PERFORMANCE AND DEGRADATION OF SEMI-FLEXIBLE MODULES IN NAUTICAL APPLICATIONS: A CASE STUDY OF THE ARARIBOIA TEAM'S CATAMARAN

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Abstract

This study examines advancements in photovoltaic (PV) systems through the Desafio Solar Brasil competition, focusing on the solar-powered catamaran of the Arariboia Team. The research highlights the commissioning of photovoltaic modules damaged throughout the entire logistics process, including transport and use. A rigorous methodology involving electroluminescence testing, I-V curve analysis, and cross-validation ensured data reliability. The results demonstrated the validation of the proposed method and a subsequent comparison of the pre- and post-competition performance, confirming the robustness of the testing protocols under controlled conditions. The findings contribute to optimizing photovoltaic applications in sustainable mobility.

Keywords: Photovoltaic Efficiency, Solar-Powered Mobility, I-V Curve Analysis, Sustainable Energy Transition.

1. Introduction

The exponential growth of photovoltaic generation has been observed globally, driven by international agreements and national incentives aimed at increasing the share of renewable sources in the global energy matrix (Governo Brasileiro, 2024; IRENA, 2024; Urbanetz et al., 2019). This expansion is a central pillar of the energy transition, a global movement seeking to replace dependence on fossil fuels with a more sustainable and diversified energy model to mitigate global warming (Moura et al., 2024). In this scenario, electric mobility plays a vital role, offering a path to significantly reduce greenhouse gas emissions in the transportation sector (Moura et al., 2024; Springer, 2023). The maritime sector, in particular, which is responsible for approximately 3% of global emissions, has been identified as a priority area for decarbonization (Freitas, 2025).

The integration of photovoltaic systems into electric vehicles, including vessels, represents more than just an auxiliary power source. This approach creates a synergistic relationship that enhances the overall efficiency of the system and accelerates public acceptance of renewable technologies. Onboard power generation reduces dependence on the grid's charging infrastructure, which is one of the main bottlenecks for the mass adoption of electric vehicles (Smart Cities, n.d.). By making the power source visible and intrinsic to the vehicle's operation, this integration also serves an educational function, increasing awareness and confidence in solar energy as a viable and practical alternative (Moura et al., 2024).

The implementation of photovoltaic systems in nautical environments presents a distinct set of challenges compared to static land-based installations. Marine systems are subject to severe operating conditions, including constant vibration, mechanical shocks from the vessel's movement, a corrosive atmosphere due to salt spray, and dynamic, unpredictable shading caused by sails, masts, or other superstructures (Arka360, n.d.; Gorilla Power Solutions, n.d.). These conditions demand robust and adaptable technological solutions.

In this context, an engineering trade-off emerges between traditional rigid photovoltaic modules and

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emerging flexible and semi-flexible panel technologies. Rigid panels offer high conversion efficiency and proven durability, but their weight and rigidity are significant disadvantages on high-performance vessels where weight is a critical factor (Beihaipower, 2023; JMH Power, n.d.). On the other hand, semi-flexible modules provide an attractive solution as they are lightweight and can conform to curved surfaces. However, these benefits come with lower durability and greater susceptibility to mechanical damage, such as microcracks and delamination (Beihaipower, 2023; JMH Power, n.d.).

The marine environment, with its simultaneous combination of mechanical, thermal, chemical, and electrical stressors, effectively acts as an accelerated aging test for photovoltaic module technologies. The damage observed by the Arariboia Team after a single competition cycle represents a condensation of failure modes that could take years to manifest in conventional installations. Consequently, nautical applications become an invaluable source of data on long-term durability and degradation mechanisms, providing crucial insights for materials scientists and reliability engineers seeking to develop more robust photovoltaic products for all sectors.

The Desafio Solar Brasil (DSB) is a university competition designed to stimulate the technological development of solar-powered vessels (Desafio Solar Brasil, n.d.a; Desafio Solar Brasil, n.d.b). Inspired by international events like the Frisian Solar Challenge , the DSB provides a platform where students from various fields can apply their theoretical knowledge in a practical and competitive environment. The multidisciplinary nature of the competition requires teams to integrate knowledge from engineering, physics, chemistry, administration, and communication to develop successful projects, turning the event into a holistic engineering exercise.

University competitions like the DSB function as low-cost research and development (R&D) incubators, bridging the gap between academic research and industrial application. The challenge forces innovation by solving practical problems under severe constraints of time, budget, and regulations. The journey of the Arariboia Team, from the Fluminense Federal University , exemplifies this process: a real engineering problem (the need for a lightweight power source) led to a solution (semi-flexible modules), which in turn generated a new problem (unexpected damage), culminating in an innovative solution (a new testing protocol). This problem-solution-problem-innovation cycle mirrors the industrial R&D process, accelerating the development of practical knowledge and tangible solutions that are often lacking in purely theoretical academic work.

This case study focuses on the Arariboia Team's experience during their preparation for the 2023 competition. The team made the strategic decision to replace their rigid modules with semi-flexible ones to reduce the vessel's total weight and thereby improve its performance. However, this change led to a critical point of failure: during initial tests, low energy yield and overheating were detected in several modules. A subsequent investigation attributed these problems to damage, such as microcracks, incurred during the transportation and handling of the panels, a vulnerability inherent to this technology.

This experience served as the primary motivation for the present study. In response, the team opted to acquire custom-made modules of national manufacture, increasing the generation capacity from 1,600 W to 1,876 W. More importantly, the team implemented a rigorous pre- and post-competition testing protocol to ensure the integrity of the modules and quantify performance degradation under real-world usage conditions. This protocol, which forms the core of this work's methodology, is presented in detail in the following section.

2. Materials and Experimental Methods

2.1 Photovoltaic Modules and Instrumentation

The experimental system consisted of the Arariboia Team's solar-powered catamaran, equipped with an array of 29 semi-flexible photovoltaic modules. The specific characteristics and appearance of the modules used in this study are illustrated in Figure 1. The modules were labeled from sol1 to sol29. An additional module, sol4, was acquired exclusively for experimental purposes and served as a control module, not being used in the competition, to allow for a direct comparison of the impact of competitive use on degradation. The nominal specifications of the modules, provided by the manufacturer, are crucial for the comparative analysis and are detailed in Table 1.

Figure 1: Semi-flexible photovoltaic module used in the experimental study.

Table 1: Manufacturer's Specification for the Semi-flexible PV Module

Characteristic	Value
Maximum Power (Pmax)	67 W
Voltage at Pmax (Vmpp)	9.9 V
Current at Pmax(Imp)	6.8 A
Open-Circuit Voltage (Voc)	11.6 V
Short-Circuit Current (Isc)	7.2 A

2.2 Module Integrity Screening by Electroluminescence (EL)

The electroluminescence (EL) test was used as an initial screening method to assess the integrity of all newly acquired modules. The principle of this test is based on the inverse phenomenon of the photovoltaic effect: by applying a direct current to a PV module, the solar cells emit radiation in the near-infrared spectrum (Figueiredo et al., 2018; IEC, 2018; Matos, 2020). This light emission, invisible to the naked eye, is captured by a specialized camera, generating an image that reveals the internal state of the module.

The EL technique functions as a kind of "X-ray" for the solar panel, allowing the detection of non-visible defects that can compromise performance and reliability, such as microcracks, cell fractures, soldering issues, inactive cell areas, and other defects that can lead to power losses and the formation of hot spots (Al-Otum, 2023; Sunevo Solar, 2021). The application of this test as a quality control step before installation was fundamental to ensuring that all modules were free from manufacturing defects or transportation damage, thus establishing a reliable baseline for subsequent performance evaluation

2.3 Adapted Protocol for I-V Curve Characterization in Low-Voltage Modules

The characterization of the current-voltage (I-V) curve is the standard method for determining the key performance parameters of a photovoltaic module, including the short-circuit current (Isc), open-circuit voltage (Voc), and maximum power (Pmax) with its corresponding voltage (Vmpp) and current (Impp).

Although the use of a variable resistance (rheostat) is one of the earliest and most established methods for obtaining I-V curves, its application in this study was integrated into a rigorous two-phase validation protocol to overcome a specific technical challenge: the available commercial I-V curve tracer (HT-IV600) had a minimum operating voltage requirement of over 15 V, while the team's individual modules had a Voc of only 11.6 V, preventing direct measurement. To ensure data reliability, this classical approach was cross-validated against commercial equipment using modules in series, providing a scientifically sound and accessible alternative for field characterization in low-voltage nautical applications.

To overcome this limitation, an innovative two-phase methodology was developed and validated:

Series Connection for Measurement with Commercial Equipment: To bypass the voltage limitation of the HT-IV600 tracer, two modules were connected in series. This configuration doubled the total voltage of the set, raising it to a level within the equipment's operating range and allowing a reference I-V curve to be obtained for the pair of modules.

Figure 2: HT-IV600 equipment used for tracing the I–V curves of the photovoltaic modules.

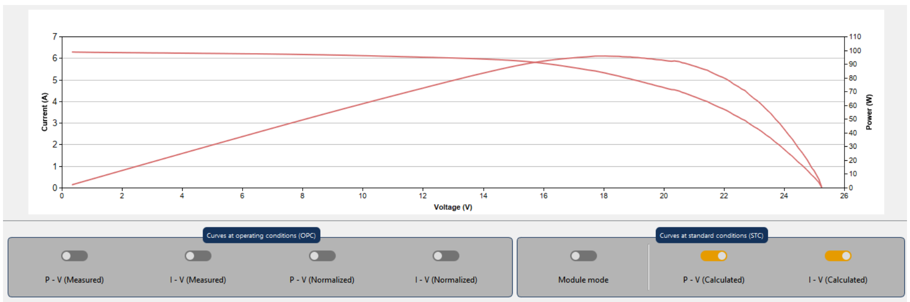

Figure 3: I–V curve of the photovoltaic module obtained using the HT-IV600 equipment.

Development and Validation of a Manual Extrapolation Method: In parallel, a manual method was implemented to trace the I-V curve of individual modules. This method used a variable load (rheostat) to sweep the module's operating curve, while two Yokogawa TY720 multimeters recorded voltage and current values in real-time. The procedure followed the guidelines of the IEC 61853-1 technical standard. For the extrapolation of the curve to Standard Test Conditions (STC), Equation 1 and 2 presents the expressions used to calculate the extrapolated voltage and current values. To validate the accuracy of this manual method, the results obtained for the series-connected module pair were compared with pre-competition data from HT-IV600. Figure 4 illustrates the electronic load utilized for the manual method of I-V curve acquisition. Meanwhile, Figure 5 presents the data obtained from the high-precision I-V curve measurement equipment in São Paulo.

$$V_{stc} = V_{opc} * (1 + \beta (T_{stc} - T_{med})) \qquad \text{(eq. 1)}$$

$$I_{stc} = I_{opc} * (1 + \alpha (T_{stc} - T_{med})) \qquad \text{(eq. 3)}$$

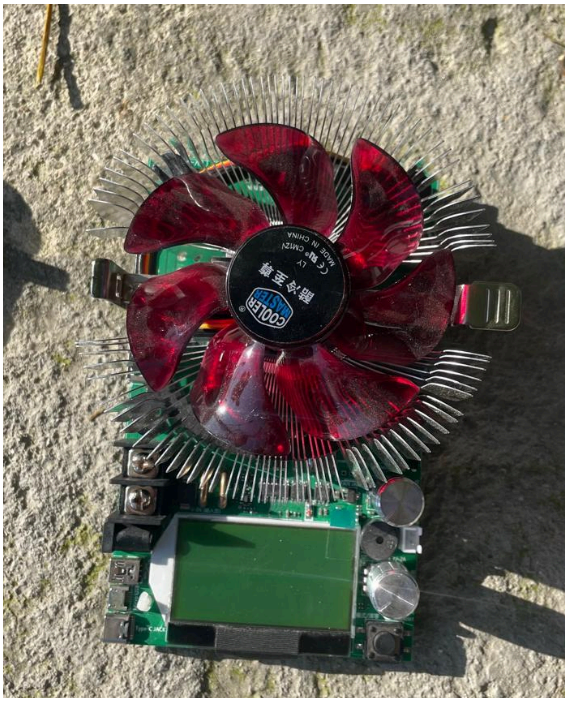

Figure 4: Electronic load used as a variable resistance in the manual extrapolation method for I–V curve tracing.

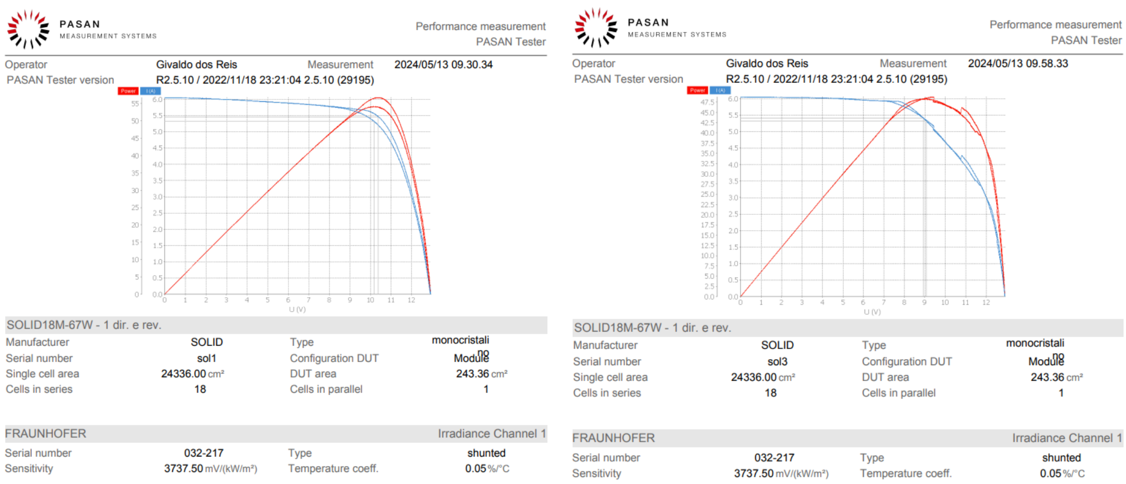

Figure 5: I–V curve result obtained using the PASAN equipment for photovoltaic module characterization.

This cross-validation allowed for the quantification of the error margin and confirmed the reliability of the manual method, which was subsequently used to characterize all modules individually. This approach was not just a practical solution to a specific problem; it constitutes a validated protocol that can be adopted by other researchers and teams in the niche of low-voltage photovoltaic systems (e.g., portable electronics, IoT sensors, other solar competition teams), where standard commercial equipment is often inadequate or oversized. By validating their methodology against a laboratory standard, the team transformed a technical challenge into a methodological contribution, providing a low-cost and scientifically sound alternative for field characterization in these specific applications.

3. Results and Discussion

3.1 Validation of the Adapted I-V Curve Measurement Protocol

The first phase of the results focused on validating the developed measurement methodology. The comparison between the I-V curves generated by the HT-IV600 and those obtained through the team's manual extrapolation method for the series-connected modules revealed a "satisfactory alignment." Furthermore, it is worth noting that this validation was performed prior to the competition. The observed consistency between the two datasets, despite the operational limitations of the team's field equipment, confirmed the reliability and procedural robustness of the adapted method. This validation was a crucial step, as it established the credibility of all subsequently collected individual module performance data, ensuring that the measurements were accurate within a known and acceptable margin of error.

3.2 Baseline Performance and Post-Competition Degradation Analysis

The central analysis of the study involved a direct comparison of the modules' condition before and after their use in the Desafio Solar Brasil. This analysis was conducted both qualitatively and quantitatively.The qualitative analysis was based on the comparison of electroluminescence (EL) images obtained before and after the competition. The post-competition images revealed the appearance of new defects, such as microcracks and areas of cells that had become inactive, which were not present in the baseline images. These defects were correlated with the mechanical stressors and vibrations inherent to operating a vessel at high speed during a competitive event.The quantitative analysis used the I-V curve data to measure performance loss. Table 2 presents a comparison of the maximum power (Pmax) parameters for representative modules. The correlation between the visible defects in the EL images and the magnitude of the power loss quantified by the I-V curve provides robust evidence of the negative impact of operating conditions on the integrity and efficiency of the modules.

Table 3 presents the comparative data between the results obtained using the PASAN system, employed as a high-precision reference at the University of São Paulo, and those obtained manually through the extrapolation method developed by the team. The analysis clearly demonstrates the performance loss of the module during the competition, showing that, despite the differences between measurement methods, both indicate a significant reduction in the maximum power output compared to ideal test conditions. This comparison reinforces the importance of validating the manual method, confirming its consistency for field performance evaluation.

Figure 6 illustrates, respectively, the Sol_1 module before and after the competition. Similarly, Figure 7 documents the condition of the Sol_3 module during the same periods. The comparative analysis of both cases highlights the generation of microcracks in the modules, resulting from the operation during the competition.

Table 2: Comparison of Manual Method to HT-IV600

Module ID	Pmax - Manual Method (W)	Pmax - HT-IV600 (W)	Error(%)
sol_1and3	94,99659 W	96,04265 W	-1,089%

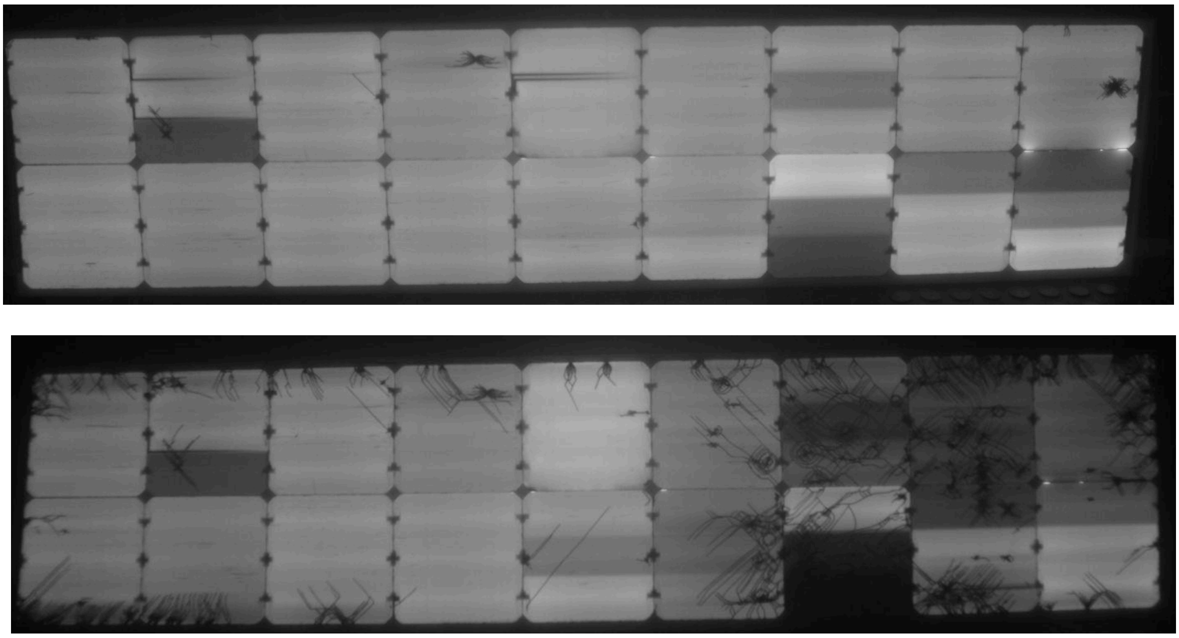

Figure 6: Sol_1 Pre- and Pos- Competition.

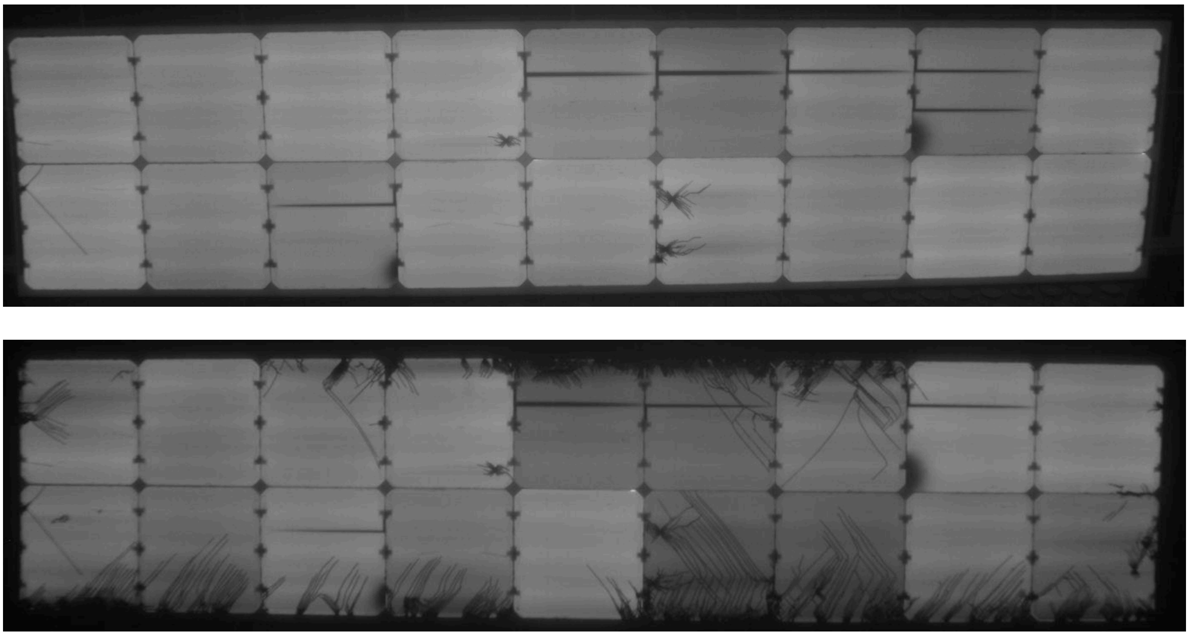

Figure 7: Sol_3 Pre- and Pos- Competition.

Table 3: Comparison of Manual Method to PASAN

Module ID	Pmax - PASAN (W)	Pmax - Manual Method (W)	Performance Loss (%)
sol_1	54,109 W	47,00541 W	-13,13%
sol_3	48,289 W	42,72685 W	-11,52%

Figure 8 depicts the measurement setup, wherein the Yokogawa TY-720 is used to measure the module's voltage and current from the electronic load. Simultaneously, other multimeters are recording temperature and irradiance data for subsequent extrapolation to STC (Standard Test Conditions).

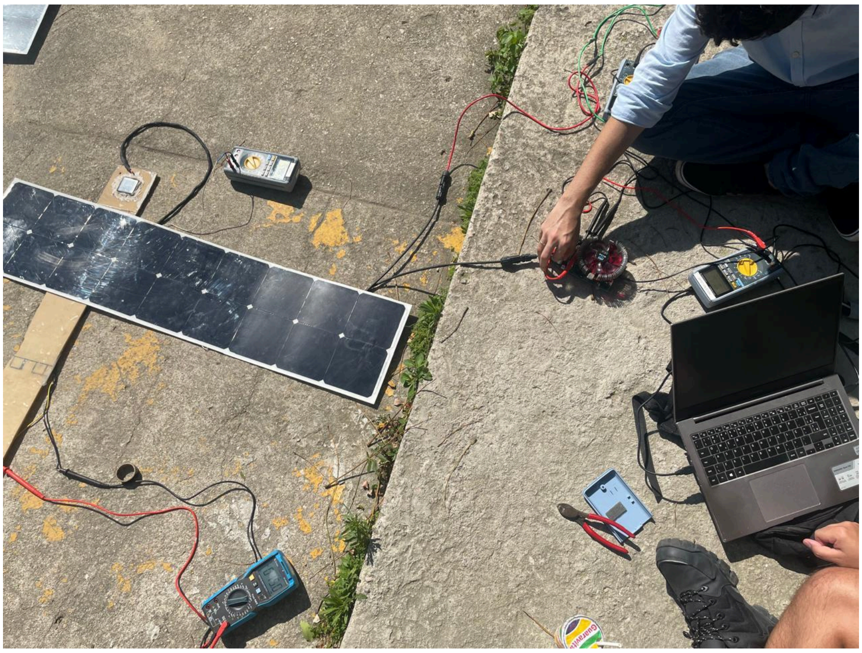

Figure 8: Experimental setup of the manual method for I–V curve acquisition.

3.3 The Performance Trade-offs of Semi-flexible Modules in High-Stress Environments

The results of this study highlight the fundamental engineering trade-off associated with choosing semi-flexible photovoltaic modules for high-performance applications. The primary benefit, weight reduction, is undeniably critical for success in nautical competitions. However, as the data conclusively demonstrate, this benefit is achieved at the cost of greater vulnerability to damage from transportation, handling, and operational stress. The quantified degradation confirms the inherent lower durability of semi-flexible modules compared to their rigid counterparts, a fact already established in the technical literature (Beihaipower, 2023).

The main conclusion to be drawn from this analysis is not that semi-flexible modules are unsuitable for marine applications, but rather that their successful implementation requires a paradigm shift in project lifecycle management. The team's initial experience of installing the modules assuming their functionality and only discovering the damage through poor performance illustrates the pitfalls of the traditional approach. The "install and forget" mentality, which may be applicable to robust rigid panels, proves insufficient for more fragile technologies. The technology itself demands a more involved, data-driven management process. Therefore, to unlock the performance benefits of flexible panels in demanding environments, it is imperative to adopt a rigorous, multi-phase quality assurance framework—including pre-installation screening and post-use assessment—as an integral and non-negotiable part of the design and operation process. This approach has significant implications for the cost-benefit analysis and operational planning of any future project utilizing this technology.

4. Conclusion and Future Perspectives

This study presents two main contributions to the field of mobile photovoltaic applications. First, the implementation and validation of a robust and low-cost protocol for the characterization of low-voltage photovoltaic modules, addressing a significant gap in field testing equipment. Second, the generation of a unique dataset that quantifies the performance degradation of semi-flexible modules in a real, high-stress, competitive marine environment. The research reinforces the critical importance of combining qualitative (EL) and quantitative (I-V curve) tests for a comprehensive assessment of photovoltaic system health, especially when using inherently less durable module technologies.

The challenges identified with current semi-flexible modules, namely their mechanical fragility, can be seen as a set of performance requirements for the next generation of solar technology. Recent advances in flexible solar cells, such as those based on perovskites, organic materials, and other thin-film technologies, emerge as promising solutions (Gressler et al., 2022; Li et al., 2021). These emerging technologies offer the potential for much greater mechanical resilience, with prototypes surviving over 10,000 bending cycles with minimal efficiency loss, directly addressing the failure modes observed in this study (Williams, 2025). Although Electroluminescence (EL) tests revealed extensive damage within the modules, the corresponding degradation in electrical power output was not proportionally severe, registering a loss of 12.33% at the cell level. While this confirms the presence of wear and degradation, a critical power loss has not yet manifested. However, it is projected that this power degradation will accelerate with the propagation or emergence of further microcracks.

The market for semi-flexible panels is expanding rapidly, with growing demand in the marine and recreational vehicle (RV) sectors, which will further drive research and development in this area (Precedence Research, n.d.; TimesTech, n.d.). The work of the Arariboia Team stands as a valuable real-world benchmark that can inform and guide this future development. By providing concrete data on failure mechanisms in demanding applications, this study helps ensure that next-generation products are designed with the harsh realities of their intended applications in mind, accelerating the transition to a truly sustainable and resilient mobility

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