wide-spread testing during module development, resulting in a lower number of failures in certification tests. The ML shows a similar trend in the years 2008–2013 but is on the rise again since 2014. Reasons for this could be the recent trend towards larger modules with thinner frames or glass–glass modules without frames. Furthermore, it has to be mentioned that due to the changes published in IEC 61215-2:2016 discussed above, the applied pressures during the tests can be generally higher, which is not resolved in this comparison.

A comparison of failure rates for the different pass/fail criteria for power degradation, visual inspection, dry insulation, and wet leakage tests is shown in Figure 9. It becomes clear that the relevance of the criteria varies strongly for the different aging tests. As discussed above, the Gate 2 criterion for power degradation is hardly relevant for DH1000 testing, but the failure rate is higher for combined tests

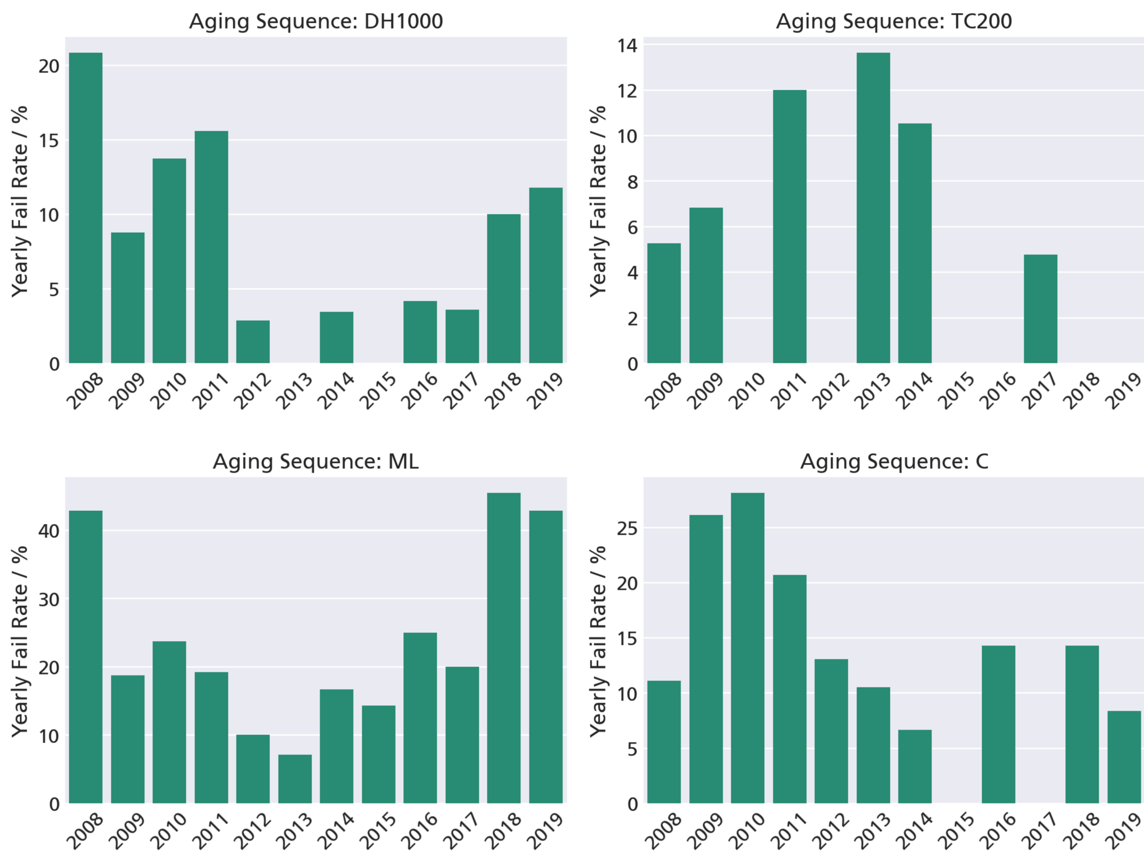

FIGURE 8 Failure rates of test sequences over the years. The rate indicates module types that fail at least one criterion of IEC 61730 or IEC 61215: (power degradation, visual, or insulation)

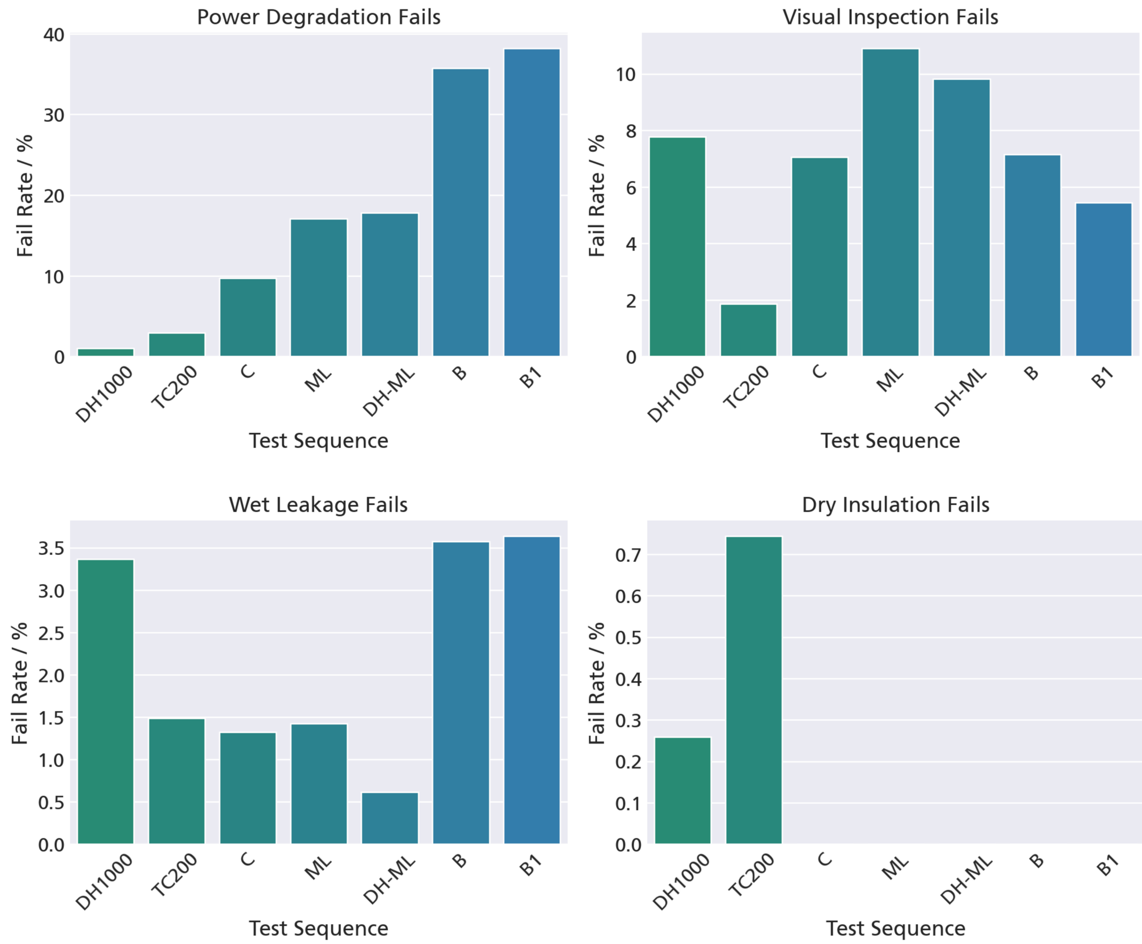

FIGURE 9 Failure rate of various criteria for different test sequences from IEC 61215 and IEC 61730. Power fail rates for the B and B1 sequences do not officially apply in the certification. A power loss of 5% is assumed here for comparison to the other tests

such as Sequence C, combined DH-ML, or Sequences B and B1. Visual failure rates lie between 5.5% and 7.5% for most test sequences except for TC200, which shows a much smaller rate around 2%. Wet leakage fail rates are below 4% for all test sequences, and out of these highest for DH1000 and Sequences B and B1. This is most likely due to degradation of encapsulant[19] or backsheet.[20] The dry insulation rates are very low (<1%) and were only ever recorded for DH1000 and TC200 over the complete time frame.

4 | CONCLUSION

In this publication, we showed results from the most important accelerated aging tests for PV modules according to IEC 61215 and IEC 61730. We thereby restricted the depth of analysis and refrained from a further breakdown of individual module and cell technologies in order to preserve client confidentiality. The analysis data shows how the temporal progress in module and cell technologies as well as modifications in the test descriptions influence the results of stress tests.

The statistical evaluation of power loss due to stress tests shows significant differences in the stability of modules beyond the simple 5% criterion. The provided information can thus help to evaluate test results, serving as a benchmark. However, the results and considerations also imply that care must be taken to consider the potential influence of meta-stable effects especially in DH and TC tests.

With regard to the sampling size of modules, we could show the importance to reproduce tests with a second module in certification, especially for tests with a low failure rate and in sequential tests. Furthermore, it could be shown that the new, combined stress sequences introduced in 2016 show the largest differences between PV module types and are therefore most useful for benchmarking modules or ranking module types based on accelerated aging tests.

With regard to normative amendments to IEC 61730, we want to point out the value of maintaining these test sequences in their current form. In our opinion, the effort and time expenditure are well worth the information about reliability and safety that is gained from these tests. Furthermore, small changes in the test procedure and scope impair the accumulation of long-term experiences with a given reliability test due to poor comparison with older technologies. Since both test sequences (B + B1) are performed in the context of IEC 61730 in any case, they would be a worthy addition to IEC 61215, including the application of a performance criterion.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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