

Article

Not peer-reviewed version

Mechanism Analysis of Photoelectric Mismatch Loss in Curved CIGS Cells: An Indoor Experimental Study

[Jun Wang](#) , Xinyi Tian , Mingjun Jiang , Guodong Lu , [Jie Ji](#) , [Qiansheng Fang](#) *

Posted Date: 7 April 2026

doi: 10.20944/preprints202604.0492.v1

Keywords: flexible photovoltaic; experimental study; curved bending forms; mismatch loss; copper indium gallium selenium (CIGS)



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a [Creative Commons CC BY 4.0 license](#), which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Mechanism Analysis of Photoelectric Mismatch Loss in Curved CIGS Cells: An Indoor Experimental Study

Jun Wang ^{1,2,3}, Xinyi Tian ^{4,5}, Mingjun Jian ^{6,7}, Guodong Lu ^{4,5} and Jie Ji ^{4,5} and Qiansheng Fang ^{2,3,8,*}

- ¹ School of Environment and Energy Engineering, Anhui Jianzhu University, Hefei, Anhui, China
- ² Anhui Province Key Laboratory of Intelligent Building and Building Energy-saving, Anhui Jianzhu University, Hefei, Anhui, China
- ³ Anhui Institute of Strategic Study on Carbon Emissions Peak and Carbon Neutrality in Urban-rural Development, Anhui Jianzhu University, Hefei, Anhui, China
- ⁴ Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China
- ⁵ Key Laboratory of Solar Thermal Conversion of Anhui Province, Hefei, 230026, Anhui, China
- ⁶ School of Architecture & Urban Planning, Anhui Jianzhu University, Hefei, Anhui, China
- ⁷ Key laboratory of Huizhou Architecture in Anhui Province, Anhui Jianzhu University, Hefei, Anhui, China
- ⁸ School of Electrics and Information Engineering, Anhui Jianzhu University, Hefei 230601, China
- * Correspondence: fqs@ahjzu.edu.cn; Tel.: +86-0551-63607346

Abstract

Flexible photovoltaic (PV) technology not only has high power efficiency but also is thin and lightweight, enabling seamless adaption to the surface of curved buildings. However, the distinctive spatial geometry of curved surfaces leads to inhomogeneous irradiance, causing electrical mismatch losses. This paper presents a systematic indoor experimental study on the electrical performance of Copper Indium Gallium Selenide (CIGS) cells under various bending configurations, including length-convex (lgvx), length-concave (lgcv), width-convex (wdvx), and width-concave (wdcv). Tests were conducted under standard testing conditions (1000 W/m², 25 °C) with central angles ranging from 0° to 180° and placed in longitudinal and horizontal orientations, respectively. Results indicate that width-bending configurations generally outperform length-bending ones due to lower mismatch losses. For width-bending, concave forms exhibit higher power output than convex forms due to a mutual reflection mechanism. Conversely, length-concave forms manifest the highest power mismatch loss (up to 319.70 mW at 180°) due to significant self-shading. These findings provide critical design guidelines for optimizing cell layouts in curved BIPV systems.

Keywords: flexible photovoltaic; experimental study; curved bending forms; mismatch loss; copper indium gallium selenium (CIGS)

1. Introduction

With the development of social economy and urbanization, energy consumption has become a global problem. The building sector was the largest segment in 2024 with a share of 34% of total global energy consumption and 37% of associated CO₂ emissions[1]. According to the China Association of Building Energy Efficiency (CABEE), in 2024, the carbon emissions caused by building operation were 2.47 billion tonnes, accounting for more than 22.10% of the country's total carbon emissions[2]. Exploring building energy efficiency and renewable energy technologies are considered two of the most important ways to address the growing energy needs of the building industry and achieve the dual-carbon goal.

Building integrated photovoltaic (BIPV) is the most widely used technology of solar photovoltaic in buildings, mainly in the form of BIPV roofs[3,4], walls[5,6], windows[7–9], and shadings[10]. In architecture design, curved building elements are highly prevalent. They not only

contribute to the creation of magnificent spatial structures but also endow buildings with aesthetically appealing facades, as vividly shown in Figure 1a-c. In China, some exemplary achievements have been made in seamlessly integrating PV modules into curved buildings, encompassing both modern and traditional architectural styles, as presented in Figure 1d-f.

In curved BIPV systems, glass-based curved PV modules have a relatively large self-weight, thus restricting their applications. Small-scale waved tiles can be applied to residential buildings directly [11,12], which takes place of the original roof. When it comes to large-scale curved surfaces, the prevailing method is to parameterize and mesh the curved surface, and integrate a planar PV module within each mesh [13,14]. This approach leads to complex support structures and load requirements. In contrast, flexible PV modules are lightweight, highly flexible, and can be seamlessly integrated with non-planar building surfaces. Moreover, in the same projection area, the installation amount of the curved PV module is larger than the flat type, yielding greater unit-area power generation. Owing to the self-shading phenomenon of curved PV modules, a detrimental mismatch effect is inevitable.



Figure 1. Photos of buildings with and without curved PV modules.

Some researches have been noticed, Liu et al. [15] developed a flexible monocrystalline silicon solar cell capable of 360° bending like A4 paper by modifying its internal structure, thereby advancing the development of curved flexible crystalline silicon solar cells. Lance et al. [16] compared the performance of PV modules with three shapes of plane, sine curve, and ellipse, and the results showed that under the same 2D projection area, the irradiance obtained by the curved surface increased by 50%, and its power curve would produce multiple peaks in a day. Therefore, it is of great significance to explore the electrical mismatch phenomenon in the application of curved flexible PV on curved buildings. Zhao et al. [17] utilized ray tracing technology to achieve coupled estimation of system-level shadow occlusion and mismatch loss. Saoud et al. [18] investigated the effect of partial shading on a complexly shaped c-Si based BIPV roof, optimizing for maximum yield to ascertain the optimal configuration and number of modules for each string using a genetic algorithm. Wang et al. [19,20] proposed a flexible CIGS-based curved PVT roof capable of producing both electricity and hot water. The experimental results indicated that the structure achieves an electrical efficiency of 14.71% and a thermal efficiency of 56.79% at a flow rate of 0.9L/min. Tian et al. [21,22] compared the electrical performance of curved with flat CIGS PV modules under various meteorological conditions and tilt angles. The results showed that the flat module outperforms the curved one at a 30° tilt angle,

with the performance gap decreasing as the tilt angle increases to 75°. The curved module exhibits a higher annual electricity especially at high inclination angles during the summer. Gong et al.[9] introduced an arc-shaped CIGS PV window by using EnergyPlus and Radiance software. The simulation results showed that the central angle of 120° arc-shaped window performs best in terms of energy used intensity. Walker et al.[23] presented a workflow for calculating BIPV system losses using a curved CIGS module. The results indicated that a longitudinal orientation outperforms an orthogonal one by 5-8%. Cai et al.[13] proposed a flexible curved c-Si PV ventilated façade assisted by a heat pump. Compared to an independent heat pump system, the integrated solution enhances the coefficient by 5.23% during the preheating process. Further, the electrical performance and power loss of 2D and 3D curved flexible Si-PV modules have been studied. The results indicated that suitable PV cell interconnection methods can significantly reduce mismatch losses, thereby enhancing power output up to 1721.21 Wh and 1604.10 Wh, respectively[13]. Bugaj et al.[24] proposed a semi-flexible PVT system based on c-Si cells, which was used to develop the testing methodology for various bendable conditions. The results indicated that when the bending angle modifier ranged from 1 to 1.1, the thermal power at a deflection of 30° was approximately 18% lower than that of the flat type, and the electrical power was nearly 14%. Pei et al.[25] investigated the different mechanical stability caused by concave and convex bending flexible perovskite solar cells. The concave type outperformed the convex type, because the conductivity decreased by the Series Resistance under convex bending form. Yun et al.[26] introduced a curved honeycomb-structured Si PV module incorporating 3D mechanical metamaterials. By systematically harnessing additional reflected/scattered photons within its tetrahedral geometry, this structure demonstrated a 28% improvement in electrical output compared to flat type. Deepika et al.[27] investigated the performance of flexible perovskite solar cells under a central angle of 60° bending state. A silica subwavelength array embedded on the substrate's surface optimizes mechanical and optical performance. The results indicated that the current density increased by 7.30% when bent downwards and by 1.90% when bent upwards. Kashayap et al.[28] investigated the performance of convex, concave and sinusoidal bendings flexible perovskite under the influence of bending radius (5-20mm) and bending amplitude (0.5-2mm). The results indicated that the flat perovskite demonstrates superior PV parameters.

Nevertheless, a review of the literature indicates that no studies have systematically investigated the mismatch phenomenon of curved CIGS PVs with length-bending and width-bending configurations. To address this deficiency, this study introduces several representative bending forms, including length-convex(lgvx), length-concave(lgcv), width-convex(wdvx), width-concave(wdcv), wavy(wy), and flat mounting(flt), which mimic typical curvature patterns of building envelopes. To validate the proposed configurations, tests were conducted under standard testing conditions (1000 W/m², 25°C) with central angles ranging from 0° to 180° and placed in longitudinal and horizontal orientations. A series of controlled experiments were conducted to characterize the electrical performance and thermal behavior of the curved PVs. The results are analyzed and discussed in the context of curvature-induced mismatch effects.

Nomenclature			
A_c	the overall area of the orthographic projection of eight curved PV/T units on the inclined surface, m²	P_{max}	the instantaneous maximum power output of the PV module,W
G_{pv}	Solar irradiation intensity on baseplate,W/m²	A_{pv}	the orthographic projection area on inclined surface area,m²
η_{pv}	Electrical efficiency,%	P_{flt}	The flat type PV power output,W
ΔP_{ml}	Power mismatch loss,W	P_{crv}	The curved type PV power output,W
PR	Performance ratio,%	FF	Filling factor
V_{oc}	The open circuit,V	I_{sc}	The short current,A
F_z	The standard uncertainty of the instruments	a_n	The nominal accuracy of the experimental instrument

X(b)	The uncertainty
------	-----------------

2. Methodology

In this section, we offer two testing platforms for PV modules with different bending configurations. The fabrication process of curved photovoltaic (PV) devices and the system structure in diverse shapes are elaborated upon. Moreover, the testing objectives are expounded, the workflow of the electrical system is outlined, and the operation procedures of the experimental equipment indoors are described.

2.1. Testing Objective

Due to the complexity of curved geometries, uneven irradiance and temperature distribution will be formed when combined with building envelope, leading to a mismatch phenomenon and partial overheating in PV modules. The non-uniformed distribution of irradiance on a curved PV surface causes part of the current to be unoutputted, while voltage mismatches shift the operating point deviate from the maximum power point (MPP), thereby affecting the output power. Additionally, the gradient of PV temperature can cause overheating in certain areas, resulting in uneven thermal stress[29]. Consequently, the service life and operational safety of the PV modules are compromised.

To explore the current and voltage mismatch mechanism of curved flexible PV cells, it is essential to gather, compute, and further analyze the actual electrical output data under various geometric parameters and experimental conditions. By conducting synchronous studies on the stable state in the laboratory and the real-use state outdoors, more precise power loss laws for curved PV cells can be derived. Several identical flexible CIGS modules were utilized to test the all-day electrical power and temperature distribution across different bending forms, including length-concave (lgcv) and length-convex (lgvx) bending, width-concave (wdcv) and width-convex (wdvx) bending, length-wavy bending (wy), and flat mounting (flt). Figure 2 illustrates the typical types of curved PVs for building envelopes placed in longitudinal orientation.

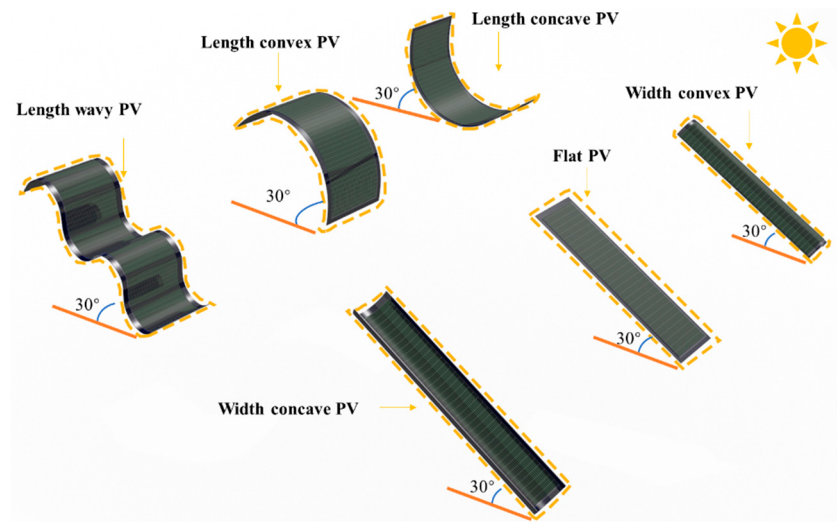


Figure 2. Different types of curved photovoltaics with a 30° tilt angle in longitudinal orientation.

2.2. The Indoor Testing Contents and Apparatus

Steady indoor testing refers to laboratory conditions where solar irradiance and ambient temperature are maintained at standard levels (STC: 1000W/m², AM 1.5G, 25°C).

2.2.1. The Sample Fabrication

The fundamental units for this indoor investigation are flexible CIGS PV cells with standard dimensions of 45 mm (width) × 105 mm (length) × 0.02 mm (thickness). To ensure a high degree of experimental precision, the length-to-width ratio was maintained above 2:1 to allow for a valid comparison between different bending orientations.

Custom-designed curved baseplates and tilt supports were fabricated using a high-precision 3D printer with Polylactic Acid (PLA) material. These baseplates were categorized into six distinct representative bending forms that mimic typical curvature patterns in modern architecture: flat (flt), length-convex (lgvx), length-concave (lgcv), width-convex (wdvx), width-concave (wdcv), and length-wavy (wy). The CIGS cells were seamlessly affixed to these curved baseplates using thermal silica gel to ensure both structural integrity and thermal connectivity. To simulate standard BIPV roof applications, all modules were investigated at a fixed tilt angle of 30°.

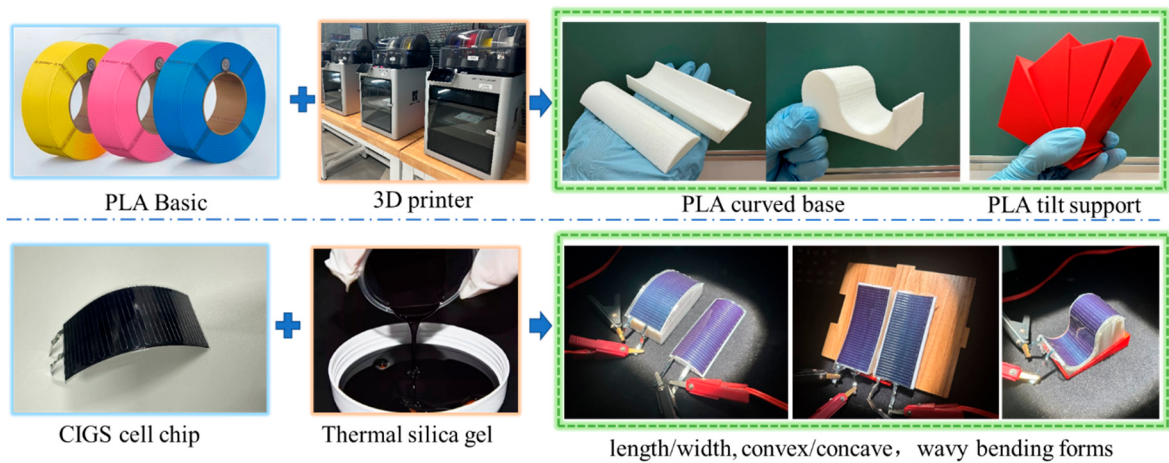


Figure 3. The manufacturing process of the curved CIGS PV cells.

Table 1. The specific geometric parameters used in the indoor testing are summarized below:

Parameters	Changes Value (unit)
Central angle	0°, 30°, 60°, 90°, 120°, 150°, 180°
Direction	longitudinal, horizontal

2.2.2. Experimental Apparatus and Procedure

The tests comprehensively evaluated the electrical performance of the cells. As depicted in Figure 4, the primary light source was an artificial AAA-class solar simulator (Oriel 94063A) equipped with air mass filters to ensure spectral compliance. The light source is an arc lamp powered by a dedicated power supply. The ambient temperature within the test chamber was strictly regulated at 25.00°C via air conditioning and monitored continuously using a high-accuracy thermo-hygrometer. Electrical parameters including current-voltage (I-V) curves, maximum power point data (Vmpp, Impp, Pmpp), and filling factor (FF) , were recorded by the Oriel®PVIV-10A system. Table 2 details the parameters of the measuring apparatus.

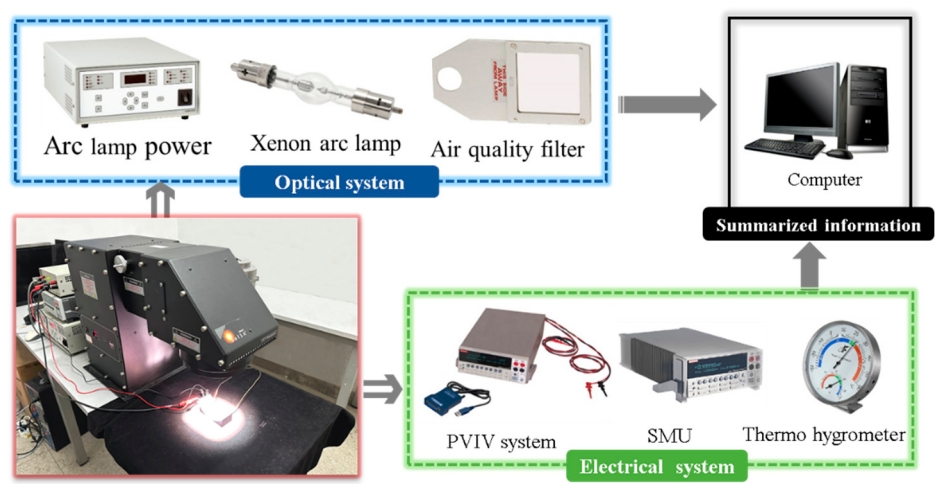


Figure 4. The schematic diagram of the indoor testing.

Table 2. Parameters of the experimental apparatus.

Content	Apparatus	Type	Accuracy
Solar irradiance	3A solar simulator	Oriel 94063A	≤2%
Light source	Arc Lamp Power supply	Oriel 69920	< 0.1%
Temperature1	Thermo hygrometer	TH608	±1.0°C
Test platform	PVIV Test System	Oriel PVIV-10A	I< 0.23%, V±0.02%, Ω±0.25°C
Electrical output	Source Measuring Unit	Keithly 2400	0.012%

2.3. Performance Evaluation Metrics

To quantitatively assess the electrical degradation and energy conversion capability of curved CIGS cells, this study employs five key indicators derived from the authors’ previous research[19,21,22]. These metrics provide a comprehensive framework for understanding the mismatch phenomena under various geometric conditions:

- (1) The electrical efficiency (η_{pv})

Defined as the ratio of the maximum power output to the incident solar energy on the orthographic projection area:

$$\eta_{pv} = \frac{P_{max}}{G_{pv}A_{pv}} \times 100\% \tag{1}$$

where: P_{max} is the instantaneous maximum power output of the PV module (W), G_{pv} is solar irradiation intensity on corresponding baseplate (W/m^2), A_{pv} is the orthographic projection area of the curved PV module on inclined surface area (m^2), the flat one is $0.49m^2$, the curved ones are $0.35m^2$.

- (2) Power mismatch loss (ΔP_{ml})

The mismatch loss in the curved PV cells/modules can be defined as the difference between the power output of a flat PV and a curved one with the same specifications[13].The mismatch loss can be defined as:

$$\Delta P_{ml} = P_{flt} - P_{crv} \tag{2}$$

where, P_{flt} is the flat type PV power output; P_{crv} is the curved type PV power output.

(3) Performance ratio (PR)

In this study, performance ratio is defined as the ratio of the power output of the curved PV to the flat PV with the same specifications, which is given below:

$$PR = \frac{P_{crv}}{P_{flt}} \times 100\% \tag{3}$$

(4) Filling factor (FF)

The filling factor is an inevitable parameter to describe the performance of PVs under partial shadings. FF is defined as the ratio of the actual maximum power output of the PVs to the rated maximum power output. The higher the value, the higher the photoelectric conversion efficiency. The formula is:

$$FF = \frac{P_{max}}{V_{oc} \cdot I_{sc}} \tag{4}$$

where: V_{oc} is the open circuit voltage (V); I_{sc} is the short circuit current (A);

2.4. Uncertainty Analysis

Uncertainty analysis is essential in experimental studies to establish credibility in the results[30]. In this study, the working temperature of the flexible PV is tested by the T-type thermocouple, and the power output of the PV under MPP is tracked by the MPPT controller. The standard uncertainty of the instruments (denoted as F_z) is calculated by Eq. (5)[31]. The standard uncertainty of each measuring instrument utilized during the experimental process is shown in Table 3.

$$F_z = \frac{Y_z}{\sqrt{3}} \tag{5}$$

where Y_z is the nominal accuracy of the experimental instrument and can be provided by the producers.

The uncertainty $X(b)$ is determined using Eq. (6), which is calculated based on the standard uncertainties of the measurement devices utilized. For the high-precision indoor PVIV system, the accuracy for current and voltage is within $\pm 0.23\%$ and $\pm 0.02\%$, respectively.

$$X(b) = \sqrt{\sum F_z^2} \tag{6}$$

Table 3. Parameters of the measuring instruments used in the experiment.

Instrument name	Test content	Type	Accuracy	Uncertainty
Solar global pyranometer	Global irradiance	Jinzhou TBQ-2	± 2%	1.15%
Solar diffuse pyranometer	Diffuse irradiance	Jinzhou TBD-1	± 2%	1.15%
Thermocouple	Temperature	T-type (copper-constantan)	± 0.5℃	0.29%
MPPT controller	Electrical power	EPEVER Tracer 1210AN	± 0.5%	0.29%
Datalogger	Data switch unit	HIOKI LR8402-21	/	/

3. Results and Discussions

The indoor tests revealed that the electrical performance of the sample PV cells without any bypass diode remained stable under controlled working conditions. The sample PV cells were small-scale and prone to forming thermal hotspots, so we tested their instantaneous power output. Given

that the solar irradiance field on curved PV cells is altered by various curvatures, in this part, we also investigated the electrical performance under different central angles.

3.1. The Power Output and Mismatch Loss

The power output and mismatch loss results demonstrated distinct regularities. As illustrated in Figure 5a-b, the flat type CIGS PV cell achieved the highest power output of 547.90mW. Among different curved flexible PV cells, regardless of the longitudinal orientation (LT) or horizontal orientation (HZ), all width bending configurations outperformed their length counterparts, with lower mismatch losses. This implies that shapes with the width facing the light source received more irradiance than those with the length facing it. For width bending configurations, the width-concave(wdcv) forms generated more electricity than the width-convex(wdvx) ones. This phenomenon can be attributed to the fact that when the long side curves upward, the two upright segments reflect off each other. This mutual reflection mechanism enhances the photoelectric conversion efficiency (PCE) of the PV cells. Conversely, in length-bending structures, the length-convex (lgvx) forms yielded a higher power output than the length-concave (lgcv) ones. This is because the two upward-angled segments on the long side of the lgcv forms would cast shadows on themselves. They had the lowest power output of 245mW, filling factor (FF) of 0.25222, the highest power mismatch loss of 319.70W, and the lowest performance ratio (PR) of 43.39%.

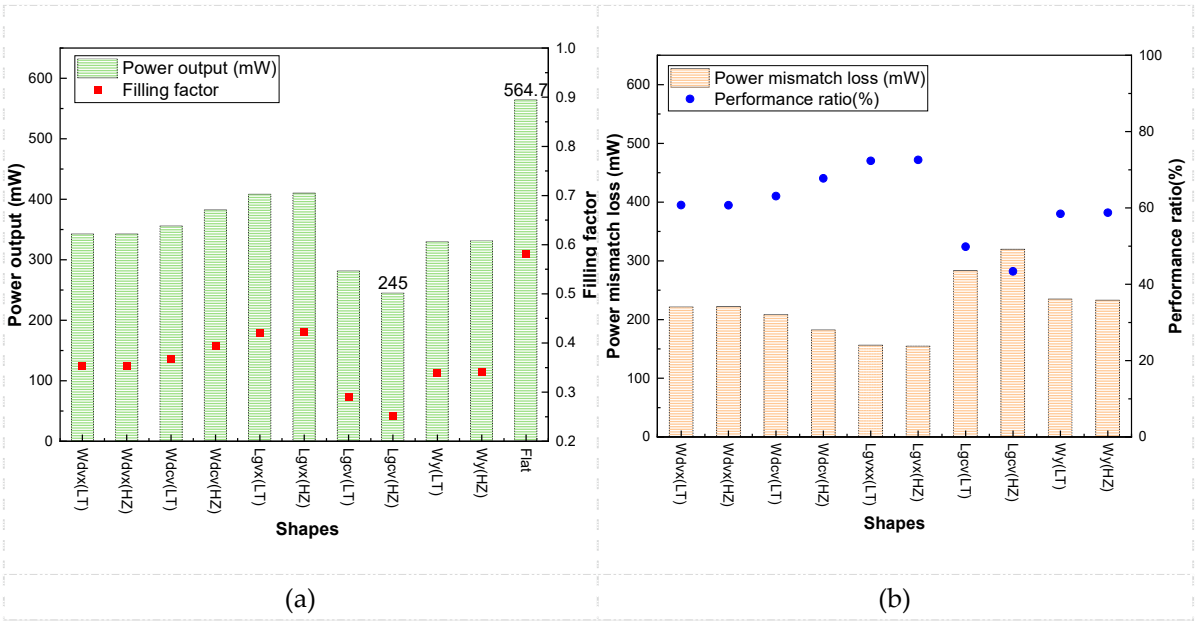


Figure 5. The power output and mismatch loss of the PV cells.

3.2. Influence of Central Angle

It is well-known that curved PV cells give rise to a mismatch phenomenon. The curvature of the curved PV surface can affect the irradiance distribution, thereby leading to a decrease in power output to varying degrees. This part describes how the electrical performance changes with various central angles. As illustrated in Figure 6a-d, regardless of longitudinal orientation (LT) or horizontal orientation (HZ), as the central angle increased, the power output and fill factor (FF) of the PV cells showed a decreasing trend. More specifically, within each group of bending orientations, the convex-shaped PV cells produced lower power outputs and FF compared to their concave-shaped counterparts. In all convex structures, the HZ oriented setups performed less effectively than those in the North-South direction. Notably, in length-bending structures, when the central angle exceeded 135°, the power output and FF of the length-convex shapes, regardless of whether they were oriented in the North-South or West-East direction, was higher than that of the length-concave shapes.

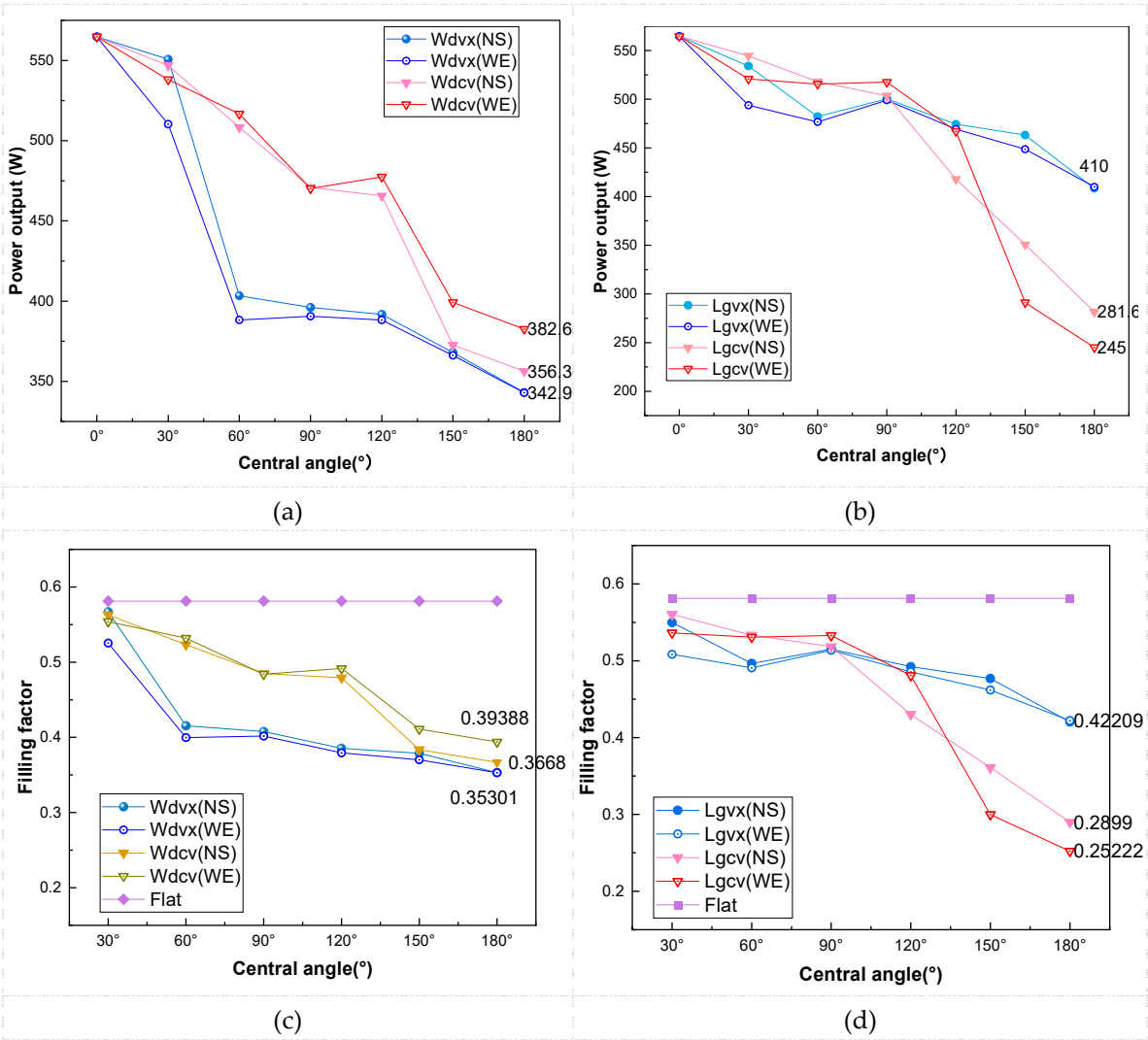


Figure 6. The power out and filling factor of PV cells with different curvature.

Based on the aforementioned data, we calculated the detailed mismatch loss and performance ratio (PR) for eight set-ups, which are presented in the following heat maps. As depicted in Figure 7a-b, the power mismatch loss increases as the central angle grows larger, while the PR decreases. Overall, the changes at each step with respect to the central angle exhibit a zigzag pattern. The adjacent data of each diagonal are more symmetrical. Specifically, the width-convex(wd vx) shape with a central angle of 30° demonstrated the minimum mismatch loss and achieved the highest PR of 97.52%. In contrast, the length-concave shape with a central angle of 180° showed the maximum mismatch loss and had the lowest PR of 43.39%. Notably, in terms of PR, the popularity statistics ranged from 70-90%.

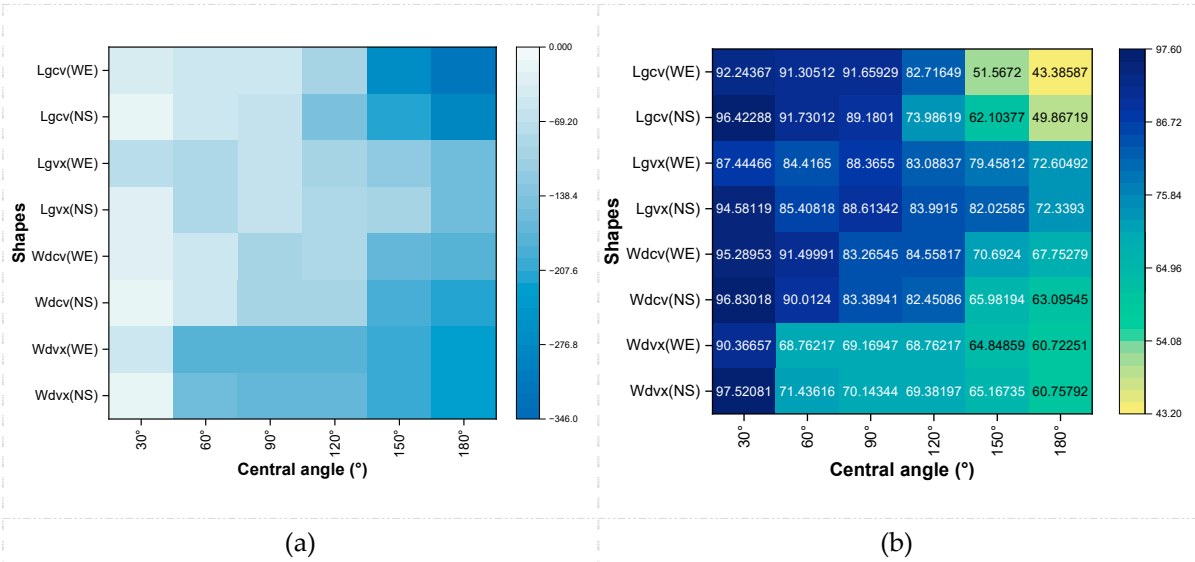


Figure 7. The mismatch loss and performance ratio of PV cells with different central angle.

In the case of width bending forms, since the curvature occurs on the short side, certain patterns can be observed. In width-convex(wdvx) structures, a larger central angle implies a closer approximation to a cylindrical shape. Consequently, the area facing to irradiance diminishes, giving rise to a more significant power mismatch loss. In contrast, in width-concave(wdcv) structures, the two long side upwards reflected irradiance to each other and increase the PCE, resulting in a lower mismatch loss.

In the case of length bending forms, since the curvature happens on the long side, certain patterns can also be observed. In length-convex(lgvx) structures, when the PV cells are set in the North-South direction, the two short sides will get closer when the central angle increases. As a result, the effective area facing the irradiance becomes smaller, leading to a decrease in the PCE and an increase in the mismatch loss. In length-concave(lgcv) structures, the upper-side segment of the PV cell will cast a shadow on itself, while the lower-side segment will reflect the irradiance to each other. From the test results, the effect from the partial shading is more significant than that of reflection.

Among all the structures, convex structures consistently exhibited lower electrical performance compare to their corresponding concave structures. This is because convex shapes received less irradiance than concave shapes, and certain portions of irradiance were reflected by the surroundings. For the heat maps, the zigzag phenomenon verified that the irradiance distributed on the curved surface was unevenly along the circumferential direction. Consequently, it will affect the photoelectrical conversion and lead to the mismatch phenomenon.

4. Conclusion

It is worth noting that the curved PV module has great potential in the application of curved BIPV buildings. In this work, a series of curved flexible CIGS PV cells with different bending forms were proposed and fabricated. The indoor experiments leads to the following conclusions:

Mismatch Patterns: In terms of curved sample PV cells, the length-bending shapes demonstrated a greater mismatch loss compared to the width-bending shapes, and the convex-shapes showed a higher mismatch loss than the concave-shaped forms. Thereby, the length-concave forms in Wes-East direction exhibited the poorest performance. They had the lowest power output and filling factor (FF), the highest power mismatch loss, and the lowest performance ratio (PR).

Geometric Optimization: As a result of the specific test arrangements, the concave-shaped structures cast shadow on themselves, which manifested diverse electrical performances depending on different experimental scenarios. Additionally, it was observed that the power outputs of the North-South orientation and the West-East orientation were remarkably close.

Critical Thresholds: Increasing the central angle exacerbates the zigzag pattern of non-uniform irradiance, with a 180° angle causing over 50% power loss in length-oriented configurations.

In future, the electrical performance of curved PV modules with varying inclinations requires further outdoor experimentation. Considering that the chipset strings are grouped and arranged parallel to the width direction, the direction parallel to the length-orientation is worthy of indepth study. Thus, it is crucial to meticulously design the inner cell layout of the flexible PV module to adapted the shape and the surrounding environment. Moreover, the complex non-planar surfaces of large-scale BIPV projects can be divided into curved PV arrays. Their connection strategies can be optimized to avoid significant mismatch losses under actual operating conditions. Overall, this research offers an effective approach to exploring the mismatch phenomena in curved PV modules with different bending configurations.

Author Contributions: Jun Wang: Conceptualization, Methodology, Investigation, Writing - Original Draft; Xinyi Tian: Conceptualization, Investigation, Formal analysis, data curation, Writing - Review & Editing; Qiansheng Fang: Writing - Review & Editing, Funding acquisition; Jie Ji *: Conceptualization, Methodology, Writing - Review & Editing, Funding acquisition.

Funding: This research is supported by Anhui Provincial Department of Education Natural Science Key Project (2022AH010018, 2024AH050233), and National Key Research and Development Project (No.2023YFC3807704, No.2022YFB4201002), National Natural Science Foundation of China (No.52238004).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. (please specify the reason for restriction, e.g., the data are not publicly available due to privacy or ethical restrictions.).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments: This research is supported by Anhui Provincial Department of Education Natural Science Key Project (2022AH010018, 2024AH050233), and National Key Research and Development Project (No.2023YFC3807704, No.2022YFB4201002), National Natural Science Foundation of China (No.52238004).

Reference

1. UNEP Ia. Global Status Report for Buildings and Construction 2024/2025. 2025.
2. CABEE. 2025 China's Carbon Emission Report on Urban and Rural Construction. 北京 2026.
3. Tian X, Wang J, Yuan S, Ji J, Ke W, Wang C. Investigation on the electrical performance of a curved PV roof integrated with CIGS cells for traditional Chinese houses. *Energy*. 2023;263.
4. Tian X, Wang J, Ke W, Ji J. Performance assessment of the curved-type multi-channel PV roof for space-heating and electricity generation in winter. *Renewable Energy*. 2024;231.
5. Hu Z, Zhang S, Hou J, He W, Liu X, Yu C, et al. An experimental and numerical analysis of a novel water blind-Trombe wall system. *Energy Conversion and Management*. 2020;205.
6. Su X, Luo C, Chen X, Jiang Q, Yu Y, El Shenawy ET, et al. Experimental and theoretical analysis of photovoltaic performance and thermal behavior for bifacial PV-Trombe wall system with reversible louvers in summer. *Energy*. 2024;312.
7. Zhang C, Ji J, Wang C, Ke W, Xie H, Yu B. Experimental and numerical studies on the thermal and electrical performance of a CdTe ventilated window integrated with vacuum glazing. *Energy*. 2022;244.
8. Shi S, Zhu N, Li Y, Song Y. Photo-thermal decoupling CdTe PV windows with selectively near-infrared absorbing ATO nanofluids. *Renewable Energy*. 2024;235.
9. Gong F, Gao Y, Tian X, Wang J, Ji J, Shi F, et al. Simulation of a novel curved photovoltaic (PV) window improving the annual daylighting and building energy performance simultaneously. *Building Simulation*. 2024;17(11):1951-69.

10. M. Krarti AK. Evaluation of static and dynamic PV-Integrated shading systems for office spaces in Australia. *Solar Energy*. 2024;277(112736).
11. Wang J, Tian X, Ji J, Zhang C, Ke W, Yuan S. Field experimental investigation of a multifunctional curved CIGS photovoltaic/thermal (PV/T) roof system for traditional Chinese buildings. *Energy Conversion and Management*. 2022;271:116219.
12. Tian X, Wang J, Ji J, Wang C, Ke W, Yuan S. A multifunctional curved CIGS photovoltaic/thermal roof system: A numerical and experimental investigation. *Energy*. 2023;273.
13. Cai J, Fang J, Liang M, Zhu Q, Shi Z, Li Q, et al. Dynamic performance enhancement in 2D and 3D curved flexible photovoltaic modules: Mismatch loss analysis and cell interconnection configurations optimization. *Applied Energy*. 2024;374.
14. Thoy EJW, Go YI. Enhancement and validation of building integrated PV system: 3D modelling, techno-economics and environmental assessment. *Energy and Built Environment*. 2022;3(4):444-66.
15. Liu W, Liu Y, Yang Z, Xu C, Li X, Huang S, et al. Flexible solar cells based on foldable silicon wafers with blunted edges. *Nature*. 2023;617(7962):717-23.
16. Lance Alpuerto RSB. Energy harvest potential of flexible photovoltaics on curved surfaces. Conference Energy harvest potential of flexible photovoltaics on curved surfaces. IEEE, p. 1-6.
17. Zhao C, Xiao J, Yu Y, Jaubert J-N. Accurate shading factor and mismatch loss analysis of bifacial HSAT systems through ray-tracing modeling. *Solar Energy Advances*. 2021;1.
18. Al-Janahi SA, Ellabban O, Al-Ghamdi SG. A Novel BIPV Reconfiguration Algorithm for Maximum Power Generation under Partial Shading. *Energies*. 2020;13(17).
19. Wang J, Tian X, Ji J, Zhang C, Ke W, Yuan S. Field experimental investigation of a multifunctional curved CIGS photovoltaic/thermal (PV/T) roof system for traditional Chinese buildings. *Energy Conversion and Management*. 2022;271.
20. Wang J, Tian X, Ji J, Xie H, Yuan S. A comparative study on curved air-based photovoltaic/thermal roofs with and without glazing. *Applied Thermal Engineering*. 2023;219.
21. Tian X, Wang J, Ji J, Lu G. The performance investigation of the flexible photovoltaic cell under non-uniform distributed illumination. *Renewable Energy*. 2025;240.
22. Tian X, Wang J, Ji J, Xia T. Comparative performance analysis of the flexible flat/curved PV modules with changing inclination angles. *Energy Conversion and Management*. 2022;274.
23. Walker L, Hofer J, Schlueter A. High-resolution, parametric BIPV and electrical systems modeling and design. *Applied Energy*. 2019;238:164-79.
24. Bugaj MA, Mik K. Can PVT bend?: The elaboration of flexible hybrid photovoltaic thermal solar collector structure and testing methodology. *Renewable Energy*. 2023;215.
25. Pei L, Yu H, Zhang Q, Li J, Wang K, Hu B. Concave and Convex Bending Influenced Mechanical Stability in Flexible Perovskite Solar Cells. *The Journal of Physical Chemistry C*. 2020;124(4):2340-5.
26. Yun MJ, Sim YH, Lee DY, Cha SI. Honeycomb-Structured 3D Concave Photovoltaic Modules Supported by 3D Mechanical Metamaterials for Enhanced Light Recapture. *Advanced Materials Technologies*. 2022;8(2).
27. Deepika, Singh A, Verma UK, Tonk A. Device Structures of Perovskite Solar Cells: A Critical Review. *physica status solidi (a)*. 2023;220(9).
28. Kashyap S, Pandey R, Madan J, Mohammed MKA. Reliability Test of 21% Efficient Flexible Perovskite Solar Cell Under Concave, Convex and Sinusoidal Bending. *IEEE Transactions on Device and Materials Reliability*. 2023;23(3):380-5.
29. Ma T, Guo Z, Shen L, Liu X, Chen Z, Zhou Y, et al. Performance modelling of photovoltaic modules under actual operating conditions considering loss mechanism and energy distribution. *Applied Energy*. 2021;298.

30. Agyekum EB, PraveenKumar S, Alwan NT, Velkin VI, Shcheklein SE, Yaqoob SJ. Experimental Investigation of the Effect of a Combination of Active and Passive Cooling Mechanism on the Thermal Characteristics and Efficiency of Solar PV Module. Inventions2021.
31. Alwan NT, Majeed MH, Shcheklein SE, Ali OM, PraveenKumar S. Experimental Study of a Tilt Single Slope Solar Still Integrated with Aluminum Condensate Plate. Inventions2021.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.