

Article

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

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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 study examines the geometric origin of photoelectric mismatch through controlled indoor experiments on bare flexible CIGS cells in six configurations: flat, length convex, length concave, width convex, width concave, and length wavy. The tests were conducted under standard test conditions at central angles from 0° to 180° and in two laboratory orientations. A two-dimensional microfacet optical model, accounting for direct-beam projection, self-shading, and inter-arm mutual reflection, was developed and calibrated against the measurements, giving an $R^2 = 0.85$ and RMSE = 5.1%. The results show that width-bending configurations retain a performance ratio (PR) above 60% over the tested angular range because the irradiance gradient is distributed across the current-collection path. In contrast, length bending aligns the gradient with the current path and leads to much larger mismatch losses. For the concave cases, mutual reflection improves performance at intermediate central angles, but this benefit is lost when self-shading becomes dominant beyond approximately 135°. The most severe case is length concave in the horizontal orientation at 180°, which retains only 43.4% of the flat-reference power, corresponding to a 56.6% loss and 319.7 mW of mismatch loss. These findings clarify how bending direction, curvature, and orientation affect cell-level mismatch and provide design guidance for curved CIGS BIPV systems.



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

1. Introduction

With the development of social economy and urbanisation, energy consumption has become a global problem. The building sector was the largest segment in 2024, with a share

of 34% total global energy consumption and 37% 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 (BIPVs) are the most widely used technology of solar photovoltaics in buildings, mainly in the form of BIPV roofs [3], walls [4,5], windows [6–8], and shadings [9]. 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, which takes place of the original roof. When it comes to large-scale curved surfaces, the prevailing method is to parameterise and mesh the curved surface and integrate a planar PV module within each mesh [10,11]. 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.

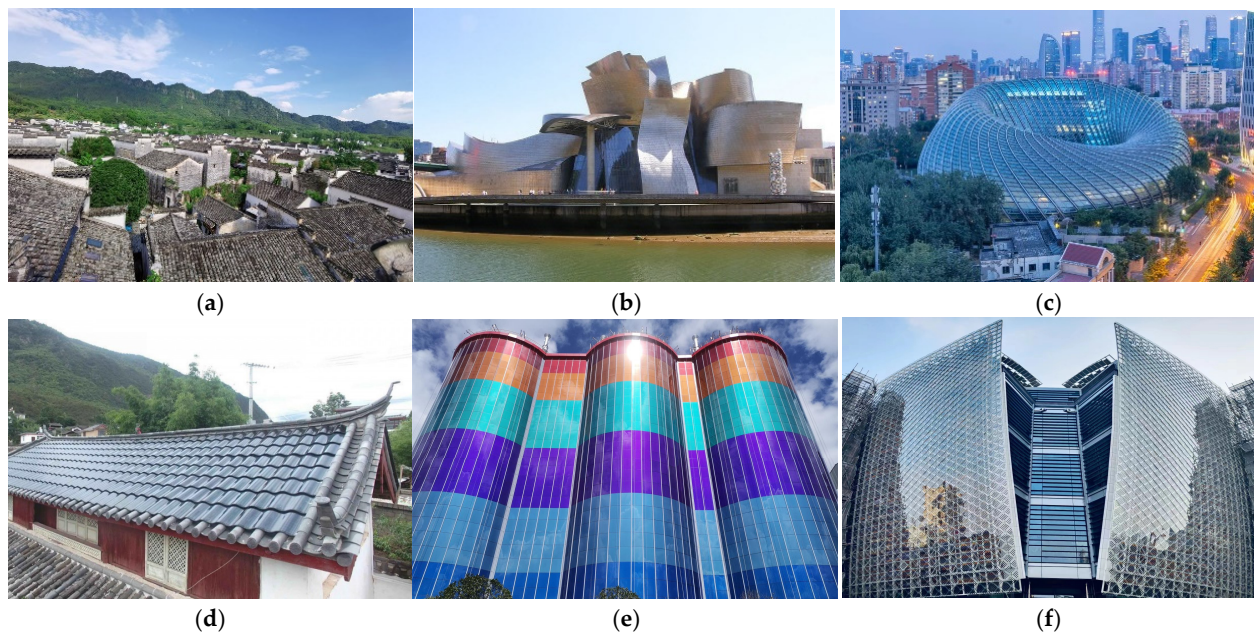


Figure 1. Photos of buildings with and without curved PV modules. (a) Huizhou traditional residents; (b) Guggenheim Museum [11]; (c) Phoenix International Media Center; (d) Han CIGS PV roof tile; (e) CdTe PV glass curtain wall; (f) CdTe semi-transparent PV facade.

Within this context, curved building envelopes have attracted growing research attention. The existing literature on curved photovoltaics can be broadly grouped into three complementary streams, summarised below.

The first stream estimates shading and mismatch losses on geometrically complex envelopes, typically by treating each PV unit as a planar module or as a black-box performance curve. Lance et al. [12] compared planar, sinusoidal, and elliptical PV surfaces and reported that for the same 2-D projection area, a curved surface can capture up to 50% more irradiance while introducing multi-peak power curves over a day. Zhao et al. [13] coupled ray tracing with electrical modelling to estimate system-level shading and mismatch losses on bifacial trackers. Al-Janahi et al. [14] used a genetic algorithm to optimise string configuration and module count on a complex c-Si BIPV roof under partial shading. Walker et al. [15] developed a high-resolution parametric BIPV workflow and showed that for a curved CIGS module, a longitudinal string orientation outperforms an orthogonal one by 5–8%. More recently, Zhang et al. [16] developed a holistic view-factor model for densely-packed bifacial curved photovoltaic arrays and reported that increasing the central angle from a planar baseline to 110° raised the bifacial gain by 27.71%, but introduced a 1.77% net energy penalty due to noon-time mutual shading among neighbouring curved units, illustrating the non-trivial coupling between curvature and array-level mismatch. Xiang et al. [17] developed an endogenous adaptive slime-mould algorithm for curved photovoltaic systems under dynamic self-shading. It improved global maximum power point tracking for multi-peak P–V curves induced by curvature-driven non-uniform illumination but focused on power recovery rather than the geometric origin of this behaviour. These studies are useful for predicting building-scale energy yield, but they treat PV units as black boxes and leave the cell-level geometric source of mismatch loss unresolved.

The second stream concerns curved CIGS modules and curved PV/T systems for building envelopes, where flexible thin-film cells are favoured for their light weight, high specific power, and competitive critical-material profile. Wang et al. proposed a flexible CIGS-based curved PV/T roof for traditional Chinese buildings, achieving 14.71% electrical and 56.79% thermal efficiencies at 0.9 L/min. Tian et al. extended this work to multifunctional and multi-channel curved CIGS PV/T roofs for combined space heating and electricity generation. Gong et al. [8] simulated an arc-shaped CIGS PV window with EnergyPlus and Radiance and identified a 120° central angle as the energy optimum. Cai et al. [10] studied 2-D and 3-D curved flexible Si-PV modules and demonstrated that an appropriate cell-interconnection scheme can reduce mismatch losses to recover up to 1721.21 Wh and 1604.10 Wh of additional energy, respectively. Bugaj et al. [18] developed a testing methodology for a semi-flexible c-Si PV/T collector and reported that at a 30° deflection, the thermal and electrical powers fall by approximately 18% and 14% relative to a flat reference. Tian et al. developed a 1200 × 1800 mm curved semi-transparent photovoltaic roof prototype using 24 flexible thin-film PV modules and monitored it outdoors for three months under coupled urban airflow and variable solar irradiance. The reported surface-temperature and wind-speed uniformity coefficients of 0.43–0.76 indicate clear non-uniformity at the module-array scale. These studies provide useful system-level data for curved CIGS and flexible-PV(T) components, but they do not isolate the cell-level mismatch behind module-level losses.

The third stream addresses the mechanical and electro-optical effects of bending on flexible cells, typically at small bending radii. Liu et al. [19] developed a foldable monocrystalline-silicon cell capable of 360° bending by modifying its internal structure. Pei et al. [20] showed that concave bending preserves the photovoltaic performance of flexible perovskite cells better than convex bending because convex bending increases the series resistance. Yun et al. [21] proposed a honeycomb-structured 3-D Si PV module supported by mechanical metamaterials, harnessing additional reflected and scattered photons to deliver a 28% improvement over a flat reference. Deepika et al. [22] reported that a silica sub-wavelength array embedded on a flexible perovskite substrate increased

the photocurrent by 7.30% under downward bending and 1.90% under upward bending at a 60° central angle. Kashyap et al. [23] examined convex, concave, and sinusoidal bending of flexible perovskite cells across bending radii of 5–20 mm and amplitudes of 0.5–2 mm and reported that the flat configuration retains superior PV parameters. Tian et al. characterised the photoelectric response of flexible CIGS cells under non-uniform illumination at the cell scale. These studies clarify the mechanical reliability and electro-optical response of flexible cells at small bending radii but not the geometric mismatch that occurs at architectural central angles up to 180°. Moruno et al. [24] provided related evidence from high-curvature cylindrical PV modules under diffuse irradiance, where step-like I–V curves were observed and the segment-wise short-circuit current correlated linearly with the local sky-view factor. This suggests that the non-monotonic electrical response is mainly caused by circumferentially non-uniform light reception rather than thermal or mechanical effects.

Overall, the reviewed studies have not isolated how length bending and width bending, or convex and concave configurations, redistribute irradiance within a single flexible CIGS cell and produce mismatch loss under controlled conditions. Our previous work [25] focused on module-scale outdoor performance and self-shading rather than this cell-level mechanism.

2. Methodology

This section presents the experimental and modelling framework to evaluating cell-level geometric photoelectric mismatch in flexible CIGS cells under controlled conditions, covering the testing objective and orientation conventions (Section 2.1), the cell structure and sample fabrication (Section 2.2), the indoor test platform and testing matrix (Section 2.3), the performance evaluation metrics (Section 2.4), the uncertainty and repeatability protocols (Section 2.5), and the 2-D microfacet optical model used to explain the geometric-optical origin of the measured mismatch (Section 2.6).

2.1. Testing Objective and Orientation Conventions

The indoor tests were conducted under standard test conditions (STCs) to isolate the photoelectric mismatch induced by bending geometry in flexible CIGS cells. By testing bare cells under controlled spectrum and temperature, the analysis avoids module- or system-level effects such as encapsulation losses, string-level current limitation, bypass-diode partitioning, and outdoor thermal or spectral variations. The results provide a cell-level basis for interpreting the outdoor module-scale behaviour reported in Ref. [26].

As bending changes the local incident angle along the cell surface, it produces non-uniform irradiance and uneven photocurrent generation. This can modify the I–V characteristics, reduce the fill factor, and increase mismatch-related power loss. This study therefore compares representative bending configurations across different central angles to clarify the effects of bending direction, curvature magnitude, and surface morphology on cell-level electrical performance.

As shown in Figure 2, two orientation conventions are used in this study. For bending configuration, length bending (lg) means that the curvature axis is parallel to the short edge and the cell bends along its long dimension, whereas width bending (wd) means that the curvature axis is parallel to the long edge and the cell bends along its short dimension. Convex (vx) denotes bending away from the light source, and concave (cv) denotes bending toward it. The four curved cases are labelled lgvx, lgcx, wdvx, and wdcv; the flat and length-wavy cases are labelled flt and wy, respectively. For laboratory orientation, LT denotes that the cell's long edge is aligned with the vertical axis of the tilted mount, while HZ denotes alignment with the horizontal axis. The LT/HZ convention is used throughout the manuscript.

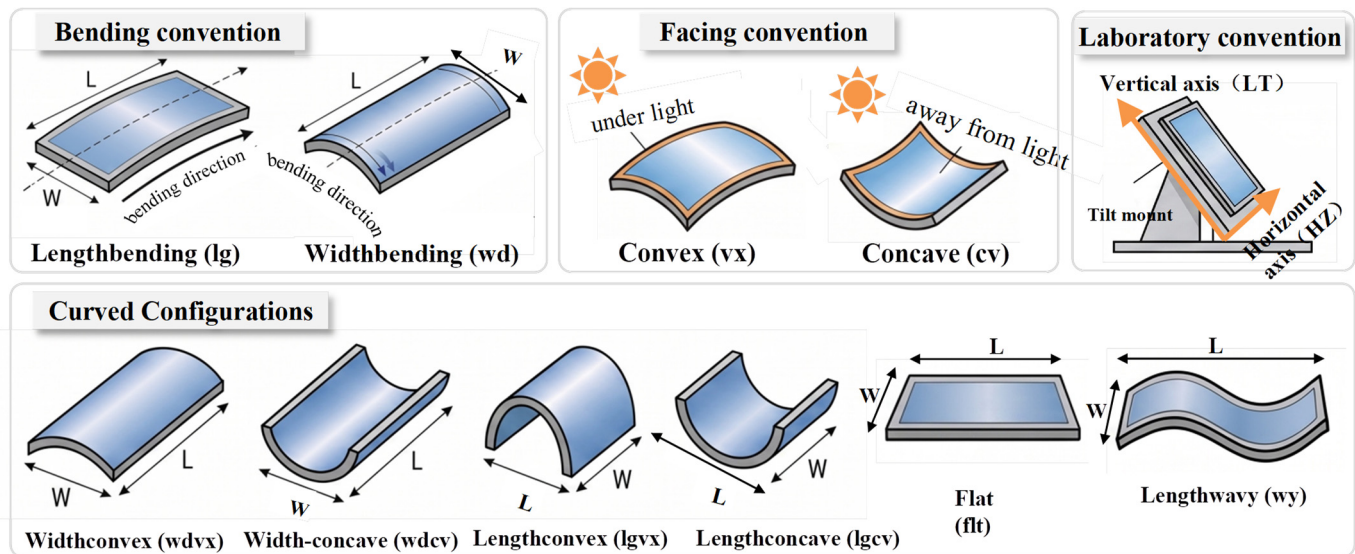


Figure 2. The bending configurations.

2.2. Internal Structure and Sample Fabrication

2.2.1. Internal Structure of the Flexible CIGS Cell

The flexible CIGS cell consists of a monolithically interconnected thin-film stack deposited on a stainless-steel foil substrate, which provides the mechanical flexibility required for the small bending radii used in the central-angle tests. Each cell has a standard dimension of 45 mm × 105 mm × 0.02 mm (thickness). The length-to-width ratio of 2.33 was selected to make the length-bending and width-bending configurations geometrically distinct. As shown in Figure 3, the active stack has a total thickness of approximately 4 μm and comprises multiple functional layers from the substrate side to the front contact. Series interconnection is formed by three laser scribes, P1, P2, and P3. P1 separates the Mo back contact, P2 connects the Mo layer to the front contact, and P3 isolates the AZO front contact. These scribes form the internal current path of the monolithic cell, which remains electrically a single-junction device without any internal bypass element. The orientation of the curvature axis relative to the cell long edge nonetheless influences how the irradiance gradient maps onto the local current generation and is used later to interpret the zigzag pattern in the measured electrical performance through the optical model developed in Section 2.6.

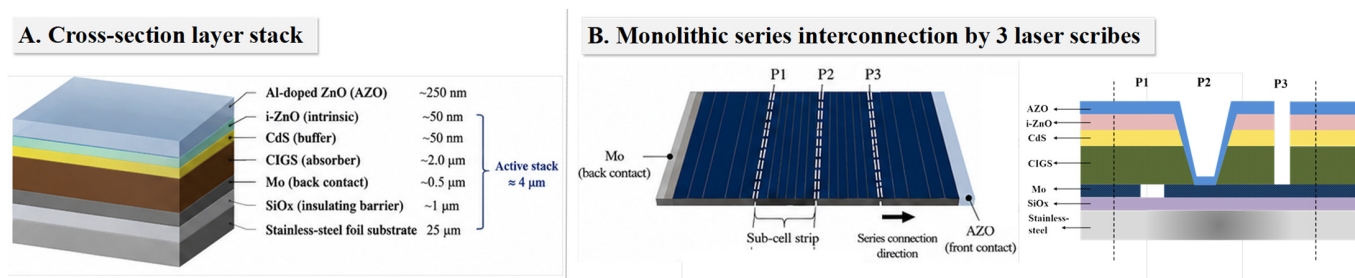


Figure 3. Interior structure of the flexible CIGS cell.

2.2.2. Fabrication of the Curved Samples

Six representative bending forms were prepared to mimic the curvature patterns observed in common curved building envelopes: flat (flt), length convex (lgvx), length concave (lgcv), width convex (wdvx), width concave (wdcv), and length wavy (wy). The geometric supports for each form were designed in Solid Works and printed in polylactic

acid (PLA) using a high-precision fused-deposition modelling 3-D printer. PLA was selected for its thermal stability under the simulator beam, its low cost, and its sufficient dimensional accuracy for the central-angle range tested. The curved baseplate and the matched 30° tilt support of each configuration were printed as a single assembly so that the bending geometry and the global tilt were aligned without an additional fixture.

Each flexible CIGS cell was bonded to its corresponding curved baseplate using thermal silica gel. The gel improved the conformity between the cell and the PLA support, suppressed local air gaps, and provided a reproducible thermal boundary condition. After bonding, all samples were cured in ambient air for 24 h before testing to eliminate any transient curing effect. The complete fabrication workflow is summarised in Figure 4.

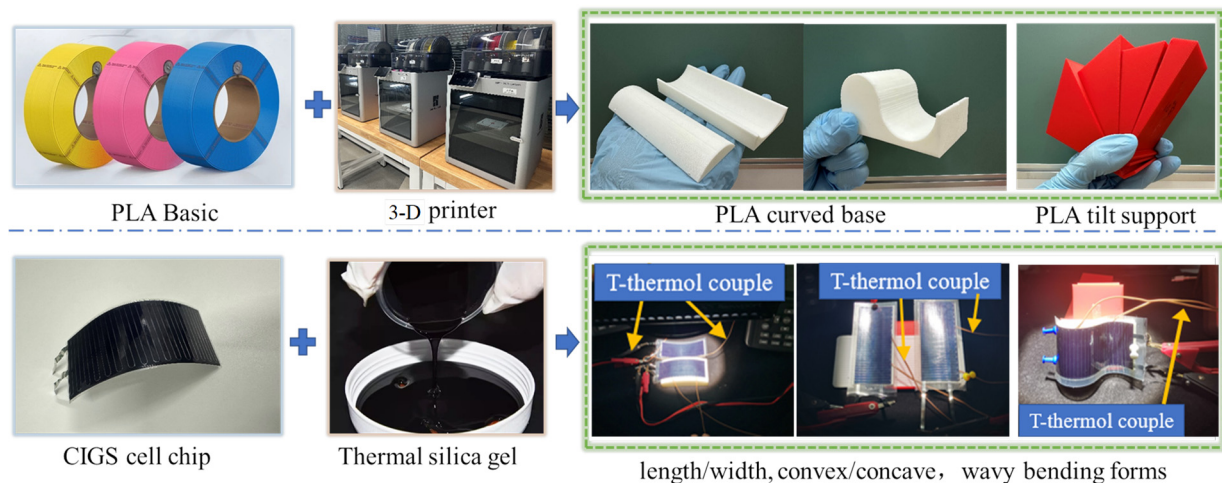


Figure 4. Fabrication workflow of the curved CIGS samples.

2.3. Indoor Experimental Platform and Testing Matrix

The test platform consists of an optical subsystem, a temperature-monitoring subsystem, and an electrical-characterisation subsystem, as schematically shown in Figure 5. The optical subsystem uses an AAA-class solar simulator (Oriel 94063A, Newport, Irvine, CA, USA) equipped with AM 1.5 G filters. The xenon arc lamp is driven by an Oriel 69920 power supply, and the irradiance on the reference plane was calibrated to 1000 W/m² before each group of measurements. The cell temperature was controlled indirectly by maintaining the ambient temperature of the test chamber at 25.00 ± 1.00 °C with air conditioning, and the temperature and relative humidity were continuously monitored using a TH608 thermo-hygrometer. In addition, a calibrated T-type (copper–constantan) thermocouple was attached on the rear side of every CIGS cell with thermally conductive adhesive and recorded continuously by the data-logger throughout each measurement run. The specifications of the measuring apparatus are listed in Table 1.

Table 1. 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%
Temperature	Thermo-hygrometer	TH608	±1.0 °C
Test platform	PVIV test system	Oriel PVIV-10A	I < 0.23%, V ± 0.02%, T ± 0.25 °C
Cell temperature	T-type thermocouple	Copper–constantan	±0.5 °C
Electrical output	Source measuring unit	Keithley 2400	0.012%

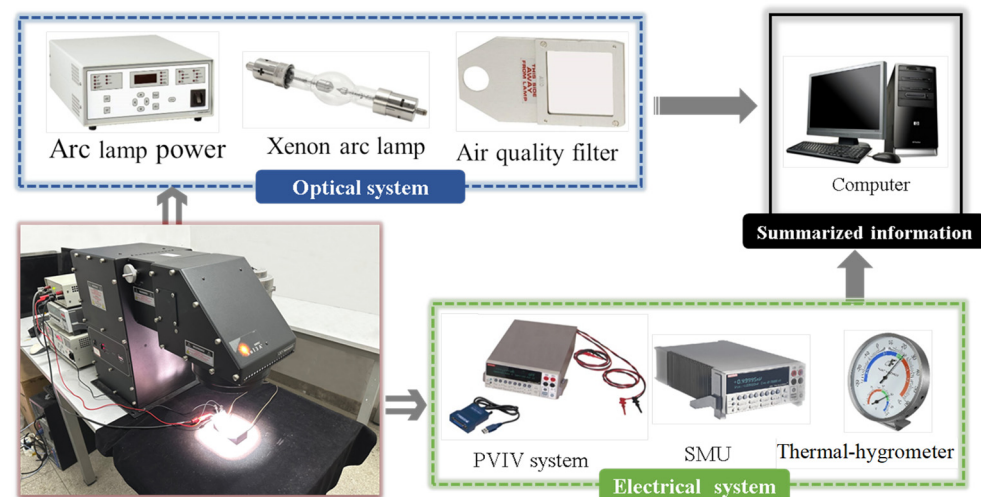


Figure 5. The schematic diagram of the indoor testing.

The electrical characteristics of each cell were measured using an Oriel PVIV-10A photovoltaic test system together with a Keithley 2400 source-measurement unit. For each tested configuration, the current–voltage (I–V) curve was recorded, from which the open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), maximum-power-point voltage (V_{mpp}), maximum-power-point current (I_{mpp}), maximum power output (P_{max}), and fill factor (FF) were obtained. Each I–V scan lasted less than 0.5 s, which was sufficiently short to avoid appreciable transient self-heating during a single electrical measurement. Therefore, under the controlled thermal boundary condition and identical PLA support backplates, the measured differences among the bending configurations mainly reflect the curvature-induced irradiance redistribution rather than temperature-driven performance variation.

The testing matrix included six representative configurations: flat (flt), length convex (lgvx), length concave (lgcv), width convex (wdvx), width concave (wdcv), and length wavy (wy). For the four circular-arc bending configurations, the central angle was varied from 0° to 180° in 30° increments, namely 0° , 30° , 60° , 90° , 120° , 150° , and 180° . The cells were mounted at a fixed tilt angle of 30° to represent a typical inclined BIPV-roof application. For each curved configuration, two laboratory orientations were tested. In the LT orientation, the long edge of the cell was aligned with the vertical axis of the tilted mount; in the HZ orientation, the long edge was aligned with the horizontal axis. This LT/HZ convention is used consistently in all subsequent figures, tables, and discussions.

The central-angle range of 0 – 180° was selected to span the curvature conditions encountered on real building envelopes. A central angle of 0° corresponds to the flat reference; small-to-moderate angles (30 – 90°) represent the gentle convex/concave curvatures typical of barrel-vaulted roofs, arched façades, and the curved eaves of the traditional roofs shown in Figure 1; and 120 – 180° represents the strong curvature of cylindrical canopies, domes, and tubular envelope elements. The limiting case of 180° corresponds to a half-cylinder, the bounding geometry beyond which a single flexible cell can no longer conform to a continuous surface without overlap. A uniform 30° increment was used so that the transition from irradiance concentration to self-shading-dominated behaviour could be resolved without excessive sampling.

To check whether the bending process introduced irreversible degradation, each physical cell was also measured in the flat state before and after the full bending-angle sweep. The pre- and post-test flat-state I–V curves were compared in terms of P_{max} ,

Voc, Isc, and FF. This verification ensured that the observed performance differences were associated with the imposed bending geometry rather than permanent mechanical damage accumulated during testing.

2.4. 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 [27]. The electrical indicators were calculated from the measured I–V curves, while the non-uniformity indicator was derived from the simulated irradiance distribution in the optical model. These metrics provide a comprehensive framework for understanding the mismatch phenomena under various geometric conditions:

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

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

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

where $P_{\max}$ is the instantaneous maximum power output of the PV module (W), G_{pv} is solar irradiation intensity on the corresponding baseplate (W/m^2), and A_{pv} is the orthographic projection area of the curved PV module on the inclined surface area (m^2). Using the projected area rather than the curved surface area enables the cell performance to be compared under the same incident aperture condition, which is consistent with the BIPV roof application scenario considered in this study.

(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 flat PV cells/modules and that of curved counterparts with the same specifications [10]:

$$\Delta P_{ml} = P_{flt} - P_{crv} \quad (2)$$

where P_{flt} is the flat-type PV power output, and P_{crv} is the maximum power output of the corresponding curved cell. A positive ΔP_{ml} indicates a curvature-induced power penalty relative to the flat state.

(3) Performance ratio (PR)

In this study, performance ratio is defined as the ratio of the power output of the curved PV cells/modules and that of curved counterparts with the same specifications, which is given below:

$$PR = \frac{P_{crv}}{P_{flt}} \times 100\% \quad (3)$$

This metric is particularly useful for comparing different bending configurations because it removes the absolute scale of the cell and directly represents the retained electrical performance after bending.

(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:

$$FF = \frac{P_{\max}}{V_{oc}I_{sc}} \quad (4)$$

where V_{oc} is the open-circuit voltage (V), and I_{sc} is the short-circuit current (A). Under non-uniform illumination, FF is sensitive to current mismatch among series-connected sub-cell strips. Therefore, a reduction in FF provides additional evidence of mismatch-induced degradation, rather than merely a reduction in total received irradiance.

(5) Non-uniformity index (NUI)

To link the measured electrical response with the simulated irradiance field, a non-uniformity index is introduced:

$$NUI = \frac{\sigma(G_{strip})}{\bar{G}_{strip}} \times 100\% \quad (5)$$

where G_{strip} is the vector of irradiance values on the $N = 50$ microfacets that discretise the cell surface in the optical model of Section 2.6, σ denotes the sample standard deviation, and the bar denotes the arithmetic mean over the N microfacets. The coefficient-of-variation form is preferred over the simpler $(\max - \min)/\text{mean}$ ratio because it uses information from all microfacets rather than only the two extremes, and it remains numerically stable across the full central-angle range without exceeding unity for the geometries considered here. NUI is therefore a geometric indicator of the spatial irradiance non-uniformity over the single-junction cell surface; a higher value indicates a larger spread in local photocurrent generation, and the NUI is used to link the optical-model prediction with the measured mismatch loss.

2.5. Uncertainty Analysis and Measurement Repeatability

2.5.1. Uncertainty Analysis

Uncertainty analysis was conducted to evaluate the reliability of the measured electrical and thermal parameters [28]. In this study, the main sources of uncertainty were the irradiance calibration of the solar simulator, temperature monitoring, voltage measurement, current measurement, and source-measurement accuracy. The instrumental accuracies are listed in Table 1.

The type B standard uncertainty of the instruments (denoted as u_B) is calculated by Equation (6), assuming a rectangular probability distribution for the instrument accuracy.

$$u_B = \frac{a_n}{\sqrt{3}} \quad (6)$$

where a_n is the nominal accuracy of the corresponding instrument provided by the manufacturer.

For a calculated quantity of $y = f(x_1, x_2, \dots, x_n)$, the combined standard uncertainty (denoted as u_c) was obtained using the root-sum-square propagation method:

$$u_c(y) = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} u(x_i) \right)^2} \quad (7)$$

For the maximum power output, $P_{\max} = VI$, the relative uncertainty can be expressed as:

$$\frac{u_c(P_{\max})}{P_{\max}} = \sqrt{\left(\frac{u(V)}{V} \right)^2 + \left(\frac{u(I)}{I} \right)^2} \quad (8)$$

For the electrical efficiency, the relative uncertainty was calculated as:

$$\frac{u_c(\eta_{pv})}{\eta_{pv}} = \sqrt{\left(\frac{u(P_{\max})}{P_{\max}} \right)^2 + \left(\frac{u(G_{pv})}{G_{pv}} \right)^2 + \left(\frac{u(A_{pv})}{A_{pv}} \right)^2} \quad (9)$$

where the projected-area uncertainty, $u(A_{pv})$, arises from the manufacturing tolerance of the 3-D-printed support and the geometric calculation of the projected cell area. Because the same cell size, same support material, and same mounting procedure were used for all configurations, the uncertainty associated with A_{pv} mainly affects the absolute efficiency value, while the relative comparison among bending configurations is less sensitive to this term.

For the performance ratio, PR, the relative uncertainty was calculated as:

$$\frac{u_c(PR)}{PR} = \sqrt{\left(\frac{u(P_{crv})}{P_{crv}}\right)^2 + \left(\frac{u(P_{flt})}{P_{flt}}\right)^2} \quad (10)$$

For the mismatch loss, ΔP_{ml} , the combined standard uncertainty was calculated as:

$$u_c(\Delta P_{ml}) = \sqrt{u^2(P_{flt}) + u^2(P_{crv})} \quad (11)$$

The high precision of the PVIV test system and the Keithley 2400 source-measurement unit provides current and voltage accuracies within $\pm 0.23\%$ and $\pm 0.02\%$, respectively. Therefore, the observed ranking of the bending forms is considered reliable.

2.5.2. Sample Consistency and Measurement Repeatability

A one-cell-per-condition protocol was adopted to eliminate any cumulative bending damage from the dataset by experimental design. The full test matrix comprises 48 combinations of bending configuration $\times$ central angle $\times$ laboratory orientation, and each combination was tested on a separate flexible CIGS cell. All tested cells came from the same production batch and the same deposition run to minimise inter-sample variability, and no single cell was reused across configurations or central angles; the results are therefore unaffected by degradation accumulated through repeated bending.

Before bonding to the curved supports, the cells were screened for flat-state comparability. Each cell was measured on the Oriel PVIV-10A system using ten repeated I–V scans, and samples with P_{max} deviating by more than 3% from the batch mean were excluded. Among the retained cells, Welch's one-way ANOVA [29] showed no significant differences in P_{max} , V_{oc} , I_{sc} , or FF at $\alpha = 0.05$ ($p > 0.10$), and the inter-cell variation coefficient of P_{max} was below 2%. These results indicate that the retained cells had comparable flat-state performance, so later differences among configurations can be mainly attributed to the imposed bending geometry. The statistics are summarised in Table 2.

Using the temperature-monitoring arrangement described in Section 2.3, each I–V scan (< 0.5 s) was started only after the rear-side cell temperature had stabilised within ± 1 °C of 25 °C. Since all configurations shared the same substrate, silicone-gel bonding, PLA support, and thermocouple arrangement, the measured differences are mainly attributed to curvature-induced irradiance redistribution rather than thermal variation.

Each curved sample was further re-measured under identical STCs on three separate days. The coefficient of variation of P_{max} remained below 2% at every central angle, confirming that the thermal-silica-gel bonding, the back-side thermocouple instrumentation, and the test platform did not introduce measurable drift over the test period. The zigzag-like trend reported in Section 3 is therefore considered reproducible rather than a measurement artefact.

Table 2. Repeatability and consistency of Pmax under different bending configurations.

Configuration	Pre-Test Pmax (Mean $\pm$ SD, mW)	Pre-Test FF (Mean $\pm$ SD)	Welch's ANOVA <i>p</i> -Value ¹	Repeat-Measurement CV of P _{max} ² (%)
flt (reference)	564.7 $\pm$ 4.2	0.582 $\pm$ 0.004	-	1.3
lgvx	562.8 $\pm$ 5.1	0.579 $\pm$ 0.005	0.18	1.6
lgcv	561.5 $\pm$ 4.8	0.578 $\pm$ 0.006	0.24	1.8
wdvx	563.9 $\pm$ 4.5	0.581 $\pm$ 0.004	0.31	1.4
wdcv	564.1 $\pm$ 4.0	0.580 $\pm$ 0.005	0.42	1.5
wy	562.2 $\pm$ 5.3	0.577 $\pm$ 0.006	0.15	1.9

Note: ¹ Welch's one-way ANOVA was applied across all cells in the flat state at $\alpha = 0.05$ to test the null hypothesis of equal means. ² The repeat-measurement CV was averaged across the seven tested central angles (0°, 30°, 60°, 90°, 120°, 150°, and 180°). Both LT and HZ orientations are included for the four curved configurations.

2.6. Two-Dimensional Microfacet Optical Model

A 2-D microfacet optical model was established to quantify the irradiance non-uniformity responsible for the curvature-induced mismatch. In the model, each curved CIGS cell was divided into discrete surface elements along the bending direction. The direct-beam irradiance received by each element under the solar simulator was first calculated, after which the single-bounce reflected exchange between opposing bent arms was added. The geometric output was then linked to the experimental performance ratio through a two-parameter calibration that accounts for the finite shunt resistance and the AZO sheet resistance of flexible CIGS cells; the calibrated form is given in Section 2.6.5. The resulting framework was used to identify the main geometric-optical contribution to the measured mismatch, rather than to reproduce the full optical field with ray-tracing-level detail.

The model was derived from the microfacet formulation previously used in our outdoor module-level analysis but was modified for the indoor STC measurements. Since the AAA-class simulator provides neither sky-diffuse nor ground-reflected radiation, these two terms were excluded. The inter-facet view-factor term was retained, however, because it accounts for mutual reflection between facing surfaces, which is particularly relevant for concave bending under a near-collimated incident beam.

2.6.1. Geometric Discretisation

As illustrated in Figure 6, the curved CIGS cell was divided into N microfacets along the bending direction. Each microfacet was assigned the same arc length; therefore, the angular span of one microfacet was expressed as $\Delta\theta = \theta_c/N$, where θ_c denotes the total central angle of the cell. In the length-bending configurations (lgvx and lgcv), the curvature axis was parallel to the short edge of the cell and the microfacets were distributed along the 105 mm length direction. In the width-bending configurations (wdvx and wdcv), the curvature axis was parallel to the long edge, and the discretisation was performed along the 45 mm width direction. The flat reference was simplified as a single planar microfacet, with its surface normal vector aligned with the global z -axis. The length-wavy configuration (wy) was treated as two adjacent half-arcs of opposite curvature, each subdivided into $N/2$ microfacets following the same rule.

Independence tests were carried out at $\theta_c = 90^\circ$ by varying N from 6 to 80. The simulated CV- NUI defined in Equation (5) varied by less than 2.3 percentage points across this range, and the calibrated PR_{sim} model of Section 2.6.5 produced fitted parameters (α , β) that varied by less than 0.04 and 0.01, respectively, between $N = 6$ and $N = 80$. Because the view-factor matrix scales as $O(N^2)$, $N = 50$ was adopted in all simulations as a balance between numerical convergence and computational efficiency. The microfacet grid is a

numerical discretisation of continuous cell surface; it does not correspond to any physical subdivision of the monolithic single-junction CIGS cell.

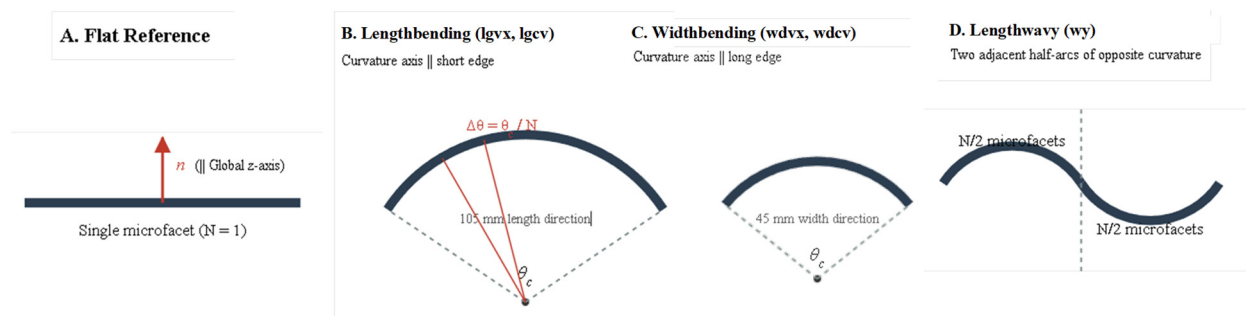


Figure 6. Discretisation of curved CIGS cell into N microfacets.

The position vector of the i microfacet centre and its outward normal vector were computed from the arc geometry. For a circular-arc bending with central angle θ_c and chord length L_0 (105 mm for length bending and 45 mm for width bending), the bending radius is

$$R = \frac{L_0}{2 \sin(\frac{\theta_c}{2})} \quad (12)$$

The angular position of microfacet i , measured from the cell symmetry plane, is

$$\varphi_i = -\frac{\theta_c}{2} + (i - \frac{1}{2}) \cdot \Delta\theta, i = 1, 2, \dots, N \quad (13)$$

The local tilt angle of microfacet i relative to the chord baseplate is $\beta_i = |\varphi_i|$ for convex bending and $\beta_i = -|\varphi_i|$ for concave bending. The whole baseplate was then rotated by the global tilt angle $\beta_0 = 30^\circ$ to reproduce the inclined BIPV-roof condition used in the experiments.

2.6.2. Direct-Beam Irradiance on Each Microfacet

For the AAA-class solar simulator, the xenon-arc beam was assumed to have a fixed incident direction, denoted by S , which was perpendicular to the calibration reference plane. The normal-incidence irradiance was calibrated to $G_0 = 1000 \text{ W/m}^2$ before each measurement set. Accordingly, the direct irradiance incident on microfacet i was calculated as:

$$G_{bm,i} = G_0 \cdot \cos \theta_i \cdot (1 - SR_i) \quad (14)$$

where θ_i is the local incident angle between S and the outward normal n_i , and SR_i is the self-shading ratio of microfacet i due to the curvature of the cell. The local incident angle is computed from:

$$\cos \theta_i = \max \left[0, -\frac{S \cdot n_i}{|n_i|} \right] \quad (15)$$

The self-shading ratio, SR_i , represents the fraction of microfacet i that is occluded by other microfacets within the same cell. Following the projection procedure used in our prior outdoor model, the four corner vertices of every other microfacet j ($j \neq i$) were projected along S onto the plane of microfacet i . The projected quadrilaterals were merged to form the potential shadow footprint. Its intersection with the area of microfacet i was then used to determine the shaded fraction:

$$SR_i = \frac{A_{sh,i}}{A_i} \times 100\% \quad (16)$$

where A_i is the area of microfacet i , and $A_{sh,i}$ is the shaded portion. For convex bending forms, $SR_i = 0$ for all microfacets because each microfacet's outward normal points away from the inside of the arc. For concave configurations, $SR_i > 0$ occurs on the arm opposite to the incident beam when part of the beam-facing arm intercepts the incoming light path. This geometrical occlusion is the origin of the self-shading effect discussed in Section 3.1.

2.6.3. Mutual Reflection Between Opposing Arms

For concave configurations, the two opposing arms of the bend see each other. Part of the beam reflected from one illuminated arm reaches the opposite arm and contributes an additional irradiance term that cannot be captured by Equation (14) alone. This term is the optical source of the mutual reflection mechanism referred to when comparing wdcv with wdvx. The CIGS cell surface is treated as a diffuse Lambertian reflector with hemispherical reflectance ρ_{pv} . Based on the manufacturer data and absorptivity used in our previous thermal model [25], ρ_{pv} was taken as 0.10. This value represents the residual reflectance after the anti-reflective layer and the AZO front contact have absorbed most of the incident energy.

The reflected irradiance on microfacet i is the sum of the contributions from every other microfacet j that has a non-zero view factor to i and that itself receives a direct beam:

$$G_{ref,i} = \rho_{eff} \sum_{j \neq i} F_{j \rightarrow i} \cdot G_{dir,j} \cdot \frac{A_j}{A_i} \quad (17)$$

where $F_{j \rightarrow i}$ is the view factor from microfacet j to microfacet i . Because the cell is much longer in the non-curvature direction than along the curvature direction, the geometry is approximated as 2-D with infinitely long parallel generatrices. Under this assumption, the view factor between two infinite strips of finite width is evaluated by Hottel's crossed-string method:

$$F_{j \rightarrow i} = \frac{(d_{ac} + d_{bd}) - (d_{ad} + d_{bc})}{2L_j} \quad (18)$$

where a, b are the two end edges of microfacet j ; c, d are the two end edges of microfacet i ; d_{xy} denotes the straight-line distance between two edges; L_j is the width of microfacet j along the curvature direction. Microfacet pairs for which the line of sight is geometrically blocked by an intermediate microfacet were assigned $F_{j \rightarrow i} = 0$, so that only directly visible pairs contribute to Equation (17). Only the first reflection bounce was retained because $\rho_{pv} = 0.10$ keeps any second-order contribution below $0.01 G_0$, which is well below the experimental uncertainty.

For convex bending forms, every microfacet faces outwards, and no two microfacets share a line of sight, so $F_{j \rightarrow i} = 0$ for all $j \neq i$ and $G_{ref,i} = 0$. For concave bending forms, the view factors increase with the central angle θ_c and approach their maximum near the closed-cylinder limit $\theta_c \rightarrow 180^\circ$, which explains why the mutual-reflection benefit becomes detectable only at large central angles in the width-concave configuration.

2.6.4. Total Irradiance and the Non-Uniformity Output

The total irradiance received by microfacet i is the sum of its direct beam and its reflected contributions:

$$G_i = G_{bm,i} + G_{ref,i} \quad (19)$$

The mean irradiance over the whole cell is:

$$\bar{G} = \frac{1}{N} \cdot \sum_{i=1}^N G_i \quad (20)$$

The NUI defined in Equation (5) is calculated directly from the simulated irradiance distribution. The same distribution is used as the model output in Section 3.1 to generate the 2-D irradiance heatmap and the microfacet-level irradiance profile along the curvature direction. Because the CIGS cell is a single-junction monolithic device with no internal bypass path, local irradiance deficits bias the cell short-circuit current toward the minimum-irradiance region of the surface, $G_{min} = \min(G_i)$. The simulated performance ratio PR_{sim} used to validate the model against the experimental PR in Section 3.1 is constructed by combining G_{min} and $\bar{G}$ through two physical correction terms calibrated against the indoor measurements; the full form is given in Equation (21) and is derived in Section 2.6.5.

The simulation workflow is summarised in Figure 7. The inputs are the bending configuration (flt, lgvx, lgcx, wdvx, wdcx, or wy), the central angle θ_c , the global tilt $\beta_0 = 30^\circ$, the reference irradiance $G_0 = 1000 \text{ W/m}^2$, and the cell reflectance ρ_{pv} . The outputs are the microfacet irradiance distribution [30], the mean irradiance $\bar{G}$, the minimum irradiance G_{min} , and the non-uniformity index NUI . The workflow was implemented in MATLAB R2023b. Each simulation case required less than two seconds on a standard desktop computer, which was sufficient for the parametric sweep covering seven central angles and six configurations.

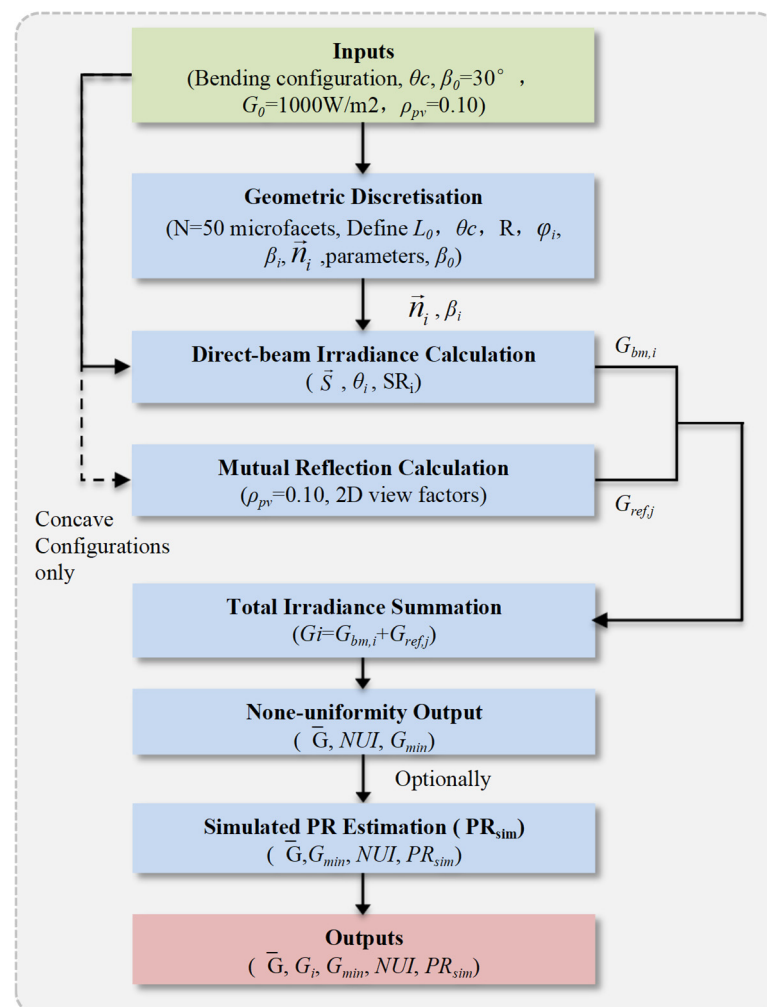


Figure 7. Workflow of the 2-D microfacet optical model.

2.6.5. Calibration of the Model Against the Indoor Measurements

The parameter-free form of the optical model gives the area-averaged sub-cell irradiance $\bar{G}$ and the minimum irradiance G_{min} but does not by itself yield a quantitative

performance ratio that can be compared with the experimental PR . Two candidate mechanisms not captured by the bare geometric model may affect the conversion from G_i to PR : the finite shunt resistance of monolithic single-junction CIGS cells, which determines how strongly local irradiance deficits bias the cell short-circuit current away from the area-averaged value, and a possible additional electrode-path loss along the short axis of width-bent cells, associated with the finite AZO sheet resistance reported for the same cell family ($\approx 25 \Omega/\text{sq}$). Both effects are introduced as physical correction parameters in the simulated performance ratio, and their magnitudes are then determined from the data:

$$PR_{sim} = \left[\alpha \cdot \frac{G_{min}}{G_{flt}} + (1 - \alpha) \cdot \frac{\bar{G}}{G_{flt}} \right] \cdot \left[1 - \beta \cdot 1_{wd} \cdot \sin\left(\frac{\theta_c}{2}\right)^2 \right] \quad (21)$$

where α is the local-deficit weighting fraction ($0 \leq \alpha \leq 1$) that controls how strongly the least-illuminated microfacet biases the predicted PR . $\alpha = 1$ corresponds to a pessimistic limit in which the minimum-irradiance microfacet sets the cell short-circuit current (the strict-series-string limit with no bypass); $\alpha = 0$ corresponds to the area-averaged limit in which the cell behaves as a uniformly illuminated diode with photocurrent proportional to the mean irradiance. For a real single-junction CIGS cell under non-uniform illumination, the cell's I-V response lies between these two limits, and α measures how much the local irradiance deficit biases the cell I-V curve away from the area-averaged case. β is the lateral-resistance coefficient ($0 \leq \beta \leq 0.5$) that penalises width-bending configurations only; 1_{wd} is unity for width bending (w_{dvx} and w_{dcv}) and zero for length bending (l_{gvx} and l_{gcv}); and $G_{flat} = G_0 \cdot \cos \beta_0 = 866 \text{ W/m}^2$ is the irradiance on the inclined flat reference baseplate.

2.6.6. Model Assumptions and Limitations

The model uses four simplifying assumptions. First, the xenon arc beam is approximated as collimated. The AAA-class simulator has a half-angle divergence of approximately $\pm 2^\circ$, which may slightly smooth the transition between illuminated and self-shaded microfacets, but has little influence on the relative ranking of the tested configurations. Second, the CIGS surface is represented as a Lambertian diffuse reflector with a uniform reflectance of $\rho_{pv} = 0.10$. Specular reflection at large incident angles and the spectral variation of ρ_{pv} are not treated separately because the AM1.5G spectrum was fixed during the indoor tests. Third, only first-bounce reflection is considered; higher-order reflections contributed less than $0.01G_0$ in the present geometries and were neglected.

Fourth, the cell is modelled as a single monolithic device, without explicitly resolving the P1–P2–P3 scribed sub-cell boundaries. The microfacet discretisation with $N = 50$ is used only for numerical integration and does not represent physical sub-cell segmentation. Explicit module-level partitioning, including substring boundaries and bypass diodes, is discussed separately in Section 4.

3. Results and Discussion

This section presents the indoor experimental results alongside the supporting model predictions. The simulated irradiance distributions first establish the non-uniformity hierarchy among the bending configurations, which is then used to interpret the measured electrical indicators and the zigzag pattern that emerges as the central angle increases from 0° to 180° .

3.1. Simulated Irradiance Distribution and Non-Uniformity Analysis

The irradiance distributions predicted by the optical model in Section 2.6 are first examined to clarify the geometric basis of the measured mismatch loss. Figure 8 shows

the 2-D irradiance maps for the six configurations at a representative central angle of 90° . The flat reference has a uniform irradiance of 866 W/m^2 , equal to $G_0 \cdot \cos 30^\circ$. For the width-bending cases (wdvx and wdcv), the irradiance gradient is mainly confined to the 45 mm width direction, resulting in moderate non-uniformity. In contrast, the length-bending cases (lgvx and lgcv) show a stronger gradient along the 105 mm length direction, with irradiance varying from about 340 W/m^2 to about 1000 W/m^2 . The length-wavy case produces the most uneven pattern, with alternating illuminated and nearly shadowed zones on the convex and concave half-arcs. The dark regions at both ends and near the inflection point correspond to locations where the local surface normal is nearly perpendicular to the incident beam, so that $\cos \theta_i \approx 0$.

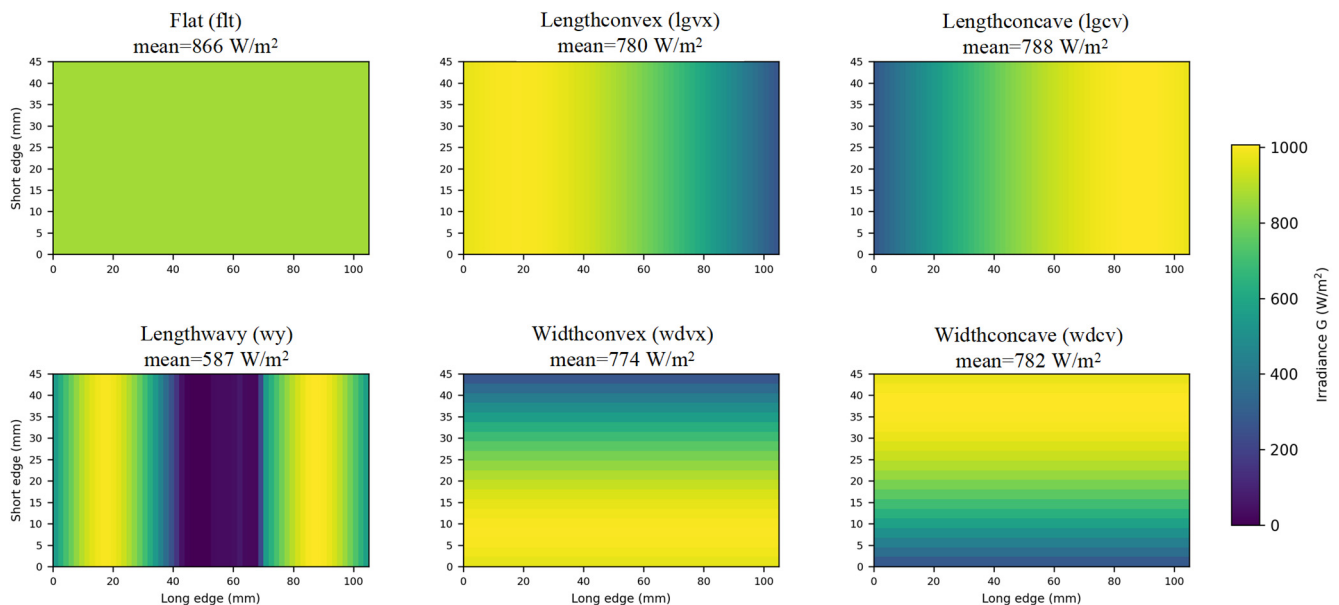


Figure 8. Simulated 2-D irradiance distribution over the cell surface at $\theta_c = 90^\circ$ under STCs.

Figure 9a compares the microfacet-level irradiance profiles of the three length-bending configurations at a central angle of 90° along the cell long axis. For the lgvx form, the irradiance increases monotonically from the windward end to the leeward end of the arc, with a maximum spread of $\Delta G_{max} = 658 \text{ W/m}^2$ and a mean irradiance of 780 W/m^2 . The lgcv form shows the reverse gradient with a similar spread of $\Delta G_{max} = 653 \text{ W/m}^2$ and a mean of 788 W/m^2 . As noted in Section 2.6.4, such deficits along the long axis bias the short-circuit current of the whole cell. This current-limiting effect is represented by the calibration parameter α introduced in Section 2.6.5. The length-wavy configuration shows the strongest non-uniformity, with the mean irradiance decreasing to 687 W/m^2 due to severe shading of the concave half-arc and ΔG_{max} increasing to 1006 W/m^2 .

The width-bending configurations show a different type of irradiance non-uniformity. Since bending occurs along the 45 mm short axis, the cell long axis is perpendicular to the curvature direction. As a result, current collection along the cell tends to average the irradiance variation across the short axis. For this reason, the CV-NUI defined in Equation (5) remains close to zero for both width-bending configurations over the full central-angle range. Within this group, wdvx and wdcv have the same projected area under the perpendicular beam, so their direct-illumination components are identical at moderate central angles. The remaining difference is associated with two competing effects that occur only in the concave case. Inter-arm mutual reflection increases the received irradiance as the two arms approach each other at larger θ_c , whereas self-shading reduces

it once the arc becomes sufficiently closed for one lateral arm to shade the other under near-vertical illumination.

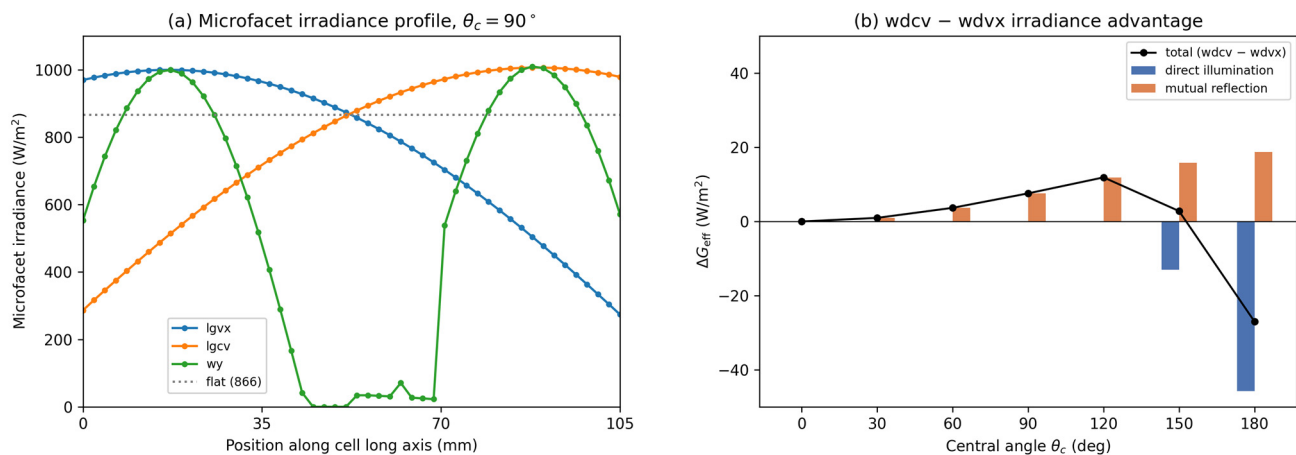


Figure 9. Microfacet-level irradiance profiles produced by the 2-D optical model.

Figure 9b decomposes the mean-irradiance difference between wdcv and wdvx into direct-illumination and mutual-reflection terms. For $\theta_c \leq 120^\circ$, the direct term is zero, and the small wdcv advantage, reaching 12 W/m^2 at 120° , is entirely due to mutual reflection. Beyond approximately 135° , self-shading appears between the lateral arms of wdcv, causing the direct term to become negative: -12 W/m^2 at 150° and -43 W/m^2 at 180° . Although mutual reflection continues to increase and reaches $+19 \text{ W/m}^2$ at 180° , it cannot offset the larger self-shading penalty. The net wdcv–wdvx difference therefore reverses near 135° and decreases to -24 W/m^2 at 180° . In short, wdcv benefits from mutual reflection at intermediate angles but becomes disadvantaged at large angles when self-shading dominates.

Figure 10a plots the CV-NUI against central angle for all configurations. The width-bending cases remain close to zero throughout the angular range because their irradiance gradient lies mainly along the short axis and is therefore averaged across the current-collection path. By contrast, the length-bending cases show a strong increase with central angle, reaching 70.1% for lgcv and 61.4% for lgvx at 180° . The length-wavy case remains at 63.1%, largely independent of θ_c , since its two half-arcs are fixed by the wave amplitude rather than by the swept central angle. The CV-NUI ranking, $\text{lgcv} > \text{wy} > \text{lgvx} > \text{wdcv} \approx \text{wdvx}$, matches the experimental mismatch-loss ranking in Section 3.2. This supports the interpretation that mismatch loss is mainly driven by surface irradiance non-uniformity, especially when the non-uniformity is aligned with the cell long edge and current-collection direction.

Figure 10b compares the simulated performance ratio PR_{sim} with the measured PR for the four single-arc configurations over six bent central angles (30 – 180°), giving 24 paired data points; the four flat references at 0° serve as the normalisation baseline. The two correction parameters in Equation (21), the local-deficit weighting factor α and the lateral-resistance coefficient β , were determined by a global least-squares fit to this dataset. The value of $\alpha \approx 0.15$ indicates that the cell response is much closer to the area-averaged irradiance limit than to the strict series-current limit, consistent with the relatively mixed photocurrent collection expected in a monolithically interconnected single-junction CIGS cell. The value of $\beta \approx 0$ indicates that the present dataset does not resolve a separate width-bending electrode-path loss: within the cell-to-cell scatter, the width-concave cells already perform close to the area-averaged ceiling. The calibration therefore reduces to an effective single parameter (α), with the underperformance of the width-convex cells absorbed through the same local-deficit term.

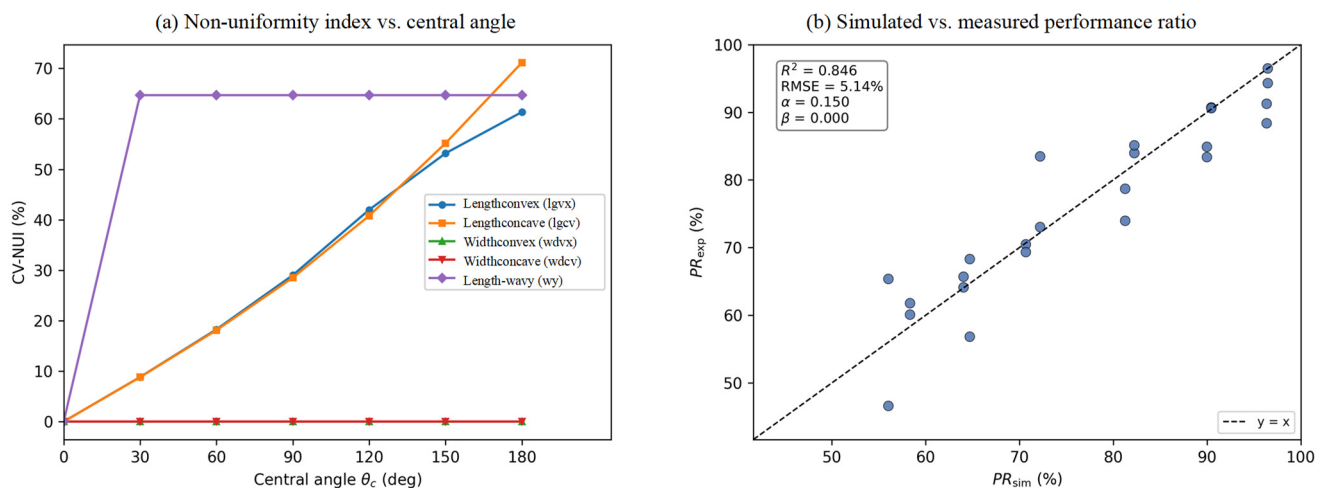


Figure 10. Non-uniformity and model–experiment correlation.

The calibrated model achieves an $R^2 = 0.85$ and an RMSE of 5.1% over the 24 bent-configuration data points ($R^2 = 0.90$ when the four flat references are included). The maximum residual error is about 11%. This discrepancy appears in width-concave configurations at moderate to large central angles, where the measured PR is higher than the model prediction. All bending tests were conducted using individual test cells, so the deviation primarily stems from performance differences between cells. For flexible CIGS devices, such inter-cell variation generally falls within the range of $\pm 10\%$ to $\pm 15\%$, which far outweighs the single-test repeatability of $\pm 2\text{--}3\%$ noted in Section 2.5.2. Accordingly, this model is developed to verify the geometric-optical working principle and capture the overall trend of mismatch loss under different bending states, rather than to achieve high-precision quantitative fitting for individual cells. The remaining scatter also reflects the modelling assumptions listed in Section 2.6.6, together with the fact that the model does not separately distinguish the tension-related underperformance of width-convex cells from the near-ideal behaviour of width-concave cells.

3.2. The Power Output and Mismatch Loss

With the irradiance hierarchy from Section 3.1, the measured electrical performance can be interpreted directly in terms of the geometric origin of the mismatch loss. Figure 11a summarises the P_{max} and FF of every configuration tested in this study. Figure 11b summarises the corresponding mismatch loss and PR . All values are taken at the central angle of 180° to highlight the worst-case behaviour of each configuration; the central-angle dependence is analysed in Section 3.3.

The power output and mismatch loss results demonstrated distinct regularities. As illustrated in Figure 11a,b, the flat-type CIGS PV cell achieved the highest power output of 564.7 mW. 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 ordering follows directly from the CV-NUI hierarchy in Section 3.1: when the curvature axis is parallel to the long edge (wdvx and wdcv), the irradiance gradient develops across the short 45 mm width, and each elementary current-collection path across the cell averages over the full gradient, so that the cell I–V curve remains close to that of the flat reference. When the curvature axis is parallel to the short edge (lgvx and lgcv), the irradiance gradient develops along the 105 mm length over which the current is collected, so that the local irradiance deficit at the leeward end of the cell biases the I_{sc} strongly and FF degrades.

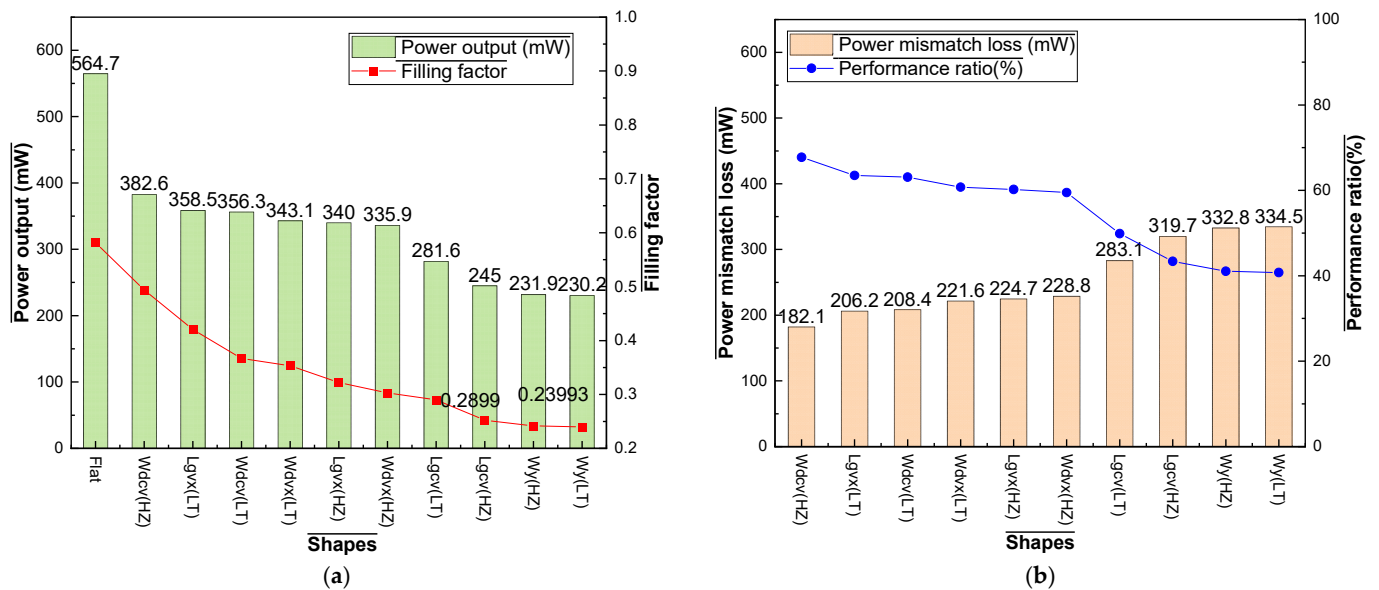


Figure 11. The electrical performance of PV cells under different configurations ($\theta_c = 180^\circ$). (a) Power output and Filling factor; (b) Power mismatch loss and Performance ratio.

Inside the width-bending group, the concave form (wdcv) produced a slightly higher power output than the convex form (wdvx) at moderate central angles, the advantage narrowed sharply beyond $\theta_c \approx 135^\circ$, approaching parity within the measurement uncertainty, in qualitative agreement with the crossover predicted by the model. Mutual reflection between cell segments competes against self-shading effects, and this trade-off, illustrated by the decomposed loss curves of wdcv and wdvx designs in Figure 9b, accounts for the performance trend seen in wdcv modules.

Inside the length-bending group, the ordering is reversed: the convex form (lgvx) outperformed the concave form (lgcv). The lgcv configuration combines a strong surface-irradiance gradient (Figure 9a) with substantial self-shading on its leeward arm, which biases the I_{sc} far below the area-averaged expectation. The lgcv configuration in the HZ orientation produced the worst electrical performance, with $P_{max} = 245$ mW, $FF = 0.252$, $\Delta P_{ml} = 319.7$ mW, and $PR = 43.4\%$, corresponding to a 56.61% power loss. The length-wavy configuration, although geometrically distinct, falls in a similar performance regime because of the severe shadowing of its concave half-arc, consistent with the high CV-NUI reported for this configuration in Section 3.1.

Concave configurations yielded nearly identical performance across both laboratory orientations. Under collimated simulator illumination, LT/HZ reorientation does not alter the curvature-induced irradiance pattern relative to the vertical incident beam. Residual differences ($<3\%$) lie within the combined measurement uncertainty from Section 2.5.1 and thus do not represent a physical orientation effect under indoor STCs. Implications for outdoor deployment, where orientations produce distinct daily irradiance profiles, are addressed in Section 4.

The present cell-level results are quantitatively consistent with the module-level literature while resolving the underlying mechanism. Tian et al. [25] reported that flat CIGS modules outperform curved ones at small inclination, with the gap narrowing as inclination increases; at the cell level, we likewise find that the flat reference yields the highest output (564.7 mW) and that the curvature penalty grows with the central angle. Cai et al. [13] showed that for 2-D curved arrays, the mismatch loss caused by non-uniform irradiance can be partly recovered (up to 1721.21 Wh) by optimised cell interconnection, a strategy that is meaningful only once the cell-level non-uniformity quantified here (CV-NUI

up to 70.1% for lgcv at 180°) is known. Wang et al. [26] found that convex longitudinal modules outperform concave ones outdoors and that concave longitudinal modules suffer the greatest self-shading loss; our indoor data reproduce this ordering ($lgvx > lgcv$ for $\theta_c \geq 135^\circ$) and attribute it directly to the simulated self-shading term (Figure 9). The worst-case 56.6% power loss ($lgcv$ -HZ at 180°) and the 43.4–97.1% PR window reported here therefore provide the cell-scale baseline that underlies these module-scale observations.

3.3. Influence of Central Angle

The central-angle dependence of the four single-arc configurations is examined in this section, with the LT and HZ orientations analysed in parallel. The width-bending and length-bending groups are presented separately because their underlying geometric mechanisms are different.

Figure 12a shows that the power output of width bending decreases almost monotonically as θ_c increases from 0° to 180° because the cell surface gradually moves away from near-normal incidence. In wdvx configurations, longitudinal orientations marginally outperform horizontal orientations, whereas the opposite trend is observed in the wdcv case. Figure 12b shows that the power output of length bending follows the same overall trend but behaves differently at the central angle of 135° . The crossover is explained by the ΔG_{eff} decomposition in Section 3.1: mutual reflection benefits lgcv at low central angles, whereas self-shading becomes dominant beyond about 135° and offsets this gain.

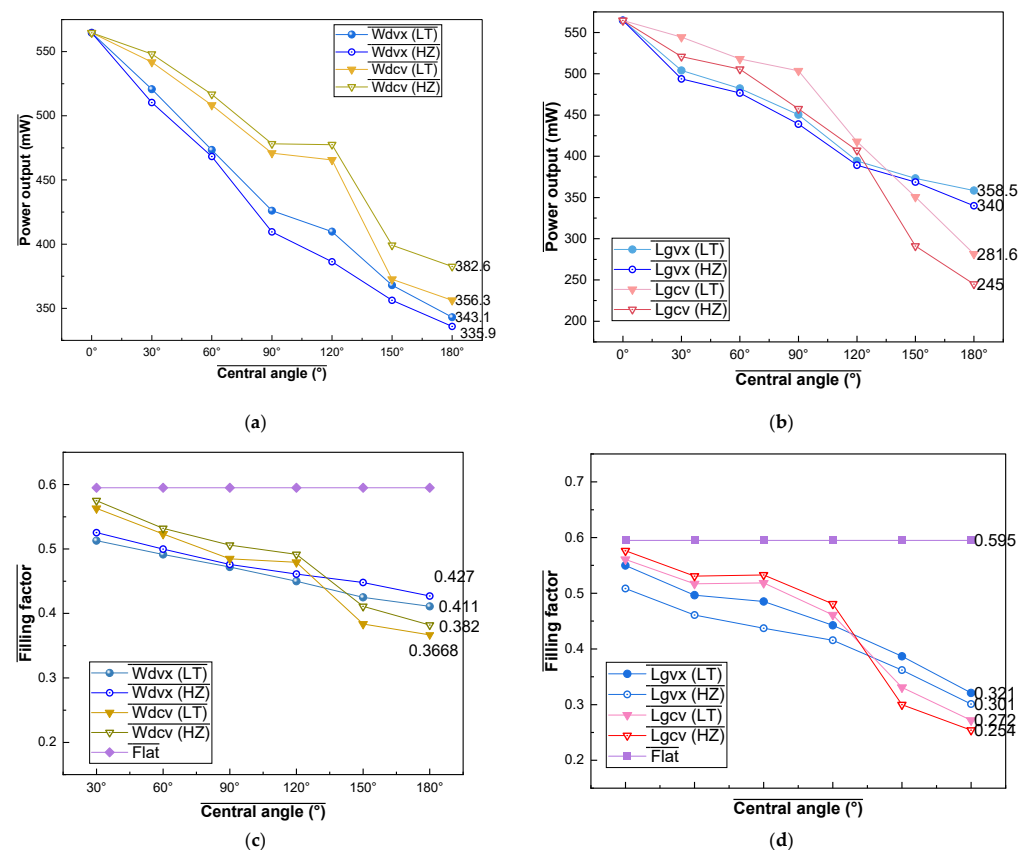


Figure 12. The electrical performance of PV cells with different central angles. (a) Power output of wdvx(LT/HZ) and wdcv(LT/HZ); (b) Power output of lgvx(LT/HZ) and lgcv(LT/HZ); (c) Filling factor of wdvx(LT/HZ), wdcv(LT/HZ) and flat; (d) Filling factor of lgvx(LT/HZ), lgcv(LT/HZ) and flat.

Figure 12c,d reveal that the trend of FF values is consistent with that of power output. The crossover agrees with the CV-NUI trend in Figure 10a, where lgcv rises steeply once the

self-occluded region expands at large central angles. The model and experiment therefore indicate the same transition from irradiance concentration to self-shading-dominated loss.

Based on the aforementioned data, we calculated the detailed mismatch loss and *PR* for all configurations, which are presented in the following heatmaps. As depicted in Figure 13a,b, two patterns emerge. Within each row, *PR* changes smoothly with the central angle, with small zigzag fluctuations near the crossover regions. These fluctuations agree with the irradiance redistribution predicted by the optical model. Across each diagonal, adjacent cells are nearly symmetric, indicating that the LT and HZ orientations behave similarly under indoor STCs. The highest *PR* is 97.1% for wdcv-HZ at 30°, corresponding to 16.6 mW power loss, while the lowest *PR* is 43.4% for lgcv-HZ at 180°, corresponding to 319.7 mW power loss. Overall, most of the tested combinations remain above the 60% *PR* range, consistent with the moderate *CV-NUI* predicted by the model.

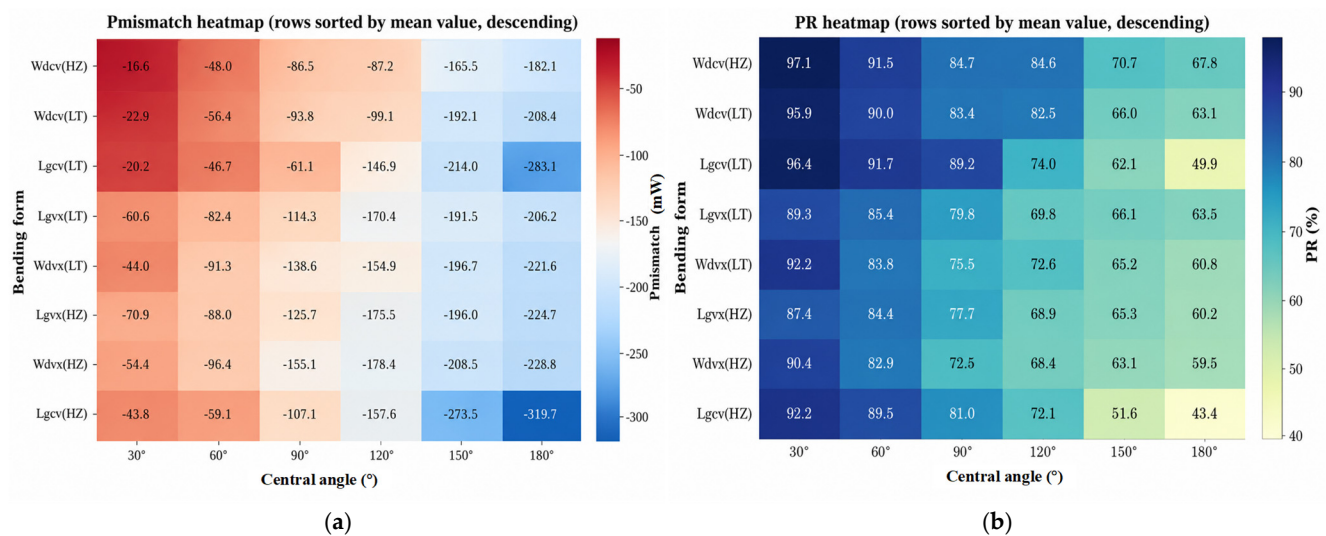


Figure 13. The heatmap of electrical performance for PV cells with different central angles: (a) Power mismatch loss of wdcv(LT/HZ) and wdcv(LT/HZ); (b) Performance ratio of lgcv(LT/HZ) and lgcv(LT/HZ).

The step-like variation of *PR* with the central angle in Figures 12 and 13 follows from three superposed geometric contributions: (i) the orthographic projected area, which shrinks with θ_c and provides only the smooth background trend; (ii) the circumferential irradiance redistribution predicted by the optical model in Section 2.6, with stepwise reductions in G_{min}/G_0 caused by near-grazing incidence in length bending or by the inter-arm view-factor transition near $\theta_c \approx 135^\circ$ in the wdcv case, as shown in Figure 9b; and (iii) the orientation of the monolithic P1/P2/P3 scribes relative to the curvature axis, which determines whether the local irradiance deficit set by (b) maps onto the cell short-circuit current (length bending) or is averaged along the current-collection path (width bending). The zigzag arises from the joint action of (b) and (c); (a) alone would give a smooth curve.

A natural design question is whether a single cell bent to a large central angle could be replaced by two cells of half the central angle, electrically reconnected. Within the present framework this is attractive because irradiance non-uniformity increases strongly with central angle in length-bending cases. For lgcv, the simulated *CV-NUI* decreases from about 70% at 180° to about 30% at 90° (Figure 10a), suggesting that splitting a 180° arc into two 90° sub-arcs would substantially reduce the irradiance spread within each segment. The benefit depends on the electrical connection. In series, the two sub-cells would still be limited by the less illuminated segment unless a bypass path is provided. In parallel, the currents can be summed, and the residual irradiance gradient is better tolerated, but voltage matching

becomes necessary. This is closely related to the module-scale interconnection optimisation discussed by Cai et al. [13] and to the bypass-diode-induced multi-peak P–V behaviour of length-bending modules discussed in Section 4. Optimising the series/parallel layout of subdivided curved cells is therefore an important topic for future work.

4. Implications for Outdoor Module-Scale Operation and Limitations

The indoor STC experiments and optical model identify the geometric-optical origin of cell-level mismatch. In real curved BIPV systems, this mechanism is coupled with dynamic solar conditions and module-level effects that are not reproduced in the indoor setup. Nevertheless, the orientation rule established here remains relevant: width bending averages the irradiance gradient across the current-collection path, whereas length bending aligns it with that path. This rule is consistent with outdoor studies on curved CIGS modules, where longitudinal/lateral layout and convex/concave design strongly influenced photoelectric performance [26,30].

Under outdoor operation, the fixed near-vertical simulator beam is replaced by a continuously changing solar position. The LT and HZ orientations, which are nearly equivalent under collimated indoor illumination (Section 3.2), therefore experience different daily solar-azimuth trajectories. This can change the LT/HZ sub-ranking within each bending configuration, although the broader trend of width-bending outperforming length-bending and wavy configurations is generally retained. In addition, convex forms may outperform the flat reference in the early morning and late afternoon, when their upward-facing arms receive low-altitude solar radiation more effectively. This behaviour is not reproduced in the fixed-beam indoor setup.

At the module scale, the monolithic cell is replaced by interconnected chip strings with bypass-diode protection. The irradiance imbalance identified at the cell level can then appear as sequential bypass-diode activation in length-bending modules, producing multi-peak P–V curves and local heating in strongly mismatched regions. A dedicated outdoor module-scale validation is beyond the scope of the present cell-level study and is left to future work. The indoor results and optical model developed here provide the mechanistic basis for that analysis.

Finally, several limitations of the present indoor study should be made explicit. First, regarding scale and packaging, the tests used 45 mm × 105 mm bare cells without EVA encapsulation, a glass cover, or a junction box, so the absolute *PR* values should not be read as direct predictors of module-level *PR*; the configuration ranking and the orientation rule are the transferable findings. Second, regarding spectrum and incidence, the AAA-class simulator provides a fixed AM1.5G, near-collimated, normal-incidence beam with no diffuse component, whereas outdoor operation involves a variable diffuse fraction and time-varying incidence angles, which may shift the quantitative crossover points (for example, the *w_{dcv}*–*w_{dvx}* crossover near $\theta_c \approx 135^\circ$). Third, regarding long-term reliability, the pre- and post-bending checks showed no measurable irreversible degradation over the test period, but damp-heat, UV, and thermal-cycling ageing of the length-bending and wavy configurations were not assessed and require separate accelerated-ageing studies.

5. Conclusions

This work has combined a controlled indoor experimental campaign on bare flexible CIGS cells with a two-dimensional microfacet optical model to identify, quantify, and explain the geometric origin of photoelectric mismatch loss in curved flexible CIGS cells. The principal findings are as follows:

- (1) Geometric origin of mismatch. The non-uniform distribution of irradiance on the curved cell surface, driven solely by the geometric central angle θ_c and the orientation

of the curvature axis relative to the cell long edge, causes part of the photocurrent not to be delivered to the load. The cell-level performance ratio decreases monotonically with θ_c and is strongly orientation dependent. The worst case occurs for the length-concave form in the HZ orientation at $\theta_c = 180^\circ$, where PR falls to 43.4%, corresponding to a 56.6% power loss.

- (2) Width bending averages, length bending aligns. When the curvature axis is parallel to the cell short edge (width bending), the resulting irradiance gradient is averaged across the current-collection path, and the cell-level PR remains above 60% at all tested central angles. When the curvature axis is parallel to the cell long edge (length bending), the gradient is aligned with the current-collection path, and a multi-tier shadow pattern develops, with the leeward tier limiting the cell current. This orientation rule is the most powerful predictive output of the study.
- (3) Single-parameter calibration and the NUI proxy. A single empirical parameter $\alpha \approx 0.15$ in Equation (21) provides a compact description of the indoor performance ratio across the six bending forms and seven central angles, with $R^2 = 0.85$ and $RMSE = 5.1\%$. The dimensionless non-uniformity index defined in Section 2.4 therefore serves as a useful geometric proxy for cell-level photoelectric mismatch loss.
- (4) Design implications. For curved CIGS BIPV design, the cell-level results translate into three practical guidelines. First, width bending should be preferred wherever the envelope geometry allows because aligning the curvature axis with the cell long edge spreads the irradiance gradient across the short current-collection path and keeps PR above 60% across the full $0\text{--}180^\circ$ range. Second, when length bending is unavoidable, the central angle should be kept as small as the architecture permits, since the length-concave penalty grows steeply once self-shading sets in beyond $\theta_c \approx 135^\circ$. Third, concave forms are beneficial only at intermediate central angles, where inter-arm mutual reflection raises the received irradiance; beyond $\theta_c \approx 135^\circ$, self-shading reverses this advantage, so concavity should not be combined with large central angles. The implications of these rules for module-scale operation, together with the limitations of the present indoor study, are discussed in Section 4.

Future work should focus on (i) extending the present cell-level optical model to incorporate the module-level bypass-diode topology and predict the multi-peak I–V curve from first principles; (ii) characterising the long-term reliability of length-bending and wavy configurations under accelerated thermal-cycling, damp-heat, and UV ageing; and (iii) designing customised chipset layouts that preserve the geometric current-averaging property of width bending at the module scale across the full range of bending radii relevant to curved BIPV envelopes.

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Nomenclature

G_{pv}	Solar irradiation intensity on baseplate, W/m^2	P_{max}	The instantaneous maximum power output of the PV module, W
A_{pv}	The orthographic projection area on inclined surface area, m^2	P_{flt}	The flat-type PV power output, W
η_{pv}	Electrical efficiency, %	P_{crv}	The curved-type PV power output, W
PR	Performance ratio, %	ΔP_{ml}	Power mismatch loss, W
V_{oc}	The open circuit, V	FF	Filling factor
u_B	The standard uncertainty of the instruments	I_{sc}	The short current, A
u_c	The uncertainty	a_n	The nominal accuracy of the experimental instrument

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