Results of the Project MULTIELEMENT
Visual Assessment of PV Module Quality

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ABSTRACT: According to high Photovoltaic (PV) system cost (especially PV Module) and the feed-in tariff in several countries (especially for building integrated applications) along with numerous PV module manufacturers, hence, the quality of the PV module is a major question for PV systems. With respect to standards of PV modules (EN 61215 and EN 61646), these are not enough to evaluate the quality of PV module. In order to solve difficulties, hence, the visual assessment of PV module quality is needed. For this work, we concentrated primarily on Building Integrated Photovoltaic (BIPV) applications and only on glass substrates; glass-glass and glass-Tedlar. Our focuses were on 5 different aspects: Inspection specification, Dimension of PV-module, Glass assessment, PV active cell assessment, and electrical connection techniques. Nevertheless, standard PV module can also be partially evaluated by this visual assessment of PV module quality. Finally, we are trying to set the first guideline for the visual assessment of PV modules quality. This assessment allows the manufacturers to conform the quality of PV modules and the planers to assess the quality of PV modules from the same assessment. Therefore, this visual assessment of PV module quality will act as a quality benchmark PV module.
Keywords: PV Module, Quality, Evaluation

1. INTRODUCTION

Photovoltaic (PV) system is one of the most widespread components for decentralized and even centralized applications to convert effectively solar energy to electricity. According to high investment of PV system (especially PV Module) and the feed-in tariff in several countries (especially in Building Integrated PV – BIPV), the number of PV-Module manufacturers increased very fast in the market. Therefore, the quality of the PV module is a major question for the PV systems. Also, the safety, aesthetic and product guarantee of PV module have to be included in this quality concept.

In the manufacturers' points of view, however, some aspects are not avoidable in the production lines, such as bubbles in laminated glass, some scratch and etc. Moreover some aspects are not related to the nominal power output of PV modules. Regarding above aspects, however, the quality of PV module, in term of power output, can not be guaranteed in long term. Therefore the PV product specification has to be established in order to assure the PV module quality from manufacturers. Also, the inspection process has to be included.

Regarding this visual quality of PV, there is just a small part in IEC61215/61646 standards [1, 2], which is not sufficient. Though, there is another standard (VDE-0126-21) concerning Building Integrated Photovoltaic (BIPV) module, there is no relevant information of visual assessment of PV modules [3]. Nowadays most of PV manufacturers follow their products individually on the conventional glass standards or guidelines, which are not properly suitable for PV panels due to different production process.

In order to solve these difficulties, the visual quality of PV modules is needed. It has to be evaluated along with standards of all relevant aspects. This assessment contains different aspects, such as dimension, bubbles, cell breakage, etc., which can reduce the PV system performance, safety or other aspects. It allows the manufacturers to conform the quality of PV modules to this assessment. At the same time, it allows the planers to assess the quality of PV modules from the same assessment.

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2. ASSESSMENT

This visual assessment focused mainly on Building Integrated Photovoltaic (BIPV) applications. Therefore, the standard PV module for conventional ground-mounted or roof-mounted applications wouldn't be discussed in this work concerning different considering points. However, some aspects from this work can also be used for standard PV modules above.

Normally, the visual assessment of PV module quality can be evaluated on the different product's phases, such as by the end of production line, after the shipment to the customer or after the installation. For this propose, we worked only by the end of production line phase. The other phases wouldn't be discussed in this work due to other relevant aspects, such as transportation, installer skills, etc. However, safety and lifetime aspects in terms of humidity, leakage, etc. had to be considered. Moreover, we concentrated primarily on PV-module on glass substrate; Glass-Tedlar and Glass-Glass modules. The other substrates, such as roof tile, aluminium or flexible foils, were not included in this work.

There are many relevant aspects concerned to this visual quality. For this work, we worked on 5 different aspects: Inspection specification, Dimension of PV-module, Glass assessment, PV active cell assessment, and electrical connection techniques. The other aspects, such as colour differences or in-homogeneous colour, wouldn't be considered in this work.

2.1. Inspection specification

Regarding the different and individual inspection specifications, there are some applicable standards (ISO 12543-6) [4] and other technical guidelines of glass [5, 6], which most of PV manufacturers conform with. Nevertheless, several manufacturers develop their own inspection specification, which are not compatible with each other. In order to contribute the same standard of visual quality of PV, the inspection specification has to be developed.

According to standards, technical guidelines of glass and manufacturer's specifications, these can be classified into surface definitions and inspection methods. There are many surface definitions, such as edge, border and main, indoor- and outdoor side, and transparent, in-transparent and opaque surfaces. At the same time, there are also several inspection methods, such as vertical or universal viewing angle, with different distances, and diffuse or artificial illumination.

Since all relevant standards, technical guidelines and manufacturers specifications have been evaluated, the surface definitions could be estimated under border surface and main surface.

According to glass standards and technical guideline based on the mounting space requirements, the border zone had been set for 15mm and 20mm from the edge for module area less than $5m^2$ and more than $5m^2$, respectively. The main surface had to be classified in four regions: Indoor/Transparent, Indoor/Opaque, Outdoor/-Transparent and Outdoor/Opaque, as shown in Figure 1.

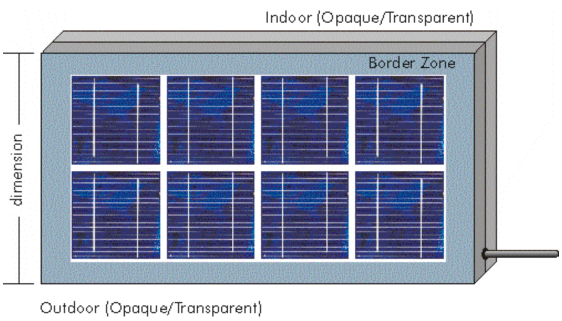


Figure 1: Inspection Zone of PV Module

At the same time, the inspection method could be evaluated by vertical viewing angles on the module with outdoor distance of 4m and indoor distance of 2m with diffuse illumination or likewise.

2.2. Dimension of PV-module

The dimension of PV-Module may not be important for standard ground-mounted PV application. However, it is one of the most important parameters for building integrated photovoltaic (BIPV) applications, especially with construction system. It has to properly conform to the conventional construction standards in order to easily replace the conventional building products. Currently there are only 2 relevant standards [7, 8], which deal with module's thickness, displacement of laminated glass and module's dimension;

To replace the conventional building products, the dimension tolerance of the PV module has to conform to the construction dimension and its standards. Regarding relevant glass standards conformed to building products, the dimension tolerance could be classified in 3 groups of module thickness; up to 8mm, 8-10 mm and over 10 mm. Figure 2 shows the dimension tolerance of the module thickness up to 8mm compared to the module dimension. If the PV module is 1000 mm width, the tolerance of the PV module would be +/- 2 mm from module width (998 mm – 1002 mm).

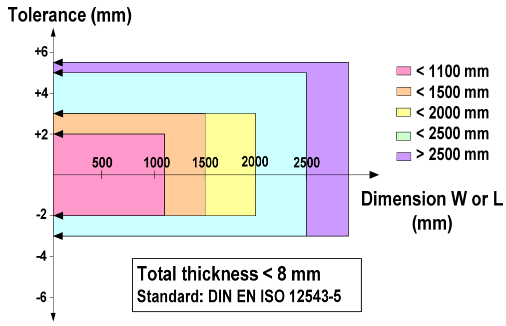


Figure 2: Dimension tolerance

The glass thickness and the displacement of laminated glass are the main parameters concerning the mounting system, especially for clamped bracket. Regarding conventional building products and standards, the tolerances were explained (as shown in Figure 3 and 4). Figure 3 shows the thickness tolerance compared with total module thickness. If the module thickness is 3 mm, the thickness tolerance would be max. +/- 0.2 mm. Figure 4 shows the displacement tolerance compared to the dimension of the module. If the module width is 1000 mm, the module displacement should not exceed 2 mm.

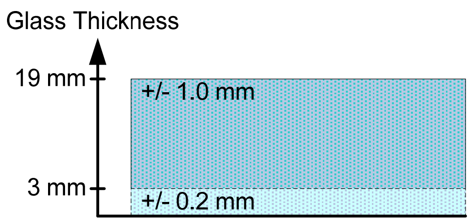


Figure 3: Glass thickness tolerances

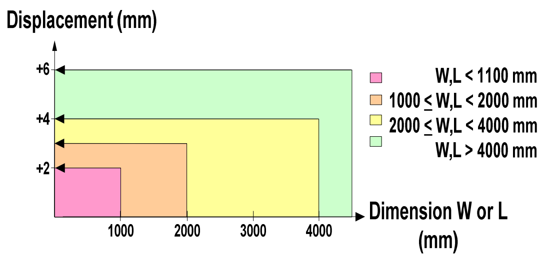


Figure 4: Displacement tolerance

However, the manufacturers give the module tolerances in range of +4 mm / -3 mm for all module sizes. This dimension tolerance does not conform to building constructions and standards, respectively. In addition, some of module specifications declare only the displacement tolerance, without any information for thickness tolerance. This displacement tolerance is in +3 mm range.

In order to absolutely employ the PV system in BIPV applications, hence, the manufacturers have to follow these 3 factors with above standards and guidelines. Consequently, these factors will help the architect or planer to simply employ the PV system in building applications.

2.3. Glass Assessment

For glass assessment, there are relevant standard and technical guidelines [4-6]; In this work, the glass assessment could be estimated as laminated glass, which the focusing point was not on the standard glass panes, but on the laminated parts. The standard glass panes can be followed with relevant glass standards.

Since the inspection specification has already been set, the glass assessment has to comply with above inspection method. Regarding the surface definitions, the assessment on border surface could be estimated as edge, point and linear failures, while the assessment on main surface could be estimated as point and linear failures. The edge failure means fractures or chipping on glass edge. The point failures refer to delamination, bubble and blur, while the linear failure refer to scratch on the module. The bubble and delamination are both air cavities inside the laminated glass. The bubble occurs during the laminated production process, while delamination occurs after laminated production process, which is directly concerned to the shrinkage of the laminated foil due to the thermal stress.

The manufacturers assessed their products' specifications based on above glass standard and guidelines. However, these glass assessments were quite different from standard and technical guideline due to their conditional production process. Therefore, they had their own individually assessments. Certainly, these assessments are less strength than above standard and technical guideline due to some unavoidable production process, especially embedded PV-active cell in laminated glass.

Regarding quality aspects, there are still other factors concerned to the quality of PV especially at border zone, such as bubbles or scratches. Regarding the standard and guideline with lower priority at border surface, the bubbles and scratches at border surface are significantly critical. The moisture can easily penetrate inside the module, which leads to higher leakage current and lower isolation resistance, respectively.

The aesthetic of the PV Module is an important aspect in this main zone assessment. The criteria of main zone could be followed with the laminated glass standards and guidelines above. However, instead of criteria of 2 panes laminated glass, the criteria of 3 panes laminated glass would be used for this assessment due to its difficulty in the product process of PV laminated glass. Nevertheless, on the backside of PV module, the criteria can be less strength than front side due to the lower aesthetic requirement.

Since all standards, guidelines and manufacturers' specification along with other quality aspects had been evaluated, it could be summarized as shown in Table 1.

SUGGESTION							
Border Zone	Edge			Unacceptable[1]			
Border Zone	Point			Unacceptable			
Border Zone	Linear			Unacceptable			
Main Zone	Point	Transparent	In- & Outdoor	Failure Size (mm)	Number of failures regarding Module area (m^2)		
					<= 1.0	1.0 – 2.0	>=2.0
				<0,5	Acceptable		
				0,5 – 1,0	No Limit, with out frequent failures [2]		
				1,0 – 3,0	2	3	1.5/m²
		Opaque	Outdoor	<0,5	Acceptable		
				0,5 – 1,0	No Limit, with out frequent failures [2]		
				1,0 – 3,0	2	3	1.5/m²
			Indoor	<0,5	Acceptable		
				0,5 – 1,0	No Limit, with out frequent failures [2]		
				1,0 – 3,0	2	3	1.5/m²
	Linear	Trans.	ID OD	< 30 mm zulässig			
		Opaque	OD	Each length: max. 15 mm			
			OD	Total length: max. 45 mm			
			ID	max 1line (>30 mm)			
ID = Indoor | OD = Outdoor							

1) small fractures is acceptable, if not concerned to module stability and module width not exceed the limit.
2) Frequency of failures: >= 4 failures for the distance from each other less than 20 cm. This distance is smaller for tripple glazing.

Table 1: Suggestion of glass assessment

2.4. PV active cell assessment

Above aspects were considered only on the quality of the building products without consideration on PV active cell. With respect to the manufacturer's specifications, the PV active cell had been assessed in various terms, such as cell breakage, grid interruption, crack, fleck, cell alignment and etc. However, these terms were differently evaluated from manufacturers due to individual criteria. The reason was that there were no relevant standards or guidelines concerning to PV active cell assessment.

According to different PV-technologies of crystalline Silicon (c-Si) and Thin-film (TF), there were 2 common assessment terms; fleck and cell alignment. The fleck term could be evaluated as antireflection, fingerprint, water and glue flecks with respect to number of flecks and its diameter. The cell alignment could be evaluated as string against module edge and string length in terms of mm per module length.

However there were still other assessment terms related directly to crystalline Silicon (c-Si); cell breakage, hair-line crack, finger interruption, bus bar and aluminium print. The difference between cell breakage and hair line crack were considered with mechanical stability of the cell. The cell breakage has totally lost its mechanical stability, while the hair line crack can still withstand its stability. However both of them have lost their electrical characteristics. Nevertheless, the hair line crack can lead to the cell breakage after a period of time. The relevant parameters of breakage cell and hair line crack are the distance between breakage cells (X_{max}) and breakage cell surface (A_1), and non-active cell, respectively. (Figure 5)

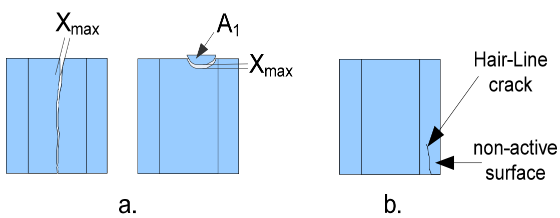


Figure 5: Parameters of cell breakage and hair line crack

Since the individual product specifications have been evaluated, it could be summarized as shown in Table 2.

SUGGESTION			
Flecks		Finger interruption	
Flecks	= 1 pcs of 5x5 mm² / cell	< 5mm	= max. 5 pcs
	= 3 pcs of 3cm²	< 25mm	= max. 1 pcs
Flecks over cell-edge	= unacceptable	< 3x3 cm²	= unacceptable
		Finger edge distance	= min. 1,5mm
Cell alignment		Bus bar	
Cell and string position	< +/- 2mm / m	Busbar width	> 3mm
Cell breakage		Busbar on cell	> 50% of cell width
Cell breakage	= 1 pcs	Backside busbar	Missing < 1x5mm²
X_{max}	= 1-2mm	Frontside busbar	Missing < 1x10 mm²
Z1	= 2% of cell surface	Aluminum print on backside	
		Over the edge	> 3mm
		Bumps	< 1.0 mm²
		Missing aluminium print	< 3,0 cm²

Table 2: PV active cell assessment

2.5. Electrical connection

Electrical connection is one of the most significant aspects relating to visual quality of PV-Module and safety, respectively. There are many parameters related to this aspect in both terms of construction and electrical safety, such as junction box, connector, electrical cables, leakage current, reverse current and etc.

There are some relevant photovoltaic standards and technical guidelines concerned to parameters above; [9-11] However there are also some parameters with no relevant standards or guidelines. For instances:

Junction Box and Connector:

The junction box and connectors of PV module in terms of components have to conform to VDE 0126-3, -5, respectively. However, the position tolerance of junction box is another parameter related to the visual assessment of quality, which has no relevant standards or guidelines.

Regarding to the position of junction box of PV module, it can also be possible to have more than 1 junction box per module; 1 positive cable and 1 negative cable. With respect to the limitation of cable channel in BIPV application in the construction, the junction box has to be located in the position, where cable length between the module should be minimised in order to reduce the cable loss and the risk of induce voltage from lightning [12].

Regarding the manufacturer's specification, it could be summarised that the position tolerance should be in range of +/- 5mm.

Cable Outlet:

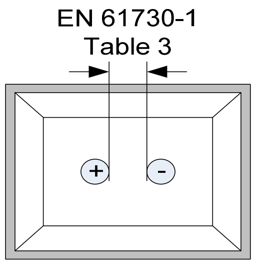
The cable outlet of PV module can be also estimated as edge connection, employed predominately in BIPV application due to aesthetic requirement. According to standards above, there were some aspects concerning the mechanical load of the cables. However, the distances of cable indention and detachment from the edge of the PV module are one of the most quality parameters of PV module, which has no standards and guidelines. There were only some manufacturers, who gave such information in approximate values. By considering product specifications, it could be summarized that the distance of cable indention and detachment from the edge of PV module should be both lower 3 mm.

On the other hand, there is an alternative edge connection by employing with cable block on the edge in order to protect the cable outlet of PV module. Nevertheless, this connection can not be done on standard glass-Tedlar module, but only on isolated glass module configuration due to its thickness.

Leakage path:

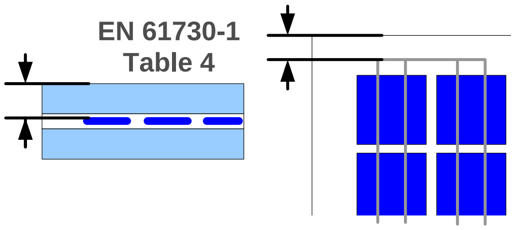
Regarding safety aspect, the leakage path between the clamping terminals inside the junction box, and conducting part with non conducting accessible point inside the module have to conform to standard EN 61730-1.

Even though the module's rated voltage is lower than 1000 V, the relevant distance had to be set for system voltage of maximum 1000V, based on the series connection of PV system standards. Therefore the leakage path between clamping terminal inside the junction box needed to be bigger than 16mm (Figure 6a). At the same time, the linkage path between conducting part and non conducting point of module should be bigger than 8.4 mm. regarding class A (Figure 6b).



System Voltage (V)	Distance (mm)
0 bis 50	6,5
51 bis 300	9,5
301 bis 600	12,5
601 bis 1000	16
1001 bis 1500	25

(a.)



Highest System Voltage (V)	Sparking distance (m.)		
	Class C	Class B	Class A
0 bis 50	2	2	2
51 bis 300		3,2	6,4
301 bis 600		3,2	6,4
601 bis 1000		4,2	8,4
1001 bis 1500		8	11

(b.)

Figure 6: a.) Leakage path between the clamping terminals inside the junction box.
b.) Linkage path between conducting part and non conducting accessible point of module

Other Declarations:

There are still other unavoidable parameters concerning the manufacturer's process, such as reverse current, positive or negative earth or capacitive leakage current.

The reverse current of PV module can occur especially at high voltage PV module. This parameter is rather critical for Thin-Film (TF) module due to lower capacity compared to crystalline (c-Si) PV module. In parallel connection, if one of PV module is shaded, its open-circuit voltage would be reduced and could be lower than operating MPP-Voltage of the system. This leads to reverse current in the shaded PV module. In addition, this reverse current will increase with numbers of PV modules in parallel. Therefore the reverse current of PV module has to be declared. Alternative, the block-diode load capacity or the total amount of PV module in parallel have to be described.

Under the operative voltage of over 20 V, the electrical charge on the surface of PV-cell, especially for back-side contact PV cell, increases and leads to higher recombination rate. This can be referred to the reversible of polarisation effect, which reduces the efficiency of PV module. As soon as the negative charge in EVA-Foil removed, the efficiency can be increased again. To remove the negative charge in EVA-Foil, hence, the positive earth has to be employed.

The TCO (Transparent Conductive Oxide) corrosion is another problem of PV-modules, which results in efficiency reduction of PV module. This happens on Thin-Film module, especially at super-state production; such as a-Si and CdTe technologies. The reason of this TCO corrosion is the reaction between TCO-coating and sodium (Na) in glass in combination with moisture, especially at border surface. To reduce this TCO-corrosion, the galvanic isolation inverter and negative earth is needed in order to set the electric field, which removes the positive charge of sodium from TCO-coating. On the other hand, the edge sealing of PV module can also be employed in order to avoid the moisture inside the module [13].

With limit range of capacitive leakage current in consideration with different inverter topologies, the disconnection of RCD (Residual Current protective Device) or Inverters can be occurred. The range of this capacitive leakage current can be influenced by module dimension, module configuration and material used, and humidity. Therefore the manufacturers have to give the value of capacitive leakage current of their modules in order to properly design PV system with certain inverter topologies [14].

Therefore, all above parameters have to be declared by PV module manufacturers. These declarations will be a guideline for the planers to properly design the PV system.

CONCLUSION

In order to answer the questions of quality of PV module, the visual assessment of PV module quality is needed. This visual assessment focused on 5 different aspects: inspection specification, dimension of PV-module, glass assessment, PV active cell assessment, and electrical connection techniques.

The inspection specification could be evaluated in terms of inspection zones and inspection method. For the inspection zones, it was classified into border and main zone, which main zone could further be classified in Indoor/Transparent, Indoor/Opaque, Outdoor/-Transparent and Outdoor/Opaque. According to the dimension of PV modules, it had to conform with relevant building codes and guidelines in order to replace the conventional building products.

The glass standard of 3 panes laminated glass would be employed in this glass assessment due to its difficulty in the product process of PV laminated glass. However, these criteria were not allowed at border zone due to leakage current and lower isolation resistance problems. The PV cell assessment was quite individually evaluated by manufacturers due to no relevant standards or guidelines. All Failures, such as fleck, cell alignment, cell breakages, crack, etc., had to be estimated under criteria in table 2.

In term of electrical connection, the junction position tolerance was +/- 5mm, while the distance of cable indention and detachment from the edge of PV module were both lower 3 mm. Also, the leakage path of between the clamping terminals inside the junction box and conducting part with non conducting accessible point of module had to conform to standard EN 61730-1 by applying in system voltage range of 1000 V. In addition, the terms of reverse current, positive/negative earth and capacitive leakage current had to be declared in order to help planers properly designing the PV systems.

In this assessment, we are trying to set the first guideline for the visual assessment of PV modules quality. This assessment will act as a benchmark of PV module specification. It allows the manufacturers to conform the quality of PV modules to this assessment. At the same time, it allows the planers to assess the quality of PV modules from the same assessment. Nevertheless this standard should not be an obstacle for the manufacturers, if the ranges are strength. At the same time, it should also answer the customer needs of quality.

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