Assessing reliability risks using the FMEA production process

Bengt Jäckel[1], Matthias Pander[1], Ringo Koepge[1], Stephan Großer[1] & Karl-Anders Weiß[2]

[1]Fraunhofer Center for Silicon Photovoltaics CSP, Halle, Germany; [2]Fraunhofer Institute for Solar Energy Systems (ISE), Freiburg, Germany

Abstract

PV manufacturing has progressed quite a bit in recent years, from handmade products entailing high human-effort-based assembly to fully automated cell and module factory production in just the last decade. Machine-based production offers high reproducibility; nonetheless, it can lack the ability to easily make required production process adjustments. Production windows can be maintained comfortably provided nothing changes; however, if materials change and require more process adjustments, those – no longer appropriate – processes can lead to variable production quality and can therefore cause long-term durability issues. This paper presents a way to evaluate production windows and related field issues using an adapted failure mode and effects analysis (FMEA) approach. Since PV modules are the most important component in terms of longevity and warranties, the focus of Fraunhofer's work has been on module manufacturing. The process, however, can also be applied to cell manufacturing and other steps in the value chain. By means of FMEA methodology, a group of equipment and module manufacturers, along with several interdisciplinary scientists, have analysed possible production issues and their impact on reliability and have determined the important factors for risk, detection and severity. The processes with the highest risk priority numbers (RPNs) are followed up with regard to process variations and a detailed indoor and outdoor test study. In view of the fact that data analytics is gaining importance for process optimization, an example is given to demonstrate how data can help to improve process stability, as well as increase efficiency, reliability and production yield.

Introduction to PV module production FMEA

Failure mode and effects analysis (FMEA) protocols have been used for several years in other industries to improve production yield, overall quality and reliability of the end product. This methodology is not limited to the product itself and its use, but can be applied to individual production processes as well. This paper describes the introduction of FMEA to certain steps of the PV value chain, while not being limited to them. Furthermore, there will be a brief discussion of how large data sets collected during manufacturing can be used to optimize production yield and efficiency, and therefore further reduce the CO_2 footprint associated with PV electricity.

"The aim of the FMEA methodology is to install enhanced and standardized procedures for future material and machinery changes within the manufacturing process."

The PV industry is always under pressure to enhance the efficiency of cells and modules [1] and optimize production processes in order to obtain higher yields, while at the same time further improve the longevity of the products and reduce costs. Most modules come with a performance warranty of at least 20 to 25 years, with some manufacturers even stating 30 or more [2]. The majority of known failures consist of mainly 'infant mortality' issues, typically occurring within the first 5 to 10 years of operation [3–11].

Wafers used in the solar sector have seen a significant increase in size in recent years, moving away from the classical 6-inch (156mm) wafer to the M12, with an edge length of 210mm. Logically, this has meant a need for considerable improvements in crystallization and wafering processes. There have also been significant changes in the development of solar cells and modules. Incremental, but still significant, technology improvement phases occur within a time frame of 6 to 12 months. Accelerated testing in climate chambers, however, should be as short as possible and durations range from a few weeks to a few months. Therefore, highly accelerated stress tests would be needed to really speed up degradation processes by a factor of around 100. In durability and reliability testing, reasonable ageing acceleration can mostly only be achieved with a factor of around 10 if a correlation to normal operation processes can still be ensured. Within these constraints, the best possible decisions must be made at each stage of PV product manufacture. The FMEA approach can help to narrow down certain risks and to add more R&D efforts to address the riskier issues that may lead to significant effects on return rates or safety concerns. Consequently, there must be a thorough understanding of which effects the test protocol should address, and what possible root cause is behind the degradation or failure mode.

The focus of the work reported in this paper is to look at all relevant production processes of a standard c-Si PV module with an adapted PV-specific FMEA protocol. The adapted FMEA procedure is set to focus on a more in-depth understanding of the severities of production process variations and material variations within given types of material. The aim of the FMEA methodology is to install enhanced and standardized procedures for future material and

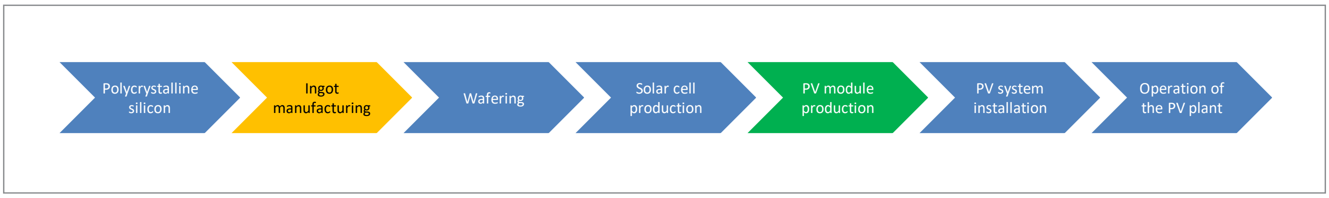

Figure 1. Major production steps in the PV module value chain.

machinery changes within the manufacturing process. The protocol should therefore help to avoid production-caused defects, enhance overall quality and lower the risk of field returns, while improving field return estimation.

Ongoing optimizations and enhancements of production processes are essential for reliable and cost-competitive products in the future. The aim of the production process FMEA approach is to basically perform a design of experiment (DoE) to optimize permissible production windows in order to achieve reliable products and/or improve production yield (more products per hour and/or better utilization of materials and reduced waste). The designed experiments should help to better address the specific related degradation and failures.

The FMEA approach

The FMEA methodology was developed by an interdisciplinary team with contributions from PV module manufacturers, research institutes and equipment suppliers. It is an analytical method of reliability engineering and performed to provide a sort of qualitative statement. Possible product defects and failures are evaluated according to their significance for the customer or during their intended use, their probability of occurrence and their probability of detection.

Fundamentals of the FMEA approach

In general, the FMEA approach can be supplemented with a study to include the criticality, for instance regarding life hazards and claim rates leading to an FMECA protocol (C = criticality). However, it was decided to reduce the complexity and to cover those issues causing life hazard risks as safety hazards, and as such set severity S = 10.

The general principle of the FMEA methodology is to identify, prioritize and rate field defects, with the aim of achieving a deeper understanding in order to overcome in the long term such risks/defects. Following the methodology of the FMEA approach, the risk priority number (RPN) is the multiplication of the rating values for severity S, probability of occurrence O and probability of detection D (in the factory). The latter is important, as this number sets a focus on specific production processes, materials and product designs. Severity, occurrence and detection can take on values of 1 (no impact, very low probability of occurrence, 100% detection probability) to 10 (severe impact, very low probability of detection, safety hazard); this results in RPNs from 1 (best product, no problems) to 1,000 (very high risk of catastrophic failure, not detectable in the factory). An additional prioritization number – the priority number (PN) – is calculated by multiplying S and O, leading to priority numbers from 1 to 100 (high risk of catastrophic failure).

An all-inclusive FMEA approach for all PV plant components is not yet feasible. The current work described here therefore mainly focused on the production processes within the PV module value chain (see Fig. 1), and how such processes can influence long-term module reliability. Some aspects, such as specific PV module designs or failures due to specific climatic/weather events, are thus excluded.

Fig. 1 shows a brief overview of the PV value chain. A detailed insight into the PV module production steps (marked in green) is given below. However, as a prime example of additional data analytics, a section of this paper will focus on the ingot manufacturing part (marked in orange).

PV module production FMEA

For PV module manufacturing FMEA, the following steps, as indicated in Fig. 2, were investigated. The sequence begins with incoming goods inspection, which also includes source material verification, such as the quality of cells and the homogeneity of (for example) backsheets and encapsulation materials.

Some of the materials require certain storage conditions (e.g. EVA, ECA), which may impact

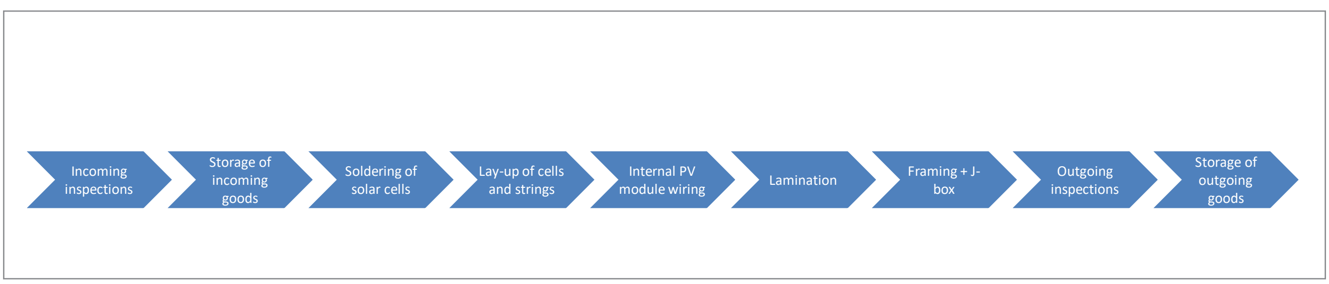

Figure 2. Main PV module production steps.

the long-term reliability of the product. Solar cell soldering (stringing), lay-up of cells and strings, contacting of cell to cross connectors, contact formation to junction box, lamination, framing (including trimming of the laminate and curing of the typically used silicone), outgoing goods inspection (important for the detection) and finally the packaging and storage of the PV modules prior to shipping were evaluated.

Before evaluating each production step, the points to allocate to a certain O, S and D (1–10) must be defined. Table 1 gives the details for the evaluation of the FMEA criteria used in this study. As can be seen in the severity definitions, the focus was on performance but also on critical issues, such as failures which can lead to serious injuries or, in the worst case, to fatality.

Depending on the type of manufacture, the emphasis/priority may lie on different topics and will be determined by process and machinery understanding. This paper focuses on the general aspects related to PV module manufacturing that can be used for any factory. Specific manufacturing for so-called *Sondermodule* (special module) [12–13] production, as used for vehicle (ViPV) or building-integrated PV (BiPV), will be discussed elsewhere.

The incoming goods inspection is intended to verify material specifications that were established on the basis of product design and proper material selection (type of material and manufacturer). This forms part of the design phase and will not be discussed here, as the focus will instead be on production. However, it is an essential procedure in order to produce reliable PV modules, since measurable material variations compared to specifications can become critical during later operation.

Depending on the supply chain and delivery lots, the storage of goods must be considered a part of the overall value chain. The impact will be minor if storage is properly carried out and according to the vendors storage specifications (time, temperature, humidity, light). The lay-up of cell strings, if done with care, and the framing process only have a minor impact on product reliability; therefore, these were not focused on in detail. It must be pointed out, however, that misaligned strings or spacings between cells and strings not as designed have an aesthetic drawback; moreover, they might cause serious 'defects' for 'Sondermodules' or may void spacing requirements stipulated by IEC 61730-1, therefore possibly leading to higher degradation rates, for example as a result of moisture ingress.

The main emphasis was placed on the electrical contact formation (e.g. soldering parameters) and lamination process. Soldering is a complex process of electrical contact formation, and the reliability highly depends on the materials (solder, solar cell, ribbon, coating) and the process parameters (temperature, time for heating and cooling). In typical PV modules there are three steps involved in electrical contact formation: 1) cell interconnection; 2) cross connection of cells; 3) cross connectors in the junction box. With modern half-cell module designs and the increased number of busbars, the cross-connection process becomes more and more important, especially in the centre of the module.

Lamination is typically a heat- and pressure-controlled process to achieve cross-linking of the materials (in the case of EVA, for example). There are several steps, including liquefaction of the encapsulant to achieve a homogeneous film of encapsulation material around all components, and a vacuum process to remove any air and moisture bubbles and cross-linked by-products. Depending

Probability of occurrence O	Impact/Severity S	Probability of detection D	Points
Unlikely	Hardly noticeable	High	1
		The error is detected in any case by common measures, so that a very prompt correction is possible.	
Very low	Fairly insignificant	Moderate	2 to 3
	Aesthetic, very little effect on performance, no impact on safety, does not fall under warranty.	Procedures are in place to enable early detection. However, measurement and test results can be misinterpreted, for example, or incorrect assessments can lead to the defect being overlooked/disregarded.	
Low	Moderately serious	Low	4 to 6
	Measurable and clear effect on performance, increased clarification effort with customers to be expected, no impact on safety. Compensation or repair is possible at reasonable expense.	Only detectable with accurate and comprehensive testing, which is rarely performed on small samples – detection likely to occur after module delivery.	
Moderate	Serious	Very low	7 to 8
	Measurable and clear effect on performance, impact on electrical safety or fire. High liability risk and high follow-up costs to be expected (e.g. module replacement).	Not detectable with common QA measures. Process monitoring does not provide any clues. Detectable using very elaborate tests, but these are not routinely performed. Detection certainly only after module delivery.	
High	Extremely serious	Unlikely	9 to 10
	Can lead to serious injuries or fatality.	There are practically no effective early detection methods. Defects only become evident in operation after delivery.	

Table 1. FMEA evaluation criteria.

on material quality (mixture of the encapsulant) and the lamination process, various things can go wrong and the defined specifications, such as transparency and degree of cross-linking, are not met. Besides the cross-linking, the process steps are also similar for other encapsulation materials, for example polyolefins (POs), and almost identical for EVA/PO-blends (POEs). Alternatives also exist, however, such as the use of silicone-based materials, where such multi-step lamination processes are not necessary. Other obstacles such as the correct and homogenous mixture of two component materials must be overcome.

Outgoing inspections play an important role in the possible detection of defects. Misaligned strings, large bubbles or impurities within the laminate, such as pieces of gloves or insects, can typically be easily identified by visual inspection. Significantly damaged cells or bad soldering will lead to low-output power modules and low fill-factors in *I–V* curve testing, and most likely will be evident in electroluminescence (EL) imaging. Such defects are deemed to not be severe in the long term, because the detection probability is very high (and hopefully will be sorted out). The more concerning issues are those that are not visible in the 100% routine testing that is typically carried out; examples are low gel content due to poor EVA material, improper working heating plates in the laminator, or bad soldering due to temperature, solder or cell variations that were not detected in the incoming goods sampling and process surveillance.

After the outgoing inspections the modules are stacked, packaged and sent to a warehouse. This is usually not an issue, but there may be transportation problems if packaging material is not carefully selected or is damaged. However, this aspect falls outside the scope of the presented study.

The results presented below focus on electrical contact formation and the influence of the encapsulation process.

Details and results of PV module FMEA

As described in detail in the previous section, the FMEA focused on the PV module production processes rather than the materials or the design itself. As indicated, the emphasis was placed on soldering (electrical contact formation) and encapsulation processes. Both are essential for the long-term reliability of the PV modules; therefore, uncontrolled and incorrect assessments of process variations can lead to significant reductions in long-term durability and so represent an increase in quality issues. A selected part of the FMEA, with the highest PN and RPN, is summarized in Table 2 and will be introduced and discussed separately below.

Predicated on the results of the FMEA, different parameters are selected that will serve as the basis for the specification of tests and for optimizing module production. Test results for specific process variations are presented in the experimental results section.

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Electrical contact formation

The electrical contacts (cell to cell, ribbons to cross connectors, and connections in the junction box) are essential elements in the electrical power output of PV modules. Each cell must be interconnected in series with an increased number of contacts (3 to 15+ busbars in multiwire technology) in order to achieve a reasonable voltage and a certain current so that the power inverters can work effectively. Typically, 20 to 24 cells are therefore interconnected in series. These undergo further serial and parallel interconnection to 60 (120 half cells) to 72 (144 half cells) in a PV module, where in a system, strings of 15 to 30 of such modules are connected in series. This results in a few thousand cells connected to an inverter input, which underlines the importance of excellent electrical interconnection of solar cells, even if there are some backup strategies, such as bypass diodes, built into the PV modules. Furthermore, it must be noted that with a further increase in solar cell size (M6 to M12), besides half-cut cells, third-cut cells are used. Additionally, other techniques, such as shingling with electrically conductive adhesives (ECAs) [15], will use even smaller fragments of cells (1/5, 1/6, ...), but contact formation by ECAs is not the focus in this paper and will be evaluated in future work.

Four selected results for cell solder interconnections are presented in Table 2 ('#1' to '#4'), which range from an RPN of 48 (acceptable) to 168 (can have significant impact). The severity of the selected processes is fairly similar (S = 7–8) and can be a significant concern. The occurrence for each is not very high (O = 3–5), but must still be considered. However, the largest difference lies within the detection probability (D = 2 or 8). With D = 2 ('#2' fluxing issue, '#4' heating issue) the process deviation is reasonably easy to detect, whereas with D = 8 ('#1' 'bad' material, '#3' ribbon crimping) it is more difficult and may require in-depth and costly analytics or detection equipment.

The first two items, 'Soldering #1' and 'Soldering #2', deal with the soldering flux application. Two cases were examined: the first discussed the problem of contaminated flux and the second with no flux application. Because for both cases the occurrence was very low and the more obvious case of no flux application can be detected very well (no soldering), no follow-up actions were considered as a result of the FMEA.

The third item ('Soldering #3') pertains to ribbon pre-treatment within the stringer machine and might not be applicable to all machinery used in PV for cell soldering. The quality of the ribbon crimp is relatively difficult to assess (D = 8). Since the

Process filter	Fault/Question	Severity S	Occurrence O	PN (S × O)	Detection D	RPN (S × P × D)
Soldering #1 – cell	• Flux is contaminated • Occurs infrequently, as typical flux nozzles will be clogged What is the impact on solder joints if impurities are integrated in the joint?	7	3	21	8	168
Soldering #2 – cell	• Flux is not applied • Occurs if flux nozzles are clogged because maintenance intervals are not properly chosen What happens to the contacts?	8	3	24	2	48
Soldering #3 – cell	• Ribbon crimp: material damage to the ribbon • Rare occurrence – typically only if broken tooling is used What is the impact of pre-damaged ribbons on long-term stability of the PV module?	7	2	14	8	112
Soldering #4 – cell	• Hot cell string: over-soldered cells due to machine stoppage • Occurs several times per day It is unclear what the long-term effects of hot cell strings are. Currently, such strings are segregated – but is that necessary?	7	5	35	2	70
Soldering #5 – cross	• Not soldered or badly soldered ribbon-to-cross connector joints • Misalignment What is the long-term impact of individually uncorrected ribbons at cross connections? Does extra bending or misalignment reduce reliability and lead to early connection fatigue? Section separated into 3–6 BB (top) and ≥9 BB (bottom).	7 5	5	35 25	4 7	140 175
Lamination #1	• Low or excessively high degree of cross-linking of EVA encapsulant • Occurs if process control for heating phase is faulty: heating phase is 20–30% too long or too short • Observation: modules look normal, with no drift of cells within the laminate How is module durability affected with over-cured EVA?	5	5	25	7	175
Lamination #2	• Low degree of cross-linking of EVA encapsulant • Occurs if fault in laminator, bad material, or lamination process performed too quickly What happens in the case of a gel content in the range 65–80% or lower?	5	5	25	7	175

Severity S: 1 (very low risk) to 10 (deadly)
Occurrence O: 1 (very low) to 10 (very high, certain)
Probability of Detection D: 1 (certain – fault will be caught on test) to 10 (fault is undetectable)

Table 2. Selected part (highest PN and RPN) of the FMEA process. (Adapted from Jaeckel [14].)

occurrence in the particular machinery used was regarded to be very low, no immediate follow-up was agreed on.

The last item ('Soldering #4') discussed here for solar cell soldering relates to process time and temperature profile during the soldering process. Such variations occur more frequently (e.g. as a result of production stoppages due to cell breakage) and therefore have a more important impact on overall production yield. As a very similar heating process is performed to cure ECA in both shingled and H-grid technologies, this FMEA step is important not only for soldering, but also for future ECA-based electrical interconnection. The focus for follow-up tests was set to that 'process-stop' observation, even when the RPN was not very high. However, in standard production, case '#4' occurs more frequently than the other discussed issues. Additionally, it allows one to gain a more in-depth understanding of the significance of permissible process windows. To investigate the effect on the long-term stability of the modules, special samples were built which incorporated the particular defect, and long-term test-to-failure experiments (including extended thermal cycling tests per IEC 61215-2 MQT 11) were commenced. The results will be given in the next section.

To conclude the soldering discussion, the impact of internal module string-to-string soldering is addressed ('Soldering #5'). Where in the past, for three to five busbar cells, 6 to 10 interconnections had to be done, for modern half-cell modules with 9 to 15+ busbars, 18 to more than 30 individual connections are necessary. For half-cell modules with the so-called *butterfly* design, this becomes even more complex in the centre of the module, because ribbons must be interconnected to one cross connector from two sides. Therefore, it becomes very likely that a connection is either not properly formed or not at all. The detection of such defective electrical connections might not be easy.

In *I–V* curve measurements, the impact of one missing ribbon for a higher number of busbars (>4) is fairly small and will most likely not be visible.

With the use of EL imaging, it is clearly visible in the case of three to five busbar cells, but becomes more difficult to see with an increased number of busbars, and almost impossible for 'bad' solder connections, where 'bad' can mean just a pressed contact without solder-joint formation. Other detection methods, such as magnetic field imaging (MFI), might be required [16]. A detailed study of this production step is planned in combination with novel detection and root cause analytic methods.

Encapsulation process

The encapsulation process is one of the key processes in PV module manufacturing, as it is intended to protect the solar cells from all environmental influences – such as moisture and mechanical hazards like snow, hail and wind – and ultimately to assure electrical safety in protecting against the hazard of electrical shock.

Most manufacturers use a lamination process to encapsulate the solar cells. Because lamination is primarily the bottleneck process, optimization is often done at this point, with a focus on reducing process time and thus increasing throughput. Lamination is a complex process requiring several parameters to be balanced out (heating, vacuum, pressure, time) and is moreover significantly dependent on material properties. It is also influenced by environmental parameters, such as ambient temperature of the manufacturing facility. Smaller variations in material properties and environmental parameters are summarized with regard to their impact on the degree of cross-linking; their impact is only slightly greater if the degree of cross-linking varies within ±10% ('Lamination #1' in Table 2). Typically, such modules show no obvious optical findings directly after manufacturing, and detection is quite challenging (D = 7).

Modules with a very low degree of cross-linking are made intentionally by significantly accelerated lamination processes, caused by a defect in the laminator, or result from very poor quality of the encapsulation material ('Lamination #2'). The latter should be detected earlier on in the incoming goods inspection. A defect on a heater plate in a laminator can occur and may not be detected immediately and depends on the type of laminator and the sensors in the laminator. In consequence, it can happen that several batches are processed prior to the problem being detected (D = 7). Depending on module tracking in the factory, such modules can be traced back, but this also depends on the sensors and tracking of modules throughout the module production process. From past experience, modules with a low degree of cross-linking demonstrate a higher probability of delamination.

An example of a six-year-old module is shown in Fig. 3(a). On the basis of the RPN and the importance for the production quality and yield, this process flaw was further evaluated, and samples were constructed to better assess the direct influence by comparing good and low degrees of cross-linking.

Experimental results

On the basis of the FMEA results, specially designed modules were constructed and tested against

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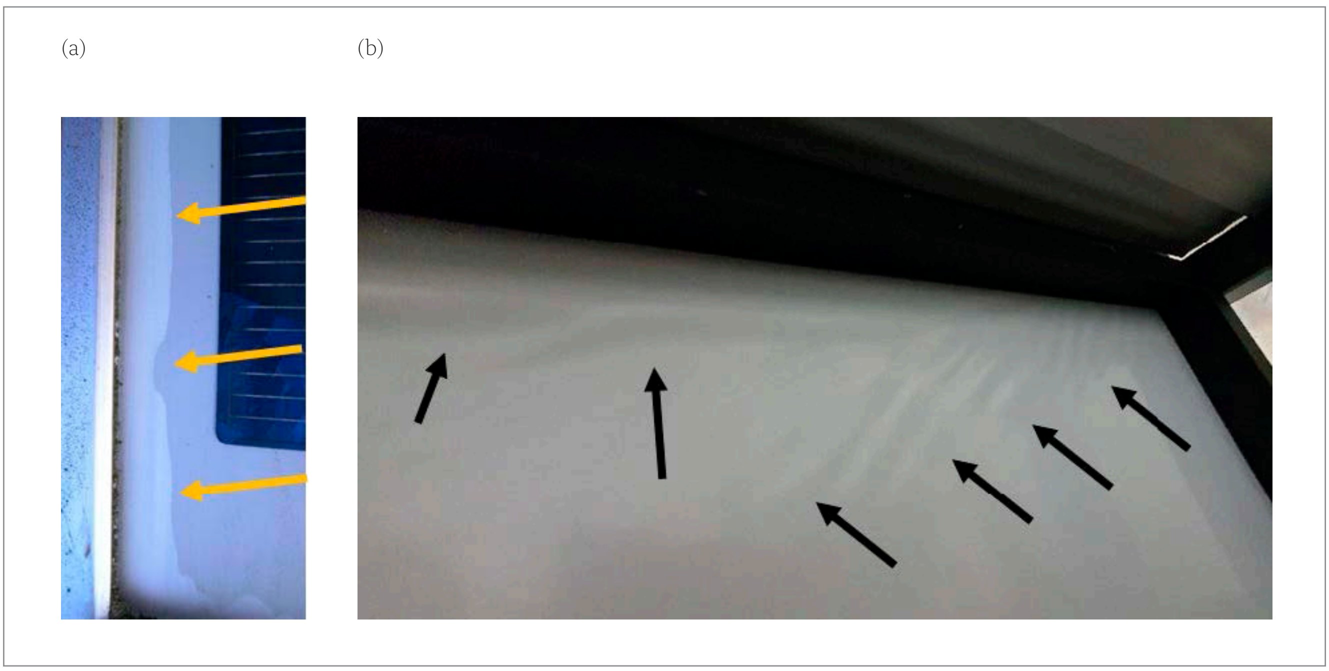

Figure 3. (a) Delamination and bubble formation of a field module from central Europe after approximately six years. (b) Large-area delamination and bubble formation of a specially prepared, low-gel-content PV module after damp-heat exposure (prior to damp heat, the backsheet was optically up to standard), similar in nature to other observations in the field (e.g. in Bosco et al. [17]).

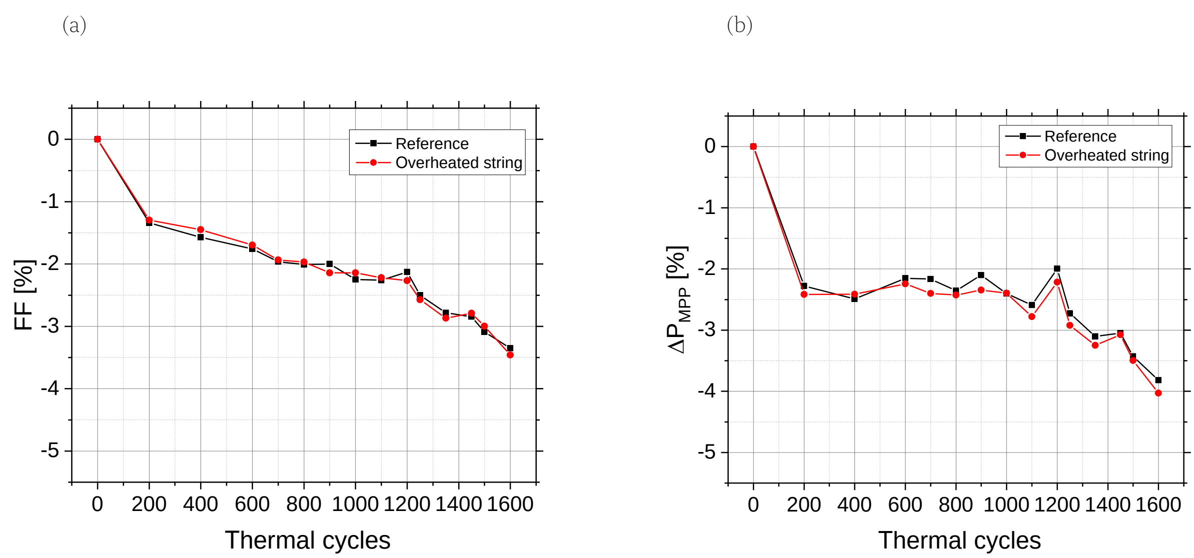

Figure 4. Results of extended TC testing of modules containing an overheated cell string: (a) trend in fill factor; (b) trend in power loss.

reference modules (in-spec, within process window) without variation of the process.

Electrical contact formation

The results for the solar cell soldering process evaluation of overheated strings are given in Fig. 4. A standard type-approval testing temperature cycling (TC) sequence in accordance with IEC 61215-2 contains 200 cycles, running from –40°C to +85°C. Even after extending the stress period by a factor of eight, to more than 1,600 cycles, no significant differences between reference and out-of-spec can be detected in *I*–*V* curve measurements. In the EL images, a darkening at the edges of the cells becomes visible (see Fig. 5); this is not correlated to the soldering process, however, since a similar darkening effect was observed on the in-spec module.

Encapsulation process

To evaluate the influence of a low degree of cross-linking (<50%), specially prepared modules were manufactured. The module output power results for extended damp-heat (DH) testing using the test parameters specified in IEC 61215, namely exposure at 85°C and relative humidity of 85% for 1,000h, are given in Fig. 6. The initial delamination effects were visible after ~1,000h of DH, as shown in Fig. 3(b). Standard modules with a high degree of cross-linking (~85%) do not show such delamination.

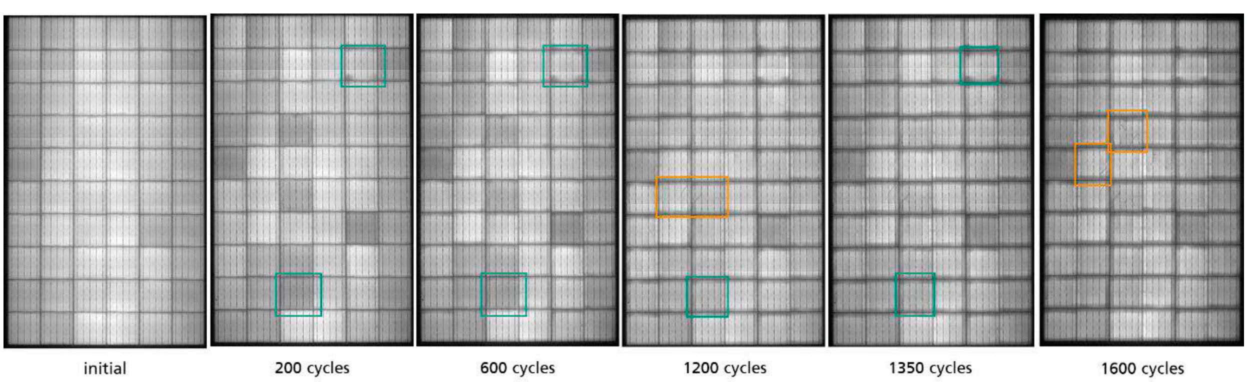

Figure 5. EL images of a module with an overheated string during extended TC tests. Cells with deteriorated edges and with homogeneity changes due to boron– oxygen (BO) degradation/regeneration leading to grey-scale variations are highlighted.

However, the power loss difference after 1,000h is not huge (2% vs 3%), but the trend of the sample with a low degree of cross-linking (red – 'low GC') is expected to be stronger than that of a normally processed module, where losses of around 3–5% are expected after 2,000h. The offset after 2,100h is related to a regeneration treatment and to the particular cells in use. The reference module would have shown a similar jump, which is a kind of dark-state non-current-injection effect.

Process data analytics

Manufacturing processes provide data over the entire PV process chain, the steps of which are shown in Fig. 1. On the one hand, simple protocols are manually established for each process step, but on the other, data are automatically mined, with a high number of values during the process time. Data management becomes necessary for all types of data, and smart analysis demonstrates the potential to reduce process issues and increase production yield [18,19]. In addition to FMEA, state-of-the-art machine-learning algorithms are able to perform process analyses. Multidimensional process data cannot be handled by humans; however, that can be analysed using computer systems by applying artificial intelligence and other approaches from machine learning. Applications for machine learning are available in every step of manufacturing.

For example, if a single process parameter exceeds the limits of the standard production window, the costs of the crystal-growth manufacturing process will increase noticeably. An exorbitant amount of energy is required and costs rise when the crystal needs to melt and is pulled again. Fig. 7(a) shows the melt temperature for approximately 60 crystallization runs, with this melt temperature being just one of 90 process parameters for each run. This means that a 90-dimensional parameter set-up describes a single process run. Successful and failed

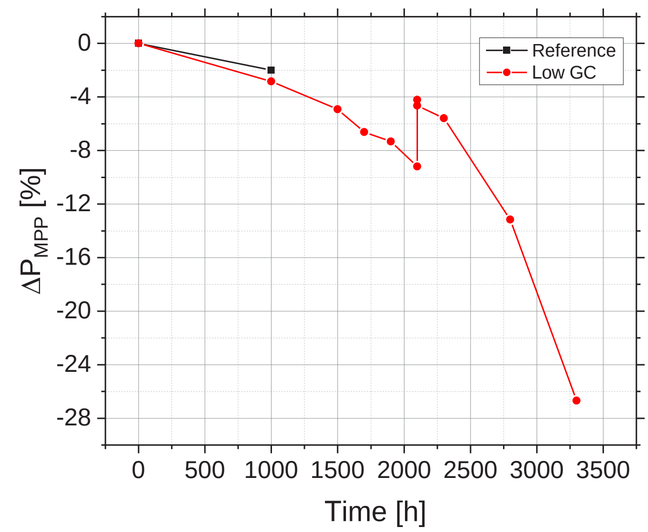

Figure 6. Latest results of extended DH testing of samples containing normally cured EVA modules (degree of cross-linking ~85%) and a module with a low degree of cross-linking of less than 50%. Cells, glass, backsheet and encapsulation material are the same in both cases. These tests are still ongoing.

processes are indicated on the graph in green and red respectively: *failed* means structure loss and re-melting of the crystal. It is not possible to manually distinguish between pass or fail by plotting 90-dimensional process data; thus, machine-learning classifiers were applied and a complete cross validation was performed for each classifier. Support vector machine (linear), support vector machine (radial basis function), K-nearest-neighbour, logarithmic regression and random forest classifier methods were applied for comparison purposes, with the logarithmic regression yielding the best prediction accuracy of 72%.

The machine-learning classification provides a probability of success that can easily be compared to all process parameters by performing a correlation

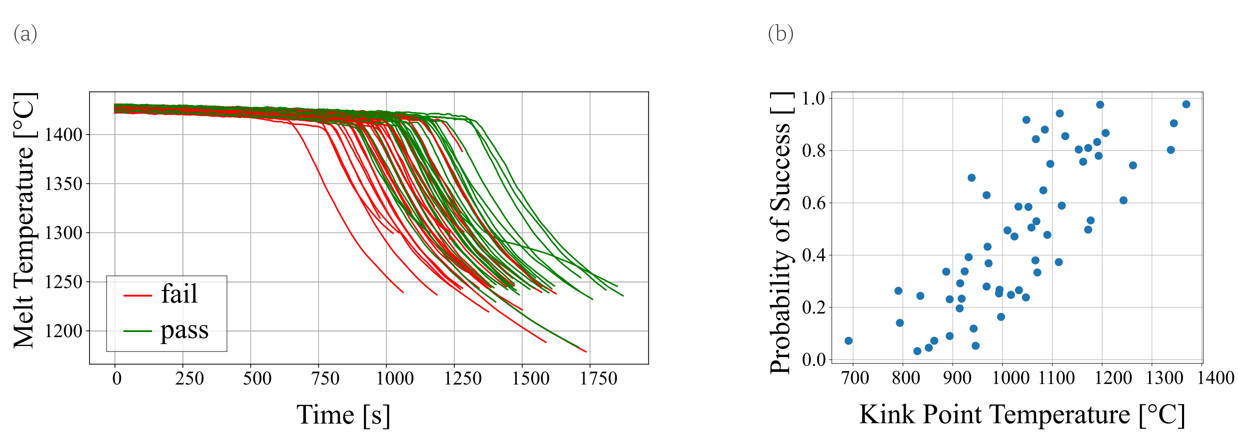

Figure 7. Application of a machine-learning algorithm to distinguish between process failure and process success. (a) One parameter (melt temperature) in 60 crystallization violates the process time limitation (process result is indicated by the colour of the curve). (b) A correlation between process parameter and process result was found by cross validation of different regression models.

analysis; the results are shown in Fig. 7(b). A linear correlation is clearly visible between the probability of success of the crystallization process and a relevant process parameter (time of drop in melt temperature). Without machine-learning support, this analysis would not be possible. By using this information, the success rate of the process can be improved as a result of visualization simplification. Thus, time consumed, costs and CO_2 emissions can be reduced, while increasing production yield and company profit.

If larger corresponding data sets are available, this kind of analysis can be applied to any process step in the PV industry and elsewhere along the chain. For instance, the given bill of materials (BOM) data together with the process data could be correlated to PV park performance data and site conditions in order to produce site-specific reliability reports.

Summary and conclusion

The interdisciplinary combination of a detailed FMEA by manufacturers, equipment suppliers and research institutes, together with modern data analytical methods, can support the future development of the entire PV value chain. On the basis of the module production and focused FMEA discussions, a long list of processes and a short list of important parameters to prioritize were developed. This insight can now be applied by the PV industry to assess new processes or materials. The FMEA approach supports the understanding of critical processes, the mitigation of unwelcome effects, and the avoidance of implementing materials and processes that will result in non-reliable products.

Similar long-term stress-testing results to those presented here have been reported in the literature [17,20–23], but the methodology for improving the understanding of the growing complexity of correlations is far more systematic, traceable and more reproducible if each step is well documented.

The results of this FMEA will be used for future applications to assess other encapsulation materials combined with different processes and module structures. Material-wise, the FMEA structure will help in figuring out critical processes, for example to adapt the current lamination process for PO or POE materials [24]. Furthermore, it can be utilized to investigate, for example, the impact of using either a polymer backsheet or a glass structure as the back-side cover.

Unfortunately, a comprehensive cross-value-chain FMEA and data collection scheme does not yet exist. The presented data analytics of just one step of the value chain has demonstrated the potential for improvements and it can enhance subsequent steps, such as the evaluation of cell efficiencies on the basis of certain wafer processes. More thought can be put into the module, including soldering and lamination, to finally link certain processes to field failures and differences in energy production.

This project has shown the feasibility of such a data-based analysis and its power to support the optimization of processes and the making of decisions. The results presented prove its potential, and motivate the use of the possibilities that also come along with digitalization and Industry 4.0 for PV reliability issues.

"The interdisciplinary combination of a detailed FMEA by manufacturers, equipment suppliers and research institutes, together with modern data analytical methods, can support the future development of the entire PV value chain."

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About the Authors

Bengt Jäckel received his Ph.D. in materials science from TU Darmstadt in 2005. Since 2007 he has been working in the PV industry, holding various positions covering the entire value chain. He joined Fraunhofer CSP in 2018 and currently heads the PV Modules, Components and Manufacturing group with a focus on multi-scale analytics to develop fundamental root-cause understanding for next-generation PV modules and components. He also leads the PV Module group at DKE and is the German representative in IEC TC 82.

Matthias Pander received his master's in mechanical engineering from Leipzig University of Applied Sciences in 2010. He has been working in the Reliability of Solar Modules and Systems group at Fraunhofer CSP since 2010. He specializes in the field of finite-element simulation of PV modules and material modelling, as well as lifetime evaluation.

Ringo Koepge received his Diploma degree in materials science from Martin Luther University Halle-Wittenberg in 2010. Since then he has been working as a research scientist with the Material and Process Analytic team at the Fraunhofer CSP. His research in the field of improvement of manufacturing processes for crystals, wafers, cells and modules focuses on data science, especially on the application of machine-learning algorithms for clustering, classification and regression of data.

Stephan Großer studied physics and received his Ph.D. in 2008, and worked in the PV industry as a process engineer and researcher. In 2011 he joined Fraunhofer CSP, where he leads a team that focuses on the microstructure diagnostics of materials and devices and the root-cause analysis of defects.

Dr. Karl-Anders Weiss studied physics and economics and holds a Ph.D. in physics. He has been at Fraunhofer ISE since 2005, working mainly on the reliability of materials for solar energy systems, with a particular focus on degradation and service-life modeling, non-destructive analytics, coatings and polymeric materials. He recently worked on sustainability topics, especially the influence of reliability and durability on sustainability or renewable energies.

Enquiries

Bengt Jaeckel
Fraunhofer Center for Silicon Photovoltaics CSP
Otto-Eissfeldt-Strasse 12
06120 Halle, Germany

Tel: +49-177-7503123
Email: Bengt.Jaeckel@csp.fraunhofer.de
Website: https://www.csp.fraunhofer.de/