Studies on the integration of flexible photovoltaic panels into architectural elements of buildings

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Abstract. Flexible photovoltaic technologies enable new possibilities for building-integrated photovoltaic (BIPV) applications, particularly on curved and non-planar architectural surfaces. This study experimentally investigates the influence of geometrical configuration and installation orientation on the electrical performance of flexible photovoltaic panels. Outdoor measurements were conducted using flat and curved modules operating under identical electrical loading conditions. Panels were evaluated at a south-facing tilt angle of 32° and at a vertical orientation representative of façade integration. Electrical parameters including current, power, voltage, and cumulative energy generation were recorded at five-minute intervals throughout the day. Results obtained from a representative measurement campaign demonstrate that the concave configuration consistently produces higher current and power output compared to a flat panel, leading to increased daily energy generation while maintaining similar voltage characteristics. The performance enhancement is attributed to improved angular acceptance of incident solar radiation provided by geometric curvature. The findings indicate that controlled curvature in flexible photovoltaic modules can improve energy harvesting efficiency in practical BIPV scenarios, supporting their integration into architectural elements such as façades, balconies, and building envelopes.

1 Introduction

The rapid expansion of renewable energy technologies has accelerated the development of photovoltaic (PV) systems adapted to diverse installation environments [1]. Flexible photovoltaic modules have attracted increasing attention due to their low weight, mechanical adaptability, and suitability for integration into non-planar surfaces and architectural elements [2]. Unlike conventional rigid crystalline silicon panels, flexible PV technologies enable installation on curved structures, façades, balconies, and irregular building components, supporting building-integrated photovoltaic (BIPV) applications [2].

BIPV systems often operate under non-optimal irradiation conditions, including variable tilt angles and vertical installations, where panel orientation significantly affects energy yield [1,3]. In such configurations, the angle of solar incidence varies throughout the day, potentially reducing performance compared to optimally tilted systems [3].

Recent studies suggest that module geometry may influence photovoltaic performance. Curved photovoltaic surfaces can modify irradiance distribution across the active area, potentially enhancing energy capture under low solar elevation or diffuse radiation conditions [4]. Flexible thin-film technologies are particularly suitable for such applications due to their tolerance to mechanical bending without significant electrical degradation [2,5].

Despite growing interest in curved photovoltaic applications, experimental comparisons between flat, concave, and convex flexible panels under identical operating conditions remain limited, especially for configurations relevant to façade integration [4].

This work experimentally evaluates the electrical performance and daily energy generation of flexible photovoltaic panels with different geometrical configurations.

In the NetZeroCity 2030/2050 vision, every square meter of building envelope must be productive. Flexible photovoltaic panels transform skyscrapers and shopping malls into “energy lungs” that support not only their own consumption, but also the charging infrastructure for electric vehicles in the vicinity. [6]

The use of flexible photovoltaic panels represents an essential technological leap for transforming current cities into NetZeroCities. Unlike classic rigid panels, flexible technology (often based on amorphous silicon or organic OPV cells) allows the active integration of surfaces that, until now, were considered “inert” from an energy point of view. [7]

The BIPV (Building Integrated Photovoltaics) concept - In a zero-emission building (NZEB - Nearly Zero Energy Building), the facade is no longer just a design or protection element but becomes a vertical power plant. Flexible panels allow integration on curved surfaces (domes, columns or roofs with complex geometries), low weight (they are up to 10 times lighter

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than glass panels, eliminating the need for structural reinforcement of old buildings). [8]

Strategic Advantages in the context of NetZeroCity

-capitalization of vertical surfaces because in crowded cities, roof space is limited. Flexible panels can be applied directly on facades facing south, east and west, capturing solar radiation throughout the day, including in winter, when the sun is low in the sky.

- unlike traditional panels that can be unsightly, flexible ones can be produced in various colors and textures. they mold to architectural details, preserving the visual identity of the building, they can be semi-transparent, serving as solar blinds or active windows.

- many flexible panel technologies (such as CIGS - Copper Indium Gallium Selenium) perform better than monocrystalline panels in conditions of partial shading or diffuse light, common in urban environments due to neighboring buildings.

To achieve "Zero Emissions" status, a building must generate at least as much energy from renewable sources as it consumes annually. Flexible panels contribute to maximized self-consumption because the energy is produced exactly where it is consumed, reducing network losses. The reduction of the embedded carbon footprint is achieved through the manufacturing process of thin flexible cells (Thin-Film) which often consumes less energy than that of classic thick silicon panels. Additional thermal insulation by applying them to the facade, which can act as an additional protective layer, reducing excessive heating of the walls during the summer.

Durability is achieved by using high-strength polymers for protection against UV and weathering. At the same time, the installation cost and application by direct bonding (peeling-and-stick) significantly reduces labor costs. Flexible photovoltaic (FPV) modules enable energy generation in applications where conventional rigid panels are limited by weight, geometry, or architectural constraints. Typical applications include building-integrated photovoltaics (BIPV) on façades and balconies, curved roofs and lightweight canopy structures, and retrofit integration on existing buildings with non-planar surfaces. Recent studies have demonstrated practical implementations of flexible photovoltaic technologies in architectural and urban environments, highlighting their suitability for curved and vertical installations. For instance, experimental investigations of flexible photovoltaic systems integrated into building envelopes and curved surfaces have shown improved adaptability and energy harvesting under varying solar incidence conditions [9,10]. These applications emphasize the growing role of flexible photovoltaics in distributed urban energy systems and nearly zero-energy building concepts.

2 Experimental setup

Flexible photovoltaic panels were investigated to evaluate the influence of geometrical configuration and installation orientation on electrical performance. The experimental setup was designed so that all configurations operated under identical conditions, enabling direct comparison between flat and curved modules

Two flexible photovoltaic panels with identical nominal electrical characteristics were used. Each panel operated independently and was connected to an equivalent resistive load of approximately 150 W under low-voltage DC operating conditions.

Table 1. Technical characteristics of the flexible photovoltaic module used in the experiments

Parameter	Value
PV technology	Amorphous silicon (a-Si) thin-film
Module type	Flexible photovoltaic module
Rated maximum power, Pmax	100 W
Maximum power voltage, Vmp	18.5 V
Maximum power current, Imp	5.41 A
Open-circuit voltage, Voc	22.6 V
Short-circuit current, Isc	5.95 A
Maximum system voltage	1000 V DC
Power tolerance	0 to +5 %
Module efficiency (STC)	approximately 8–9 %
Operating temperature range	−40 °C to +85 °C
Physical dimensions	1000 mm × 670 mm × 2.5 mm
Module area	0.67 m²
Module weight	approximately 5.5 kg
Electrical output	DC
Standard test conditions (STC)	1000 W/m², AM 1.5, 25 °C

The panels were installed in two primary orientations: a south-facing tilted configuration at an inclination angle of 32°, and a vertical installation (90°) representing building - integrated photovoltaic applications. In addition to the flat reference configuration, concave and convex geometries were evaluated through controlled geometric deformation. For concave configurations, the curvature axis was arranged in both vertical and horizontal directions to examine the influence of irradiance distribution and incidence angle across the module surface [11]. The same electrical load and measurement conditions were maintained for all configurations throughout the experiment to ensure a controlled comparison. Electrical parameters, including voltage, current, and output power, were continuously recorded during daylight hours under natural outdoor environmental conditions. The measurements were conducted simultaneously for both modules to minimize the influence of temporal variations in solar irradiance and ambient temperature. Special attention was given to maintaining identical mounting height and spatial positioning of the modules in order to avoid mutual shading effects. Environmental conditions such as partial cloud cover and ambient temperature variations were naturally present and affected both configurations equally during the measurement period.

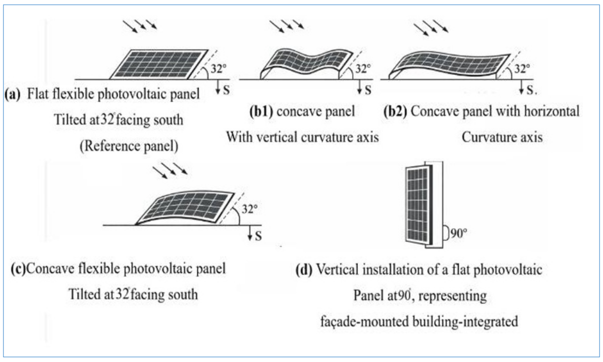

Fig. 1. Investigated photovoltaic panel geometrical configurations and installation orientations.

Electrical measurements included open-circuit voltage, load current, instantaneous power, and accumulated generated energy, recorded at five-minute intervals throughout daylight hours. All panels were installed at equal height and spacing to minimize shading effects and mutual interference. Voltage and current were measured using digital multimeter following standard DC measurement practice.

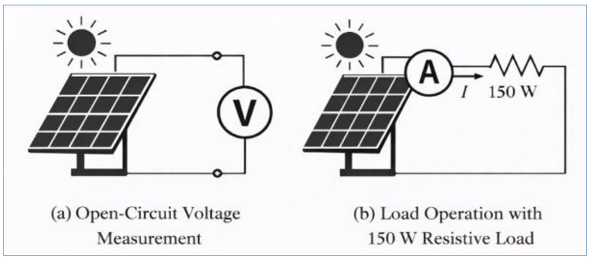

Fig. 2. Electrical measurement configurations used in the experiments: open-circuit voltage measurement and load operation using a 150 W resistive load.

3 Results and discussion

3.1 Experimental data selection

The experimental campaign included measurements conducted over multiple outdoor days under varying environmental conditions. Due to page limitations, results from a representative experimental day corresponding to the highest ambient temperature (≈25°C) are presented. This condition allows evaluation of system performance under demanding operating conditions while maintaining clear comparison between panel configurations. Consistent trends were verified across all measurement days.

3.2 Current behaviour

The load current profiles exhibit the characteristic bell-shaped behavior typical of photovoltaic generation. The concave configuration consistently produces higher current values throughout most of the operating period, with more pronounced differences during morning and afternoon hours. The concave configuration reached a peak load current of approximately 2.8 A, compared to about 2.6–2.65 A for the flat panel, corresponding to an increase of roughly 6–8% during peak solar conditions. This difference is consistently observed around midday, indicating improved current generation for the curved configuration.

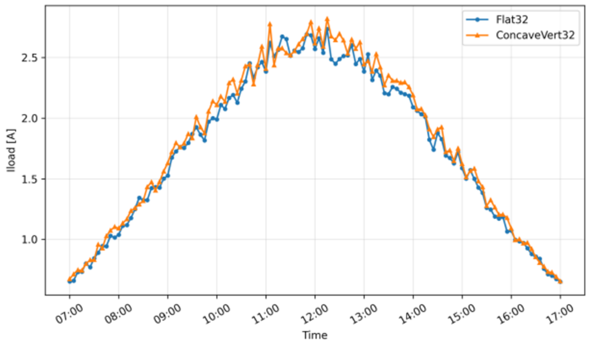

Fig. 3. Representative load current comparison.

3.3 Power performance

The power profiles follow the same trend observed in the current measurements, as increased generated current directly results in higher output power. The improvement appears continuously rather than at isolated peaks, indicating sustained performance enhancement throughout the day. Temperature-related variations typical for photovoltaic modules are expected and do not affect the relative comparison between configurations [9]. The concave configuration achieved a maximum output power of approximately 7.2–7.4 W, while the flat configuration reached about 6.6–6.8 W, corresponding to an improvement of roughly 7–9% in generated power. The higher power output of the concave panel is particularly noticeable around midday, confirming the beneficial effect of geometrical curvature on energy conversion performance.

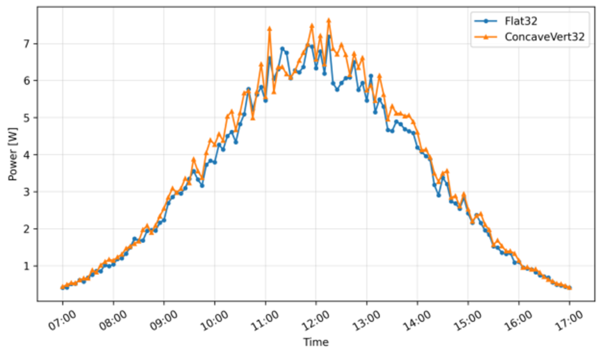

Fig. 4. Representative output power comparison.

3.4 Energy accumulation

Cumulative energy generation demonstrates the practical impact of the observed electrical differences. The concave configuration achieves higher accumulated energy over the entire operating period, with gradual divergence between the curves as time progresses. This result confirms that small but persistent increases in current and power translate into meaningful gains in total harvested energy. As shown in Figure 5, the cumulative generated energy reached approximately 35–36 Wh for the concave configuration and about 33–34 Wh for the flat configuration by the end of the measurement period, corresponding to a difference of roughly 6–7**%** in total daily energy production.

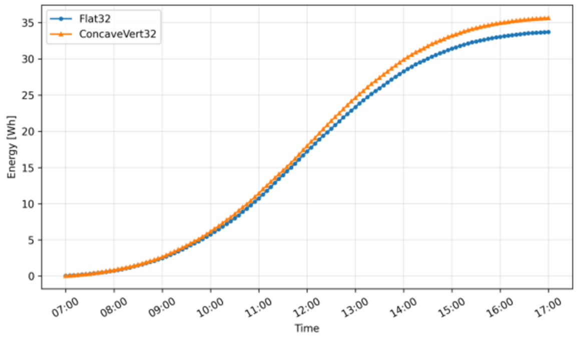

Fig. 5. Representative cumulative energy generation

3.5 Voltage characteristics

Voltage behaviour remains nearly identical for both configurations during operation. The similarity in voltage levels indicates that performance improvement is primarily driven by increased current generation rather than voltage variation, which is consistent with photovoltaic operating principles [12]. As illustrated in Figure 6, the output voltage remained nearly constant for both configurations throughout most of the measurement period, with typical values around 20.5–20.8 V and only minor differences between the two panels. A rapid voltage decrease is observed near the end of the day due to reduced solar irradiance.

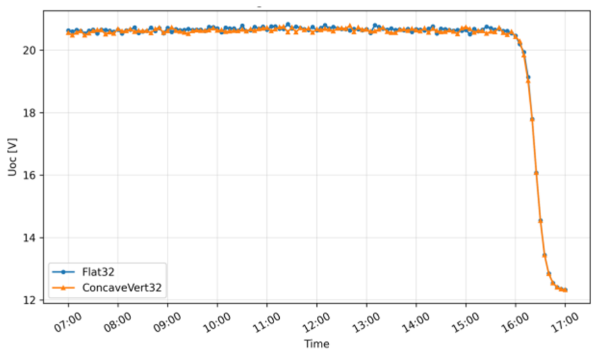

Fig. 6. Representative open-circuit voltage comparison

3.6 Discussion

The experimental results demonstrate that geometric curvature enhances effective solar energy utilization in flexible photovoltaic modules. The observed improvement under elevated temperature conditions further supports the robustness of the proposed configuration under realistic outdoor operating environments [10]. A detailed examination of the measured electrical parameters indicates that the concave configuration produces higher current values compared to the flat reference panel during most daylight hours. This behavior suggests an improved angular acceptance of incoming solar radiation, allowing a larger portion of incident irradiance to contribute to electrical generation even when the solar elevation angle deviates from the optimal orientation. As a result, the curved surface reduces sensitivity to instantaneous sun position variations.

The difference between configurations becomes more pronounced during morning and afternoon periods, when the angle of incidence is typically less favourable for flat panels. Under these conditions, portions of the concave surface remain closer to perpendicular alignment with incoming solar rays, which contributes to increased charge carrier generation and improved current output. Around solar noon, when irradiation conditions approach optimal alignment for all configurations, the performance gap decreases, indicating that curvature mainly improves off-peak operating intervals rather than peak irradiance performance.

The experimental measurements also show that voltage variations between configurations remain relatively small, while current differences dominate the observed power increase. This behaviour is consistent with photovoltaic operating principles, where current is primarily influenced by incident irradiance, whereas voltage is more strongly related to material properties and temperature effects. Consequently, the improvement in generated energy is mainly attributed to enhanced current production rather than voltage enhancement.

For vertically installed configurations, the results highlight the feasibility of energy generation under façade-like conditions. Although instantaneous power levels are lower compared to tilted installations, measurable energy production is maintained throughout extended periods of the day. This characteristic supports the applicability of flexible photovoltaic modules for building-integrated photovoltaic systems where optimal orientation cannot be achieved.

Overall, the experimental observations confirm that controlled geometric deformation can improve energy harvesting stability under variable outdoor conditions. The curved configurations demonstrate reduced dependence on precise installation angles, which represents an important advantage for architectural integration scenarios where structural and aesthetic constraints limit conventional photovoltaic deployment.

3.6.1 Conclusion

This study evaluated the performance of flat and concave flexible photovoltaic panels through outdoor measurements under natural environmental conditions. The results show that the concave configuration consistently produced higher current and power output compared to the flat panel, particularly under elevated temperature conditions [13].

The increase in cumulative energy indicates that geometric curvature improves effective solar irradiance utilization, while voltage characteristics remain nearly unchanged between configurations. The performance improvement persisted throughout the operating period, suggesting a stable and sustained effect rather than a transient response.

These findings suggest that incorporating curvature into flexible photovoltaic modules can enhance energy harvesting in practical applications. Future work will focus on long-term performance evaluation and optimization of curvature geometry under varying environmental conditions

In addition, experimental observations indicate that geometric curvature contributes to improved operational stability under varying solar incidence conditions. The reduced dependence on precise panel orientation suggests that curved flexible photovoltaic modules may provide more consistent energy production throughout the day compared to conventional flat configurations.

From a practical implementation perspective, the demonstrated performance enhancement highlights the potential of geometrically adapted flexible photovoltaic panels for integration into architectural structures where optimal tilt angles cannot be maintained. Such adaptability may support broader deployment of photovoltaic technologies in urban environments and building-integrated photovoltaic applications.

Overall, the results confirm that controlled geometric modification represents a feasible passive approach for improving photovoltaic energy harvesting without increasing system complexity. Continued investigation under extended operating periods and diverse environmental conditions will further clarify the long-term benefits and optimization potential of curved photovoltaic configurations.

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