



A transient multiphysics modeling framework for microclimate in photovoltaic-integrated green roofs

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ARTICLE INFO

Keywords:

Photovoltaic integrated green roofs (PVIGR)
Dynamic 3D CFD modeling
Suggested modeling framework
Microclimate analysis

ABSTRACT

Rooftop photovoltaic (RPV) systems can increase local temperatures and reduce module efficiency due to high solar absorption, whereas photovoltaic-integrated green roofs (PVIGR) can mitigate these thermal effects through their vegetated layers. Given the intricate coupled multiphysics processes governing the PVIGR microclimate, a CFD-based numerical framework is essential for quantifying the influence of meteorological conditions and system configurations, as well as for elucidating the underlying mechanisms under real-world operating conditions. However, existing numerical models often oversimplify physical processes within vegetation and inadequately represent rooftop conditions, which limits mechanistic understanding and, consequently, the development of targeted optimization strategies. This study develops a well-validated transient 3D CFD-based multiphysics modeling framework for the PVIGR microclimate, resolving turbulence, radiative heat exchange, shading, transpiration, and PV energy conversion. Three key methodological choices are evaluated: transient versus steady-state simulations, uniform versus power-law inlet wind profiles, and surface radiation versus heat source methods. Results show that transient simulations avoid exaggerated local overheating, the power-law wind profile better represents rooftop airflow, and volumetric heat sources accurately capture heat transfer within tilted PV modules, while surface radiation for vegetation surfaces accounts for uneven energy input caused by shading. Next, microclimate comparisons show that under the simulated environmental inputs, PVIGR lowers roof and module temperatures by up to 13 °C and 1.6 °C relative to RPV. These temperature reductions correspond to an estimated decrease of up to 80 W/m² in roof surface heat gain and a power increase of up to 2.6 W for a single module under the analyzed conditions. Finally, mechanism analysis shows that while vegetation mainly enhances module radiative heat loss, sub-module convection remains the dominant cooling pathway, suggesting that improved convective transfer may be a promising direction for enhancing PVIGR performance. The proposed numerical framework provides a modeling basis and mechanistic insights that inform PVIGR design and optimization. The results also indicate the potential of PVIGR systems for improving thermal regulation of the roof and PV performance.

1. Introduction

Solar photovoltaics (PV) are projected to dominate global renewable capacity expansion through 2030 [1]. In densely populated urban areas, land scarcity restricts ground-mounted installations, making rooftop PV (RPV) a vital solution [2]. However, commercial PV modules convert only a small fraction (20%) of incident solar radiation into electricity, while the majority is dissipated as heat [3]. The resulting thermal penalty degrades module efficiency and elevates rooftop heat exposure, raising concerns over the environmental impacts of widespread urban PV deployment [4–6].

Photovoltaic-integrated green roofs (PVIGR) combine elevated PV modules with underlying vegetation to mitigate these thermal challenges [7]. The plant can cool the roof and PV modules through evapotranspiration, while the modules provide shading that protects vegetation during periods of high solar load [8–10]. Field studies have reported local thermal and energy benefits [11,12]. However, these benefits are conditional rather than guaranteed, as they depend on weather conditions, plant species, system geometry, and near-roof airflow. Consequently, short-term empirical observations are insufficient to isolate these coupled processes or to generalize performance

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<https://doi.org/10.1016/j.energy.2026.142632>

Received 22 June 2026; Received in revised form 22 September 2026; Accepted 4 October 2026

Available online 10 October 2026

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beyond specific test sites. A physics-based numerical modeling framework is essential to evaluate precisely when and why PVIGR delivers environmental and energy advantages.

Numerical modeling has established an important foundation for examining PV-vegetation interactions in ground-mounted agrivoltaics. Costa et al. [13] quantified ground-level radiation attenuation and crop shading, whereas Kim et al. [14] estimated photosynthetically active radiation and economic outcomes under different shading ratios. Computational fluid dynamics (CFD) studies have extended this work by resolving PV temperature and airflow [15], incorporating soil physical and thermal processes [16,17], and representing vegetation effects [18]. These studies demonstrate the value of numerical modeling for characterizing agrivoltaic microclimates, but their direct transfer to PVIGR is limited by four rooftop-specific features: (i) modules are generally installed below 2 m for safety [19]; (ii) parapets and surrounding buildings attenuate the local wind field [20]; (iii) PVIGR commonly uses spatially dispersed, independently operated units rather than continuous arrays [19]; and (iv) vegetation is supported by a shallow substrate, typically less than 20 cm deep, constructed on the building envelope rather than rooted in natural ground [10].

PVIGR numerical research has evolved along distinct lines, with existing models primarily focusing on long-term energy yield or large-scale spatial configuration optimization. Specifically, Teng et al. [21] evaluated the power generation potential and city-scale environmental impacts of PV green roofs. Cavadini and Cook [22] coupled a roof energy balance model with a solar model and estimated the annual yield benefit of green roofs. Žižak et al. [23] calculated PV-green-roof energy fluxes from meteorological inputs and system geometry, including shading and view-factor treatments. Most recently, Xu et al. [24] developed a high-resolution bidirectional feedback framework to identify installation configurations and vegetation characteristics that improve module cooling. Although these studies have provided valuable insights into PVIGR performance at building and urban scales, their models generally overlook transient microclimate evolution, realistic near-roof wind profiles, and layer-resolved PV heat deposition. Recent comprehensive reviews [25–27] similarly identify the lack of a validated multiphysics framework that integrates these elements with radiative transfer, evapotranspiration, and coupled heat and moisture transport to predict PVIGR thermal and electrical responses. This limitation impedes the identification of the meteorological conditions and physical pathways governing PVIGR performance, thereby constraining targeted, configuration-specific optimization.

Addressing this research gap is imperative to elucidate how rooftop microclimates govern PVIGR performance, thereby advancing system design from empirical extrapolation to physics-based optimization. To this end, this study establishes and experimentally validates a transient 3D CFD multiphysics modeling framework tailored for PVIGR systems. The framework employs a sequential coupling strategy, wherein a steady-state turbulent airflow field is first resolved and subsequently used to drive dynamic radiation, sensible and latent heat, and moisture transport within the coupled PV-vegetation-soil-roof domain. By explicitly integrating turbulent aerodynamics, canopy transpiration, substrate moisture diffusion, shortwave/longwave radiative exchange, and PV energy conversion, this work advances PVIGR research through three main contributions:

- Systematic evaluation of modeling strategies: Three modeling choices are systematically evaluated to identify suitable approaches for rooftop PVIGR simulations: transient versus steady-state calculations, power-law versus uniform inlet wind profiles, and energy inputs for modules and vegetation.
- Quantitative assessment of thermal and electrical synergies: The dynamic thermal fields and power outputs of PVIGR are rigorously compared with those of the RPV system under realistic meteorological conditions, isolating the specific temperature reductions and electrical yield gains enabled by vegetation.

- Mechanistic elucidation of PV module cooling pathways: Surface heat flux distributions and energy balance components are explicitly deconstructed to quantify the relative contributions of radiative exchange and sub-module convective heat dissipation, establishing a physical foundation for PVIGR design optimization.

The subsequent sections are organized as follows: Section 2 details the development of the 3D CFD model and the simulation framework. Section 3 validates the model based on experimental data and provides a comparative analysis of the core modeling approaches. Section 4 compares PVIGR with a conventional PV roof, quantifies the thermal benefits of PVIGR for both the building roof and the PV modules, discusses case-based thermal responses, and outlines possible directions for the future improvement of PVIGR. Finally, Section 5 summarizes the key findings of this study. The appendices present grid convergence, uncertainty, and PV-soiling analyses to demonstrate the robustness of the simulations.

2. Methodology

2.1. Experimental site

The PVIGR experimental sites, located on the campus of the Hong Kong University of Science and Technology (HKUST) in Clear Water Bay, Hong Kong SAR (22.338°N, 114.264°E), are selected as the basis for CFD modeling, validation, and environmental data input. HKUST hosts one of the largest solar power systems in Hong Kong. The region is characterized by a typical maritime subtropical monsoon climate, with hot and rainy summers (May–September) and mild, dry winters (December–February). Overall, the high temperatures, humidity, and abundant solar radiation experienced in Hong Kong for most of the year, combined with its dense urban landscape and substantial energy demands, make it an ideal site for investigating PVIGR.

At each experimental site, a sensor tree is installed to monitor ambient temperature (T_{amb}), relative humidity (ϕ), wind speed, and wind direction. Pyranometers are employed to measure solar irradiance on both horizontal and tilted surfaces. Two fine-wire thermocouples are installed on one representative PV module, with one attached to the front surface and the other to the rear surface near the module center. The thermocouple junctions are placed in direct contact with the module surfaces and secured using transparent insulating tape, with fine wiring used to minimize physical disturbance. Operating on the Seebeck effect, these sensors determine temperature by measuring the generated thermoelectric voltage. For model validation, the rear-surface thermocouple serves as the primary benchmark for PV operating temperature. In contrast, the front-surface thermocouple is retained strictly as an auxiliary measurement due to unstable readings caused by direct solar exposure and surface adhesion challenges.

As illustrated in Fig. 1(a), the PVIGR experimental platform consists of two south-facing PV modules (Jinko Tiger 415 W), each measuring 1.8 m in length and 1.0 m in width, installed at a 22° tilt angle and positioned 0.6 m above a 0.2 m-thick soil layer planted with Sedum. In addition, a soil thermometer is installed beneath the PV panels, approximately 20 cm from the lower edge along the north-south centerline between the two modules, and the probe is inserted approximately 2 cm into the soil. The experimental platform has remained operational under continuous monitoring since February 2024. A quality-controlled 12-month monitoring record from February 2024 to January 2025, including PV module temperature, ambient air temperature, relative humidity, wind speed, and solar irradiance acquired at 1-min intervals, was analyzed and reported in our previous year-long field study [28]. The experimental data highlighted Sedum as an ideal ground cover plant for low-profile PV installations due to its excellent cooling performance, strong drought resistance, and minimal maintenance requirements. Furthermore, these measurements form part of a publicly available dataset comprising quality-controlled microclimate,



Fig. 1. The selected experimental sites. (a) PVIGR; (b) Concrete rooftop PV system (RPV).

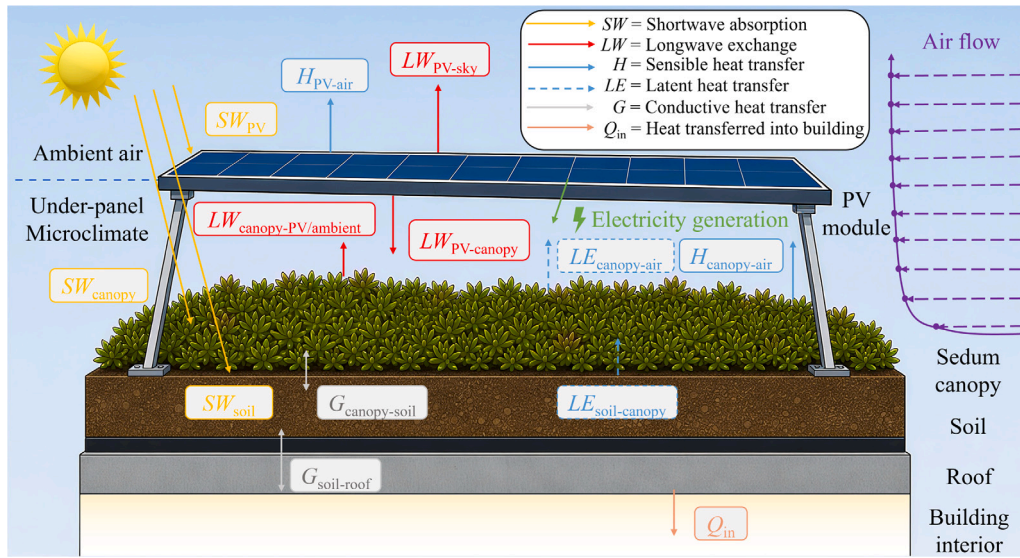


Fig. 2. Schematic diagram of the studied PVIGR system and related physical processes.

PV generation, and meteorological records from seven campus rooftops, spanning 1 April 2024 to 1 October 2025 [29].

For comparison, a reference RPV system with identical PV module specifications was constructed on an exposed concrete roof located approximately 50 m from the PVIGR platform, as shown in Fig. 1(b). Due to terrain constraints, PV modules in the RPV system are oriented at an azimuth angle of 240° with a tilt angle of 10° , a minimum clearance of 0.8 m above the ground and row spacing greater than 50 cm to minimize mutual interference. One of the thermocouples installed beneath the modules measures ground temperature, providing data to validate the model's accuracy in simultaneously simulating both ground and module temperatures.

2.2. Overall modeling framework

The intricate interactions between PV modules and green roof ecosystems yield distinctive combined effects through multiphysics processes. Indeed, the microenvironment formed by the integrated system represents a synergy of multiple effects. As shown in Fig. 2, the energy transport within the system is primarily driven by three key physical phenomena: (i) fluid flow, which includes airflow in the environmental and vegetation domains; (ii) heat transfer, encompassing solar radiation transfer, longwave radiative exchange between surfaces, conduction

in solid components, and convection between fluids and solids; and (iii) mass transfer, involving soil evaporation and plant transpiration. Furthermore, a portion of the solar radiation absorbed by PV modules is converted into electricity rather than heat, while their shading effect limits the underlying surface from receiving sunlight [30]. Taking all these factors into account, a comprehensive numerical multiphysics model is developed for the PVIGR system to elucidate the interaction mechanisms between photovoltaic modules and vegetation.

The complex structure and multi-scale nature of vegetation introduce significant modeling challenges, particularly when incorporating transpiration-induced cooling effects into the simulation. To accurately simulate microclimate changes driven by convection, radiation, evaporation, and transpiration, the vegetation domain is modeled as a porous medium. This approach reduces the computational complexity of leaf-resolved modeling while allowing the main 3D effects of plants on airflow, heat, and moisture transport to be represented at the canopy scale.

Fig. 3 illustrates the modeling framework proposed in this study. Environmental conditions, material properties, and PV configurations serve as inputs. Some of these are further parameterized based on theoretical analysis to derive the intermediate variables required for the CFD model. Appropriate sub-models are then applied to couple and

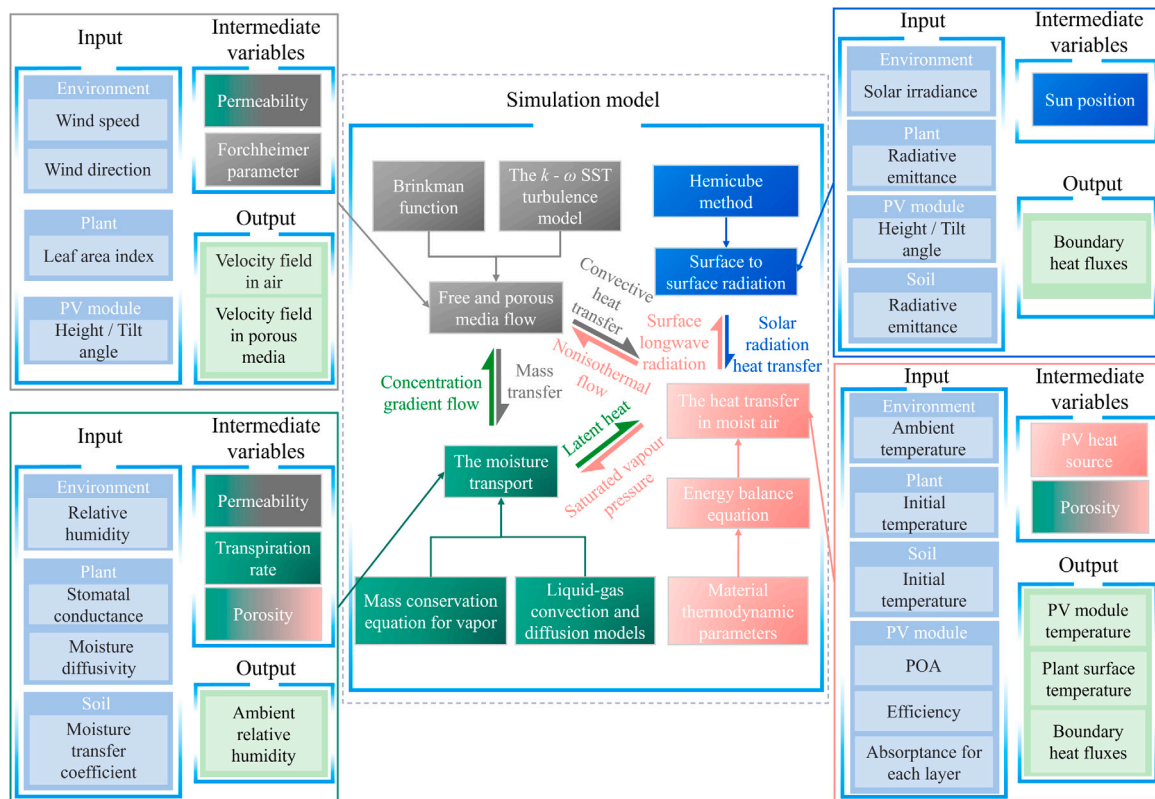


Fig. 3. Modeling process, framework and core parameters.

solve the physical fields, producing outputs that characterize the microclimate. Physically, the following four processes and their couplings are modeled simultaneously:

- (I) The free flow in the air domain and the flow through the porous medium within the vegetation.
- (II) The heat transfer in moist air and porous media involves both sensible and latent heat.
- (III) The transport of water vapor from vegetation and soil to the air occurs through evapotranspiration.
- (IV) The solar radiation incident on the system, along with the solar and thermal longwave radiative exchange between the PV modules and the plants, includes shading effects.

These processes are implemented in COMSOL Multiphysics using the Free and Porous Media Flow interface, with the Brinkman formulation applied in the porous vegetation domain; Heat Transfer in Moist Air; the Moisture Transport in Air interface, with the Hygroscopic Porous Medium formulation applied to moisture transport in the porous vegetation domain; and Surface-to-Surface Radiation interface. Fig. 3 summarizes the coupling among these interfaces.

2.3. Modeling geometry and material properties

In this study, COMSOL Multiphysics is utilized to simulate the microclimate of the PVIGR system. A full-scale 3D CFD model is developed based on the experimental site, incorporating the free air domain, ground, soil (simplified as a solid body), vegetation (modeled as a porous medium), and PV modules.

The size of the air domain in the model substantially influences the simulation results, particularly the velocity field and the resulting convective heat transfer calculations. As shown in Fig. 4(a), the computational domain is defined as $16 \text{ m} \times 12 \text{ m} \times 5 \text{ m}$, based on the following considerations:

- The height and width of the air domain are defined based on the blockage ratio of the PV modules. In rooftop scenarios, considering that the wind load increases significantly at higher elevations, the tilt angle of the modules is typically within 30° . This geometry will result in a maximum blockage ratio of 3% under the proposed air domain, aligning precisely with the recommended threshold [31].
- The streamwise extent of the computational domain is selected to allow sufficient flow development upstream of the PVIGR unit and to limit the direct influence of the inlet boundary on the local flow field. In the present model, the inlet boundary is placed at a distance greater than five times the chord length of the PV module [32].
- To verify whether the domain length is sufficient to achieve fully turbulent airflow, the Reynolds number (Re) is calculated using a typical wind speed of 2 m/s and the distance from the velocity inlet to the soil center as the characteristic length. Compared to the critical threshold of 5×10^5 for turbulent flow over a flat plate [33], the resulting $\text{Re} = 1.0 \times 10^6$ confirms that the airflow is fully turbulent at the domain outlet.

Furthermore, the presence of the planter's outer wall results in the vegetated area being slightly smaller than that of the soil. The experimental platform features Sedum, a low-growing species from the Crassulaceae family, with the vegetation height set at 0.2 m above the soil surface. The modeling of the PV modules is fully consistent with the experimental setup, fixed in a south-facing orientation and reconstructed layer by layer to replicate their actual structure, with a total thickness of approximately 4.6 mm, as shown in Fig. 4(b). This describes the typical structure of a monofacial monocrystalline PV module, characterized by a slim overall thickness and an anodized aluminum alloy frame enclosing the edges, with a thickness of less than 2 mm. In the model, this frame is simplified by assigning aluminum properties to the four boundary surfaces.

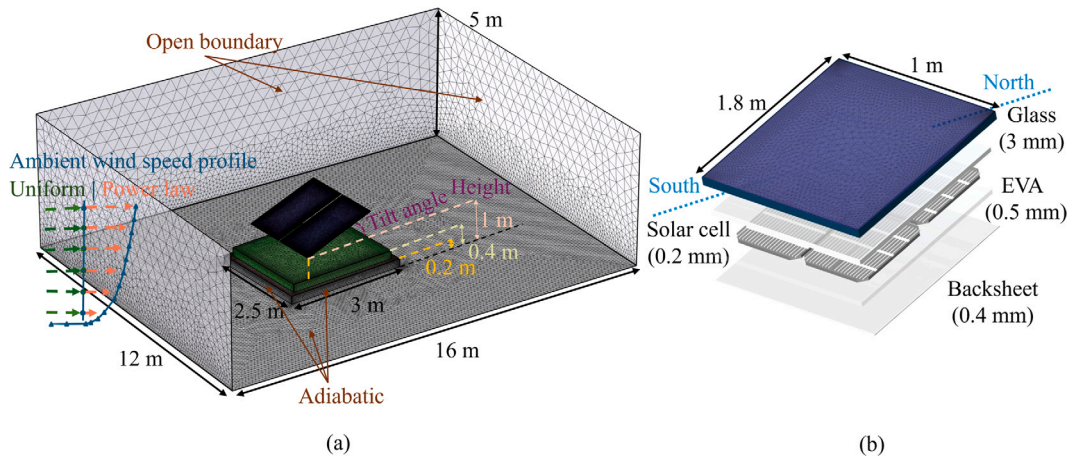


Fig. 4. Geometry of the modeling domain, mesh scheme, dimensions, and key variables. (a) Computational domain; (b) PV module.

Table 1
Material properties in the model.

Material	Density [kg/m ³]	Thermal conductivity [W/(m K)]	Specific heat capacity [J/(kg K)]	Solar absorptance	Thermal longwave emittance
Glass	2450	0.70	790	0.02	0.85
EVA	940	0.21	1560	0.04	–
Solar cell	2330	130	677	0.91	–
Backsheet	1200	0.15	1250	0.20	0.90
Concrete rooftop	1980	1.37	880	0.65	0.90
Soil	2086	2.05	1695.7	0.80	0.70
Vegetation	600	0.50	1470	0.84	0.95

Note: “–” indicates the parameter is not applicable in this layer.

In addition to geometric dimensions, the thermophysical properties of each PV module layer, as well as those of the concrete rooftop, soil, and vegetation [34–41], are crucial for accurately simulating the physical processes, which are summarized in Table 1.

2.4. Assumptions and governing equations

The CFD model is based on a set of assumptions that reduce computational complexity and mitigate numerical instabilities while ensuring physical fidelity. These assumptions allow for accurate results to be obtained within a manageable time frame, even with the coupling of multiple physical fields.

- Given the negligible impact of the double-column mounting structure on the area beneath the PV modules, the support pillars are excluded from the model.
- Each layer in the PV module uniformly absorbs incident radiation, and the cell layer is opaque to sunlight.
- The module rear-surface temperature is used to approximate the cell operating temperature [42].
- To preserve a common basis for comparing key modeling strategies, plant transpiration is represented using a canopy-scale resistance formulation. Temporal variations in vapor release are driven by the local vapor concentration gradient, while the integrated resistance term is specified to represent a well-watered, fully developed Sedum canopy under the monitored rooftop condition.
- When compared with experimental data, the average environmental parameters over the studied interval are used as initial conditions, while short-term temporal fluctuations are neglected.

Accurate modeling of the PVIGR system demands the simultaneous consideration of the interacting physical processes in the ambient environment and within the vegetation layer. The governing equations for each physical field are summarized below.

2.4.1. Free and porous media flow

The simulation of airflow in the environment employs the Reynolds-averaged Navier–Stokes (RANS) equations, which are known for their computational efficiency and ability to capture mean flow characteristics. Among the various RANS turbulence models, the Shear Stress Transport (SST) k - ω model is selected due to its high accuracy in near-wall regions and stability in free-flow regions. It effectively handles flow separation, adverse pressure gradients, and complex boundary layer problems. Its accuracy has also been well-validated in PV system applications [43,44]. The governing equations are formulated in the k - ω framework, with turbulent kinetic energy (k) and specific dissipation rate (ω) as the dependent variables.

$$\rho \frac{\partial k}{\partial t} + \rho \mathbf{u} \cdot \nabla k = P_k - \rho \beta_0^* k \omega + \nabla \cdot ((\mu + \sigma_k \mu_T) \nabla k) \quad (1)$$

$$\rho \frac{\partial \omega}{\partial t} + \rho \mathbf{u} \cdot \nabla \omega = \frac{\rho \gamma}{\mu_T} P_k - \rho \beta_1^* \omega^2 + \nabla \cdot ((\mu + \sigma_\omega \mu_T) \nabla \omega) + 2(1 - f_v) \frac{\rho \sigma_\omega^2}{\omega} \nabla \omega \cdot \nabla k \quad (2)$$

where ρ is the density, $\mathbf{u}$ is the velocity, σ_k and σ_ω are diffusion coefficient constants; β^* denotes a parameter used to close the dissipation term, γ is the production coefficient, and μ and μ_T represent dynamic viscosity and turbulent viscosity, respectively. f_v is the blending function used to switch between the k - ω formulation near the wall and the k - ϵ formulation in the free-stream region. The production term P of turbulent kinetic energy is expressed as:

$$P_k = \mu_T \left[\nabla \mathbf{u} : (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} (\nabla \cdot \mathbf{u})^2 \right] - \frac{2}{3} \rho k (\nabla \cdot \mathbf{u}) \quad (3)$$

Airflow in the computational domain is modeled using a coupled free and porous media flow formulation, in which the Navier–Stokes equations describe the flow in the open regions and the Brinkman equations describe the flow within the porous substrate. The Brinkman equations extend Darcy’s law by including viscous shear stresses alongside the pressure gradient and gravitational body force, allowing momentum transport in porous media to be resolved with an accuracy

comparable to that of the Navier–Stokes equations. In the porous domain, $\mathbf{u}$ denotes the Darcy velocity. This unified formulation ensures continuity of both $\mathbf{u}$ and p across the interface between the free-flow and porous regions. Accordingly, flow in the porous medium is governed by the continuity and momentum equations, which together constitute the Brinkman equations:

$$\frac{\partial}{\partial t}(\epsilon_p \rho) + \nabla \cdot (\rho \mathbf{u}) = Q_m \quad (4)$$

$$\frac{\rho}{\epsilon_p} \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \frac{\mathbf{u}}{\epsilon_p} \right) = -\nabla p + \nabla \cdot \left[\frac{1}{\epsilon_p} \left\{ \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu (\nabla \cdot \mathbf{u}) \mathbf{I} \right\} \right] - \left(\kappa^{-1} \mu + \frac{Q_m}{\epsilon_p^2} \right) \mathbf{u} + \mathbf{F} \quad (5)$$

where p is the pressure, ϵ_p is the porosity, κ is the permeability of the porous medium, Q_m is a mass source term, and $\mathbf{I}$ denotes the identity tensor, which is used to convert the scalar pressure into its tensor form.

The effects of gravity and other forces acting on the fluid are represented by the body force term $\mathbf{F}$. The Forchheimer resistance is included to account for the obstructive effect of plant leaves on airflow, expressed as a body force proportional to the square of the velocity:

$$\mathbf{F} = -\rho \left(\frac{C_F}{\sqrt{\kappa}} \right) |\mathbf{u}| \mathbf{u} \quad (6)$$

The rooftop vegetation was a mature Sedum layer with a low stature and dense horizontal coverage. In modeling terms, this corresponds to a compact porous canopy with limited internal ventilation, which is consistent with the aerodynamic behavior expected for dense succulent ground covers on shallow substrates. Based on values reported in studies treating vegetation as a porous medium [34,45,46] and refined via image-derived leaf area index from the experimental platform, the porosity ϵ_p , permeability κ , and Forchheimer parameter C_F are specified as 0.6, $4.07 \times 10^{-7} \text{ m}^2$, and 0.45, respectively.

Furthermore, because natural variations in ambient temperature are insufficient to significantly affect air density, all simulations assume air to be an incompressible Newtonian fluid. To solve non-isothermal flow, the Boussinesq approximation is applied to account for buoyancy-driven flow caused by differences in density.

2.4.2. Moisture transport in moist air and porous medium

In most natural environments, the spatiotemporal variation in water vapor concentration is small and does not significantly affect the density of moist air. Under the dilute-species assumption, the mass conservation equation for water vapor is used to describe the evolution of its molar concentration in air. This equation accounts for convection via the velocity field, binary diffusion in air, and the effects of the volumetric moisture source, G .

$$M_v \frac{\partial c_v}{\partial t} + M_v \mathbf{u} \cdot \nabla c_v + \nabla \cdot \mathbf{g}_w = G \quad (7)$$

where M_v is the molar mass of water vapor, c_v is the molar concentration of vapor (mol/m^3). The diffusive flux of water vapor $\mathbf{g}_w$ ($\text{kg}/(\text{m}^2 \text{ s})$) accounts for molecular diffusion in air. At the soil surface, $\mathbf{g}_w$ is prescribed as the evaporation flux and is modeled through a concentration-driven convective mass transfer formulation, in which the vapor flux is proportional to the concentration gradient between the soil and the external air ($c_{v,\text{ext}}$).

$$-\mathbf{n} \cdot \mathbf{g}_w = M_v h_m (c_{v,\text{ext}} - c_v) \quad (8)$$

The heat and mass boundary layer analogy is employed to express the moisture transfer coefficient h_m as a function of the heat transfer coefficient h , the vapor diffusion coefficient in air D , and the thermal conductivity k_d :

$$h_m = \frac{D}{k_d} \left(\frac{k_d}{\rho C_p D} \right)^{1/3} h \quad (9)$$

In addition to soil evaporation, water vapor generation from plant transpiration is accounted for by incorporating the biological characteristics of the vegetation. The transpiration rate E_c is determined by the vapor concentration gradient and the total diffusion resistance. As Sedum is a linear-leaved herbaceous species, transpiration is assumed to occur throughout the vegetation domain rather than being confined to the outer surface. Accordingly, a volumetric source term, G ($\text{kg}/(\text{m}^3 \text{ s})$), is introduced to represent the mass of water vapor generated per unit plant volume per second.

$$G = E_c \cdot \text{LAD} = \frac{c_{\text{leaf}} - c_v}{r_s + r_a} \cdot \text{LAD} \quad (10)$$

where c_{leaf} is the saturated water vapor concentration within the stomatal cavity. LAD (leaf area density) is defined as the ratio of leaf surface area to the volume of the plant domain. The resistance along the transpiration pathway is the sum of stomatal resistance (r_s) and the diffusion resistance of water vapor through the boundary layer (r_a). The transpiration source is formulated at the canopy scale. In this study, the combined resistance term ($r_s + r_a$) is prescribed as a constant effective resistance of 260 s m^{-1} , calibrated against reported evapotranspiration rates of a Sedum roof monitored over a month-long summer period under high-temperature conditions [47], where the ambient temperatures were comparable to the validation conditions evaluated in this work. Local microclimatic conditions, such as ambient relative humidity and airflow, dynamically influence the transpiration rate E_c through the resolved vapor concentration field c_v in Eq. (10). While stomatal resistance in natural environments dynamically responds to leaf temperature, vapor-pressure deficit, solar radiation, and plant moisture status, this physiological dependency is simplified in the present model to provide a consistent canopy baseline.

In porous media, moisture exists in both vapor and liquid phases and is transported through convection and diffusion. Combining the mass conservation equations for the liquid and vapor phases, and assuming incompressible liquid water ($\rho_l \approx 996.84 \text{ kg}/\text{m}^3$), yields a single governing equation that describes the overall moisture transport under two-phase coexistence:

$$\frac{\partial w(\phi)}{\partial t} + \nabla \cdot (\omega_v \rho_g \mathbf{u}_g) + \nabla \cdot \mathbf{g}_w + \nabla \cdot (\rho_l \mathbf{u}_l) + \nabla \cdot \mathbf{g}_{lc} = G \quad (11)$$

$$\mathbf{g}_{lc} = -D_w \frac{\partial w(\phi)}{\partial \phi} \nabla \phi \quad (12)$$

where $w(\phi)$ is the total moisture content, which is a function of relative humidity ϕ ; ω_v is the vapor mass fraction in moist air; the subscripts l and g correspond to liquid water and water vapor, respectively. $\mathbf{g}_{lc}$ denotes the capillary liquid water flux, modeled in Fickian form as the product of the effective liquid capillary diffusivity D_w and the moisture content gradient. D_w in green-roof substrates has been reported to span roughly two orders of magnitude, from 10^{-10} to $10^{-8} \text{ m}^2/\text{s}$, depending on the moisture content [48]. In this study, a representative mid-range value of $1 \times 10^{-9} \text{ m}^2/\text{s}$ is adopted, consistent with the typical operating moisture conditions encountered in Sedum-based green roofs. A sensitivity analysis under meteorological inputs used in the subsequent simulations showed that varying D_w across four orders of magnitude (from 10^{-11} to $10^{-7} \text{ m}^2 \text{ s}^{-1}$) changed the simulated transpiration latent heat by less than 0.2%, indicating that the present results are insensitive to this parameter within the tested range.

2.4.3. Heat transfer in moist air, porous media, and PV modules

Heat transfer within the system and between the system and the environment occurs through conduction, convection, and radiation, which is primarily addressed by solving the energy equation.

$$\rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) + \nabla \cdot (\mathbf{q} + \mathbf{q}_r) = \left(\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p \right) + \boldsymbol{\tau} : \nabla \mathbf{u} + Q_H + Q_V + Q_P \quad (13)$$

where C_p is the specific heat capacity at constant pressure, $\mathbf{q}$ is the heat flux by conduction, $\boldsymbol{\tau}$ is the stress tensor. The radiative heat flux $\mathbf{q}_r$

accounts for the thermal radiation emitted by the PV module, ground, plant, and soil surfaces toward the sky. The net incoming longwave flux from the sky to the system is expressed as:

$$-\mathbf{n} \cdot \mathbf{q}_r = \varepsilon_s \sigma (T_{\text{sky}}^4 - T_{\text{PV}}^4) \quad (14)$$

where σ is the Stefan–Boltzmann constant and ε_s represents the surface emittance. The effective sky temperature T_{sky} is determined from the downward atmospheric longwave (LW) radiation at ground level via Eq. (15). This relation is based on the gray-body approximation of the atmosphere, in which the downward LW flux is expressed as a fraction of the blackbody emissive power at the near-surface air temperature T_a . The Brunt model with calibrated coefficients is adopted to estimate the effective sky emissivity ε_{sky} (Eq. (16)), where P_w (Pa) denotes the partial pressure of water vapor. This approach is adopted because it provides sufficiently high accuracy while relying solely on routinely measured meteorological variables, making it practical for long-term numerical simulations when direct LW radiation measurements are unavailable [49].

$$T_{\text{sky}} = \left(\frac{\text{LW}}{\sigma} \right)^{1/4} = \left(\frac{\varepsilon_{\text{sky}} \sigma T_a^4}{\sigma} \right)^{1/4} = T_a \varepsilon_{\text{sky}}^{1/4} \quad (15)$$

$$\varepsilon_{\text{sky}} = 0.618 + 0.056 \sqrt{P_w} \quad (16)$$

This study couples the transport of water vapor with the mass diffusion equation by introducing a source term Q_H into the moist air energy conservation equation. This term accounts for the diffusive flux of thermal enthalpy arising from air and vapor concentration gradients in moist air.

$$Q_H = -(C_{p,v} - C_{p,a}) \mathbf{g}_w \cdot \nabla T \quad (17)$$

where $C_{p,v}$ and $C_{p,a}$ denote the specific heat capacities at constant pressure for vapor and air, respectively.

The general heat source is defined as the sum of two components: the heat contribution from vegetation Q_V and that from PV modules Q_P . Q_V appears with a negative sign in the energy equation, indicating that vegetation transpiration removes latent heat from the system. To adapt the Penman–Monteith equation to the present model while accounting for plant-specific traits, the leaf area density (LAD), the active leaf area coefficient K_c (mean value of 0.9), and the psychrometric constant γ_v are incorporated [50,51].

$$Q_V = -K_c \text{LAD} (\rho C_p)_{\text{air}} \frac{E_c}{\gamma_v} \quad (18)$$

Furthermore, the configuration of the PV heat source is defined according to the radiative transfer path within the module, assuming that plane-of-array solar radiation (I_{POA}) does not penetrate the cell layer, as shown in Fig. 5. The module's anti-reflective treatments enable reflection to be implicitly accounted for through the layer-specific absorptance (α) listed in Table 1. The total volumetric heat source Q_P is decomposed into three components: $Q_{P,\text{glass}}$, $Q_{P,\text{EVA}}$, and $Q_{P,\text{cell}}$, corresponding to absorption within the glass, EVA, and cell layers, respectively. A and V represent the surface area and volume of each layer.

$$Q_{P,\text{glass}} = \frac{I_{\text{POA}} \alpha_{\text{glass}} A_{\text{glass}}}{V_{\text{glass}}} \quad (19)$$

$$Q_{P,\text{EVA}} = \frac{I_{\text{POA}} (1 - \alpha_{\text{glass}}) \alpha_{\text{EVA}} A_{\text{EVA}}}{V_{\text{EVA}}} \quad (20)$$

$$Q_{P,\text{cell}} = \frac{I_{\text{POA}} (1 - \alpha_{\text{glass}}) (1 - \alpha_{\text{EVA}}) \alpha_{\text{cell}} A_{\text{cell}} - I_{\text{POA}} \eta_{\text{cell}} A_{\text{cell}}}{V_{\text{cell}}} \quad (21)$$

According to the manufacturer's datasheet, the reference conversion efficiency of solar cells under standard test conditions is set to $\eta_{\text{ref}} = 21.25\%$. The actual efficiency, which accounts for temperature and wind effects, is computed using the following expression.

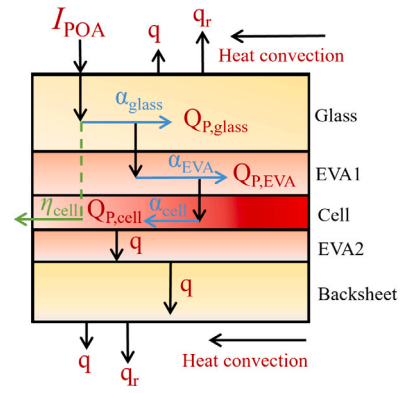


Fig. 5. Thermophysical processes and energy balance framework of the integrated PV layer.

$$\eta_{\text{cell}} = \eta_{\text{ref}} [1 - \beta_{\text{cell}} (T_{\text{cell}} - T_{\text{ref}})] \quad (22)$$

where β_{cell} is the temperature coefficient, which takes an empirical value of 0.41% for monocrystalline silicon modules [52]. The reference temperature T_{ref} is 25°C. Although heat absorption is explicitly partitioned among the internal module layers, it is assumed to be laterally uniform within each layer. This assumption is suited for the clear-sky, unshaded validation periods evaluated in this study, during which the modules were clean and operated without observable defects. In our field experiment setup, potential shading from site geometry, array spacing, and surrounding structures was systematically evaluated using 3D shadow analysis, allowing an unshaded noontime window to be identified for model validation [28].

In addition to external shading, surface contamination can also induce non-uniform irradiance across PV modules. While the baseline validation focuses on clean conditions, the framework can accommodate localized optical and thermal effects by redistributing layer-specific heat sources, as demonstrated in Appendix C. Model limitations concerning electrical feedback under partial shading and the required electro-thermal coupling are discussed therein.

In the porous vegetation domain, the medium consists of a solid matrix, moist air, and liquid water. Under the assumption of local thermal equilibrium across all phases, heat transfer in this multiphase porous medium can be described by a single energy equation:

$$(\rho C_p)_{\text{eff}} \frac{\partial T}{\partial t} + (\rho_g C_{p,g} \mathbf{u}_g + \rho_l C_{p,l} \mathbf{u}_l) \cdot \nabla T + \nabla \cdot \mathbf{q} = Q_H + Q_V + Q_S \quad (23)$$

where Q_S represents the thermal sink driven by the phase change of water during soil moisture evaporation, which is quantified directly from the moisture transport equation. In contrast to moist air, heat transfer in a porous medium requires treating the three phases as a single mixture. This approach incorporates effective volumetric heat capacity $(\rho C_p)_{\text{eff}}$ and other thermodynamic parameters into the equations, explicitly accounting for energy contributions from component diffusion, capillary flow, and phase change.

2.4.4. Solar and surface-to-surface radiation

The radiation module in COMSOL is employed to simulate the transfer of solar radiation to the ground, incorporating the shading of PV modules and the longwave radiative exchange among surfaces within the PVIGR system. In this study, experimentally measured global horizontal irradiance (GHI) and POA irradiance on the PV module surface are used as the radiation input. During transient simulations, the ground-received irradiance is calculated at each time step, accounting for variations caused by the changing position of the sun relative to the PV module.

In the surface-to-surface radiation calculations, all radiating surfaces are treated as diffuse gray surfaces that emit and reflect radiation uniformly in all directions. A wavelength of 2.5 μm is used as the threshold

to assign shortwave solar absorptance and thermal longwave emittance, as listed in Table 1. The radiosity of each surface is determined through the radiosity–irradiation equilibrium formulation:

$$J_i = \rho_{d,i} (G_{m,i}(J_i) + G_{ext,i} + G_{amb,i}) + \varepsilon_{s,i} \sigma T_i^4 \quad (24)$$

where ρ_d represents diffuse reflectance, J denotes radiosity, which is the sum of diffusely reflected and emitted radiation. G_m represents the mutual radiation exchange between the PV module and the underlying ground, vegetation, or soil surfaces, with view factors calculated using the hemicube method. G_{amb} and G_{ext} represent environmental radiation and irradiation from external sources, respectively. The subscript i denotes a spectral band interval in multispectral band calculations, where radiative properties are classified into shortwave and longwave bands using a 2.5 μm wavelength threshold.

2.5. Boundary conditions, initial conditions, solution strategy and solver

As illustrated in Fig. 4(a), the free air domain is modeled as a cuboid, with the left face designated as the velocity inlet. The remaining lateral faces and the top face are defined as open boundaries to simulate unrestricted domain extents, allowing natural fluid and heat exchange with continuous mass flux, while the ground consists of a concrete base covered by a soil layer. To reduce computational costs during multiphysics coupling, heat and mass transfer calculations in the ground are confined to the area beneath the PV modules. Meanwhile, the outer ground surfaces, lateral soil boundaries, and sides of the PV modules are treated as impermeable, adiabatic, and non-slip walls.

The velocity profile at the air inlet is modeled using a power-law equation to realistically reproduce the wind speed gradient near the rooftop, ensuring that the model captures reasonable shear in the near-wall region:

$$\frac{u}{u_r} = \left(\frac{z}{z_r} \right)^{1/7} \quad (25)$$

where the exponent 1/7 represents a standard empirical approximation for neutral atmospheric boundary layer flow over open terrain [53]. Although larger power-law exponents are typically required where the approach flow develops over a continuous, high-roughness urban building cluster, the rooftop experimental site at HKUST (located in the coastal Clear Water Bay area of Hong Kong) is situated outside the dense urban center and experiences unobstructed marine airflow. In this study, the reference height z_r is set to 2 m, corresponding to the anemometer's mounting height above the rooftop surface of the experimental platform, and the reference velocity u_r used in the modeling framework is measured by this anemometer at the specific time for each simulation case.

Experimental measurements of ambient temperature, relative humidity, and solar irradiance are used as initial conditions for transient simulations. Heat sources are defined as constant values determined by the incident radiation. PV module temperatures are initially set to match ambient conditions, while soil and vegetation temperatures are initialized 2 °C higher to account for daytime solar exposure.

Given that the fluid flow is not significantly influenced by heat and moisture transport, it is semi-decoupled from the multiphysics process to enhance computational efficiency. Accordingly, the model's solution strategy is executed in three sequential steps. First, the wall distance is initialized, and its reciprocal is calculated to determine the nearest wall distance, ensuring the boundary-layer accuracy required by the low-Reynolds-number turbulence model. Second, the turbulent wind field is solved under steady-state conditions, with the converged solution serving as input for the next step. Finally, a transient simulation is conducted to characterize the heat and mass transfer processes within the system, using the coupling relationships illustrated in Fig. 3.

Considering the characteristic time required for the system to reach a quasi-steady state under solar heating, each case is simulated for

two hours with a fixed time step of 10 min. Temporal discretization is performed using the backward differentiation formula with implicit time stepping, ensuring excellent stability for stiff multiphysics problems. At each time step, the resulting linear systems are solved using the multifrontal massively parallel sparse direct solver (MUMPS), which is chosen for its computational efficiency, numerical stability, and robustness in handling large-scale problems. All simulations are conducted on a Windows Server (x64) system powered by an AMD EPYC 9575F (64-core processor) with 384 GB of RAM. Prior to result analysis, a grid convergence test is conducted, as detailed in Appendix A.

3. Results and discussion

The 3D CFD model is initially developed and refined through a systematic evaluation of key modeling techniques. This includes comparative analyses of steady-state and transient approaches, the specification of inlet wind speed, and the modeling scheme for solar heat sources, as shown in Fig. 6. Based on these findings, the selected combination of techniques is then applied to construct the final model. The established model is validated against measured PV module and ground surface temperatures under both RPV and PVIGR scenarios.

3.1. Comparison of modeling approach: transient or steady state

In CFD, selecting the appropriate modeling approach is crucial to ensuring accurate simulations and meaningful analyses. The primary decision lies between steady-state and transient methods. Mathematically, steady-state analysis assumes that physical quantities remain constant over time, representing a stationary process without temporal derivatives. In contrast, transient analysis incorporates time-dependent terms, solving state changes iteratively over discrete time steps to capture dynamic behavior. From a physical perspective, steady-state conditions idealize transient processes as their equilibrium state after infinite development, making them widely used to minimize computational resources or when time-varying behavior is not of primary interest.

In the context of PVIGR systems, a recent study [24] has modeled each time point as an independent steady-state case, simulating representative temperature distributions under specific environmental conditions without the high cost of transient simulations. However, real-world rooftop environments are characterized by significant temporal meteorological fluctuations, where system states evolve continuously over time. Consequently, steady-state simulations that are limited to discrete time points may fail to fully capture the thermal dynamics inherent in transient processes. To evaluate the impact of different modeling strategies, a comparative analysis is conducted, and the resulting microclimate differences are visualized. As illustrated in Fig. 7, comparison using the environmental inputs from April 12 at 12:00 is selected as a representative case study. The measured wind speed at the 2-m reference height for this case is 0.62 m/s, which is prescribed as u_r in the inlet profile. Both a steady-state solution and transient simulations at 30 min and 2 h are performed to quantify the discrepancies in the simulated microenvironment.

The quantitative results show strong agreement between the two modeling strategies in predicting the microclimate around the PV modules. At the time instance of 2 h, the temperature difference on the module backside is only 0.41 °C, and the relative humidity in the adjacent air differs by just 2.90%. This indicates that in open, naturally ventilated environments where solid–air heat exchange dominates, the steady-state and transient approaches yield similar thermal and hygro-metric fields. Notably, the module temperature at 30 min is 0.58 °C lower than at 2 h, suggesting that the transient simulation requires an adequate duration to reach quasi-steady conditions. However, substantial differences arise in the near-ground zones involving vegetation and soil. Compared to the transient results at 2 h, the steady-state

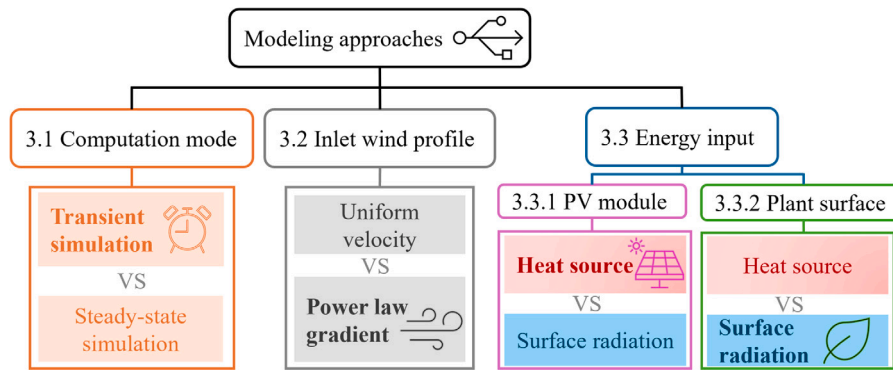


Fig. 6. Comparative analysis for the core modeling strategies.

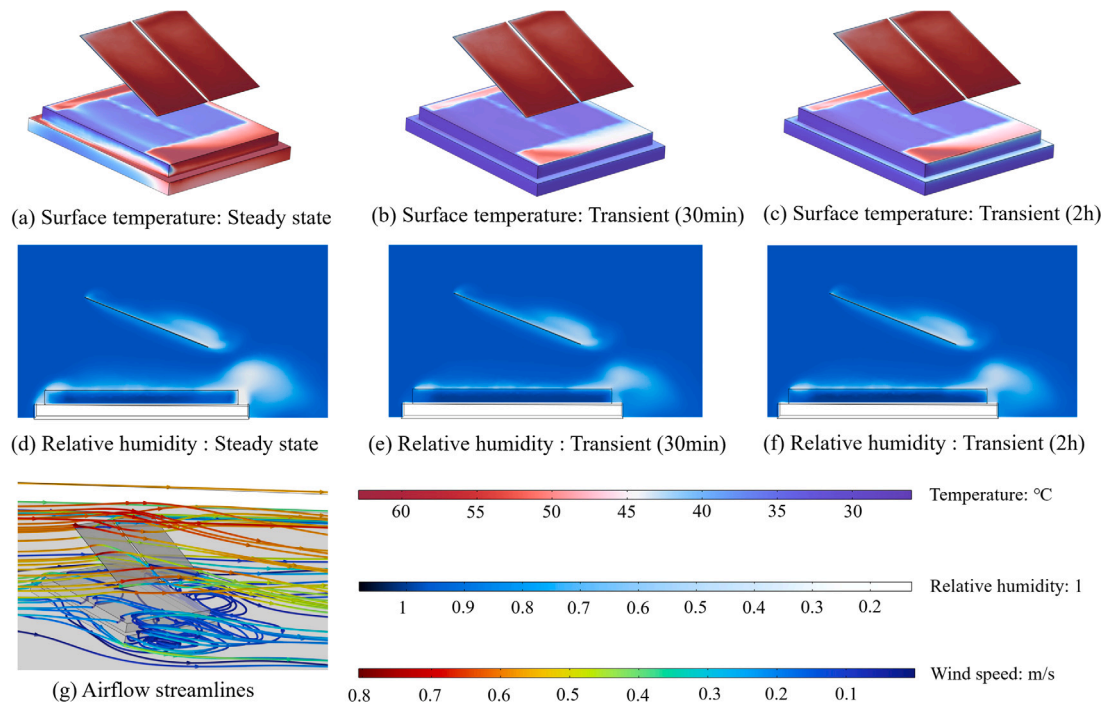


Fig. 7. Comparison of steady-state and transient simulations at 30 min and 2 h using environmental inputs from 12:00 on 12 April.

simulation overestimates the average plant surface temperature by 3.70 °C and the soil surface temperature by 13.77 °C. Consequently, the higher temperatures around vegetation in the steady-state case result in a 5.70% lower relative humidity in the surrounding air than that predicted by the transient simulation.

The discrepancies primarily arise from the systematic overestimation of plant and soil surface temperatures by the steady-state simulation. Due to the high flow resistance within the vegetation canopy, convective heat transfer between the plant and the surrounding air is significantly restricted, as illustrated by the steady-state wind speed field in Fig. 7(g). Under steady-state conditions, a fixed wind direction leads to the formation of localized high-temperature zones on the leeward side, with their positions directly determined by the wind direction. In contrast, the transient calculation allows the thermal and moisture fields to evolve from the specified initial conditions under the measured environmental conditions for each case, avoiding the indefinitely sustained equilibrium implicit in the steady-state solution. The steady-state assumption of a fixed, indefinitely sustained wind field exaggerates localized heat accumulation, hindering an accurate representation of the true thermal response of the vegetation–soil system under transient meteorological conditions.

Therefore, for PVIGR systems with dense vegetation planted directly on the rooftop and fully exposed to incoming airflow, transient simulations offer a more accurate representation of the internal microclimate. All transient results presented below are taken from the 2-hour simulation, representing the quasi-steady state achieved from the initial conditions within a short time frame.

3.2. Comparison of domain inlet wind speed profile: uniform or power law

Because airflow strongly governs convective heat transfer within the system, selecting an appropriate inlet wind profile is critical. As shown in Fig. 4(a), uniform and power-law wind profiles were compared to assess their accuracy in representing realistic rooftop airflow conditions.

The power-law profile describes the increase in wind speed with height within the atmospheric boundary layer. However, rooftop PV systems are typically installed at low elevations, with modules positioned close to the roof surface to minimize wind loads. Additionally, parapet walls further reduce near-roof wind speeds, as confirmed by the experimental data in Fig. 14(c). Consequently, the wind speed at module height is considerably lower than the free-stream velocity. To

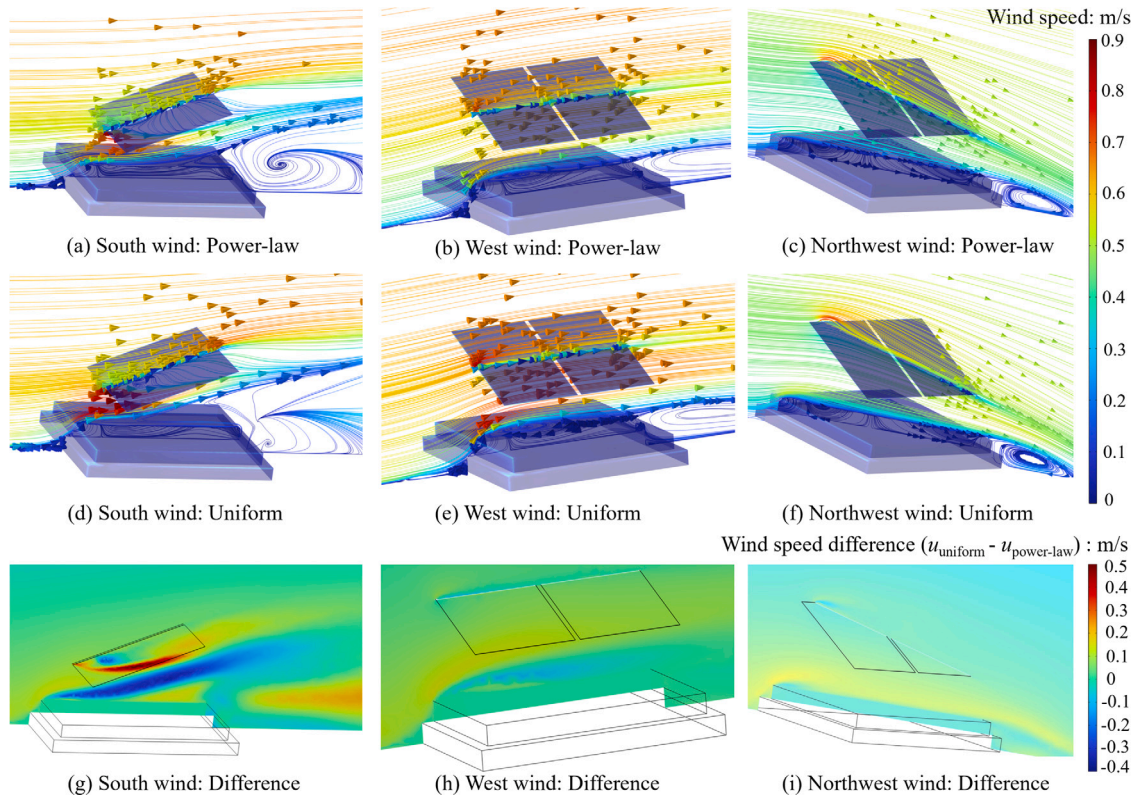


Fig. 8. Flow field streamlines around the PVIGR system under three wind directions using power-law and uniform wind profiles, and the corresponding differences at cross-section surfaces.

investigate the impact of different inlet wind speed profiles on the flow field around the PVIGR system, three representative cases are selected with south, west, and northwest winds. Wind speeds measured at 2 m above the roof for these directions (0.63 m/s, 0.63 m/s, and 0.48 m/s, respectively) are applied as uniform inlet velocities and compared with the results obtained using the power-law wind profile. The comparative results of the wind fields obtained from the steady-state simulation are presented in Fig. 8.

Although the overall wake structures remain morphologically consistent between the two inlet wind profiles, volume-averaged wind speeds within the vegetation are substantially higher with the uniform inlet profile: 35.1%, 40.5%, and 48.7% greater than those obtained with the power-law profile under south, west, and northwest winds, respectively. The uniform inlet velocity profile increases near-surface wind speeds around PV modules and above vegetation, enhancing the kinetic energy influx into the rooftop region. This amplifies shear stresses on the windward side and in the wake regions, increasing turbulent kinetic energy production and promoting stronger localized turbulent mixing. Internal flow variations are governed by how the inflow direction interacts with the frontal area of the PV modules. When the wind strikes the windward face perpendicularly (south wind), obstruction is maximized, leading to strong flow separation and turbulence, as seen in the first column of Fig. 8. In contrast, west winds flow along the module sides, reducing the effective frontal area and resulting in weaker wake disturbances. Moreover, due to the substantial flow resistance of the plant canopy, the internal airflow is strongly influenced by the inlet wind profile.

To evaluate the suitability of simulated inlet wind profiles for realistic rooftop microclimate prediction, measured wind speed and direction at a height of 2 m on April 11 are used as inputs. Simulations are performed using both uniform inlet velocity and power-law wind profiles, focusing on the vertical wind profile from the ground to roughly 1.2 m near the module's lower edge, as marked in Fig. 4(a). Fig. 9 compares the simulated vertical wind speed profiles at the sensor

location with experimental measurements taken from an anemometer positioned 55 cm above the roof surface and horizontally aligned with the center point of the left PV module (viewed from north to south). While this figure focuses on the local vertical profile, a detailed pointwise validation comparing simulated and measured wind speeds at the 55 cm measurement height will be provided in a later section. Quantitative results indicate that uniform inlet velocity often overestimates local wind speeds within the PVIGR system, deviating from actual near-ground flow fields. Below 0.4 m in the vegetation domain, wind speeds remain low due to strong attenuation by vegetation acting as a high-resistance porous medium. At 11:00 and 15:00, westerly winds flow directly over the vegetation, creating a strong turbulence zone that results in similar wind fields for both inlet wind profiles.

Overall, utilizing the power-law profile at the domain inlet offers a more accurate representation of the airflow field within the system, making it the preferred method for accurate PVIGR microclimate simulations.

3.3. Comparison of methods to model solar energy input to the system

Solar radiation serves as the primary energy source that drives microclimate dynamics within PVIGR systems. CFD simulations typically employ two approaches to model solar energy input: the heat source method, which incorporates solar radiation as an equivalent heat source term in the energy conservation equations, and the surface radiation method, which explicitly tracks the propagation of radiative fluxes throughout the domain. In the heat source method, the solar energy absorbed by each PV module layer is represented as a volumetric heat source, as expressed in Eqs. (19) to (21). For the plant layer, a uniform heat flux is applied to the plant surface, calculated from the shading ratio determined by the geometry of the system, as detailed in Section 3.3.2. Alternatively, the surface radiation method models the sun as an infinite external radiation source emitting parallel light to the system, as illustrated in Fig. 10(b). This approach calculates the

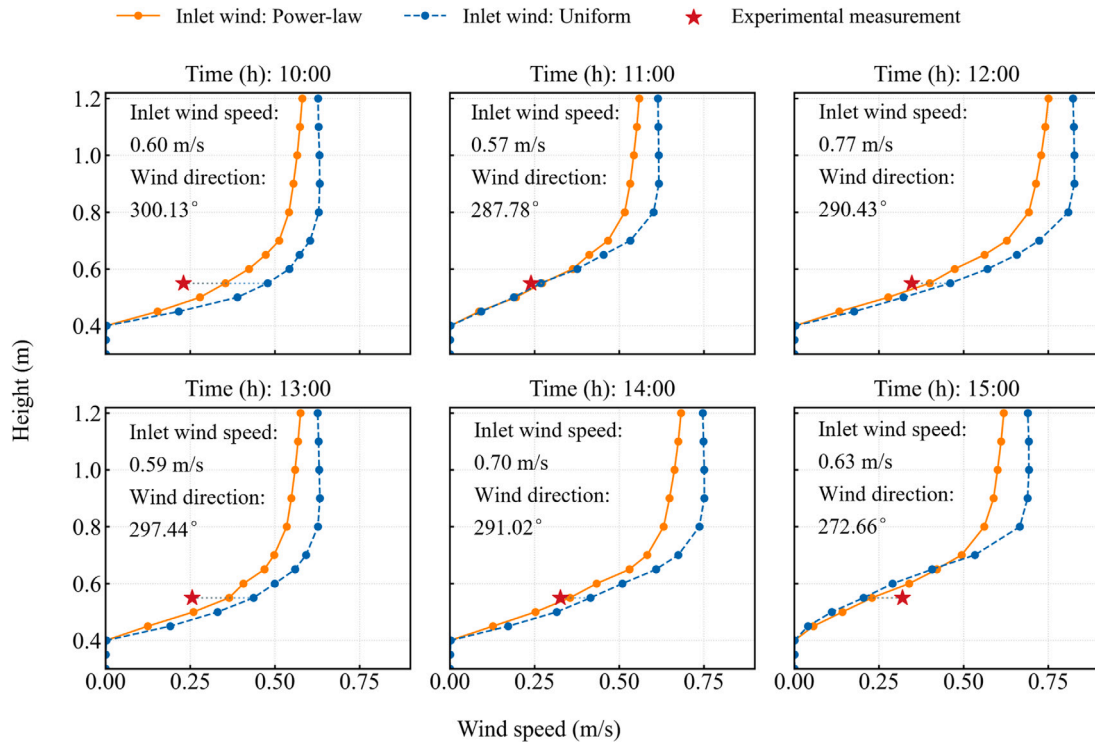


Fig. 9. Comparison of simulated wind speed profiles with experimental measurements on April 11, using both uniform and power-law inlet profiles.

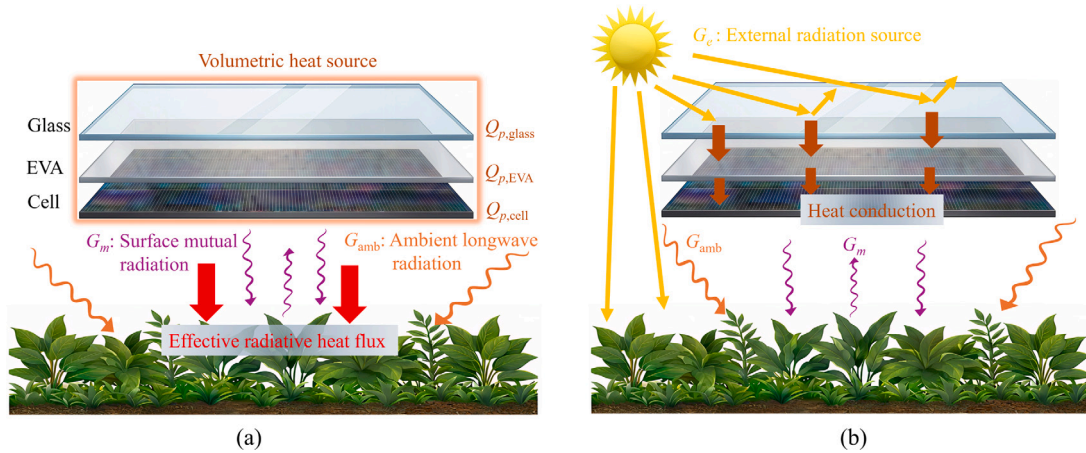


Fig. 10. Comparison of energy input methods: (a) heat source and (b) surface radiation.

incident solar flux on both the PV modules and the underlying surface based on the system geometry and the spatiotemporal position of the sun, thereby capturing the dynamic shading effects cast onto the green roof.

Fundamentally, these two approaches differ in their treatment of heat transfer mechanisms. The surface radiation method applies solar irradiance directly to the module's upper glass cover and subsequently transfers heat to the underlying layers through conduction. The fraction of absorbed radiation converted to electricity is accounted for by adjusting the surface absorptance. However, this process neglects internal radiative transfer through the glass and EVA layers, potentially resulting in less accurate predictions of module temperature compared to the heat source method. Additionally, the solar flux on the vegetation layer is treated as a non-uniform boundary condition, where unshaded areas receive full incident irradiance, and shaded areas receive none. In contrast, the heat source method distributes volumetric heat generation across internal layers of PV based on material properties, providing a

more suitable representation of energy absorption within the PV module. However, for the plant surface, the uniform heat flux prescribed by the heat source method cannot represent the non-uniform radiation distribution.

This section evaluates the application of both methods to PV modules and the vegetation region, comparing their predictive performance to recommend the most suitable approach for PVIGR modeling.

3.3.1. Solar energy input on PV modules

In the heat source method, the total incident heat flux on the PV surface is re-distributed as a volumetric heat source across different module layers based on their thermal properties, as shown in Eqs. (19) to (21). In contrast, the surface radiation method in COMSOL represents the sun as an infinitely distant, parallel light source. The solar position (defined by the solar elevation angle, azimuth angle, and incident direction) is determined based on the specified geographic location, time zone, date, and time. The irradiance level (GHI) at a solar zenith angle

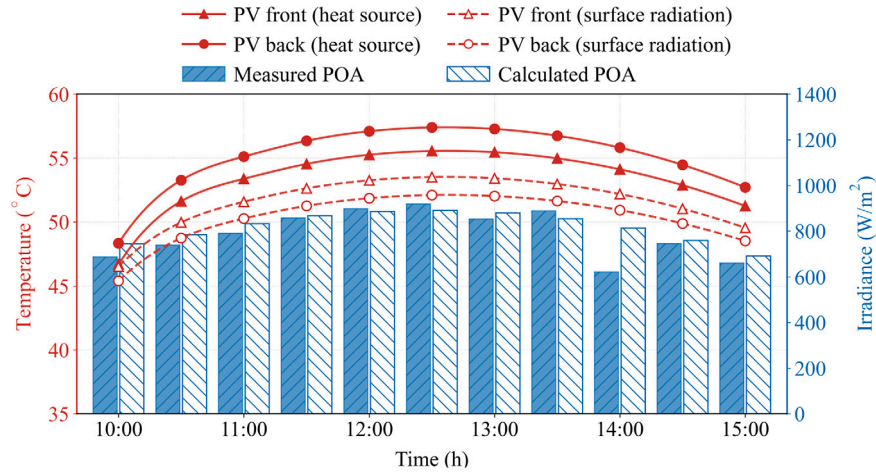


Fig. 11. Comparison of POA and PV module temperatures using surface radiation and heat source methods. The environmental input data are instantaneous measurements taken on April 12, 2024.

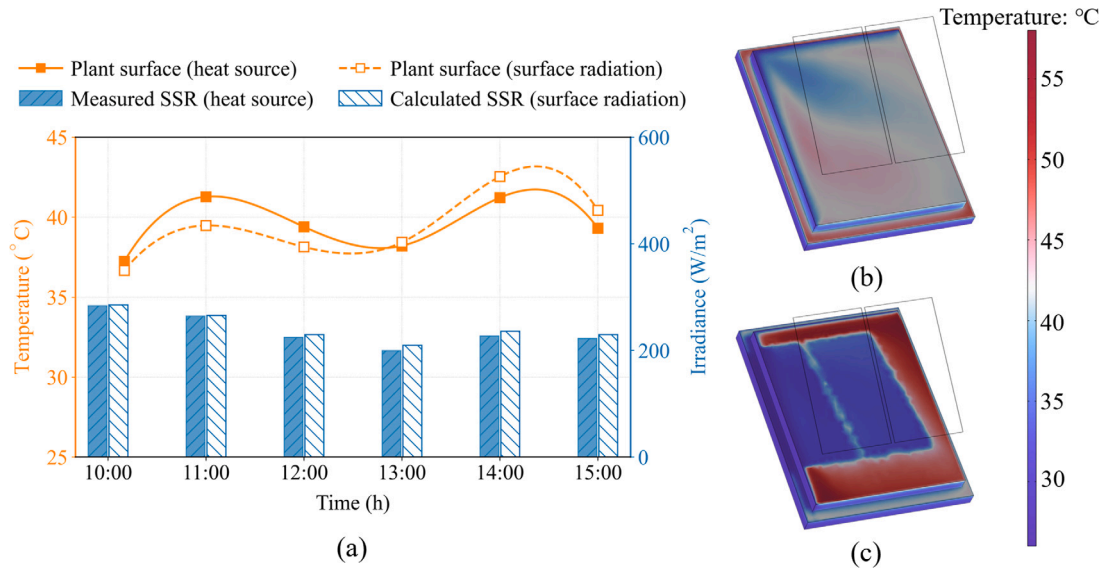


Fig. 12. (a) Comparison of averaged SSR and plant surface temperatures using heat source and surface radiation methods. (b, c) Plant surface temperature distributions at 11:00 derived from the heat source and surface radiation methods, respectively. The environmental input data are instantaneous measurements taken on April 12, 2024.

equal to 0° is specified as an input (denoted as reference irradiance); then the POA on the PV surface is automatically calculated based on solar position, PV orientation, and tilt angle. When compared to real-world scenarios, the surface radiation approach has two limitations: first, it models only the solar beam while ignoring diffuse light from the atmosphere; second, its temporal variation in irradiance level is based on GHI rather than POA. Consequently, the calculated POA on the module surface may deviate from field measurements. Fig. 11 compares the POA measurements collected at 30-minute intervals between 10:00 and 15:00 on April 12, 2024, with the corresponding values calculated using the surface radiation method, where the measured peak GHI (approximately 920 W/m^2 at 12:40, when the solar zenith angle is near 0°) is used as the reference irradiance. Although a clear-sky day is considered, the calculated irradiance shows noticeable deviations from the measured values, particularly in the afternoon due to short-term shading on the POA sensor. Furthermore, during the morning and afternoon periods, the calculated POA is around 4% to 8% higher than the measured values, while during noon, a 3% underestimation occurs.

In addition, Fig. 11 compares the modeled PV temperatures using the heat source and surface radiation methods, with calculated POA as energy input. By applying identical solar heat input in both methods, temperature differences are solely attributed to variations in the heat transfer mechanisms of the two methods. The results show that the surface radiation method leads to overall lower PV module temperatures, with the front-side temperature approximately 1.3°C higher than the backside of the module. However, in real world operations, the backside of the PV module is in direct contact with the solar cells and has a more restricted heat dissipation path, typically resulting in higher temperatures than the front surface [54]. This discrepancy arises because the surface radiation method applies the irradiance solely to the module's front surface, resulting in inaccurate temperature predictions across the various PV layers.

In summary, the calculated POA from the surface radiation method deviates from measured irradiance and fails to realistically represent the internal heat distribution among the module layers. In contrast, the layer-specific volumetric heat source method offers a more physically

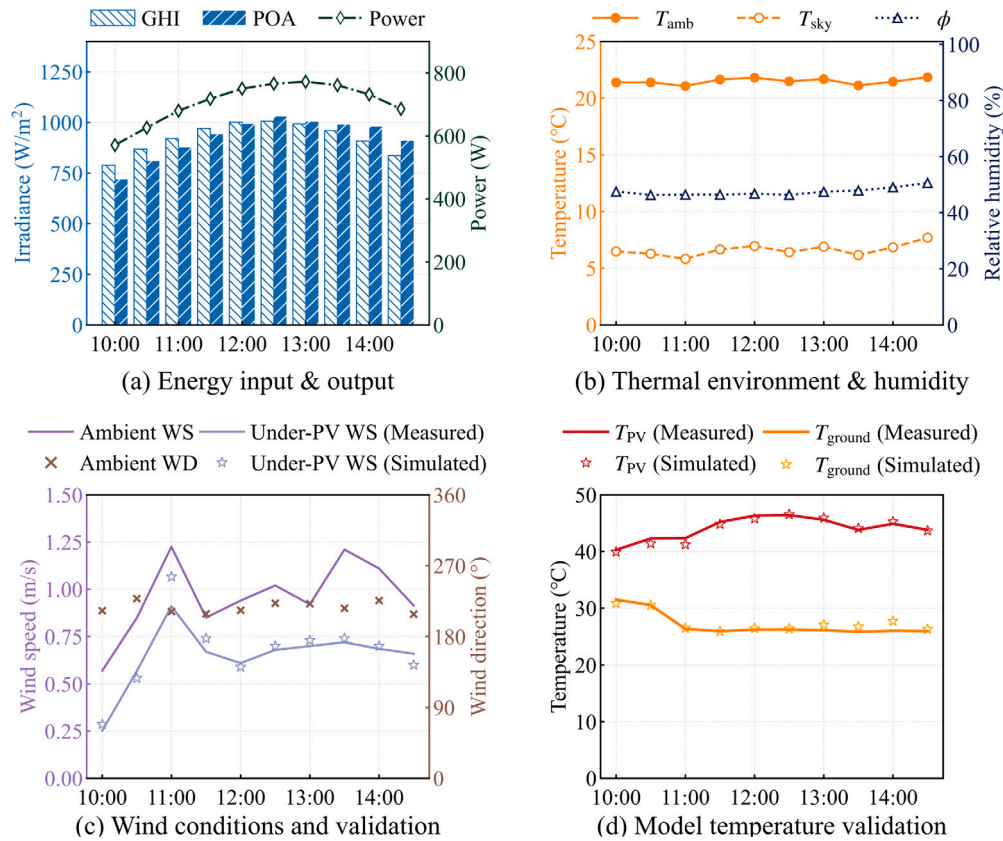


Fig. 13. Environmental inputs for the RPV system and model validation based on measured PV module and ground surface temperatures. (a) Measured Solar irradiance on ground and PV module surfaces, and PV power output. (b) Measured ambient air temperature, relative humidity, and sky temperature. (c) Measured ambient wind speed (WS), direction (WD), along with a comparison between measured and simulated wind speeds beneath the PV module. (d) Comparison of simulated PV module and ground surface temperatures with experimental measurements for model validation.

consistent approach and should be used to model solar energy input to the PV module.

3.3.2. Solar energy input on the vegetation

The horizontal vegetation layer within the PVIGR system receives sub-canopy solar radiation (SSR), which is affected by the shading of the overlying PV modules.

In the heat-source method, a spatially uniform effective radiative heat flux, defined as the measured SSR, is applied over the plant surface, as illustrated in Fig. 10(a). This flux represents the area-weighted average of the measured GHI incident on unshaded regions and zero irradiance over shaded regions. The shaded area is defined as the overlap between the PV shadow and the plant layer, and therefore depends on both the solar position and the PV configuration. In contrast, the surface-radiation method explicitly resolves the spatiotemporal distribution of shadows, thereby directly providing the corresponding non-uniform SSR over the vegetation surface. The SSR obtained from the two methods, together with the resulting average vegetation temperatures, is presented in Fig. 12(a).

As shown, although both energy-input methods yield similar SSR over the vegetation layer, the surface-radiation method predicts plant surface temperatures that differ slightly from those obtained with the heat-source method, with deviations of less than 2°C . This difference arises because the surface-radiation method resolves the non-uniform SSR distribution, thereby producing spatially heterogeneous plant surface temperatures, as illustrated in Fig. 12(b and c). These heterogeneous heating patterns interact with the surrounding airflow, leading to local variations in convective cooling and, consequently, in plant surface temperature.

In summary, the surface radiation method provides accurate energy input while effectively capturing the spatial distribution of plant

temperature caused by module shading, making it the more suitable approach for modeling radiation and temperature distributions beneath PV modules.

3.4. Model validation

The modeling framework developed in this study adopts the techniques selected from the preceding comparative analyses, as highlighted by the bold selections in the schematic overview of Fig. 6. Transient simulations are employed to accurately capture time-dependent microclimatic dynamics. A power-law wind profile is used at the inlet to represent realistic near-roof boundary-layer conditions. Layer-specific volumetric heat sources are applied to the PV modules to reflect internal radiation propagation and absorption, and surface radiation is adopted for both vegetation and ground surfaces to account for time-dependent shading and spatially non-uniform irradiance. This hybrid approach forms the foundation for the detailed performance evaluation presented in the following section.

To validate the comprehensive numerical framework, the model is rigorously compared against measurements from both the RPV and PVIGR systems in the dedicated experimental setup. The validation cases were selected from the long-term monitoring archive described in Section 2.1. Although sensor accuracy and reliability have been extensively validated, with part of the dataset already released as open access [55], rigorous screening remains necessary when selecting measurements for model validation. To ensure consistent comparison, representative clear-sky days are identified based on field observations exhibiting stable wind conditions, calibrated pyranometer measurements with irradiance trends consistent with PV power output, temperature and humidity records cross-validated against nearby sensors,

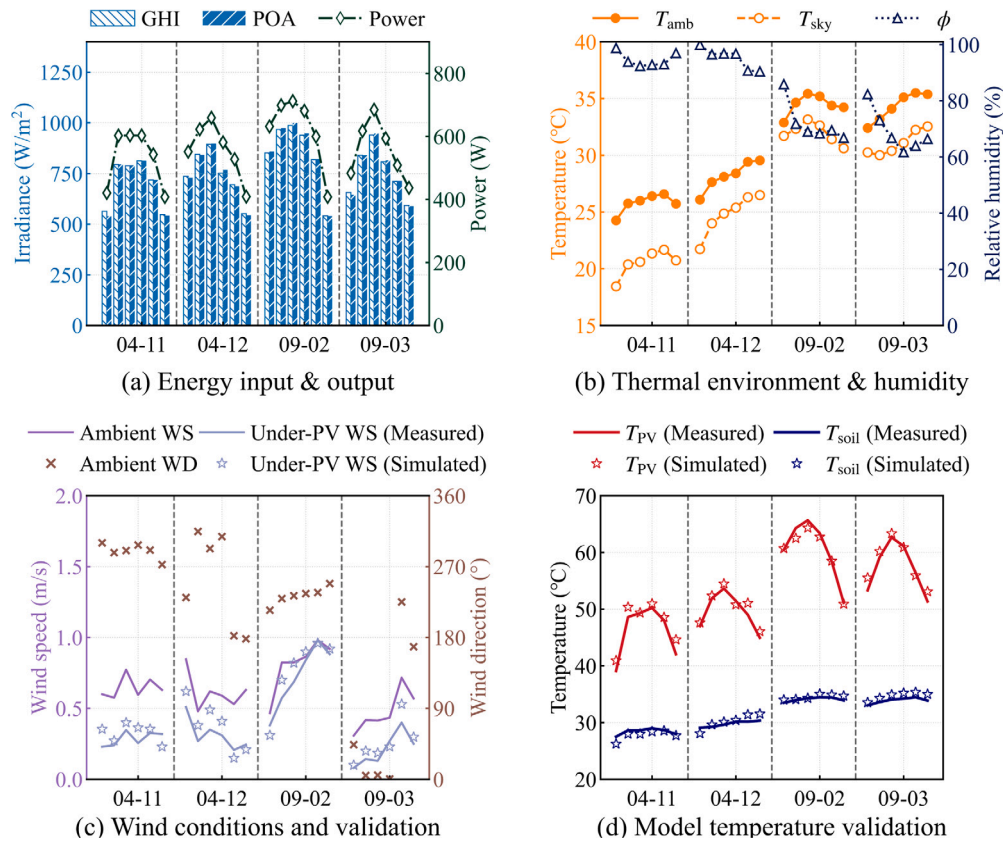


Fig. 14. Environmental inputs for the PVIGR system and model validation based on measured PV module temperatures. (a) Measured solar irradiance on ground and module surfaces, and PV power output. (b) Ambient air temperature, relative humidity, and sky temperature. (c) Measured ambient wind speed (WS), direction (WD), along with a comparison between measured and simulated wind speeds beneath the PV module. (d) Comparison of simulated PV module and soil temperatures with experimental measurements for model validation.

Table 2

Quantitative validation metrics for measured and simulated temperatures ($e = T_{sim} - T_{exp}$).

System	Monitored variable	n	MAE (°C)	RMSE (°C)	MBE (°C)	MAPE (%)
RPV	Module rear surface	10	0.46	0.55	−0.23	1.06
	Ground surface	10	0.52	0.73	0.38	1.95
PVIGR	Module rear surface	24	1.00	1.23	0.55	1.96
	Soil temperature	24	0.65	0.75	0.28	2.09

and healthy vegetation growth with uniform porosity and no significant weed competition.

Based on these criteria, model validation is conducted using the following days in 2024: March 12 for the RPV system, April 11, April 12, September 2, and September 3 for the PVIGR system. The study focuses on the period from 10:00 a.m. to 3:00 p.m., which represents peak hours for both plant photosynthesis and PV power generation. All model input data are based on experimental measurements, with hourly averages applied to minimize short-term fluctuations. The measurement data and model validation results for the RPV system are summarized in Fig. 13.

The experimental data from the RPV system indicate clear skies, steady wind direction, and moderate humidity, which are typical spring conditions in Hong Kong. The thermocouple measuring module temperature is mounted near the upper-middle part of the module's backsheets, while the ground sensor is positioned beside a concrete support under the module's edge. Direct solar irradiance drives rapid surface heating during the morning hours. However, from noon onward, the monitored area transitions into the shadow of the PV modules. This obstruction of solar radiation leads to a noticeable reduction and stabilization of the local ground surface temperature. The model demonstrates high fidelity against experimental data, maintaining deviations below 2 °C.

These results verify that the model effectively captures the complex thermal gradients and cooling effects of the ground surface induced by PV shading. Validation of the airflow field at a height of 55 cm below the module further confirms the performance of the model. Given the highly variable outdoor environment, some discrepancies between predicted and measured wind speeds are unavoidable at certain times, such as at 11:00. Overall, the agreement is satisfactory, with errors remaining below 5% for most of the period, indicating that the model, when driven by measured ambient wind speed and direction, can reliably capture the airflow beneath the PV modules.

For the PVIGR system, environmental data and validation results spanning spring and autumn across four representative days are presented in Fig. 14. As summer approaches, the climate is characterized by elevated temperatures and humidity, with prevailing winds from the northwest and north. The simulated wind speed beneath the module shows fluctuating behavior; despite occasional deviations, its overall temporal trend and range align closely with the experimental measurements. Under these field conditions, the simulated module and soil temperatures closely reproduce the measured temporal evolution. Statistical error metrics for both the RPV benchmark and the PVIGR system are summarized in Table 2.

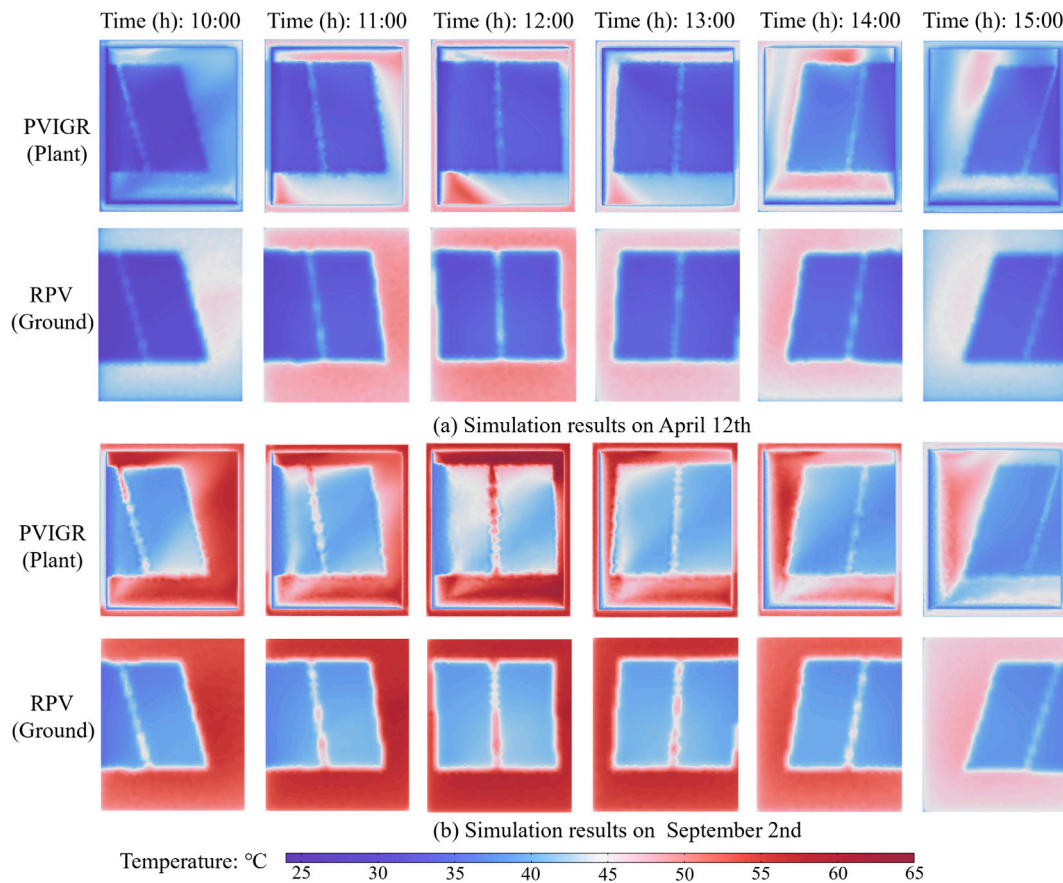


Fig. 15. Temporal evolution of plant surface temperature distributions in the PVIGR system and ground surface temperature distributions in the RPV system, based on environmental inputs from: (a) April 12 and (b) September 2.

The metrics were computed from paired measured and simulated values at identical timestamps. Across all four validation comparisons, the RMSE ranges from 0.55 to 1.23°C, the MAE from 0.46 to 1.00°C, and the MAPE from 1.06% to 2.09%. The near-zero MBE values (ranging from -0.23 to 0.55°C) indicate limited overall bias in the multi-physics solver. Overall, these error metrics objectively demonstrate the high fidelity of the transient modeling framework in capturing rooftop microclimate dynamics.

4. Applications of the proposed CFD model

Rooftop vegetation is widely recognized as a facilitator in mitigating the UHI effect, improving building insulation, and reducing indoor heat conduction and cooling demands. When combined with PV systems, plant evapotranspiration can enhance PV efficiency by lowering module operating temperatures [28]. This section uses selected measured environmental inputs from April 12 and September 2, 2024 to illustrate how the validated model can be applied to compare PVIGR and RPV microclimates under representative rooftop conditions. The following analyzes are intended to provide case-based application examples and a preliminary interpretation of the simulated thermal responses.

4.1. Comparison of PVIGR and RPV systems

Differences in location, installation schemes, and the surrounding environment between the experimental RPV and PVIGR systems make strict comparability under real-world measurements challenging, underscoring the advantages of numerical simulation. To enable a controlled numerical comparison, the RPV setup is constructed directly from the validated PVIGR framework as a strictly matched benchmark.

By maintaining identical domain geometry, numerical settings, and measured meteorological inputs while replacing only the vegetation-soil layers with an exposed concrete roof, this baseline isolates the microclimatic impacts attributable specifically to the green roof under the evaluated two-day conditions.

As illustrated in Fig. 15, under the shading effect of PV modules, both the vegetation in the PVIGR system and the concrete surface in the RPV system exhibit significant thermal gradients, the evolution of which is intrinsically linked to solar positioning. It should be noted that the modeled vegetation represents a vigorous, densely developed Sedum canopy. As a typical Crassulaceae ground cover, Sedum forms a shallow but compact succulent layer, in which a substantial leaf area is compressed into a relatively thin vegetated volume. This structural characteristic leads to a comparatively high effective leaf area density and strong intra-canopy aerodynamic resistance. Under low-wind roof conditions, restricted ventilation within the canopy weakens convective heat removal from the plant layer, leading to locally elevated vegetation temperatures, although the canopy continues to provide net cooling to the roof system. In contrast, the concrete substrate demonstrates a more uniform temperature distribution. Temporally, the elevated ambient temperatures and solar radiation levels in September result in overall higher temperature ranges compared to April. Throughout the study period, shading from the PV modules effectively lowered temperatures across most of the vegetation surface but also markedly reduced the solar radiation available to plants.

Fig. 16 compares the system temperatures of PV modules, vegetation, and the roof surface. Major environmental factors that influence thermal behavior are also shown. The quantitative results indicate that, for most of the period, the cooling effect of plant transpiration effectively mitigates localized heat accumulation, lowering vegetation temperatures in PVIGR by up to 4.27 °C relative to the

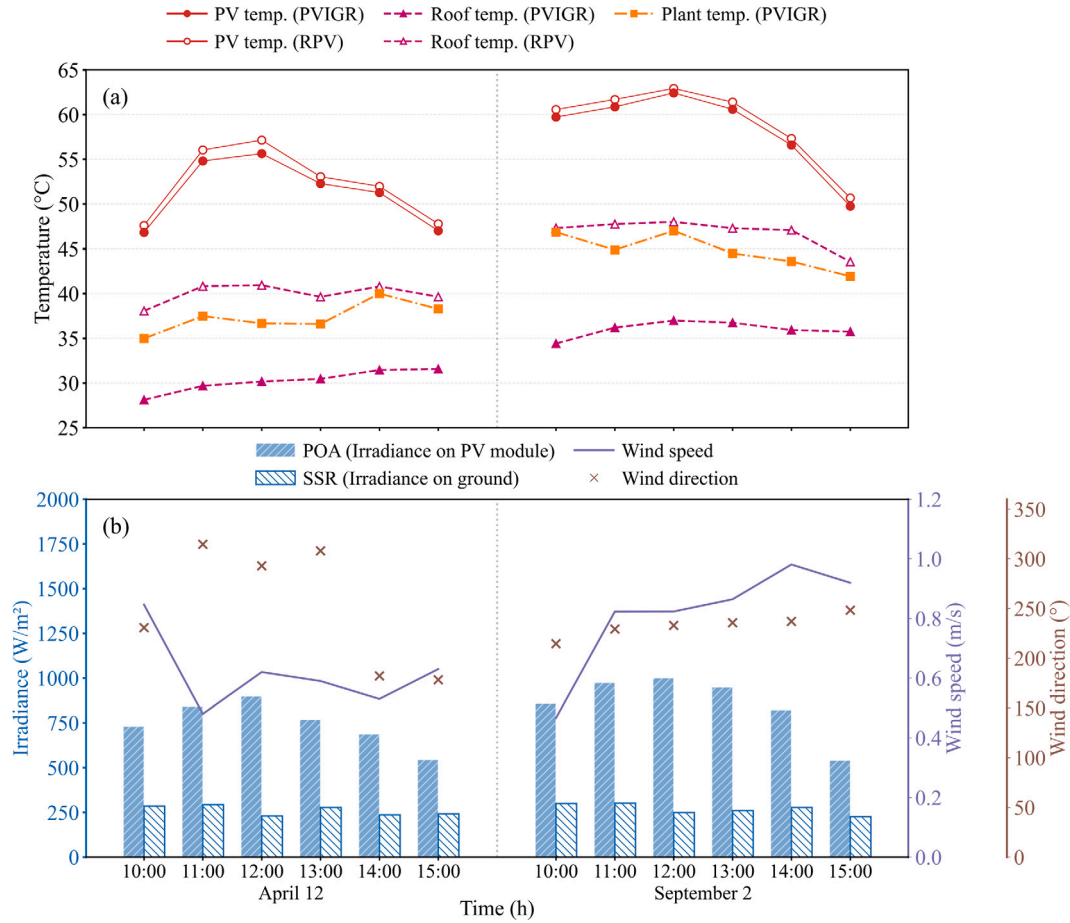


Fig. 16. (a) Average temperatures of the PV module backside, vegetation surface, and roof surface for the PVIGR and RPV systems, based on measurements from April 12 and September 2, 2024. (b) Corresponding environmental inputs: ambient wind speed, wind direction, module-received POA, and SSR on the vegetation and roof surfaces.

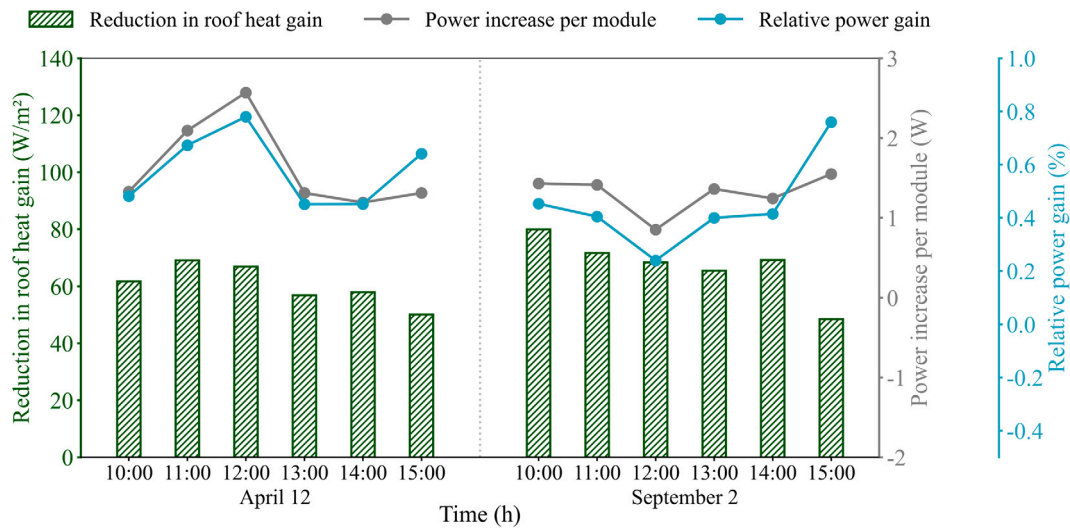


Fig. 17. Reduction in roof heat gain, power increase per module and relative power gain in PVIGR relative to the reference RPV system, based on environmental inputs from April 12 and September 2.

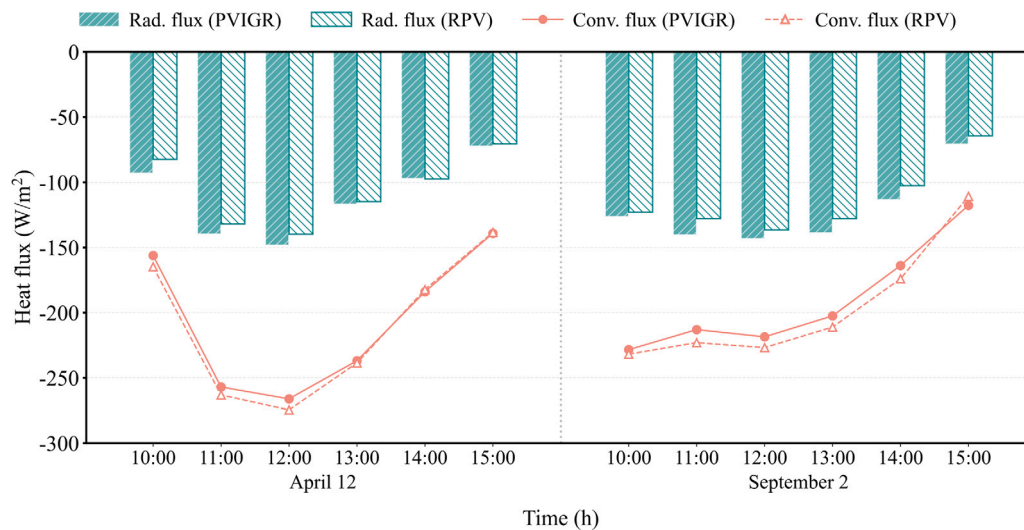


Fig. 18. Outgoing heat fluxes on the back surface of PV modules, based on environmental inputs from April 12 and September 2.

concrete ground in RPV. However, under unfavorable wind conditions (e.g., near-southerly winds), the high aerodynamic resistance of the vegetation limits convective cooling, resulting in elevated vegetation temperatures.

In the simulated cases, vegetation consistently provides a cooling benefit to the PV modules, with a maximum temperature reduction of 1.6 °C. Nevertheless, under September's high-temperature conditions or when vegetation temperatures increase, the temperature difference between the PV modules in the PVIGR and RPV systems becomes trivial. For the thermal impact on building surfaces, the vegetation and soil layers on green roofs significantly reduce roof surface temperatures and minimize temperature fluctuations through shading, transpiration cooling, and soil thermal buffering. In both analyzed seasonal cases, the PVIGR system reduced the average roof surface temperature by up to 13 °C compared to the reference RPV system, highlighting the substantial advantage of green roofs in mitigating roof heat gain and their potential to reduce building cooling demand.

Furthermore, the cooling effect provided by the PVIGR system can be directly translated into quantifiable improvements in electrical output, along with an estimated reduction in roof heat gain. Based on the temperature-dependent PV model defined in Eq. (22), Fig. 17 illustrates the power increase per module and the corresponding relative power gain compared to the reference RPV system. The relative power gain is defined as the temperature-induced power increase normalized by the measured module power at the corresponding time step.

The results show that the peak power increase, approximately 2.6 W per module, occurs at 12:00 on April 12 and represents the strongest absolute electrical benefit among the analyzed periods. By contrast, the maximum relative power gain is observed at 15:00 on September 2, reaching approximately 0.8%. Clear seasonal and diurnal variations are also evident: in April, the electrical benefit generally increases toward noon, whereas in September, the opposite trend is observed. Furthermore, PVIGR provides a clear cooling effect at the roof level. Using a typical heat transfer coefficient of 6.2 W/m² K between the roof exterior and interior surfaces for tropical buildings [56], the vegetation-induced reduction in roof temperature is estimated to lower the roof heat gain by up to 80 W/m² during the simulated period. Overall, under the present rooftop configuration and the analyzed conditions, the simulated PVIGR effect on electrical output is modest but measurable, whereas a more pronounced benefit is observed in the estimated reduction of roof heat gain.

The magnitude of simulated PV cooling in this study generally align with the typical ranges reported in recent research, which observed maximum module temperature reductions of approximately 1.8 °C

[57]. However, greater cooling effects have also been reported under specific system configurations, with temperature reductions reaching 3 °C [21] or even up to 10 °C [18]. Such variation across existing studies indicates the need for further research into the integrated performance of PVIGR systems and points to significant potential for optimization and performance enhancement.

4.2. PV module cooling mechanisms in PVIGR system

The developed CFD model can also be used to examine the simulated heat fluxes in the analyzed cases, helping to interpret the possible cooling pathways in PVIGR. The following comparison is intended as a mechanistic analysis of coupled heat and mass transfer. For instance, analyzing the heat fluxes from the backside of PV modules can elucidate vegetation-enhanced heat dissipation mechanisms, offering insights for system optimization. Fig. 18 presents a comparison of the convective and radiative heat fluxes, representing outward heat losses from the module surface to the surroundings via conductive-convective and radiative pathways, respectively.

According to the simulation results, convective heat transfer to the ambient air is the dominant cooling pathway for the PV module, while radiative heat exchange also represents a substantial component of the overall heat dissipation. The higher longwave emittance of the vegetation enables it to provide enhanced radiative cooling to the module, even when its temperature is slightly higher than that of the roof temperature in RPV, thereby underscoring the advantages of vegetation in promoting radiative heat dissipation. Nevertheless, the vegetation-induced peak increase in radiative heat flux does not align with the maximum cooling effect on the PV module, as the module temperature is governed by the combined influences of radiative, convective, and internal conductive heat transfer. The simulated cases show that vegetation generally reduces convective heat transfer on the backside of the PV modules, resulting in weaker convective cooling in the PVIGR system compared to the RPV system. However, under favorable wind conditions (e.g., at 15:00 on September 2), the combined effect of enhanced radiative cooling and improved convective conditions can result in a more effective reduction in module temperature.

In general, the cooling effect of vegetation on PV modules is primarily driven by enhanced radiative heat flux, rather than the commonly perceived enhanced convective heat dissipation caused by a cooler microclimate. However, the aerodynamic resistance of the vegetation often disrupts airflow within the system, weakening convective heat dissipation from the PV modules. Regarding whether the water vapor diffusion around the module will have a cooling effect, Fig. 7(c) shows

that under windy conditions, especially at high ambient humidity, water vapor does not accumulate above the vegetation. The spacing between the vegetation and PV modules prevents transpired vapor from reaching the module surface, eliminating additional latent heat absorption near the modules.

Within the present simulated cases, reduced sub-module ventilation is associated with weaker convective heat removal from the PV modules. This observation suggests that ventilation-related design factors may be important for PVIGR cooling performance. Promising avenues for system optimization include selecting high-transpiration, low-profile vegetation to enhance radiative cooling, together with structural adjustments that lower the roof-canopy spacing while preserving the required clearance between the PV modules and the vegetation.

5. Conclusions

This study develops a numerical simulation framework to characterize the microclimate of photovoltaic-integrated green roof (PVIGR) systems. The model is rigorously validated against measurements from a dedicated experimental platform, encompassing PV module temperatures, ground temperatures, soil temperatures and wind speed. Through a detailed analysis of core modeling techniques, it quantifies the integrated thermal benefits of PVIGR relative to conventional rooftop photovoltaic (RPV) systems and elucidates the key mechanisms driving enhanced module cooling performance.

The comparative analysis highlights several numerical modeling insights important for accurately resolving the coupled physical fields of the microclimate of PVIGR systems. First, steady-state computations reasonably reproduce ambient humidity, wind speeds, and module temperature distributions but overestimate localized warming in vegetation zones. In contrast, transient simulations yield more realistic temperature distributions, underscoring their essential role in accurately capturing dynamic microclimates. Second, for inlet wind speed boundary conditions, although near-roof wind speeds are generally low, uniform profiles overestimate overall wind speeds and amplify local turbulence, increasing in-canopy velocities by over 30%. Therefore, the power-law inlet profile is better suited to maintaining the fidelity of the simulated near-roof wind field in the present case. Finally, solar heat source modeling should distinguish between PV modules and vegetation: the layered heat source method replicates radiation propagation within PV modules, enabling precise plane-of-array (POA) irradiance estimates, while the surface radiation approach is better suited for vegetation, as it dynamically accounts for module-induced shading to resolve actual surface temperature and irradiance distributions.

Comparisons with the reference RPV system under identical conditions reveal that vegetation consistently provides a cooling effect on PV modules, with a maximum temperature reduction of 1.6 °C across the two simulated days. This cooling leads to a measurable electrical benefit under the analyzed conditions, with the maximum power increase reaching about 2.6 W per module and the maximum relative power gain reaching approximately 0.8%. Additionally, the presence of vegetation and soil reduces roof surface temperatures by up to 13 °C compared to sun-exposed concrete, corresponding to an estimated maximum reduction of 80 W/m² in roof heat gain during the simulated period. This suggests that the cooling benefit of vegetation is more pronounced at the roof level than for PV modules.

Furthermore, this study analyzes the module cooling mechanisms by comparing surface heat fluxes and temperature variations, indicating the role of vegetation's high emittance in enhancing the radiative cooling of the modules. In the analyzed cases, convective heat transfer appears to be the main cooling pathway for the PV modules, while diffusion of water vapor does not provide direct benefit to module temperature reduction. The simulated results further suggest that the ventilation conditions beneath the modules may strongly influence the cooling response. Based on these observations, several promising avenues for future design refinement are identified. The modeling

Table A.1

Summary of testing conditions and selected meshing details.

Testing conditions		Meshing details	
Ambient temperature	28.11°C	No. of elements	4 349 456
POA	900 W/m ²	Average element quality	0.73
GHI	893 W/m ²	No. of layers	15
Relative humidity	96%	First layer thickness for ground and plant surface	0.00018 m
PV power	659 W	Growth ratio	1.2
Wind speed	0.62 m/s	First layer thickness for PV module surface	0.00018 m
Wind direction	293°	Average y ⁺ for plant surface	≈0.4

framework established in this study provides a validated methodological foundation for reliable PVIGR simulation under realistic rooftop conditions. It will also support future extensions to larger PV arrays and more complex rooftop environments and provide a basis for further evaluating their potential roles in roof thermal regulation and solar energy utilization.

CRedit authorship contribution statement

Haoran Chang: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ip Cheng:** Validation, Resources, Investigation, Data curation. **Liutao Chen:** Writing – review & editing, Software, Resources, Investigation, Data curation, Conceptualization. **Xin Wei:** Visualization, Software, Resources, Investigation, Conceptualization. **Zhe Wang:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Mengying Li:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used GPT-5 to improve the language and readability. After using these tools, the authors reviewed and edited the content as needed, taking full responsibility for the content of the publication.

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.

Acknowledgments

The authors gratefully acknowledge the substantial support from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. C6003-22Y).

Appendix A. Grid convergence test

The computational domain is discretized using unstructured tetrahedral and prismatic grids. Boundary layer meshes are refined at the ground, PV modules, vegetation, and soil surfaces to directly resolve the viscous sublayer, enhancing the accuracy of near-wall flow field calculations. The grid convergence test is performed using the environmental conditions measured at noon (12:00) on April 12, as listed in Table A.1. At this time, the microenvironment within the PVIGR system differs markedly from the ambient conditions, making it a representative case for assessing mesh sensitivity.

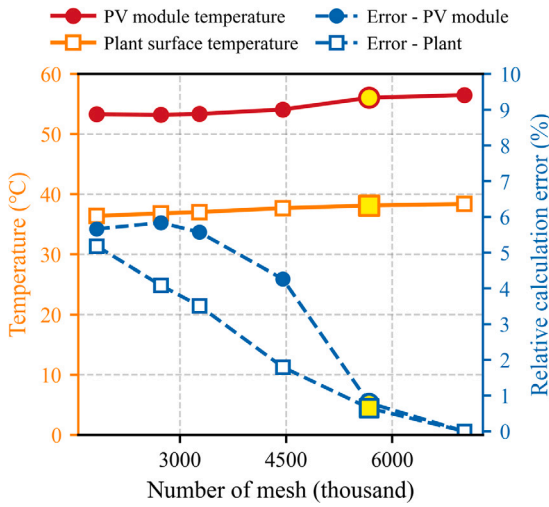


Fig. A.1. Grid convergence test: average temperatures of PV modules and vegetation, and corresponding relative errors with respect to the finest mesh.

Following the consistent meshing strategy, six progressively refined grid configurations are developed: mesh 1 (1.8 million elements, coarsest resolution), mesh 2 (2.7 million elements, coarser), mesh 3 (3.3 million elements, coarse), mesh 4 (4.4 million elements, fine), mesh 5 (5.7 million elements, finer), and mesh 6 (7 million elements, finest). The average temperature on the rear surface of the PV modules and the mean vegetation surface temperature are used as evaluation metrics. For each grid resolution, the relative error is computed with respect to the solution obtained using the finest mesh. The results are shown in Fig. A.1.

The simulation results indicate that the average temperatures of both PV modules and vegetation increase with mesh refinement. When the mesh size exceeds 5 million elements, further refinement leads to a less than 1% relative discrepancy compared with the finest grid. Based on this comparison, Mesh 5 is identified as an optimal candidate, as indicated by the yellow symbols in Fig. A.1. To further substantiate this preliminary selection using a standardized numerical metric, the GCI analysis is conducted as described below.

The Grid Convergence Index (GCI) based on Richardson extrapolation is calculated using the three finest grids (Meshes 4–6) to quantify the discretization uncertainty. For the unstructured 3D meshes, the

Table A.2

Grid Convergence Index (GCI) results for the three finest meshes.

Monitored variable	Average temperature (°C)			GCI ₃₂ (%)	GCI ₂₁ (%)	β
	Mesh 4	Mesh 5	Mesh 6			
PV temperature	54.11	56.07	56.52	1.41	0.40	1.008
Vegetation temperature	37.70	38.14	38.39	2.43	1.60	1.007

GCI₃₂ compares Mesh 4 with Mesh 5, whereas GCI₂₁ compares Mesh 5 with Mesh 6.

representative grid size is defined as $h_i = N_i^{-1/3}$, where N_i is the number of elements. The refinement ratio between two adjacent grids is $r_{21} = h_2/h_1$, where subscripts 1 and 2 denote the fine and medium grids, respectively. The fine-grid GCI is calculated as:

$$GCI_{21} = F_s \frac{|\phi_2 - \phi_1| / \phi_1}{r_{21}^{p_1} - 1} \times 100\%, \quad (A.1)$$

where ϕ is the monitored temperature, p_1 is the apparent order of convergence estimated from the three grid solutions, and $F_s = 1.25$ is the recommended safety factor. The GCI values of the two successive grid pairs are reported in Table A.2. The asymptotic range of convergence is verified using the standard ratio $\beta = GCI_{32}/(r_{21}^{p_1} GCI_{21})$, which approaches unity when the solutions exhibit the expected Richardson convergence behavior. The calculated β values are 1.008 for the average PV module rear surface temperature and 1.007 for the mean vegetation surface temperature, confirming that the three finest meshes are within the asymptotic range of convergence. For the selected Mesh 5 relative to Mesh 6, the GCI₂₁ values are 0.40% and 1.60% for the PV module and vegetation surface temperatures, respectively.

Together with the asymptotic-range check, these estimates indicate that further refinement from Mesh 5 to Mesh 6 has a limited effect on the monitored temperatures. Consequently, Mesh 5 is selected for all simulations in this study, as it yields mesh-independent predictions while reducing grid size by 19.2% (1.35 million fewer elements) compared with Mesh 6.

Appendix B. Uncertainty analysis

The uncertainty assessment considers three distinct sources: experimental measurement accuracy, residual spatial-discretization uncertainty, and the propagation of uncertainty in the measured meteorological inputs. The measurement ranges and specified accuracies of the instruments used to establish the uncertainty bounds are summarized in Table B.1. For solar irradiance, a conservative input

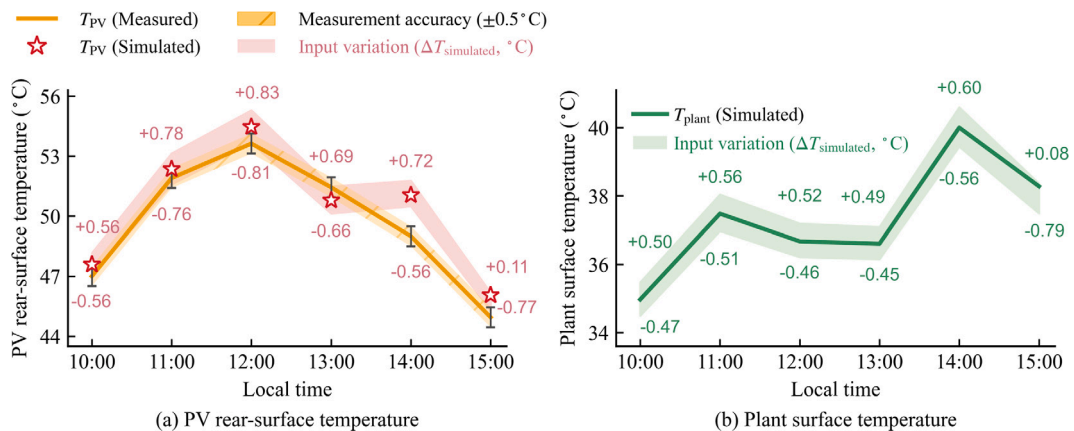


Fig. B.1. Simulated temperature uncertainty envelopes induced by meteorological input uncertainties across six hourly PVIGR cases on 12 April. (a) PV module rear-surface temperature. (b) Mean vegetation surface temperature.

Table B.1
Instrument specifications.

Variables	Instrument	Range	Precision
PV surface temperature	K-type thermocouple	−189 to +660°C	±0.5°C
Wind speed	HY-SA3E ultrasonic anemometer	0–70 m s ^{−1}	±3%
Relative humidity	QTHPB humidity sensor	0%–100%	±3%
Solar irradiance	SMP10 pyranometer	0–1600 W m ^{−2}	<±7 W m ^{−2} at 200 W m ^{−2}

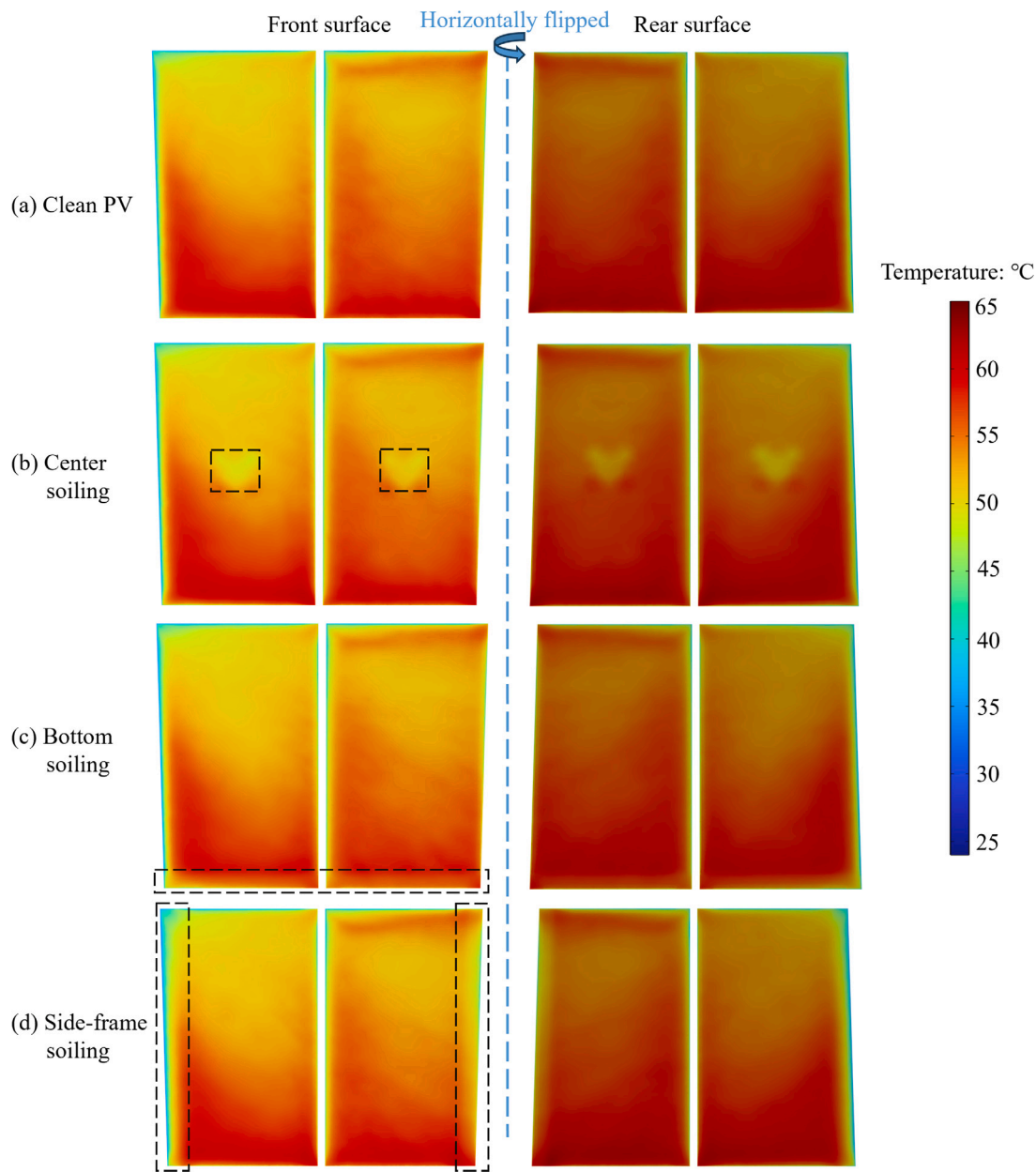


Fig. C.1. Simulated PV module temperature distributions for the clean reference and illustrative non-uniform soiling cases at 12:00 on 12 April. The left and right halves show the front- and rear-surface temperatures, respectively. From top to bottom, the rows show: (a) the clean reference case; (b) a 20 × 20 cm central soiling patch; (c) a 10 cm-wide lower-edge soiling band; and (d) two 10 cm-wide side-edge soiling bands. Dashed outlines identify the prescribed soiled regions.

perturbation bound of $\pm 2\%$ is specified to account for combined operational field uncertainties, including pyranometer zero-offset, directional and temperature response errors, and non-linearity. The GCI analysis in [Appendix A](#) provides the discretization component by quantifying

the residual numerical uncertainty associated with finite mesh resolution. Evaluating these sources independently ensures that mesh discretization errors are clearly distinguished from discrepancies caused by instrument tolerance or input variability.

For the six hourly simulation cases on 12 April, experimental input uncertainty was quantified by simultaneously varying the measured wind speed, solar irradiance, and relative humidity within their instrument accuracy limits. The warm bounding scenario applies a wind speed of -3% , irradiance of $+2\%$, and relative humidity of $+3\%$; conversely, the cool bounding scenario enforces the opposite perturbations. The prescribed variations define upper and lower bounds for the simulated temperature response to plausible measurement variations in the meteorological inputs.

Fig. B.1 compares the simulated temperature envelopes with the field thermocouple measurements. For the rear-surface temperature of the PV module, the simulated deviations from the baseline range from $+0.11$ to $+0.83^\circ\text{C}$ in the warm scenario and from -0.81 to -0.56°C in the cool scenario. The corresponding deviations in the average vegetation surface temperature range from $+0.08$ to $+0.60^\circ\text{C}$ and from -0.79 to -0.45°C , respectively. This metric is evaluated as a sensitive indicator of meteorological input propagation because the plant interacts directly with the ambient atmosphere and solar radiation, making it highly responsive to input fluctuations.

Overall, the simulated uncertainty envelopes indicate that input-driven temperature fluctuations remain limited. The PV temperature uncertainty band overlaps the $\pm 0.5^\circ\text{C}$ thermocouple accuracy interval across five of the six sampled hours. Since the input-induced numerical variation is comparable in magnitude to the measurement tolerance, the discrepancies between model predictions and field measurements remain within acceptable physical limits, supporting the reliability of the validation analysis and the proposed framework.

Appendix C. Thermal effects of non-uniform soiling on PV modules

The effects of non-uniform dust deposition on PV module temperature distributions were evaluated using the simulation case of 12 April at 12:00. Soiled regions were prescribed on the outer glass surface, where incident irradiance was locally partitioned into reflection (21%), dust-layer absorption (2%), and transmission into the underlying module layers (77%), following the optical mechanisms detailed by Smedstad et al. [58]. Three soiling patterns were evaluated against the clean reference: (i) a 20×20 cm central patch, (ii) a 10 cm-wide lower-edge band, and (iii) two 10 cm-wide side-edge bands. All other computational settings remained identical to the baseline framework.

Fig. C.1 presents the simulated temperature distributions after two hours of transient operation. Front-surface cooling remains modest relative to that on the rear surface, as heat absorption within the dust layer partially offsets the reduced solar gain in the underlying layers. Rear-surface cooling is more pronounced, reaching approximately 3°C beneath the central patch, where lateral conduction moderates spatial temperature gradients. The lower-edge soiling band produces a maximum local temperature reduction of approximately 3.5°C in a region inherently warmer under northwesterly inflow. For the side-edge soiling, the cool rear-surface zones extend approximately 3 cm farther toward the module interior relative to the clean reference, yielding local reductions of 1 to 2°C .

These simulations capture the non-uniform thermal response to localized irradiance attenuation and heat source redistribution. Electrical feedback is omitted from the present thermal formulation: under operational conditions, non-uniform cell irradiance can trigger current mismatch and reverse-bias heating, potentially counteracting the optical cooling effect and generating localized hot spots. Resolving these coupled electro-thermal phenomena requires a spatially explicit optical model integrated with a cell- or string-level circuit solver that incorporates reverse-bias breakdown dynamics and bypass diode behavior.

Data availability

Data will be made available on request.

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