ANALYSIS OF ORGANIC PHOTOVOLTAICS APPLICATION IN TUBELIKE BUS STATIONS OF CURITIBA: DEGRADATION, SEASONAL AND SHADING EFFECTS

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Abstract

The integration of organic photovoltaic (OPV) technology in urban public infrastructure presents a promising alternative to conventional energy systems, particularly in structures where architectural constraints limit the use of traditional photovoltaic modules. This study investigates the feasibility and efficiency of OPV implementation in the emblematic tubelike bus stations of Curitiba, Brazil. A detailed analysis was conducted using previously acquired data from experimental installations at a prototype station, focusing on performance metrics under varying seasonal, shading, and degradation conditions. The results analyze the degradation over two years, influenced by both environmental exposure and installation conditions. Seasonal variations significantly affected energy output, and shading effects, particularly in heavily vegetated areas, revealed complex interactions that may mitigate thermal degradation. This study supports the potential of OPVs in urban renewable energy, while emphasizing the need for optimized installation.

Keywords: Organic Photovoltaics, Renewable Energy, Seasonal Variation, Shadowing Effects, Urban Solar Integration

1. Introduction

The increasing urgency of climate change and the global push toward carbon neutrality have driven exponential growth in renewable energy adoption. Solar energy has emerged as the cornerstone of this transition due to its scalability, technological diversity, and geographic adaptability. In 2024, solar photovoltaics accounted for over 28% of new global electricity generation capacity, yet over 90% of installed systems still rely on crystalline silicon (c-Si) cells. While c-Si remains the benchmark for efficiency and cost, its inherent rigidity and opacity restrict integration in complex or transparent urban structures.

The next generation of photovoltaics aims to move beyond this limitation, enabling energy generation directly integrated into building envelopes, vehicles, and urban infrastructure. Among these innovations, Organic Photovoltaics (OPVs) stand out due to their combination of light weight, mechanical flexibility, and optical properties, as it is possible to see in **Figure 1**. Made from conjugated polymers and small-molecule organic semiconductors, OPVs can be fabricated using low-temperature, roll-to-roll printing on flexible substrates, reducing manufacturing costs.

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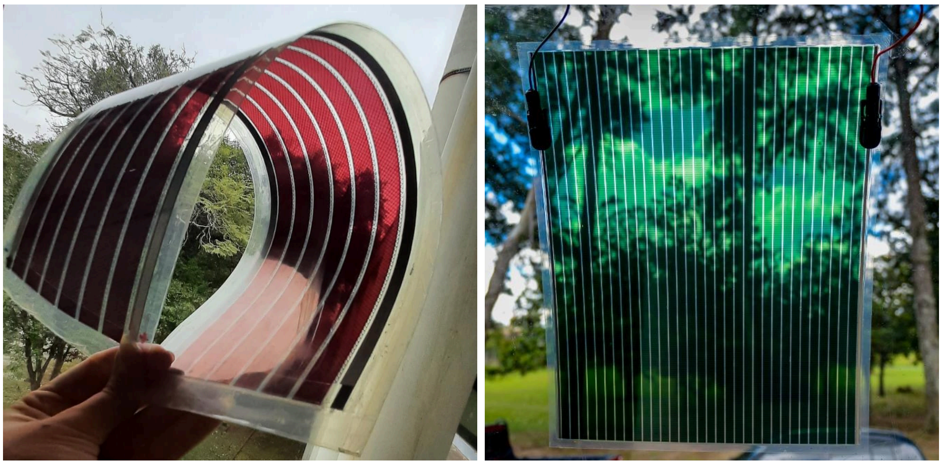

Figure 1. Picture of different organic photovoltaics, showcasing its flexibility, and transparency.

Although efficiencies in laboratory prototypes have surpassed 20% in 2025, commercial OPVs typically deliver 3–10%, depending on formulation and encapsulation. Despite lower efficiency, the specific power (W/kg) and power-to-thickness ratio (W/mm) of OPVs far exceed those of silicon modules, making them advantageous for applications where weight or transparency is a constraint. Furthermore, OPVs perform relatively well under diffuse or low-light conditions, which are common in high-latitude or cloudy regions like Curitiba. Their semi-transparency and aesthetic adaptability make them ideal for integration into architectural designs where silicon panels cannot be used. This flexibility opens possibilities for innovative applications in urban contexts such as windows, curved surfaces or public transport stations.

However, OPVs face persistent challenges related to stability, encapsulation, and photodegradation, especially under UV exposure and humidity. These degradation pathways cause loss of efficiency and color changes over time, driven by oxygen diffusion and molecular rearrangement in the active layer. Consequently, the long-term reliability of OPVs in real-world installations remains one of the most active areas of research in photovoltaic science.

The present work investigates the deployment of OPV technology in one of Brazil's most recognized urban design symbols: the tubelike bus stations of Curitiba. The project connects applied research and social engagement by transforming a decommissioned station into a living laboratory, a real-scale prototype where renewable energy, urban design, and community interaction converge.

2. The Tubelike Bus Station of Curitiba

Curitiba, known worldwide for its innovative Bus Rapid Transit (BRT) system, has long been a pioneer in urban sustainability. Introduced in 1991, the tubelike bus stations (*Estações Tubo*) were designed by Abrão Assad to optimize passenger flow, reduce boarding time, and provide weather protection. The cylindrical shape, as presented in **Figure 2**, composed of aluminum, glass, and steel, offered visual transparency and modularity while symbolizing Curitiba's forward-thinking approach to design.

Each station consumes electricity for lighting, automatic doors, charge systems, and accessibility lifts. Across more than 350 stations, this results in substantial annual energy demand. Since these structures are part of the city's cultural heritage, they cannot be modified with rigid or opaque solar panels. Consequently, flexible and semi-transparent OPVs emerge as a perfect match, integrating renewable generation without altering the architectural identity of the stations.

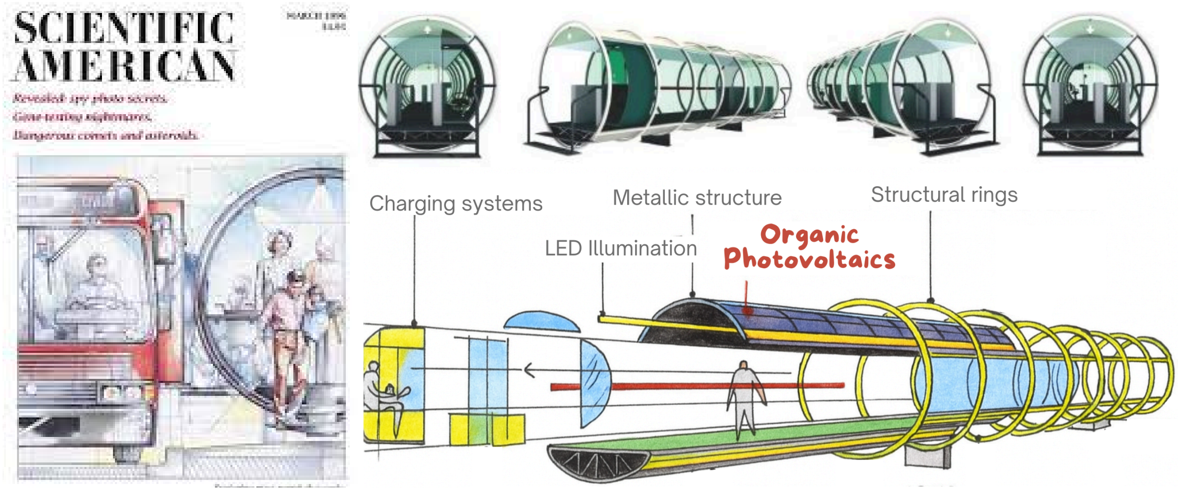

Figure 2. The March 1991 cover of Scientific American featured Curitiba's tubelike bus stations as symbols of innovative urban mobility (available online). The accompanying schematic illustrates the tubelike structure of the bus stations and the organic photovoltaics integration to the station (Adapted from archive/ Abraão Assad).

Recognizing this compatibility, URBS donated a decommissioned a bus station to the Federal University of Paraná (UFPR) for experimental research purposes. The structure, originally used along one of the central BRT corridors, was transported to the UFPR campus in 2018. It underwent restoration and instrumentation under the coordination of the Nanostructured Devices Research Group (DiNE). The initiative sought to transform the disused station into a functional research and demonstration unit, officially named "*Estação de Pesquisa Tubo de Ensaio*", the "Test Tube Research Station" (**Figure 3**). This prototype became the first installation of organic photovoltaics in a public transport structure in Latin America. The project aimed to evaluate both the technological feasibility of OPV integration and its urban visibility as a communication platform for renewable energy innovation. The installation features 28 OPV modules arranged in a configuration that covers the upper portion of the station, supplying direct current (DC) to operate LED lighting and USB charging ports for visitors (Tempesta et al., 2022).

From a broader perspective, the *Tubo de Ensaio* prototype reinterprets the historical role of Curitiba's tubular stations, from a symbol of transport innovation in the 1990s to a living test for sustainable energy technologies in the 2020s. The very same structure once celebrated on the cover of Scientific American in March 1991 now serves as a real-scale laboratory linking architecture, renewable energy, and urban culture.

The strategic visibility of these stations also enhances their potential as public communication tools for environmental awareness. Every citizen who passes by or interacts with a solar-powered station encounters a tangible manifestation of the city's renewable future. This dual function makes Curitiba's tubular stations not only a testing ground for new materials but also a bridge between science and society.

Figure 3. Picture of the *Tubo de Ensaio* prototype installed at UFPR campus with OPV modules applied on the roof.

From an energy system perspective, distributed microgeneration using OPVs in such transport nodes contributes to the concept of decentralized energy resilience. Instead of relying solely on the centralized grid, each station could generate and partially store its own energy for auxiliary uses. When multiplied across an entire city network, this could represent a measurable reduction in operational costs and CO_2 emissions, while also serving as a demonstration corridor for renewable technology deployment in urban settings. Their visibility, historical importance, and compatibility with flexible solar technology turn them into a natural interface between science, infrastructure, and civic identity. The *Tubo de Ensaio* prototype thus stands as both a continuation of Curitiba's legacy of urban innovation and a forward-looking platform for exploring the future of organic photovoltaics in the built environment.

3. Outreach and Educational Integration

The decision to transform a decommissioned bus station, an emblematic element of Curitiba's daily life, into a functional solar-powered laboratory was guided by the idea that public visibility is a catalyst for scientific engagement. Unlike conventional research facilities, which are often confined to laboratories, the *Tubo de Ensaio* exists as an open and interactive space situated at the intersection of technology and the public. Its transparent architecture and symbolic value as part of the city's transport identity make it a natural medium for demonstrating the social relevance of clean energy technologies.

From 2019, the *Tubo de Ensaio* hosted a series of guided visits, workshops, and outreach events, coordinated by the Federal University of Paraná (UFPR) and the DiNE Research Group. More than 5000 visitors, including university students, high school groups, teachers, architects, and local residents, have participated in hands-on activities exploring solar energy concepts and OPV operation principles. These visits typically include demonstrations of current–voltage (I–V) measurements, lighting powered by the station's OPVs, and comparisons between organic and silicon-based photovoltaic materials.

Figure 4. Visitors observing OPV modules during public exhibitions at UFPR's Tubo de Ensaio station.

The initiative integrates UFPR students from physics, chemistry and engineering in extension activities aligned with the United Nations Sustainable Development Goals (SDGs), and the project has been showcased at Curitiba Innovation Fair, Smart City Expo, and the SBPC Annual Meeting.

The *Tubo de Ensaio* directly supports at least four SDGs: SDG 7: Affordable and Clean Energy, by showcasing renewable generation through OPVs; SDG 9: Industry, Innovation, and Infrastructure, by connecting academic research with real-world applications; SDG 11: Sustainable Cities and Communities, by demonstrating low-impact energy solutions for public infrastructure; and SDG 13: Climate Action, by raising awareness about energy transition and carbon footprint reduction.

These alignments reinforce the station's role not only as a research object but as a social instrument for climate education. Visitors are encouraged to reflect on the relationship between individual behavior, technological innovation, and environmental responsibility. In this sense, the *Tubo de Ensaio* transcends its function as an experimental site, it becomes a physical metaphor for sustainable transition in urban life.

4. Methodology

The *Tubo de Ensaio* prototype is a cylindrical aluminum and glass structure approximately 10 meters long, 2.5 meters in diameter, and 3.2 meters in total height when mounted on its platform. The original internal configuration, including the entry and exit doors, ticket validation devices and seating, was preserved to maintain architectural fidelity. Structural modifications were minimal and limited to the metallic upper arc, which was used to attach the flexible photovoltaic modules and cables.

A total of 28 OPV modules were installed on the structure, distributed as 14 pairs of devices connected in series (**Figure 6**). Each module has an active area of approximately 7559.04 cm^2, leading to a total photovoltaic area of about 20 m^2. The modules were produced by Sunew, a Brazilian company specializing in large-area organic photovoltaic films based on polymer:fullerene blends using proprietary formulations.

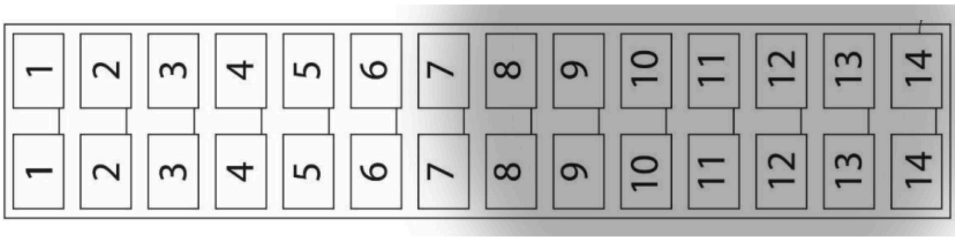

Figure 6. OPV module layout, showing set 2 (fully exposed) and set 14 (partially shaded).
(Source: Adapted from Tempesta et al., 2022.)

To analyze the effect of geometric positioning, modules were arranged in zones with different exposure conditions. The upper left arc (set 2) receives full sun for most of the day, while the upper right zone (set 14) is partially shaded by vegetation and surrounding buildings. This layout enables comparative analysis of how shading and local temperature variations affect degradation and output.

All electrical measurements were performed using a Keysight B2901A Precision Source/Measure Unit (SMU). This instrument allows simultaneous current–voltage (I–V) characterization with high accuracy, suitable for low-power OPV devices. Measurements were conducted under real solar irradiance conditions, without artificial light sources, to capture authentic outdoor performance.

Solar irradiance was monitored using a Phywe® digital luxmeter positioned at the same tilt angle as the module plane. A conversion factor of 1 klux = 0.0079 W/m^2 was applied to estimate irradiance in watts per square meter. Ambient temperature and surface temperatures of the OPV films were measured using an infrared thermometer. The active area of the panels is 7559,04 cm2

The I–V curves were recorded quarterly, at noon, covering representative periods of summer, autumn, winter, and spring. The following performance parameters were derived from the J–V data: Short-circuit current density (J_{sc}) [mA/cm^2]; Open-circuit voltage (V_{oc}) [V]; Fill Factor (FF) [%]; Power Conversion Efficiency (PCE) [%]. Each parameter was calculated according to standard photovoltaic equations.

5. Results and Discussion

The long-term outdoor operation of the organic photovoltaic (OPV) modules installed on the tubelike research bus station revealed valuable insights into the environmental durability and performance behavior of this emerging solar technology under real urban conditions. Two representative sets of modules: set 2, fully exposed to sunlight, and set 14, under partial shading, were continuously monitored over two years, from 2018 to 2020. Their electrical response demonstrated how irradiance, temperature, humidity, and local shading interact to shape the long-term evolution of OPV efficiency and stability.

The seasonal current–voltage (J–V) characteristics obtained from these modules, shown in **Figure 7**, illustrate clear differences in behavior across the four seasons and over time. In the initial stages, both sets presented the typical diode-like response expected from polymer-based devices, with open-circuit voltages around 45 V, short-circuit current densities between 14 and 16 mA/cm², and fill factors ranging from 50 to 60%. The average power conversion efficiency (PCE) at installation varied from 2.5% to 3.0%.

The two-year monitoring revealed typical OPV degradation patterns but with strong dependence on sunlight exposure. Set 2, under direct sunlight, degraded more rapidly, showing a PCE decrease from 2.71% to 0.29%. Set 14, under partial shading, retained relatively more of its initial efficiency, dropping from 2.91% to 0.47%. Fill factor values also declined accordingly. Performance analysis across seasons revealed clear cyclic fluctuations. In winter, both sets exhibited reduced output due to lower irradiance and increased humidity. In summer, however, PCE values temporarily increased up to +30% recovery for set 2 and +50% for set 14, indicating reversible trap dynamics and annealing effects in the organic layer.

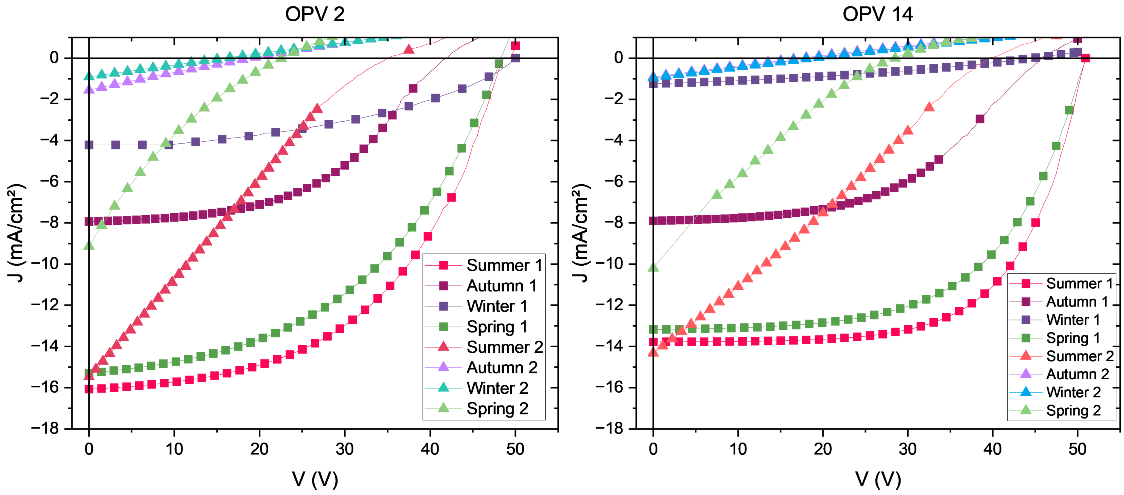

Figure 7. ***Representative I–V curves for Sets 2 and 14 during seasonal campaigns (Summer, Autumn, Winter, Spring) across two years of outdoor exposure. Each curve represents an average of five independent measurements under measured irradiance of 200–400 W/m².***

As exposure progressed, both sets exhibited gradual rounding of the J–V curves near the maximum power point, reflecting increased series resistance and reduced charge extraction. This evolution was more pronounced for set 2, which experienced higher irradiance and frequent surface temperatures exceeding 60 °C during summer, which can influence organic solar cell degradation (Mateker and McGehee, 2017). In contrast, set 14 degraded more slowly, a result of the partial shading that provided moderate thermal protection. During winter, both sets displayed lower current output due to reduced solar intensit. Interestingly, a slight recovery of PCE was consistently observed after cooler periods, suggesting reversible morphological relaxation of the polymer blend. This reversible recovery indicates that OPV performance can fluctuate seasonally as a result of thermally activated reorganization of donor–acceptor domains. In this sense, environmental cycles not only degrade the devices but also intermittently restore their structural order, revealing the dynamic nature of organic semiconductors in field conditions.

The temporal evolution of the main photovoltaic parameters: power conversion efficiency (PCE), fill factor (FF), is summarized in **Figure 8**. Over the two-year period, both sets displayed clear degradation trends, though with distinct rates. After approximately 24 months, Set 2 retained about 11% of its initial PCE, while Set 14 retained around 16%. These values correspond to degradation constants of roughly 0.0047 day^{-1} and 0.0031 day^{-1}, respectively, confirming the significant mitigating role of shading.

A closer inspection of the data reveals that, although the power conversion efficiency (PCE) fluctuated substantially with seasonal cycles, the fill factor (FF) exhibited a steadier and more monotonic decline over time. The PCE showed clear oscillations, typically improving during warmer, high-irradiance months and decreasing in the cooler seasons, reflecting the direct influence of irradiance, temperature, and spectral distribution on instantaneous device output. Both module sets, regardless of their exposure conditions, followed this seasonal “breathing” pattern: the efficiency dipped during winter, recovered partially in spring, peaked again in summer, and then fell back in autumn. These reversible changes underscore how PCE, while useful for quantifying instantaneous performance, is highly sensitive to external environmental variables and therefore not an entirely reliable indicator of true material degradation in outdoor applications.

In contrast, the fill factor demonstrated a consistent downward trend independent of seasonal irradiance variations. For both sets 2 and 14, the FF decreased progressively across the two years without the temporary recoveries observed in PCE. This steady decline points to intrinsic, irreversible degradation processes, such as the formation of interfacial traps, electrode delamination, and increased series resistance, rather than to short-term environmental fluctuations. In other words, while PCE reflects the environmental responsiveness of the device, FF reflects its structural health. From a diagnostic perspective, this distinction is critical: the fill factor emerges as a more stable and meaningful parameter for assessing the genuine aging and reliability of OPV systems operating in real-world environments. Monitoring FF trends over time can thus provide a more accurate measure of degradation kinetics, independent of transient climatic effects, and should be prioritized as a key indicator in long-term performance studies of organic photovoltaics.

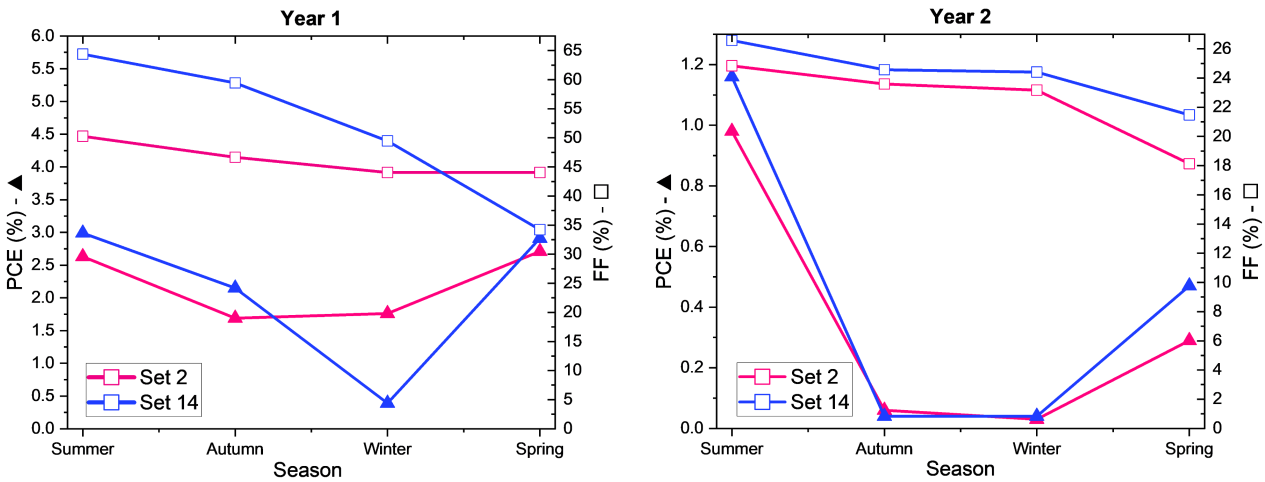

Figure 8. ***Evolution of photovoltaic parameters (PCE, FF) for sets 2 and 14 across two years.***

Although shading reduced instantaneous energy yield, it extended the operational life of the modules by lowering temperature stress and ultraviolet (UV) exposure. The open-circuit voltage remained relatively stable during the first year, decreasing modestly by approximately 10% in the shaded set, compared to approximately 20% in the exposed set, after the year prolonged exposure. This trend suggests that interfacial degradation and encapsulation fatigue, rather than bulk recombination, were the dominant causes of performance loss. The short-circuit current, on the other hand, was more sensitive to cumulative irradiance and to the deposition of dust and particulates on the module surface (Brito et. al.., 2022)

Environmental data collected throughout the study period provided additional insight into the physical processes underlying these trends. Ambient temperatures in Curitiba ranged from as low as -3 °C in winter nights to peaks above 30 °C, and at the module surface to 58ºC during summer afternoons, while relative humidity frequently exceeded 85%. Such variations impose cyclic expansion and contraction on the thin polymer layers, leading to microcracks, delamination, and gradual optical degradation. Visual inspection confirmed that set 2 modules showed significant edge darkening and partial delamination after the 24 months, whereas set 14, under milder conditions, remained visually stable longer. The microclimate around set 14, partially shaded by vegetation, produced slightly lower temperatures, which likely contributed to its slower degradation rate. This passive cooling effect illustrates how environmental design can influence the operational longevity of organic photovoltaics when integrated into architectural surfaces.

UV radiation proved to be another decisive factor. The ultraviolet index in Curitiba often reaches extreme levels, among the highest worldwide for its latitude. Continuous UV exposure accelerates the photo-oxidation of polymer chains and the diffusion of oxygen through encapsulation barriers. Since the modules in this study used thin PET-based substrates with encapsulation, their UV stability was limited compared to glass-laminated photovoltaic technologies. Future implementations may mitigate these effects by using UV-selective coatings, thicker hybrid barrier films, or lamination under protective glazing.

The overall degradation behavior can be interpreted as the combined effect of several interconnected mechanisms. Oxygen and water vapor diffusion through the encapsulation barrier oxidize the active layer, reducing charge mobility and photoconductivity. Moisture infiltration near module edges causes electrode corrosion and increases series resistance. Long-term thermal exposure promotes phase segregation within the polymer:fullerene blend, disrupting charge transport pathways. Surface soiling further decreases optical absorption. Although these effects differ in origin, their cumulative impact follows exponential decay kinetics consistent with ISOS-D3 accelerated aging standards.

The comparative performance of sets 2 and 14 demonstrates the importance of local environmental context for photovoltaic integration. The fact that a shaded module retained a greater fraction of its initial efficiency than one in full sun emphasizes that for organic photovoltaics, maximizing irradiance does not necessarily maximize performance longevity. Instead, a balance between exposure and protection appears crucial. These results also highlight the relevance of OPVs for architectural-scale applications where partial shading is unavoidable, such as curved facades, covered walkways, or public shelters. In such cases, the lower light intensity is compensated by the extended service life and maintained visual quality of the installation.

From a broader perspective, these findings illustrate both the potential and the limitations of organic photovoltaics for urban energy generation. Despite the expected degradation, all modules continued to operate and supply low-voltage power for lighting and USB outlets throughout the entire experimental period. This operational resilience under real environmental stress validates the feasibility of OPV use in public infrastructure when system design accounts for material characteristics. Rather than evaluating these devices solely by their initial power conversion efficiency, it becomes more meaningful to consider functional durability, energy per lifespan, and aesthetic integration as key performance metrics.

The shading-induced resilience observed in the tubelike bus station suggests new design strategies for future deployments. Instead of avoiding shaded areas, architects could purposefully incorporate OPV materials into zones where natural shading moderates temperature, thus extending module lifetimes. Such adaptive installations could combine low-intensity but persistent power generation with greater visual comfort and thermal stability. When multiplied across many stations or facades, this approach could yield distributed renewable energy generation while maintaining harmony with urban design principles.

Looking ahead, several research directions emerge from this study. Continuous data acquisition systems could replace manual measurements, enabling finer temporal resolution and correlation with meteorological variables. Advanced OPV formulations based on non-fullerene acceptors or new structures could be tested in similar conditions to assess material improvements. Furthermore, exploring encapsulation methods using UV-filtering laminates could drastically improve stability in high-radiation environments.

The results of this field experiment confirm that integrating photovoltaic research directly into public infrastructure bridges the gap between laboratory innovation and practical application. The "*Tubo de Ensaio*" serves not only as a technical platform for evaluating OPV performance, but also as a tangible demonstration of how science can inhabit urban spaces. In this sense, the continuous interaction between environmental exposure, material response, and public visibility transforms the station into a living laboratory, one that generates both data and awareness. By combining research, design, and public engagement, this project illustrates a model for how emerging solar technologies can contribute to the aesthetic, functional, and environmental transformation of cities.

6. Conclusion

The study conducted at the *Tubo de Ensaio* Research Station in Curitiba provides one of the most comprehensive field evaluations to date of OPV modules integrated into a real urban infrastructure. The results confirm that while OPVs are inherently sensitive to environmental variations, they can operate reliably for extended periods and provide meaningful energy generation for low-power urban applications when properly designed and installed.

Throughout two years of continuous outdoor exposure, the OPV modules exhibited pronounced seasonal variations in performance. The PCE followed a recurring pattern of decline and recovery, responding directly to changes in solar irradiance, temperature, and spectral conditions. Efficiency typically decreased during winter due to lower light intensity and partially recovered in summer as irradiance increased. These oscillations demonstrate the strong environmental coupling of OPV devices, which are capable of reversible morphological and electronic adjustments to their surroundings. However, because of these fluctuations, the PCE alone cannot be regarded as a definitive measure of material degradation in outdoor conditions.

In contrast, the FF displayed a continuous, monotonic decline over time, regardless of seasonal cycles or exposure conditions. This consistent downward trend indicates that FF is less influenced by transient environmental factors and more directly linked to irreversible degradation processes such as interfacial deterioration, increased internal resistance, and morphological disorder. The comparative stability of FF as a degradation marker suggests that it provides a more accurate and intrinsic measure of device aging in real-world OPV applications. In this context, FF should be considered a primary diagnostic parameter for evaluating long-term stability and reliability in outdoor performance studies.

The analysis also highlights the dual role of environmental conditions in determining OPV longevity. While modules fully exposed to sunlight achieved higher instantaneous efficiencies, they also degraded more rapidly due to elevated temperatures, ultraviolet exposure, and moisture ingress. Conversely, modules installed in partially shaded zones maintained lower short-term efficiency but demonstrated significantly slower performance loss. This finding emphasizes that thermal management and microclimatic moderation are as important as irradiance optimization in extending OPV lifetime. Architectural integration strategies that include controlled shading or passive cooling could therefore enhance the durability of these systems in real-world installations.

Despite measurable degradation, all modules continued to function throughout the two-year study, successfully powering lighting and low-voltage devices within the station. This functional resilience underlines the feasibility of OPV integration into public infrastructure and reinforces the idea that performance evaluation for such technologies should prioritize energy yield over lifetime, aesthetic adaptability, and maintenance simplicity, rather than focusing exclusively on peak efficiency metrics.

The results obtained here contribute valuable field data to the global effort of understanding OPV behavior under natural conditions. They demonstrate that while current materials may not yet match silicon technologies in lifetime or efficiency, they possess unique architectural and environmental advantages: flexibility, light weight, semi-transparency, and visual integration, that make them ideal candidates for distributed, visible, and educational solar applications in urban contexts.

Future work will expand this research by implementing continuous data acquisition systems for real-time monitoring, exploring advanced OPV formulations, and testing improved encapsulation strategies with hybrid barrier layers and UV-filter coatings. Integrating predictive modeling and data analytics will also help to quantify degradation kinetics more precisely and guide preventive maintenance practices.

Ultimately, the *Tubo de Ensaio* project demonstrates that embedding renewable energy research into the public landscape not only advances technological understanding but also strengthens public awareness and civic engagement with the energy transition. By transforming a historical symbol of urban mobility into a functional solar laboratory, the project connects scientific innovation with daily life, showing that the path toward sustainable cities depends as much on materials and engineering as on visibility, education, and design.

7. Aknolegments

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