Fundamental study related to the development of modular solar panel for improved durability and repairability

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Abstract
Solar panels around the globe are primarily designed as a plug-and-play solution and the end users are not allowed to repair the panel in case of damage. Natural loadings such wind, snow, sand and hail can lead to irreparable damage to the solar panels and the easiest solution to fix the damaged solar panel is to replace it. This design philosophy leads to a huge quantity of electronic waste as it completely ignores the repairability of the solar panels. In this regard, the presented research work details the development and testing of modular solar panel with performance similar to the traditional design. The modular design was tested for power transfer, re-connection upon impact and the ability to replace the selected parts in case of permanent damage without the need of replacing the entire solar panel. This experimental research work delivers a modular solar panel design that has ease of repairability in case of damage. Furthermore, a detailed economic analysis has been provided for several real-world scenarios that indicate its suitability over existing commercially available solutions.

ABBREVIATIONS

| Symbol | Definition |
|--------|------------|
| A      | Device area                      |
| E      | Solar irradiance input           |
| FF     | Fill factor                        |
| I_L    | Light generated current           |
| I_{mp} | Current value at the maximum power |
| I_{mpp} | Current at maximum power point   |
| I_o    | Diode reverse saturation current  |
| I_{SC} | Short circuit current             |
| k      | Boltzmann’s constant (1.381 \times 10^{-23} \text{ J K}^{-1}) |
| n      | The ideality factor               |
| PV     | Photovoltaic (solar)             |
| q      | Electron charge (1.602 \times 10^{-19} \text{ C}) |
| STC    | Standard test conditions         |
| T      | Junction temperature             |
| V      | Voltage across the diode terminals |
| V_{mp} | Voltage value at the maximum power |
| V_{mpp} | Voltage at maximum power point |
| V_{OC} | Open circuit voltage             |

1 | INTRODUCTION

Renewable energy is the future for sustainable development and nature friendly co-existence as human species. One of the key proponents of renewable energy portfolio is the solar energy owing to its vast abundance, free availability, ease and variety of applications. Researchers have tried to adopt solar energy for power generation on a large variety of applications. With increased awareness comes investments in renewable energy sector as rapidly growing countries look for alternatives for their growing energy demands. Traditional hydro-electric or coal-fired power plants take a long time to come online and are...
becoming less attractive as compared to the fast-paced implementation of renewable energy. In this regards, solar energy offers an attractive solution to the leaders that allows them to connect their population to the national grid using fast and cheap alternatives [1, 2]. Similar considerations are valid for war-torn countries such as Libya, Syria, and Yemen where traditional solutions require a huge investment and long-time to construct them, while renewable energy solutions appear as a quick and reliable solution that can be implemented at grass root level [3].

One of the key challenges faced by the solar industry is the durability and repairability of the solar panels (PV). Since, the entire PV industry has primarily been competing with traditional fossil fuels for gaining the share of the energy market [4, 5]. Hence, the industry has been forced to be on a strict economic diet with manufacturers finding innovative ways to lower the cost of PV modules to make them feasible for mass application. In pursuit of lower costs, the industry has ignored its own carbon footprint leading to huge electronic waste and has been forced to cut cost of production, transportation, handling, placement, and installation. Such changes included lowering the thickness of PV cells to 100 μm [6] along with other material compromises. This has led the industry to develop solar panels that fall under the category of plug-and-play solution which makes their application easier while completely ignores the durability and repairability of the panels. Currently, almost all the solar panels available in the market can be ranked as onetime application with no consideration for on-site repairs. In case of any damage owing to any reason whether environmental or human error, the only solution available to the customers is to replace the panel.

Recently, solar highways [7] were proposed to generate power using highways but faced several engineering challenges owing to poor durability of the solar panels. Saleem et al. [8] overcame some of the durability issues of the solar highways by developing materials that are able to transmit light generated by solar panels. However, there is large gap in the research avenue related to the solar panel repairability and durability. Abdelhamid et al. [9] summarized various techniques that can be adopted to identify micro-cracks in the solar cells for improving the waste at production stage. Chan et al. [10] used laser doping for edge isolation for crack arresting. Gupta et al. [11] tested the performance of the solar panels against varying types of hail impacts and found the performance of the modern panels to be satisfactory, however, the researchers reported that the permanent damage caused by the hail loading can lead to reduced performance of the solar panels. Greppi et al. [12] and Angele et al. [13] developed an innovative hybrid solar panels with improved durability for application on roof tops and developed a method to embed solar cell in roof tiles. However, the efficiency and cost of these solutions are still high. Furthermore, no on-site repair mechanism exists that can be adopted by end users for easily repairing the solar tiles/solar panels. Lia et al. [14, 15] presented the use of electrical energy storage (EES) to be deployed with solar modules and also presented a multi-stage energy storage and management strategy to overcome energy demand peaks and develop a microgrid network. This work can be used to optimize the scheduling leading to reduction in cost and removal of uncertainties in the energy supply chain.

In light of the above discussion it was evident to the research team that the on-site repairability of the solar panels is an area where little research work had been conducted. Hence, the presented research work details the development, testing, and economic analysis describing the payback for real-world scenarios of a modular solar panel. Factors that affect the performance and efficiency of the PV panel over its life span are taken into consideration and the presented solution can be applied for real-world applications. The research work brings to the attention of the reader an innovation modular design for solar panel which can result in improved repairability and replacement of damaged parts thus leading to lower electronic waste. The presented solution can lead to the emergence of a new repair and maintenance job sector for the renewable industry. Furthermore, the use of modular design will lead to lower carbon footprint and lowering of the risk factor associated to the environmental damage for the solar module site. The presented manuscript has been sub-divided into the following sections. The proceeding section details the background followed by the methodology, experimental testing results of existing solar panels to establish the benchmark values, design and development of modular solar panel and pay-back analysis for real-world scenarios and finally the conclusions along with highlighting the future direction of research and development.

2 | BACKGROUND

PV cells depend on the P-N junction philosophy as a working principle. A basic solar cell form is a P-N junction with two types of semiconductors and two types of impurities added to increase the conductivity forming a P-type and a N-type semiconductors. Both semiconductors are laid on top of each other to form two layers with two different types of charge carriers. Positive carriers are called holes and negative carriers are called electrons. Between the two layers specifically in the P-N junction, a depletion region is formed where neither hole nor electrons exists. In order to generate electrical current through the junction, electrons need enough energy to jump over the depletion region and combine with holes on the other side of the junction. Incoming photons in the form of solar radiation excite the electrons with the needed energy to jump over the depletion region generating electrical flow across the junction. The basic ingredient to manufacture solar cells is silicon (Si). Silicon is collected and melted under high temperatures to form high purity silicon ingot (up to 99.999% pure silicon) with the help of some chemical compounds. After casting silicon ingots, they go through slicing process to produce silicon wafers with thickness around 200 μm [16]. This historic trend of reducing the thickness of the solar wafer has led to complications in the design of PV panels. The current design of PV panels has evolved to be irreparable, leading to lack of durability. After producing the wafers, the surface of the wafers is roughened by chemical etching process. Increasing the surface roughness lowers the reflection of radiation off the surface. In addition to chemical
etching, the wafer surface is coated with anti-reflective coating (such as Silicon nitride \( \text{Si}_3\text{N}_4 \)) to further decrease the reflections of the surface [17]. The last step is printing electrically conductive paste (such as aluminium paste) on the cell surface to collect the generated charges and make contact locations where tabbing ribbons will be placed later. At this step, the wafer is called cell and can be electrically connected with another cell. After manufacturing the solar cells, a solar panel is assembled by connecting number of cells in series by connecting the front surface (the negative side) of one cell to the back surface (the positive side) of the next cell with tabbing ribbons [18]. Figure 1 depicts the typical manufacturing steps involved with the development of a typical PV panel.

The performance of a solar panel is measured with several parameters that primarily depend on the generated current and voltage difference. Short circuit current, \( I_{\text{SC}} \), is the current produced by the panel and is measured around a small resistance calculated using Equation (1) [18].

\[
I_{\text{SC}} = I_l - I_o \left[ e^{\frac{(V_{\text{OC}} + R_S)}{n k T}} - 1 \right] 
\]

where \( I_l \) is light generated current, \( I_o \) is diode reverse saturation current, \( q \) is electron charge \( (1.602 \times 10^{-19} \text{ C}) \), \( V \) is voltage across the diode terminals, \( n \) is the ideality factor, \( k \) is Boltzmann’s constant \( (1.381 \times 10^{-23} \text{ J K}^{-1}) \), \( T \) is junction temperature and \( R_S \) is the cell resistance modelled as series resistance. Open circuit voltage, \( V_{\text{OC}} \), is the measured voltage across the module when no load is connected is calculated using Equation (2) [18].

\[
V_{\text{OC}} = \frac{n k T}{q} \ln \left( \frac{I_l}{I_o} + 1 \right)
\]

Multiplying \( V_{\text{OC}} \) and \( I_{\text{SC}} \) gives the maximum theoretical power, which is not considered as the actual output of the panel under standard conditions. Besides that, two more parameters are used to represent the actual output of the module, which are, \( V_{\text{max}} \), the actual maximum voltage difference produced by the module under standard test conditions, and \( I_{\text{max}} \), the actual maximum current produced by the module under standard test conditions. Usually \( V_{\text{max}} \) and \( I_{\text{max}} \) are referred to as rated voltage \( V_R \) and rated current \( I_R \). Both parameters are recorded under standard test conditions (STC) where cell temperature is 25 °C, solar irradiance is 1000 W m\(^{-2}\) and mass of air coefficient is equal to 1.5. The multiplication of these values gives the actual maximum power \( (P_{\text{max}}) \). One more parameter that links the theoretical and actual produced power is the fill factor, FF, calculated using Equation (3). The fill factor represents the power fraction that can be acquired from a module under STC, in other words it is the measure of a module quality in collecting power from the maximum available power generated by the cells [18].

\[
\text{FF} = \frac{P_R}{P_{\text{max}}} = \frac{V_{\text{max}} \cdot I_{\text{max}}}{V_{\text{OC}} \cdot I_{\text{SC}}}
\]

\[
\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{P_{\text{mp}}}{(E)(A)} = \frac{(V_{\text{mp}})(I_{\text{mp}})}{(E)(A)}
\]

The efficiency (\( \eta \)) of the solar is defined as the ratio of the power output of a module relative to the power input for specific solar radiation. It is calculated using the Equation (4), where \( V_{\text{mp}} \) and \( I_{\text{mp}} \) are the maximum power voltage and current, respectively. \( E \) is the solar irradiance input and \( A \) is the module area. The efficiency of a solar module is affected by other factors such as shading, dust accumulation, or cloudy days. These factors negatively affect the performance of a solar module. For solar modules to work at the maximum efficiency, shading and dust accumulation should be at minimum levels. All these factors were taken into consideration while developing the modular solar module. The next sections detail the development, testing and real-world economic analysis of the novel modular solar panel presented in the research manuscript.

3 | METHODOLOGY

The first stage of development consisted of structural evaluation of existing PV panels. For this purpose, six panels were selected for impact testing using standard impact testing protocol ASTM E1038 [19]. It is worth mentioning to the readers that all commercially available solar panels available in the market are tested using the standard testing protocol. However, real world testing has revealed that even the solar panels that complete the quality test depict damage owing to hail loading and other environmental conditions [10–13]. Hence, in-order to bring the presented research work closer to reality the PV modules were tested until cracking point. These cracked modules are not repairable using any repair technique currently available in the market and the only possible solution available to the client
is to replace the damaged modules. Figure 2 presents the testing protocol adopted in the experimentation.

For this purpose, the PV modules results to be presented pertain to impact loading leading to damage to the PV modules. Each module was tested before the application of impact loading using electroluminescence test as shown in Figure 3(A) to judge the presence of any cracks prior to the loading. This step was conducted as a quality assurance measure. Afterwards the samples were subjected to increasing impact loading using hail balls till damage occurred as shown in Figure 3(B). The objective of this test was to simulate the hail collision in a controlled environmental condition. Hail hits were simulated using a pressurized chamber that shot different sizes and types of balls into a predetermined location on the module. For the presented research work a 25 mm diameter plastic ball was used to imitate the hail collision. The rationale behind this decision was the ability of the specified sized ball to impart a specific amount of energy into module resulting in damage as shown in Figure 3(B). Furthermore, the decision to use plastic balls to simulate hail impact was influenced by control of variables such as the size of ice ball and its melting process during its travel through the atmosphere. Figure 3(C) presents the electroluminescence image after the impact loading. The power output at the standard test conditions (STC) was measured for each module before and after the impact test in order to compare power loss due to generated damage. From the presented results it is evident that the impact loading resulted in damage to several cells surrounding the impact location as shown in Figure 3(C).

The next section details the power loss measurement as a result of the impact load testing.

### 3.1 Experimental setup

For module testing, a 150-Watt module was selected (Kayen-150-18V), containing 36 cells connected in series. Before the application of impact loading to the modules, the output power of each one was determined using a pulse simulator under STC i.e. cell temperature of 25 °C and solar irradiance of 1000 W m$^{-2}$. In addition to the power determination test, an electroluminescence photo was recorded as a control to see internal cracks that are generated by the impact loading. The damage was then simulated using a pressurized gun that shot 25 mm diameter plastic ball at a predetermined location on the module. During experimentation, the pressure was raised gradually until the ball had energy capable of inducing damage to the glass shield on top of the solar cells. Impact locations were selected to induce damage between two cells. Furthermore, testing was conducted in the centre of a cell and at corners to record the behaviour of crack propagation in each case.

The modules were tested by varying the number of hits in order to relate the number of impacts to the power loss. Table 1 summarizes the testing results for the modules depicting the electrical characteristics before and after the impact loading. From the presented results it is evident that 8.6% drop in power generation occurred under standard test conditions. There is no significant effect on open circuit voltage ($V_{OC}$) and short circuit current ($I_{SC}$), however, the maximum power point current
TABLE 1  Parametric comparison between module A and B before and after impact

|                | Module A |                | Module B |                |
|----------------|----------|----------------|----------|----------------|
|                | $V_{oc}$ (V) | $I_{sc}$ (A) | $V_{mpp}$ (V) | $I_{mpp}$ (A) | $P_{mpp}$ (W) | FF (%) |
| **Single impact** |          |                |          |                |                |        |
| Before         | 22.66    | 8.92           | 17.83    | 8.38           | 149.35         | 73.91  |
| After          | 22.49    | 8.66           | 18.34    | 7.44           | 136.55         | 70.15  |
| Loss (%)       | −0.76    | −2.94          | 2.87     | −11.12         | −8.57          | 3.75   |
| **Three Impacts** | | |          |                |                |        |
| Before         | 22.66    | 8.80           | 18.38    | 8.36           | 153.61         | 77.06  |
| After          | 22.48    | 8.59           | 18.35    | 7.02           | 128.74         | 66.69  |
| Loss (%)       | −0.78    | −2.40          | −0.16    | −16.05         | −16.20         | 10.37  |

FIGURE 4 (A) PV module with impact damage owing to hail impact, (B) close-up of the impact damage

($I_{mpp}$) had an 11% drop. This finding can be justified with the rational that since the solar cell is the main source of current so a damage to the solar cell would lead to reduction in generated current which is indicated by reduction in $I_{mpp}$. As $I_{mpp}$ represents the current flowing through the solar module owing to power generation. For module B with multiple impacts as shown in Table 1, it is evident that larger damage resulted in larger loss of power. $V_{oc}$ and $I_{sc}$ had a reduction of 0.78% and 2.40% respectively, on the other hand, $I_{mpp}$ reduced by 16%, whereas $V_{mpp}$ was not affected much with a slight drop of 0.16%. The combination of the drop in maximum power point current and voltage led to 16% drop in the maximum power output of the module, which is a much larger reduction as compared to module A. The testing results showed that the impact mainly affected the $I_{mpp}$ value with a slight effect on $V_{mpp}$ value. Furthermore, it can be deduced from the test results that the output power, $P_{mpp}$, loss increases with increasing in impact loading.

Figure 4 presents the impact loading on the PV module A which was subjected to single impact loading, along with the close-up of the impact location. Prior to the application of hail impact, the location was marked on the PV module. The location presented in Figure 4 was selected based on the rational to view the extent of damage in case when the hail impact occurs in between the two connected cells. Figure 5 presents the electroluminescence scan of the PV module before and after the impact loading along with the close-up of locations with maximum damage. It is evident from the presented results that from the naked eye view of the PV module the damage seems to be limited the single location as shown in Figure 4, however, the electroluminescence scan reveals that even a single impact of the hail can result in multiple locations of damage as shown in Figure 5. The possible explanation of this can be the fact that the adhesive attaching the solar cell to the glass panel is the cause of transferring the impact stresses to the multiple locations around the PV module. Furthermore, as the glass panel breaks the propagating cracks transfer the energy to the solar cell thus causing a large amount of damage by spreading the impact energy. Figure 6 presents the impact testing for module B which was subjected to multiple impacts in order to ascertain the increase in damage with increase in impact loading. Prior to the application of loading the impact loading, its location on the panel face was selected based on the following strategy: (a) impact loading in between two cells, (b) impact loading in the middle of the cell and (c) impact loading at the corner of the cell. The objective of this was to study the extent of damage based on each loading. Figure 6(A) depicts the extent of impact damage to the top glass while Figure 6(B,C) presents the electroluminescence scan before and after the application of impact loading. From the results, it can be seen that damage is not limited to the impact location. Upon impact, the energy imparted by the hailstone is spread through the top glass to adjacent areas of the PV module. This leads to excessive damage in cells surrounding
is creating a module out of cells that are self-contained in small units, which can be connected in series. This design allows the module to isolate the damage in small units that can be easily replaced in an existing system, thus lowering the overall replacement cost and electronic waste produced to the environment. The current design for solar panels consists of cells, such as 32, 36 or 48, connected in series. The problem with the current existing design of PV modules is its high replacement cost and lack of repairability e.g. a single hail impact can damage 10 cells out of a 36-cell panel. The end user is forced to replace the entire panel in-order to recover the lost efficiency. This design philosophy of existing PV module design leads to large amount of electronic waste, 70% of cells which were not damaged out of 36-cell PV panel would need to be replaced thus adding to cost and waste. Generally, there are two possibilities of crack propagation into the solar cells. The first is that both layers are fused together with strong adhesive, and the second is the silicon cells are very brittle/delicate due to material properties and the manufacturing process that produces cell thicknesses close to 100 μm [20]. Taking these factors into consideration, the current fabrication form of solar modules makes it incredibly hard to repair a broken unit leaving replacement as the only achievable choice, and even with replacement comes a huge waste of material.

The design of the modular solar panel consists of two main components as shown in Figure 7 i.e. cell housing and connection element. The modular cell unit assembly consists of three parts: top clear cover to allow solar radiation transmission, solar cell could be either monocrystalline or polycrystalline and the bottom thin rigid cover to hold the cell flat with minimum stresses. The connection element consists of two parts that hold the cell assembly together from the top and the bottom. The sandwich structure as shown in Figure 7 is embedded into the connection bracket. Figure 8 presents the assembly of modular design connected in series and in parallel. The design philosophy of the presented modular solar cell assembly is centred around ease of replacement and repairability. Furthermore, since each cell assembly is contained in its own individual unit the damage caused by the impact loading owing to any environmental or man-made errors can be limited to single or multiple units which can be replaced easily without having a major impact on the overall efficiency of the PV site. This can lead to lower cost of maintenance while also reducing the environmental impact caused by electronic waste. In addition, the added dimension of repairability makes the provided solution immensely feasible for off-grid applications and applications in under-developed nations where plug-and-play one-time use strategy cannot yield economic results. Figure 9 presents the structure of the 3D printed connection assembly. It is to be brought to the attention of the readers that during the iterative design and development stage, the research team experimented with several designs and shapes. Hence, 3D printing was chosen for ease of modification and production. However, for mass production the research team believes that the connection bracket can be manufactured using traditional manufacturing techniques, this will lead to high production rate and much lower cost. However, in the presented research work for

3.2 | Design and development

It was evident from the module testing protocol that it took a single impact to destroy the panel and leave permanent power loss. In order to overcome this problem, this presented research work introduces a new modular design that increases the feasibility of replacing parts of the module that are damaged owing to impact loading. The fundamental idea of the presented design

the impact location. As the impact loading increases the damage also increases. Furthermore, the true extent of damage caused by the impact loading is not visible through the naked eye and can be assessed by the electroluminescence scan.

Based on the above experimental evidence it was clear that the true assessment of hail damage cannot be judged using the visual inspect method. Furthermore, there is no reliable repair method available in the market that can be adopted to isolate and repair the damaged module. Even a single impact by hailstone can result in damage to multiple cells in a module. The only economic solution available to client with damaged PV modules is to replace the entire module in order to gain the lost efficiency. The main reasoning behind this lack of repairability is the fundamental design philosophy of the PV modules which are designed as a plug-and-play one-time use products. Hence, the proceeding section details the design, development process, and economic assessment of the modular PV cell that can be adopted for improved repairability and durability of PV panels.
lab prototyping 3D printing was employed. Figure 10 presents the internal structural design details of the connection bracket. Inside the connection bracket, two neodymium magnets are placed near the edge to work as joining element that holds two cell assemblies together. Once two cells are brought close, they snap together in place. This strategy of assembly was adopted for an “average joe” to install the developed modular PV assembly. The neodymium magnets serve dual function of holding cells together in position, along with shock absorbers by absorbing impact loads causing them to disconnect and re-connect automatically for smaller impacts thus saving the cells form absorbing direct impact energy and causing permanent damage. In-between the two connecting parts, a notch design was introduced, as shown in Figure 10, for the aim of assisting self-alignment, support, and adding resilience to the connection. The objective of adding the notch was to provide additional structural stability to the connection assembly as earlier prototyping test showed that connection assemblies without the notch failed under torsional loading. The notch eradicated the torsional stress concentration at the connection points and on edges. Electrical connection between two cells was achieved through the small tunnel inside the connection assembly as shown in Figure 11.

It is worth noting that the design team was facing a challenge to design a junction that would allow electrical connection
in a way that could be disconnected and re-connected upon impact loading. Hence, the junction in the presented design is not permanent as is the case with the PV modules currently available in the market, where tabbing ribbons between the cells are soldered together permanently. However, the designed junction connection has the capability of accommodating sudden disconnection without introducing any damage to the connectors. Keeping that in mind, the junction was designed to employ direct contact to connect two cells and deliver the power. The connection occurs when all ribbons coming from the top of cell 1 are connected to cell 2 as shown in Figure 12. This connection design eliminates the need for permanent connection allowing the cells to be detachable without stressing the connectors. Furthermore, the design strategy allows the unskilled and untrained worker to install the proposed PV modules. It is to be brought to the attention of the readers that the new modular design would increase the surface area by approximately 20% as compared to the conventional PV module, however, this increase in surface area owing to modular design allows for replacement of single cell thereby making the repairs cheap, efficient, and economical. The proceeding section details the real-world economic feasibility of the presented design solution in comparison to the existing PV panel design and also presents comparative economic analysis by taking into consideration real-world realistic scenarios.

4 | REAL-WORLD ECONOMIC FEASIBILITY ANALYSIS

The presented analysis will focus on materials, life span, and cost of both designs. The estimation presented is based on the development process of the design where materials were not acquired in bulk quantities and locally available in the market using off-the-shelf market prices for analysis. In addition, the estimation will show the expected price of a single unit i.e. cell housing assembly plus electrical connection. Since, for mass production, prices can be considerably lowered using bulk purchase and advance purchasing hence, in real-world application the economic benefits will be even more in favour of the presented modular design.

A typical PV module consists of following materials i.e. (1) PV cells: monocrystalline / polycrystalline silicon wafers, (2) top cover: tempered glass, clear cover that protects the cells, (3) panel frame: aluminum, provides the main structure around the panel, (4) adhesive: EVA (ethylene-vinyl acetate), (5) junction box: plastic, (6) cells connections: tabbing wires (tin copper), (7) back cover: photostable polymer, provides temperature insulation and moisture protection. While the presented modular design in the research work consists of (1) PV cells: VIKO-CELL 4.5 W polycrystalline silicon solar cell, (2) top cover: clear acrylic plexiglass, (3) adhesive: epoxy resin, (4) cells wiring tabbing ribbons (tin copper), (5) back cover: plastic sheet, (6) electrical connection between cells: PLA (polylactic acid or polylactide), (7) magnets: small neodymium magnets, make two cells snap in place together. One point to keep in mind while dealing with solar systems is that the string i.e. number of modules connected in series, performance is affected by the performance of a single module in the string. Hence, shading on one panel will reduce the string output drastically. For this comparison of life span of the PV site, we assume a 150-W panel with 36 cells with an average price US$ 250 (SR 937, approx.). The PV panel is similar to the ones tested for impact loading during hail testing. Assuming a solar system with 10 modules will result in a total number of cells equal to 360 cells. On the other hand, a solar system based on the introduced design will have 360 cells. Table 2 represents the actual market cost of each component used for the cost comparison. The values presented include all forms of taxes in order to bring the comparison as close as possible to real-world. In addition, it is brought to the reader’s attention that although Table 2 represents real world prices, the purchase process was not in a bulk purchase form, each item were ordered in small quantities during the development process and there is room for finding better materials with better prices. The proceeding section details the cost analysis and life-cycle assessment to ascertain the feasibility of the presented modular PV design in comparison to the conventional design under three real-world scenarios. The objective of this exercise is to communicate to the readers the economic feasibility of applying the modular PV design in real-world conditions.

| TABLE 2 | Cost calculation of materials employed for prototype development |
|---------|---------------------------------------------------------------|
| Part    | Material        | Sale qty. | Cost ($) | Qty. | Cost/ part ($) | Unit |
| PV cells | 4.5-W PV cells | 1         | 0.8      | 1    | 0.8            | —    |
| Top cover | Acrylic plexiglass | 5574  | 32       | 294  | 1.7 cm²       |
| Bottom cover | Plastic sheet | 5574  | 32       | 295  | 1.7 cm²       |
| Adhesive | Epoxy        | 25       | 10       | 5.0   | 2.0 mL        |
| Magnets | Neodymium    | 20       | 11       | 2.0   | 1.1 m (metre) |
| Tabbing ribbons | Tin copper | 20      | 15       | 1.9   | 1.4 m (metre) |
| Connect. | PLA         | 1000     | 30       | 70    | 2.1 g (gram)  |
| Total ($) | 10.8       |

FIGURE 12 Sectional view detailing the electrical connection details of cell connected in series
### 4.1 Scenario no. 1: Damage due to environmental factors such as snow/hail

This section details the damage assessment and its financial implications caused by the typical environmental factors such as snow loading or hailstorm. These calculations can also be used to prepare the insurance claims for the financial re-imbursement as any negligence in identifying the extent of damage will lead to lost efficiency on PV modules which will lead to lost profits for the owners of the PV site. In case of damage due to impact, cracks will spread through the standard panels affecting more cells increasing losses, while in a system with modular cells design the spread of a crack is limited to one cell area. The detachable design of the presented modular electrical connection between cells will arrest the cracks to propagate between them because there is no physical path for the propagation to reach the next cell. In this case, damage will happen only at the impact locations, unlike traditional modules where damage can spread to other cells far from the impact position. This has already been shown in the hail testing as presented in the previous section. Thus, adopting the presented modular design in solar systems will reduce losses due to impact damage by controlling the propagation of cracks through modules, resulting in fewer parts needing to be replaced in order to restore the damage. Furthermore, the replacement process will be more efficient. As shown earlier during experimental testing (see Figures 5 and 6), a single impact loading can affect multiple cells in a traditional solar module, however, there will be cells with no damage inside a module that need to be replaced as a whole unit. This intern leads to lost cost for insurance companies and electronic waste which is fast becoming a major environmental hazard. However, in comparison the presented modular solar design, a single damaged cell will need to be replaced resulting in more efficient replacement and less waste. Table 3 presents the damage comparison between the traditional market available PV panel and the presented modular PV design for two percentages of damage i.e. 30% and 70%, respectively. Table 4 represents the cost of repair/restoring the damage in order to recover the lost efficiency of the system owing to hail impact for both percentages of damages. From the presented scenarios as shown in Tables 4 and 5, it can be ascertained that the modular system will lead to approximately 90% savings in cost as compared to traditional PV system. Hence, it can be deduced that the modular PV system is more effective in arresting the damage thus leading to lower cost of repairs/replacements.

### 4.2 Scenario no. 2: Thermal degradation

This section details the damage assessment and its financial implications caused by the thermal degradation that occurs over the lifecycle of the solar module. Thermal degradation is a long-term factor that affects the performance of PV modules over time. Solar modules are subject to heat cycles throughout the day with temperature ranging from +80 to 20 °C. This continues change in the temperature can lead to the development of hot spots or shunts. Hot spots are defects that affect solar cells in the form of small spots that dissipates the generated current

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**Table 3** Scenario no. 1 damage comparison between conventional panels and modular cells

| Scenario no. 1 | Traditional panel | Modular design |
|----------------|-------------------|----------------|
| 30% system damage | Number of cells per unit 36 | 1 |
| System units 10 | System units 360 | |
| Damaged units 3 | Damaged units 3 | |
| Power loss units 3 modules | Power loss units 3 cells | |
| Cells to replace 108 | Cells to replace 3 | |
| 70% system damage | Number of cells per unit 36 | 1 |
| System units 10 | System units 360 | |
| Damaged units 7 | Damaged units 7 | |
| Power loss units 7 modules | Power loss units 7 cells | |
| Cells to replace 252 | Cells to replace 7 | |

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**Table 4** Scenario no. 1 comparison of replacement costs between two types of conventional modules and modular module design

| Scenario no. 1 | Module type | 36-cell (150 watt) | Modular cells (4.5 watt) |
|----------------|-------------|-------------------|------------------------|
| 30% system damage | Average price per cell (USD) 6.94 | 11.00 |
| Damage replacement cost (USD) 750.00 | 33.00 |
| 70% system damage | Average price per cell (USD) 6.94 | 11.00 |
| Damage replacement cost (USD) 1750.00 | 77.00 |
| 95% savings for both damage percentages |

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**Table 5** Scenario no. 2 damage comparison between conventional panels and modular cells

| Scenario no. 2 | Traditional panel | Modular design |
|----------------|-------------------|----------------|
| 50% system damage | Number of cells per unit 36 | 1 |
| System units 10 | System units 360 | |
| Damaged units 5 | Damaged units 36 | |
| Power loss units 5 modules | Power loss units 36 cells | |
| Cells to replace 180 | Cells to replace 36 | |
| 90% system damage | Number of cells per unit 36 | 1 |
| System units 10 | System units 360 | |
| Damaged units 9 | Damaged units 36 | |
| Power loss units 9 modules | Power loss units 36 cells | |
| Cells to replace 324 | Cells to replace 36 | |
in the form of heat resulting in losses in power output of the module [21]. Shunts are another form of defects that solar cells are subject to, they can lead to hot spots also but this time due to the development of a micro-crack that is a result of thermal stresses [22, 23]. Similar to hot spots, microcracks are invisible cracks in the cell structure that work as resistance that dissipates flowing current in the form of heat [24, 25]. The problem with shunts and hot spots is that once they start, they keep on growing causing more damage and losses to the whole module. Considering the same PV system for comparison as presented in scenario 1. A new comparison is presented between conventional solar system and modular solar system with thermal degradation in the system. It is hard to predict the behaviour of thermal degradation, but for this comparison, it is assumed to be 50% and 90%, respectively. From the results presented in Table 5, it is evident that degradation will affect a total of 36 cells in 5 and 9 different panels, respectively, leading to replacement of 180 cells and 324 cells for traditional panel as compared to 36 cells for modular PV design. Furthermore, Table 6 presents the cost of repairs/replacement for the damages from the presented results it is evident the application of modular PV design will result in approximately 68% of savings for 50% damage and 82% savings for 90% damage. Thus, it can be deduced that the modular PV design is more efficient and effective in resisting thermal degradations.

4.3 Scenario no. 3: Mechanical stresses

The following section details the cost analysis of both traditional PV modules and the modular design owing to mechanically induced stresses owing to transport, handling, placement, and installation. Solar panels are subject to mechanical stresses throughout their life span. Mechanical stresses can also occur after installation owing to strong winds, these stresses can lead to defects that will reflect on the module performance. This case study represents the impact of mechanical stresses on both designs of solar modules. In this presented scenario it is assumed that 100 solar panels with 36-cell per panel are shipped to a location to be installed in a solar system. A typical 5% damage due to transportation mechanical stresses is considered in the presented analysis. A total of 5 panels will be partially damaged. Considering that only 50% of each panel is damaged, a total of 90 cells can be considered damaged as the shipment reaches the installation site. In this scenario, a total of 180 cells, in 5 modules, will need to be replaced due to the design of conventional solar modules. On the other hand, modular design reduces the number of cells that need replacement by 50% (90 cells) since, each individual cell can be replaced thus eradicating the need to replace functioning cells. This leads to lower cost of replacement and also results in reduced electronic waste. Table 7 presents the cost comparison for the two design strategies and it can be seen that 21% of the cost can be saved for replacing the damaged cell considering 5% damage. Hence, the modular design can lead to saving of time, cost and labour needed for maintenance of PV site. Figure 13 depicts the summary of fundamental characteristics differences between the two design approaches i.e. traditional market available design strategy and the presented modular design strategy. From the presented evidence and economic analysis, it is evident that the presented modular design approach can lead to lower cost of repairs and replacement as compared to traditional PV panels. The proceeding section details the economic analysis related to payback period for the real-world application scenarios in order to ascertain the applicability of the proposed modular design.

4.4 Payback analysis

One important factor that is always taken into consideration while designing a solar system is its payback period. This period represents the time needed for the investment to start generating profit. This kind of financial analysis is typically used to analyse cash flow, which refers to total amount of profit achieved, or capital invested into a project. The payback analysis is commonly used to evaluate the feasibility of an investment such as solar power plants. The main point of conducting such analysis is to compare the investment in any project. The same strategy has been adopted to access the feasibility of the conventional solar system as compared to the innovative modular solar system. In order to conduct a valid comparison...
few assumptions were made to ensure that both systems are evaluated on same basis. The objective of this section is to compare the two systems in terms of initial capital investment, payback period i.e. time needed for the investment to turn profitable, cost of repairs/replacement in case of damage and the tradeoffs that both systems go through during their life span. Payback period of any renewable energy project depends on many factors such as its location, environmental conditions, geological conditions, need for repairs, replacement and maintenance, importance of the project and its utility. However, all these conditions are considered uniform for both systems as both systems are considered to be located at the same site. Hence the main factor that governs the payback period is the drop in output power. Less power output will translate into longer payback periods. This factor has a much higher impact on the traditional PV panels. A single hail impact can lead to permanent damage of the conventional PV panel, while in case of modular design only the cells that get damaged from the hail impact can be replaced easily. Thereby leading to lower cost of investment needed to restore the site back to its pre-damage condition. While for the traditional panel the only solution available is to replace the entire panel thereby leading to higher costs, larger electronic waste and delay in payback period.

Based on the above presented explanation the processing section presents the payback cash flow analysis for real-world scenarios. For ease of analysis a site consisting of 10 solar panels representing an array, connected in series are considered. The cost of each panel is considered as US$ 250 (SR 937 with conversion factor US$ 1 = SR 3.75). The mentioned cost includes installation and mounting components such as J-bolts, shingles, nuts etc. The rationale for taking these costs into consideration is based on the fact that all these costs will be included as part of the project for application under real-world conditions. The initial cost of a conventional solar module system would be US$ 2500 (SR 9375). On the other hand, a modular system will cost US$ 3960 (SR 14,850) based on unit price US$ 11 (SR 41). Since this comparison is focused on the effect of replacing damaged parts in the system on the payback period, it was conducted under the assumptions that; (a) both systems life spans are 25 years, (b) system failure is introduced in mid-life span point i.e. the 12th year, (c) constant working conditions throughout the system life span, (d) both systems have the same power output, working hours, weather conditions and power billing rate, (e) damage and replacement patterns will follow the cases explained earlier, (f) transportation, installation, and other costs are same for both cases. The rational for these assumptions is based on the logic that the research team aims to focus on the cost of repair and replacement between the two competing design philosophies. Hence these assumptions have logical background.

It is to be brought to the reader’s attention that some of these assumptions are deliberately negatively affecting the performance of the presented modular design e.g. the cost of transport of modular panel will be much less as compared to traditional panel. Furthermore, it is assumed that the damage will be induced at mid-span i.e. at 12th year of the life cycle. This is an uncontrollable and un-predictable phenomenon as environmental impact can happen at any time after installation. In addition, only a single environmental impact is considered during 25 years of the project life span, whereas in reality there can be several environmental impacts on the project site during the life span, which will favour the modular design for its ease of replacement and lower cost of maintenance. The rationale for this is to provide evidence of the financial feasibility of the presented novel modular design in worst case scenario.
The payback analysis is conducted for scenario no.1 with two replacement percentage i.e. 30% and 70% as shown in Figures 14 and 15 respectively. Furthermore, the payback analysis is also conducted for scenario no.2 with the replacement percentages of 50% and 90% as shown in Figures 16 and 17 respectively. Figure 14 depicts the payback curves for both conventional and modular systems. The initial cost of modular system is higher than the initial cost of the conventional system, therefore break even point for modular system is delayed 30 months. At mid-life point where the damage is introduced to the system, the graph shows bigger drop in profit due to the added costs of modules replacement in conventional design compared with modular design. On the other hand, with 70% replacement as shown in Figure 15, the modular solar system has more financial advantage. With the increase in the system damage, the replacement cost of conventional system becomes higher to the point where it exceeds the replacement costs of modular system. This is referred to as inflection point as shown in Figure 15. Inflection point represents the time when the conventional commercially available PV system become more expensive to install and operate as compared to the presented innovative modular system. Afterwards, the modular system becomes more economically feasible as compared to traditional PV solution.

In the second scenario, 50% and 90% replacement are taken into consideration as shown in Figures 16 and 17 respectively. With 50% replacement as shown in Figure 16 the payback analysis reveals that modular solar system requires less replacement costs in a tradeoff with high initial cost. On the other hand, conventional system reached the break even point in 50 months due to the lower initial cost but requires a huge re-investment to return to normal electricity production after the environmental impact. Similarly, for 90% system damage as shown in Figure 17, the replacement cost of conventional solar panels exceeds the cost of modular system giving it the financial benefit and better payback. However, the re-investment needed to return the system back to its pre-damage conditions makes the modular system more favourable.

The above shown cases discuss hypothetical situations with small-scale systems. In real-life situations with large scale systems, a single storm can destroy a whole system in a matter of hours. For example, PVEL a company specialized in testing PV modules and assisting the solar systems damage for assisting clients in developing their insurance claims after environmental damage, published one of the site assessments on a webinar [26]. They showed (see Figure 18) that a single hail can devastate the PV site and render it useless for energy production. Furthermore, the field engineers elaborated that it is possible to
have PV panel that suffer no visual cracks owing to hail impact, but they might have micro-cracks that can lower the efficiency of the PV panel [27–30]. These micro-cracks only become visible in an EL image as shown in Figure 19. Hence according to industry professional and researchers [26, 31, 32], the PV panel with invisible cracks can lower the production of PV site and increase the repair cost leading to up to four times larger insurance claim.

5 | CONCLUSION

This research work presents the design and development of a novel innovative modular solar panel. From the presented experimental work, the following conclusions can be drawn.

- The presented modular solar panel design provides ease of replacement and repairability as compared to traditional plug-and-play one-time use solar panels commercially available in the market.
Comparison analysis between the modular design approach and the conventional solar panel design showed that the modular design required less costs to replace damaged components improving the performance and ease of repairability of the system.

As is the case with any design and development work, there is always room for improvement. The aim here is to bring to the attention of reader's the areas of further research. In this regards the research team aims to conduct large scale real-world testing of the developed prototypes to evaluate their performance in real-world conditions and to judge their thermal performance. Furthermore, testing method for quality assurance needs to be developed for the proposed solution. In addition, a new system for cleaning the front glass needs to be developed for dust removal. It is unclear the impact dust will have on the connection joints and overall performance of the modular system. These areas are a topic of further research and development.

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