Journal of Engineering and High Technology

Volume 1
Issue 1
November Edition 2025

Comparison of prototype designs of wavy solar roof tiles and flat solar roof tiles for BIPV applications

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Received 15 July 2025
Revised 28 October 2025
Accepted 13 November 2025

ABSTRACT

This study compares the design efficiencies of two types of solar roof tile prototypes—flat and curved—in converting solar energy into electrical energy. Both types of solar tiles were tested under similar environmental conditions, including the light intensity, temperature, and roof tilt angle. The key parameters analyzed included output power, energy conversion efficiency, and performance stability over a defined period. The experimental results indicate that the flat solar roof tile exhibits a slightly higher conversion efficiency under optimal irradiation conditions. However, the curved solar roof tile demonstrated better performance in capturing light at varying incident angles, particularly during the morning and late afternoon, owing to its curved shape, which enables more uniform light absorption throughout the day. The study concludes that the selection of a solar roof tile type should be tailored to geographical conditions and specific user needs, as each design offers distinct advantages in terms of efficiency and installation flexibility.

Keywords: solar roof tiles, flat and curved prototypes, energy conversion efficiency, incident light angle, photovoltaic performance, building-integrated photovoltaics

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1. INTRODUCTION

The utilization of renewable energy, particularly solar photovoltaics, has expanded rapidly as countries seek to meet rising energy demand while reducing greenhouse gas emissions and environmental impacts (Pillai et al., 2022). Within this transition, solar roof tiles have emerged as an innovative technology that integrates photovoltaic cells directly into roofing elements, allowing them to function simultaneously as weatherproof building envelopes and on-site electricity generators (Biyik et al., 2017; Wajs et al., 2019). As part of the broader family of building-integrated photovoltaics (BIPV), solar roof tile systems are designed to enhance energy efficiency while maintaining architectural aesthetics and ensuring seamless integration into the building envelope (Biyik et al., 2017; Pillai et al., 2022).

The geometric design of solar roof tiles, whether flat or curved, can significantly affect the solar energy conversion efficiency. Zhang et al. (2022) reported that at low tilt angles, flat modules exhibit superior performance compared to curved modules, whereas curved modules may outperform flat modules under certain conditions. Furthermore, Wang et al. (2022) proposed a radiation distribution model for curved surfaces and a five-parameter-based electrical model to predict the system performance.

However, comparative studies evaluating the efficiencies of flat and curved solar roof tiles remain scarce, particularly in tropical climates such as Indonesia. This study aimed to compare the energy conversion efficiencies of both designs under similar operational conditions. The results are expected to provide insights for optimizing solar roof tile selection in terms of technical performance and economic feasibility across diverse climatic and architectural contexts.

2. LITERATUR REVIEW

2.1. Prototype design and development

Prototype design and development is the initial process of designing and developing a system or product in the form of a model that can be tested, evaluated, and refined before full-scale implementation (Putra, 2021). Prototyping is a technique used in system development, in which an early version of software or a physical system is built to visualize the system's functions and interactions. The primary goal of prototyping is to better understand user requirements and reduce the risk of design errors prior to the full system development (Putra, 2021).

2.2. Solar Energy and Photovoltaic Cells

Among the various renewable energy sources, solar energy is one of the most promising and environmentally sustainable. Photovoltaic (PV) cells function through the photovoltaic effect, in which incident sunlight on a semiconductor surface induces electron excitation and movement, resulting in the generation of an electric current (Green, 1982).

2.3. Building Integrated Photovoltaics (BIPV)

Building-integrated photovoltaics (BIPV) are photovoltaic systems integrated into building elements, such as roofs, walls, and windows. This technology offers added value by not only generating energy but also serving as a structural and aesthetic component of the building (Peng, Lu, & Yang, 2013). Solar roof tiles are an emerging form of BIPV technology.

2.4. Solar Roof Tile

Solar roof tiles are roofing materials that are integrated with photovoltaic modules. Solar tiles can be categorized into two main types: flat and curved. Flat tiles typically offer simpler installation and a consistent angle for light capture, whereas curved tiles provide aesthetic advantages and enable a more uniform distribution of light across the surface, particularly under varying sunlight conditions (Wang et al. 2022).

2.5. Efficiency of Photovoltaic Panels

The efficiency of solar panels is influenced by various factors, such as the material type, tilt angle, solar radiation intensity, ambient temperature, and surface geometry of the module. A study by Huld et al. (2011) indicated that variations in the tilt and orientation of panel installation significantly affect the amount of energy generated. For curved panels, the non-uniform distribution of angles relative to incoming sunlight can lead to reduced efficiency unless systematically optimized (Wang et al., 2022).

3. RESEARCH METHOD

A quantitative experimental approach was adopted in this study to compare the energy efficiency of two types of solar roof tiles—flat and curved—under controlled outdoor environmental conditions. The experiment involved real-time monitoring of solar irradiance and electrical output from each module in an open-air testing environment. See Figure 1

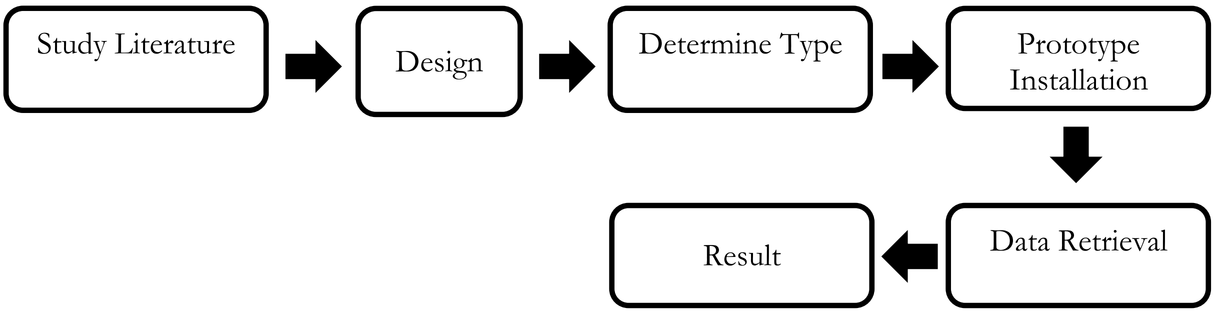

Figure 1. Research Flow Chart

4. RESULT & DISCUSSION

4.1 Design

The planning and design of the BIPV prototype, incorporating both flat and curved roof tiles, commenced with the creation of technical drawings and the selection of appropriate solar tile specifications (Figure 2 &3)

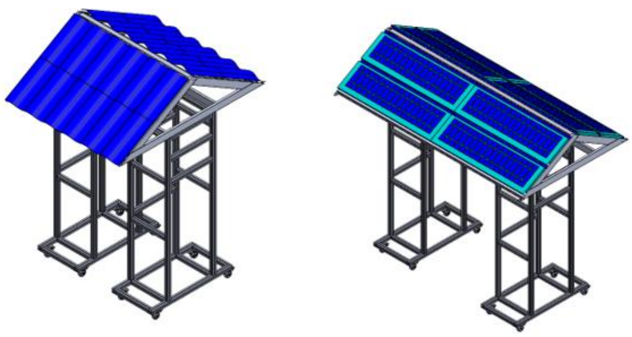

Figure 2. Prototype of Curved Solar Roof Tiles and Prototype of Flat Solar Roof Tiles

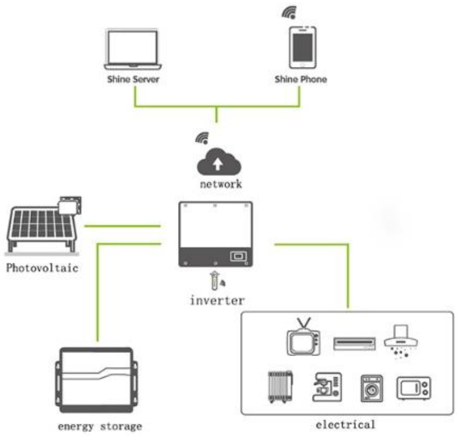

Figure 3. Prototype Installation Diagram

4.2 Solar Panel Types

See Figure 4 and Table 1 for detail about solar panel types.

Figure 4. Solar Roof Tile Specification

Table 1. Description of Solar Proof Tile Spesification'

No.	Description	Flat	Curved
1	Dimension	1260 x 480mm | 630 x 480mm	700 x 500mm
2	Peak Power	87Wp | 35 Wp	30 p

4.3 Prototype Installation

The prototype installation utilized a primary frame made of 40×40 mm aluminum profiles, with the roofing structure constructed from lightweight steel. The flat solar tile array comprised 8 modules (1260 × 480 mm, 87 Wp each), totaling 696 Wp. The curved solar tile array consisted of 10 modules (700 × 500 mm, 30 Wp each), yielding a total capacity of 300 Wp (Figure 5).

Figure 5. Prototype Installation

The control system comprises a 3 kW hybrid smart inverter, a battery storage unit consisting of two 12V 150 Ah lead-acid batteries connected in series, and a combiner panel that interfaces the solar roof tile system with the public utility grid (Figure 6)

Figure 6. Control Panel Installation

4.4 Results and Analysis

The data acquisition process was carried out through online monitoring systems accessible via both web and mobile platforms. The web-based interface utilized the *dessmonitor.com* platform, whereas mobile data tracking was performed using the *SmartESS* application (Figure 7-10 & Table 2).

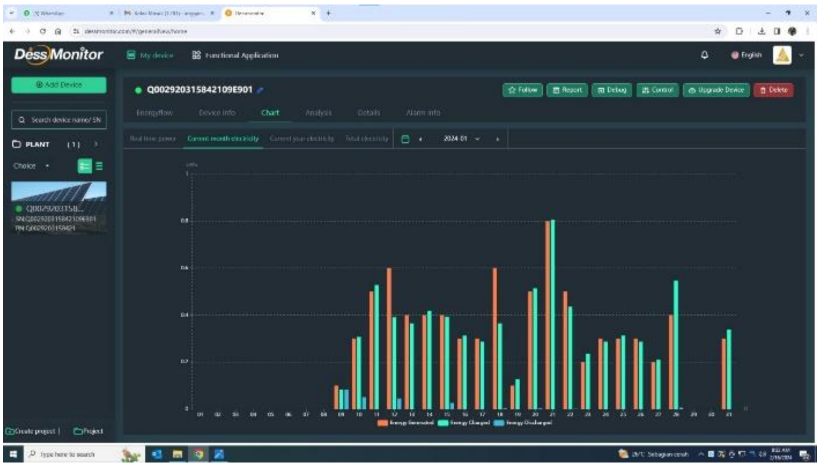

Figure 7. Web-Based Online Monitoring

Figure 8. Mobile Monitoring

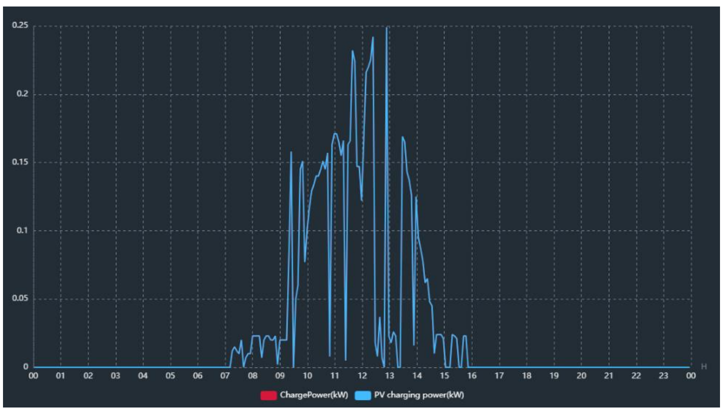

Figure 9. Energy Performance Monitoring of Curved Solar Roof Tiles

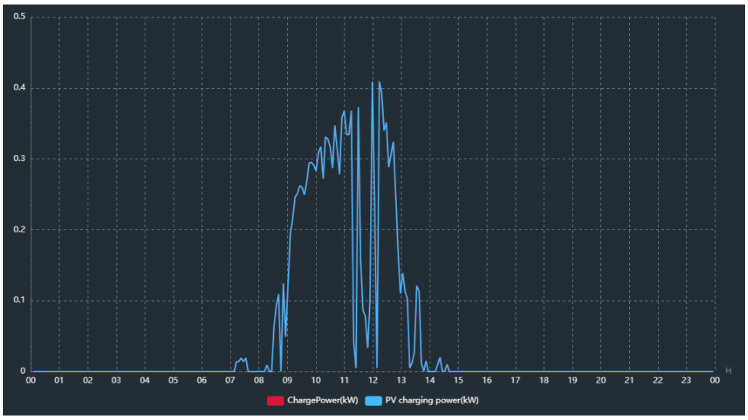

Figure 10. Energy Performance Monitoring of Flat Solar Roof Tiles

Table 2. Power Output per Square Meter (W/m²)

No.	**Type**	**Area (m²)**	**Period (Day)**	**Total Power Generated (kW)**	**Total Power Generated / m² (kW/Day)**
1	Flat	4.84	1	3	0.62
2	Curved	3.5	1	2	0.61

5. CONCLUSION

This study demonstrates that both flat and curved solar roof tile prototypes are technically feasible for building-integrated photovoltaic (BIPV) applications and capable of delivering comparable electrical performance under tropical outdoor conditions. The experimental results show that flat solar roof tiles achieve marginally higher energy conversion efficiency under optimal irradiance and tilt settings, as reflected in the slightly superior daily energy yield per square meter. In contrast, the curved solar roof tiles exhibit better ability to capture solar radiation over a wider range of incident angles, particularly during morning and late afternoon periods, leading to more uniform power generation throughout the day.

These findings imply that there is no single universally superior design; instead, the selection between flat and curved solar roof tiles should be determined by site-specific factors such as geographic location, typical sun path, shading patterns, roof geometry, architectural requirements, and user preferences. Flat tiles are more suitable where roof orientation and tilt can be optimized for peak efficiency, while curved tiles offer advantages in less ideal conditions and where aesthetic integration and broader angular acceptance are prioritized. Future work should extend the monitoring period, involve multiple seasons and locations, and incorporate economic analysis and lifecycle assessment to more comprehensively evaluate the trade-offs between both designs for large-scale BIPV deployment.

Ethical Approval
Not Applicable

Informed Consent Statement
Not Applicable

Authors' Contributions
DAP led the research project, designed the experimental setup, analyzed the data, and prepared the manuscript draft. R and RNR contributed to the prototype fabrication, experimental testing, and data collection. JI and MN assisted in performance measurement, result interpretation, and visualization. HS, KM, and TJ provided technical validation, supervision, and critical review of the manuscript.

Disclosure Statement
The Authors declare that they have no conflict of interest

Data Availability Statement
The data presented in this study are available upon request from the corresponding author for privacy.

Funding
This study did not receive any external funding.

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