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TOPICAL REVIEW

Accelerated aging tests vs field performance of PV modules

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Abstract

The solar conversion market with photovoltaic (PV) systems has experienced and is experiencing an enormous growth worldwide and—according to the agreed goals of many countries to protect the climate—will further grow over the coming decades. Investments related to PV became an important financial product with the special feature of very long contract durations. A typical setting is an operation of more than 20 years, during which the generation of electricity and also revenues are expected. Sometimes Power Purchase Agreements with durations of up to 50 years have been reported. Taking these long operational times into account, quality, durability, reliability, and degradation rates become a crucial topic for the investment and for all stakeholders. PV modules are the dominating components in this regard since they prevail the investment and—due to their sheer quantity—are in most cases hard to replace if a system has PV module immanent issues. Accelerated ageing tests are in general used to ensure the quality of PV components. These tests are partly standardized, for PV mainly by the International Electrotechnical Commission IEC and related national committees. These standards are used for type approval testing or safety testing, which can also address legal issues. Accelerated ageing tests are also adapted to specific needs and for example used for quality assurance (QA) of manufacturers or service life prediction (SLP) by manufacturers or research institutes. All the efforts are taken to gain more knowledge about the behavior of PV modules in operation and thus the accelerated tests have to be related to normal operation. Since PV is used around the globe, the conditions vary significantly depending on the location of installation, from dry and sunny deserts to mountain climates to tropical or maritime climates. In addition, the type of installation has severe influence on the operational conditions of PV modules i.e. mounted on a roof, roof integrated, open rack—or even in upcoming applications like floating PV. The papers attempt is to give an overview on the state of the art of accelerated testing and field performance analysis of PV modules with focus on the developments over the last five to ten years. Developments are described and the status is analyzed regarding the significance of tests including the latest developments and open scientific gaps related to the envisaged correlation of accelerated tests with field performance. In the end the reader is enabled to differentiate between reliability testing and service life prediction. The understanding for a comprehensive approach of reliability testing including field evaluation data will be developed.

1. Introduction

The market for photovoltaic (PV) systems has experienced and is experiencing an enormous growth worldwide and—according to the agreed goals of many countries to protect the climate—will further grow over the coming years and decades. Investments related to PV became a key financial product with the special attribute of very long contract durations. Typically, more than 20 years of operation are expected. Taking these long operational times into account, quality, durability, reliability, and degradation rates become a crucial topic for the economic success of PV.

Recently also sustainability assessments Life Cycle Assessment (LCA), Levelized Cost of Electricity (LCOE) became of major significance for the renewables industry. For such assessment models the degradation effects are essential, hence reliability and degradation data is of highest value for all investments and stakeholders. Based on the concern for reliable PV modules and reliable statements on durability and degradation, big efforts have been taken during the last decade. The Know-How on degradation effects and rates as well as on failure modes of PV modules in the field and related accelerated tests were improved.

Accelerated ageing tests, with subsequent characterization, are in general used to ensure and measure the quality of PV components and are used for a long time [1]. These tests are adapted to specific requirement and for example, used for quality assurance (QA) [2] of manufacturers or service life prediction (SLP) [3] by manufacturers and research institutes.

These efforts are taken to gain further knowledge about the behavior of PV modules in operation and therefore accelerated testing need to be related to normal operation. It will enable a phenomenological correlation of degradation effects occurring under basic laboratory conditions compared to complex outdoor conditions. Since PV is used around the globe, the conditions vary significantly depending on the location of installation [4]. In addition, the type of installation has high impact on the operational conditions. Whether PV modules are mounted on a roof, or in open rack, are roof integrated—or even in upcoming applications like floating PV, vehicle integrated PV, or in agricultural implementation—it has significant influence on the operational conditions.

All these variations make it necessary to relate accelerated tests to field performance of PV modules. This paper attempts to give an overview on the state of the art of accelerated testing and field performance analysis of PV modules including the latest developments and open gaps. For detailed information on physical degradation mechanisms and related chemistry, it is recommended to consult further literature, e.g. [5, 6], since this would be beyond the possibilities of one publication. The paper enables to differentiate between reliability testing and service life prediction.

2. Background

Based on the demand for reliable PV modules and reliable statements on durability and degradation, big efforts have been taken during the last decade to improve the know-how on degradation effects and rates, as well as failure modes of PV modules in the field and related accelerated tests.

Different directions of scientific and technological developments in the area of field performance analysis and accelerated testing can be reported, including numerous publications reporting on degradation of fielded PV modules and systems, as e.g. [7–10]. The 'classical' accelerated tests like the standardized damp heat (DH) or UV or thermal cycling testing have been applied extensively on big numbers of modules and module types. Testing has been done also far beyond the testing durations/cycles given in the IEC standards, delivering lots of data which can e.g. be analyzed for a correlation between specific loads and specific failures. But still, these tests have not been developed to simulate normal outdoor operation. Therefore, several research groups have tried to develop accelerated tests with the aim to directly simulate the outdoor conditions and accelerate the related effects. In this area of activity significant progress can be seen. Still, there is a lot of work to be done to make such tests easier and especially more common, since they are still rarely applied. Other approaches aim at developing tests to screen for specific failures. Here especially established tests for potential induced degradation (PID) and light and elevated temperature induced degradation (LeTID) can be named.

Being aware that the degradation and reliability of PV modules depends on the specific conditions of the location and the installation they are operated in, great efforts can be documented in the analysis of field performance of PV modules, including correlation of operational loads with failures. Recently, approaches to map climatic conditions and relate the local climatic conditions to degradation rates or failure risks using degradation modelling have been proposed. These approaches and all the Service Life Prediction efforts bring together know-how and data from accelerated testing and field performance analysis. Respectable progress is noted but still many research questions are open.

3. Field performance of PV modules

Field performance of PV modules is the one relevant parameter, which is crucial for durability and reliability. In the end, field performance determines the bankability and economic success of PV plants. Field performance is also key for all tasks related to testing, qualification, and benchmark setting. This benchmarking is used for activities and analysis of accelerated ageing. Accordingly, the modules are differentiated regarding their field performance, and the single module performance (over time) depends on the specific conditions of the location and the application/installation. The reasons for testing modules in the field are various and rarely limited to only one single scope. But for sure field performance measurements are an essential part to determine conditions for artificial degradation testing and for the design of such tests. And for sure, the most important point, accelerated testing needs to be validated by field performance. The optimization and adaption of standard test conditions relies on the understanding of effects from the fields in different locations. The statistics of enormous numbers of accelerated ageing tests are worthless, if none of those effects can be reproduced in the site of interest. In addition, not every module has necessarily to withstand all the weathering conditions from extremely dry and cold to hot-humid climatic conditions. An adaption of material is highly recommended for reliability and for substantiality aspects and for the optimum in field performance.

This chapter analyses the state of the art of loads and operational conditions for PV modules. Included are sections on different load parameters. Special focus is on location specific load effects and the progress of work related to these topics.

3.1. Loads and conditions

For PV, there are no standardized radiation, temperature, or humidity conditions for operation or testing in outdoor installations. This implies that we are dealing with non-standardized conditions and loads, when analyzing the conditions of PV systems in operation mode. There are also neither 'damp-heat' conditions without irradiation, nor cyclical temperature loads with constant humidity in the field. The various stressors should always be considered. Beyond that, there are special cases, such as condensation and frost or soiling. These cases are sometimes as unstandardized as bird droppings, or mechanical impacts from close traffic which are not covered in the established tests and investigations. This makes research on loads and conditions in outdoor applications essential to develop an understanding for degradation and reliability of exposed PV modules. A good overview on work and results on loads and conditions and their impact on PV reliability can usually be found in reports of IEA PVPS, mainly covered by Task 13 [11] as e.g. [3, 5, 6].

A survey in the IEA report [12] also hints to the fact, that among the vast number of laboratories and industry with climatic cabinets not many studies have been conducted for long term PV module field exposure. From the 15 international participants only 5 survey participants are veterans with outdoor testing of PV modules with more than 10 years of experience and more than 100 modules tested, and on the other side 5 survey participants are 'newcomers' with 2–4 years' experience and mostly smaller test facilities. Despite the restriction of the survey to the IEA PVPS Task 13 consortium, it represents well the state of art of today's module outdoor testing and experience. The survey includes 33 test facilities in different climates and all relevant climatic zones: warm and tempered, arid, continental, tropical and alpine.

Performance and energy yield measurements of single modules is typically used in combination with monitoring of ambient climatic conditions to analyses the correlation of PV modules degradation to operational loads. Sometimes, but unfortunately not always, microclimatic conditions e.g. module temperatures, are monitored in parallel. Measurements under real conditions should be done over at least one year for representative purposes under any climatic condition. The result of such a monitoring activity is only valid for the specific site on which it has been measured and it is also important to check whether the monitoring time is representative for the local climate. There are some research activities trying to correlate local climatic conditions with degradation effects, focussing on module effects [13] or on materials or material classes [14].

The following sub-chapters will give an overview on the different climatic stressors and how they are determined and analyzed regarding degradation effects.

3.1.1. Temperature

Temperature loads are of major importance for more or less all degradation effects since it directly influences physical and chemical reactions, and elevated temperatures accelerate such processes [15]. Especially organic materials are affected by temperature impacts [14]. Due to this effect, temperature is one of the most relevant stressors influencing degradation of modules in operation. PV modules always operate at elevated temperatures, compared to ambient conditions [16] if they are not technically cooled. For the determination of the temperature load, it is important to use the module temperature (microclimate) and not the ambient temperature (macroclimate) since they differ significantly. The module temperature mainly depends on the ambient temperature, irradiation, module design, wind, and installation. There are models which allow the calculation of module temperatures with adequate accuracy using ambient climatic conditions and type specific parameters as input factors [16, 17]. Comparing the situation at one specific location, the type of installation has the biggest influence [18, 19]. Open rack installations typically ensure relatively low module temperatures while roof integrated installations lead to extremely high operational temperatures due to the insulation effect. In extreme conditions even temperatures above 100 °C have been reported [20], which is of twofold severity. On one hand, degradation effects are extremely accelerated in such conditions. On the other hand, the previous module qualification with standardized type approval tests becomes invalid, since type approval only uses 'accelerated tests' with up to 85 °C (see section 6.1). This means that these tests, compared to the real operation conditions, not only lose entirely their acceleration, but they might also not even trigger all degradation processes which take place under normal operation conditions.

For the most typical PV module technologies and designs, lots of measured and calculated temperature load data is available, partly even transferred into global load maps [21] but for new module types or application types like floating or vehicle integrated PV modules, no reliable data base for module temperatures is available, yet.

3.1.2. Humidity

PV modules are exposed to different humidity levels in different climates. The presence or absence of water in the ambience is together with the temperature load one of the main factors for degradation effects. Relative humidity as main driver in several degradation mechanisms e.g. corrosion, embrittlement, discoloration, optical and adhesion losses directly affect the lifetime and energy yield of PV modules. Many activities have been reported on theoretical moisture ingress into the polymeric components [22] and the influence of the ingress mainly as material defect-based research [23]. However, the interlink and proof of actual water concentration in the fielded modules and reliable measurements methods are still under investigation [24]. Further, only few papers can be found which analyze the influence of the sole humidity conditions and their effects on degradation/performance of modules in the field in a detailed way. Some papers include humidity related research [4, 25] but none has been found, which has its main focus on humidity effects for PV modules. Humidity data of local climates are available, since it is included in all geographic related data sets and maps as e.g. the most known Köppen-Geiger climate categorization system [26]. For PV modules, the microclimatic load is not identical with the ambient humidity conditions hence calculations using irradiation and temperature data are necessary to estimate microclimatic humidity loads. Such calculations are partly used to create degradation risk data sets and maps [4, 24] and supported by measurement technologies [27].

Publications and worldwide activities currently report on humidity effects on polymeric materials of PV modules, specifically used in back sheets [14, 28]. The reported results show the importance of including humidity loads in accelerated tests for qualifying materials for PV applications and a tendency towards test with combined loads can be recognized. Nevertheless, it must be mentioned that the integral effect of humidity loads on PV modules requires more dedicated research.

3.1.3. (Ultraviolet) Irradiation

UV radiation has been identified as a major reason for degradation of PV module materials, especially the polymeric components, for a long time now [14, 29]. Research mainly focussed on the specific local loads [25], sometimes including mapping or transfer into risk maps [4]. Issues with cracking of backsheet materials in the fields after relatively short exposure times led [30] to the awareness that UV testing has to be combined with appropriate humidity exposure to generate meaningful results [14]. Taking this into account, it can be realized that many groups work on the development of appropriate combined testing sequences including UV loads (section 4). It is also common knowledge in the meantime, that the standardized UV exposure according to IEC 61215 with little as 15 kWh m^{-2} is in approximation only simulating 3 months of normal operation in moderate climates, which is insufficient in relation to more than 25 years of outdoor operation. Due to the fast-growing market of PV installations in desert regions, the extreme UV doses in many deserts, often accompanied by high temperatures [25, 31] should be integrated in the testing and qualification with more emphasis, to address the sensitivity of polymeric materials [14].

3.1.4. Temperature changes

Fielded PV modules, in addition to the above-mentioned loads, experience alternating temperature cycles at different resolutions; hourly, daily, monthly, or annually. These temperature cycles induce thermo-mechanical stress/fatigue on a PV module, which mostly leads to degradation modes such as solder interconnections breakage, cell cracks, and glass breakage and fatigue of polymeric components [30, 32]. Additionally, temperature cycles could also accelerate degradation mechanisms induced by other stresses. The IEC 61215 thermal cycling test (TC 200) was designed to evaluate the ability of the module to withstand thermal mismatch, fatigue and other stresses caused by temperature fluctuations. Like other IEC tests, the question always remains how these tests are comparable to outdoor performance. The authors in [33] performed a comparative study of modules subjected to TC200 and TC50HF10 tests which are described in sections 10.11 and 10.12 of the IEC 61215 standard respectively, to outdoor performance. Their findings show that the trends in degradation where not perfectly comparable. In this regard, the development of indoor tests that can accurately simulate real outdoor conditions is still under research. There are also improved approaches based on finite element method (FEM) calculations used to simulate thermo-mechanical behaviors of different PV modules [34, 35]. Simulation approaches are important because of their flexibility and ability to quantify stress levels for a large variety of scenarios ranging from process-induced stress up to field conditions.

3.2. Climate specific loads and effects

Climatic conditions are depending on the location of the installation of the PV modules and on their type of installation, as already described before. Several research groups have analyzed the effects of the different climatic loads, as in [36] or [37]. The papers show that there is a significant influence of the local climate on the degradation rate but the real correlations between the stressors and the degradation processes are not really understood. This is also valid for a correlation to specific failure modes. There are several contributions reporting on the correlation of material degradation effects with climatic impacts, as in [38] or [39] and some groups even try to define risk priority numbers according to the local climatic conditions [40]. The results show that the climatic conditions, which PV modules experience, are different and cannot be simply translated into standardized tests. As these—by nature—require that the typical operational load is comparable in all places of application.

Apart from the analysis of specific data, the availability of data for local loads is continuously advancing. To be recognized is that loads for PV modules differ from ambient conditions, consequently the usability of classical weather service data is limited. Different maps have been developed, which use models to translate the ambient climatic conditions into microclimatic loads for PV modules [41]. The approaches partly get even further and include kinetic reaction models for different typical degradation processes and create PV risk maps or even typical degradation rate maps covering big parts of the globe [4].

The described approaches work with the distinctive stressors, temperature, humidity, and irradiation, typical present at all locations. Despite that, there are other load factors, which are only relevant in specific locations. But since they can become predominant loads at these locations they are not to be neglected, as the following sub sections show.

3.2.1. Soiling loads

The term soiling describes the dust settlement and accumulation onto the surface of PV modules. It is among the prevalent environmental loads, of temperature, humidity, and irradiance, one of the major concerns in reliability and yield of the exposed components and systems in the harsh environmental condition of the arid climate. Arid areas, rich in sunshine, are of special interest, because only a small fraction of those uninhibited deserts regions could theoretically provide the entire world with renewable solar energy. The pressing problem is how to minimize or mitigate yield losses caused by soiling. Now, the focus of research has been on high potential regions, such as the Middle East North Africa (MENA) as well as other desert locations i.e. in Australia, the United States or Chile. Even tropical areas i.e. in India, rich in solar irradiance, can be utilized. Hence, there is literally a boom of research on soiling related reliability issues in arid, and to some extent also tropical locations in the last decade. Further comprehensive reviews can be found in [42–44] or [45] and its update in [46]. We try to give an overview on the dominating issues and topics of the tremendous number of publications related to soiling of the last years.

Although, worldwide R&D efforts have been intensified in the last decade, still the effects of dust accumulation on PV performance cannot be predicted but are measured and analyzed by show cases in defined locations. Quantification measurements with local focus e.g. in dry-maritime environment show yield loss even beyond 80%, enhanced by a roadside construction site [47]. Yield losses up to 50% are not uncommon for hot and dry desert environments. Outdoor measurements on utility scale are conducted to further qualify different PV module technologies in spite of the soiling effects [48–50]. Daily soiling losses can range from as low as 0.01% d^{-1} (Europe, North America) up to 1%–2% d^{-1} in particular arid regions of MENA or East Asia [51]. Soiling rates at particular locations in different climate zones of South America (Brazil) are measured to be in the moderate range of 0.15% d^{-1} [52].

A commonly assumed degradation rate for c-Si technologies of 0.5% yr^{-1}, used for warranty and reliability calculation, has to be adjusted to 1.4% yr^{-1} for desert environments. This high degradation rate can be explained by synergies of different influencing stressors, including soiling loads. Especially corrosion effects (see section 3.2.3) are enhanced by soiling. Common knowledge is that the infrastructure of the solar farm and installation conditions (tilt, orientation) does strongly influence the soiling effects [53]. Instrumentation to measure and monitor yield losses include soiling sensors [54], or the comparison with the electrical parameters of frequently cleaned reference cells/modules [55, 56].

Certain is, there are location-depended dust adherence mechanisms, traced back to different dust attributes. Composition and particle morphology of dust grains and soiling components are under research with different analytical tools e.g. by microscopy, environmental scanning electron microscopy, x-ray diffraction or x-ray fluorescence [57–59]. To minimize the issue of the location dependent yield loss due to dust composition, suitable mitigation approaches of active and passive nature are to be selected. As active methods cleaning solutions are applied, like manual or automatized mechanical cleaning or more advanced electrodynamic systems [60, 61]. Optimization scenarios and economic aspects are considered within the cleaning studies [50, 60]. Still under research are the long-term effects by the different cleaning systems on the durability of the system and surfaces since cleaning requires cycles at least 2–4 cleanings per month in high soiling-risk locations. In such arid regions water scarcity, high wind velocities and an increased concentrations of airborne particles are also factors to be included in reliability considerations. Ambient conditions and environmental loads play a major role [50, 60].

Passive mitigation solutions, such as 'easy-to-clean' coatings, interact with the dust layers itself to supposedly prevent the dust to build strong bonds with the surface. There are hybrid coating solutions, being under test [62, 63]. Interactions of coatings and deposited dust [60, 64], but also with the mechanical cleaning methods are simulated in indoor testing. This enables to better study soiling behavior e.g. with fine particles [65], the transmittance loss and reflection properties of solar glass with dust coverage [66–68].

The durability of material e.g. surface roughening by abrasion [58, 61, 69] or degradation effects by accelerated testing is also under investigation, such as accelerated ageing tests of anti-soiling coatings [70, 71].

Modelling soiling further includes approaches, such as mathematical models, numeric approximations [72], trend analysis with data mining [73] or machine learning methods [74], as well as artificial neural networks [75–77]. Maps showing approximations of the regional soiling risks can be generated with Geographical Information Systems [78, 79]. Still, further research is necessary to completely cover and understand the multidimensional issue of soiling.

3.2.2. Mechanical and snow loads

Mechanical loads, such as wind, snow and ice accumulation on PV module surfaces have an influence on performance and reliability. They cause among other things cracked cells, cracked glass and bent alloy frames [80].

In three of the five climate zones, the moderate, subpolar, and polar climate zones, snow fall, icy precipitation, and accumulation are to be expected and their harmful consequences to be mitigated. Those consequences involve damage to the infrastructure, yield losses, mechanical stress on the module frames, glass, and PV cells as well as electrical safety issues due to harmed insulation. Energy losses of up to 15% annually, or 90% per month, are reported for the US [81, 82]. Studies of optical effects on transmittance and albedo by coverage and shading reveal differences in the uniform and partial shading [83]. Also, the tilt angle has a strong influence on a snow coverage, such that inclinations up to 80° and 90° show the least coverage [84]. Although the mechanical load tests on PV modules, according to IEC 61215, are carried out, potential failures of non-homogeneous loads on inclined modules rather than horizontally oriented ones give completely different load characteristics. After only 15% of the load used in the standardized test, frames start to deform [5]. IEC 62938 provides a method to simulate non-uniform load characteristics and defines a test procedure accordingly for framed PV modules since 2020 [85]. In the coming decades, North Europe awaits increasingly heavy snow loads on buildings according to reports in the architectural sector, due to warmer climate, which enforces wet winter-precipitations [86]. Hence, the mechanical damage through long-term heavy snow loads on different module construction styles is still under research [87]. The aim is to qualify PV modules as snow-load resistant. Module properties less disposed to snow load damage might be, but are not exclusively, modules with silicone-based adhesives, frameless and of shorter height [5]. Also, the sliding behavior off and on module surfaces are under research in connection to the melting behavior of snow on modules. Results from this research is the recommendation for rather larger and frameless modules [88].

Diverse mitigation solutions are suggested [89] i.e. to mitigate effects of heavy snow loads, other than shoveling the snow from the modules, using reversing current to heat up the modules [90, 91]. Although, the freezing of meltwater poses a risk in damaging the PV modules, it seems that the issue was solved and a working system is implemented [92]. Besides that, a removal of snow always poses the risk to damage the solar module [93].

Furthermore, wind loads are also a relevant aspect for mechanical loads placed on PV modules as they occur in almost all applications. The specific characteristic of wind loads is the highly dynamic behavior [94, 95]. Highest wind loads occur as gusts and consequently are hard to measure. Gusts can also trigger vibrations of modules [96]. Numerical tools are used to analyze the reaction of PV modules on such wind loads [97], sometimes supported by wind-tunnel experiments [98]. It is reported that the type of installation and the design of the modules, especially the aspect ratio has strong influence on the occurring loads [99]. It has also been shown that the design and the aspect ratio lead to type specific eigenfrequencies of modules [96, 100], which can be correlated to the susceptibility to gusts with specific properties. Typical failure modes of dynamic mechanical loads are cell cracks [101].

3.2.3. Corrosive loads

One of the chemical degradation processes of PV modules, determining the whole reliability, is the corrosion of the single components [102]. Corrosion research in the field of PV reliability is especially in maritime climates of significance, due to location-specific weather conditions. Methods for mapping atmospheric corrosivity have been presented [103]. Further, exposing components in multiple climates to investigate reactions make reliability and corrosion stability testing more realistic, since the corrosion rate of the atmospheric corrosivity is controlled by time of wetness [104], temperature and electrolyte composition [105]. That makes the atmospheric corrosion in maritime locations more likely to be destructive for the bill of materials (BoM) of PV modules, caused by present salt, high levels of airborne chlorine, paired with high moistures levels and usually also elevated temperatures. Research on aluminum and alloys present these effects on module frames [106].

Ambient environment may further contain corrosive gases. The most publicly noted one is the bad smelling and hygroscopic Ammonia. Questions arose, if PV modules are affected in the presence of elevated concentrations, since Ammonia attacks and corrodes specifically copper and its alloys in the presence of moisture [107]. Up to now, the authors know of at least two in the last decade designed tests to qualify modules for such environment but have not seen reports of degradation caused by those specific environmental conditions under normal operation conditions.

Humidity (section 3.1.4) is crucial for corrosion effects within the module. Moisture ingress is the precursor of most degradation effects, such as metal grid corrosion and loss of adhesion [23]. However, humidity is the carrier for pollutants and hence activator for electrochemical reactions, too. Degradation effects in aquatic systems have been of interest long before and are still of interest for system materials around and at the PV module [108]. Now, with the implementation of floating PV technology, PV modules are exposed to constant wetting. A controlled and reproducible test with salt water for the exposure offshore is applied to understand the effects. Up to 14% performance loss after 30 days were stated for all technologies. Whereas alterations of transmittance through a salt deposition does not have significant effects [109]. Under research are also the effects of desert conditions on the corrosion of modules, where also humidity and condensation next to ambient pollutants are present [110] (see also section 3.2.1 soiling).

Corrosive loads have been studied in harsh environment and have been shown to have influence on the PID risk, hence the overall performance of the system [111, 112, 112].

Measurement of ambient chloride deposition can be done by the wet candle method, according to ISO 9225, with a rain-protected wet textile surface [113, 114]. Other analysis majorly focuses on the impacts of the degradation on solar cells. Contact failures of front contacts [115], and soldered bonds are used as basis for lifetime prediction of PV modules [116]. Surface corrosion on solar cell level can become noticeable as snail tracks [117].

PV module degradation analysis can be carried out with Raman spectroscopy on the polymeric encapsulant to understand the decomposition and the release of acetic acid under high moisture levels [118, 119]. The release of acid and its corrosive effects in contact with surrounding module component, such as interconnectors have been analyzed and described [120].

4. Accelerated aging: definitions and purpose

Accelerated ageing tests are widely used and address different purpose. Some general terms are important to understand to evaluate tests and data. This chapter gives an overview of the general purpose of accelerated aging tests and its basic terms.

4.1. Accelerated aging

Accelerated ageing describes tests which aim to trigger degradation processes of materials or products and to identify design flaws during product development, to prevent failures during field operation and improve product reliability. The tests are meant to speed up possible destructive processes and loss of functionality of material and take place significantly faster than under normal operation condition. Reliable results shall be achieved in a very short period and at low costs. The tests can be performed with different purpose and scientific approaches, as described in sections 4.4, 6 and 7. A very generic description given by the Confederation of European Environmental Engineering Societies CEEES can be found in [121]. To enable accelerated ageing, the degradation provoking factors must be increased. There are in general three possibilities to achieve the acceleration:

- constant, representative high stress level of one or more degradation factors for a long period, in PVs for example irradiation around the clock or constantly high temperatures

- Increasing the stress factor(s) above normal operational stress level to apply higher doses to the sample, in PVs for example testing at higher than usual UV-intensity or relative humidity,
- Increasing the temperature to accelerate chemical degradation processes.

All types of acceleration the natural aging come along with risks. So, it is important to be aware that increased loads can provoke processes and effects which are not relevant for normal operation [122]. It is equally important to consider that in most accelerated tests, the relative intensity of the different present stressors to each other is changed in comparison to the normal operation.

4.2. Acceleration factor

Following the objective of accelerated ageing, processes that occur in normal operation shall be accelerated. But typically, the aim is to keep the process and reaction types similar. Similarity is represented by the acceleration factor (AF), which is defined as

$$\mathrm{AF} = \frac{t_{\mathrm{test}}}{t_0}$$

with t_{test} the testing time during accelerated ageing; and t_0 the exposition time under normal conditions, which is necessary to provoke similar effects.

Since different physical and chemical processes show different dependencies on stress factors, they then have different acceleration factors. Stay aware, that one acceleration factor is typically only valid for one specific process. In a given material sample many (chemical and physical) processes take place during accelerated testing. For each of the processes one specific acceleration factor is effective, which means that only one general determined or chosen acceleration factor is invalid for many of the ongoing processes. For the generation of measurable degradation effects, typically several processes interact. Still, to be able to use the concept of accelerations factors in applied testing, often one acceleration factor is calculated and applied. It describes the acceleration of one occurring and targeted degradation effect, which can be measured. It is usually not a specific (chemical) degradation process. In PV e.g. yellowing of encapsulation materials or performance loss of PV modules are often chosen for such measurements and not the (chemical) process itself behind.

For mathematical modelling the idea of the rate domination process has been developed [25]. This approach estimates that one physical or chemical process e.g. hydrolysis or UV drive chain scission, is dominating the development of the degradation effect of interest. So, one relevant acceleration factor can be determined, which is representing the behavior of the sample regarding one specific degradation effect.

4.3. Stress factors

PV module degradation is dependent on multiple factors such as manufacturing processes, installation sites, mounting conditions and the type of the module. To understand the long-term behavior of PV modules, it is a prerequisite to assess the stress factors acting on the modules and correlate the module's response to the applied stresses. Stress factors determine the degradation of PV module components and hence the service life of PV modules. Accelerated aging tests are designed to simulate the effects of different stress factors on different degradation mechanisms, identified in the field. Several stress factors relevant for PV reliability are discussed in literature [3]. In table 1 major stress factors and the corresponding accelerated aging tests are given based on IEC 61215 for crystalline silicon modules, IEC 61646 for thin film modules and IEC 62108 for CPV modules. The emergence of new photovoltaic designs and applications (e.g. offshore/floating PV, vehicle integrated PV) calls for new tests beyond existing standards to best describe their degradation behaviors under different stress factors.

In the evaluation of PV module reliability, two distinctions are made from climatic stresses: macroclimate and microclimate stresses. Macroclimate stresses describe the ambient weather conditions around the PV module and microclimate describes the conditions experienced by the specific PV module components. For example, 'ambient temperature is macroclimate, and module temperature is microclimate'. This means that microclimate stressors have a direct influence on PV module degradation mechanisms. In degradation evaluation and predictions, microclimates are used to describe the degradation kinetics. However, it should be noted that there is a strong correlation between macroclimatic and microclimatic conditions. In most cases, microclimatic conditions are not directly measured but estimated from macroclimate conditions using different mathematical models [123, 124]. Therefore, the accuracy of these transformation models is crucial for understanding and correlating the degradation kinetics to stress factors [125].

4.4. Quality assurance

An important driver for the development and application of accelerated ageing tests is quality assurance (QA). In all established industries manufacturers use accelerated ageing tests to ensure a defined quality level.

Table 1. Stress factors vs accelerated aging test and degradation modes for PV modules.

Stress factor	Accelerated aging test	Degradation mode/mechanism
Temperature and Humidity	Damp Heat	Corrosion Encapsulant adhesion Junction box adhesion Delamination
Temperature cycles	Thermal Cycles	Broken cells Junction box adhesion Broken interconnect
Solar Irradiance	UV test	Encapsulant and backsheet discoloration Cracks in polymeric backsheets Delamination and bubbles
Frost	Humidity Freeze	Junction box adhesion Delamination Inadequate edge deletion
Wind and snow load	Static Mechanical Load	Broken glass Broken interconnect ribbons Broken cells Structural failures Electrical bond failures
Wind Gusts	Dynamic Mechanical Load	Broken glass Broken interconnect ribbons Broken cells Electrical bond failures
Hailstones	Hail Test	Broken glass Broken cells
Salt water and salt mist	Salt Mist Spray	Corrosion

Such tests shall help to identify issues of products during production or directly after production. The aim is to identify problematic products, and to be able to take measures in production or stop products before they enter the market. For that purpose, it is essential that tests are quick, highly reproducible, easy to apply and not too costly. This limits possibilities for the definition of QA tests, which is especially problematic for products with very long expected lifetimes—as PV [126]. Nevertheless, most of the standardized tests, as described in section 6.1 are also applied for QA purpose. In addition, several of the failure mode specific tests described in section 6.2 are typically additionally applied for QA e.g. PID testing to qualify cells. In most cases are DH, thermal cycling (TC) and UV testing applied by the manufacturers, sometimes even with testing durations exceeding the requirements of the standards [127]. Due to their test durations of typically several weeks, they do not fulfill the requirement of delivering results during production.

Another aim of QA is to test as many samples as possible. In ideal case, each sample should be tested before it leaves production. This is unfortunately not possible with accelerated ageing tests, since they affect the sample irreversibly and can degrade the product severely.

Besides manufacturers, sometimes QA type testing is also applied by/for investors, importers, or traders to ensure quality, or it is requested by banks or insurance companies. Many of them have specific testing protocols [2] which have to be applied to come into business. All these QA tests or testing sequences just define a specific level of loads for product quality evaluation, but they do not correlate with specific applications, climates, locations, or service lifetimes.

In PV industries, the importance and awareness of QA and especially meaningful and comparable QA testing procedures has been increased significantly over time. A catchable result is the meanwhile established institution of the International PV Quality Assurance Task Force (PVQAT) which leads global efforts to craft quality and reliability standards for solar energy technologies. Now 12 Working Groups are active in PVQAT addressing different important QA topics [128]. PVQAT already developed several inputs and proposals for standardization of IEC level and established numerous round-robin tests or other measures to improve comparability and know-how on accelerated testing and QA in PV.

5. Testing equipment, conditions, and related limitations

Accelerated testing requires adequate equipment, which comes with specific properties and yet limitations. Depending on the purpose of testing, different equipment has to be used. The following sections give insights in the world of accelerated testing equipment with special focus on developments over the last years. Furthermore, set-up related testing conditions, approaches and limitations are presented.

As side note, soiling testing equipment and conditions are not included since accelerated (laboratory) soiling testing is not seen as a typical accelerated ageing test. Soiling typically causes (partly) reversible effects and so not classical degradation. Soiling nevertheless can influence degradation and ageing. Please see sections 3.2.1 and 3.2.3 regarding these topics. Description of laboratory soiling setups can be found in the literature given in section 3.2.3.

5.1. Loads and conditions

For all accelerated ageing tests, the testing conditions must be carefully determined (see sections 3.1 and 4.3). The selected test conditions then specify the needed test equipment. Selection criteria are e.g. the number of controlled load factors or the size of the samples. In many cases this logical decision process can unfortunately not be used. There are two reasons. First, available equipment is limiting the flexibility of the test set-up. Second, technological limitations of equipment make some tests impossible or increases the effort inappropriately. The following sub-sections analyze the situation for the different stress factors.

5.2. Temperature testing

Temperature has a major influence on the reaction rate and reaction kinetics of all chemical processes and for that reason, also on degradation processes of PV modules, as described in section 3.1.1. The temperature in accelerated ageing tests is therefore of highest importance and influencing all processes. Sole thermal ageing by exposing products to elevated temperature conditions is done in oven like thermal chambers. Small chambers can heat up to 750 °C or even above. Typical standardized testing temperatures in PV are around 80 °C–90 °C.

In irradiation testing, the sample temperature can differ from the ambient chamber temperature. Irradiation can significantly elevate sample temperatures. For evaluation of the loads, the sample temperature is a key factor. It must be analyzed or taken as control parameter. For several chemical processes, especially for organic materials—in PV mainly the polymeric encapsulation and backsheet—specific degradation processes can only commence above a material-specific threshold temperature. So, if the device's normal operation is below such a threshold temperature and testing is above, different processes will be triggered. Then the accelerated test cannot deliver any reasonable information on temperature degradations the normal operation mode [129]. For the most common encapsulation material EVA such a threshold temperature is in the range of 85 °C–90 °C [130]. Due to the high impact of temperature on reaction rates, also temperature homogeneity within the tests is very important to ensure the comparability of results.

5.3. Relative humidity testing

Relative humidity exposure in accelerated ageing tests on PV modules is facilitated in climatic cabinets, which are available in all sizes. Most make sure to fit at least 2 PV modules simultaneously. The commonly used test for humidity exposure is the so-called DH test at 85 °C and 85% r.h. for 1000 h, as defined in IEC 61215. This test is typically applied for quality assurance purpose, often also in extended versions with up to 3000 h or 4000 h. There are only few developments recognizable which try to vary the conditions e.g. to determine acceleration factors, which would be necessary to correlate the test with outdoor exposure [131, 132]. Unfortunately, no reasonable progress regarding correlation of DH-tests to real outdoor conditions can be mentioned, which is a severe shortcoming since DH testing is probably the most used accelerated test in PV industries. Phenomenological degradation effects on PV modules e.g. interfaces (EVA-Glass) after DH exposure are reported [133]. The material-oriented research shows, that moisture often plays a synergetic role with UV, as e.g. for surface crack formation of backsheets [134].

It is important to set and design the accelerated ageing tests properly and adjust them for real loads not to rule out the good material (see sequential combined stress testing) [135].

When talking about humidity testing, it is important to mention the water vapor permeation rate properties of PV modules, mostly the polymeric components, such as backsheets or encapsulants for Glass-Backsheet modules or edge sealants for Glass-Glass modules. Degradation effects of water permeation into encapsulant or backsheet during damp-heat testing is described in recent publications [133] by a consortium of PV and polymer research institutions, in the framework of the Solar-Train project (www.solar-train.eu). There are set-ups to determine the WVTR and barrier properties of polymeric films, which consist of a permeation cell connected to a mass spectrometer. The tests are performed under elevated DH conditions and can vary, but usual settings are at 38 °C and 90% r.h.

5.4. UV testing

UV testing of PV modules and materials is commonly used for qualification testing for a long time. On module level, typically the UV exposure with a dose of 15 kWh m^{-2} at 60 °C defined by IEC 61215 is often used as a benchmark. The dose of the test is only comparable to approximately three months of outdoor exposure in moderate climates. The test is therefore only named 'UV preconditioning' in the IEC standards. Different set ups are used to apply the irradiation, using Metal-Halide or Xenon lamps (Xe), fluorescent tubes or as coming technology, LED light sources [136]. Xe sources provide a spectrum, which is close to the solar spectrum. Consequently, Xe sources transport alongside much heat to the sample, because of its longwave IR irradiation. To avoid the extra temperature influence by heating the sample, fluorescent tubes or LEDs are used, even with higher UV intensities. They make it easier to test at controlled sample temperatures. The different light sources also deliver different spectra [137], which can be problematic especially, if results of different tests shall be compared. That is a major shortcoming for current UV testing.

Since the PV community is aware of the shortcoming of the IEC type UV exposure, typically multiples of the 15 kWh m^{-2} are applied. But usually, the used doses are still far below the typical lifetime doses of modules. One reason for that is the high cost of testing, since samples cannot be stacked as in a DH or TC testing set-up. They rather need the full frontside area exposed to the irradiation. A further reason is the limitation of acceleration, caused mainly by thermal effects of light sources. The limited size of many UV testing cabinets and the importance of UV testing for polymeric components [14] are major reasons why high dose UV testing is often only applied to smaller material samples or mini sample modules. Currently, in the last five years since approximately 2016, polymeric backsheet materials are of special interest for industry and research. Since backsheets are directly exposed to the environment including UV loads, occurring failures e.g. cracks, are now studied intensively. Crack formation, one of the most common failure modes of the backsheets, leads to safety concerns. A special type of crack, channel cracks (fragmentation) were only observed on samples treated with UV [134].

5.5. Thermal stress testing

Temperature cycling (TC) tests are mainly applied to analyses the effects of internal mechanical stresses due to different thermal expansion coefficients of module materials. These tests are regularly applied to qualify material, but there is not much development notable regarding scientific analysis of the tests or development of new or adapted TC tests. The temperature cycling sequence defined by the standard IEC 61215, which uses temperature ramps from -40 °C to $+85$ °C and back for 50 or 200 times, is almost exclusively used. There are only few activities reported, which vary the conditions significantly. Typical variations of the IEC based tests only touch the numbers of cycles. Often extended IEC 61215 thermal cycling (TC) tests are reported with up to 800 cycles or even more. One approach would be to use highly accelerated thermal cycling tests, which apply faster temperature changes [138]. Other researchers propose increasing the temperature range or ramp rates [139]. Others have conducted studies to generate temperature cycle profile from *in-situ* climatic conditions to improve the accuracy of thermo-mechanical degradation [140].

More dedicated work to develop correlations between the accelerated TC tests and thermal stress effects, which occur at normal operation mode, would be necessary, since no validated model for this question has been reported so far.

5.6. Corrosion testing

Accelerated corrosion tests aim to simulate degradation effects of atmospheric corrosivity in fielded PV modules. These tests shall help to determine the corrosive effects during service life and qualify material for corrosive atmosphere. To start and accelerate corrosion processes the established standardized test method is an exposure to enhanced aggressive conditions compared to which a module will experience in normal operation. In general, full-size modules or components are exposed to the corrosive effects of salt mist in climatic chambers. During those salt spray tests a combination of saline atmosphere, high temperature and high relative humidity is applied. However, long term studies found poor correlation between such accelerated corrosion tests and field exposure, still they are incorporated in many product qualification specifications [102]. Most studies in R&D on PV modules only investigate the effects of single loads, i.e. temperature cycles [141] or moisture levels, including condensation, on the corrosion process [115, 118, 120, 142].

Atmospheric corrosion is an electrochemical process, which combines humidity as electrolyte and ambient pollutants. Such conditions are simulated in salt spray chambers [143]. Accelerated tests with such specific climate chambers are based on normative standards [144–146].

These testing conditions were, originally intended for other purposes, i.e. DIN 60068-2-52 (cyclic testing) for corrosion resistance in marine environment, transferred to test PV modules. Even if it is known that such tests do not imitate the various climatic conditions worldwide and are less inspired by the atmospheric corrosion of fielded PV modules, they are used. However, indications can be made on corrosive effects e.g. on the metallic components such as the module frame or interconnectors, or on other components, i.e. coatings or glass [115]. Also, effects of acetic loads on metallic cell materials have been analyzed, as e.g. on silver-ink and silver-based metallization in PV modules [147].

There are many specifications made for the salt spray test. Grouped are the tests into neutral salt spray test, acetic acid salt spray test, copper accelerated acetic acid salt spray test, and cyclic salt spray test. The classic salt spray test, called neutral salt spray test, originally designed for paints and coatings is commonly used for electronical devices. It is carried out under constant spraying conditions at 35 °C and with a 5% salt solution of sodium chloride (NaCl) for several hours and up to one week. However, PV modules are found to be quite durable in such testing conditions [110]. That, and the fact that there are limitations to the chamber, make such test long and costly. Limitation to the chamber account to space restrictions, since modules cannot be stacked in the chambers, because the salt mist settles vertically onto the surfaces. In recent studies, alternatives are presented, and conditions are optimized in regard of adding demanding and realistic alternating procedures, i.e. temperature cycling (TC) and a sequence of humid and dry times. Several UV/salt mist/DH sequences are established to test the impact of weathering factors in combination with corrosive atmosphere on PV modules [110]. Tests and sequence from other sectors, such as the car industry or solar thermal research [148], do influence the test design. Tests, which are characterized by several salt spray stages, variations of salt concentration, stages of higher and lower levels of temperatures, as well as higher and lower levels of humidity with subsequent resting stages have been reported. They put the sample under additional stress due to the frequently changing environment [149]. These tests can also include humidity-freeze cycles [150].

5.7. Mechanical testing

Accelerated mechanical testing is mainly done using the standardized tests according to IEC 61215, as described in section 7.1. These tests are sometimes varied using higher loads or more cycles to increase the effect of testing. Nevertheless, the test still has significant weaknesses. On one hand, it applies static loads, which would typically represent snow loads. But the test is applied at room temperature, which means material behavior can be different than in outdoor operation when snow loads occur. Especially polymeric materials show temperature dependent mechanical properties. On the other hand, it applies loads in different directions (up and down) which would represent wind loads but wind loads occur as gusts which means highly dynamic. Some work has been reported addressing these issues [151]. The impact of testing at cold temperatures has been analyzed [152], as well as effects of dynamic mechanical testing [153, 154]. Some groups also addressed effects of non-uniform loads or asymmetric module designs [155] and the effects on specific failures, as cell cracks [156].

Hail impact testing is not described here since hail typically leads to spontaneous catastrophic failures and so the testing can also not be seen as a classical test, because accelerating degradation effects take place over time. There is also no relevant development in hail testing to be noted.

Abrasion testing is typically addressed in the framework of soiling analysis and is also not covered here in detail. Nevertheless, an adapted abrasion testing standard for PV has been published recently: IEC 62788-7-3:2022 '*Measurement procedures for materials used in photovoltaic modules—Part 7–3: Accelerated stress tests—Methods of abrasion of PV module external surfaces*'.

6. Testing approaches for accelerated ageing tests

The stipulation of appropriate accelerated ageing tests must take several parameters into account, as described in sections 3 and 4. It has a significant influence on the outcome and therefore also on the usability of results. This chapter will give an overview on general approaches and terms as well as ongoing developments and discussions.

6.1. Test design

Sections 3 and 4 describe possible purposes for accelerated testing and the stressors/load parameters and conditions, which must be included in accelerated tests, depending on the specific goal. These parameters open a multidimensional space of loads, intensities, durations, and sample types, which must be included when a specific test is designed. Furthermore, appropriate characterization methods have to be identified. It is therefore recommended to carefully analyze the needs and possibilities defined by the testing purpose, the application, and the available testing infrastructure in the experimental design phase. Few guidelines dedicated to PV can be found in literature [122] but besides that, literature from other industries using environmental engineering and accelerated ageing tests for long time can be used. Especially automotive industries offer a lot of experience in this topic [157].

As soon as the testing purpose and the technical capabilities are known, the sample design must be fixed, if no full-size samples shall be used due to technical or financial limitations. The samples must include all materials/parameters, which are relevant for the specific question. So, if chemical reactions/degradation shall be provoked, it is important that all reaction partners are available in comparable amounts as in normal operation. For tests addressing mechanical topics, especially the aspect ratio and often also the total dimensions are necessary to be fixed values. The sample design also must include requirements, which occur from the planned characterization methods to. This is of special importance if samples are used with designs different from normal modules to enable e.g. humidity ingress monitoring.

In the next step the test parameters have to be set to ensure that the expected reaction of the sample is enabled. Therefore, all relevant influencing loads for the physical or chemical reactions must be included. For example, if a UV-driven degradation process is expected, but it requires the presence of H_2O for the reaction to happen, a plausible level of water and irradiation must be ensured. The determination of testing parameters can be supported by numerical simulation, typically using FEM or computational fluid dynamics (CFD) [158].

Looking on the BoM of the samples, specific threshold loads for the included materials must be identified. To know and respect the threshold loads avoids provoking processes in the accelerated tests, which are not occurring in reality. It must be ensured that the test is performed in a load regime, which triggers only wanted and similar to the real operational degradation. Similar induced degradation processes, compared to the ones of outdoor operation, warrant meaningful results. The most critical load parameter for this issue is typically temperature. Testing at too high temperatures is especially critical for organic materials. Using too high intensities provokes unrealistic effects and leads to failures, which are not representative and relevant for a normal operation. With testing parameters exceeding the threshold values, it is more likely to terminate all types of samples instead of generating valuable results. The aim remains, to address a functional and sustainable development of PV industry, see also section 6.4.

6.2. Sequential vs. combined testing

There are different approaches to address the issue of serving multiple load factors/stressors in accelerated ageing tests (see also sections 2–4). One approach to meet the requirement is designing tests where the different load factors are applied in a serial way and still be effective, even though they are not happening at the same time [159]. Sometimes serial testing is used to narrow down on influencing factors to address specific failure modes one at a time [160]. This approach is called sequential testing. It is used in most tests of the IEC 61215 series and is also most common in the laboratories testing PV modules. The reason for the dominance of sequential tests is the reduced requirements for testing equipment and less complex test designs and so lower costs.

During the second approach samples are exposed to all relevant load factors for the degradation effect of interest in parallel at the same time. The method is named combined testing. The load factors, which must be included during combined test setups can be numerous. Especially if the overall degradation of a PV module is under research, without a pre-defined focus on a specific failure mode, all load factors must be included. This makes testing equipment extremely complex and is—in full consequence implemented—technically almost beyond the realm of possibility. In application typically, the trinity of load factors temperature, humidity and UV radiation are combined in test sequences. These combined tests use specially designed equipment [104]. They are often named UV-Damp-Heat tests since the applied conditions are close to the IEC type damp-heat and UV exposure conditions. These tests are, due to high hassles, only sporadically applied for full size modules. However, combined testing of small samples is in common usage, since small climatic cabinets are easier to employ and less expensive [133]. These combined tests could prove, that they are able to reveal effects which are not present when load factors are applied separately. In [133] is described, not surprisingly but now proven, that EVA as standard encapsulant for PV cells suffers the strongest chemical and optical degradation when high UV, high temperature and high humidity are combined simultaneously.

Sometimes so-called highly accelerated stress tests (HAST) are also mentioned when talking about combined testing. These tests typically do not address the purpose, idea, and approach as mentioned above. HAST also combines some loads but typically use intensities far above normal operation, including the risk of testing above threshold intensities (see section 6.1). Probably the most common HAST is the pressure-cooker test sometimes used for material testing in PV [161, 162].

Several research groups are working on the development of combined testing sequences, to simulate outdoor conditions more realistically. There are premature efforts of addressing different climates and using full size climatic cabinets. As leading target value is for example the microclimatic humidity level within the modules used [104]. It has also been reported that the exposure to combined loads leads to degradation patterns which are close to patterns after outdoor operation [163]. Further work analyzed the pros and cons of the different testing approaches [164]. Latest developments combine ideas of sequential and combined testing to reach the goal of ensuring realistic load levels of humidity, temperature, and UV. Throughout the hybrid tests, there are parts with combined loads (with UV, T, and RH) and sequential parts (in this case temperature cycling) to keep effort and technical requirements limited. For the module accelerated sequential test, a development over time is recognized [165–167] for example, with tests designed for loads on backsheet materials. Work has also been reported including external mechanical loads into combined tests [168].

All the work shows that the definition and development of the tests, sequential or combined, require numerical simulations to calculate the microclimatic loads during field exposure or accelerated testing. The reason behind their need is that these parameters are defining the relevant loads for each sample and therefore must be used as guiding parameters.

6.3. Test to failure vs fixed test duration

The total duration of accelerated tests can be defined with different approaches. On one hand a pre-defined sequence or number of sequences, defined according to section 5.1, can be applied. Doing so, all parameters of the implementation of the test, namely duration, intensities, total loads, intermediate steps etc are pre-defined and the test is terminated when the planned end is reached. The samples are typically characterized initially and at intermediate steps and/or at the end of the test sequence using pre-defined measurement technologies. The sample behavior is then described using measured degradation effects or performance parameters and, if necessary, sample rankings are generated accordingly. This approach is used when the test is expected to simulate a specific threshold load level. Samples withstanding these loads are seen as qualified for the application.

On the other hand, samples can be exposed to a pre-defined test or testing sequence without pre-defined duration. In this case a specific failure effect or failure mode is defined before starting the test and the samples are exposed until they show the defined failure. This so called 'Test to failure' approach is often used if failure kinetics are not known, but the failure type is seen as critical. They are there to identify samples which can withstand the testing environment as long as possible without showing the specific failure. Samples are ranked afterwards according to the exposure time until failure. For the test to failure approach, suitable time steps to take breaks from testing for (material) characterization must be defined. Suitable non-destructive and non-disruptive characterization methods must be defined to identify the failure as soon as it occurs.

6.4. Limits for acceleration

One of the genuine goals of accelerated testing is to use an acceleration factor as high as possible. It makes tests shorter, typically cheaper and delivers results faster, what is a key element in development processes. Especially in PVs, with expected operational times of several decades, high acceleration factors are desired and crucial. Unfortunately, the possibilities for acceleration are limited if meaningful results shall be generated. Most important are material related limitations for acceleration (compare section 4.1). All materials have different load regimes and, in the regimes, different physical and/or chemical processes occur. To ensure meaningful results of accelerated testing, the accelerated test must trigger similar processes as in normal operation, which requires the sample to be in the same load regime as in outdoor operation. Prominent examples for such material-related limitations are temperature limits of polymeric materials. Testing Polyolefins at temperatures above 100 °C will for example certainly provoke degradation, but not within the similar processes as in operation at below 80 °C. That means a transfer of the accelerated test results to normal operation conditions is not permitted [1, 166, 168, 169].

Further limitations can be due to technical limitations of equipment if e.g. climatic cabinets cannot ensure constant or required temperature or humidity levels because of the parallel use of high intensity irradiation.

7. Established accelerated tests

Accelerated testing has been used in PVs for a long time and there are several very established tests, which are applied all around the world. This chapter gives general information about new developments of the most established tests and testing purposes, which are type approval standards and failure specific tests.

7.1. Type approval and safety standards

Accelerated ageing tests, included in the international type approval and safety standards, are the most commonly applied tests and sequences for PV modules. The tests are defined by the Technical Committee TC 82, Working Group WG 2 of the International Electrotechnical Commission IEC. Their latest version is the IEC 61215–2:2021 *Terrestrial photovoltaic (PV) modules—Design qualification and type approval—Part 2: Test procedures*.

The safety standard IEC 61730–2:2016 *Photovoltaic (PV) module safety qualification—Part 2: Requirements for testing* included nearly the similar accelerated ageing tests on module level. Thus, they are discussed together.

The standardized tests aim to ensure a certain quality and safety level, which is not directly linked to a specific load or operational situation. There can neither a correlation be withdrawn beyond the title 'Terrestrical photovoltaic…' nor a defined lifetime. The tests focus solely on quality and design flaws and help to identify early default and deficiency, also known as 'infant mortality' issues. The most common standardized accelerated aging tests are the following:

- Damp Heat (DH) [*Module Quality Test MQT 13*]: exposure at 85% r.h., at 85 °C for 1000 h. DH is often used to identify degradation effects caused by high humidity and temperatures e.g. in coatings or polymers.
- Temperature Cycling (TC) [*MQT 11*]: exposure to 50 or 200 temperature cycles between −40 °C and 85 °C. TC is used to provoke degradation related to internal mechanical stress e.g. in electrical connections or tension in polymeric materials.
- UV preconditioning (UV) [*MQT 10*]: exposure to 15 kWh m^{-2} of UV light. It is used to provoke UV degradation effects, mainly in polymeric materials.
- Hot Spot Testing [*MQT 9*]: exposure to full illumination with partial shading of one cell to provoke hot spots and test safety under these conditions.
- Humidity Freeze (HF) [*MQT 12*]: exposure to 10 cycles from −40 °C to 85 °C, at partially 85% r.h. HF is used to test effects of freezing water and humidity on and in materials, especially porous material.
- Mechanical Load (ML) [*MQT 16*]: exposure to an external mechanical load of at least ±2400 Pa to test effects of snow or wind loads.

The majority of these tests have not gone through significant changes during the last years or even decades and they most likely neither will, because they do not aim at simulating outdoor operation. But still, they are applied mostly all companies and institutions working on PV reliability issues. Further tests are defined in the standards, but they are mostly not accounted as accelerated tests. A description can for example be found in [122].

Often the standardized tests, mainly DH, TC and UV, are applied for even longer times and more cycles as requested by the standards. Test results from DH4000, with elevated humidity and temperature conditions for 4000 h, or TC600 and TC800, with 600 or 800 thermal cycles, are published very often with the aim to state an elevated quality level. But it is important to mention again, that they are not directly linked to real operational load conditions, and they especially do not differentiate between different load situations of different applications or locations. Instead, the tests should help to identify weaknesses and issues of materials and designs as statistical analysis shows [170]. Some tests, here especially the UV test should be mentioned, only apply a relatively low dose of stress. The required 15 kWh m^{-2} only correspond to approximately three months of outdoor operation in moderate climates. A correlation to mid- and long-term exposure is not given, nor a correlation to more intense irradiations in other climate zones. As infant mortality screening it might not even be sufficient for other than moderate climate zones.

Since the tests are standardized and applied for decades, comparability of results is in general expected by the public, especially if tests are performed by accredited test labs. Nevertheless, there are severe differences, which can lead to different results, as exemplarily older comparison of UV tests among different test labs showed [137]. It is expected that the situation did not improve in the meantime. Recommendation on that issue is not to change methods during the qualification of devices and not expect results to be easy to analyze after a change. Many attributes of testing equipment and conditions have to be considered otherwise.

There have also several failure specific tests been developed and standardized but they are not completely established. Descriptions of failure specific test can be found in section 7.2.

7.2. Failure specific tests

There are several specific failure modes which can occur in PV modules under different conditions [6]. For some of them, the most relevant failures for the PV technology, specific tests have been developed to analyze the modules susceptibility. The sensitivity towards specific loads or the susceptibility for the specific failures are targeted. A very wide-ranging overview on failure modes of PV modules including the driving loads and the measurement and—whenever available—the physical or chemical explanation of the failure modes can be found in [5]. Some failure modes have been already analyzed in depth and they are seen as so important that related testing standards have been established. One of these failure modes which was analyzed during the last decade is PID [164, 171, 172]. It is reported that in the meanwhile developed tests and the established standard 'IEC TS 62804–1:2015 *Photovoltaic (PV) modules—Test methods for the detection of potential-induced degradation—Part 1: Crystalline silicon*' are helpful to identify PID prone modules, but the relevant processes are not completely understood or modelled. That leading to incidents where qualified modules still developed PID.

A degradation effect that became very important in the last couple years is the LeTID. LeTID is currently major focus topic of research among scientific institutions and test labs [173–175]. Here, several tests and even standards have been developed, as to mention IEC TS 63202-4 ED1—*Photovoltaic cells—Part 4: 'Measurement of light and elevated temperature induced degradation of crystalline silicon photovoltaic cells'* on cell level. But this effect typically takes very long time to develop, and thus it is still hard to differentiate between LeTID effects and 'normal' degradation effects especially during simple type approval testing.

8. Service life prediction and correlation of accelerated testing on real operation

The final goal of accelerated testing is predicting the service life of PV modules under normal outdoor conditions. The chapter gives an overview on developments related to service life prediction (SLP) of PV modules using data of accelerated ageing tests and the correlation of these tests with outdoor operation and effects.

8.1. Service life prediction

PV module components degrade over time during operation, which leads to electrical performance loss [7–10]. The service life of a PV modules depends mainly on the BoM, PV technology and the climate which the PV module operates in, as these two factors highly influence the type and rate of degradation mechanisms. PV reliability research mainly aims at: developing models to predict the degradation rates as well as the service life of PV modules with acceptable accuracy, and to propose lab-based accelerated ageing tests that can simulate near to real-world conditions and their impact on PV modules.

There is an increasing interest in understanding how PV modules and components degrade over time and service life prediction of PV modules. Indeed, this can be shown by the trends in the number of publications focusing on these topics over the years (see figure 1). From the figure it is clear though that there is a slow development on lifetime prediction models on comparison to degradation studies.

To develop degradation rate or service life prediction models, a more detailed understanding of the specific degradation mechanisms and their interactions need to be investigated. The dedicated accelerated ageing tests help to identify degradation mechanisms in isolation by applying specific stresses that induce these degradation mechanisms. The unsolved puzzle is on how to combine the induced degradation mechanisms from indoor accelerated ageing based-on specific stressors to predict the service life of PV modules in outdoor operation with combined stressors. According to the recent IEA-report on service life estimation of PV modules [3] the use of accelerated ageing tests to predict the service life of PV modules is still a challenge. Although, different approaches are available, based on physical and statistical methods to extract the degradation rates from operational PV modules, not so much progress has been done to develop service life models based on physical- and chemical-degradation of PV components that can allow 'what if' simulations.

The few authors [176, 177] that have developed physics-based models use an empirical approach with a general assumption that the degradation rate kinetics depend on a single dominating degradation mechanism neglecting the intermediate steps involved in degradation kinetics (see also section 4.2). To develop more reliable service life prediction models, degradation pathway network models for specific degradation modes using network structural equation modelling (netSEM) analysis (mapping stressors, mechanism, and responses) [178], need to be integrated in degradation rate models. The netSEM analysis is useful to understand the complex interactions between variables and includes metrics that highlight statistically significant relationships. This provides an in-depth insight into the mechanisms of degradation in PV modules.

The assessment and evaluation of degradation of PV modules with different BoM, PV technologies and in different climates is crucial input to validate and develop realistic hypothesis of service life prediction models. Comprehensive studies such as the one by Jordan *et al* [179] where more than 11 000 degradation rates from over 200 publications were assessed and categorized according to PV technology and climate zones need to be updated to keep track of the degradation behavior of new PV technologies and BoMs in the field. This can be useful to validate the sensitivity analysis of service life prediction models based on technology and climate zones.

8.2. Correlation of accelerated testing on real operation

Apart from the standardized pass/fail criteria, accelerated testing is aimed at investigating the degradation behavior of PV module components under different testing conditions. The degradation assessment from indoor accelerated testing should mimic the degradation of PV modules in real operating conditions. For example, the schematic diagram figure 2 shows an ideal cycle for PV module reliability studies and correlation of accelerated testing to real operation.

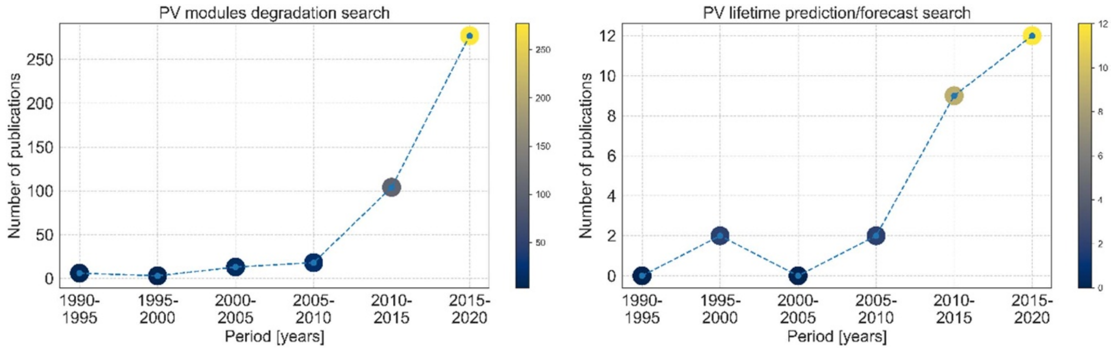

Figure 1. Trends on the number of publications grouped into five years periods on PV/photovoltaic module degradation and PV/photovoltaic lifetime prediction/forecast. Data generated from google scholar with the keywords only in the title to filter papers mainly focusing on the topics.

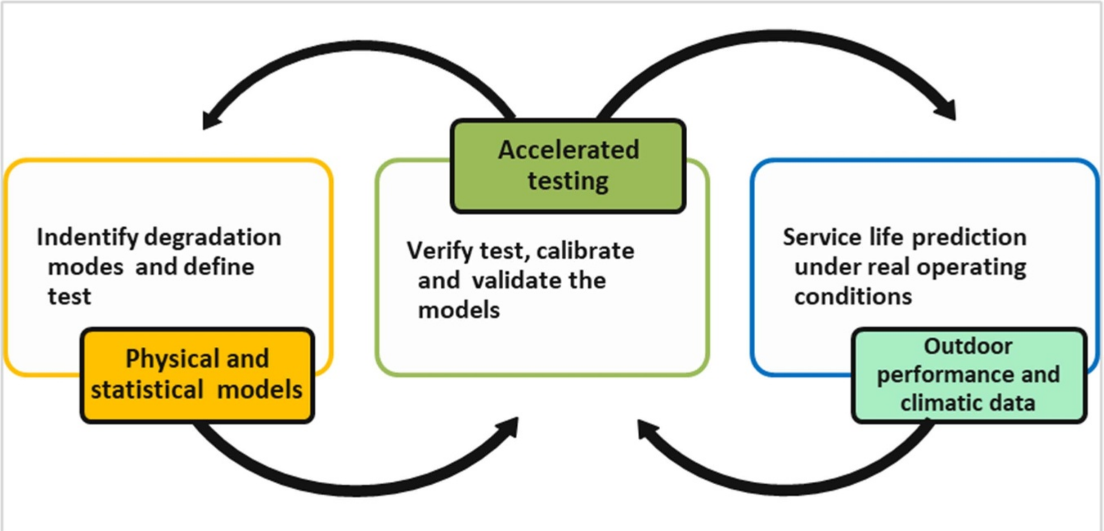

Figure 2. Correlation cycle of accelerated testing to real operation of PV modules.

Every block of this cycle is an input for the others e.g. starting at block one, degradation modes can be identified based on failure mode and effect analysis studies [180] and using models, experimental design to induce the degradation modes can be achieved. In block two, the tests are verified using accelerated testing conditions and the generated data help to calibrate the models. The calibrated models are then applied to predict the service life of PV modules in real operating conditions using real environmental data in block three. The analysis can also start from the analysis of performance data (block three) of already installed modules if available, to developing validated models (block one).

But the question remains 'to what extent is this cycle valid?' or 'to what extent are the accelerated indoor tests comparable to real life exposure?'. This indeed remains a challenging question due to the complexity of PV module designs. Firstly, PV modules come in different technologies, with different bills of materials and operate in different locations with very different climatic conditions. All these differences lead to a variety of degradation modes and degradation rates [170]. Secondly, frequent changes of PV module designs, technologies, and materials [181], represent an additional lack of understanding of the degradation modes since new materials and technologies usually come with reliability challenges. For example, improving a specific PV module component to be resilient to a specific degradation mode might induce a completely new degradation mode. Such challenges and the lack of long-term understanding about the performance and reliability of these new materials hinders the correlation of accelerated testing to real operation. In addition, in outdoor operation PV modules experience a combination of numerous climatic stressors at the same time in comparison to controlled conditions in indoor testing. The combination of different stressors leads to synergetic tendencies of the induced degradation modes and might induce degradation modes not identified during accelerated aging testing. This means that the induced degradation modes during indoor experiments could differ from the ones induced in real life operation hindering the correlations. The vice-versa is true, too, due to the extreme stressors applied during accelerated aging testing, some degradation modes might be triggered which might not really be observed in real operations.

Despite the challenges in the indoor-outdoor correlations, several research groups are working towards these challenges, for example in [182], the authors adapted/advanced the existing standard procedures for PV modules/components testing to optimize the testing that can simulate certain climatic conditions. They applied time-dependent and repeating exposure to combined climatic and environmental stressors (temperature, temperature cycles, humidity, irradiation, mechanical load, salt mist) to induce performance losses, material degradation, and failures in test modules that resemble those effects occurring in real-life PV installations under comparable climatic and environmental conditions. In another study [168], the authors proposed a combined-accelerated stress test, that can simultaneously combine multiple stress factors to mimic natural environment. This kind of simultaneous combined stress factors testing improves the simulation of near-to field degradation modes hence allowing correlation of indoor testing to real life operation. The bottom line here is that, to allow a good correlation of indoor accelerated testing to real life PV module operation, accelerated testing beyond the standardized pass/fail criteria should be used.

Additionally, the authors in [25, 151, 176], have proposed and applied empirical physical models that can help to translate indoor testing conditions to outdoor conditions. However, the models only focus on specific stress factors applied during the accelerated testing and not on a combination of different stresses. A model that combines numerous climatic stress-factors together with a combined stress-testing protocol could provide a good solution for correlation of indoor testing to real-life operation and could allow more accurate lifetime prediction based on indoor testing.

9. Conclusion and outlook

The research activity on accelerated ageing and field performance of PV modules has significantly increased during the last decade. The increasing interest finds its causes in the growing market accompanied with the technological development and diversification, along with the rising importance of PV for the financial sector. The latter is demanding reliable quality and performance data. The need for such data has been increased since reliability data has major impact on the sustainability and economy of the generated electricity.

Field performance is the crucial parameter for all PV installations since it determines the economic success. It is therefore essential to provide relating data in general for a successful deployment of PV modules and in particular for quality and reliability assurance purposes. Progress has been noted in determining operational load conditions in field use. This leads to improved availability of data sets on (environmental) climatic conditions and microclimatic loads on the sample. That can be used to overall describe the parameters and sample itself. This progress enables improved load and risk analysis and for example, the creation of maps for load factors and expected degradation rates. But there is still a clear shortcoming notable regarding the public availability of validated data. These include microclimatic data and the direct translation from module and local data into degradation effects and degradation rates. However, there are estimations available on the dominating processes but concluding and sound scientific explanations on dose-response relationships and reaction kinetics are still missing. Comprehensive analysis and data sets for upcoming technologies for example, floating PV or vehicle integrated PV, are not yet available.

Recent progress in accelerated ageing research mainly addresses the lacking correlation of accelerated tests to real operational conditions. Different load factors have been tried to combine in tests or test sequences to approximate the ultimate benchmark, which is the real outdoor conditions. Also, tests have been designed to address specific failure modes and for identifying degradations effects in materials. Meanwhile, some of such tests are commonly used and have partly even been transferred into standardized tests. In quality assurance, typically the tests defined in IEC 61215 are still dominating, even if they cannot be related to Service Lifes or translated into operational conditions. Often the test durations are simply multiplied to target higher quality levels, which is critical since they anyway cannot certify for a specific degradation rate nor lifetime.

Numerical simulation tools are regularly used to support the pre-definition of testing conditions. Especially in the ongoing development of combined and sequential testing programs with different loads factors, simulations can help to find meaningful and (cost) efficient test designs.

Substantial progress was made in modelling of degradation rates and predicting service lifetimes. These models include multi-step degradation calculations for PV modules. Field data are analyzed and the (expected) dominating degradation processes predicted with statistical and physical models. For an efficient use of these models, validated high quality data from outdoor operation is as crucial as module type specific data from accelerated ageing tests, and derived kinetics data.

It is expected that there will be a continuously increasing interest in the field of accelerated ageing and field performance research in future. This development is already driven by the financial sector and by required sustainability assessments. If sufficient emphasis is placed on the aforementioned shortcomings and presented limitation are carefully handled, a sound state of the art of model-based reliability, yield and service life predictions seem within reach in the coming ten years. That said, this prediction is made under the condition of available data, validated (material) degradation parameters and field performance data sets, which is only to be accomplished with comprehensive and suitable field data for statistical analysis.

Data availability statement

No new data were created or analyzed in this study.

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