STANDARDIZED SYSTEM OF THREE-DIMENSIONAL PHOTOVOLTAIC AND PHOTOTHERMAL STRUCTURES

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Abstract

Globally, residential and commercial buildings consume between 20% and 40% of the energy produced in developed countries—surpassing industry and transport. In the U.S. alone, buildings use 75% of electricity and emit 30% of carbon dioxide. Experts from UC Berkeley suggest that energy self-sufficiency in buildings is crucial to achieving Net Zero goals. This paper presents the conceptual design of a prototype for a three-dimensional structural system engineered in steel or aluminum inspired by Heberto Castillo's tridilosa and Buckminster Fuller's geodesic principles, integrated with concentrated photovoltaic (CPV) panels as active roofing. The system is suitable for buildings with large roof spans like industrial warehouses, sports facilities, greenhouses, and more. We designed and tested the structure experimentally and through optical, mechanical, and economic simulations, confirming that it achieves equal or better performance than conventional PV setups, with a short-term ROI.

Keywords: *Three-dimensional structures, concentrated photovoltaics, active roofing, energy efficiency, BIPV. Insert 5-7 keywords*

1. Introduction

Globally, buildings account for around 30% of total energy consumption and are responsible for 26% of energy-related emissions [1]. In this context, finding new ways of building, integrating emerging technologies and innovative materials is critical to achieving net-zero goals and the Sustainable Development Goals (SDGs).

Among the main research areas seeking to reduce the carbon footprint of buildings and promote energy self-sufficiency are Building-Integrated Photovoltaic (BIPV) systems, which use photovoltaic technology both as an architectural material and as a source of electricity generation [2]. However, despite the concept of dual functionality, PV systems integrated into roof structures are often installed as secondary superimposed elements, functioning either as an additional roofing layer or as independent photovoltaic plants in industrial settings. This approach reflects a limited architectural and structural integration of PV technology.

In response to this limitation, this work proposes a novel methodology for incorporating photovoltaic cells directly into lightweight roof structures, enabling both structural and functional integration rather than simple attachment. This approach opens new possibilities for the implementation of photovoltaic systems in both urban and rural contexts.

The proposed incorporation of photovoltaic systems into lightweight roof structures is based on three main components: structural integration, renewable energy optimization, and architectural adaptability. From a structural perspective, the design is inspired by the Tridilosa system developed by engineer Heberto Castillo, as well as by the three-dimensional structural principles explored by Buckminster Fuller [3,4]. These structural concepts are characterized by their efficient spatial geometry, which allows the construction of spatial roof structures capable of covering large spans with reduced material consumption.

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The geometry of the Tridilosa enables the incorporation of concentrated photovoltaic (CPV) systems as an integral part of the ceiling structure. This configuration offers a novel approach to the construction of lightweight roofs suitable for large-span applications, such as industrial facilities, sports complexes, and agrovoltaic installations, while simultaneously contributing to energy generation. By integrating CPV systems directly into the roof structure, it becomes possible to harvest both photovoltaic and photothermal energy, enabling a dual use of the available surface area. One of the main objectives of this research has therefore been to design an appropriate three-dimensional structural system capable of incorporating CPV technologies.

Concentrated Photovoltaic systems combine photovoltaic modules with optical components that increase the solar radiation received by the photovoltaic surface. The level of concentration can vary from low (<10 suns), medium (10–100 suns), and high (100–2000 suns) to ultra-high (>2000 suns) [5]. While increasing solar radiation can improve the electrical efficiency of photovoltaic cells, it also raises the temperature of the modules, which may reduce performance if not properly managed. For this reason, CPV systems are often equipped with cooling mechanisms. In low-concentration systems, passive cooling strategies such as natural air convection are generally sufficient, whereas high-concentration systems typically require active cooling systems, commonly based on water circulation [6].

Among the most economical and architecturally adaptable CPV configurations is the V-cavity system (**Fig. 1**). Research conducted by Y. Tripanagnostopoulos and collaborators demonstrates that this configuration can achieve an average concentration of Ct ≈ 1.4 suns for incident rays between 15° < θ < 45°, Ct ≈ 1.2 for θ < 15°, and Ct ≈ 1.3 for θ > 60° [7]. The interest of this configuration for the present work lies in its versatility for architectural integration while maintaining the electrical advantages associated with CPV systems.

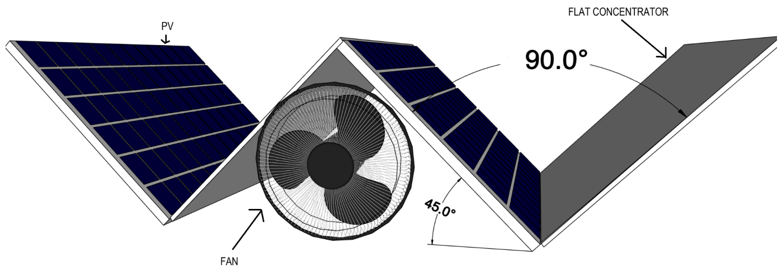

Fig. 1. V-cavity concentrated photovoltaic (CPV) configuration with active cooling through air ventilation.

From an architectural perspective, the proposed system also offers flexibility for a variety of applications. In urban environments, such structures could be integrated into public infrastructure, such as bus stations, where they could generate electricity while occupying already-used public space and potentially function as charging points for small electric vehicles, such as bicycles or motorcycles. This type of infrastructure could contribute to promoting sustainable mobility while generating additional social benefits.

In rural contexts, the proposed approach may support agrovoltaic applications, for example through the integration of photovoltaic roofing systems into greenhouse structures. In addition, the lightweight structural design is particularly suitable for large-span coverage, making it applicable to sports facilities and industrial buildings.

This paper presents the conceptual design of a lightweight three-dimensional structural roofing system inspired by the tridilosa system and geodesic structural principles, capable of integrating concentrated photovoltaic technology for energy generation in large-span buildings.

2. Materials and Methods

Our innovative system was first developed by designing the three-dimensional structures according to several architectural requirements, such as the hermetic incorporation of PV and reflective sheets into the structure, the standardization of construction methods, the solution for water collection, and emergency responses to extreme climate events, but future research should explore the chaotic dynamics of the ambient environment.

The structural elements design was conceived to be manufactured in extruded aluminum; however, we are also working on other material alternatives (as stated in the patent request). Extruded aluminum profiles are considered the most ideal material because they enable a simple assembly process for the roof by following a few technical steps.

Figure 2 shows one unit of our system. In section (a), the complete structure is displayed without the roofing components. Structurally, the system was primarily designed to be made of extruded aluminum. It was specifically engineered to receive panels and mirrors, including screw receivers for the diagonal elements, and incorporate a built-in channel for service and rainwater collection. The system also includes the diagonals that form the three-dimensional structure that resist shear forces (b). The diagonal beams have internal channels for screw fixation (c), and the integration of the CPV system is illustrated in (d).

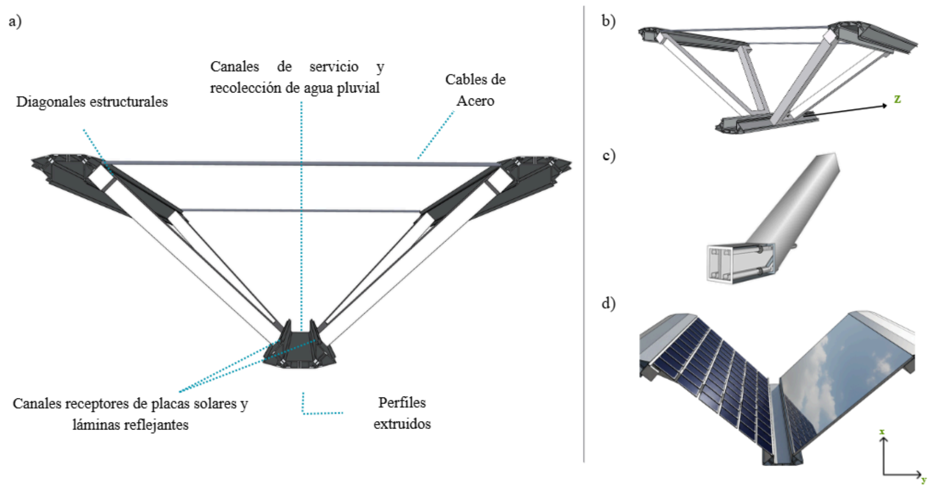

Fig. 2. Three-dimensional structure with integration of panels and reflective mirrors for use in lightweight roofs.

A scaled prototype (**Fig. 3**) was built to test the CPV system and to evaluate the practical challenges associated with constructing a tridilosa-inspired structure using aluminum. The prototype was assembled using amorphous silicon (a-Si) solar cells and reflective aluminum sheets as the roofing material. The materials used for the prototype were selected based on their availability and their suitability for experimental testing. The detailed characteristics of the components used are presented in Table 1.

From an electrical perspective, the objective was to obtain a higher output current; therefore, the solar cells were connected in parallel.

The experimental setup was designed to demonstrate the potential of the proposed arrangement compared with traditional photovoltaic (PV) installations. The prototype was used to evaluate the performance of the proposed CPV system under different PV configurations. In addition, several tests were conducted on a single CPV unit to measure the power–voltage (P–V) and current–voltage (I–V) characteristic performance curves, as well as to assess the cooling effect produced by natural air convection using the same experimental setup.

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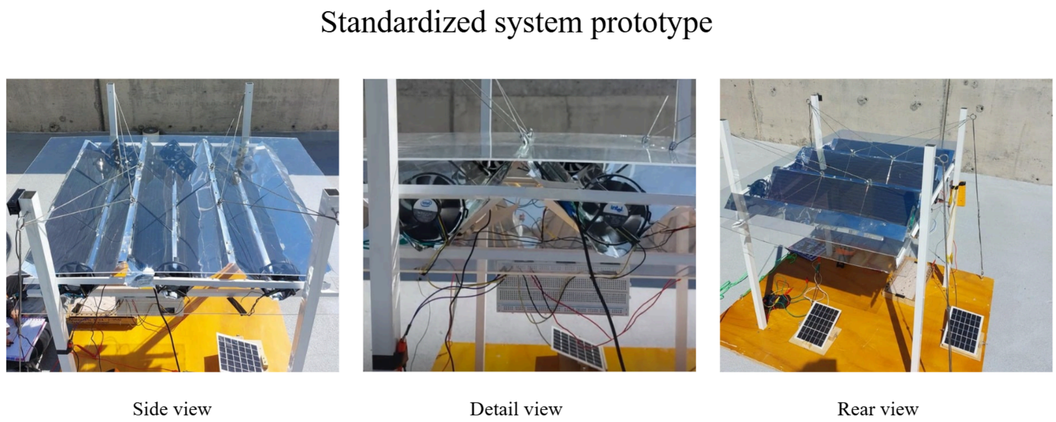

Fig. 3. Different views of the scale prototype.

Based on the fundamental law of electrical power and Ohm's law, an experimental variable-resistance setup was designed to test the electrical performance of the prototype. Different resistance values ranging from 130 Ω to 0 Ω were sequentially applied to simulate different load conditions. For each resistance value, the corresponding voltage (V) and current (I) were measured in order to construct the current–voltage (I–V) and power–voltage (P–V) curves used to evaluate the system performance.

During the experiments, additional parameters were monitored, including ambient temperature, PV module temperature, and solar irradiance (E_e). The average irradiance during the tests was E_e ~ 950 W/m^2 with ambient temperatures ranging between 30°C and 35°C. The surface temperature of the solar modules increased during operation until reaching a steady value of ~ 55°C.

The electrical power output was calculated according to $P = I \cdot V$ where P represents the electrical power output, I the current, and V the voltage.

Furthermore, ray-tracing simulations were performed with Tonathiu software for a latitude of 23.4° North, corresponding to San Luis Potosí, Mexico, in order to analyze the system's behavior during critical solar positions throughout the year, particularly during the equinoxes and solstices.

From an economic perspective, the initial investment cost of the proposed system was estimated and compared with that of conventional roofing solutions used to cover large spans, such as multipanel and arched steel roof or barrel roofing systems. The return on investment (ROI) was then calculated based on the additional electrical energy generated by the proposed CPV configuration

Prototype		
Materials	**Description**	**Integration**
Photovoltaic modules	P_{max}= 0.84 W I_{mp}= 140 mA V_{mp}= 5V Weight= 0.241kg Dimensions 149x199x3.2 mm	Were used as covering elements or roof parts
Aluminium sheets	99% reflective	Were used as covering elements or reflecting roofing parts
Aluminium profiles	Columns: Square traverse section, 2.5 cm side Tridilosa structure: 1.27 cm L profiles	Were used to made the Tridilosa structure
Steel wires	3 mm diameter	Were used to suspend the roof
Fans	5 W	Were used for advection cooling
Photovoltaic system powering fans for active cooling	P_{max}= 3.7 W ± 7.5% I_{mp}= 0.40 A V_{mp}= 9.0V Weight= 0.38kg Dimensions 180x150x18 mm	Were used to powering fans for active cooling

Table. 1. Description and integration of materials used in the build of scale prototype.

3. **Results**

The first model was made for a unit CPV system, consisting of a single Si-A module oriented at 45° with respect to the horizontal, configured in a V-cavity with a flat concentrator. These measurements were compared with those from a PV module oriented at 22.5° and 45°, and a fan was added to observe whether it had any impact. **Figure 4** shows the results according to the Si-A panel characteristics, but in the CPV cases there is a slight difference in power output. The PV oriented at 22.5° exhibited the lowest power, corresponding to 0.73 W; after that, we have the CPV system without cooling at 0.77 W, and then almost the same performance between the CPV with cooling and the PV oriented at 45° corresponding to 0.81 W. The difference in output power is more notable for multipanel prototypes.

Multipanel prototype results comparing the power capacity of different configurations—PV at 23°, PV at 45°, CPV at 23°, and CPV at 45° relative to the horizontal, without cooling—are presented in **Figure 5**. The maximum potential was achieved by the CPV system, represented by the red curve, where P_{max}= 3.26 W while the PV module oriented according to the recommended latitude, shown in pink, reached P_{max}= 2.79 W, indicating that CPV systems can enhance PV efficiency.

In the same figure, it can be observed that the PV modules oriented at 45° relative to the horizontal exhibits a higher power output (P_{max}= 3.03 W) than the oriented at 23°. The power output was expected to be approximately P_{max}~ 7.6 W/m^2, but in all cases, it was less than half of the expected value. This discrepancy could mainly be explained by losses due to module connections (which may have high resistance) or high temperatures. Associations with shaded areas or strong E_e variations are discarded.

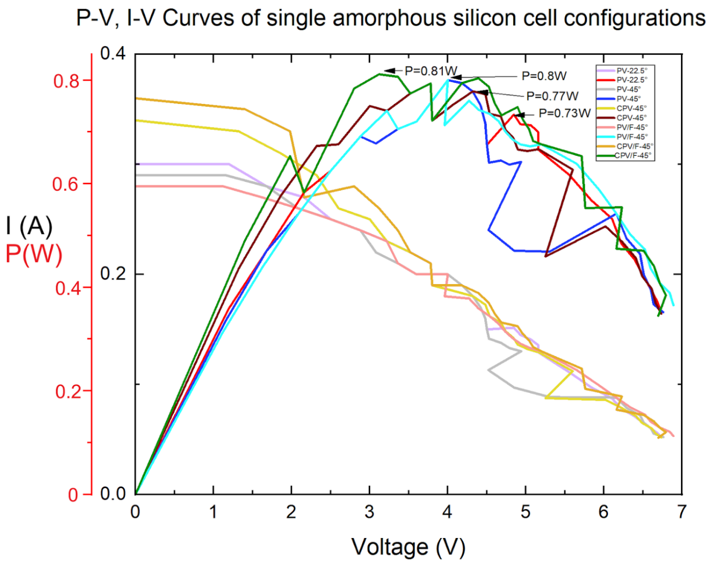

Fig. 4. P–V and I–V curves obtained from experimental measurements of the unit CPV system.

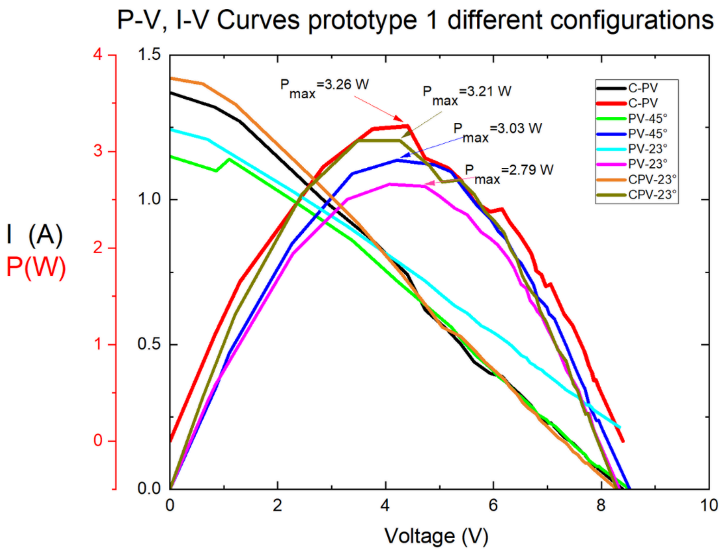

Fig. 5. P–V and I–V curves obtained from experimental measurements of the scale multipanel prototype.

To complement the power output results, ray-tracing simulations were performed to illustrate the flux distribution on key dates, such as the equinoxes and solstices. **Figure 6** presents heat maps of the solar incident flux on the photovoltaic modules. They were obtained by simulating 10 thousand rays for each season, and assessing the number of direct and reflected rays (considering a reflectance of 0.90) hitting the PV panel. The rectangles represent the areas of the PV systems that receive both direct solar radiation and reflected rays from the reflective sheet located in front of the V-cavity. The flux measurements for the solstices and equinoxes provide distribution limits for our system. From **Figure 6**, blue and green tones are interpreted as the expected irradiance on the PV surfaces, whereas the yellow–red distribution corresponds to the contribution of the reflective material, which enhances the incident flux on the PV modules. When combined with an efficient cooling system, this configuration shows strong potential for achieving higher power output. The sun positions during the solstices and equinoxes are displayed in the same graphic to provide a visual integration of the system.

From the above results, we found that integrating CPV systems with *Tridilosa* structures is viable, as the power output is expected to be higher than in a fixed well-oriented PV configuration. With our novel design aimed at improving the structural integration of lightweight ceiling systems, this approach demonstrates significant potential.

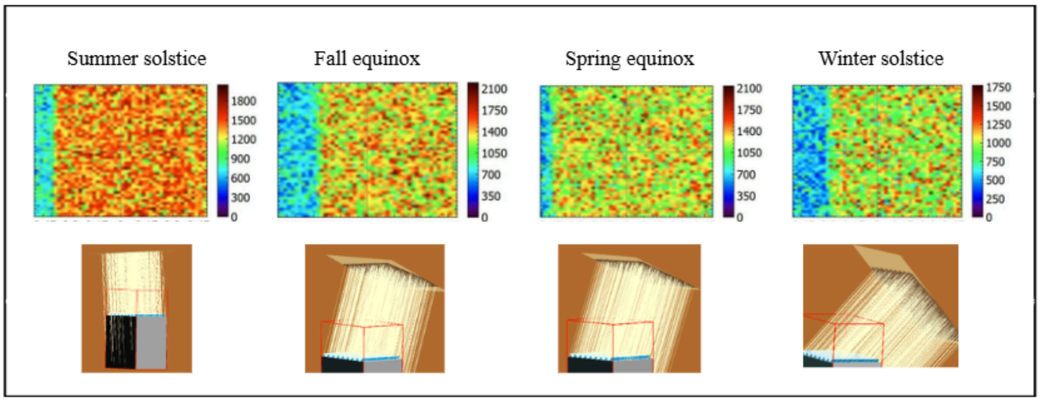

Fig. 6. Incident flux distribution and solar position for solstices and equinoxes in the CPV system.

Additionally, we conducted a preliminary estimation of the investment cost to build a standardized system and calculated its return on investment (ROI). This analysis was performed in nominal terms, without considering economic adjustments such as inflation or interest rates. The calculation assumed a total covered area of 800 m², using 550 W PV modules with dimensions of 2 m × 1.13 m × 35 mm.

For an 800 m² covered area, the system can accommodate approximately 210 PV modules, yielding a total installed capacity of 115 kWp. Considering an average solar availability of 5 kWh/m²·day, a representative value for Mexico, the estimated annual energy production is approximately 182 MWh/year. This corresponds to the average electricity consumption of around 115 Mexican households.

It should be noted that this estimation does not account for the incorporation of a concentrated photovoltaic (CPV) stage. Assuming a concentration factor of 1.4 suns, the effective system capacity could increase to approximately 161 kWp. Under this condition, and provided that adequate thermal management (passive or active cooling) is implemented to mitigate efficiency losses, the annual energy production could reach approximately 258 MWh/year under the same solar availability conditions. This would correspond to the electricity demand of roughly 150 Mexican households.

In this context, and assuming a domestic electricity tariff from the Comisión Federal de Electricidad (CFE) of approximately 1 MXN/kWh, the return on investment (ROI) can be estimated in terms of annual energy savings for both the conventional photovoltaic system and the proposed solution.

Since a photovoltaic plant typically offers a strong 10%–20% annual return on investment (ROI) with a payback period of 6–12 years, driven by energy savings, the intrinsic dual use potential and the concentration stage of our proposal improves the ROI by at least 20% and diminishes the payback period for 5-10 years depending on the scale and other project related issues. With a 25+ year lifespan, the systems may yield total returns exceeding 300%–500%. Higher returns can be achieved through high utility rates, strong solar radiation, tax incentives, and net metering.

Finally, a comparative economic analysis was conducted between the proposed system and two conventional alternatives: standard photovoltaic plants and curved roofing systems. The results of this comparison are presented in **Fig. 7**.

The initial investment for the proposed standardized solar roof is higher than that of a conventional solar PV plant. However, the integration of a concentration stage enables at least 20% increase in energy harvested and allows for dual use of the land. Unlike a standard solar PV plant, whose sole purpose is electricity generation, the proposed system is designed both to serve as a building structure and to supply its energy needs. As a result, while the costs associated with our approach are higher, its multifunctional benefits extend beyond those of a standalone PV power plant, making a direct comparison does not give a full picture.

More experiments of the photothermal part of the roofing system will be performed and presented in future works, as well as the structural dynamic analysis of the system.

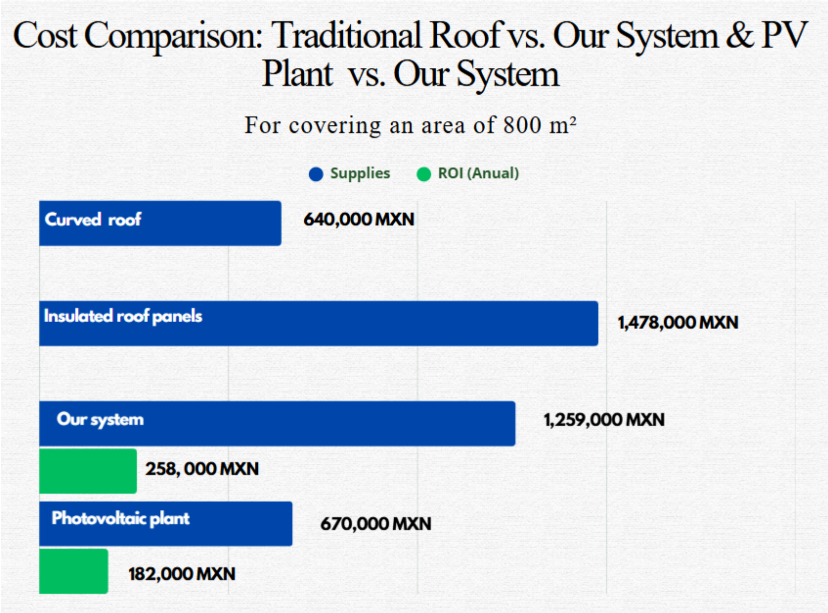

Fig. 7. Economical comparison between our innovative system with the two main competitors solar plants and conventional roof into the industrial sector, the economical comparison was in nominal terms.

4. Conclusions

We have presented a novel roofing system and analyzed its photovoltaic performance throughout model experiments and simulations. The roofing system is designed to cover large-span areas, providing thermal comfort, electric power generation from solar energy harvesting, and protection against weather.

The roofing system integrates PV, translucent and reflective panels, as well as flat photothermal collectors as covering elements. The structural elements are extruded aluminium profiles that enable the construction of a hermetically sealed cover, while maintaining good drainage of rain or washing water, and facilitating the construction process through standardized joints and nodes.

The energy harvesting elements are integrated into a V-cavity solar concentration configuration of a reflecting (passive) and a PV or PT (active) element, which require air-driven cooling systems or fans to improve the energy-harvesting efficiency.

Ray tracing simulations corroborate the experimental results showing an increased efficiency in this V-cavity CPV configuration.

Furthermore, a preliminary investment evaluation of our system against the conventional roofing system into the industrial sector and standard PV solar plants. This analysis clearly shows the versatility and economic benefits of the proposed roofing system.

5.

6. Acknowledgments

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