2021 PV Module Quality Report

White Paper - Trends in PV Module Quality from over 60 GW of Independent Quality Assurance

As the PV market continues its rapid expansion, investors, developers, and owners are regularly challenged by technological advances, manufacturing changes and supply chain constraints. Assuring them that reliability and long-term performance will remain intact is not solved by warranties and standards alone. The only proven method for protecting module quality is to stress test modules as well as conduct independent quality assurance of manufacturing processes. 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 60 GW of PV modules.

Contents

1. Background

Between 2016 and 2020, PI Berlin independently assessed the quality of over 60 GW of newly manufactured PV modules. An analysis of the data collected over this period offers valuable insights into recent manufacturing and product defect trends within the industry. This knowledge also provides opportunities for process and product improvement as solar PV gains greater acceptance and new technological challenges emerge.

2. The Importance of Quality

The solar PV market continues to grow rapidly. With this growth comes an even greater need for quality. The number of manufacturers continues to grow, new factories are being built, new manufacturing equipment is being installed, more manufacturing is being sub-contracted, and materials are constantly changing due to advances in technology and supply chain constraints. The extent of ongoing changes represents a real risk to quality.

Anyone investing in, or buying, a solar project must take into consideration the quality of PV modules as it directly impacts both the performance and the return on investment (ROI) over the life cycle of a solar facility. PV modules are governed by a basic set of design and safety standards required by either the International Electrotechnical Commission (IEC) or by the Underwriters Laboratories (UL) (in the USA). These standards set minimum requirements for module construction but do little to set standards for manufacturing quality or long-term performance.

Standards and manufacturer warranties provide some potential comfort to the investor or buyer, but the only proven way to assess and protect long-term PV module quality and performance is to define and thoroughly stress test the materials used to construct the module as well as to conduct independent diligence and quality assurance on the manufacturing processes used to assemble PV modules. These are the most cost-effective, efficient and beneficial solutions for buyers and investors who want long-term performance assurances and a dependable return on investment.

3. Assessing Manufacturing Quality

The quality of PV modules manufactured for a specific project is determined during the manufacturing process, not afterward. To assess and assure quality, direct oversight of all critical manufacturing processes is required including major steps such as cell stringing and lamination.

Non-destructive physical re-inspection is also used to confirm the manufacturing quality of finished PV modules before they ship. Inspecting workmanship quality is done through visual inspection and flash testing, and mitigation of potential safety or performance problems through repeat electroluminescence (EL) imaging of the cells. In some instances, a secondary validation of manufacturing quality to identify potential latent defects may be warranted by conducting selective destructive testing.

Typical PI Berlin manufacturing oversight flow

PI Berlin oversight of PV module manufacturing typically follows the manufacturing process from start to finish, as follows:

- Material verification and certification compliance; incoming quality controls
- Material storage, expiry, and preparation controls
- Cell soldering (stringing) quality and quality controls
- Cell defect/crack screening; cell bow, and warp monitoring
- Material placement controls; lamination quality and quality controls
- Gel content and cell peel strength results
- Equipment calibration, maintenance, and cleaning
- Material and/or equipment contamination
- Frame application, sealing and, curing controls
- Junction box application, soldering, and curing controls
- Junction box diode and electro-static discharge controls
- Flash testing and EL imaging
- Safety testing and related controls; climatic controls

Specific criteria are applied to each process. These are designed to enable clear decision making in terms of determining what manufacturing conditions represent good quality and which do not. Manufacturing conditions which do not represent good quality will trigger corrective action, and more importantly, quarantine and inspection of potentially affected PV modules.

Table 1: 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.

Typical PI Berlin physical re-inspection flow

PI Berlin re-inspection of finished PV modules usually takes place on a sample basis following the ISO 2859 standard to ensure a statistically relevant sampling and inspection process:

- Visual inspection: checking component quality and assembly workmanship
- EL imaging: checking for cell cracks and other potential latent cell defects
- Flash (I/V) testing: checking electrical characteristics

Defects are classified by their severity in terms of potential buyer or owner impact, as shown in *Table 1*.

Product containment and remedial action is triggered if the quantity of defects in any selected group of samples exceeds defined thresholds.

4. Trends in PV Module Quality

Over the past five years, PI Berlin has conducted independent quality assurance on more than 550 solar projects and 60 GW of modules. Trends in PV module quality have been identified by analyzing the data collected from production oversight and pre-shipment re-inspection. Based on this data, PI Berlin has systematically categorized and evaluated all the defects in manufacturing processes and finished product which have been observed.

Figure 2: PI Berlin QA Engineer performing pre-shipment inspection

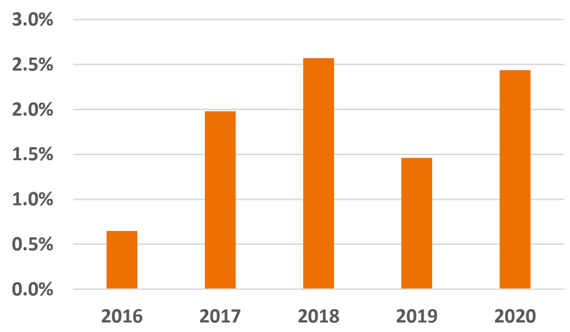

Figure 3: Annualized, global PV module defect rates based on independent PI Berlin data (from 2016 to 2020)

4.1 Constant Change Keeps Defect Rates Elevated

The global, annualized defect rates for newly built PV modules in recent years has fluctuated between 1.5 %, or 15,000 defective parts per million, and 2.5 %, as shown in *Figure 3*. On the surface, these numbers look minimal, but given the impact that only one or two defective PV modules can have on a complete module string, these numbers can have a measurable impact on system performance.

Somewhat surprisingly, our data shows that the defect rate in 2016 was lower than subsequent years (0.65 %). One of the major contributing factors to this lower rate was that 'standard' crystalline silicon solar cell-based modules were the predominant product type on the market at the time and the manufacturing processes for this product were relatively mature and stable. From 2017, changes in module technology, design, materials, processes, and equipment have proliferated. These include the introduction of new mono-crystalline cell technologies (including PERC), cut-cells, bifacial cells and double glass modules. These changes have been accompanied by an increase in the use of more sophisticated and automated manufacturing equipment designed to reduce labor costs, but not always conducive to consistently better quality, particularly in the early stages of deployment.

The more recent shift towards larger wafers and multi-busbar cell technology in 2020 has kept defect rates elevated. Interesting to observe that major product, technology, and manufacturing transitions always need to be accompanied by updated quality acceptance criteria. In many cases it takes time for these criteria to be developed and refined to accommodate the new potential risks created by each change. The adoption and refinement of updated quality acceptance criteria often trails the introduction of product or manufacturing changes – sometimes by several months.

4.2 Manufacturing Defects

Based on the extensive independent oversight of production which PI Berlin has conducted, the manufacturing processes representing the top five sources of defects for modules are as follows:

1.) Cell soldering
2.) Material lay-up
3.) Material control
4.) Rework
5.) Junction box application

Together, these five processes contribute more than 65 % of the total defects observed in module production processes as shown in *Figure 4* below.

Cell soldering

Cell soldering represents 20 % of all observed defective manufacturing processes. Soldering has experienced several technological innovations over the past several years, mainly in interconnect technologies. These include half-cut cells, multi-busbar cells, and shingled or physically overlapping cells. These innovations increase not only module power performance, but also add greater risk to quality if the soldering processes are not well adapted to the new technology.

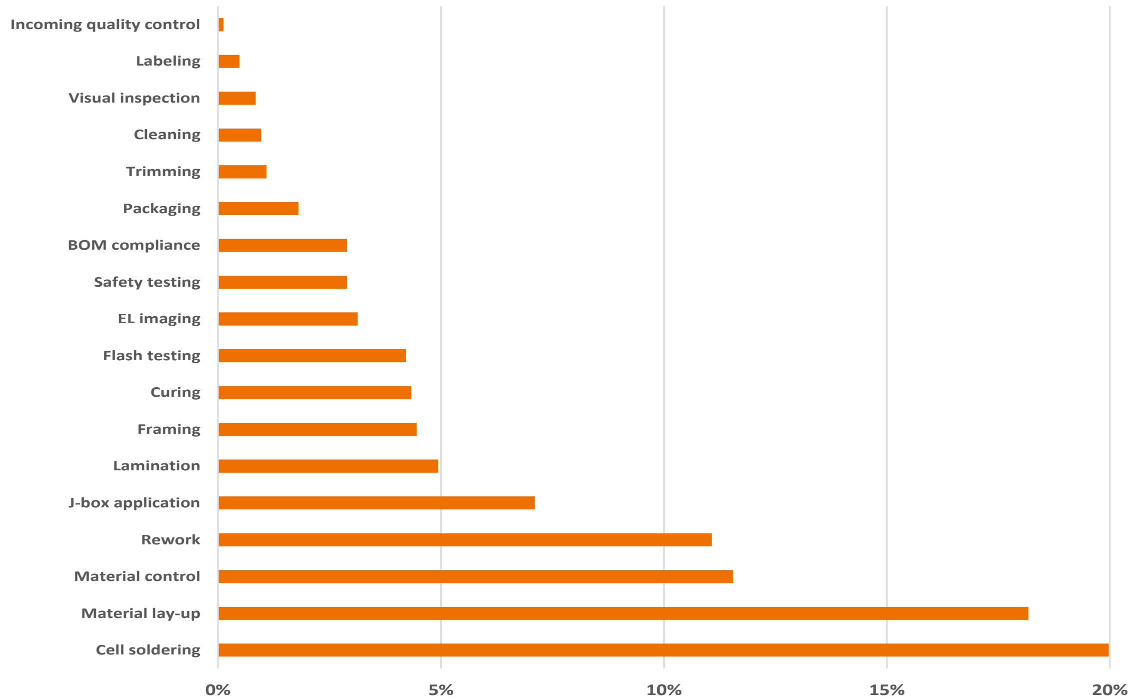

Figure 4: Sources of PV module defects in the manufacturing process (from 2016 to 2020)

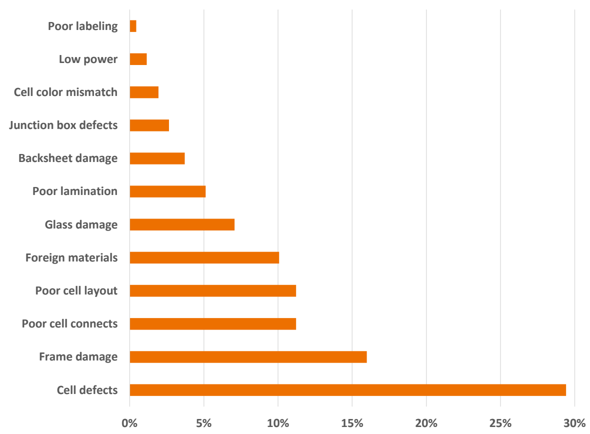

Figure 5: Distribution of defects in faulty PV modules (2006 - 2020)

Defective cell soldering processes are often due to insufficient control of key process parameters. This includes cell soldering temperature and time. Temperatures may not be set correctly, or they are calibrated incorrectly. Solder flux, a material designed to assist the soldering process, may also not be properly quality assured. The result can be soldered joints, on and between cells, weakening the long-term reliability of electrical connections within the module. Quality assurance of soldered joints on the cell is often done through a process called *peel strength* testing. This testing is sometimes inadequately performed such that poor quality soldering, if it occurs, is not reliably detected.

4.3 Product Defects

Just as cell soldering represents the number one source of defects in manufacturing, the cells themselves represent the number one source of defects in finished modules as identified by pre-shipment re-inspection. As shown in *Figure 5*, cell defects represent almost 30 % of the total observed defects in finished modules.

Cell defects are typically identified through repeat EL imaging of the finished modules. These are often defects that have slipped through the manufacturer' inspection processes. EL images are particularly important because they can show the presence of both overt and latent defects in the modules that are not visible to the naked eye. Cell micro-cracks of this type are an example that can propagate over time and cause more serious module performance or safety problems in the field.

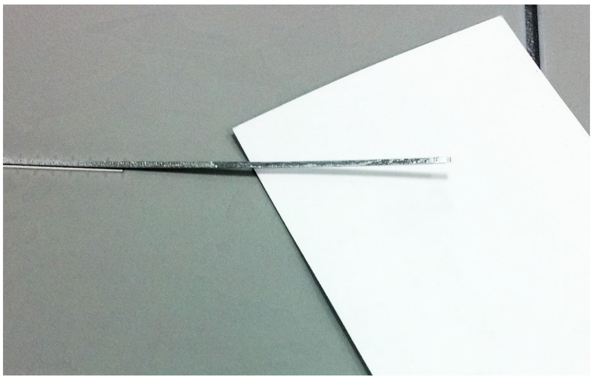

Figure 6: Defective cell soldering and interconnection

Another interesting observation is that frame damage ranks as the second leading source of module defects. While a damaged frame itself may not present an obvious reliability or safety concern to the module, damage to anodization layers on the frame can lead to corrosion in the field. Frame damage rarely occurs during module manufacturing itself. Instead, frames are often damaged upon receipt by the module manufacturer and not well screened prior to use in production. In fact, component material defects represent over 60 % of all module defects, including defects with:

- Cells
- Frames
- Glass
- Backsheets
- Junction boxes

Control of material quality further up the supply chain is therefore becoming increasingly important for module manufacturers in controlling finished module quality – and something module buyers and/or project owners need to be scrutinizing as well.

4.4 Technologies as a Risk Factor

Various technological advances introduce new risks. A comparision of recent developments is shown in *figure 7*.

Bifacial modules exhibit a clearly higher rate of defects compared to mono-facial modules. In PI Berlin's experience, the challenge with bifacial modules is a result of both the new cell design and the new module construction. Soldering the rear-side of bifacial cells is different to the soldering of the rear-side of conventional mono-facial cells and this can present the manufacturer with challenges in adapting the cell soldering processes. In addition, bifacial modules are typically constructed with two sheets of glass rather than one sheet of glass on the front and a polymeric back-sheet on the rear. Additional inspections are needed to assure the quality of the rear-side of a bifacial module, and these are not always well conducted, or performed often enough. Rear-side power measurement of bifacial modules is infrequently performed at the factory.

The other major new technologies – multi-busbar cells and double glass modules show a slight increase in defect rates but nothing too significant. Manufacturers have constantly been increasing the number of busbars on cells over the past ten years, so this change has been incremental. Similarly, double glass construction is not new to the industry, although bifacial modules have driven recent adoption. Thin film and building integrated modules have been designed around a double glass construction for many years.

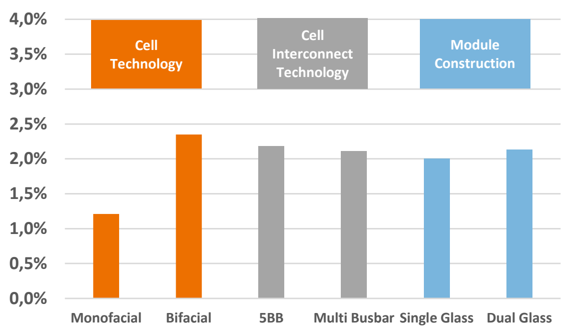

Figure 7: PV module defect rates related to technology changes (from 2016 to 2020)

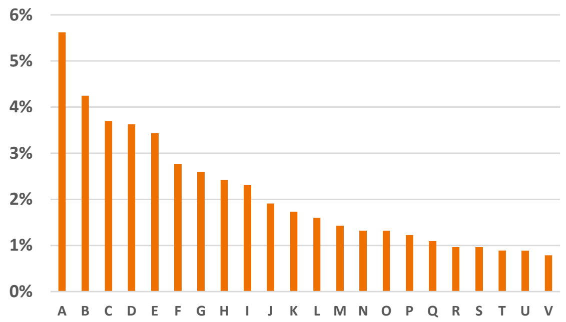

Figure 8: PV module defect rates for Tier 1 and 2 manufacturers (from 2016 to 2020)

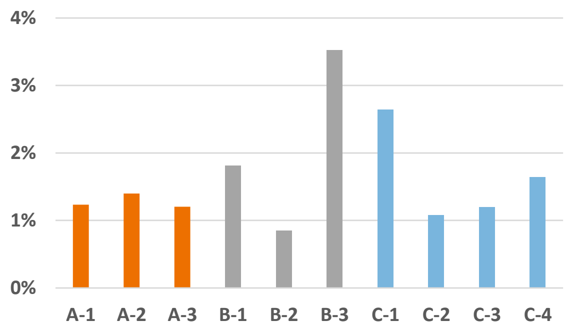

Figure 9: Defect rates of a single manufactuer in three factories (A-C) and differnt workshops (1-4)

4.5 Variability of Quality Among Manufacturers

After more than 20 years of industrial–scale PV module manufacturing, the solar industry still shows significant variability in quality from module manufacturer to manufacturer – cost and volume often still takes precedent over establishing and maintaining high quality management systems.

PI Berlin has completed a significant volume of quality assurance on modules from 22 major PV module manufacturers – mostly Tier 1 and Tier 2 manufacturers. *Figure 8* shows differences in defect rates between these manufacturers – ranging from under 1 % for the best performers to over 5 % for the worst. With an average defect rate of 2 %, around 60 % of manufacturers demonstrate above average quality control in manufacturing. Only 5 manufacturers, or just under 25 % of the total, have consistently achieved defect rates under 1 %. These manufacturers would be regarded as having achieved excellent, consistent quality.

Tier 1 manufacturers are mixed throughout these results, thereby supporting the ongoing hypothesis that buying from a Tier 1 manufacturer does not guarantee *Tier 1 quality* - especially without proactive steps taken to manage quality.

4.6 Quality Within a Single Manufacturer

Another sustained trend is that quality within a single manufacturer can vary depending on the product, workshop, or equipment used to manufacture it. An example for a single manufacturer is shown below in *Figure 9*. Each bar represents the defect rates observed in a particular workshop within a single factory location and each color represents a different factory. The same variability can be observed from factory to factory. The use of OEMs or contract manufacturers has also continued to increase in the past few years, adding to the variability in quality observed by PI Berlin.

4.7 Quality from Various Countries

More than 90 % of the world's supply of PV modules comes from Asia, in which China, Vietnam, Malaysia, Thailand, Cambodia, and India represent the top countries by volume. Manufacturing outside of China is designed primarily to serve the US market which places tariffs on cells and modules manufactured in China.

Among these countries, factories based in India have exhibited the lowest defect rates, although the relative volume produced in India is still small compared to other Asian countries. India does however have a long history of producing PV modules with the likes of Tata BP Solar being an earlier producer. Cambodia is a relative newcomer in PV module manufacturing, but thus far OEM factories based in Cambodia are performing reasonably well compared to others in southeast Asia. Factories in Thailand on the other hand, have exhibited the highest defect rates at over 2.5 % on average.

It should be noted that the overall difference in quality by country is much less significant than manufacturer to manufacturer or between factories within a single manufacturer. Buyers and investors in the industry have been concerned about the increasing geographic diversity and its potential impact on quality, but so far the observed differences in quality country to country are not significant.

5. Conclusion

Continual change has been a hallmark in the PV industry over the past five years, and its impact on quality has been measurable. Much of the change which the industry continues to undergo is a necessary part of improving the competitiveness, efficiency, and scale of solar power. Without it, solar power could not continue growing its market share in the global energy sector.

However, module buyers, project owners, and investors need to remain mindful of the risks to quality, which growth creates. Poor quality can ultimately lead to solar power not meeting its economic and environmental sustainability promises, which in turn could negatively impact the long-term growth of the industry. It's therefore important we pay as much attention to quality as we do to technology and other commercial considerations.

The good news is that risks to quality can be mitigated with relatively little effort and expense to the buyer, via contractual requirements and independent quality assurance at the factory.

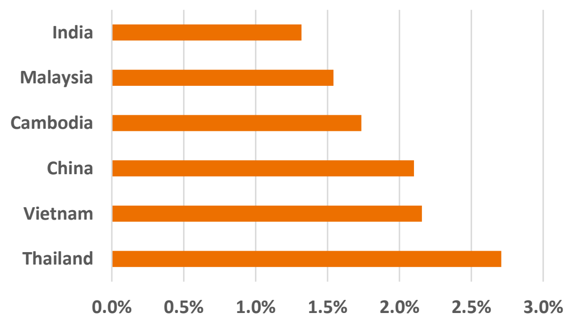

Figure 10: Comparison of various countries and the observed defect rates in PI Berlin supported projects

The Author

Fei Lu leads factory services for PI Berlin worldwide, including auditing and production supervision of photovoltaics and battery storage systems. Previously, Lu served as Director of Module Technology at the Chinese corporation Jiangsu Linyang Photovoltaics Technology and prior to that as Senior Engineer and Project Lead for Product Development at REC Solar in Singapore. He holds multiple patents and has a Master of Science in photovoltaic technology from the University of New South Wales in Australia.

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

For more information on services provided by PI Berlin please contact your local PI Berlin representative or email us at usa@pi-berlin.com. Check us out on the web at pi-berlin.com or follow us on LinkedIn at pi-berlin.