P3C TECHNOLOGY AND SOLUTIONS PVT. LTD.

Internship Report

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Submitted To: Dr. Ankit Rao

Head of Department R&D

31.07.2025

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Declaration

I, **Palash Verma**, hereby declare that the internship work entitled "**Internship Report**" is carried out at **P3C Technology & Solutions Pvt. Ltd., Manesar, Haryana** under the guidance of **Mr. Ashutosh Mishra**, in fulfilment of the completion of **2 months** internship at the company. To the best of our knowledge, this work has not been submitted in part or full for the award of any degree, diploma, fellowship, or similar title from any university, institute or company.

I also declare that the work presented in this report is original and does not contain any confidential information pertaining to the company. I assume full responsibility for ensuring that this report complies with all applicable legal and ethical standards.

Date: 31.07.2025

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Dr. Ankit Kumar Rao	**Ms. Shalini**
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Acknowledgment

I would like to express my sincere gratitude to **Mr. Ashutosh Mishra**, **Head of the Spin Coating and Testing Team** at P3C Technology and Solutions Pvt. Ltd., for his continuous guidance, mentorship, and support throughout the course of my internship. His technical expertise, patient supervision, and constructive feedback played a crucial role in shaping my learning experience and allowed me to explore the intricacies of solar technology from both a practical and research-oriented perspective.

I am especially thankful to **Dr. Ankit Rao**, **Head of the R&D Department**, for providing me with the opportunity to be a part of innovative and ongoing research projects within the company. His leadership and commitment to fostering a dynamic and inquisitive research environment were highly motivating and greatly contributed to my overall professional development.

I would also like to extend my appreciation to the entire team at P3C Technology and Solutions Pvt. Ltd. for their collaboration, encouragement, and willingness to share knowledge and ideas. From the spin coating laboratory to the testing and integration divisions, every interaction added depth to my understanding and inspired me to delve deeper into the challenges and possibilities of solar energy systems.

This two-month research internship has significantly enriched my practical understanding of solar energy technologies, particularly in areas such as spin coating, perovskite cell encapsulation, and the real-world integration of solar modules. The exposure to indoor and outdoor testing environments, as well as participation in collaborative experimental setups, has helped me bridge the gap between theoretical knowledge and engineering application. I look forward to applying the skills and insights gained here in future academic and industry projects.

Introduction

Perovskite solar cells (PSCs) represent a transformative leap in photovoltaic technology. With their unique crystal structure, perovskites have garnered immense interest due to their ability to achieve high power conversion efficiencies (PCE) while maintaining low fabrication costs. Their lightweight, semi-transparent, and flexible nature makes them attractive for next-generation applications such as wearable electronics, building-integrated photovoltaics, and space-based solar platforms.

The internship aims to explore practical advancements in PSCs, pushing them closer to real-world implementation. The core objective is to increase device efficiency, evaluate operational behavior, and conduct extensive testing to identify degradation mechanisms like moisture ingress, UV degradation, and interface instability.

A crucial aspect of this exploration is developing scalable fabrication techniques that preserve performance while reducing material and environmental costs. Additionally, emphasis was placed on studying the reproducibility and batch uniformity of the fabricated cells to ensure consistency in performance. The ability of these cells to function under varying environmental conditions was also a major focus of this effort.

Throughout the internship, I engaged in fabricating various PSC architectures, performing spin coating and testing encapsulated and non-encapsulated cells under diverse indoor and outdoor conditions. By conducting such hands-on experimentation, I aimed to understand the challenges faced during real-world deployment and contribute toward solving issues like thermal stress, delamination, and efficiency loss.

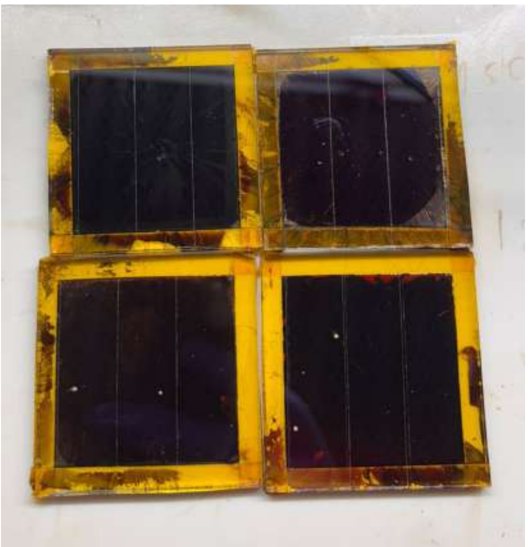


Figure 1: 2 inch PSCs- Spin Coating

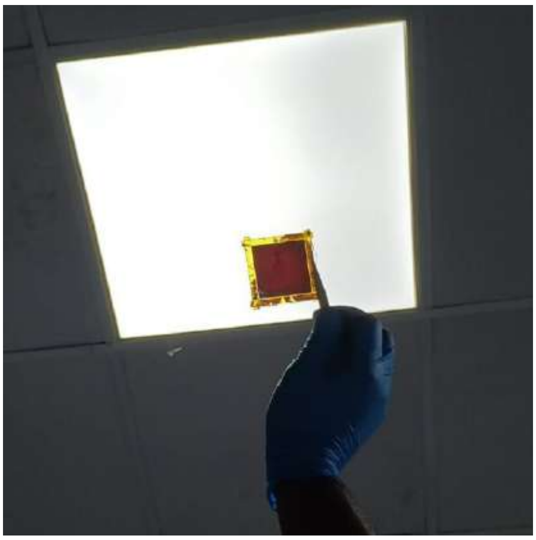


Figure 2: Film Quality Inspection

Experimental Setup

4.1 Ossila Solar Simulator

Figure 3: Ossila Solar Simulator

Ossila Solar Cell Simulator is a laboratory-grade light source used to evaluate the performance of photovoltaic devices, particularly perovskite solar cells (PSCs). It mimics the spectral output of natural sunlight, typically AM1.5G, to provide a controlled and repeatable environment for solar testing. The simulator uses a calibrated xenon or LED light source with uniform intensity across the active area, ensuring accurate measurement of parameters such as short-circuit current (Isc), open-circuit voltage (Voc), fill factor (FF), and power conversion efficiency (PCE). A standard solar simulator setup consists of the light source, a calibrated reference cell for intensity calibration, and a source-measure unit (SMU) for I-V curve tracing.

In the context of perovskite research, the Ossila Solar Simulator is employed to test individual cells and modules under stable indoor conditions. Cells are placed under the lamp, and their response to illumination is recorded using software. The system allows comparison of fabrication techniques, layer uniformity, and degradation under controlled light soaking. This is especially valuable before outdoor testing, enabling consistent benchmarking of devices. For our project, the simulator was used to characterize cells developed by the Spin Coating and Slot Die teams, providing initial efficiency readings before environmental and NISE validation tests were conducted.

4.2 Holmarc UV Ozone Cleaner

Figure 4: Holmarc UV Ozone Cleaner used for substrate treatment

Before spin coating is carried out, the fluorine-doped tin oxide (FTO) glass substrates undergo a crucial cleaning and surface activation process using a Holmarc UV Ozone Cleaner. This treatment step is designed to enhance the substrate's surface energy, improve wettability, and promote strong adhesion of subsequent solution-processed layers. The UV Ozone Cleaner functions by emitting ultraviolet light at wavelengths of 185 nm and 254 nm. These wavelengths are responsible for generating ozone (O_3) from molecular oxygen present in the ambient air. The reactive ozone, in combination with high-energy UV photons, facilitates the breakdown and removal of organic contaminants, hydrocarbons, and surface residues through oxidative reactions.

Before initiating the UV-ozone treatment, the FTO substrates are thoroughly sprayed with high-purity nitrogen gas to remove dust particles, lint, and other physical contaminants. Additionally, Kapton tape is used to mask specific regions—such as electrode contact areas—that must remain free of any deposited film for electrical connection. Once the UV ozone treatment is complete, the resulting FTO surface becomes uniformly hydrophilic. This change in surface chemistry is critical for achieving an even and defect-free spread of the precursor solution during spin coating.

The effectiveness of this surface modification directly influences the quality of the deposited films, ensuring better crystallinity, reduced pinholes, and enhanced mechanical and electrical integration within the device architecture. Thus, the UV ozone cleaning process serves as a foundational step in the fabrication of high-performance optoelectronic devices, including perovskite solar cells and related thin-film technologies.

4.3 Spin Coating

Figure 5: Spin coater used for thin film deposition

Spin coating is a widely used technique for fabricating thin films from liquid precursors. In this process, a small quantity of solution is dropped onto the center of a substrate, which is then rotated at high speed. The centrifugal force spreads the solution outward, forming a thin, uniform film. The final thickness depends on factors such as solution viscosity, spin speed, duration, and ambient conditions.

During the internship, two spin coaters were employed: the EZ Spin PR Coater by APEX Instruments and a programmable spin coater from Delta Scientific Equipment Pvt. Ltd. These devices allowed precise control over spin parameters and facilitated the fabrication of consistent, high-quality films.

Three functional layers in the perovskite solar cell architecture were deposited using spin coating: the Electron Transport Layer (ETL), the perovskite absorber layer, and the Hole Transport Layer (HTL). The ETL was spin-coated at high speeds to achieve compact, thin films. The perovskite layer involved a two-step spin process with anti-solvent dripping for proper crystal formation. Lastly, the HTL was deposited under moderate spin conditions to ensure full surface coverage without defects.

Spin coating played a critical role in device fabrication, enabling uniform, multi-layered structures essential for efficient perovskite solar cell performance.

Spin Coating- Substrate Preparation

Substrate preparation formed the backbone of daily lab activity and was essential for achieving high-quality device layers during fabrication. Transparent conducting substrates such as FTO-coated glass were routinely cut to precise dimensions depending on the target cell size. These substrates were then cleaned using sequential sonication steps to remove surface contaminants. Following this, selective etching was performed to isolate electrodes, and masking was applied using Kapton tape to define the active area.

Plasma treatment was carried out before every spin coating session to make the surface hydrophyllic and ensure proper adhesion of layers. A wide range of cell designs were prepared including 2 cm and 2-inch single-cell devices, three-cell modules, and six-cell configurations on 2-inch substrates. This allowed systematic study of spin-coating behavior, layer uniformity, and performance variations across multiple architectures and substrate types.

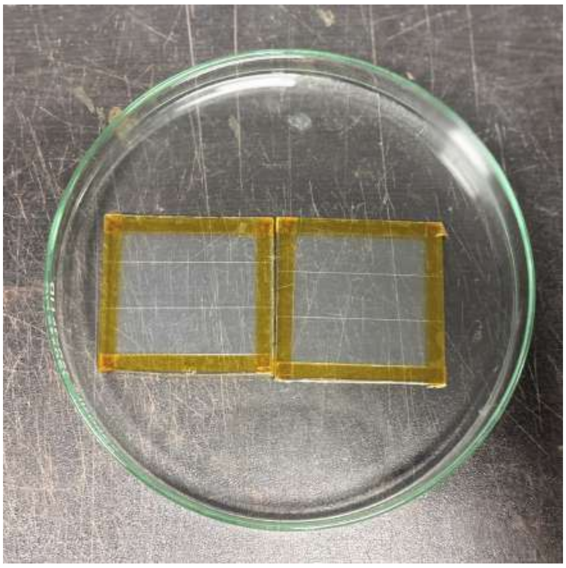


Figure 6: 2 inch substrates

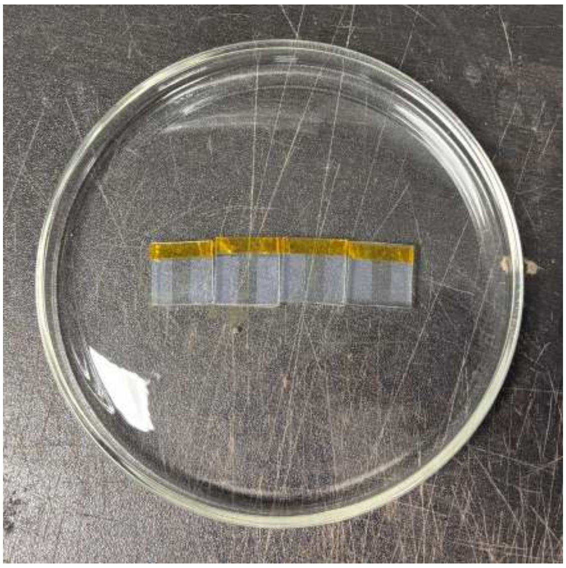


Figure 7: 2 cm substrates

Outdoor Tests

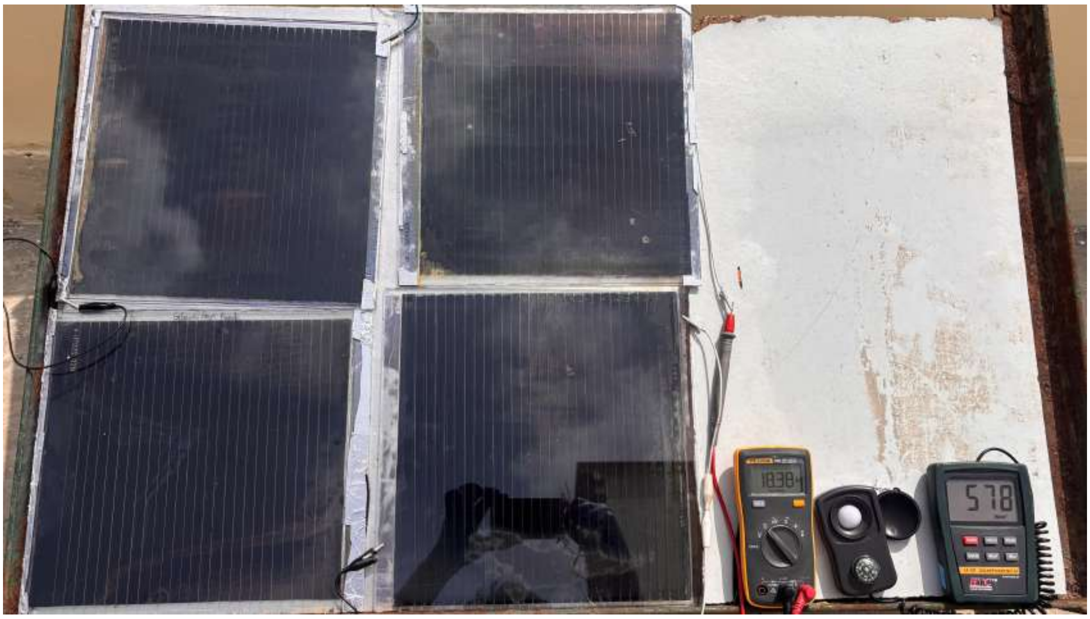


Figure 8: Four 1-foot panels in parallel: 18.38 V, 160 mA (578 W/m^2)

Due to the limited sample holder size of the **Ossila Solar Cell Simulator**, the full-sized perovskite modules measuring 1 foot and 6 inches could not be tested under controlled indoor illumination. Consequently, outdoor testing was conducted under real-world environmental conditions to assess their photovoltaic behavior, durability, and overall reliability. The panels were exposed to direct natural sunlight on a clear day, providing a realistic simulation of operational conditions. In one setup, four 1-foot perovskite panels were connected in parallel under a solar irradiance of 578 W/m^2. The configuration produced 18.38 V and approximately 160 mA, leading to a total power generation of nearly 3 W.

This result highlighted the practical scalability and applicability of these flexible modules for real-world energy harvesting. In a separate experimental arrangement, two 1-foot panels were connected in series. They produced voltages of 22.62 V and 18.71 V respectively, yielding a combined output of around 41 V—significantly surpassing the typical 28 V obtained from similar-sized commercial silicon modules. These outdoor tests were essential not only for characterizing photo and thermal degradation behaviors, but also for validating the modules' effectiveness and resilience under prolonged field exposure and operational stress.

Encapsulation Tests

7.1 Damp Heat Test

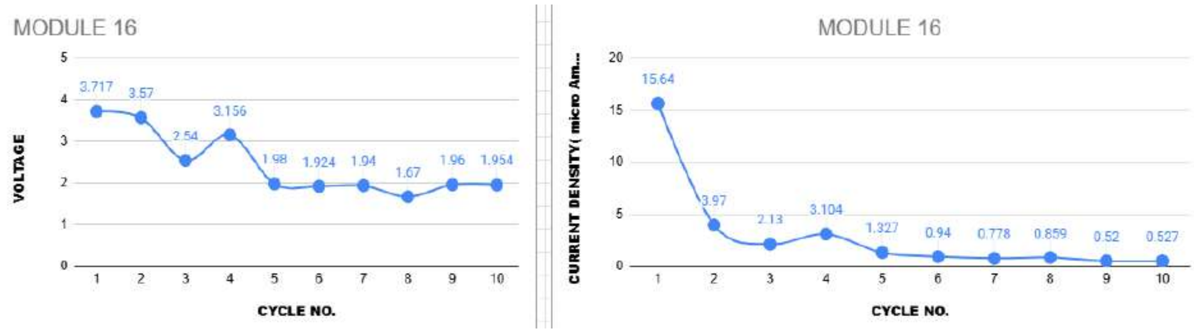


Figure 9: Voltage and current degradation across 10 cycles under thermal stress (Module 16)

The damp heat test is a widely used accelerated aging method to assess the thermal stability and reliability of photovoltaic cells. In this study, perovskite solar cells were subjected to controlled heating on a hot plate maintained at approximately 85 °C for 20 minutes. This procedure was intended to simulate high-temperature operating environments, such as rooftop installations or indoor modules exposed to localized heating.

The electrical characteristics were recorded after each heating cycle. As shown in the figure above, Module 16 exhibited a sharp decline in both open-circuit voltage and short-circuit current density over 10 thermal cycles. The initial voltage dropped from 3.717 V to 1.954 V, while current density fell from 15.64 $\mu A/cm^2$ to just 0.527 $\mu A/cm^2$. The most significant losses occurred during the first three cycles, suggesting rapid interfacial degradation and reduced charge extraction efficiency.

These losses are primarily attributed to thermal expansion, ion migration, and phase instability within the perovskite layer and the transport interfaces (ETL/HTL). Heating can also promote defect formation, moisture ingress, and delamination, all of which contribute to performance decay.

The results clearly highlight the vulnerability of perovskite devices to thermal stress and emphasize the importance of incorporating robust encapsulation layers and thermally stable transport materials in device design. Enhancing thermal durability is crucial for the long-term viability of perovskite photovoltaics in real-world applications.

7.2 Water Dip Test

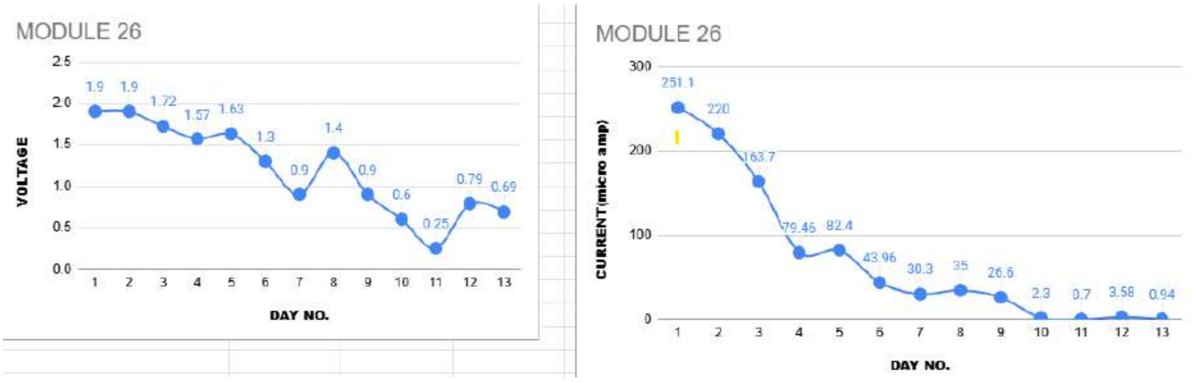


Figure 10: Voltage and current degradation across 13 cycles, submerged in water (Module 26)

The water dip test evaluates the waterproofing effectiveness of encapsulated perovskite solar modules. In this experiment, fully encapsulated modules were submerged in deionized water at room temperature for 13 consecutive days. Voltage and current measurements were recorded daily to assess the long-term electrical stability and moisture ingress resistance of the encapsulation strategy.

As illustrated in the figure above, Module 26 experienced significant electrical degradation over time. The initial voltage of 1.9 V declined steadily to 0.69 V by day 13, while the short-circuit current dropped from 251.1 µA to just 0.94 µA. Most of the current loss occurred in the first 6 days, suggesting rapid water diffusion through potential pinholes or delamination zones.

This deterioration is primarily attributed to moisture intrusion into the active layers, leading to perovskite decomposition and interface degradation. Despite encapsulation, the sharp decline in performance indicates that the protection was insufficient against long-term water exposure.

Notably, minor recovery in both voltage and current is seen on days 11–12, which may be due to temporary drying or measurement variability. However, the trend confirms irreversible damage beyond that point.

These results emphasize the critical role of encapsulation in real-world applications and the need for water-impermeable, UV-stable barrier layers. Improving edge sealing, barrier adhesion, and hydrophobic properties is essential for enhancing the durability of perovskite devices in humid or submerged environments.

7.3 Ambient Test

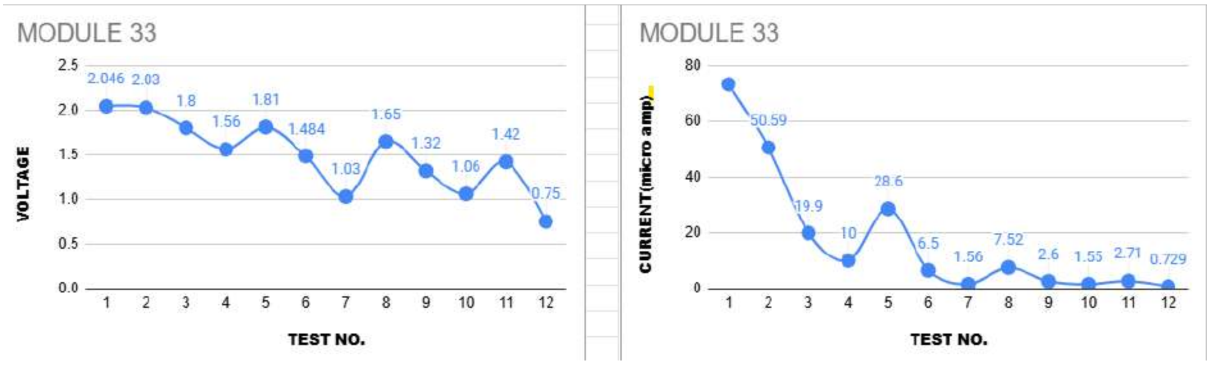


Figure 11: Voltage, current degradation across 12 cycles in ambient conditions (Module 33)

This test investigates the dark stability of encapsulated perovskite solar cells under ambient indoor conditions. The device was stored at room temperature (25°C) in complete darkness, but not under vacuum or inert atmosphere. Voltage and current values were recorded each day for 12 consecutive days to track shelf-life degradation in air-exposed environments.

The data for Module 33, displayed in the figure above, reveals notable degradation. The initial open-circuit voltage of 2.046 V fell to 0.75 V, and the current declined dramatically from 73.1 µA to 0.729 µA. Most of the degradation occurred in the first 4–5 days, after which the values plateaued at lower levels, indicating accelerated degradation due to atmospheric exposure and slowed kinetics once major decomposition pathways had progressed.

The voltage drops are associated with charge carrier recombination losses, while the current reduction reflects poor charge extraction, likely caused by defect formation in the perovskite or transport layers. Encapsulation delays but does not fully prevent ingress of oxygen and moisture, which catalyze perovskite decomposition into PbI_2.

This test underscores the importance of long-term barrier stability even in visually benign conditions. Despite no direct thermal or UV stress, devices stored in ambient environments degrade considerably, highlighting the sensitivity of perovskite materials to air, and reinforcing the need for hermetic encapsulation in future commercial applications.

Projects

8.1 Tata Ace Hybrid EV: Partial Shading and Panel Monitoring

M6				
S. No	Distance (cm)	Voltage (V)	Current (mA)	Intensity (%)
1	13.8	1.19	4	60
2	13	1.33	5	70
3	12.3	1.42	5	80
4	11.6	1.73	6	90
5	11	1.74	7	100

ABX3 RTP				
S. No	Distance (cm)	Voltage (V)	Current (mA)	Intensity (%)
1	13.8	2.14	3	60
2	13	2.18	3	70
3	12.3	2.36	3	80
4	11.6	2.44	4	90
5	11	2.71	5	100

M6, ABX3 RTP- Parallel				
S. No	Distance (cm)	Voltage (V)	Current (mA)	Intensity (%)
1	13.8	1.38	7	60
2	13	1.55	8	70
3	12.3	1.67	8	80
4	11.6	1.74	10	90
5	11	1.76	12	100

Figure 12: Voltage and current output for M6, ABX3 RTP, and parallel configurations under varying intensities

In the Tata Ace EV project, four solar panel modules, each rated at 40V, are connected in parallel to increase the total current, aiming for a cumulative power output of 1.2 kW. However, real-world outdoor operation introduces challenges such as partial shading. When one panel is shaded and the others are fully illuminated, the output voltage of the shaded panel drops. In parallel configuration, voltages do not add up; instead, the lowest voltage dominates.

When one panel's voltage drops due to reduced intensity, it acts like a load, allowing reverse current to flow. The combined voltage dips closer to the average voltage of the two mismatched panels. To mitigate this, bypass diodes are introduced to prevent reverse current, while an MPPT controller with microcontroller logic disconnects panels that fall below threshold voltage. A boost converter then regulates a constant 40V output.

8.2 Indoor Applications: DC Motor Operation with Perovskite Panels

One of the significant advantages lies in the broad absorption spectrum, which extends beyond the near-infrared region. Unlike traditional silicon cells that are more limited in spectral response, perovskite cells can harvest energy from a wider range of wavelengths, making them especially suitable for low-light and indoor applications.

This enhanced sensitivity opens up a range of use-cases previously unfeasible for solar energy, including the powering of small electronics indoors. A notable example is the operation of low-power DC motors commonly used in appliances like coffee frothers. Conventionally, such devices rely on disposable or rechargeable batteries containing environmentally hazardous elements such as lithium or cadmium.

To explore a sustainable alternative, we set out to power a DC motor using a perovskite solar panel. The motor required a minimum startup voltage of 3V and a current of approximately 70mA. With this specification in mind, we fabricated compact 2-inch perovskite cells.

The final prototype achieved an output of 3.1V and 82mA under standard indoor illumination. This was sufficient to operate the motor reliably, demonstrating the feasibility of perovskite solar technology for powering micro-appliances without relying on toxic or non-renewable energy storage systems. This proof-of-concept serves as a step toward cleaner, decentralized energy solutions for indoor environments.

Figure 13: Fabricated 6-inch perovskite solar cell powering a DC motor

Experiments

9.1 Soaking Tests

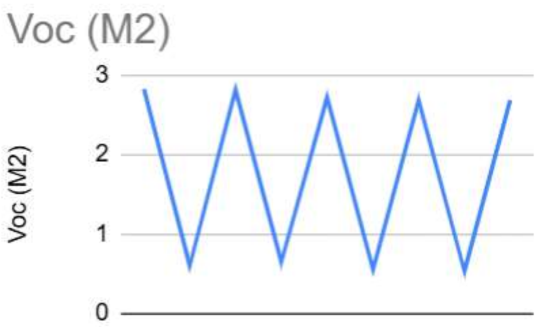


Figure 14: Voltage Photo-degradation

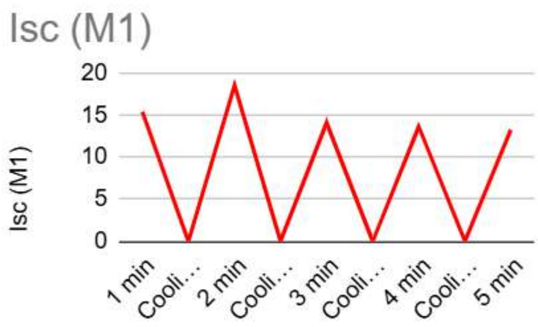


Figure 15: Current Photo-degradation

To assess the thermal and photonic stability of perovskite solar cells (PSCs), soaking tests were conducted on nine 2-inch, 3-cell modules under 1000 W/m² light for 2 minutes. Open-circuit voltage (Voc) readings taken at 1, 1.5, and 2 minutes revealed gradual voltage drops, especially in M2.1, which fell from 2.6V to 2.0V—indicating early photodegradation. To examine long-term effects, repetitive soaking-cooling cycles were performed.

As shown in the graphs, both Voc (M2) and short-circuit current Isc (M1) declined over cycles, with M1's Isc falling from 17 mA to 12 mA. These diminishing peaks suggest irreversible degradation mechanisms such as ion migration or delamination. The results stress the need for improved encapsulation, cooling, and testing to ensure long-term PSC module stability.

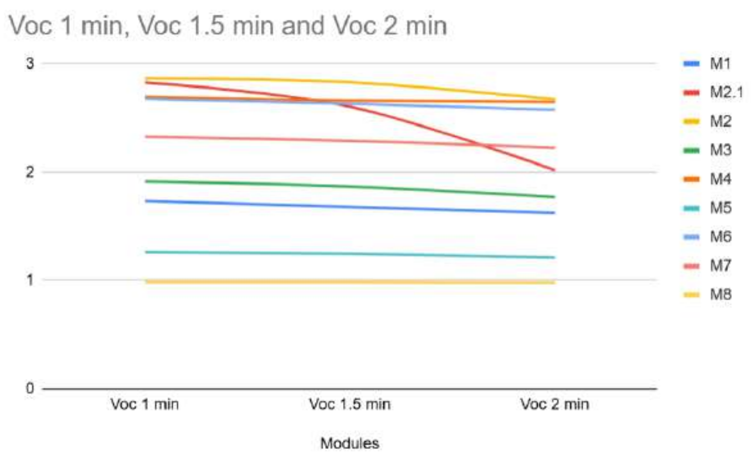
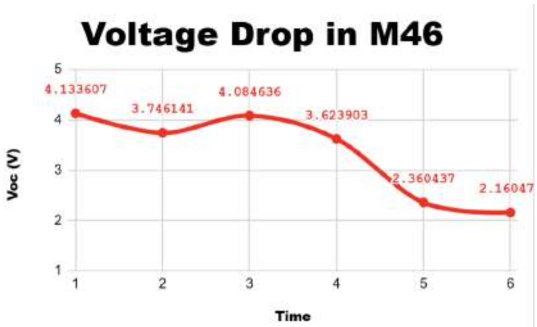


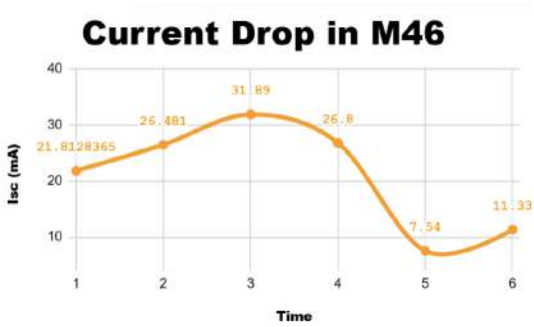
Figure 16: Voltage Drop in 9 Modules

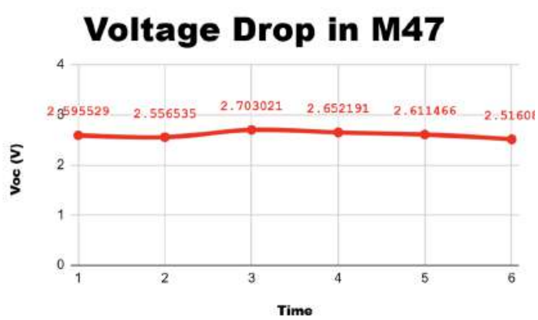
9.2 Environmental Factors Affecting Solar Panels

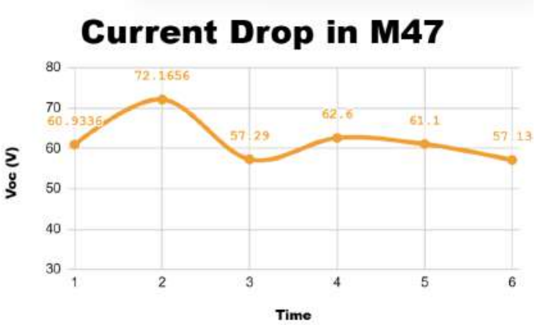
9.2.1 Internal Degradation

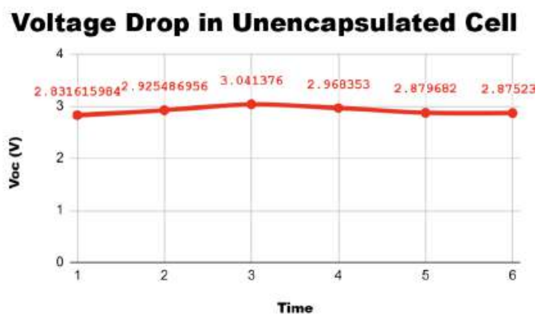
To study internal degradation in perovskite solar cells, three modules—two encapsulated (M46, M47) and one unencapsulated—were tested indoors under a solar simulator while stored in vacuum for a week. All cells maintained stable voltage and current, showing minimal degradation in inert conditions. However, when M46 was exposed to ambient air for one day, its performance dropped sharply: voltage fell from 4.13 V to 2.16 V, and current from 21.81 mA to 11.33 mA. This highlights that encapsulation alone is insufficient. Environmental isolation like vacuum or inert gas is essential to prevent internal degradation and ensure long-term reliability of perovskite solar cells.











9.2.2 Photo-degradation

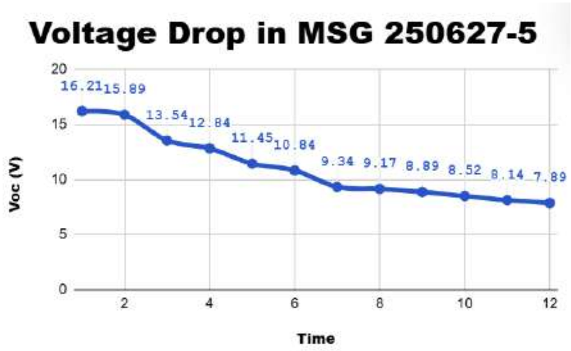


Figure 17: Encapsulated Cell 1

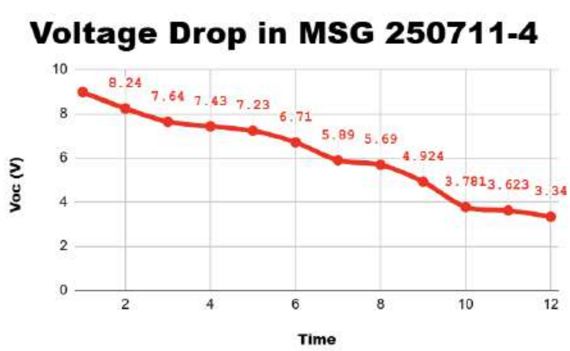


Figure 18: Encapsulated Cell 2

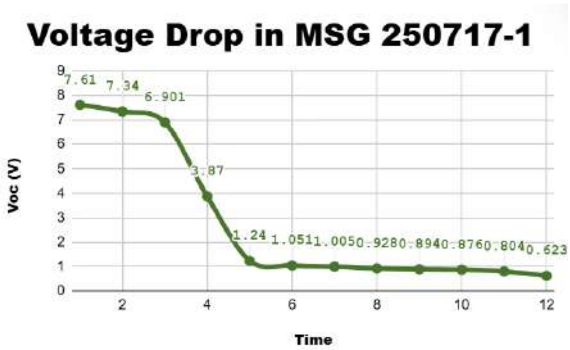
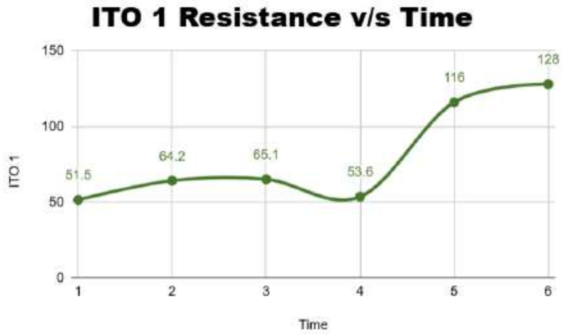


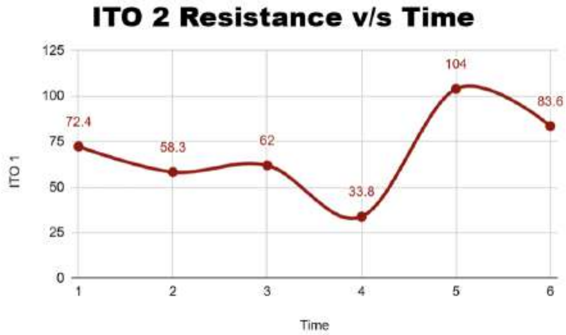
Figure 19: Unencapsulated Cell

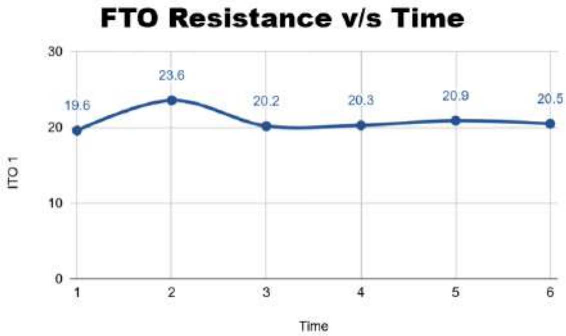
The graphs illustrate the impact of photo-degradation on three distinct photovoltaic modules subjected to prolonged light exposure. MSG 250717-1, an unencapsulated cell, shows a steep and rapid decline in V_{oc} from 7.61 V to 0.623 V within 12 time units, indicating severe degradation and likely operational failure. This behavior suggests high vulnerability to photonic and environmental stress due to the absence of protective layering. In contrast, MSG 250711-4, which is encapsulated, exhibits a more gradual voltage drop from 8.24 V to 3.34 V, reflecting improved photo-stability and moderate protection.

The third module, MSG 250627-5, demonstrates the best performance, starting with a significantly higher initial V_{oc} of 16.21 V and degrading only to 7.89 V, indicating strong resilience to degradation over time. These findings highlight that prolonged light exposure significantly diminishes photovoltaic performance, but the degradation rate is heavily influenced by device architecture and protective measures. Enhancing encapsulation can thus play a crucial role in extending the operational life and stability of solar cells in real-world environments.

9.3 Flexible Substrates: Coating Removal Issues







Resistance and temperature readings were recorded over several days to evaluate the durability of the conductive layers on different transparent electrodes—FTO on glass and ITO on flexible substrates. The FTO-coated glass sample showed minor fluctuations in resistance, ranging from 19.6 Ω to 23.6 Ω before stabilizing around $20 - 21$ Ω, indicating strong thermal and structural stability under prolonged exposure.

However, both ITO 1 and ITO 2 on flexible substrates demonstrated significant increases in resistance over time. ITO 1 rose sharply from 51.5 Ω to 128 Ω, and ITO 2 fluctuated drastically, dipping to 33.8 Ω and then peaking at 104 Ω before ending at 83.6 Ω.

These trends suggest that the ITO layers underwent substantial degradation, leading to a decline in electrical conductivity. Visual inspection revealed partial peeling and delamination of the ITO films, likely accelerated by heat stress.

This behavior poses a critical issue for applications in harsh environments. In particular, the rooftop mounting of solar cells on a TATA Ace hybrid EV, exposed to direct sunlight, could induce similar thermal conditions. If left unresolved, the deterioration of the conductive layer would result in severe efficiency losses. Therefore, thermally insulating adhesives were investigated as a potential solution to mitigate heat-induced layer degradation.

NISE Certification and Testing

Figure 20: 1ft Solar Panel Modules Made by Slot Die Team: 22.62 V, 18.71 V (383 W/m^2)

The Spin Coating and Slot Die Coating Teams produce various perovskite solar cell designs, from small test cells to large-area modules. Each module undergoes a strict evaluation process, including measurement of open-circuit voltage, short-circuit current, fill factor, and power conversion efficiency (PCE).

Modules are tested under standard illumination conditions both indoors (simulator) and outdoors (sunlight), and only those exhibiting strong electrical performance and visual stability are shortlisted for further certification processes.

Any device achieving a PCE near or above 20%, which is considered a benchmark efficiency, is marked for submission to the National Institute of Solar Energy (NISE). NISE performs independent validation using standardized testing protocols. These certified modules help verify the reliability, repeatability, and commercial potential of the team's fabrication techniques. The certification serves as a seal of quality and allows for public reporting and industry demonstration of results. High-performing 1ft panels, such as those shown above, have successfully met these standards and are currently under review at NISE for formal accreditation.

Research Paper: Scalable Fabrication Methods of Large-Area (n-i-p) Perovskite Solar Panels

This research presents scalable fabrication methods for large-area (n-i-p) perovskite solar panels using eco-friendly and industrially feasible techniques. Two device architectures are examined: planar and mesoporous. The planar configuration features a flat electron transport layer (ETL) beneath the perovskite absorber, while the mesoporous design incorporates a TiO_2 scaffold to enhance charge transport and interface stability. Both designs include a gold electrode and transparent conductive oxide (TCO) on glass substrates.

The study maps the charge carrier pathways through detailed energy band diagrams, illustrating how sunlight excites electrons in the perovskite, which are then transported to the ETL and external circuit. Simultaneously, holes move toward the hole transport layer (HTL). The authors outline six possible energy loss or transfer routes, stressing the importance of reducing recombination.

Scalability is demonstrated through successful fabrication of 15 cm × 15 cm modules using slot-die and blade coating, confirming consistent film quality. The work supports the viability of these architectures for real-world solar energy applications.

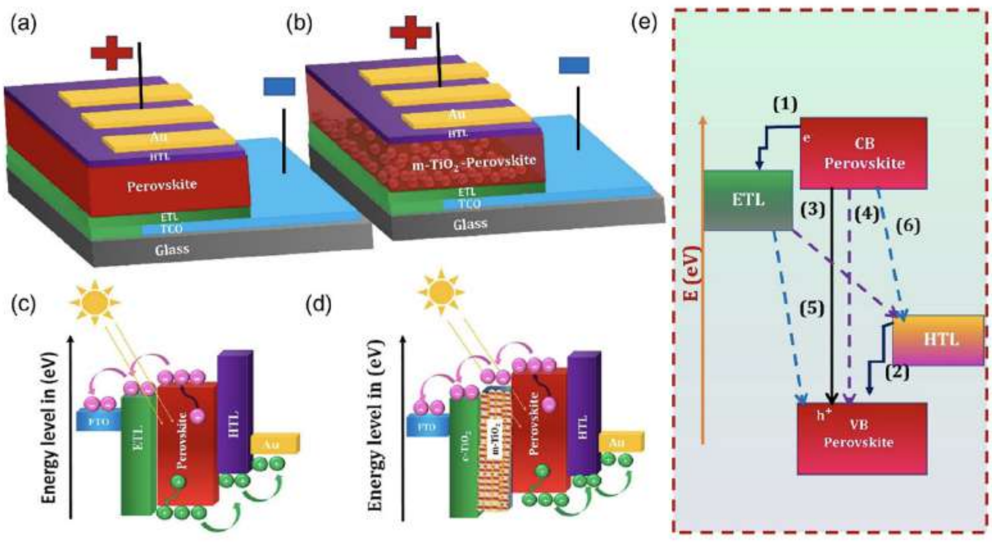


Figure 21: Architectures and energy diagrams for planar and mesoporous (n-i-p) perovskite solar cells

Conclusion

The conducted experiments offer comprehensive insight into the stability, degradation, and performance of various photovoltaic cell components under real-world conditions. FTO (fluorine-doped tin oxide) on glass demonstrated superior stability in resistance over time, indicating its robustness for high-temperature applications. On the other hand, ITO (indium tin oxide) coated on flexible substrates displayed significant resistance increase and visible peeling, suggesting mechanical and thermal weaknesses under prolonged exposure to environmental stressors.

Photo-degradation tests highlighted the vulnerability of unencapsulated cells, where a sharp drop in open-circuit voltage (V_{oc}) was observed, indicating severe electrical degradation. Encapsulated samples showed more moderate and gradual declines, emphasizing the importance of proper encapsulation techniques to preserve cell performance. These results clearly point out that material selection, protective layering, and thermal management are crucial in determining the longevity and efficiency of photovoltaic devices.

Water immersion and ambient exposure studies revealed that even minor environmental factors can impact electrical parameters significantly. In both cases, slow but measurable degradation occurred, stressing the need for durable sealing and waterproofing measures when cells are exposed to moisture or fluctuating indoor conditions. These insights are critical, especially when deploying solar modules in hybrid EVs or outdoor structures, where consistent exposure to heat, humidity, and light is unavoidable.

One of the most alarming observations was the dramatic resistance hike in ITO layers, which could drastically affect current flow and output power. This makes a compelling case for replacing ITO in flexible applications or enhancing its mechanical bonding with substrate layers using thermal adhesives. The investigation into thermally insulating adhesives presents a promising direction to maintain integrity under operational stress and could potentially solve issues of delamination.

In summary, the project underscores that long-term photovoltaic performance is not only a matter of initial efficiency but also of structural and environmental durability. Strategic material engineering, improved adhesion, and careful encapsulation can substantially enhance the reliability of solar modules across various use-cases.

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