2022 PV Module Quality Report

White Paper - Trends in PV Module Quality from over 70 GW of Independent Quality Assurance

Investors, developers, and owners continue to be challenged by technological advances, product improvements and supply chain disruptions. Project delays due to COVID-19 restrictions, shipping constraints and supply chain traceability requirements have only exacerbated the situation. Independent quality assurance of manufacturing processes and finished goods remains crucial to assure reliability and long-term performance of PV modules. The data presented in this article will share insights and trends in quality that PI Berlin has observed through factory-based quality assurance on over 70 GW of PV modules.

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1. Background

In 2021, PI Berlin independently assessed the quality of over 8 GW from ten PV module manufacturers and seven OEMs, increasing the five-year total assessed to over 70 GW. An analysis of the quality data collected over the 2016 to 2020 period, presented in the 2021 PV Module Quality Report, offered valuable insights into manufacturing and product quality trends within the PV industry. This year's report provides additional data from 2021 that helps buyers and investors in the industry better understand the latest process and product trends.

2. The Importance of Quality

The PV industry has faced several major challenges in the past year including:

- The introduction of ultra-large modules based on super-sized silicon wafers that has proliferated the number and size of module types on the market and triggered new rounds of quality testing and changes in system integration.
- Increasing reports of damage to modules due to extreme weather events including hail and wind.
- Demands on the industry to set higher standards for environmental and social governance, including greater transparency in the solar supply chain.
- Increasing adoption of energy storage that increases the complexity of projects and project development.

Supply chain disruptions in the industry have increased buyer and investor concern, not only for quality, but also for completing projects on time. Significant delays in projects have been observed in the past year whether due to COVID-19 restrictions, increasing shipping costs, shortage of shipping capacity, new import rules, government tariff-circumvention investigations or supply chain traceability requirements.

Apart from delays, these disruptions have resulted in direct challenges to module quality coming from unexpected or last-minute switches in manufacturers, factory locations, module types or bills of materials. Manufacturers have also increasingly had the upper hand in supply negotiations which inevitably

means that some quality requirements, demanded by the buyer, may have to be sacrificed to secure supply.

It is crucial to pay close attention to quality to ensure the longevity and reliability of a PV project. Completing PV projects using alternate bills of materials or working with unfamiliar suppliers heightens the concerns of buyers and investors who have specific quality expectations and want to protect their assets.

PI Berlin expects the industry will start paying more attention to the end-of-life disposal and recycling of modules, particularly in the USA. As the fleet of existing PV installations age, and new deployments accelerate, the industry has an ever-growing disposal problem for the future. PI Berlin expects that the quality of a module will be defined not just by its safety, performance, and reliability but also the ease with which it can be recycled or re-used.

3. Assessing Manufacturing Quality

PI Berlin assesses the manufactured quality of newly built PV modules using two methods: production supervision and pre-shipment inspection.

Production Supervision oversees the individual manufacturing processes used to assemble a PV module from start to finish. Some of the assembly processes, such as cell stringing and lamination, can have a fundamental effect on the reliability of a PV module if not controlled properly.

Pre-shipment Inspection of finished PV modules serves to check the modules for any obvious physical defects, commonly using a mix of three different inspection methods: visual inspection, flash testing and electroluminescence (EL) imaging. EL imaging is a vital tool to help identify any defects within the cells.

Pre-shipment inspection is usually done by splitting the entire production for a specific project into batches. Using standardized ISO 2859 sampling rules, modules out of each batch are statistically sampled for inspection. Acceptable quality levels (AQL) are then applied, the most common being AQLs of 0.65 or

Table 1: PV module defect classification

Category	Defect severity
Critical	May create a safety hazard or cause early-life product failure or significant performance loss in the field.
Major	May cause near-term under-performance or more rapid performance degradation than expected.
Minor	May cause long-term under-performance or more rapid performance degradation than expected over time.

1.5 for major defects. This determines how many modules can have defects before an entire batch is rejected by the buyer.

Any defect identified through production supervision or pre-shipment inspection is categorized as critical, major, or minor depending on its likely impact to module safety, performance and reliability as shown in Table 1. The number of defects that are tolerated in a batch of modules depends on the severity of each defect.

4. More Materials Brings More Risks

The reliability of a PV module is determined by both the quality of manufacturing and the quality of materials used. A single type of PV module is typically certified with many different materials. This leads to potentially hundreds of different material combinations that may be used to assemble a single module type.

A key step in managing module reliability is controlling the Bill of Material (BOM), and more specifically the individual BOM combinations. Change or modify one material and the reliability of the whole module can be influenced. Reliability testing of all BOM combinations is an essential tool for buyers to verify module quality.

Figure 1 shows the high number of unique BOM combinations (>50) that were certified for single module types in an uncontrolled BOM scenario. This data is based on 35 selected projects that PI Berlin managed in 2021 which represents 5.7 GW of modules and nine different manufacturers

If BOM control is implemented through appropriate terms in a supply contract, the number of unique BOM combinations can be significantly reduced to no more than ten. This provides the manufacturer with flexibility in supply chain management and the buyer with better access to consistent module reliability.

Once in active manufacturing, the number of BOM combinations usually decreases further to only one or two in over 90 % of cases. Once a product is in manufacturing, and out of supply chain control, the tendency is to limit the number of different material types to maintain consistency.

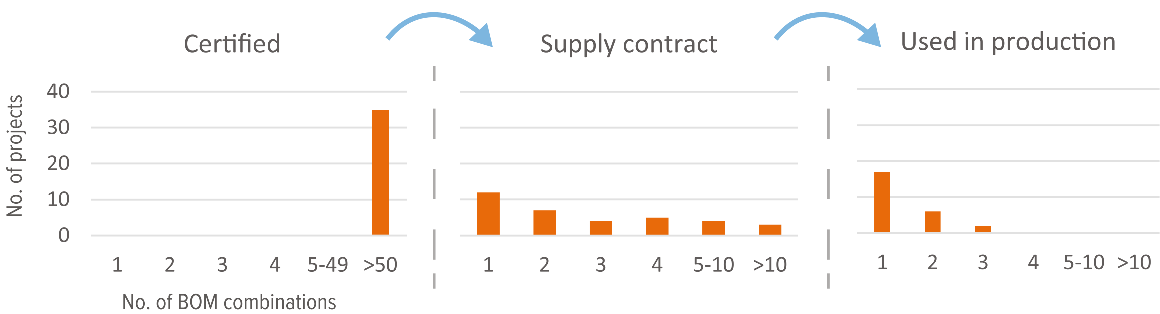
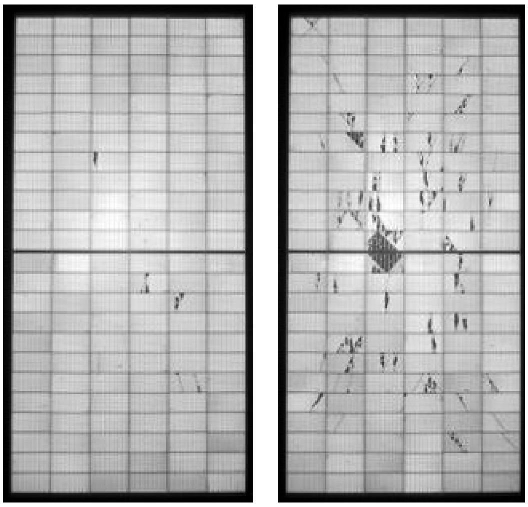


Figure 1: Benefits of BOM control in limiting BOM combinations



1.72 % degradation 5.74 % degradation

Figure 2: *Mechanical Stress Sequence results vary dramatically for two glass and backsheet modules of the same model type, from the same manufacturer, but with slightly different BOMs.*

4.1 Impact of Bill of Materials (BOM) Selection

Mechanical Stress Sequence Testing conducted by PV Evolution Labs (PVEL)

Seemingly minor changes to the BOM can have a major impact on test results, as showcased by recent results from PVEL's Mechanical Stress Sequence (MSS). During MSS testing, PVEL has two primary objectives: to determine whether cells in PV modules are vulnerable to cracking under mechanical pressure and if cell damage is likely to cause power loss in the field. Strong MSS results are most important in project locations with extreme weather events and conditions, including heavy snow and high winds.

In Figure 2, PVEL tested two modules from the same manufacturer with the same model type. Both had very similar designs, but small changes in the BOM caused big differences in the results. Both modules shared the same 3.2 mm glass thickness, encapsulant base resin, cells, number of cells, cell interconnects, back sheet, frames, and frame sealants. The decision to use different glass suppliers and different encapsulant suppliers was enough to cause a 5.74 % degradation and significant cell cracking in the second module. The first module is considered a top performer with less than 2 % degradation.

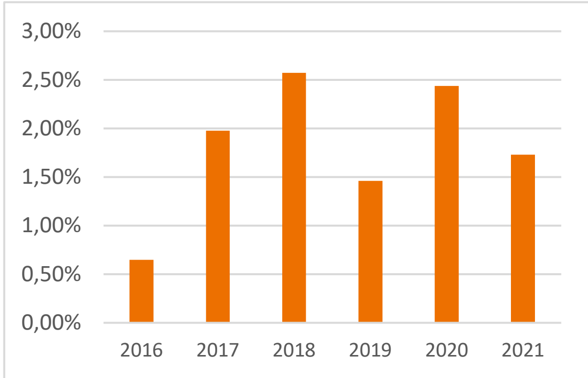


Figure 3: Annual aggregate defect rates in newly built PV modules

5. Trends in PV Module Quality

Although 2021 was a challenging year for investors, developers, and owners, there was good news. Data collected through projects in Vietnam, Thailand, Malaysia, and Cambodia show that the annual, aggregate defect rate for newly built PV modules in 2021 was 1.73 %. This was an improvement over 2020 which saw an annual defect rate of 2.44 %. This is the second lowest defect rate seen since 2017 (Figure 3).

The key improvements observed by PI Berlin include the use of more automated manufacturing equipment and more intelligent defect detection processes. As an example, there are now often three or four rounds of EL detection spread across manufacturing processes which proactively identifies defects in finish modules.

5.1 Product Defects

The number one concern for PV modules was cell defects, which represented one third of all the observed defects (Figure 4). While cell defects also represented the number one concern back in 2020, the proportion of cell related defects grew in 2021. Cell stringing, or interconnection-related defects saw a similar increasing trend.

With the introduction of super-sized wafers, 182 mm and 210 mm, most major module manufacturers began radical overhauls of their manufacturing processes to accommodate the shift to larger cell sizes.

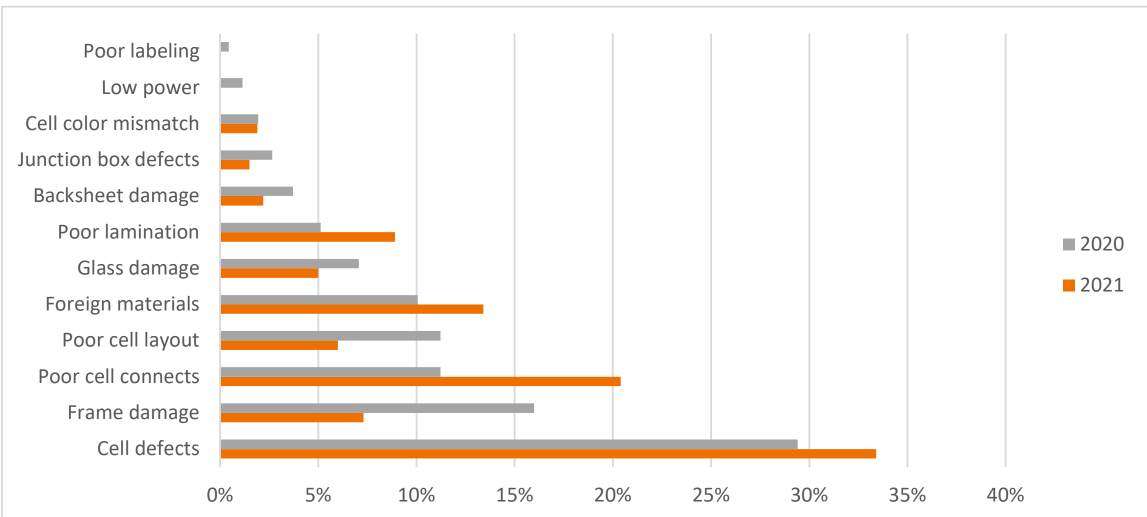


Figure 4: Distribution of defect types in newly built PV modules (2020/2021)

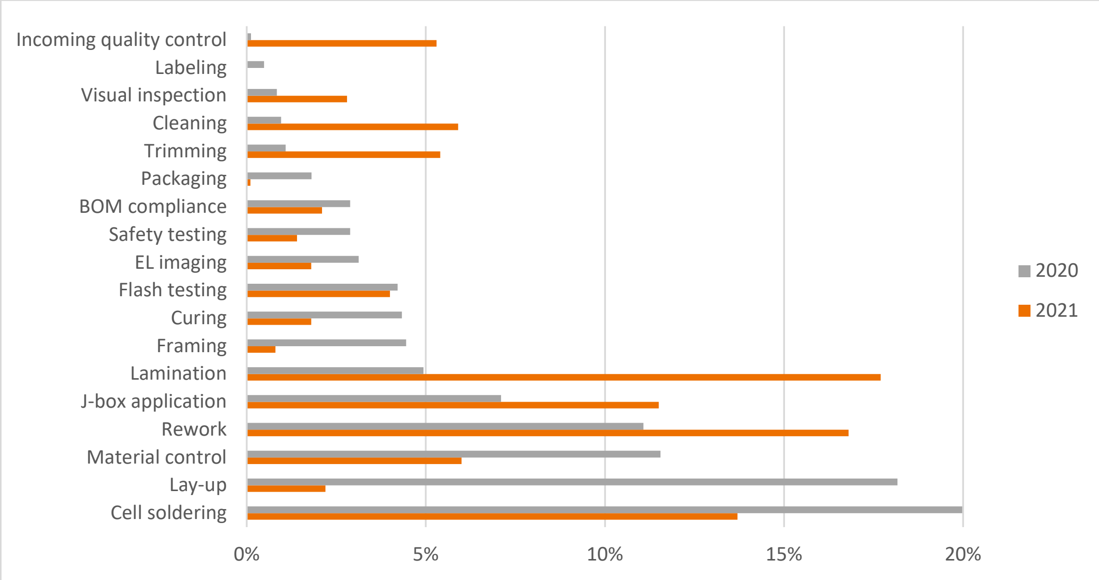


Figure 5: Distribution of PV module manufacturing defects (2020/2021)

This meant the installation of new manufacturing equipment, including cell stringing machines designed to handle cells of different sizes with more electrical interconnects. As the cells got larger, they increasingly needed to be cut into smaller cells. This allowed modules to keep the electrical characteristics necessary for efficient PV system designs. These new cell cutting processes introduced more risk to cell damage if the cutting was inaccurate.

There was a reduction in defects due to poor cell layout, even though cell layouts grew more complex with the introduction of larger modules. This major technological shift, while clearly a benefit to the industry in the long-term, has also presented a new challenge to maintaining consistent module quality.

The increase in poor quality lamination is likely tied to the growth in the assembly of double glass modules with bifacial cells. The lamination process using two sheets of glass, rather than one sheet of glass and a polymeric backsheet, requires a greater degree of precision in manufacturing to avoid, for example, air bubbles being trapped inside.

5.2 Manufacturing Process Defects

Cell soldering, used to interconnect solar cells in a PV module was no longer the number one contributor to manufacturing process defects in 2021 as can be seen in Figure 5. This is likely because multi-busbar cell technology implemented since 2019 had reached maturity and consistency in quality had been achieved.

Lamination of the module has become the most significant manufacturing process defect observed, increasing from 5 % of all process defects observed in 2020 to over 15 % in 2021. Due to shortages of encapsulants in 2021, there have been regular changes in the encapsulants. There has been the introduction of hybrid encapsulation systems using different types of encapsulants within a single module, for example EVA and POE, or composite type films.

It can be more challenging to achieve good quality lamination with mixed encapsulants as they may not cure as well under the same conditions. The long-term chemical and physical compatibility of different encapsulants combined within a single module is also still being assessed by independent test laboratories.

On a positive note, the module lay-up process saw major improvement in 2021 with a reduction in cell layout-related defects in finished modules. One reason is that half-cut cells, used in large format modules, reduce the total length of an individual cell string in a module. This helps to increase the accuracy and stability of the lay-up process.

5.3 Technology as a Risk Factor

New technologies usually bring benefits but can also introduce new risks. Figure 6 compares defect rates between some basic different technologies used in PV modules:

- Cell type: mono- or bifacial
- Cell inter-connection type: regular or multi-busbar
- Module construction: single or double glass
- Cell size: 158.75, 182 or 210 mm

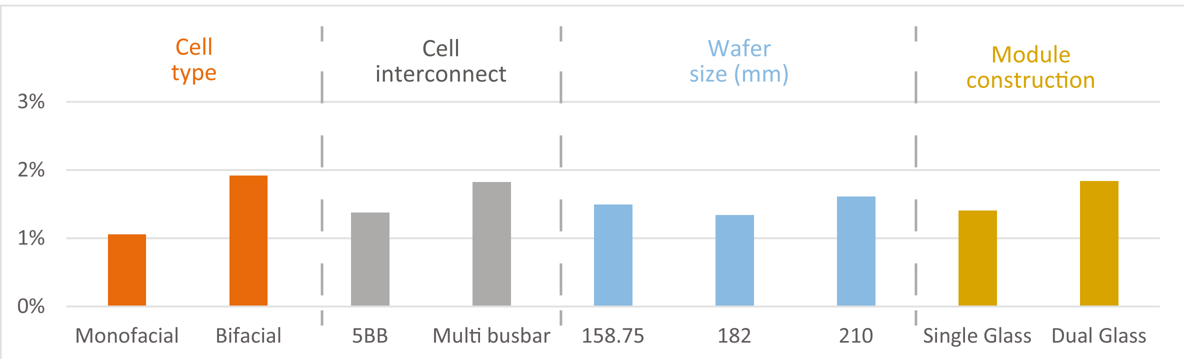


Figure 6: Differences in defect rates by technology type

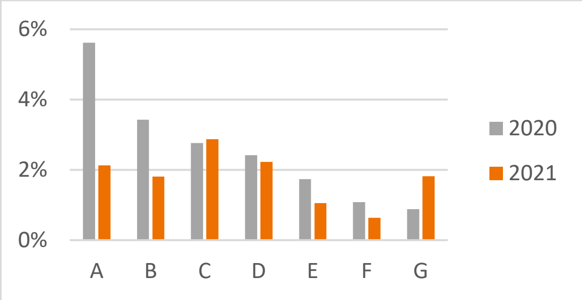


Figure 7: Module defect rates by manufacturer

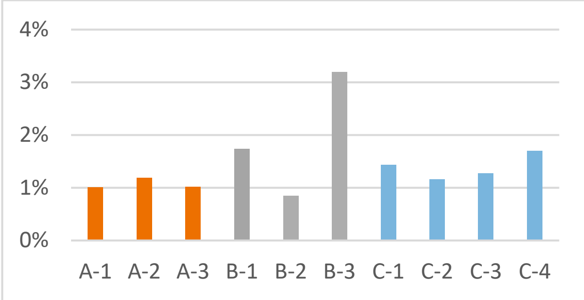


Figure 8: Differences in quality between workshops used by three different manufacturers (A, B,C) as measured by module defect rates (2021)

Bifacial cells and double glass, technologies related to bifacial modules, resulted in higher defect rates compared to older technologies. It remains to be seen if this will be a lasting trend.

An increase in defect rates was observed with the newer cell interconnect technologies. The number of electrical connects within a single cell has increased significantly. This has clear benefits in terms of increasing cell efficiency and reducing the impact of any cell cracking by providing more locations within a cell where power can be reliably extracted. However, it has resulted in more complex cell stringing processes, especially as the interconnects have become finer or different forms of interconnects are used.

Interestingly, there has been no significant change in overall defect rates with the introduction of the larger cells themselves. This is likely because some of the changes which have increased defect rates have been offset by other changes which have reduced defect rates. For example, increased defect rates of cell cutting have been offset by the reduced defect rates of shorter strings.

5.4 Quality Among Manufacturers

PI Berlin has conducted a significant volume of quality assurance on modules produced by a wide range of PV module manufacturers over the past ten years. It has therefore been possible to observe trends in quality from specific module manufacturers over time.

Figure 7 compares the defect rates observed at seven different module manufacturers in 2020 and 2021. It shows that some manufacturers are very consistent with quality, and some manufacturers are variable. Fortunately, in 2021 most manufacturers either achieved similar defect rates to the year before or made significant improvements. Only one of the seven saw an increase in defect rates, though from a lower starting point than some of its peers.

Manufacturers A and B saw significant declines in defect rates, manufacturers C and D were stable, and manufacturer G saw a doubling in their prior defect rate. It is clearly possible for manufacturers to obtain defect rates below 1 %, but PI Berlin has not seen that happening on a consistent basis.

It is still vitally important for the buyer to play an active role in managing quality of the product they are purchasing, even though there are manufacturers who shown consistent quality over consecutive years. History may not always be a good guide to the future, especially with the numerous advancements in manufacturing.

5.5 Quality within a Single Manufacturer

Another similar sustained trend is that quality within a single manufacturer can vary depending on the product, workshop, or equipment used to assemble it. Figure 8 shows the defect rates observed at different workshops used by three different manufacturers (A, B and C). Manufacturer A performs consistently across all observed workshops with defect rates around 1 %, manufacturer B is highly variable with defect rates ranging from below 1 % to over 3 % depending on the workshop, and manufacturer C is also relatively consistent, but with higher observed rates than manufacturer A.

The trend of variability within a single manufacturer means it remains incumbent on the buyer to limit the number of factories and workshops used to manufacture product for specific projects. Third party quality assurance must be applied to all the workshops used so that consistent quality can be assured.

6. Conclusion

PI Berlin expects to report on more material variability in 2022 as supply chain challenges have increased. The company has observed more last-minute changes in bills of materials used in projects and manufacturers less willing to contractually commit to limiting BOM combinations.

The solar PV market continues to grow rapidly. With this growth comes an even greater need for quality. COVID-19 restrictions, increasing shipping costs, shortage of shipping capacity, new import rules, government tariff-circumvention investigations and supply chain traceability requirements have presented significant challenges. It is, therefore, crucial for investors, developers, and owners to continue engaging third party, independent quality assurance to ensure that quality requirements are met.

The Author

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About PI Berlin

PI Berlin is the leading technical consultant for complex PV projects. PI's service portfolio includes project development, risk management and quality assurance for PV power plants and components. The strength of PI results from the combination of expertise in the areas of factory production, laboratory testing, and PV power plant performance. The ability to carry out quality assurance from the factory to the field - and to consider the interactions among the different areas - creates a high degree of security and transparency for our customers. Internationally, PI is represented by subsidiaries in Germany, the USA, Spain, and China.

With 550+ factory audits worldwide of 91 GW production capacity, PI has a profound market insight. Our well-founded and, above all, independent audits enable potential quality issues to be identified early. Potential risks are classified according to their severity and can be addressed accordingly. PI's auditing approach enables the customer and producer to address the findings with transparency – the producer improves their processes and develops trust in their product, and the customer receives higher quality modules. The majority of the auditing team is well-positioned in south-east Asia with an office in Shanghai. However, PI conducts on-site factory audits for modules, inverters, and mounting systems around the world.

The testing of PV modules and the operation of special PV laboratories continues to be a core competence of PI Berlin – with a laboratory in both Berlin and China. The focus of the Berlin office is on reliability testing and fault analysis, while the laboratory in China specializes in independent production monitoring. In addition, partner laboratories in Japan and India operate with reliance on PI technologies and processes.

The service portfolio for PV power plants includes both classic engineering services and extended quality assurance. Monitoring the entire supply chain with subsequent control of the installation is essential for reliable operation after connection to the grid. As a reliable partner, PI is always available. PI's portfolio of more than 2.5 GW of successfully completed power plant projects - in more than 30 countries, across nearly all continents - speaks for itself.

Contracts are an important link between the factory, laboratory testing, and application in the field. The contractual arrangements surrounding PV power plants are complex, but must provide a clear definition of what is to be delivered and under what conditions. PI's experience shows that many problems can be avoided if contracts are well-designed. With PI's involvement in the procurement of 4.5 GW, our experience and continuous market observation make PI a well-informed partner – ready to assist in the drafting of new, or reviewing proposed contracts.

Contact

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