

Self-cleaning and photovoltaic characteristics for solar cell with FEP film in curved building

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ABSTRACT

This study addresses the demand for lightweight, flexible, highly transparent, and self-cleaning cover materials in curved-building integrated photovoltaics, proposing fluorinated ethylene-propylene film as an alternative to glass. Based on wetting-state mechanism and surface-energy theory, we investigated outdoor dust accumulation, photovoltaic performance, and city-specific power generation prediction, defining the suitable application scope of FEP across regions. Results show that FEP's low adhesion and hydrophobicity reduce soiling density by up to 52.6% compared to glass. Under rain, snow, or wind, self-cleaning is more effective at low tilt angles due to surface properties; under other weather conditions, higher angles become superior mainly due to gravity. Moreover, FEP-covered cells exhibit anti-reflection effects, increasing maximum power by 4.28–6.03% and achieving faster voltage stabilization. Using experimental data, a random forest model was built to predict power generation for eight cities across four solar resource zones in China. In regions with annual total irradiation $\geq 7000 \text{ MJ/m}^2$, the gain from FEP is relatively low due to Auger recombination; in areas with irradiation $\leq 3600 \text{ MJ/m}^2$ and lower outdoor temperatures, the gain is more pronounced ($\approx 6.4\%$) owing to excellent moisture resistance. FEP film is particularly suitable for Class IV solar resource zones.

1. Introduction

Against the backdrop of the global energy transition and architectural innovation, curved building envelopes have emerged as a prominent design paradigm that integrates modernist aesthetics with functional performance. According to market research, the global curved glass market for buildings is projected to reach \$5.12 billion by 2024 and expand at a compound annual growth rate (CAGR) of 6.15% to \$8.67 billion by 2033, accounting for a significant share of the overall building services market [1]. Despite their architectural appeal, curved geometries often exhibit elevated energy consumption relative to rectangular forms due to increased aerodynamic friction, exacerbated thermal bridging, and higher maintenance complexity. Integrating photovoltaic (PV) systems into such structures—specifically Building-Integrated Photovoltaics (BIPV)—has been identified as a viable strategy to mitigate carbon emissions and reduce reliance on fossil fuels while enhancing on-site generation efficiency [2].

Nevertheless, the irregular geometry of curved facades introduces substantial challenges for cleaning and maintenance. Conventional cleaning platforms, crawler-mounted devices, or suspended access equipment typically struggle to adhere or secure properly to curved surfaces. Furthermore, the accumulation and adhesion behavior of dust, water droplets, and particulate matter vary significantly with local inclination and curvature, leading to preferential soiling in concave, convex, or undulating zones. During cleaning operations, gravity-induced slippage of fluids along curved profiles diminishes cleaning efficacy and may induce secondary contamination. Consequently, PV modules mounted on curved surfaces face elevated operational costs and less predictable soiling rates, thereby exacerbating dust-induced performance degradation. Dust accumulation adversely affects PV performance both directly—by attenuating incident irradiance and elevating cell temperature—and indirectly, through partial shading, hot spot formation, and accelerated long-term degradation [3]. Prior studies report efficiency losses ranging from 10% to 17% under conditions of

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infrequent cleaning [4]. Bao et al. [5] demonstrated a highly transparent superhydrophobic F-SiO₂ coating (water contact angle $\sim 158^\circ$) that facilitates particle removal via droplet rolling, limiting transmittance loss to approximately 2.7% (from 89.6% to 86.9%) and minimizing photoelectric conversion efficiency degradation to less than 0.03%. Therefore, mitigating transmittance loss due to long-term soiling while preserving or enhancing the initial optical transparency of flexible PV cover materials constitutes a pressing research priority.

In recent years, researchers have begun to focus on various self-cleaning technologies for photovoltaic covers to mitigate losses caused by dust accumulation. Among current studies, numerous passive dust removal techniques exist. Liu et al. [6] proposed a rechargeable electrostatic dust removal technology based on carbon nanotube transparent conductive films (CNTs-TCTF). Experiments demonstrated a dust removal rate of 99.78% under the relative humidity of 70% and the electric field strength of 6 kV/cm. Shahzad et al. [7] systematically analyzed the factors influencing dust accumulation on PV modules and the efficacy of various cleaning technologies. The study pointed out that advanced automated cleaning systems—such as robots, drones, and AI-driven systems, represent an efficient future direction for addressing dust accumulation issues. Attia et al. [8] proposed a wind-driven mechanical vibration dust removal technology. By converting wind speed into panel vibration via a cam-piston mechanism, it achieved a 70% dust removal rate at a 15° tilt angle with a vibration force of 3.128 N. Widely adopted passive dust removal technologies generally rely on external energy inputs, exhibit limited environmental adaptability, and require continuous operational support, leading to additional consumption of human and material resources. Given these limitations, research focus has gradually shifted toward exploring active dust prevention technologies. For instance, Al Bakri et al. [9] reported that a TiO₂-based superhydrophilic nanocoating (SurfaShield G) increased maximum power by 20% and efficiency by 2.3% in outdoor tests. Tobosque et al. [10] achieved a 64.7% reduction in dust accumulation via alkaline etching of glass surfaces, with only a 13% loss in transmittance. Rahool et al. [11] fabricated biomimetic micro-nano structures using nano-second laser texturing, estimating a 4–8% efficiency enhancement despite some transmittance trade-off. Je Min Lee et al. [12] employed nanoimprint lithography to create hexagonal silica microcavities, realizing superhydrophobicity (contact angle 166.4°) and a 1.3% gain in photovoltaic efficiency. However, although approaches such as chemical modification and laser etching on the surface of photovoltaic glass can enhance its self-cleaning properties, changes in transmittance are overlooked. In some cases, surface structural damage may even lead to light transmission loss. Against this backdrop, researches on hydrophilic and hydrophobic materials have become particularly crucial. For instance, Ahmed et al. [13] reported that superhydrophilic SiO₂ nano-coatings (contact angle 16.5°) reduced dust accumulation in outdoor Egyptian conditions, yielding 64.7% higher short-circuit current and 65.2% greater maximum power. Joshi et al. [14] developed a sol-gel SiO₂-MgF₂ anti-reflective coating with superhydrophilicity (contact angle $<6^\circ$) and high weatherability ($<0.5\%$ transmittance loss after 100 h aging), achieving 98.1% visible and 96.6% solar transmittance. Appasamy et al. [15] synthesized a nitrogen-doped TiO₂/SWCNT hydrophilic coating exhibiting 72.4% methylene blue degradation and confirmed no adverse impact on module electrical output. Chundi et al. [16] formulated a sprayable quantum-sized TiO₂ coating with superhydrophilicity (contact angle $<5^\circ$ in 60 min), which reduced dust-induced power loss by 2.5% in field tests. However, the practical application of hydrophilic materials still faces several limitations. Photocatalytic decomposition heavily relies on ultraviolet light intensity, and self-cleaning effectiveness significantly diminishes under insufficient illumination [17]. Hydrophobic materials can fundamentally circumvent light dependency through inherent surface properties, making them an attractive direction for addressing dust accumulation on photovoltaic cover. Walz et al. [18] developed a sol-gel SiO₂-TiO₂ nanoporous hydrophobic coating that increased module electricity

generation by 3.05–3.52% in outdoor tests without transmittance loss, proving particularly effective for low-tilt (10°) systems. Zhao et al. [19] numerically modeled superhydrophobic silica coatings, identifying wind speed, tilt angle, and particle size as key regulators of anti-soiling performance, with a maximum simulated dust reduction of 37.4%. Tachibana et al. [20] achieved a 75% weight reduction in crystalline silicon modules by replacing glass with 25 μm PET film, though a 10% performance degradation was observed after 6000 h of damp-heat exposure (85 $^\circ\text{C}/85\%$ RH). While conventional glass offers excellent optical transmittance and durability, its high density and rigidity hinder application in curved or flexible BIPV configurations. Lightweight polymeric alternatives such as PET provide flexibility and cost advantages but suffer from inferior initial transmittance and susceptibility to UV-induced yellowing and optical decay [21]. Similarly, PVDF films exhibit relatively low transmittance and are prone to chemical degradation, micro-delamination, and mechanical decline under prolonged UV exposure owing to their lower fluorine content [22]. Additionally, comparative material data indicate that FEP exhibits a significantly lower elastic modulus (0.43 GPa) and higher elongation at break ($\sim 300\%$) than ETFE (1.5 GPa, $\sim 230\%$) and PVDF (1.1 GPa, $\sim 200\%$) [23]. This combination of lower stiffness and higher ductility allows FEP to better accommodate substrate curvature and bending deformation during lamination without generating excessive internal stress. In this context, fluorinated ethylene propylene (FEP) films, as a high-performance fluoropolymer material, demonstrate a range of superior properties including superhydrophobicity, low friction coefficient, high optical transmittance, chemical inertness, corrosion resistance, low dielectric constant, flame retardancy, good mechanical properties, thermal stability, and flexibility [24]. Unlike TiO₂-based photocatalytic coatings that rely on UV activation, or nanostructured SiO₂ superhydrophobic surfaces prone to irreversible degradation from low-surface-tension contaminants, FEP requires no light for self-cleaning and its dense fluorinated surface resists permanent fouling, with any performance loss being recoverable by simple washing [25, 26]. Recent experimental work by Haydock-Wilson et al. [27] has further confirmed that FEP-based laminates retain superhydrophobicity and chemical stability after 1000 h of accelerated UV exposure combined with 1000 linear abrasion cycles. Moreover, Dever et al. [28] reported that exposure to simulated space radiation and thermal cycling did not significantly degrade the tensile strength or elongation of FEP, underscoring its inherent resistance to environmental embrittlement. These characteristics enable FEP to be integrated into photovoltaic module structures via conventional thermoplastic processing, offering a promising material option for flexible building-integrated photovoltaic (BIPV) cover designs.

In the context of building-integrated photovoltaics (BIPV), cover materials serve a dual purpose, they protect photovoltaic cells while also functioning as integral components of the building envelope, replacing conventional construction materials to contribute to architectural aesthetics, energy performance, and sustainability. By integrating renewable energy generation with building functions, BIPV systems enable façades, roofs, and skylights to act simultaneously as structural elements and power-producing surfaces, thereby reducing overall construction costs and enhancing the energy autonomy of the built environment. Currently, research on fluorinated ethylene propylene (FEP) materials—a promising candidate for such applications—remains largely at the laboratory exploration stage. These studies have primarily focused on enhancing hydrophobicity, optimizing optical performance, utilizing FEP as a hydrophobic coating substrate, and evaluating its stability through surface modification and microstructure regulation. However, there is a notable lack of systematic performance data under real-world outdoor conditions. In particular, when FEP films are employed as flexible photovoltaic covers in BIPV systems, the specific role of their surface characteristics in suppressing dust deposition and the subsequent impact on power generation efficiency have not been thoroughly investigated through systematic outdoor empirical studies.

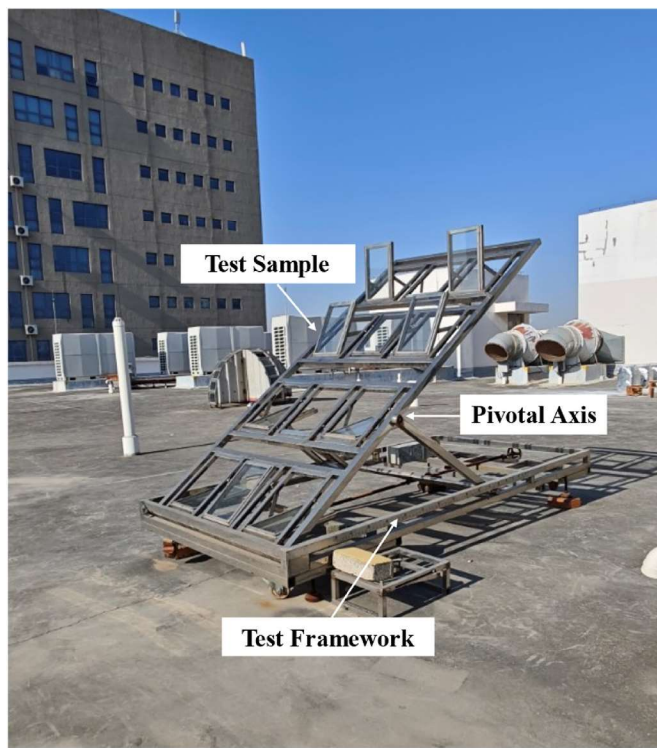


Fig. 1. Self-cleaning experimental platform.

And recent reviews have highlighted the weight-reduction and breakage-resistance advantages of polymer cover materials such as polycarbonate over conventional glass [29], the present study extends these concepts to FEP films and proposes their use as flexible photovoltaic cover materials. Through long-term outdoor natural dust deposition experiments, the influence of factors such as tilt angle, wind force, and precipitation on dust accumulation behavior on FEP surfaces was elucidated, and the regulatory roles of key parameters including surface energy, hydrophobicity, and friction coefficient in the dust-suppression mechanism were systematically clarified. Furthermore, the photoelectric response characteristics of FEP-based photovoltaic modules under varying radiation intensities and internal resistances were analyzed via power output tests. Based on a Random Forest model for power gain prediction, the application potential of FEP films across different solar resource regions was delineated, thereby providing both a theoretical foundation and practical support for optimizing their region-specific deployment in BIPV systems.

2. Experimental setup, instruments, and methods

To quantitatively analyze the self-cleaning effect of FEP film (Teflon® FEP), dust accumulation experiments of FEP film and photovoltaic glass (named as PV glass) in natural environment have been conducted, along with contact angle tests. Wherein the bonding surface of the FEP facing the PV cell is electrostatically treated. The photovoltaic characteristics of FEP film applied to solar cell have also been investigated.

2.1. Self-cleaning property

As shown in Fig. 1, the experimental setup was located on the rooftop of the Tianjin Chengjian University Training Center (Tianjin, 117°E, 39°N), facing south. The sample dimensions were 140 mm × 100 mm. The experimental cycle lasted 75 days, with measurements taken every 5 days at 10:30 a.m. The test instruments were shown in Fig. 2 and Table 1. The operator, wearing clean medical gloves, measured the dust

accumulation mass gravimetrically. And three replicate measurements were performed for each tilt angle. Using a JJ124BC digital balance, the sample was placed steadily in the center of the weighing pan, and the reading was taken after stabilization. The inclination angles of the samples were adjusted by Digital Protractor DP-360M to 0°, 25°, 50°, 75°, and 90°. Digital Protractor's magnetic base was placed on the surface of the measured object. PM10 and PM2.5 values, wind force and direction, and air temperature were sourced from measurements by the Ecological Environment Monitoring Center of Xiqing District, Tianjin.

Before the self-cleaning experiment, contact angle measurements were firstly performed using Contact Angle Meter JC2000D, in which the hanging drop method was employed. A droplet was deposited onto the sample surface using a micropipette. Measurements were taken at multiple distinct points. Extreme values were excluded, and the average of the remaining values was the final result. Prior to test, sample surfaces were ensured to be clean, flat, and free of impurities.

2.2. Photovoltaic performance

The photoelectric (PV) experiment was conducted within the Training Center of Tianjin Chengjian University. The experimental setup and schematic diagram were respectively shown in Figs. 3 and 4.

The experiment utilized a single crystalline silicon solar cell, with the FEP film laminated using EVA encapsulant, and employed the Artificial Solar Simulator TYD-PD1 to gain solar radiation intensity from 200 W/m² to 800 W/m². Here, Handheld Radiation Meter Apogee MP-200 (Calibrated) was used to gain the solar radiation intensity. BX8 dual-tube hand-cranked scribing rheostat served as a variable resistor to obtain different resistances, as shown in Fig. 5. Type K thermocouples connected to an Agilent 34970 A data logger were applied to record the temperature of the front part of cell. The Fluke 15 B MAX Digital Multimeter measured parameters including DC and AC voltage, and DC and AC current etc.

3. Experimental results and analysis

3.1. Dust accumulation density

Tianjin, situated on the North China Plain, is influenced by the East Asian monsoon and borders ancient plateaus and desert regions. Monsoons frequently bring strong winds [30]. Wind transports substantial amounts of sand and dust to the Tianjin region, while also blowing up surface dust and particulate matter to form fallout. In addition, Tianjin serves as a major industrial base in China, hosting some industrial enterprises and petrochemical plants. These facilities may emit large quantities of particulate matter, soot, and exhaust gases during production, with the particulate matter forming airborne dust accumulation [31]. Furthermore, during the heating season, due to coal-fired heating and industrial emissions, fine particulate matter readily suspends and accumulates over Tianjin. Fig. 6 shows the changes in monitored PM2.5 and PM10 levels during the experiment. PM2.5 ranges from 4 to 192 µg/m³, with an average of 52 µg/m³ and a peak value on Day 52. PM10 ranges from 16 to 300 µg/m³, averaging 88 µg/m³ with a maximum on Day 30. Periods with relatively high PM2.5 and PM10 values occur on the days 6–16, 25–30, 45–57, and 64–65. When fine airborne dust contacts with the sample surface, some particles would be adsorbed and exchange energy with existing surface particles, while others rebound into the air. Adsorbed dust particles possess zero velocity components perpendicular to the surface, retaining only those parallel to the solar cell surface and then undergoing diffusion migration across the module surface. During this process, the particles gradually lose energy, cease movement, or collide and coalesce with other particles. When dust accumulation reaches a certain threshold, stable nuclei form, attracting further particle adsorption and facilitating growth. As nuclei multiply and fuse, they ultimately form a layer of accumulated dust. Fig. 7 and Table 2 illustrate wind force, outdoor air temperature and wind



(a) Electronic Scale JJ124BC



(b) Digital Protractor DP-360M



(c) Contact Angle Meter JC2000D

Fig. 2. Experimental instruments for self-cleaning.

Table 1
Experimental instrument parameters.

Instrument	Type	Range	Accuracy
Electronic Scale	JJ124BC	0 - 120 g	0.1 mg
Digital Protractor	DP-360M	0 - 360°	0.1°
Handheld Radiation Meter	Apogee MP-200	0 - 2000 W/m ²	±5%
Contact Angle Meter	JC2000D	0-180°	±0.1°
Artificial Solar Simulator	TYD-PD1	—	—
Digital Multimeter	Fluke 15 B MAX	DC Current: 10 A; DC Voltage: 1000 V	DC current: 1.5% ± 3; DC voltage: 0.5% ± 3

direction during the experiment. Prevailing winds are northwest, south, and southwest, with light rain on Day 30, light snow on Days 32 and 33, and moderate to heavy snowfall accompanied by strong winds on Days 35 and 36. On Day 70, from 7:00 to 8:00, there is a brief light rainfall

(unforecast).

To evaluate the reliability and dispersion of the experimental data, error bars are included in the analysis. Fig. 8 shows a comparison of dust accumulation between FEP film and PV glass at various tilt angles. Error bars represent standard deviation ($n = 3$), calculated using Eq. (1).

$$S = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{(n-1)}} \quad (1)$$

where, n represents the number of repetitions, $n = 3$; x_i represents the dust accumulation density obtained from each replicate at various tilt angle and each experimental time; $\bar{x}$ represents the average dust accumulation density for the same tilt angle and each experimental time.

As shown in Fig. 8, the error bars associated with both FEP film and PV glass are relatively narrow across all tested angles (25° to 90°), indicating high repeatability and low measurement variability within the experimental setup. Notably, the error bars for the two materials exhibit minimal to no overlap at any given tilt angle. This consistent

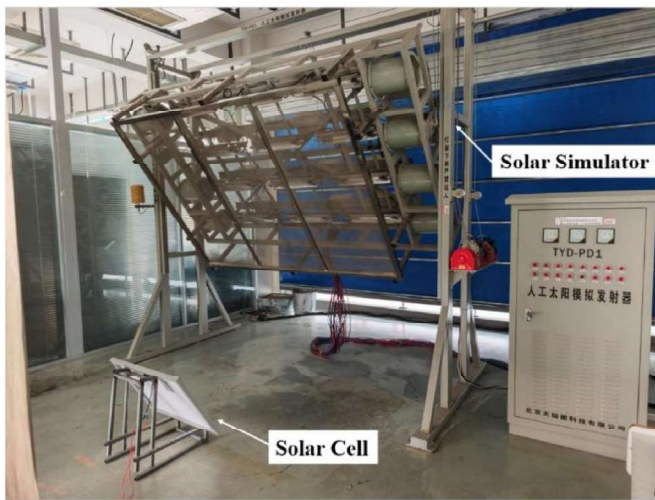


Fig. 3. Experimental setup.

separation confirms that the observed reduction in dust accumulation on FEP film is statistically robust and not an artifact of random experimental noise.

Figs. 9 and 10 show the curves of dust accumulation density on the FEP film surface and traditional photovoltaic glass surface over time.

A Weather Conditions

As shown in Figs. 9–10, the dust accumulation densities on both FEP film and photovoltaic glass surfaces exhibit an increasing overall trend with the experimental days.

During the experimental periods from days 0–10 and days 15–20, the dust accumulations on both FEP film and photovoltaic glass surfaces increase significantly. This is attributed to the fact that, at the experiment's outset, both the FEP film and photovoltaic glass surfaces have been freshly cleaned, carrying electrostatic charges. This could attract airborne dust particles, leading to a noticeable increase in initial dust accumulation and forming a dust layer. Furthermore, In 15 to 20 days, lower wind speeds result in increased dust accumulation on the module.

During the 25th to 30th day, lower wind speed, predominantly at force 1, and poor air quality, with the PM10 reaching a peak of $300 \mu\text{g}/\text{m}^3$, result in increased dust accumulation on the sample surfaces under gravitational force (the rainfall on day 30 occurs after the test completed). During the experimental period from days 40–65, the dust accumulation density on the sample surface gradually increases, with the dust layer becoming progressively thicker. The accumulation rate eventually stabilizes. This occurs because dust continuously settles from the air, adheres to the existing dust layer on the sample surface, and forms accumulations.

During the days 10–15 and days 20–25, the dust accumulation densities on both the FEP film and photovoltaic glass surfaces decrease. For the former at a tilt angle of 90° , it decrease from $0.22 \text{ g}/\text{m}^2$ to $0.20 \text{ g}/\text{m}^2$ and from $0.21 \text{ g}/\text{m}^2$ to $0.20 \text{ g}/\text{m}^2$, respectively. This reduction coincides with periods of strong winds in Xiqing District, Tianjin, as shown in Fig. 7. During days 10–15, there are two days of southwest wind above force 3. During days 20–25, four days of northwest wind exceed force 3, with a relatively lower airborne dust concentration (see Fig. 6), the average concentration of PM2.5 $17.5 \mu\text{g}/\text{m}^3$ and that of PM10 $40.8 \mu\text{g}/\text{m}^3$. At higher wind speed, dust particles adhering to the module surface can be swept away by airflow. During the 30th to 40th day, dust accumulation density shows a pronounced downward trend. At a tilt angle of 90° , it decreases from $0.22 \text{ g}/\text{m}^2$ to $0.2 \text{ g}/\text{m}^2$ for the FEP film, while decreasing from $0.31 \text{ g}/\text{m}^2$ to $0.25 \text{ g}/\text{m}^2$ for the photovoltaic glass. This period is characterized by air quality being poor only on day 30, with PM2.5 of $125 \mu\text{g}/\text{m}^3$ and PM10 of $300 \mu\text{g}/\text{m}^3$, then good over the subsequent 10 days, with PM2.5 of $8 \mu\text{g}/\text{m}^3$ and PM10 of $21 \mu\text{g}/\text{m}^3$ on the 40th day, concurrent with light to moderate snowfall in Xiqing District, Tianjin, accompanied by strong winds. Although the ambient temperature is below freezing (Fig. 8), direct sunlight causes the snow to reach its melting point. Under gravitational influence, melted snow slides down and washes away dust from the surfaces, while any remaining dust particles that are not removed by the snow can be blown away by the strong winds. Notably, samples with a tilt angle of 0° are unable to autonomously remove accumulated snow under the snowfall conditions on days 32 and 35, and their surface dust accumulation characteristics are therefore not discussed in the subsequent analysis.

On the morning of the 70th day, a brief light rainfall occurs. At tilt angles of 90° and 75° , the surface dust accumulation densities for the FEP film decrease from $0.26 \text{ g}/\text{m}^2$ and $0.35 \text{ g}/\text{m}^2$ on the 65th day to

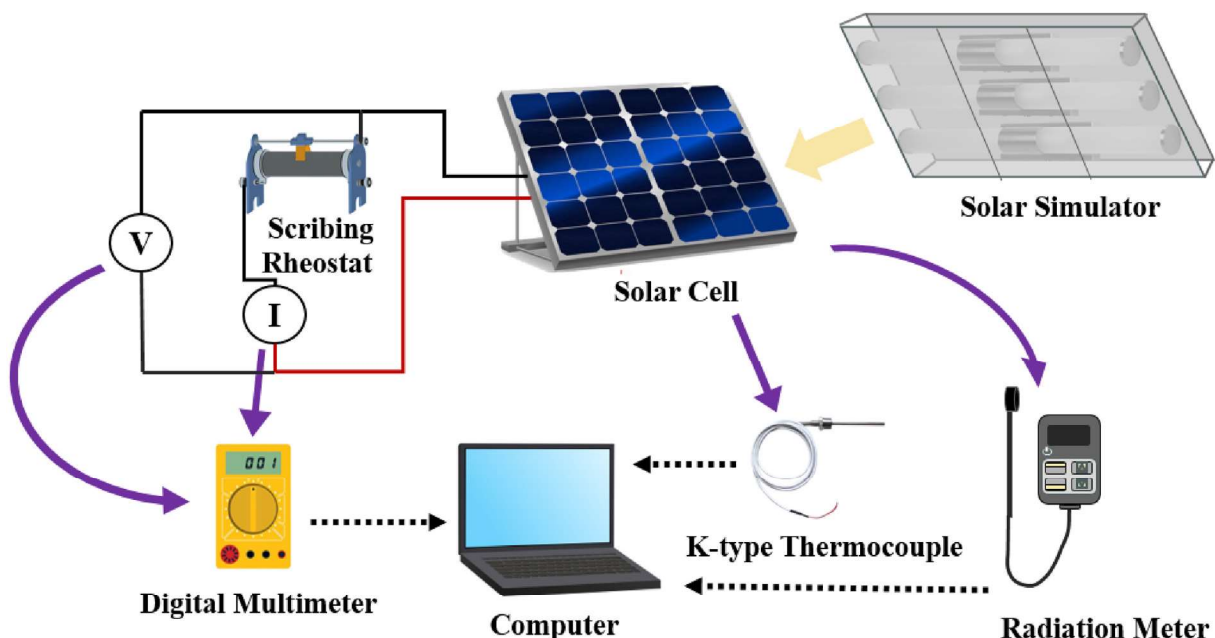


Fig. 4. Schematic diagram.



(a) Apogee MP-200



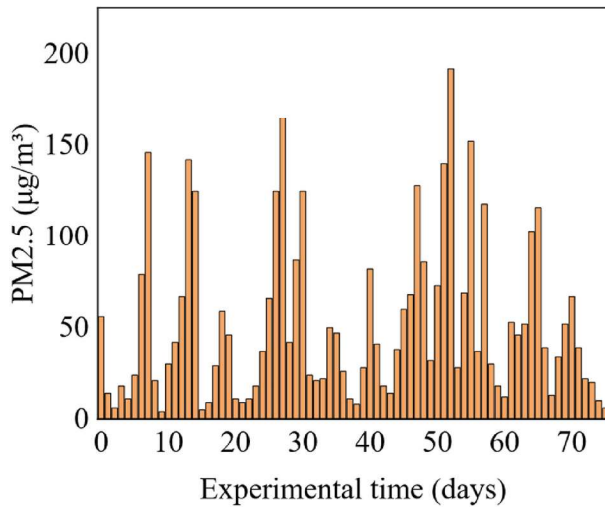
(b) BX8 Dual-Tube Hand-Cranked Scribing Rheostat



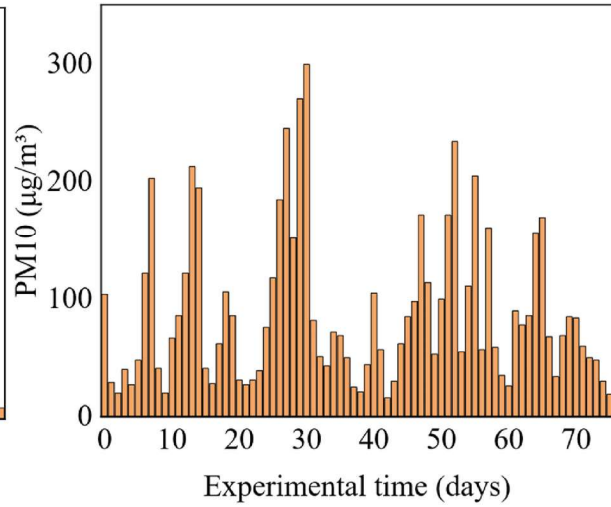
(c) Agilent 34970A



(d) Fluke 15B MAX

Fig. 5. Photovoltaic experiment instruments.

(a) PM2.5



(b) PM10

Fig. 6. Monitoring values.

0.24 g/m² and 0.33 g/m², respectively, whereas they gradually increase with decreasing tilt angle. This reduction primarily results from the strong hydrophobicity of the FEP film and contact angle up to 112.18°

(see Fig. 11), no significant decline in hydrophobicity is observed over the 75-day experimental time notably. When rainwater contacts the FEP film surface, the hydrophobic properties limit the spreading of

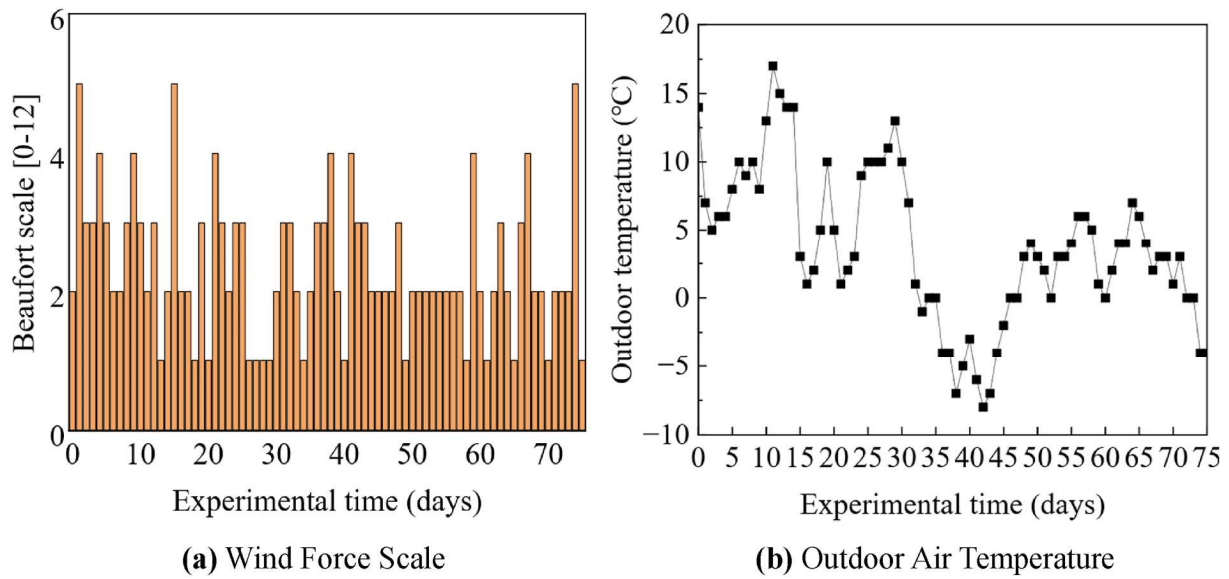


Fig. 7. Weather condition.

Table 2
Meteorological parameters.

Days	0	1	2	3	4	5	6	7	8	9	10	11	12
Weather Condition	Cloudy	Sunny	Cloudy	Cloudy	Sunny	Cloudy	Cloudy	Cloudy	Sunny	Sunny	Sunny	Sunny	Sunny
Wind Direction	N	N	N	N	N	W	SW	SW	NW	NW	SW	NE	SW
Days	13	14	15	16	17	18	19	20	21	22	23	24	25
Weather Condition	Fog	Cloudy	Sunny	Sunny	Cloudy	Fog	Sunny	Cloudy	Sunny	Sunny	Sunny	Cloudy	Cloudy
Wind Direction	S	NW	NW	NW	SW	NW	NW	SW	NW	NW	NW	NW	NW
Days	26	27	28	29	30	31	32	33	34	35	36	37	38
Weather Condition	Cloudy	Cloudy	Sunny	Sunny	Light rain	Cloudy	Light snow	Light snow	Fog	Moderate Snow	Heavy Snow	Cloudy	Clear
Wind Direction	NW	SW	SW	SW	NW	E	NE	N	SW	NE	NE	N	NW
Days	39	40	41	42	43	44	45	46	47	48	49	50	51
Weather Condition	Clear	Cloudy	Fog	Sunny	Sunny	Fog	Fog	Cloudy	Cloudy	Cloudy	Sunny	Cloudy	Fog
Wind Direction	NW	NW	NW	NW	NW	W	NW	W	NW	NE	NE	W	NW
Days	52	53	54	55	56	57	58	59	60	61	62	63	64
Weather Condition	Fog	Clear	Cloudy	Cloudy	Sunny	Sunny	Cloudy	Sunny	Sunny	Cloudy	Sunny	Sunny	Sunny
Wind Direction	NW	NE	NW	W	NW	W	NW	NW	NW	SW	NE	SW	NW
Days	65	66	67	68	69	70	71	72	73	74	75		
Weather Condition	Fog	Cloudy	Sunny	Sunny	Cloudy	Cloudy	Fog	Cloudy	Cloudy	Sunny	Sunny		
Wind Direction	NW	NE	N	NW	SW	W	E	NE	NE	NW	NW		

raindrops. The droplets remain nearly spherical and roll off rapidly under the combined action of a larger gravitational component and smaller adhesive force. As they roll, the droplets easily dislodge surface dust. However, for the FEP film at tilt angles of 50° and 25° , the gravitational force of the rainwater is often insufficient to overcome its adhesion to the surface, thereby allowing dust particles to remain and leading to a gradual increase in surface dust density. Meanwhile, the surface dust accumulation density for the photovoltaic glass exhibits a gradual increasing trend across all tilt angles. At a tilt angle of 90° , the surface dust accumulation density increases from 0.48 g/m^2 on the 65th day to 0.52 g/m^2 . This phenomenon occurs because the smaller contact angle of the photovoltaic glass (12.90°) allows lighter raindrops to spread and adhere to the surface. As the rainwater evaporates, it leaves

behind small, adhered dust particles on the glass. Simultaneously, atmospheric dust continuously accumulates on the photovoltaic glass surface, resulting in an increase in the total mass of deposited dust.

B. Tilt Angle

During the 75-days experimental period, the dust accumulation density on the FEP film surface increases from 0 to 0.27 g/m^2 (at 90°), 0.35 g/m^2 (at 75°), 0.48 g/m^2 (at 50°), and 0.60 g/m^2 (at 25°). For photovoltaic glass at tilt angles of 90° , 75° , 50° , and 25° , the surface dust accumulation density increases from 0 to 0.56 g/m^2 , 0.68 g/m^2 , 0.85 g/m^2 , and 1.08 g/m^2 , respectively. For both FEP film and photovoltaic glass, dust accumulation density decreases with increasing tilt angle. As

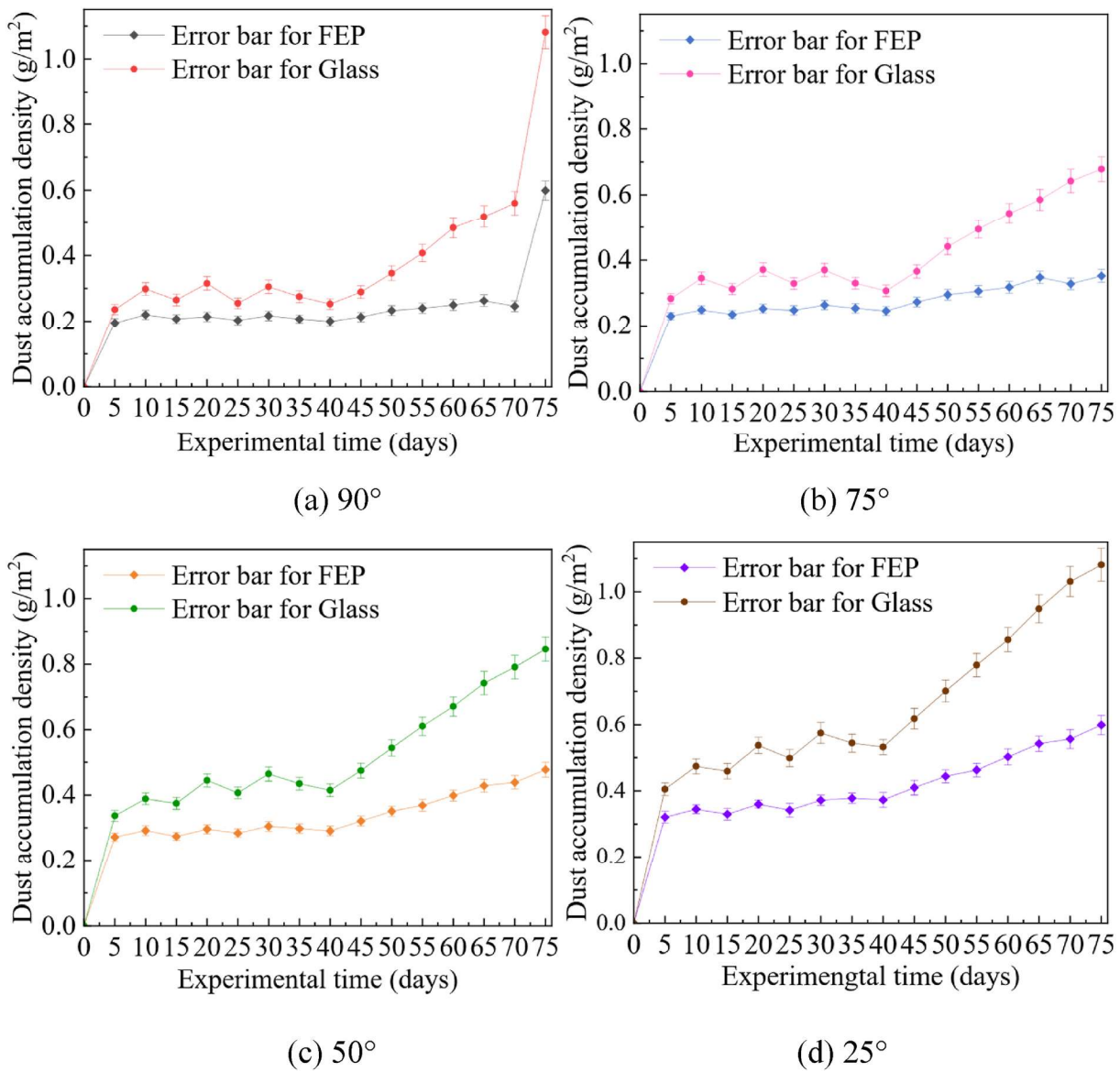


Fig. 8. Error bars.

the tilt angle increases, the gravitational component parallel to the surface (F_S , Eq. (2)) strengthens and becomes the dominant detachment force. The adhesion forces (F_R , Eq. (3)) remain largely unchanged. When $F_S > F_R$, dust particle slip and detachment occur. Consequently, dust is more easily removed from steeper surfaces, resulting in a lower dust accumulation density than on surfaces with lower tilt angles [32].

$$F_S = mg \sin \beta \quad (2)$$

$$F_R = mg \cos \beta + F_{\text{vander}} + F_{\text{electrostatic}} \quad (3)$$

where, F_S represents gravitational detachment force parallel to the panel surface, N; F_R represents total adhesion force perpendicular to the panel surface, N; F_{vander} represents van der Waals force, N; $F_{\text{electrostatic}}$ represents electrostatic force, N; β represents tilt angle, rad.

Under identical tilt angles, the dust accumulation density on FEP film surface is lower than that on photovoltaic glass surface. At tilt angle of 25°, it is 0.60 g/m² for FEP film, while 1.08 g/m² for photovoltaic glass. This difference stems from the distinct surface properties of FEP film compared to photovoltaic glass. FEP is a perfluorinated copolymer of tetrafluoroethylene and hexafluoropropylene. The high bond energy of C–F bonds and the dense coverage of fluorine atoms on its surface grant

FEP remarkable chemical inertness, resulting in extremely low surface energy and a characteristically non-polar surface [33]. Such a molecular structure leads to predominantly weak van der Waals interactions between FEP macromolecular chains [34]. The combination of weak intermolecular forces and low surface energy results in feeble adhesion between FEP and dust particles, making stable attachment difficult. Furthermore, FEP material exhibits a low friction coefficient and excellent hydrophobicity. When rainwater comes into contact with the film surface, it readily forms spherical droplets that roll off rapidly, effectively removing loosely adhered dust and thereby achieving a self-cleaning effect.

3.2. Cleaning effect

To compare the dust accumulation density difference between FEP film and photovoltaic glass surfaces, the dust density reduction coefficient K is calculated by Eq. (4),

$$K = \left(1 - \rho_m / \rho_0\right) * 100\% \quad (4)$$

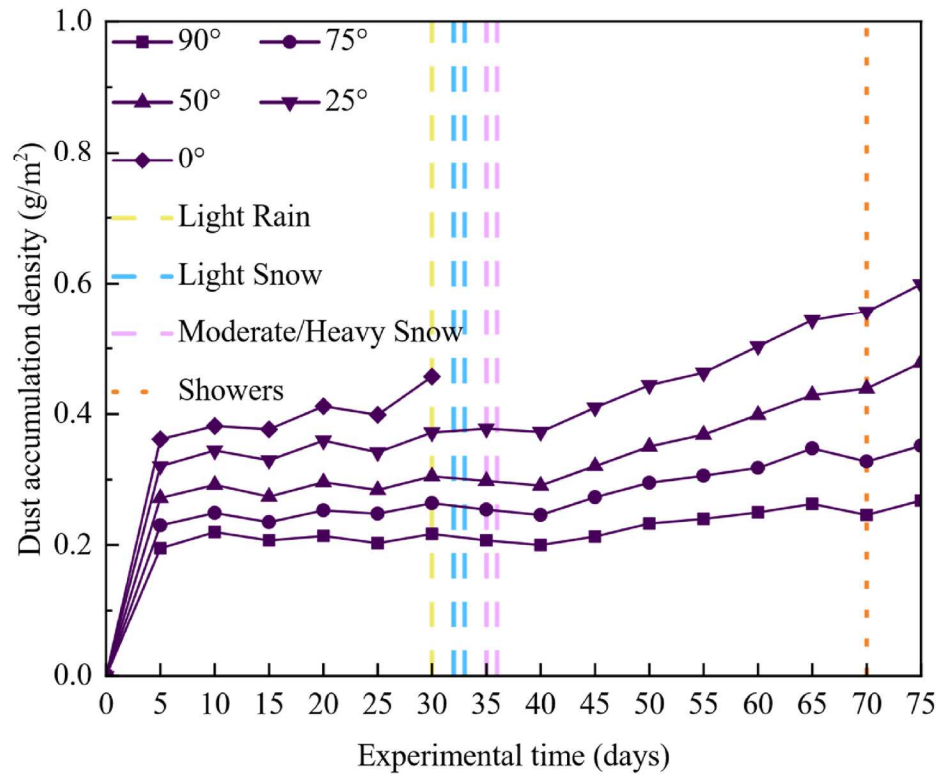


Fig. 9. Dust accumulation density on FEP film surface.

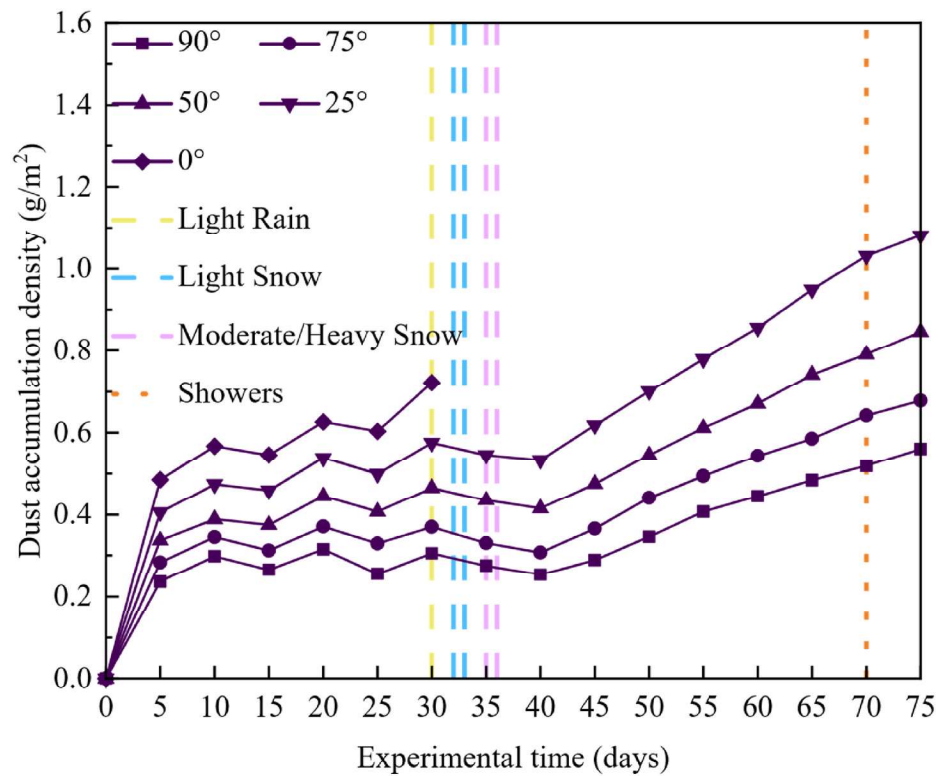


Fig. 10. Dust accumulation density on photovoltaic glass surface.

where, ρ_m represents the dust accumulation density for FEP film at a given angle, g/m²; ρ_0 represents the dust accumulation density for photovoltaic glass at a given angle, g/m².

As shown in Fig. 12, during the windy conditions on days 10-15 and

20-25, and the rain and snow conditions on days 30-40, the FEP film at a 25° tilt angle exhibits the better cleaning performance, with a larger K value compared to other angles. During the 10-15 day period, higher PM2.5 and PM10 in the air, combined with the strong southerly wind

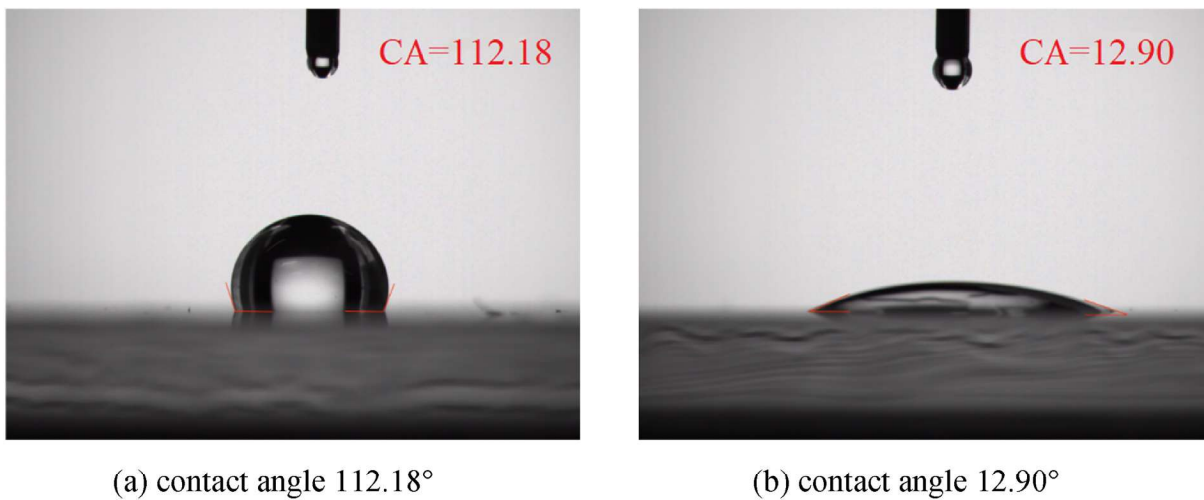


Fig. 11. Surface contact angles of FEP film (a) and PV glass (b).

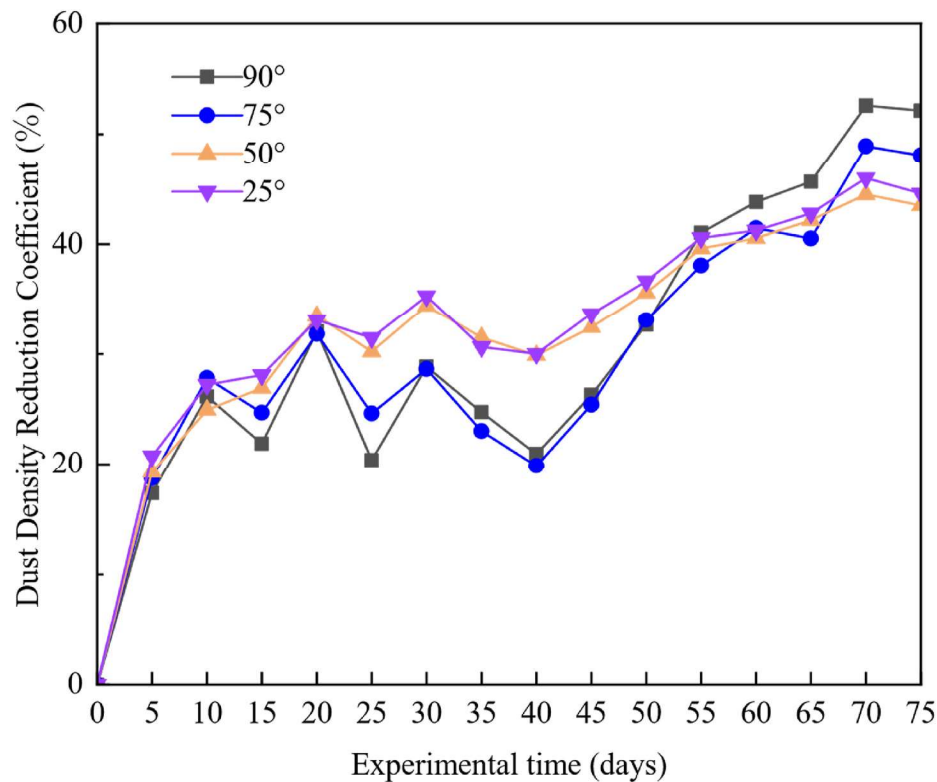


Fig. 12. Dust density reduction coefficient.

and the low surface friction coefficient and adhesion characteristic of FEP, allow the self-cleaning advantage to be more fully realized at lower tilt angles. In contrast, at higher tilt angles where gravity dominates, the difference in dust accumulation density between FEP and traditional glass is smaller, leading to a relatively lower K value. Similarly, during the 20-25 day period, with lower particulate concentration and north-west wind, dust is more easily removed from the surface of the low-tilt FEP film, whereas at high tilt angles, dust is mainly cleared by gravity, limiting the effectiveness of the FEP film. During the rain and snow period in days 30-40, material surface characteristics still play a dominant role at low tilt angles. The hydrophobicity of the FEP film causes rain and snow to form rolling droplets that effectively carry away dust. In contrast, the photovoltaic glass surface is prone to mud cementation,

forming retained water films or stains, resulting in a large K value. At high tilt angles, the intensity of rain and snow scouring increases, diminishing the influence of material surface properties. The cleaning effects of FEP and glass become more similar, so the K value at 90° is lower than that at 25°. Under other weather conditions, judging by the rate of increase in the K value, the tilt angles of 90° and 75° demonstrate better self-cleaning effects due to gravity promoting easier dust slippage from steeper surfaces. Thus, under strong wind or rain/snow conditions, smaller tilt angles are more conducive to leveraging the self-cleaning advantages of FEP film. In breezy, windless, drizzling, or rainless conditions, larger tilt angles exhibit better anti-soiling performance, due to the combined action of large gravitational component, small adhesion, and strong hydrophobicity, resulting in a larger K value.

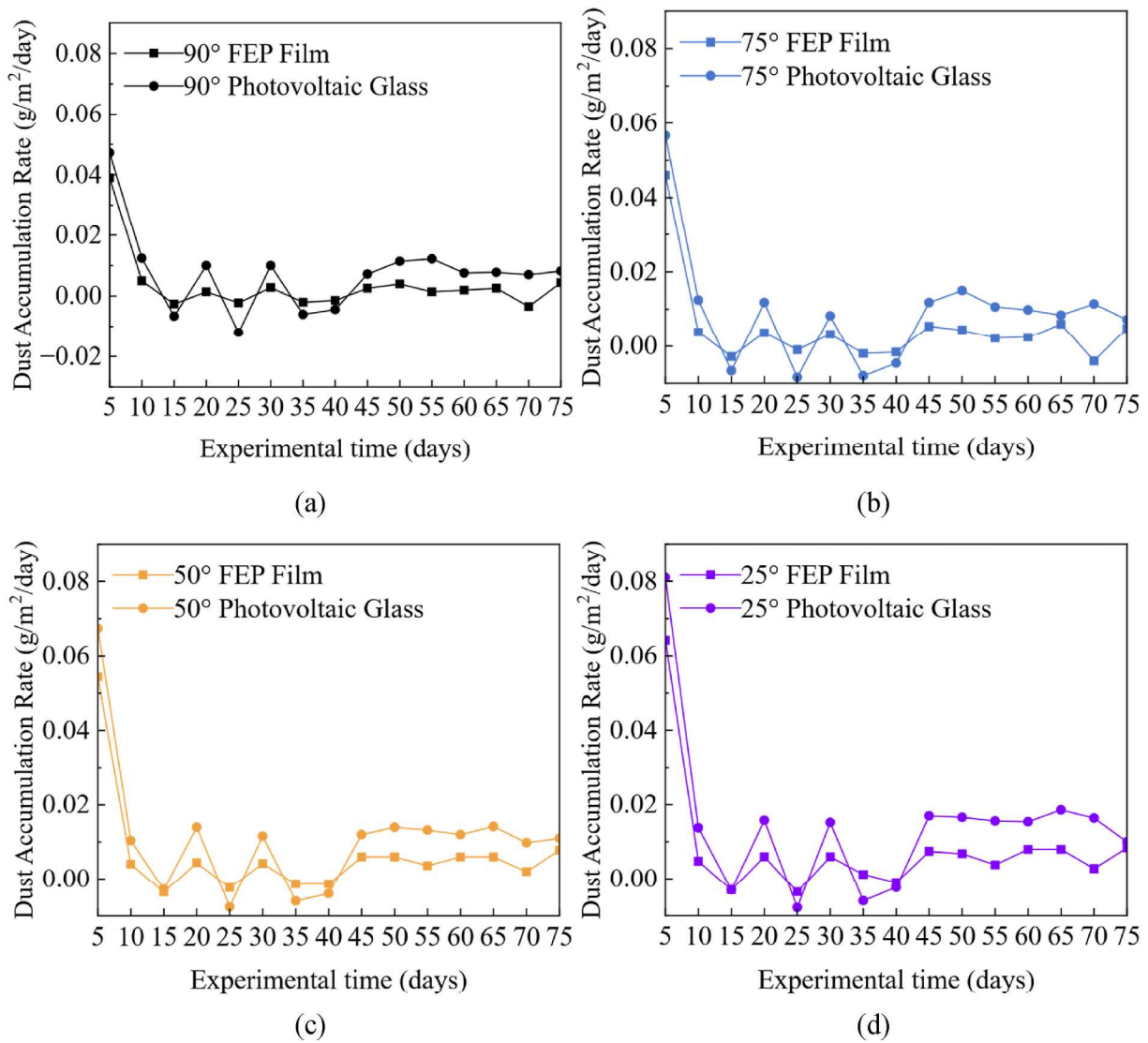


Fig. 13. Dust accumulation rate.

To more objectively reflect the impact of the environment on surface dust accumulation, the density change per unit time is introduced, expressed as the Dust Accumulation Rate (DAR):

$$DAR = (\rho_s - \rho_h) / \Delta d \quad (5)$$

where, ρ_s represents the dust accumulation density during a specific experimental period, g/m^2 ; ρ_h represents the dust accumulation density during the previous experimental period, g/m^2 .

As shown in Fig. 13, the average DAR of FEP film is lower than that of photovoltaic glass at all angles. At 25°, the average DAR of FEP film is 0.008 $\text{g/m}^2/\text{day}$, while that of photovoltaic glass is 0.014 $\text{g/m}^2/\text{day}$. This indicates that FEP film exhibits a slower rate of surface dust accumulation than photovoltaic glass, thereby achieving higher transmittance. It follows that, relative to photovoltaic glass, outdoor environments exert a lesser influence on the cleanliness of FEP films.

3.3. Photovoltaic characteristic

A. Load Resistance

Figs. 14 and 15 illustrate the comparisons in output current and voltage of solar cells respectively with FEP film and traditional

photovoltaic glass, at different load resistances and solar radiation intensities.

As shown in Figs. 14 and 15, when the load resistance remains constant, the output current and voltage gradually increase with rising solar radiation intensity. This occurs because the semiconductor material in the solar cell absorbs more photons, generating more electron-hole pairs through the photoelectric effect. The built-in electric field within the PN junction then separates these photo-generated carriers directionally, resulting in a larger photo-induced current [35]. When solar radiation intensity remains constant, increasing resistance causes output voltage to rise, but output current gradually decreases to a stable value. At higher solar radiation intensity levels, although the concentration of photogenerated carriers is greater, temperature rise intensifies the thermal motion of electrons in the semiconductor material, enhancing the probability of spontaneous recombination of electron-hole pairs. A significant number of carriers annihilate through recombination during transport, causing output current to decline more rapidly with increasing resistance, ultimately stabilizing around 0.17 A under all operating conditions. Under constant solar radiation intensity and load resistance, FEP film solar cell exhibits higher output current. This is because FEP film reduces light reflection and scattering. The transmittance measured by Fourier Transform Infrared Spectrometer remains above 92% across the entire spectrum (as shown in Fig. 16),

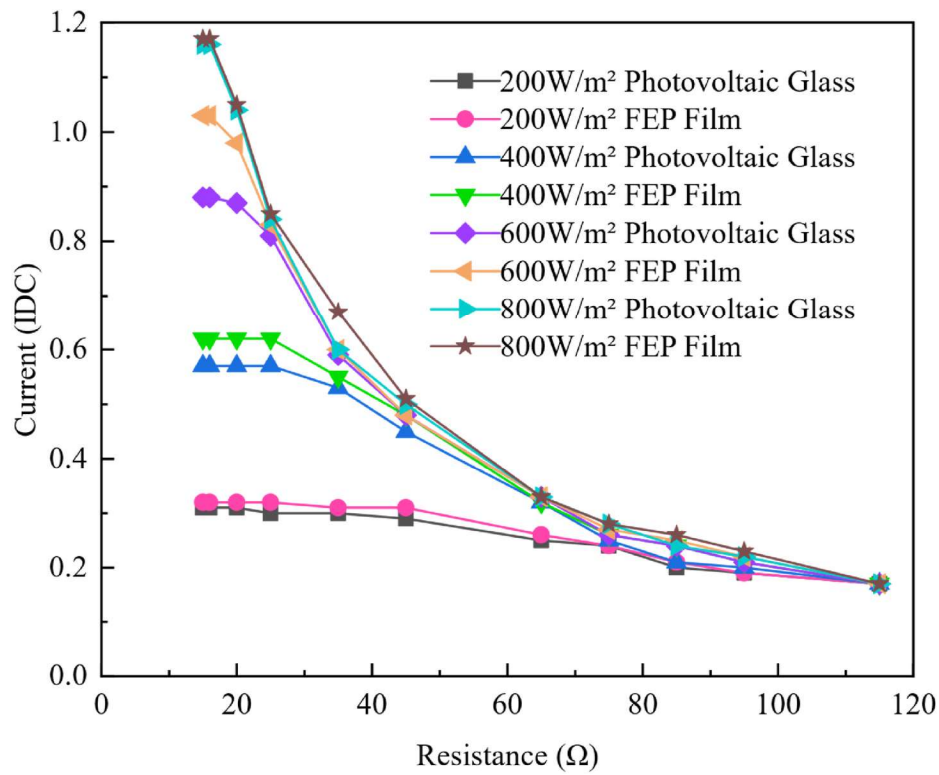


Fig. 14. Output Current vs. Resistance.

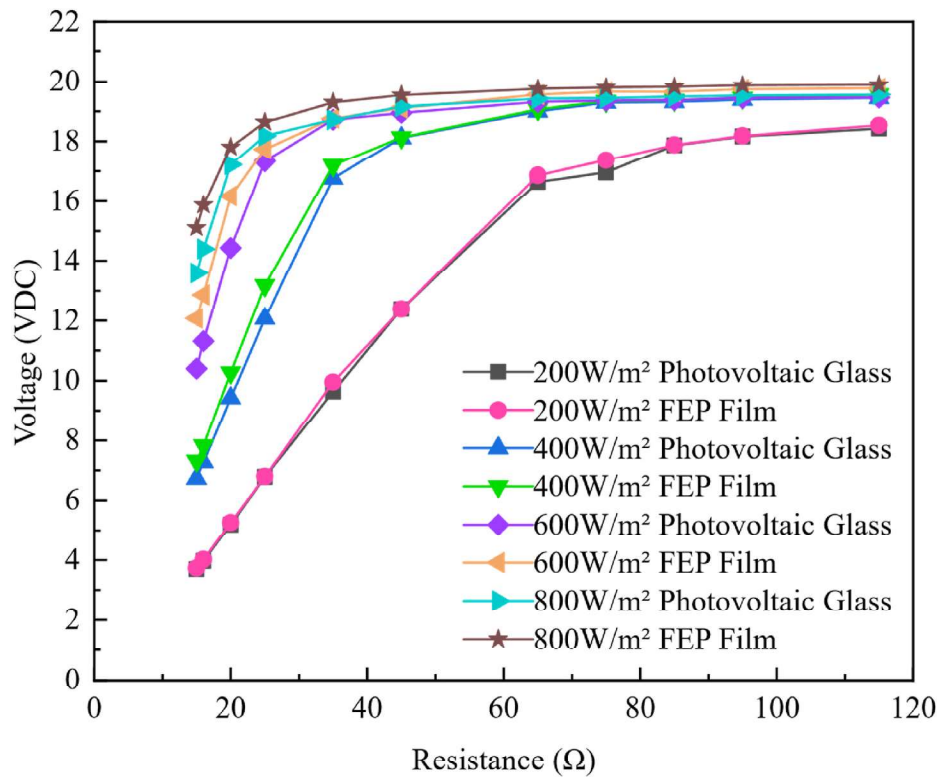


Fig. 15. Output Voltage vs. Resistance.

with a direct solar transmittance of 95.86%. Enhanced transmittance not only allows more photon energy to be absorbed and converted into current by the solar cell, thereby increasing output current and enabling more efficient conversion of solar energy into electricity, but also causes

greater heat accumulation on the solar cell surface. As shown in Fig. 17, the temperature of FEP film for the solar cell is higher than that of traditional glass under all solar radiation intensities, which also constrains the photovoltaic output characteristics. The measured

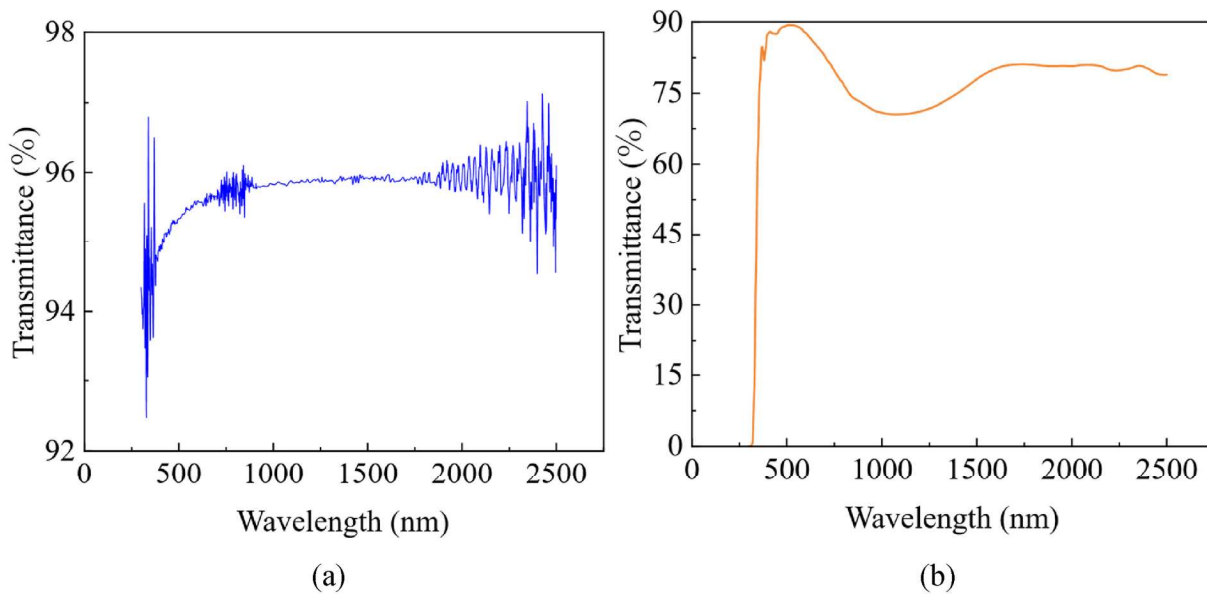


Fig. 16. FEP (a) and PV glass (b) Near-Infrared Transmittance.

temperature coefficient of power for the FEP film solar cell is $-0.42\%/^{\circ}\text{C}$. Potential mitigation strategies for the FEP-induced temperature elevation include passive ventilation design or phase-change material integration.

Fig. 15 also indicates that under the same solar radiation intensity, the output voltage of FEP film solar cell increases more rapidly and stabilizes sooner than that of traditional glass solar cell, particularly at higher solar radiation intensity levels. This demonstrates that FEP film can better optimize output voltage characteristics. This is attributed to the anti-reflective properties of FEP film, which allow more photons to be rapidly absorbed by the solar cell, enabling faster saturation of the photocurrent within the solar cell.

B Photovoltaic Characteristic Curve

Fig. 18 depicts the current-voltage curves in different solar radiation intensities for solar cells, respectively with FEP film and traditional glass.

At a given solar radiation intensity level, the output power of the solar cell first increases and then decreases. As the output voltage increases, the output current initially remains stable with slow variation, then begins to decrease rapidly. That is, when the output voltage remains within the range corresponding to the maximum power point, the output current changes minimally. This occurs because the current is primarily determined by sunshine at this stage and can be approximated

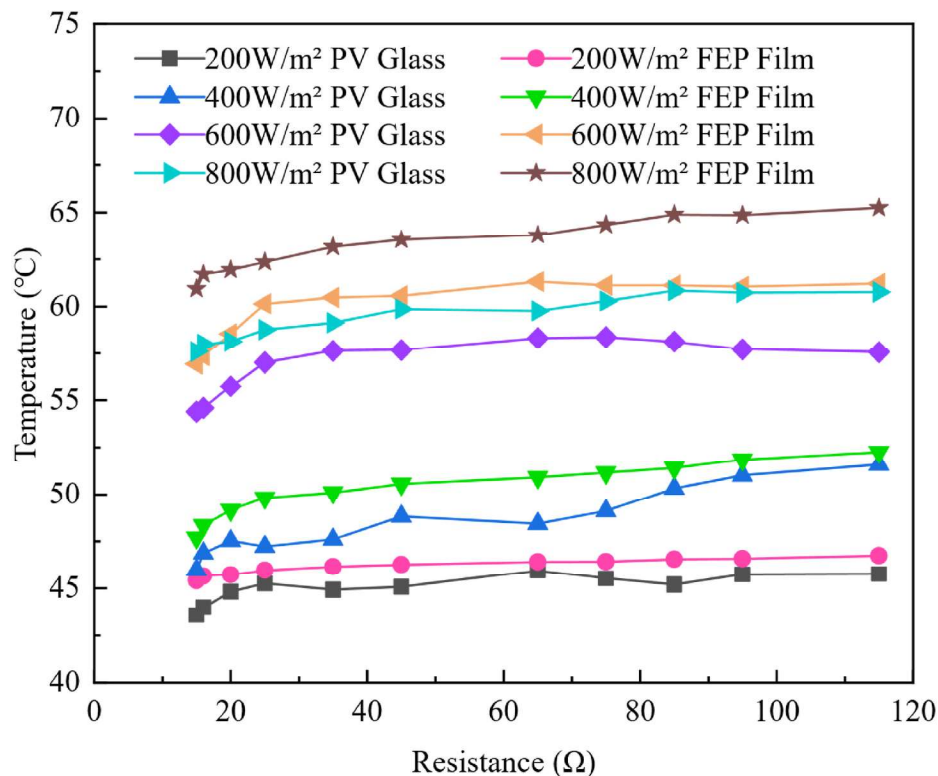


Fig. 17. Temperature vs. Resistance.

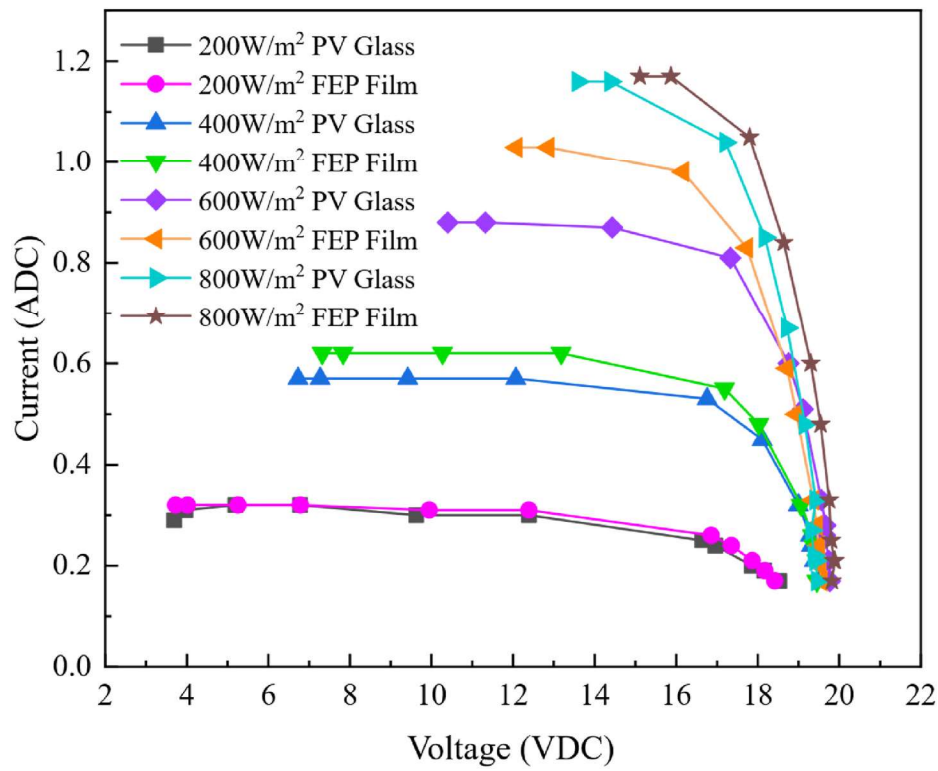


Fig. 18. Photovoltaic characteristic curve.

as a constant current source. However, as the voltage continues to increase toward the open-circuit voltage, the high voltage across the solar cell reduces the potential barrier at the PN junction. This significantly increases the reverse saturation current of the diode, causing the photo-generated current to be offset by the diode's leakage current, and consequently the net output current decreases rapidly. Fig. 18 indicates

that as solar radiation intensity changes from 200 W/m² to 800 W/m², the maximum power values of the FEP film solar cell are 4.38 W, 9.45 W, 15.85 W, and 18.69 W, exceeding those of the traditional glass solar cell by 5.29%, 6.03%, 4.62%, and 4.28%, respectively.

Based on experimental data, a cubic spline interpolation method is employed to plot the resistance corresponding to the maximum output

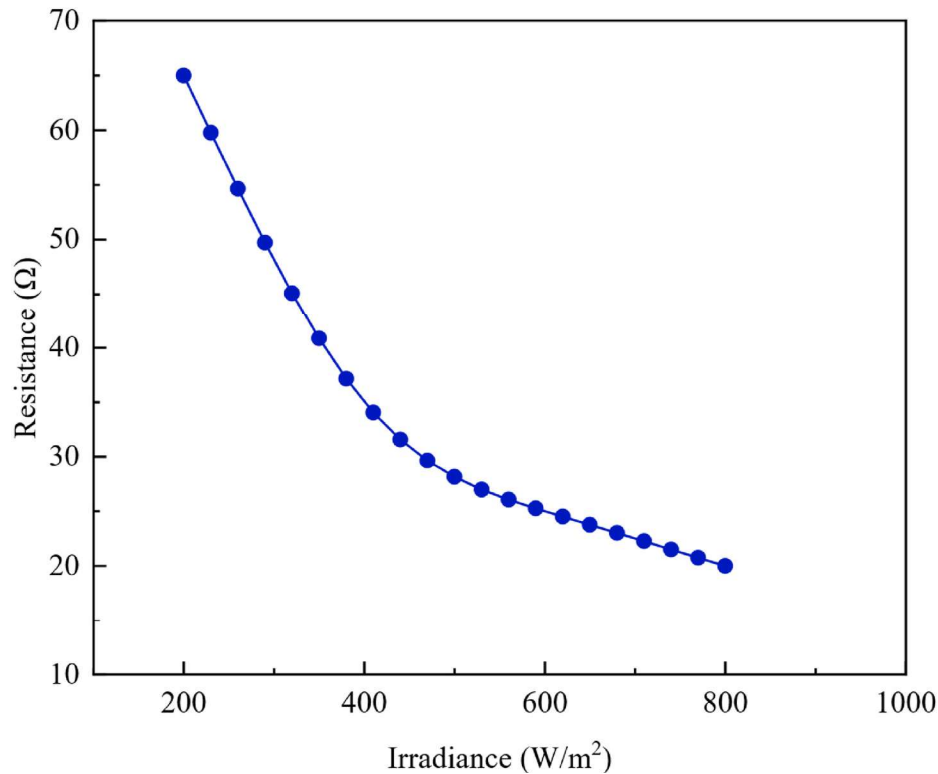


Fig. 19. Solar Irradiance vs. Load Resistance.

Table 3
Uncertainty of measured parameters.

Physical Quantity	Type B uncertainty $u(X)_B$	Type An uncertainty $u(X)_A$
Dust Mass	1.83%	3.88%
Area	0.709%	0.34%
Solar radiation	2.5%	1.79%
DC voltage	0.289%	0.564%
DC Current	0.866%	3.39%
Temperature	0.43%	0.329%

power at different solar irradiance levels, as shown in Fig. 19. When solar irradiance is low, the maximum power point of the solar cell corresponds to a high resistance value, while as the solar irradiance increases, the situation is the opposite. This occurs because increased solar radiation intensity raises the number of excited electron-hole pairs, significantly increasing the output current at the maximum power point, whereas the output voltage at the maximum power point remains relatively stable with minimal variation. This characteristic is essentially consistent with the pattern of open-circuit voltage variation, being primarily influenced by the material itself and temperature [36]. When solar radiation intensity changes from 200 W/m^2 to 800 W/m^2 , the load resistance value corresponding to the maximum power point decreases from 65Ω to 20Ω .

C. Experimental Error

The standard uncertainty in the experimental measurement has been evaluated using the Type B evaluation and the Type A evaluation methods [37], with the results presented in Table 3.

Based on the above uncertainty calculations, it is evident that the measured data in the self-cleaning and photovoltaic experiments, is reasonably reliable. The experimental results can be utilized for further analysis and research.

4. Case study

4.1. Random forest model

The output power of a photovoltaic (PV) module is determined by its I–V curve, which is a nonlinear function of parameters such as irradiance and temperature. While increased irradiance enhances photogenerated current, it also raises module temperature and reduces open-circuit voltage. These two effects are coupled through the exponential response of the I–V curve, causing changes in power generation to be far from a simple linear superposition. Such complex nonlinear coupling originates from the diode characteristics of PV cells and the distinct mechanisms by which environmental parameters affect electrical responses. By integrating multiple decision trees, Random Forest can capture intricate nonlinear relationships and interaction effects among variables without requiring predefined mathematical models. It is therefore particularly suited to such multi-factor coupled engineering scenarios and can directly handle mixed-type data—capabilities that traditional linear models lack. Therefore, this paper uses experimental data and employs Python programming to train a Random Forest model, then to predict the electricity generation for representative cities and analyze its application effectiveness. Based on statistical learning theory, its randomness is reflected in Bootstrap sampling (constructing the sample set) and the selection of splitting variables (e.g., solar radiation intensity). By integrating multiple decision trees generated through recursive node sample partitioning, the final results (current, voltage) are produced via voting or averaging [38].

Feature selection is a critical step in constructing decision trees, determining sample partitioning capability and model's final classification. It is essential for addressing photovoltaic data and sudden illumination changes. Methods include information gain, information gain rate, and Gini index. The Gini index offers the highest computational efficiency, making it more suitable for large-scale data processing. A lower Gini index indicates less data uncertainty, while a higher value signifies greater uncertainty. Let dataset D contain n samples, with its data category defined as $C = \{c_1, c_2, \dots, c_m\}$. These m category elements partition D into m subsets $\{D_1, D_2, \dots, D_m\}$. The Gini index of dataset D is

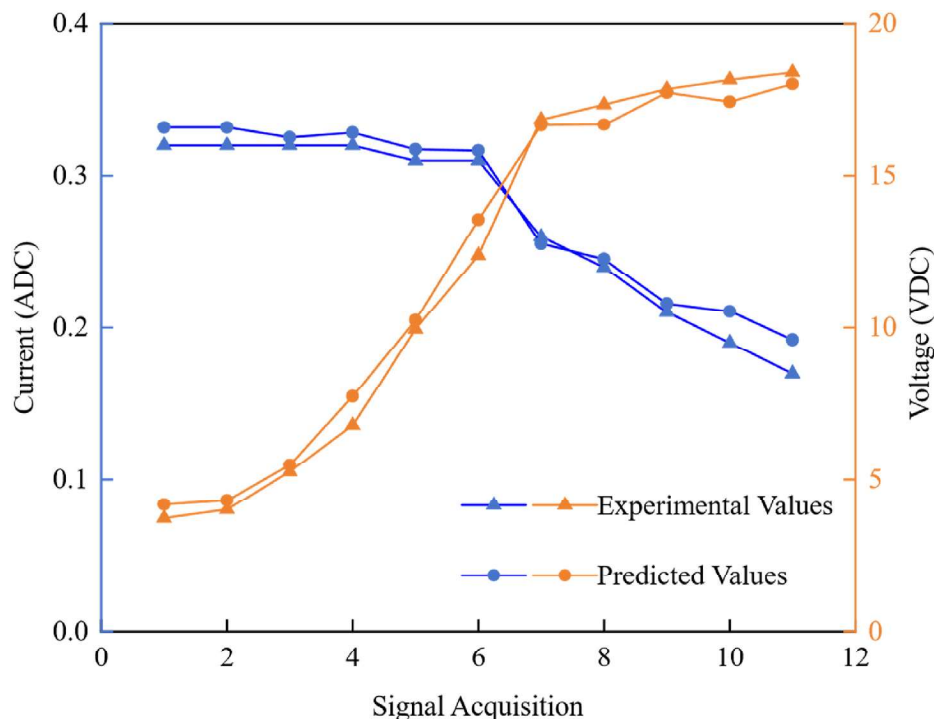


Fig. 20. Experimental values versus Predicted values for Current and Voltage.

Table 4
Typical cities.

Solar Resource Zone	Representative City	Annual Total Irradiation (MJ/m ²)	Annual Average Temperature (°C)
Class I	Hami	7475	10
	Hetian	7011	13
Class II	Ruili	6447	21
	Sanya	6346	27
Class III	Nanning	4234	22
	Zhanjiang	4716	24
Class IV	Guiyang	3581	15
	Yibin	3156	18

calculated as,

$$\text{Gini}(D) = 1 - \sum_{i=1}^m (|D_i|/n)^2 \quad (6)$$

where, n represents the total number of samples; D_i represents the number of samples belonging to category c_i .

Let A be a feature of dataset D , with k distinct values $\{a_1, a_2, \dots, a_k\}$.

Under the condition that $A = a_j$ ($j = 1, 2, \dots, k$), dataset D is partitioned into $D_1, \dots, D_h$ parts. The Gini index of this partition is,

$$\text{Gini}(D, A = a_j) = \sum_{i=1}^h (|D_i|/n) \text{Gini}(D_h) \quad (7)$$

where, D_h represents the subset of samples for which feature A takes the value a_j .

By comparison, the feature with the smallest Gini index is selected as the current optimal splitting feature. This feature maximizes the reduction of dataset uncertainty and enhances the purity of data partitioning. Based on this criterion, decision trees can automatically screen out the most effective features for photovoltaic data classification, providing a reliable feature selection method for accurately identifying critical issues such as sudden changes in sunlight.

During the model training process, the feature importance ranking derived from the random forest algorithm indicates that solar irradiance contributes most significantly to the predictive output, followed by internal resistance, while ambient temperature ranks lowest among the three input variables. A five-fold cross-validation method is employed in this study, wherein 80% of the samples are used as the training set and

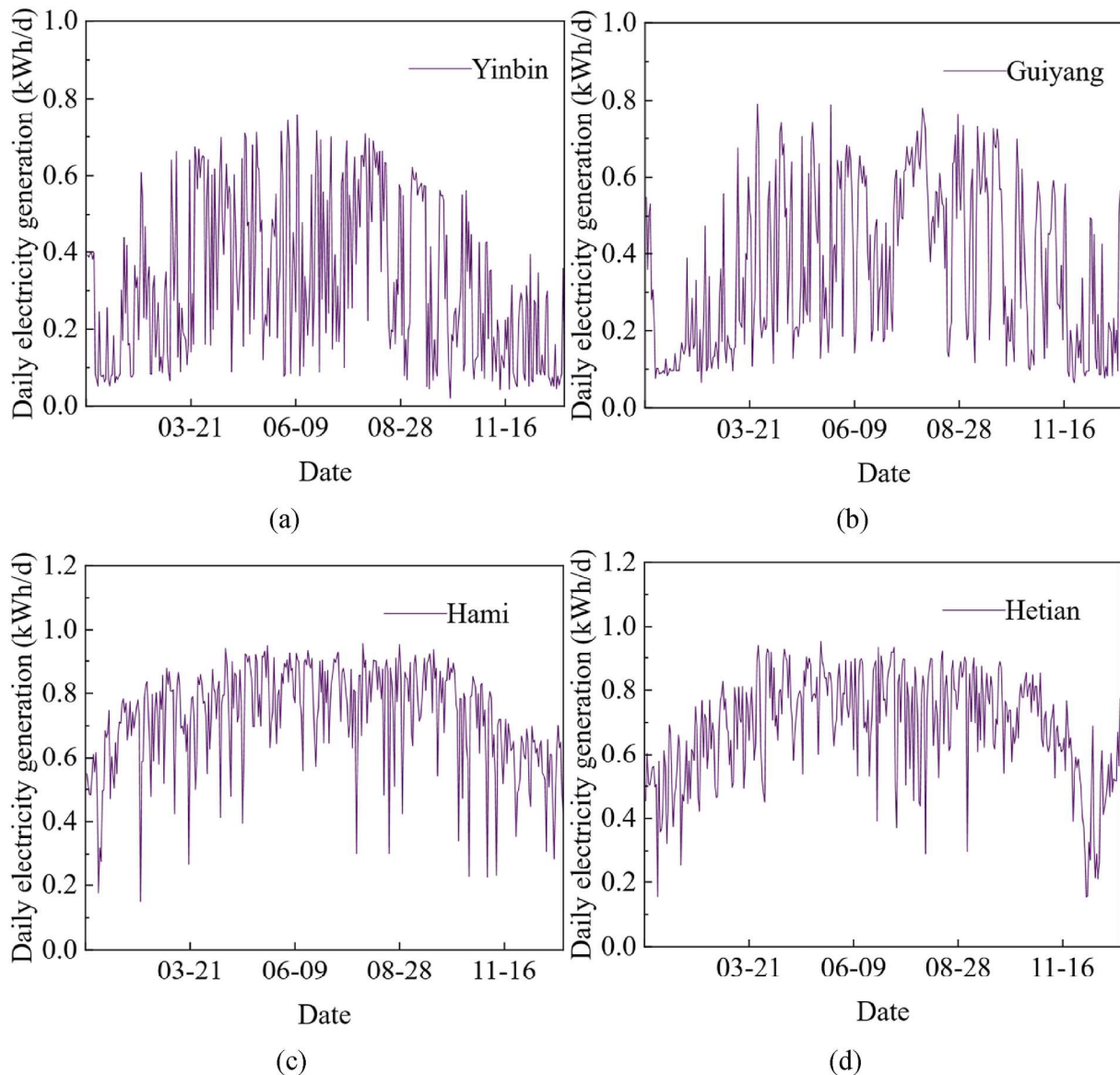


Fig. 21. Daily electricity generation by region.

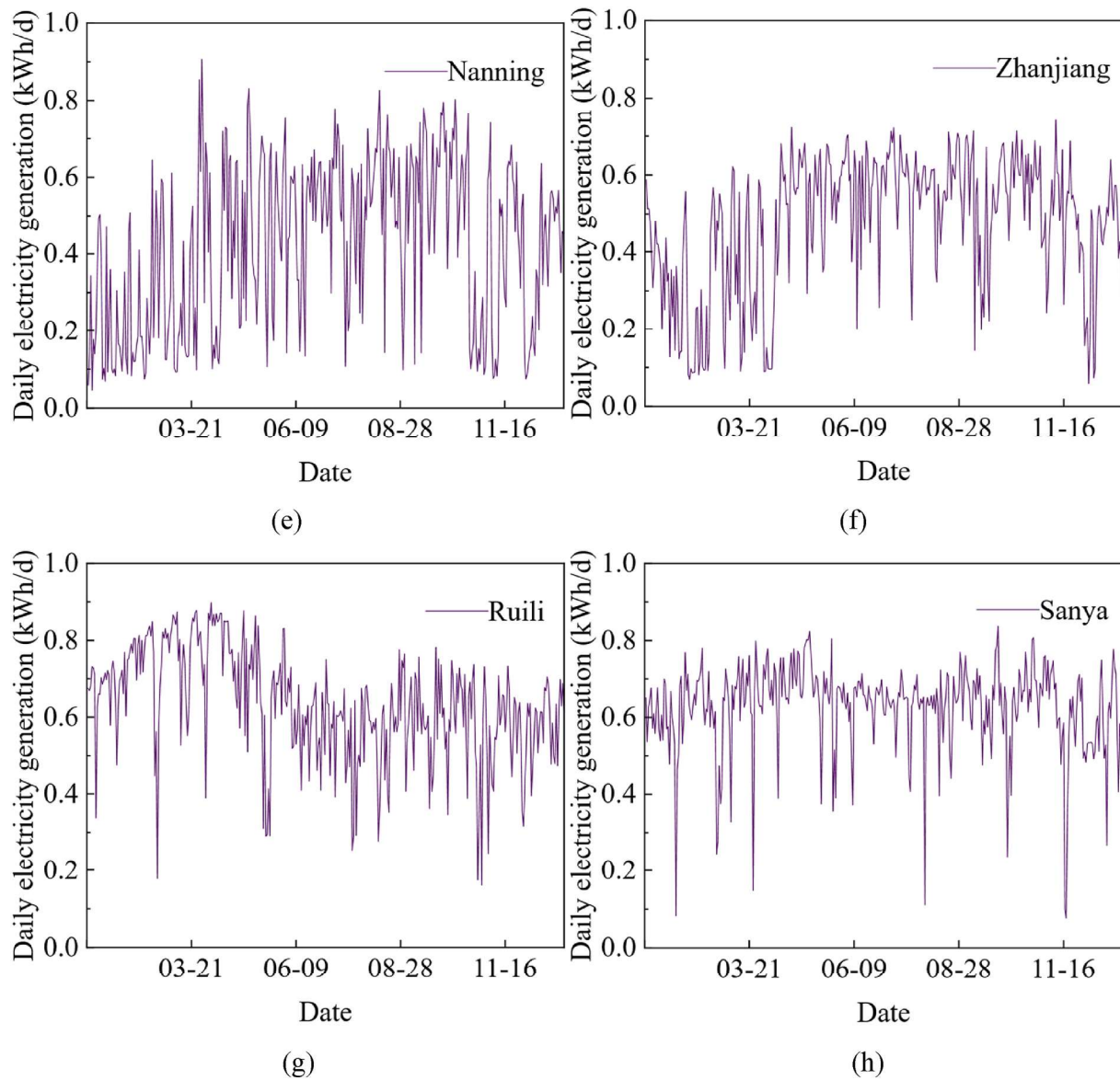


Fig. 21. (continued).

the remaining 20% as the validation set to evaluate the model's generalization performance and stability and to perform prediction. The cross-validation yields a coefficient of determination (R^2) of 0.968 ± 0.048 and a root mean square error (RMSE) of 1.182 ± 0.530 , demonstrating that the model maintains stable predictive accuracy and low variance.

Using parameters such as solar radiation intensity, resistance, and ambient temperature from the experimental data in Section 3.2 as input variables, while current and voltage as output variables, a random forest model has been trained. Fig. 20 shows the training results at a solar radiation intensity of 200 W/m^2 , with the predicted data compared to experimental values.

Fig. 20 demonstrates the random forest model's good accuracy, with predictions closely matching experimental data. The prediction accuracy can reach 96.59%, providing a reliable basis for the next step of predicting urban electricity generation.

4.2. Typical cities

Two representative Chinese cities from each of the four solar resource zones have been selected according to "Evaluation standard for application of renewable energy in buildings" [39], as shown in Table 4. The annual average temperatures are sourced from "Design code for heating ventilation and air conditioning of civil buildings" [40]. Hourly temperature and solar radiation intensity for each city are from "Typical meteorological database handbook for buildings" [41]. These data are then input into the random forest model in Section 4.1 to predict electricity generation for solar cells respectively with FEP film and traditional glass.

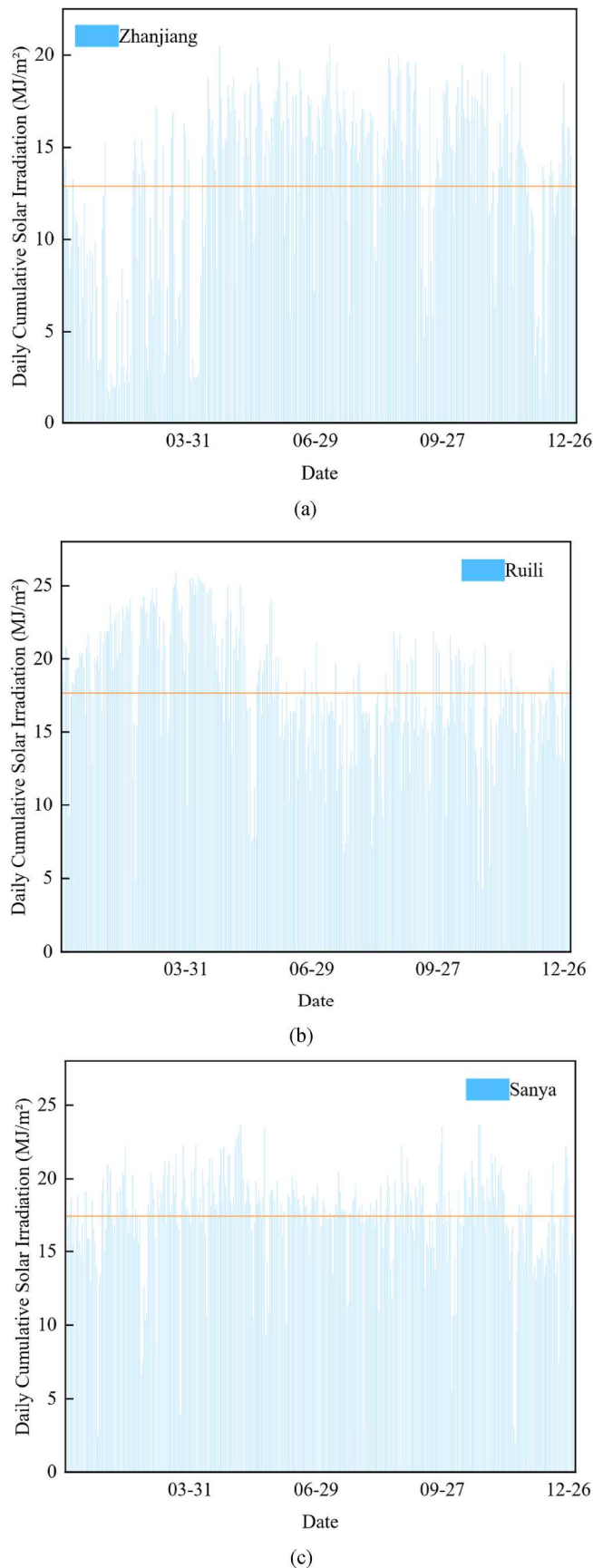


Fig. 22. Daily cumulative irradiation in three regions.

4.3. Prediction of performance enhancement

A Daily and Seasonal Electricity Generation

Fig. 21(a)–(h) display the daily electricity generation of solar cell equipped with FEP film for eight cities.

As shown in Fig. 21, the daily electricity generation in Yibin, Guiyang, Hami, Hetian, and Nanning exhibits identical trends over time, generally firstly rising and then declining. It exhibits a pattern of firstly decreasing, then increasing, and finally decreasing in Zhanjiang, while showing a trend of firstly increasing, then decreasing, and finally increasing in Ruili and Sanya. The maximum values of electricity generation in Zhanjiang, Ruili, and Sanya are 0.74 kWh, 0.9 kWh, and 0.84 kWh, respectively, occurring on November 10, April 5, and September 27. This occurs because electricity generation performance is significantly influenced by irradiance. The trend in daily electricity generation for Zhanjiang, Ruili, and Sanya is fundamentally consistent with that of daily cumulative irradiation, as shown in Fig. 21(f)–(h) and Fig. 22.

Fig. 21 also reveals significant seasonal variations in photovoltaic electricity generation across eight cities. Yibin, Guiyang, Hami, and Hetian all exhibit peak quarterly generation during summer, followed by spring, and autumn and winter. Taking Yibin as an example, electricity generation reaches 39.49 kWh in summer, dropping by 38.37% in autumn. This occurs because the spring and summer seasons in Yibin, Guiyang, Hami, and Hetian feature substantially higher hours of sunshine (duration with solar radiation intensity exceeding 120 W/m^2), compared to autumn and winter. Their quarterly total irradiation also follows the pattern of higher value in spring and summer than in autumn and winter (see Figs. 23–24). Nanning and Zhanjiang exhibit peak quarterly electricity generation during summer and autumn, with relatively lower output in spring. This is partly because sunshine duration in spring for these cities is shorter than that in autumn (see Fig. 23), and partly due to persistent frontal precipitation caused by southward-moving cold air, and warm and moist air current from the South China Sea during spring, resulting in predominantly stratocumulus cloud cover [42]. Stratocumulus clouds have high reflectivity, reducing the amount of radiation received at the surface and decreasing the solar radiation absorbed by solar cell. Nanning's electricity generation in spring is 14.45% lower than that in autumn, while Zhanjiang's spring generation is 14.81% lower than that in autumn. Conversely, Sanya and Ruili exhibit significantly lower electricity generation in summer than that in spring, with their quarterly peak total generation occurring in spring (see Fig. 21(g)–(h)). On one hand, although that Sanya has longer daily sunshine hours in summer, the low solar radiation intensity at each time results in lower total summer irradiation. On the other hand, as shown in Fig. 25, Sanya's average summer temperature exceeds 29.8°C . High temperature increases the intrinsic carrier concentration in semiconductor materials, weakening the built-in electric field at the P-N junction and thereby reducing the open-circuit voltage [43]. Since that the impact of temperature on short-circuit current is relatively limited, power reduction occurs, decreasing by approximately 0.4% for every 1°C increase in temperature [44]. Similarly, Ruili's summer and autumn electricity generation is significantly lower than spring levels, primarily influenced by seasonal total solar irradiation. Ruili's subtropical monsoon climate features intense southwest monsoons during the rainy season, delivering abundant moisture that concentrates over half of annual precipitation in summer and autumn [45]. Persistent thick cloud cover significantly reduces solar irradiation, resulting in Ruili's summer and autumn solar irradiation respectively of 1432 MJ/m^2 and 1438 MJ/m^2 , lower than that in spring (see Fig. 24). As shown in Fig. 21, except for Ruili, the winter electricity generation of other cities is lower than that in other seasons, in view of reduced sunshine duration and lower radiation levels. Due to Ruili's low latitude maintaining a high solar altitude angle, the reduction of daylight hours in winter is less

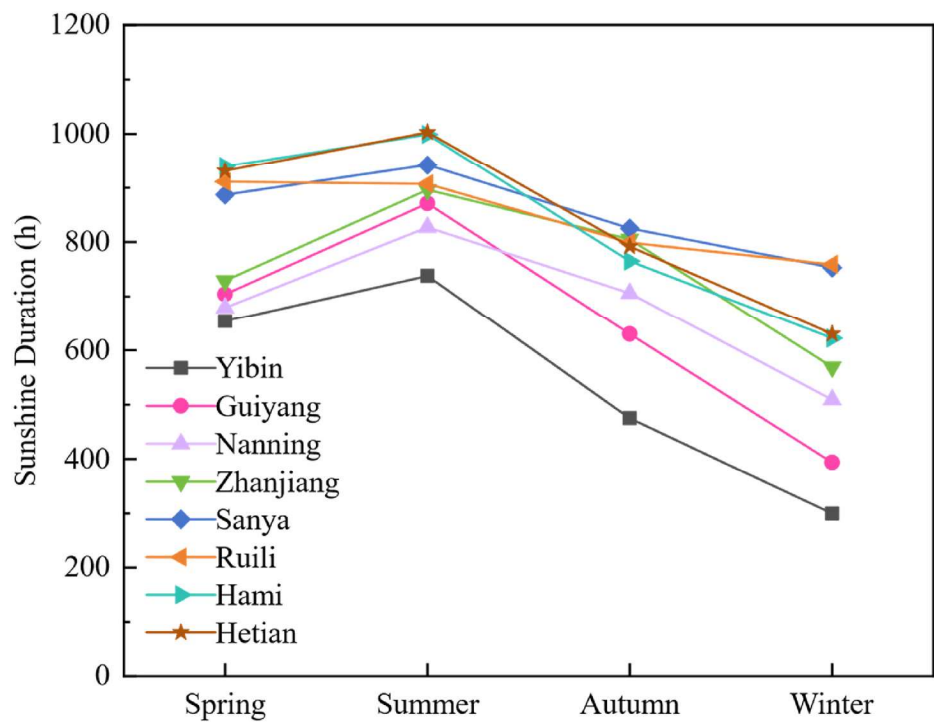


Fig. 23. Sunshine duration by region.

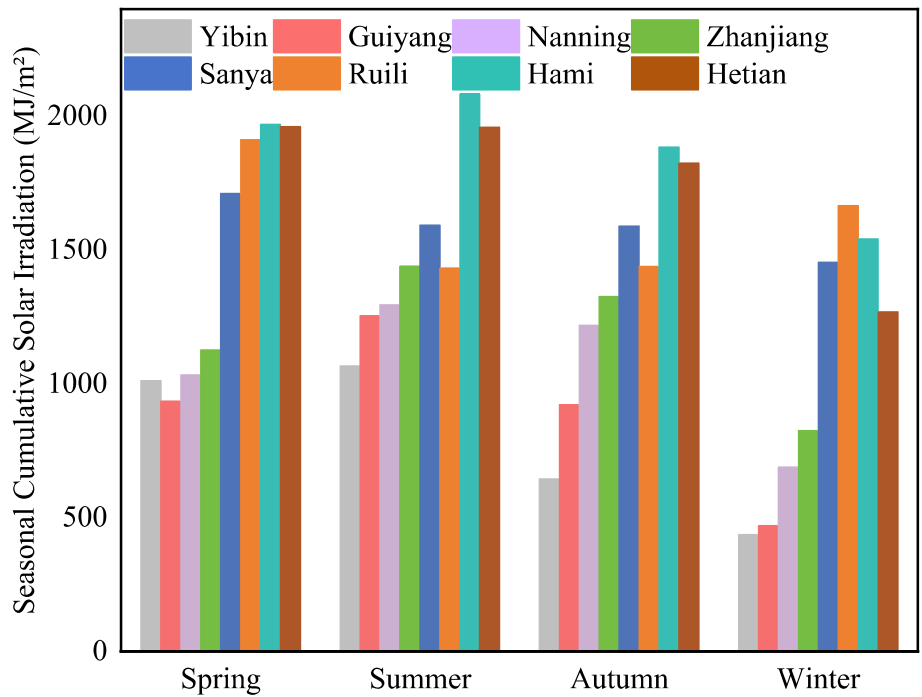


Fig. 24. Seasonal cumulative solar irradiation by region.

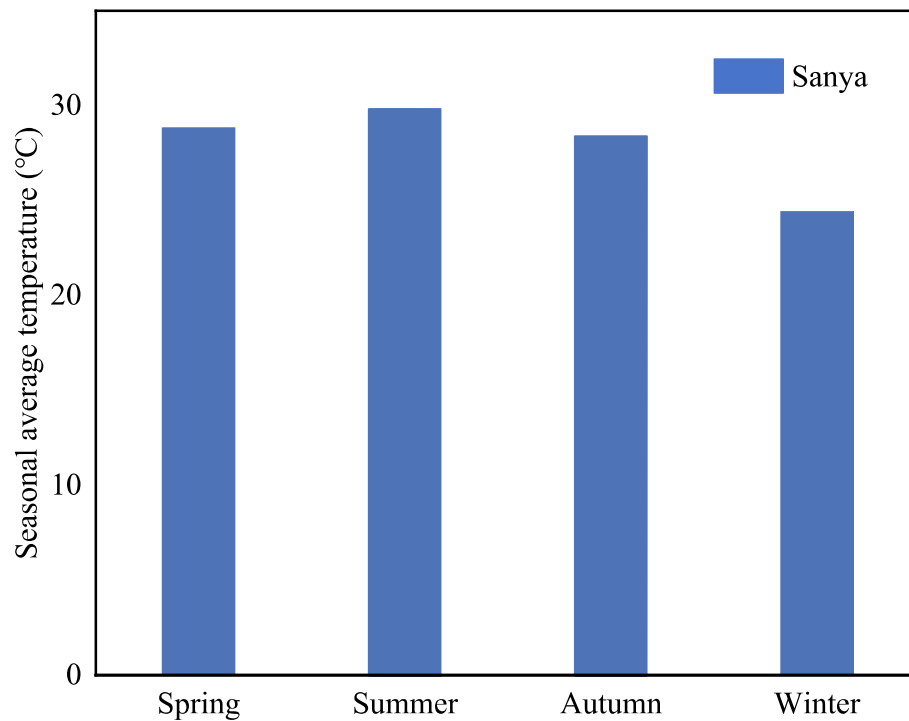


Fig. 25. Seasonal average temperature in sanya.

pronounced. At the same time, there are many sunny days and few cloud cover in winter. High-elevation location on the Yunnan Plateau also enhances atmospheric light transmission, resulting in the higher electricity generation in winter, second only to that in spring.

B Annual Electricity Generation

Fig. 26 shows the annual electricity generation of FEP film and traditional glass solar cells across various cities.

As shown in Fig. 26, both of FEP film and traditional photovoltaic glass exhibit significant regional variations in photovoltaic electricity

generation performance, along with Hami ranking first, followed by Hetian, Ruili, Sanya, Zhanjiang, Nanning, Guiyang and Yibin in turn. Meanwhile, compared to photovoltaic glass, the performance of FEP film solar cell has improved in all eight cities, with an average increase of 5.67%. Among them, the enhancements in Yibin and Guiyang are significant, respectively reaching 6.35% and 6.4%. This is attributed to their frequent overcast and rainy weather, which results in high ambient humidity and reduced solar irradiance. The annual total radiation in Yibin and Guiyang is only 3156 MJ/m^2 and 3581 MJ/m^2 . Increased humidity exacerbates the Potential Induced Degradation (PID) effect, detrimental to electricity generation [46]. Using water as the polarity

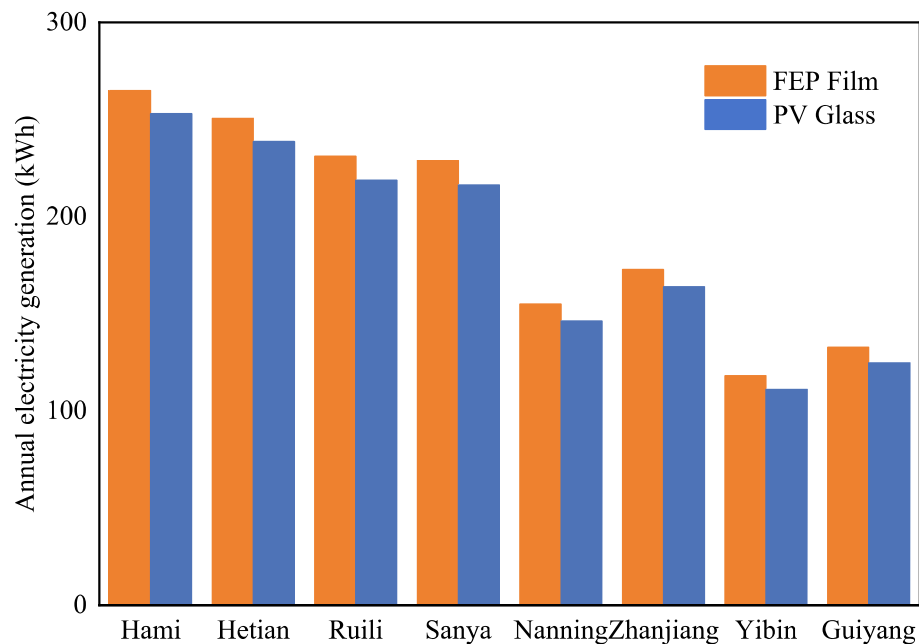


Fig. 26. Annual electricity generation by region.

benchmark, the FEP film exhibits an absorption rate below 0.01% [47], which exhibits excellent moisture resistance, blocking water vapor intrusion and reducing the risk of PID, thereby significantly enhancing the electricity generation of solar cell equipped with FEP film. Hami and Hetian show smaller increases of 4.72% and 5.01%, respectively. This is because Hami and Hetian belong to Class I solar resource zones with exceptionally abundant solar resources. Hami's annual total irradiation is 7475 MJ/m², while Hetian's is 7011 MJ/m². High irradiance exceeding 800 W/m² accounts for over 19%. The FEP film, possessing high transmittance, exhibits greater probability of multiple exciton collisions due to larger solar irradiation delivered onto the semiconductor material, more readily inducing Auger recombination effects [48]. The underlying principle is that elevated temperatures cause an exponential increase in the concentration of thermally excited charge carriers, leading to a contraction of the bandgap. This results in the substantial recombination of photo-generated carriers, causing their disappearance. Consequently, the number of effective carriers available for electricity generation diminishes, thereby suppressing the photovoltaic effect. In regions characterized by high ambient temperatures, the diminished temperature differential between the module and the sky suppresses radiative cooling efficiency, thereby exacerbating the elevation of operating temperatures [49]. Concurrently, under high irradiance conditions, the augmented current density amplifies ohmic losses—which scale with the square of the current—resulting in degradation of the fill factor [50]. Moreover, elevated temperatures alter the refractive index of silicone encapsulants, inducing spectral mismatch in antireflection coatings and contributing to short-circuit current losses in multi-junction cells [51]. Thus, the electricity generation enhancement rate of films incorporating FEP is relatively modest. Ruili and Sanya have annual total irradiation of 6447 MJ/m² and 6346 MJ/m², respectively. Electricity generation with FEP film increases by 5.66% in Ruili and 5.85% in Sanya. Zhanjiang's annual solar irradiation is lower, 4716 MJ/m². Due to significant fluctuations in its daily cumulative irradiation, electricity generation decreases under high irradiance due to the Auger recombination effect and under low irradiance due to the inability to excite the photovoltaic effect. The combined effect of these two factors results in only a 5.4% increase in Zhanjiang.

5. Conclusion

This study proposes FEP film—characterized by high permeability, excellent anti-dust adhesion ability, and lightweight properties—as an alternative to traditional glass applied in solar cell. Comparative experiments on self-cleaning and photovoltaic characteristics in between have been conducted to investigate its beneficial effects. Main conclusions are drawn as follows.

- FEP film exhibits markedly superior anti-dust adhesion performance, with the dust density reduction coefficient up to 52.6%. It features a relatively low surface friction coefficient and adhesion force, reducing the adsorption strength and adhesion stability of dust particles. Meanwhile, its hydrophobicity (contact angle of 112.18°) prevents water from spreading and forming liquid bridge on the surface, thereby cutting off the dissolution and recrystallization of soluble dust particles and avoiding cementation phenomena. Benefiting from these surface properties, the more pronounced self-cleaning effect of FEP film at lower tilt angle is observed under strong wind, rain, or snow conditions. However, in calm or light wind and light or no rainfall conditions, subject to the gravitational effect, the cleaning effect is more prominent at higher tilt angles. Moreover, outdoor environmental factors exert minimal influence on the self-cleaning performance of FEP film, with the average dust density change rate decreasing by 38.9% compared to traditional glass.
- FEP film solar cell captures more photon energy, thereby exciting more electron-hole pairs, accelerating the attainment of saturation

photocurrent, and stabilizing output voltage. Compared with traditional glass solar cell, the maximum power output is enhanced by 4.28–6.03%. Furthermore, as incident solar irradiation increasing, the output current increases. However, the operating temperature of the solar cell also rises correspondingly, which increases the intrinsic carrier concentration and weakens the built-in potential of the PN junction. As a result, output voltage shows little variation, and the resistance corresponding to the maximum power value decreases.

- Training a regression model based on the random forest algorithm using existing experimental data, the simulations reveal that significant regional differences in photovoltaic power of eight cities across China's four solar resource zones, regulated by factors such as irradiation, temperature, and humidity etc. Meanwhile, electricity generation in each city exhibits pronounced seasonal fluctuations, closely related to sunshine duration, temperature variation, and climate type etc. Compared to traditional glass, FEP film solar cell yields minor gain in regions with annual total irradiation exceeding 7000 MJ/m², due to more likely induced Auger recombination effect. It demonstrates a significant gain of about 6.4% in regions with annual total irradiation below 3600 MJ/m² and lower outdoor temperature, while a moderate gain level in areas with annual total irradiation between 3600 MJ/m² and 7000 MJ/m² and higher outdoor temperature.

While FEP's durability reduces replacement-related carbon and enables mechanical recycling at end-of-life, substitution for glass entails higher upfront cost yet offers system-level weight savings in select applications.

CRediT authorship contribution statement

Xianli Li: Writing – review & editing, Validation, Methodology. **Huazhi Dong:** Writing – original draft, Formal analysis. **Xu Chen:** Supervision, Formal analysis. **Chen Liu:** Software, Methodology. **Wanxiang Yao:** Visualization, Validation. **Yao Chang:** Data curation, Conceptualization.

Declaration of competing 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.

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Data availability

Data will be made available on request.

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