The impact of static wind load on the mechanical integrity of different commercially available mono-crystalline photovoltaic modules

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Abstract
Mechanical integrity of Photovoltaic (PV) modules, which is dependent upon the materials used and the manufacturing process, plays an important role in their performance and electrical output. Besides, the mechanical integrity of the modules is also affected by environmental conditions. Mechanical loads, which include loads produced by wind, snow, rain, and hail, tend to degrade the performance of the PV module by generating stresses and enhancing micro cracks and defects. This research aims to investigate the impact of wind loads on the performance degradation of PV modules. The overall objective was to investigate the reliability of modules available in Pakistan. Wind loads were simulated through an indigenously developed setup which allowed application of uniform load of 2400 Pa on the modules as per international standards (IEC 61215 and ASTM E1830-15). A total of 12 PV modules, from three different vendors, each of 50 W rated power, were subjected to solar flash testing and electroluminescence imaging before and after the application of three cycles of mechanical load test. Greatest effect of wind loads was observed for modules which had defects present prior to the application of load. A maximum drop of 3.19% in the power output and 8.24% increase in the series resistance was observed. The results highlight that wind load has the ability to initiate cracks, propagate the pre-existing ones as well as damage the grid fingers.

Keywords
degradation, electrical efficiency, mechanical integrity, photovoltaic modules, wind load

1 INTRODUCTION

With the rapid depletion of fossil fuels, a paradigm shift to renewables has been observed in recent years. Extensive research is being carried out to explore sustainable and eco-friendly resources of energy. Much progress has been made in these efforts, focused mainly toward harnessing energy by water, wind, sun, and various other energy banks. Solar energy is a renewable energy source that is substantial and whose utilization is economically sustainable. Photovoltaics (PV) are
the most widely used system for harnessing solar energy providing 3.0% of the gross electricity production worldwide till 2019. According to International Energy Agency (IEA), PV is the energy technology with the fastest growth and was estimated to pass 600 GW global installations by 2019, which actually exceeded 627 GW by the end of 2019. The Renewable 2019 report by IEA predicts a 2.5 times increase from 2020 to 2024, with an addition of 586-765 GW which will make the total installed PV capacity exceed 1 TW. Although PV technology is divided into three generations, the crystalline silicon solar cells (including both mono and poly) cover over 80% of the current world installed capacity.

During their lifetime, PV modules are exposed to different climatic conditions like wind, snow, rain, hail, temperature fluctuations, humidity, dust, and high voltages. Among these, wind, snow, and hail impose mechanical loads on the module, affecting the performance adversely. Wind can produce static as well as dynamic mechanical loads on the PV modules and degrade its mechanical integrity. The mechanical integrity of PV modules is greatly influenced by its design, type of material used, the manufacturing process, and the method of handling during transportation. Stresses are induced in the PV modules right from the fabrication process, which generate micro cracks in them. These residual stresses can be a site for further crack initiation. Additional stresses are induced in the modules by the wind loads during field operation, which can propagate the already existing cracks or generate new cracks. These cracks provide resistance to the flow of electric current and reduce the power output of the modules. Moreover, if a crack gets initiated and propagates along the width of the cell, it can isolate the active cell area; this causes a significant drop in the power output and efficiency. All these factors contribute to degradation in their performance. Typical degradation rate for the efficiency of PV modules is estimated to be 0.5%-1% per year, corresponding to a lifetime of 25-40 years before the nominal efficiency drops by 20%. However, long term exposure or severity of mechanical loads can affect the effective lifetime significantly due to breaking of cell interconnections, cracking of the glass, failure of the solder joints, and breaking of the cells. Although the cracks produced in the cells due to wind load cause a power drop of only up to 2.5% in the module, these cracks make the PV modules vulnerable to other defects. The wind loads in combination with other failure modes degrade the mechanical integrity of the module and can significantly diminish its performance. Kajari-Schroder et al have shown that out of the cracked cells, 29% had undergone degradation after wind loading and 200 humidity freeze cycles, and 7% had developed inactive cell areas. According to Lamprini Papargyri et al, a survey on more than 250 PV modules has revealed 20% of power loss due to cell cracks in combination with browning and delamination of ethylene vinyl acetate (EVA). Also, breakages and cracks are followed by other degradation types such as corrosion and hot spot generation which can substantially reduce the power output of the modules. Hence, the performance of PV module is dependent upon its mechanical integrity in addition to the incident irradiation and PV conversion efficiency.

Loss of mechanical integrity is categorized as a major defect in PV modules. Thus, quality standards need to be strictly implemented during selection of materials, design, and manufacturing process of the modules. In an effort to decrease cost, manufacturers have reduced the thickness of the wafer from 300 microns to 200 microns, and sometimes even to 100 microns. This has made the solar cells vulnerable to breakage and cracks during manufacturing, lamination, and storage. Improper techniques during fabrication like inaccurate handling of solar cells during the series/parallel combination of the cells or during the lamination process, can give rise to micro cracks in the cells which are not visible to naked eye but may become the reason of drop in performance of the modules. Moreover, thermal stresses are also generated in the solar cells during the soldering process due to difference in the coefficient of thermal expansion of the silicon and metallic parts, which can act as sites for micro crack initiation during their field operations due to wind load. Studies have been conducted to analyze stresses in wafers during the manufacturing cycle where the wafers are subjected to mechanical loads such as sawing and manual handling. The breaking of silicon wafers during handling and transport has been analyzed previously and stress analysis of solar cells during the soldering process has also been studied to determine the residual stresses induced by this process. Furthermore, Barata had noted that the effect of wind load was maximum when the wind strikes perpendicular to the main axis of the module.

This research aims to investigate the impact of static wind load on the performance of mono-crystalline PV modules commercially available in Pakistan. These modules differ greatly in their performance as they belong to different grades and quality. PV modules from three different vendors with similar parameters were subjected to the same loading conditions as imposed by static wind using the ASTM E1830-15 and IEC 61215 standards. Pre- and post-testing data obtained by electroluminescence (EL) imaging and solar flash testing were compared and analyzed to identify the impact of wind loading on mechanical integrity of PV modules. From here onward, the word “mechanical testing” refers to the “static wind load test” performed in this study.
2 | MATERIALS AND METHODS

2.1 | Materials

Three sets of four commercially available mono-crystalline PV modules were bought from three different vendors (total 12 modules). Although the price of the modules varied, all had the same rated power (50 W) and working voltage. The three sets are named as Type I, Type II, and Type III modules (Table 1). Type I modules are imported from People Republic of China (PRC); no manufacturer is specified and are the most commonly used modules for household applications in Pakistan. Type II modules were obtained from a Pakistan-based local module manufacturer, Akhtar Solar PLC, Hattar, Pakistan. Type III modules are provided by Power Highway, Lahore, Pakistan; they are imported from abroad and manufactured by a Bloomberg Listed Tier 1 PV Manufacturer. The price per watt of the modules increases from Type I to Type III. All the modules had mono-crystalline silicon cells sandwiched between EVA layers which act as an encapsulant. Tempered glass of standard thickness (3.2 mm) was used as a superstrate (front cover) while Tedlar worked as back sheet. Aluminum frame was used to hold and mechanically support the laminate. The construction of the module is shown in Figure 1A. All the modules have 36 cells arranged differently in different types. The modules had similar dimensions with only a slight difference among the different types (Table 1).

2.2 | Performance characterization

EL imaging and solar flash testing were carried out on the modules before and after the application of mechanical load. Both tests were performed at PV Lab Pakistan, located at Quaid-e-Azam Solar Park (QSP), Bahawalpur, Pakistan. EL imaging identifies any cracks present in the cells because the input current is unable to reach the cracked regions and such regions appear dark in the image.33 This test was performed on an EL tester using a DSLRA camera (Nikon D700, Japan) at standard testing conditions (STC). For EL test, the modules were made forward biased and a current equal to short circuit current ($I_{sc}$) of the modules was supplied to them. Solar flash testing was performed using AAA-class solar Simulator (PASAN S.A CH-2000 Switzerland) at STC.34 Data obtained from these tests were analyzed for mechanical degradation and subsequent drop in electrical power output.

| TABLE 1 | Prices and sample identification of PV modules investigated |
|---|---|---|---|---|
| S. no. | Supplier | Sample ID | Per watt price (PKR) | Per watt price (USD) | Dimensions (mm²) |
| 1 | Local Vendor | Type I | 70 | 0.636 | $666.7 \times 539.75$ |
| 2 | Akhtar Solar | Type II | 100 | 0.909 | $666.75 \times 533.4$ |
| 3 | Power Highway | Type III | 120 | 1.091 | $673.1 \times 546.1$ |

**FIGURE 1** (A) Exploded view of the PV modules used for the analysis. (B) Experimental setup for the mechanical testing.
Mechanical Load Testing. A purpose-built setup developed conferring to the international standards (ASTM E1830-15 [30] and IEC 61215 [31,32]) was used for conducting mechanical testing of the modules, (Figure 1B). Wind load was simulated through a sandbag, which allowed application of a uniform load successively on the front and back surfaces of the modules. In accordance with the ASTM and IEC standards, a load of 2400 Pa was applied on the front side of the module for 1 hour followed by same load on the back side for 1 hour. This completes one cycle of the test; three cycles of similar loading constituted a complete test. A custom made bag was used to apply the required pressure, which was filled with fine grain sand so that the load can be uniformly distributed over the modules. The required weight of the sand was calculated considering area of the PV modules. Modules were fixed in the setup according to the mounting configurations given by the manufacturer.

3 | RESULTS

The results of the EL testing describing the defects/cracks in the modules are presented first which is followed by a report of the effect of these cracks on the electrical parameters of the tested modules.

Type I PV Modules. Figure 2 shows the results obtained by EL testing of the representative two of the four Type I Modules before the mechanical testing. The defects/cracks observed in the EL images of the modules before the mechanical testing, are shown in red circles while the yellow circles show the finger interruptions detected in the modules prior to mechanical load test. The cracks developed in the wafer due to the wind load test are shown in white rectangular boxes while the cracks on the fingers are shown in yellow boxes in the post-mechanical testing EL images of the modules. The already existing cracks which have propagated during the application of load are shown in red boxes. As observed from the EL images in Figure 2, very few micro cracks were found in the first sample (Type I-1), while various defects/cracks can be identified in the second sample (Type I-2). These include diagonal cracks oriented at +45° (labeled “a”) and −45° (labeled “b”), a small black region (labeled “c”), regions where both cracks in the cell as well as finger interruptions are seen (labeled “d”), and micro cracks (labeled “e”). The finger interruptions are also visible in some other regions in Type I modules, encircled in yellow in Figure 2.

EL images of the same modules after application of mechanical loading are shown in Figure 3. It can be observed that the static wind load was able to initiate new cracks, and also affect the pre-mechanical testing cracks. Various cracks oriented diagonal to the busbars are clearly visible in module Type I-1, which were not present prior to the mechanical testing. Moreover, damages to the metallization are seen in the EL images obtained after the mechanical testing. Similar effect of the wind load test on module Type I-2 can be observed.

Type II PV Modules. EL images of two Type II modules (Type II-1 and Type II-2) showed the presence of only a single notable crack prior to loading (Figure 4). The same modules after undergoing the mechanical loading are shown again in Figure 5. Two new cracks have appeared in module Type II-1, while the black region also became darker. Changes in module Type II-2 are more pronounced after the application of the wind load. The image shows not only small cracks, but also completely black regions (labeled “a”).

**FIGURE 2** EL images of the two Type I modules (A) Type I-1 and (B) Type I-2 before mechanical testing.
**FIGURE 3** EL images of the two Type I modules (A) Type I-1 and (B) Type I-2 after mechanical testing

**FIGURE 4** EL images of the two Type II modules (A) Type II-1 and (B) Type II-2 before mechanical testing

**FIGURE 5** EL images of the two Type II modules (A) Type II-1 and (B) Type II-2 after mechanical testing
Although the mechanical load did affect the cracks pattern, the changes are much less in Type II modules as compared to Type I. Some finger grip interruptions are also visible in the Type II modules (Figure 4).

**Type III PV Modules.** In stark contrast to the Type I and Type II modules, the mechanical loading did not cause any damage of the Type III modules (Figures 6 and 7). It was observed that the modules were crack free before the application of loads and remained crack free after undergoing the mechanical load test.

**Solar Flash Testing.** Representative results of solar flash testing of each type of module are given in Table 2. Only three parameters namely maximum output power (MPP), series resistance ($R_{series}$), and fill factor (FF) will be discussed in this article.

Highest mean percent decrease in power of 3.19% was noted for the Type I modules, followed by 2.33% and 0.56% decrease in the Type II and Type III modules, respectively. A similar trend among the three different module types was observed in the decrease of FF. The series resistance increased by 8.24% for the Type I modules, and only by 1.79% for the Type III modules. The SD calculations showed that the Type I modules has the greatest variation from one sample to another, while the Type III samples were the most consistent.

### 4 | DISCUSSION

EL images of the PV modules from different vendors showed different levels of defects prior to mechanical testing. Type I modules had the maximum number of defects/cracks including small black region, diagonal cracks (oriented at $+45^\circ$ and $-45^\circ$), and micro cracks (see Figure 2). A darker region near the edge of a cell in Type I-1 is seen (labeled “c” in Figure 2A) which may be due to the breakage of the cell edge. A black region is also observed in the EL image of Type I-2 module (labeled “c” in Figure 2B). Such darker region may appear because of the cracks penetrating
deep into the cell and disconnecting the active cell area, due to which the region may have been electrically isolated from the module. These pre-loading cracks in the cells originate due to stresses generated during cell manufacturing, module lamination, and transportation. Furthermore, the orientation of these cracks relative to the busbars also plays a significant role in the increase of series resistance. Cracks parallel to the busbars result in a severe increase of electrical resistance, while cracks diagonal to the busbars affect the power output mildly. Identification of only a few cracks in Type II modules and none in Type III modules is indicative of their better manufacturing and handling techniques.

Moreover, the EL images of Type I and Type II modules showed finger interruptions as can be seen in Figures 2 and 4 (encircled in yellow). Micro cracks generated in the regions near the grid fingers or busbars during the silicon cell fabrication process cause damage to the fingers due to thermal stresses induced during the lamination process. This causes increase in the series resistance of the fingers and reduction in the brightness of the EL image in these regions due to which the damaged fingers appear darker in the image. The defect become prominent due to the thermal cycles experienced in the field or during the thermal cycle test in IEC 61215. Such faults are visible as rectangular black regions in EL images of the modules, also seen in Figures 2 and 3.35-38

Application of the static wind load had an impact on the size and intensity of the cracks in two ways: aiding the propagation of existing cracks and initiation of new cracks. The propagation of existing cracks in the modules due to the static wind load test was evident from the EL images. The micro cracks visible in these images prior to mechanical testing (shown in red circles in Figure 2, labeled as “e”) grew due to the application of mechanical load. This can be noticed by looking at Figure 3, where the regions labeled as “e” show larger cracks. In general, the greatest effect of the loading was noted in Type I modules, with additional black regions, different types of cracks, and finger interruptions observed (Figure 3). Appearance of a few cracks and darker regions in Type II modules, and none in Type III modules stipulate better performance of these modules during their lifetime. The higher susceptibility of the Type I modules to crack formation and propagation is an indication of their lower quality and strength. Another notable outcome from the investigation was the variation of quality observed among the PV modules from the same vendor. As far as mechanical integrity is concerned, Type I modules showed a lot of variation among themselves, Type II module had shown few variations while Type III modules found to be quite uniform. The same trend is observed in the standard deviations of the electrical efficiency tests. This behavior also elucidates the practice of standard manufacturing and material handling techniques by the Type III module manufacturer.

The cracks developed in the silicon cells (wafers) appear in an irregular shape in the EL images, as seen in Figures 2-5, whereas any crack that damages the metallic part of the cell is seen as regular rectangular area in the EL image. Such defects can appear as completely black or gray regions, depending upon the level to which the crack damages the metallization.38,39 By analyzing the EL images taken after mechanical testing, certain rectangular dark or black regions were observed, which are shown in yellow boxes in Figures 3 and 5. These regions are generated because of the micro cracks that are less conspicuous, but when the stresses are applied on them, they grow and damage the metal fingers. Thus, increasing the resistance of the fingers due to which such regions appear as (rectangular) dark areas in the EL images. Similar appearance of the fingers in the EL images has been reported in the literature before.38-41 In addition, Figures 2B and 3A,B show regions where both cracks and finger interruptions are noticed. These regions are enclosed in
FIGURE 8  Mean percentage change in MPP, fill factor and series resistance after mechanical testing. SD bars are also shown.

yellow circles (labeled “d” in Figure 2B) and in yellow boxes (labeled “e” and “f” in Figure 3). The cracks present in the silicon wafer, in such areas, grow and damage the metallization and thus the rectangular dark regions are detected in the EL images.

The power generated by module depends on several factors, such as irradiance, reflectivity of glass, module manufacturing, mechanical integrity, and conversion efficiency. The different crack pattern produced due to mechanical loads affect the electrical performance of PV modules, which was quantified through solar flash testing. Highest percent decrease in MPP (3.19%) was observed for Type I modules while only a minor decrease of power (0.56%) was noted in Type II modules after mechanical testing. Similar trend was observed in case of FF, which in addition to MPP also reflects the changes in $V_{oc}$ and $I_{sc}$ (Figure 8 and Table 2). As far as the series resistance is concerned, it arises from the resistance provided by the cells themselves, due to metallization (busbars and fingers), and internal structural defects such as cracks. The $R_{series}$ increased by 8.24% for the Type I modules, 4.91% for the Type II modules, and only 1.79% for the Type III modules. This increase in $R_{series}$ is again reflective of the EL images discussed above. The greater drop in the MPP and FF, and increase in the $R_{series}$ in Type I modules, is attributed to the greater number of cracks, damage to the grid fingers and electrical isolation of part of the cells in these modules.

Interesting results can also be observed when comparing the prices of the modules with their performance under wind loads. Both EL imaging and solar flash testing confirms the anticipated results that higher cost lead to better performance, however, the price difference between Type II and Type I modules is less when compared with the degradation in their performance. A more thorough cost optimization analysis can be performed to select the most appropriate choice for a given application.

4.1  Analysis of cracks observed after wind load test

An analysis was conducted to study the cracks found after the wind load test in the EL images of the modules. As discussed above, some cracks were also visible in the modules prior to mechanical testing, which are also quantified here.

4.2  Classification of cracks

The cracks were divided into five types on the basis of their orientation and visibility, namely random direction cracks, diagonal cracks oriented at $+45^\circ$ and $-45^\circ$ to the busbars, dendritic cracks, and cracks which produced black or dark regions in the EL images. Figure 9 shows the percentage occurrence of cracks in the EL images of Type I & Type II modules (Type III modules did not show any cracks) prior to mechanical testing while the cracks found in the modules (Type I & II) after wind load test are shown in Figure 10.

Out of the total cracks observed in the modules before wind load test, only a single crack was seen in the Type II modules (shown in Figure 4A) while all the other cracks were found in Type I modules. The total number of cracks observed in the post-mechanical testing EL images of the modules was 237 among which only 5.5% were found in Type II modules while the rest of 94.5% (224) were seen in Type I modules. The percentage occurrence of the different types of
cracks after the mechanical testing can be seen in Figure 10, in which the dendritic cracks were the least (2%) while the cracks in the random directions were the greatest. As seen from Figures 9 and 10, the percentage occurrence of random direction cracks, which also include the cracks having multiple directions, was greatest. The different cracks found in the modules are shown in Figure 11.

As, the Type I modules showed greatest number of cracks after the application of wind load, so an analysis was separately conducted to study the percentage occurrence of the cracks in these modules. The type I modules were individually named as L1, L2, L3, and L4. Figure 12 shows the percentages of the cracks produced in Type I modules due to the wind load test. It can be seen that maximum percentage of every type of crack was produced in L1 module, while minimum percentage of cracks was created in L4 module.

### 4.3 Spatial occurrence of cracks

From the EL images of the cracked cells, it was observed that majority of the cracks were present near the busbars while the rest were distributed in different regions of the cells. Among the total cracks found in the modules under investigation, almost 60% of cracks were found near the busbars (shown in Figures 13 and 14). This is because of the residual stresses that are induced in the modules during the soldering and/or the lamination process, thus becoming the site for crack initiation and propagation. During the mechanical testing, additional stresses are applied on the modules, which in combination with these residual stresses cause the cells in these regions to crack.
An interesting observation about the cracks present in the modules prior to mechanical testing was made during the crack analysis. Some cracks which were less conspicuous before the application of load, become severe and dark/black regions were visible in the EL images (at the same location) taken after the mechanical testing, as shown in Figure 15. This also confirms that the wind load has the tendency of propagating the already existing cracks. A crack which is generated during the manufacturing or transportation and is less severe can propagate deep into the cell and degrade the module’s performance.
5 CONCLUSIONS

The study showed that wind load can generate cracks as well as enhance the pre-existing cracks in the modules. Different types of cracks were identified in the EL images of the modules after the wind load testing including diagonal cracks (oriented at $+45^\circ$ and $-45^\circ$ to the busbars), dendritic and random direction cracks, and cracks which produced black regions in the cells. An analysis of these post-mechanical testing cracks revealed that 50% of them were oriented in random directions while 33% were diagonal to the busbars. The wind load was also able to damage the metallization (grid fingers) as observed from the EL images. Greatest drop in peak power (3.19%) and FF (2.46%), and increase in series resistance (8.24%) was found in the Type I modules, which had the greatest number of cracks. The Type II modules showed some deterioration in their performance due to wind loads, with the peak power decreasing by 2.33%. Negligible deterioration in electrical performance was noted for the best modules tested (Type III), which did not exhibit any change in mechanical integrity due to wind loads, as determined through EL images. The investigation also identified greatest variation from one sample to another for the Type I modules, while the Type III samples were the most consistent. The improved performance of the Type III modules could be attributed to the use of standard manufacturing and material handling practices. Thus, PV module manufacturers should be encouraged to improve their manufacturing process for attaining better performance throughout the life of the module.

ACKNOWLEDGEMENT

The authors would like to pay gratitude to Mr. Umer Mustafa and Mr. Waqar Lodhi of PV Lab Pakistan for their great help and support in performing the solar flash and EL testing of the modules.

AUTHOR CONTRIBUTIONS

Rizwan M. Gul: Conceptualization; project administration; supervision. Muhammad Ali Kamran: Methodology; resources; visualization; writing-review and editing. Fahad Ullah Zafar: Data curation; formal analysis; investigation; resources; visualization; writing-original draft. Muhammad Noman: Methodology; resources; supervision; writing-review and editing.

PEER REVIEW INFORMATION

Engineering Reports thanks Yiqing Dai, Abdülkerim Gök, Michael Owen-Bellini, and other anonymous reviewers for their contribution to the peer review of this work.

CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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REFERENCES

1. Kajari-Schröder S, Kunze I, Köntges M. Criticality of cracks in PV modules. Energy Procedia. 2012;27:658-663. https://doi.org/10.1016/j.egypro.2012.07.125.
2. IEA-PVP ST1-37:2020. Snapshot of global PV markets; 2020.
3. Jäger-Waldau A. Snapshot of photovoltaics—February 2019. Energies. 2019;12:1–7. https://doi.org/10.3390/en12050769.
4. IEA, “Renewables 2019, Market Analysis and Forecast from 2019 to 2024.” Paris: IEA Publications; ISBN 978-92-64-30684-4, 2019.
5. Gangopadhyay U, Jana S, Das S. State of art of solar photovoltaic technology. Conf Pap Energy. 2013;2013:1-9. https://doi.org/10.1155/2013/764132.
6. Borri C, Gagliardi M, Paggi M. Fatigue crack growth in silicon solar cells and hysteretic behaviour of busbars. Sol Energy Mater Sol Cells. 2018;181:21-29. https://doi.org/10.1016/j.solmat.2018.02.016.
7. Ennemri A, Logerais PO, Balistrou M, Durastanti JF, Belaidi I. Cracks in silicon photovoltaic modules: a review. J Optoelectron Adv Mater. 2019;21:24–92.
8. Haase F, Kasewieter J, Nabavi SR, Jansen E, Rolfes R, Köntges M. Fracture probability, crack patterns, and crack widths of multicrystalline silicon solar cells in PV modules during mechanical loading. IEEE J Photovoltaics. 2018;8:1510-1524. https://doi.org/10.1109/JPHOTOV.2018.2871338.
40. Iskra Z, Juhl MK, Weber JW, Wong J, Trupke T. Detection of finger interruptions in silicon solar cells using line scan photoluminescence imaging. *IEEE J Photovoltaics*. 2017;7:1496-1502. https://doi.org/10.1109/JPHOTOV.2017.2732220.

41. Tseng DC, Liu YS, Chou CM. Automatic finger interruption detection in electroluminescence images of multicrystalline solar cells. *Math Probl Eng*. 2015;2015:1-12. https://doi.org/10.1155/2015/879675.

**How to cite this article:** Gul RM, Kamran MA, Zafar FU, Noman M. The impact of static wind load on the mechanical integrity of different commercially available mono-crystalline photovoltaic modules. *Engineering Reports*. 2020;2:e12276. https://doi.org/10.1002/eng2.12276