



Experimental and numerical study on ventilation modes and construction optimization of ventilated-photovoltaic vacuum glazing in high-altitude cold climates

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ABSTRACT

This study investigates a ventilated photovoltaic vacuum glazing system to address the thermal and energy demands of buildings in high-altitude cold climates. The thermal and electrical performance of different ventilation modes was experimentally measured on a platform in a high-altitude cold region, and the data were used to validate a thermal and electrical simulation model in COMSOL incorporating pressure correction. The validated model was then employed to analyze dynamic energy performance and seasonal variations of three ventilation modes. Furthermore, a dedicated annual ventilation strategy for plateau climates is proposed, and the individual and interactive effects of key design parameters on winter energy gain were examined. The main findings indicate that: (1) the optimized ventilation strategy raised energy gain by 53.48% in winter and 55.84% during the transitional season, while in summer, daytime outdoor air circulation reduced heat gain by 13.22% but boosted power generation by 6.35%; (2) the cell coverage ratio negatively influenced energy gain, while depth of cavity and surface emissivity showed positive effects, with a significant negative interaction between cell coverage ratio and surface emissivity; and (3) optimal winter performance was achieved with a cell coverage ratio of 0.5–0.6, a cavity depth of 200–250 mm, and a surface emissivity above 0.22. This work offers practical insights for designing and operating the ventilated photovoltaic vacuum glazing system in high-altitude cold climates, thereby helping alleviate local energy supply pressure.

Abbreviations

BIPV	Building Integrated Photovoltaic
CCR	Cell Coverage Ratio
CdTe	Cadmium Telluride
CFD	Computational Fluid Dynamics
COP	Coefficient of Performance
Cv(RMSE)	Coefficient of Variation of Root Mean Square Error
DOM	Discrete Ordinate Method
DD	Dimension of the Cavity Depth
Em	Infrared Surface Emissivity
MBE	Mean Bias Error
PV	Photovoltaic
PV-DSF	Photovoltaic Double-Skin Façade
V-PVVG	Ventilated-Photovoltaic Vacuum Glazing
STPV	Semi-Transparent Photovoltaic

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TMY	Typical Meteorological Year
Symbols	
E_{pv}	Electrical power generation
Q_{pv}	Equivalent electrical power generation
Q_c	Convective heat
Q_{c-p}	Convective heat gain
Q_{c-n}	Convective heat loss
Q_r	Long-wave radiative heat
Q_{r-p}	Long-wave radiative heat gain
Q_{r-n}	Long-wave radiative heat loss
Q_{air}	Recovered air heat
Q_{air-p}	Recovered air heat gain
Q_{air-n}	Recovered air heat loss
Q_{sol}	Transmitted short-wave radiative heat
Q_{total}	Total energy flux

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Q_{gain}	Energy gain
Q_{loss}	Energy loss
Q_{total}	Total energy gain

1. Introduction

1.1. Research background

Buildings account for approximately 36% of global final energy use and 40% of CO₂ emissions [1]. As the world's largest emitter, China's pursuit of its “Dual Carbon” goals [2] hinges on increasing clean energy in the building sector [3]. Solar energy, a key renewable source for buildings [4], makes Building-Integrated Photovoltaics (BIPV) a critical technology for achieving carbon neutrality [5]. The Tibet region possesses exceptional solar resources (annual global horizontal irradiation >1972 kWh/m²; Fig. 1(a)), yet it suffers from a cold climate, prolonged heating demand, and scarce conventional energy, creating a pressing energy supply-demand challenge [6]. Its high-altitude geography results in a unique climate characterized by intense solar radiation, low air temperatures, large diurnal temperature swings, and low atmospheric pressure [7,8], which differs significantly from standard cold climates such as those of Beijing and Xi'an (Fig. 1(b)). This distinctive environment imposes specific and complex requirements on building envelope design and solar energy utilization strategies, thereby shaping the unique application characteristics of BIPV technologies in this region.

Windows are a critical weak point in building envelopes, accounting for 40% of energy consumption and heat loss [9]. Semi-transparent photovoltaics (STPV) integrated into the facade offer a promising solution by generating electricity while actively regulating the building's light and thermal environment [10]. However, STPV performance is highly climate-sensitive, and inappropriate design can substantially increase building energy use. Therefore, optimizing STPV systems to maximize both electricity and heat gain is an effective approach to alleviating the dual energy pressure in Tibet.

1.2. Literature review

As a key technology for reducing building energy use, STPV has evolved through several structural forms (Fig. 2). The basic single-glazing PV (Photovoltaic), a PV layer between glass panes [11], outperforms conventional windows in saving energy but offers limited insulation in extreme cold [12]. Adding a second indoor glass pane creates double-glazing PV with an air gap [13]; it is effective in hot climates like Algeria but shows modest savings in cold/temperate regions like East Asia [10]. Ventilated double-glazing PV and Photovoltaic Double-Skin Façade (PV-DSF) incorporate a ventilated cavity, enabling mode switching for seasonal adaptation and improving climatic adaptability [14].

To overcome performance limits, Photovoltaic Vacuum Glazing (PVVG) was developed, using a vacuum layer to nearly eliminate conductive/convective heat transfer, thus providing superior insulation [15]. Studies confirm it significantly reduces net heat gain/loss in extreme climates [16,17]. Structural refinements followed: 2L-PVVG simulations show the vacuum interlayer suppresses heat conduction [18]; 3L-PVVG achieves better thermal-electrical performance than traditional PV windows [19,20]; and 4-layer configurations (e.g., Insulated/Laminated PVVG) further lower U-value, especially in cold regions [21–23]. Among these, Venti ventilated photovoltaic vacuum glazing (V-PVVG) stands out for thermal management. Zhang et al. [24, 25] modeled and tested it in hot-summer/cold-winter zones, comparing it with Insulated PVVG, and developed an energy model to evaluate its annual performance across five Chinese climate zones.

Research on V-PVVG in high-altitude cold regions remains notably insufficient, with prior work focused largely on climates such as hot-summer/cold-winter zones. For the Tibetan Plateau — characterized by low temperature, low atmospheric pressure, intense solar radiation, and large diurnal temperature swings — this study proposes that the V-PVVG system can optimize the management of both heat and electricity.

The reduced atmospheric pressure significantly alters the heat transfer inside the ventilated cavity, a phenomenon that cannot be captured by standard constant-pressure models. Moreover, existing ventilation strategies in the literature are often empirically determined for plain climates without rigorous analysis, making them particularly unsuitable for direct application in high-altitude environments. Consequently, neither a dedicated annual ventilation strategy nor quantitative design insights regarding the influence of key parameters on system performance in high-altitude cold climates are available. The core contribution of this study is to fill these gaps by proposing a climate-specific annual ventilation strategy and, under this strategy, revealing the individual and interactive effects of key design parameters on net energy gain.

Therefore, this study aims to:

- (1) Validate the numerical model against high-altitude field data, incorporating pressure correction for low-pressure conditions;
- (2) Analyze dynamic energy performance and seasonal differences of ventilation modes to propose an annual strategy for plateau climates;
- (3) Under the recommended winter strategy, investigate the individual and interactive effects of key design parameters— cavity coverage ratio (CCR), cavity depth (DD), and infrared surface emissivity (Em) [24–27] — to develop an energy-efficient V-PVVG design.

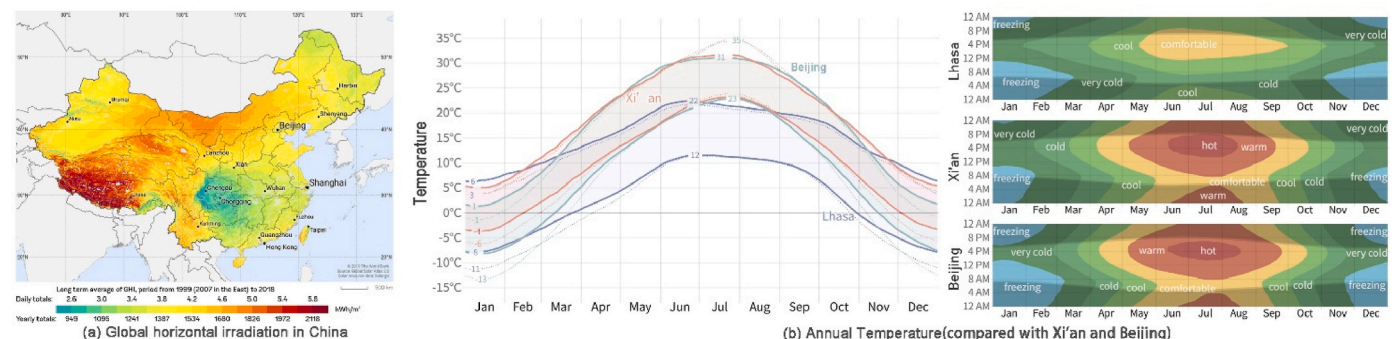


Fig. 1. Solar radiation and temperature conditions in Lhasa.

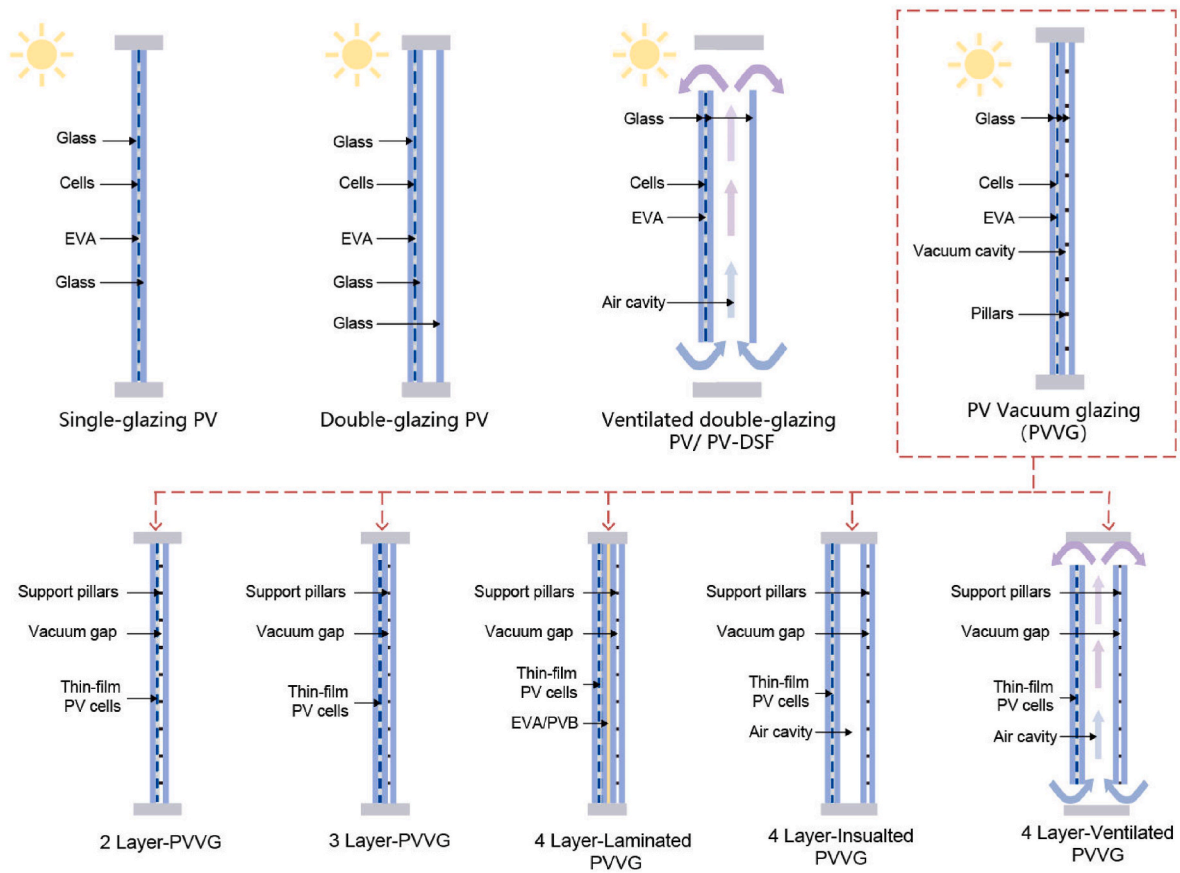


Fig. 2. Configurations of STPV.

2. System description and research methods

2.1. System description

The V-PVVG comprises an outer Cadmium Telluride (CdTe) photovoltaic glass and an inner vacuum glazing unit (Fig. 3(a)). The outer PV glass faces the outdoors for solar absorption, while the vacuum unit faces the indoors. A vacuum gap (pressure <0.1 Pa) between its panes reduces gaseous heat transfer to negligible levels and is maintained by stainless-steel pillars spaced for mechanical stability [18,21,24,28]. A

Low-E coating on the vacuum layer's outer surface enhances insulation, beneficial in cold climates [29]. An air cavity between the two glass units, with operable top and bottom vents, allows mode switching for PV cooling, waste-heat recovery, or insulation.

Ventilation modes are defined by airflow direction: insulation, indoor air circulation, and outdoor air circulation [30]. Their corresponding heat-transfer processes are shown in Fig. 3 (b). In insulation mode, absorbed solar radiation is converted to electricity, generating waste heat. Long-wave radiation and natural convection transfer heat toward the vacuum glazing [29]. The low-E coating and vacuum

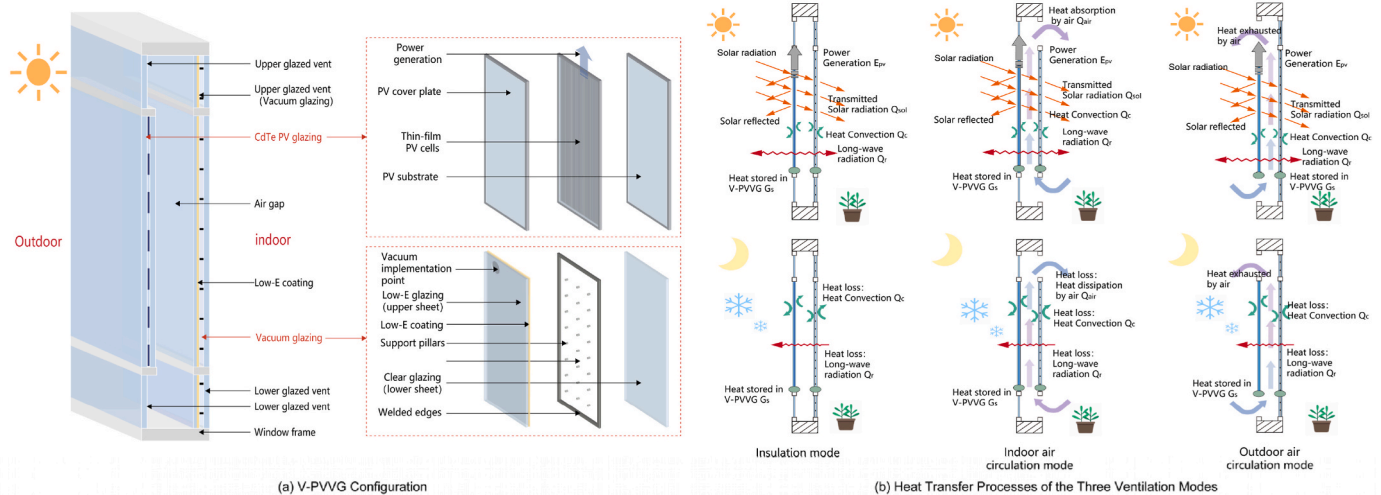


Fig. 3. Configuration of V-PVVG.

environment suppress radiative and conductive/convective transfer, so only minor heat passes via pillars or residual radiation to the inner pane; this inner surface then exchanges heat indoors via radiation and convection. In ventilated modes, airflow is driven by thermal-pressure difference [31]. Heated air rises and exits the upper outlet, preventing stagnation. In indoor-circulation mode, this heat is supplied indoors; in outdoor-circulation mode, it is exhausted outside [32].

2.2. Research methods

2.2.1. Research framework

The V-PVVG system was evaluated for Lhasa, a representative high-altitude cold climate. An experimental platform was constructed, and a COMSOL model incorporating low-pressure correction was validated against measured data. Based on the validated simulation model, the seasonal energy performance of the system in the high-altitude cold region was analyzed, yielding a dedicated ventilation strategy tailored to this unique climate. Under this strategy, simulations were subsequently performed for winter conditions to examine both the individual and interactive effects of CCR, DD, and Em on energy gain. Through this analysis, the optimal configuration was identified. As shown in Fig. 4.

2.2.2. Optimization parameter ranges

The CCR range was set at 0.4–0.9, considering both the optimal ranges reported in previous studies [24,25,33] and the practical limits of commercially available PV modules to avoid unrealistically low generation cases [34]. Six DD values (50–300 mm) were chosen from literature [35,36], and six Em levels (0.02–0.42, 0.84) were selected based on coating studies [21] to systematically assess their impact on thermal and electrical performance.

2.2.3. Evaluation metrics

The total electrical power generation is calculated by Eq. (1):

$$E_{pv} = \frac{G_i \cdot \eta \cdot A_{pv}}{A} \quad (1)$$

where E_{pv} is the total electrical power generation (kWh), η is the electrical conversion efficiency, A_{pv} is the area of the PV glazing (m^2), and A is the total area of the window (m^2).

The electricity generated by the V-PVVG system substitutes for the electrical energy that would be consumed by a heat pump to deliver equivalent heating. Following established practice in photovoltaic window research [37,38], the Coefficient of Performance (COP)-based conversion (from TICA guidelines, based on Lhasa's indoor setpoints and climate, as shown in Fig. S1) is adopted to reflect the actual end-use energy benefit, and is defined by Eq. (2):

$$Q_{pv} = E_{pv} \cdot COP \quad (2)$$

Heat exchange at the inner glass surface occurs through long-wave radiation and convection. Based on the Stefan–Boltzmann law, the long-wave radiative flux is given by Eqs. (3) and (4):

$$q_r = \varepsilon \cdot \sigma \cdot (T_s^4 - T_{sur}^4) \quad (3)$$

$$Q_r = q_r \cdot t \quad (4)$$

where ε is the surface infrared emissivity of the glass surface (approximately 0.84 for ordinary glass), $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$, T_s is the temperature of the inner glass surface (K), T_{sur} is the mean radiant temperature of the indoor environment (K), t is the calculation period (h), and Q_r is the long-wave radiative heat per unit area (kWh), with Q_{r-p} and Q_{r-n} denoting radiative heat gain and loss, respectively.

The convective heat flux is given by Eqs. (5) and (6):

$$q_c = h_c \cdot (T_a - T_s) \quad (5)$$

$$Q_c = q_c \cdot t \quad (6)$$

where h_c is the convective heat-transfer coefficient ($\text{W}/(\text{m}^2 \cdot \text{K})$), T_a is the indoor air temperature far from the wall (K), and Q_c is the convective heat per unit area (kWh/m^2), with Q_{c-p} and Q_{c-n} denoting convective heat gain and loss, respectively.

For the indoor air circulation mode, the sensible heat recovered from the cavity airflow is defined as Q_{air} , with Q_{air-p} and Q_{air-n} denoting air heat gain and loss, respectively.

Based on fluid energy transport [39], it is calculated by Eq. (7):

$$Q_{air} = \frac{\rho_a \cdot C_a \cdot A_{ch} \cdot u \cdot (T_{out} - T_{in}) \cdot t}{A} \quad (7)$$

where ρ_a is the air density (corrected for Lhasa's altitude at 20 °C, 0.72 kg/m^3), C_a is the specific heat capacity of air, u is the average air velocity in the cavity (m/s), A_{ch} is the cross-sectional area of the air flow channel (m^2), and T_{out} and T_{in} are the air temperatures at the upper and lower vents, respectively (°C).

The total energy gain per unit area (Q_{total}) and the instantaneous total energy flux density (q_{total}) are calculated by Eqs. (8) and (9):

$$Q_{total} = Q_r + Q_c + Q_{sol} + Q_{air} + Q_{pv} \quad (8)$$

$$q_{total} = \frac{Q_{total}}{t} \quad (9)$$

where Q_{total} is the total energy gain per unit area of the window inner surface (kWh/m^2), Q_{sol} is the transmitted short-wave irradiation ($\text{kWh}/$

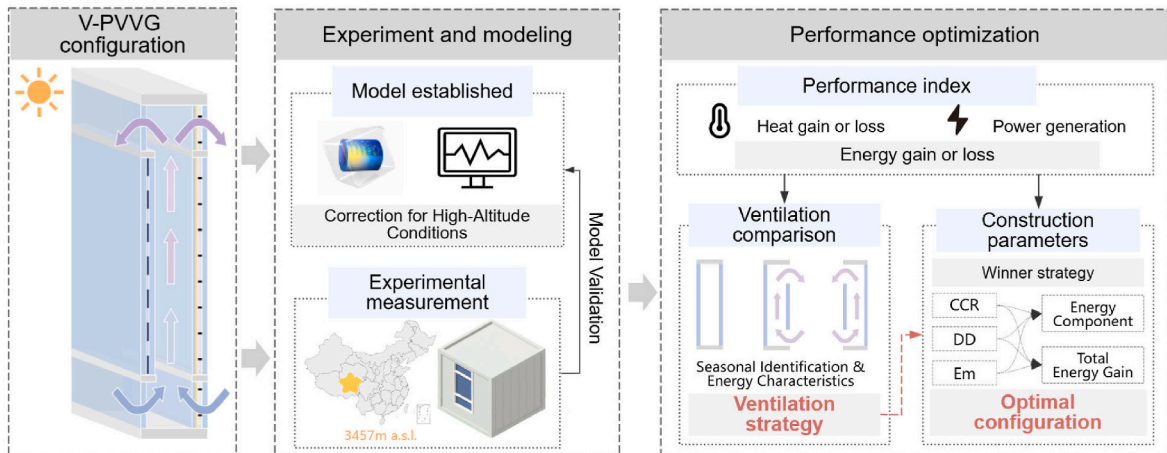


Fig. 4. Research framework.

m^2), and q_{total} is the total energy flux density per unit area of the window inner surface (W/m^2 ; positive for gain, negative for loss).

The total energy gain can be decomposed into gain and loss components as expressed in Eq. (10):

$$Q_{\text{total}} = Q_{\text{gain}} + Q_{\text{loss}} \quad (10)$$

For the V-PVVG system, Q_{gain} and Q_{loss} denote the energy gain and loss per unit area over the same period, respectively (kWh/m^2).

3. Model development

3.1. Climatic parameters and indoor settings

The experimental site in Kangding (3457 m a.s.l.) is situated at a higher altitude than its local meteorological station (2615 m a.s.l.). To obtain reliable long-term high-altitude cold climate data, Lhasa (3650 m a.s.l.) was selected as the representative site for simulation. Both sites are located in the Tibetan region and share key climatic traits: intense solar radiation, dry, thin air, and large diurnal temperature variation, which similarly influence the thermal performance of building envelopes.

Fig. 5 presents monthly typical-day data for Lhasa derived from the 8760-h Typical Meteorological Year (TMY) [8], where hourly records of solar irradiance, ambient temperature, and wind speed were averaged to represent each month's typical conditions. Air temperatures are low year-round, with severe cold in winter and cool conditions in summer, and show pronounced diurnal and seasonal variation.

Following the methodology used in prior window system studies [28, 40], the indoor temperature was held constant to isolate the thermal characteristics of the building envelope. Indoor temperature setpoints followed the plateau climate of Lhasa. Based on GB50736-2012 [41], heating design typically uses 18–20 °C with 0.2 m/s air speed. For Lhasa's heating season (Nov–Mar) and April (<10 °C avg.), 18 °C was set [42]. During May, Sep, and Oct (10–15 °C avg.), 20 °C maintained comfort with lower energy use [43]. Summer (Jun–Aug, 16–17 °C avg.) required no cooling; measured indoor temperatures averaged 21–22 °C [44], and 22 °C was set.

3.2. Thermal model

The V-PVVG thermal model was developed in COMSOL Multiphysics 6.4 [45] for Computational Fluid Dynamics (CFD) simulation, coupling solid heat transfer, fluid dynamics, and radiation. The standard k – ϵ model of the Reynolds-averaged Navier-Stokes equations, which is widely validated for turbulent natural convection in window cavities and offers reliable accuracy for engineering applications [46,47], simulated the air-cavity flow, and the Discrete Ordinates Method (DOM) [48] handled radiation.

A temperature-dependent photovoltaic power generation model was

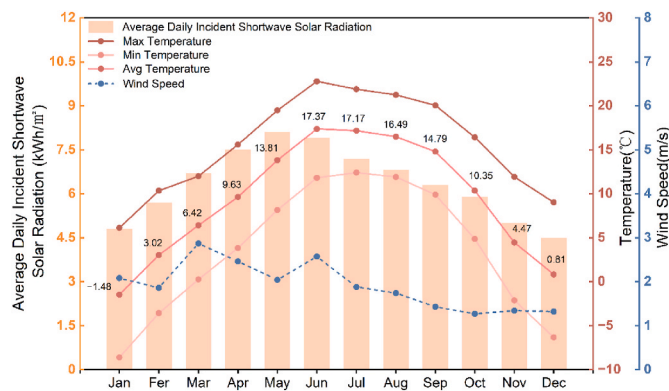


Fig. 5. Climatic parameters in Lhasa.

established and coupled to the thermal model via the PV glazing temperature interface.

The following assumptions were applied in developing the heat transfer model:

- Negligible heat transfer at glazing-frame joints due to highly insulating frames;
- Uniform indoor/outdoor air temperature distributions;
- Complete conversion of radiative interactions to thermal energy;
- When ventilation ports are open, the inlet airflow is assumed to be fully developed;
- Residual gas pressure in vacuum cavities (0.001 Pa) allows substitution of conduction, radiation, and convection with an equivalent thermal conductivity.

Geometric and material parameters followed the experimental prototype, with key photovoltaic electrical and material thermophysical properties provided in Table 1.

3.2.1. Coupled solid-fluid heat transfer

The coupled solid-fluid heat transfer mechanism governing photovoltaic glazing, tempered glass, and vacuum layers is described by Eq. (11):

$$-k\nabla^2 T = Q_{\text{rad}} \quad (11)$$

where T , Q_{rad} , and k represent temperature, radiative heat source, and thermal conductivity within respective domains, with Q_{rad} denoting heat generation from radiation-medium interactions.

The outdoor ambient temperature ($T_{\text{ext,out}}$) is assigned based on the climate data for Lhasa, and the indoor ambient temperature ($T_{\text{ext,in}}$) is prescribed according to the specific indoor control strategy.

Convective exchange at the outdoor and indoor surfaces provides the boundary conditions in Eqs. (12) and (13), respectively:

$$-k_{pv} \frac{\partial T}{\partial x} \Big|_{x=x_0} = h_{\text{od}} (T_{\text{ext,out}} - T) \quad (12)$$

$$-k_{gla} \frac{\partial T}{\partial x} \Big|_{x=x_i} = h_{\text{id}} (T_{\text{ext,in}} - T) \quad (13)$$

where x_0 and x_i denote the x-coordinates along the thickness direction of outdoor and indoor glazing surfaces, respectively; h_{od} and h_{id} are the outdoor and indoor convective coefficients; k_{pv} and k_{gla} are the thermal conductivities of the PV glazing and tempered glass.

The adiabatic boundary conditions along the top and bottom edges of the glazing system are defined by Eqs. (14) and (15):

Table 1

Critical thermophysical properties.

Parameter	Value
Thermal capacity of photovoltaic glazing	850 J/(kg·K)
Density of photovoltaic glazing	2232.14 kg/m ³
Thermal conductivity of photovoltaic glazing	0.98 W/(m·K)
Density of tempered glass	2500 kg/m ³
Thermal capacity of tempered glass	703 J/(kg·K)
Thermal conductivity of tempered glass	1 W/(m·K)
Equivalent heat transfer coefficient of vacuum layer	0.106787 W/(m ² ·K)
Absorption coefficient of tempered glass	0.2(1/m)
Scattering coefficient of tempered glass	0(1/m)
Absorption coefficient of air	0.001(1/m)
Scattering coefficient of air	0(1/m)
CCR of photovoltaic glazing	0.7
Surface emissivity of Low-E film	0.12
Transmittance of Low-E film	0.06
Vacuum layer pressure	0.001Pa

$$k \frac{\partial T}{\partial x} \Big|_{x=0} = 0 \quad (14)$$

$$k \frac{\partial T}{\partial y} \Big|_{y=0} = 0 \quad (15)$$

when ventilation ports are open, inflow boundary conditions are governed by Eqs. (16) and (17):

$$-n \cdot q = \rho \Delta H \cdot n \quad (16)$$

$$\Delta H = \int_{T_u}^T C_p dT + \int_{p_u}^{p_a} \frac{1}{\rho} (1 - a_p T) dp \quad (17)$$

where ΔH is the enthalpy change from the upstream state (T_u, p_u) to the inlet state (T, p_a), C_p is the specific heat at constant pressure, ρ is fluid density, and a_p is thermal expansion coefficient.

The outflow boundary uses a zero-normal-flux condition, as governed by Eq. (18):

$$-n \cdot q = 0 \quad (18)$$

the transient energy balance for the coupled solid-fluid interface is given by Eq. (19):

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \cdot \nabla T + \nabla \cdot (-k \nabla T) = Q \quad (19)$$

where T is temperature; t is time; C_p is heat capacity; ρ is density; Q is heat source term; k is thermal conductivity; and u is the fluid velocity vector.

Low atmospheric pressure at high altitude reduces air density, weakening natural convection and lowering convective heat-transfer efficiency. To ensure accuracy, the coefficient h_c must be pressure-corrected. In COMSOL's heat transfer module, this correction is performed by specifying the local atmospheric pressure and adjusting the convective heat transfer coefficient in the heat flux boundary condition for internal or external natural convection. The model applies an ASHRAE-based method for indoor low-speed conditions [49]. The baseline indoor natural-convection value is obtained from Eqs. (20) and (21):

$$h_{c,natural} = C \cdot (\Delta T)^{\frac{1}{3}} \quad (20)$$

$$\Delta T = |T_a - T_s| \quad (21)$$

where ΔT is the absolute temperature difference between the surface and air (K), and the empirical coefficient C is taken as $1.31 \text{ W}/(\text{m}^2 \cdot \text{K})$ for indoor vertical surfaces according to ASHRAE.

Pressure correction of the convective coefficient follows the ASHRAE formulation [50]. The corrected coefficient $\bar{h}_c$ is obtained from the baseline value $h_{c,natural}$ through Eq. (22):

$$\bar{h}_c = \left(\frac{p}{p_0} \right)^{0.891} \cdot h_{c,natural} \quad (22)$$

where F is the correction factor, p is the local atmospheric pressure (65,400 Pa for Lhasa), and p_0 is the standard sea-level atmospheric pressure.

3.2.2. Radiation heat transfer

All domains were assumed to be ideal gray bodies, with radiative heat transfer modeled using the DOM. The governing equation of the DOM is given by Eq. (23):

$$\hat{s} \cdot \nabla I(\hat{s}_i) = \alpha I_b(T) - \beta I(\hat{s}_i) + \frac{\sigma_s}{4\pi} \sum_{j=1}^m \omega_j I(\hat{s}_j) \phi(\hat{s}_j, \hat{s}_i) \quad (23)$$

where ω_j is direction-dependent quadrature weights, $\hat{s}_j$ is discrete direction, and m is the order of DOM.

Boundary conditions for semi-transparent surfaces were implemented. The condition for the indoor surface is defined by Eq. (24):

$$I_w(\hat{s}_i) = \frac{\rho}{\pi} \sum_{\hat{n} \cdot \hat{s}_j \geq 0} w_j I_w(\hat{s}_j) \hat{n} \cdot \hat{s}_j - \frac{\tau}{\pi} q_i + \varepsilon I_b(T) \quad (\hat{n} \cdot \hat{s}_i < 0) \quad (24)$$

where $I_w(\hat{s}_i)$ is the radiative intensity at surfaces. ρ , τ , and ε representing surface reflectivity, transmittance, and emissivity, respectively; $\hat{n}$ is the surface normal vector; and q_i is the net radiative heat flux, given by Eq. (25):

$$q_i = \sigma \varepsilon (T^4 - T_{ext}^4) \quad (25)$$

where T is the temperature of the inner glass surface, T_{ext} is the indoor mean radiant temperature. and σ the Stefan-Boltzmann constant. The outdoor surface boundary condition follows an analogous formulation with the radiation direction reversed. The indoor surfaces surrounding the V-PVVG system were assumed to be gray bodies with an infrared emissivity of 0.9, a typical value for common interior finishes [50].

Low-e films exhibit low infrared emissivity and high infrared reflectivity, with boundary conditions defined by Eqs. (26–29):

$$q_{rout} = \sum_{\hat{n} \cdot \hat{s}_j \geq 0} w_j I_w(\hat{s}_j) \hat{n} \cdot \hat{s}_j \quad (26)$$

$$q_{rin} = \sum_{\hat{n} \cdot \hat{s}_j < 0} w_j I_w(\hat{s}_j) \hat{n} \cdot \hat{s}_j \quad (27)$$

$$I_{w_u}(\hat{s}_i) = \frac{\rho}{\pi} q_{rout_u} - \frac{\tau}{\pi} q_{rin_d} + \varepsilon I_{b_u}(T) \quad (\hat{n} \cdot \hat{s}_i < 0) \quad (28)$$

$$I_{w_d}(\hat{s}_i) = \frac{\rho}{\pi} q_{rout_d} - \frac{\tau}{\pi} q_{rin_u} + \varepsilon I_{b_d}(T) \quad (\hat{n} \cdot \hat{s}_i < 0) \quad (29)$$

where q_{rout} is emitted radiative heat flux, q_{rin} is incident radiative heat flux, $I_{w_u}(\hat{s}_i)$ and $I_{w_d}(\hat{s}_i)$ represent boundary radiative intensities at back and front surfaces, respectively, $\varepsilon I_{b_u}(T)$ and $\varepsilon I_{b_d}(T)$ denote blackbody radiative intensities at back and front surfaces, q_{rout_u} and q_{rout_d} are emitted radiative heat fluxes at back and front surfaces, and q_{rin_u} and q_{rin_d} are incident radiative heat fluxes at back and front surfaces.

Hourly solar irradiance on the south facade was obtained from TMY data using Meteonorm software. The hourly solar irradiance was applied as shortwave radiation on the outer surface of the PV glazing using the solar irradiance method. The volumetric radiative source G and the radiative flux Q_r are solved via Eqs. (30) and (31):

$$G = \sum_{i=1}^m w_j I(\hat{s}_i) \quad (30)$$

$$Q_r = \nabla \cdot q_r = \alpha (G - 4\pi I_b(T)) \quad (31)$$

Assuming zero incident intensity at the top and bottom surfaces of the glazing system, the boundary condition is defined by Eq. (32):

$$I_w(\hat{s}) = 0 \quad (32)$$

3.2.3. Airflow in cavity

This study investigates natural convection heat transfer in V-PVVG air cavities, utilizing the Boussinesq approximation to simplify the numerical solution. Density variations are characterized by Eq. (33):

$$\rho = \rho_0 [1 - \beta(T - T_0)] \quad (33)$$

where ρ is air density at temperature T , ρ_0 (corrected for high-altitude conditions) is air density at reference ambient temperature T_0 , and β is the thermal expansion coefficient of air.

The governing equations for the k- ε turbulence model are defined by

Eqs. (34–36):

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{u_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_m + S_k \quad (34)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial(\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{u_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{C_{1\varepsilon} \varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - \frac{C_{2\varepsilon} \rho \varepsilon^2}{k} + S_\varepsilon \quad (35)$$

$$u_t = \frac{\rho C_\mu k^2}{\varepsilon} \quad (36)$$

where k and ε represent the turbulent kinetic energy and its dissipation rate, respectively; u_t is the eddy viscosity; G_k and G_b are the generation of turbulence kinetic energy due to mean velocity gradients and buoyancy, respectively; Y_m accounts for the contribution of fluctuating dilatation; $C_{1\varepsilon}$, $C_{1\varepsilon}$, $C_{3\varepsilon}$ are model constants; S_k and S_ε indicate user-defined source terms; and σ_k and σ_ε denote turbulent Prandtl numbers for k and ε .

When ventilation ports are open, the airflow is driven by thermal pressure difference. The inlet velocity depends on the ventilation mode: for indoor air circulation, it is determined by buoyancy-driven flow with indoor air speed set to 0.2 m/s [41]; for outdoor air circulation, it is determined by the processed typical monthly day wind speed data.

When ventilation ports are open, the inlet boundary condition is set as a velocity inlet defined by Eq. (37):

$$u = -U_0 n \quad (37)$$

where u is the normal inflow velocity; n denotes the outward-pointing boundary normal vector; U_0 represents the magnitude of the normal inflow velocity.

The outlet is set as a pressure outlet with zero gauge pressure, where the absolute pressure equals the local atmospheric pressure of Lhasa. For outflow boundaries, standard pressure conditions are applied, governed by Eqs. (38) and (39):

$$P_{hydro} = P_{ref} g \cdot (r - P_{ref}) \quad (38)$$

$$P_{ref} = 0 \quad (39)$$

With reference pressure $P_{ref} = 0$, the absolute pressure at the boundary equals p_0 .

3.3. Electrical model

The simulated hourly temperature of the PV glass cell from COMSOL's heat transfer module was used in a temperature-corrected power generation model [51], defined by Eqs. (40) and (41):

$$E_{pv} = \frac{G_i \cdot \eta \cdot A_{pv}}{A_0} \quad (40)$$

$$\eta = \tau_1 \cdot C \cdot \eta_0 [1 - \beta(T_{pv} - 25)] \quad (41)$$

where G_i is the incident irradiance, τ_1 is the front-glass transmittance, A_0 is the total window area, η_0 is the efficiency at Standard Test Conditions (STC), C is the cell coverage ratio, β is the temperature coefficient, and T_{pv} is the PV cell operating temperature.

3.4. Numerical verification

To verify mesh independence, five meshes (78k–254k cells) were analyzed. Cross-sectional average temperatures at seven heights at were extracted (Fig. S2). As shown in Table S1, the deviation between the 157k mesh and the 254k mesh is minimal, with a relative error of only 0.012%, far below the 1% threshold. The selected Fine mesh satisfies mesh independence, balancing accuracy and computational cost, and

was used for all subsequent simulations.

An adaptive BDF scheme (RTOL = $1e^{-3}$) was used, with time steps averaging 210 s (range 18–852 s), well below the envelope's thermal response time, confirming time-step independence. Results were exported as 15-min averages.

4. Experiment and model validation

4.1. Experimental platform

The V-PVVG system was installed on the south wall of a container-based test room in Kangding, Sichuan. For the experimental baseline model, key parameters are provided in Table 2. The PV glazing employs a 0.7 CCR CdTe film [52]. The vacuum unit incorporates a 0.12 low-E coating as commonly adopted in practice [53]; its high vacuum negates residual gas conduction. The DD follows the mid-range value recommended in Refs. [35] and [36].

Fig. 6 shows the experimental platform and measurement configuration. Pyranometers measured south-facing and transmitted irradiance. Three thermocouples were uniformly placed on each glass layer and within the cavity. The inner glass surface was fitted with an HS-30 and an RS-30 sensor for total and infrared radiative heat flux, respectively. A central thermocouple recorded room air temperature. All sensors were logged by a CR1000X data logger. A microclimate logger, an I-V curve tracer, and anemometers (at vents) recorded environmental parameters, electrical performance, and airflow, respectively. Instrument details are in Table 3.

4.2. Experimental results

To evaluate performance under the plateau climate, three ventilation modes were tested: insulation (Jul 3–6), indoor air circulation (Jun 28 – Jul 2), and outdoor air circulation (Jul 11–14). Based on data completeness and weather stability, three representative days per mode were selected for analysis. Weather conditions are shown in Fig. 7. The marked performance differences among the modes underscore the need for a systematic ventilation strategy, and a descriptive statistical comparison of their hourly-averaged key performance indicators is provided in Table S2.

Fig. 8 compares the three ventilation modes. The outdoor air circulation mode has the highest convective and radiative heat losses, followed by the indoor and insulation modes. Using the insulation mode as a baseline, the indoor mode achieves measurable daytime heat recovery.

Table 2

Detailed parameters of the experimental platform.

Parameters	Data
PV glazing:	
Dimensions of PV glazing	800 mm(width) 1200 mm(height) 7 mm(thickness)
PV glazing type	3.2 mm glazing + 0.6 mm cell + 3.2 mm glazing
CCR	0.7
Temperature coefficient	−0.189%/°C
V _{mpp}	129.3(V)
I _{mpp}	0.73(A)
Vacuum glazing:	
Vacuum glazing Type	5 mm Low-E glazing + 0.2 mm vacuum gap + 5 mm clear glazing
Vacuum gap Pressure	0.001Pa
Em	0.12
Pillar Definition	radius 1.5 mm - pacing 30 mm
Conductance of Vacuum cavity	0.107 W/(m ² ·K)
Dimension of air cavity:	
DD	150 mm
Dimensions of glazed vents	400 mm(height) 800 mm(width)
Hot box:	
Dimension of room	2100 mm(width) 2100 mm(height) 2700 mm(height)
Walls and roof materials	Polystyrene

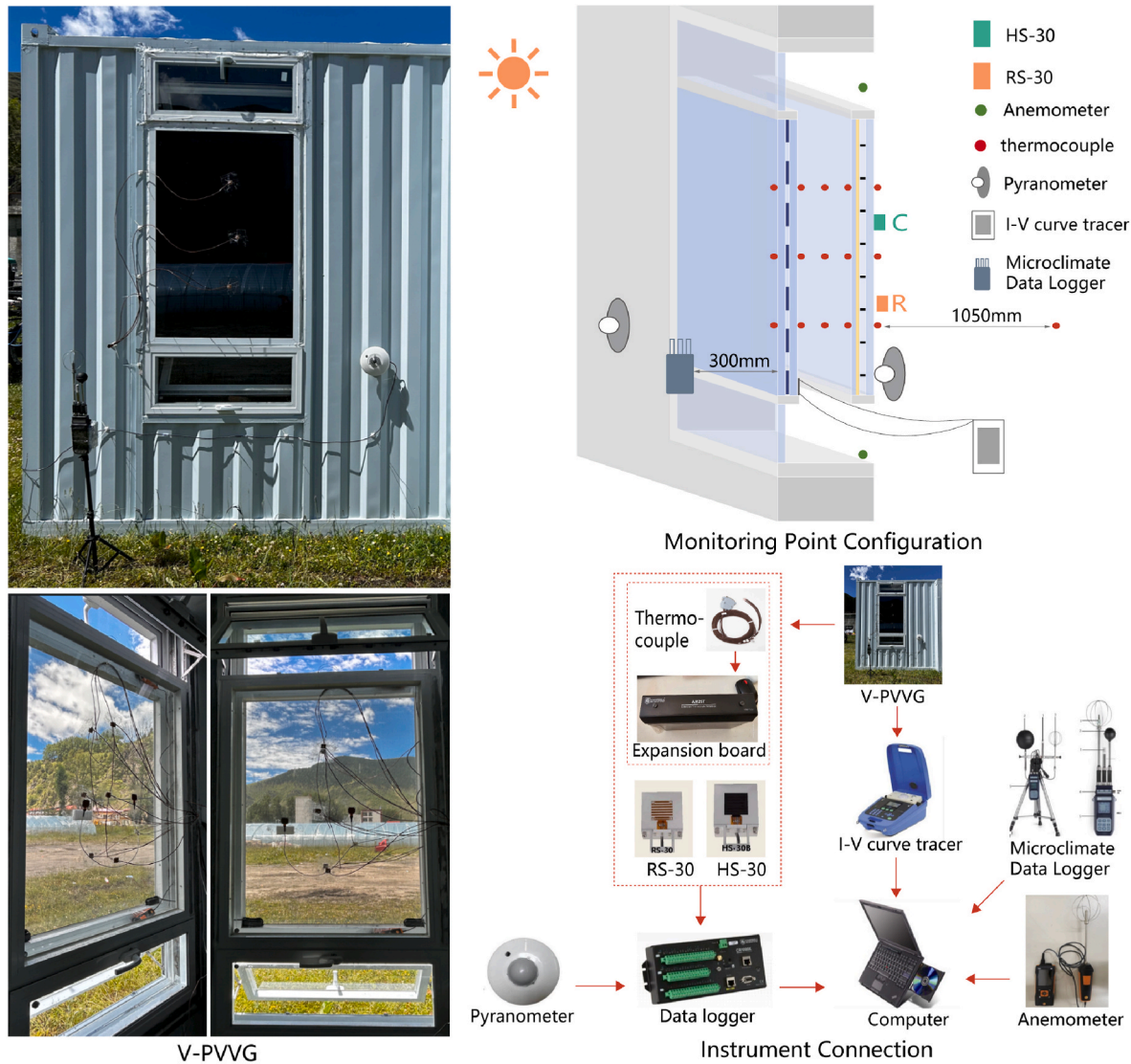


Fig. 6. Experimental platform and measurement setup.

Table 3
Measurement instruments.

Experimental equipment	Specification	Measurement error
I-V curve tracer	EKO MP-11	±1.0%
Conduction heat flux meter	HS-30	±3%
Infrared radiation heat flux meter	RS-30	±3%
Pyranometer	TBQ-2	±2%
Microclimate Data Logger	HD32.3 TC	±3%
Anemometer	Testo 440	±2%
Thermocouple	Type T	±0.5 °C
Thermocouple expansion board	AM25T	±0.2 °C@-25~+50 °C
Data logger	Campbell SCI CR1000X	/

The outdoor mode shows the highest electrical efficiency; the indoor and insulation modes generate 90.18% and 83.18% of their average power, respectively. In solar utilization efficiency, the insulation and outdoor modes reach 70.7% and 54.3% of the indoor mode's performance. These pronounced differences confirm that no single mode is optimal across all metrics and time periods, highlighting the need for an adaptive ventilation strategy to maximize annual energy gain.

4.3. Model validation

The reliability of the simulation model was verified by comparing experimental and simulated results using Mean Bias Error (MBE) and Coefficient of Variation of Root Mean Square Error (Cv(RMSE)) [24,54]. The metrics are defined by Eqs. (42) and (43):

$$MBE(\%) = \frac{\sum_{i=1}^n (E_i - S_i)}{\sum_{i=1}^n E_i} \quad (42)$$

$$Cv(RMSE) = \frac{\sqrt{\sum_{i=1}^n \left(\frac{E_i - S_i}{n} \right)^2}}{\sum_{i=1}^n \frac{E_i}{n}} \quad (43)$$

where E_i and S_i are the experimental measurements and simulation results, respectively; n indicates the number of data points; and i represents different data points.

Model validation was conducted using two-day experimental data for heat flux, recovered air heat, transmitted solar radiation, and power generation. Due to different measurement methods, the time resolution varies: power generation was recorded at 10-min intervals, while the other three parameters were logged as hourly averages. Fig. 9 presents

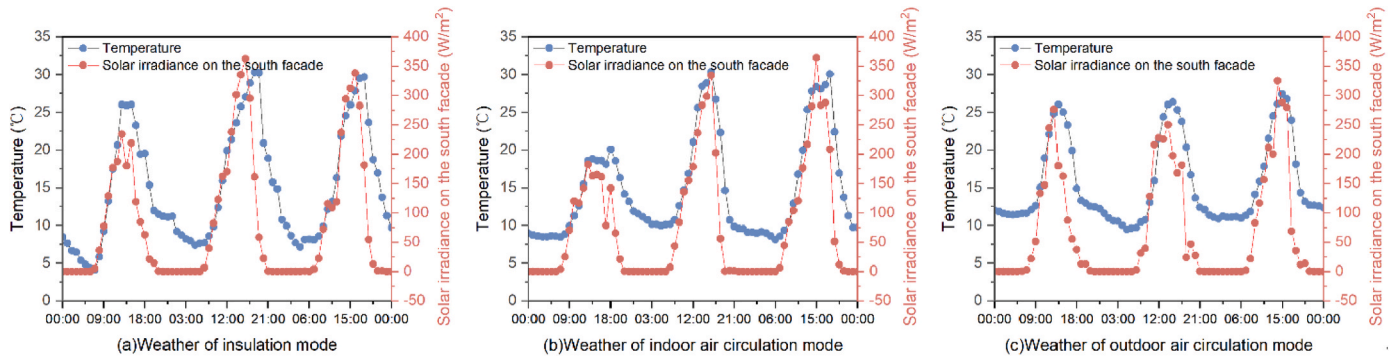


Fig. 7. Weather conditions during the experiment.

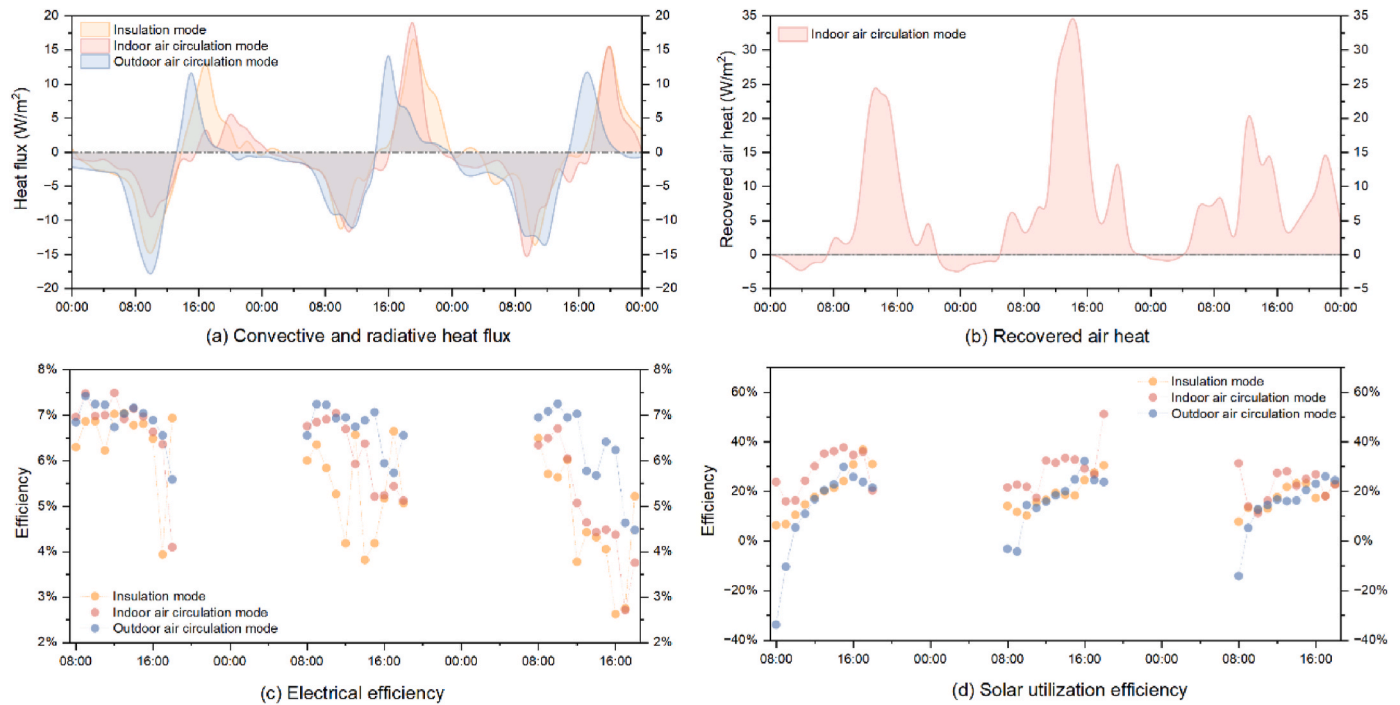


Fig. 8. Experimental results of the three ventilation modes.

the evaluation metrics for all four categories, confirming that all error values are within acceptable thresholds and establishing model credibility for subsequent parametric studies.

5. Results and discussion

This section analyzes the ventilation strategy and optimizes construction parameters for the V-PVVG system in Lhasa. First, using simulated data from monthly typical days, the year is clustered into three seasonal operating conditions to analyze variations in energy performance and derive an optimized ventilation strategy. Finally, the individual and interactive effects of key construction parameters on energy performance are examined under the proposed strategy in winter, leading to an energy-efficient V-PVVG design adapted to the plateau.

5.1. Optimization of ventilation strategy

5.1.1. Identification of typical seasons

Based on diurnal energy variations on typical monthly days, K-Means clustering grouped the year into three seasons: winter (Jan–Mar,

Oct–Dec), summer (Jun–Aug), and transitional (Apr, May, Sep). ANOVA confirmed significant inter-cluster differences (see Table S3 and S4).

Table 4 summarizes the seasonal energy performance. The indoor air circulation mode yields the highest Q_{gain} , exceeding the insulation and outdoor modes by 51.5% and 123.0% in winter, but also incurs larger Q_{loss} in transitional/summer seasons. The insulation mode shows the smallest Q_{loss} under all conditions. The outdoor air circulation mode performs weakest, with the lowest Q_{gain} and highest Q_{loss} (-0.434 kWh/m^2 in winter).

Peak performance analysis reveals thermal dynamics: the indoor mode dominates daytime (80.7% of hours with the highest q_{total}) as solar-driven PV heating maximizes internal recirculation benefits. At night, the insulation mode ensures best heat retention. The outdoor mode accounts for 100% of daytime hours with the lowest q_{total} , especially in winter and summer, as unconditioned outside air imposes a thermal penalty.

5.1.2. Hourly energy characteristics

Fig. 10 illustrates the diurnal variation of q_{total} for the three ventilation modes. In winter and transitional seasons, the indoor air circulation mode reaches a peak of 209 W/m^2 around midday (14:00–15:00),

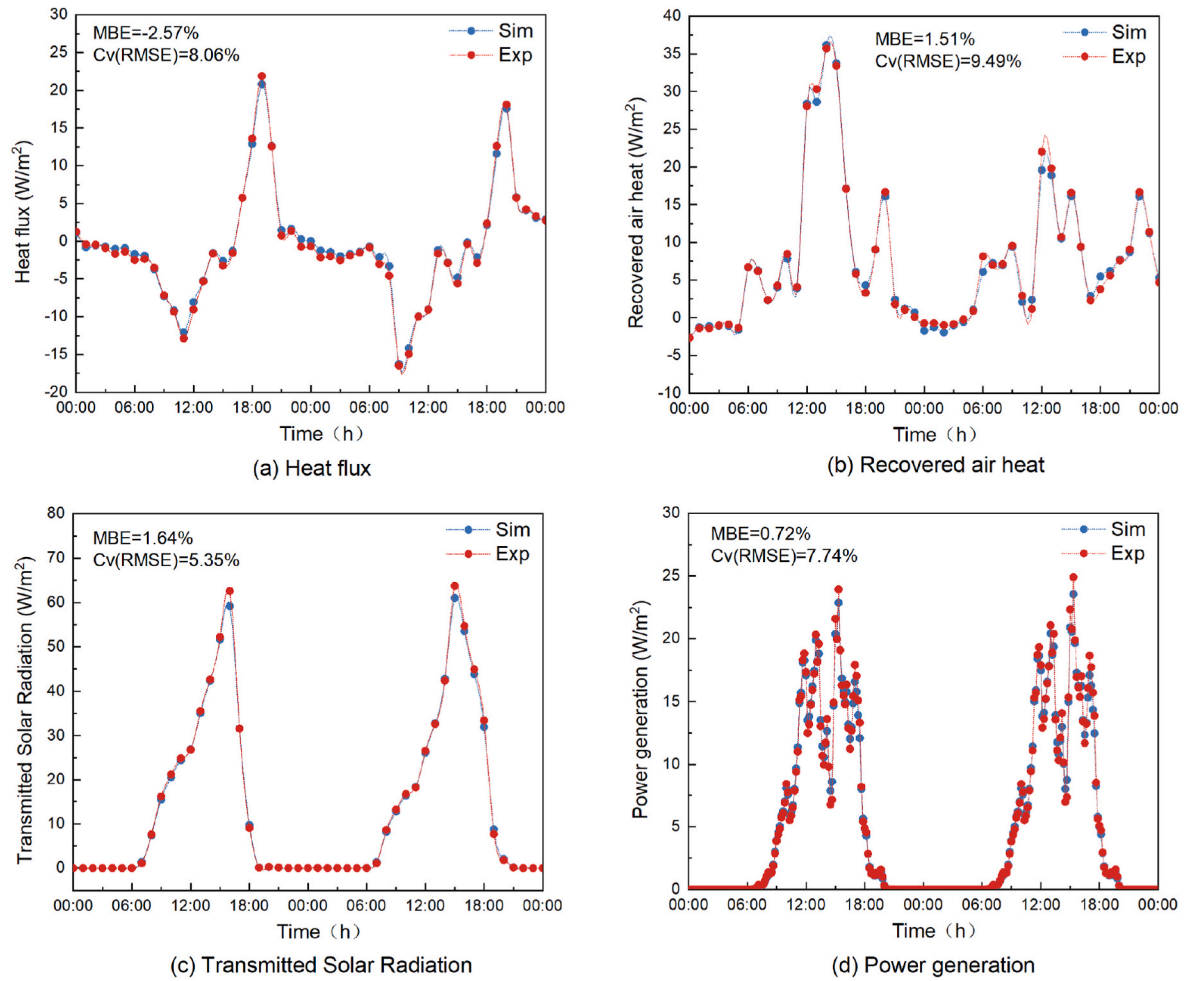


Fig. 9. Validation of thermal and electrical model: experimental-simulated data correlation.

Table 4

Energy characteristics of the three ventilation modes in different seasons.

Mode	Metric	Winter		Transitional season		Summer	
		Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
Insulation	$Q_{\text{gain}}(\text{kWh/m}^2)$	0.889		0.562		0.442	
	$Q_{\text{loss}}(\text{kWh/m}^2)$	-0.073		-0.046		-0.053	
	highest q_{total} duration ratio	20.00%	100.00%	31.11%	100.00%	6.67%	100.00%
	lowest q_{total} duration ratio	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Indoor air circulation	$Q_{\text{gain}}(\text{kWh/m}^2)$	1.347		0.838		0.831	
	$Q_{\text{loss}}(\text{kWh/m}^2)$	-0.361		-0.273		-0.216	
	highest q_{total} duration ratio	80.00%	0.00%	68.89%	0.00%	93.33%	0.00%
	lowest q_{total} duration ratio	0.00%	37.25%	0.00%	72.55%	0.00%	80.39%
Outdoor air circulation	$Q_{\text{gain}}(\text{kWh/m}^2)$	0.604		0.439		0.393	
	$Q_{\text{loss}}(\text{kWh/m}^2)$	-0.434		-0.190		-0.115	
	highest q_{total} duration ratio	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
	lowest q_{total} duration ratio	100.00%	62.75%	77.78%	27.45%	100.00%	19.61%

benefiting from heat recovered from PV power generation. However, this advantage gradually diminishes toward evening as heat losses increase. In contrast, the insulation mode consistently maintains the highest q_{total} during nighttime hours, significantly outperforming the outdoor air circulation mode. In winter, the average difference between the insulation mode and the outdoor air circulation mode is 26.62 W/m², highlighting its superior heat retention capability. In summer, the insulation mode exhibits the lowest q_{total} during the daytime, effectively blocking external heat gain. Meanwhile, the indoor air circulation mode peaks in the early afternoon (around 16:00) but drops below the insulation mode by evening. The insulation mode minimizes nocturnal heat

loss, a characteristic that holds across all seasons.

5.1.3. Ventilation strategy

Lhasa has a prolonged heating season with high thermal demand, while summers are cool, shifting the focus to power generation. Based on the V-PVVG's seasonal performance, an optimized ventilation strategy was developed (Fig. 11). Using the indoor air circulation mode in winter and the transitional season daytime increased Q_{total} by 0.475 kWh/m² (53.48%) and 0.314 kWh/m² (55.84%), respectively, compared to insulation mode alone. In summer, daytime outdoor air circulation reduced Q_{total} by 9.7%, with a 13.22% decrease in heat gain and a 6.35%

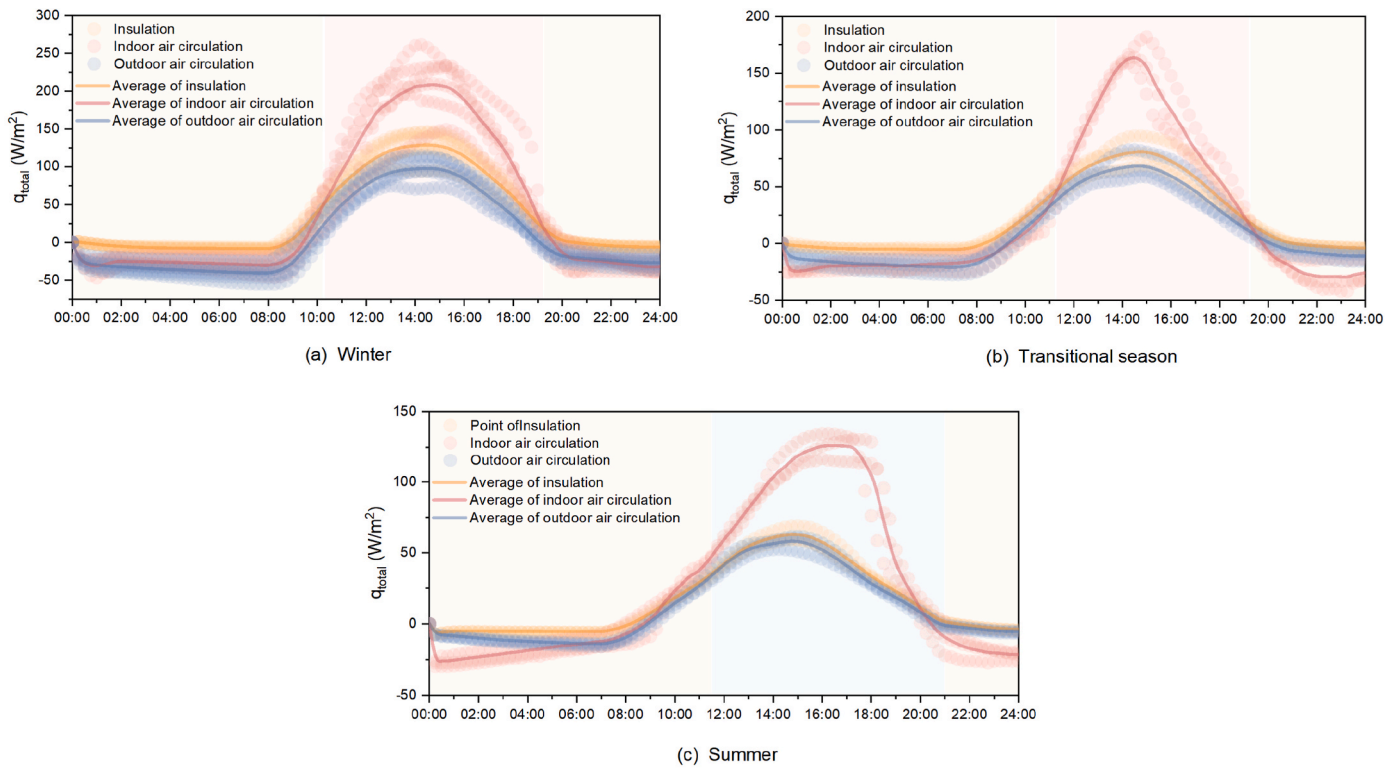


Fig. 10. Variation of q_{total} across three ventilation modes on typical seasonal days.

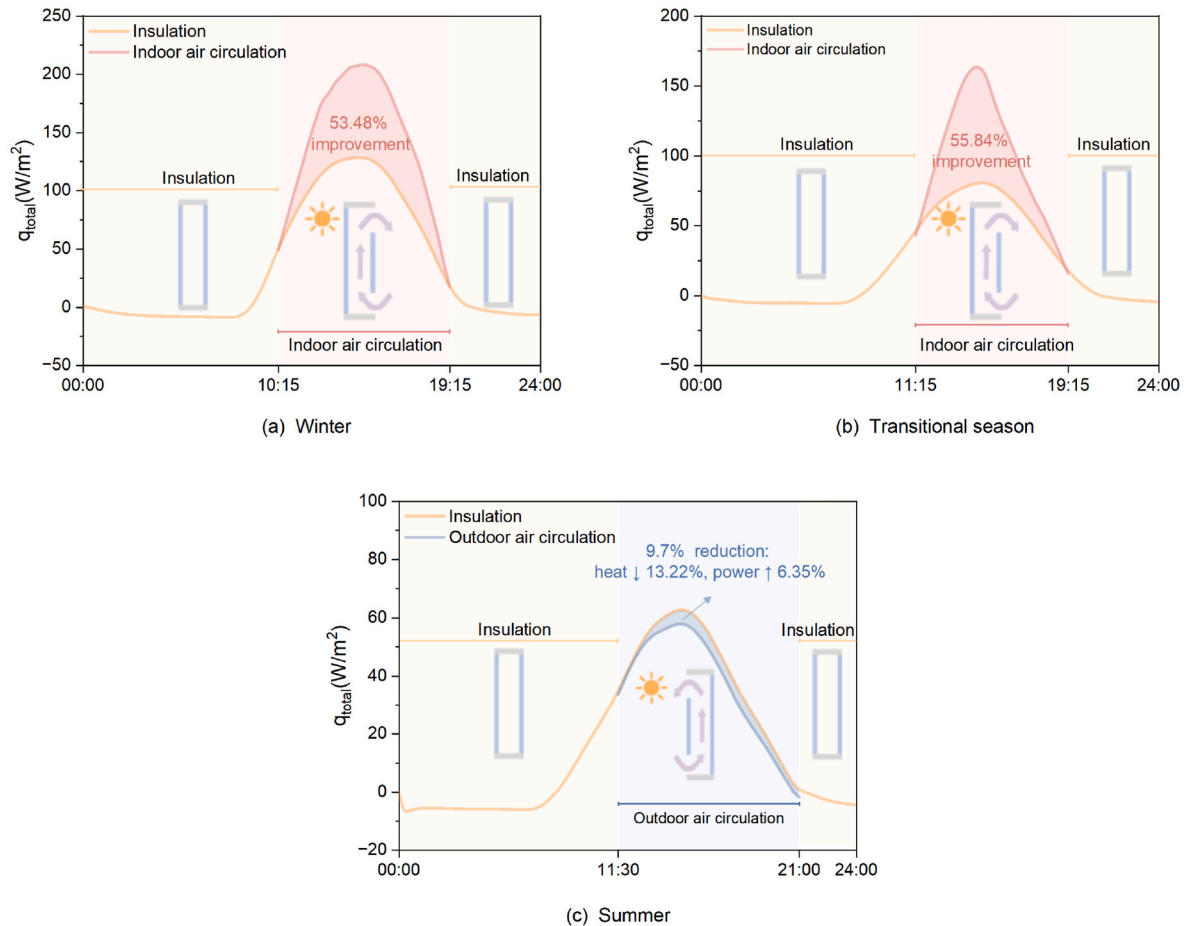


Fig. 11. Ventilation strategy and its associated energy gain benefits.

increase in electricity generation.

Therefore, to maximize annual energy benefits, the following ventilation strategy is recommended: indoor air circulation in winter (Oct–Mar, 10:15–19:15) and transitional season (Apr, May, Sep, 11:15–19:15) daytime; outdoor air circulation in summer (Jun–Aug, 11:30–21:00) daytime; and insulation mode at all other times.

5.2. Impact of construction parameters on system performance

To examine system performance under extreme cold, January, with the lowest temperatures and the most distinct performance differences between ventilation modes, was selected as representative. The proposed winter strategy (indoor air circulation 10:15–19:15, insulation at night) was applied, and parametric simulations were performed to optimize the construction parameters.

5.2.1. Impact of individual parameter variations on energy components

Fig. 12(a)(b)(c) illustrates the variations in individual energy components in the three different construction parameters. Pearson correlation analysis was conducted to quantify the relationships between these parameters and the energy components, as shown in Fig. 12(d).

CCR correlates positively with Q_{pv} and Q_{air-p} but negatively with Q_{sol} , requiring a trade-off among these three. It also correlates negatively with daytime gains (Q_{r-p} , Q_{c-p}) and positively with nighttime losses (Q_{r-n} , Q_{c-n}), indicating that higher CCR suppresses daytime heat loss but amplifies nocturnal dissipation. DD correlates negatively with Q_{c-n} and Q_{r-n} . Em correlates positively with Q_{sol} and nighttime loss components, meaning higher emissivity enhances both solar transmittance and radiative cooling.

5.2.2. Interactive effects of multi-parameter variations on energy gain

Table S5 in the Supplementary Material provides the energy performance data for the 216 parameter configurations formed by varying CCR, DD, and Em. Response surfaces of Q_{total} , Q_{gain} , and Q_{loss} as functions of CCR, DD, and Em are presented in Fig. 13(a), (b), (c). Q_{total}

ranged from 1.198 to 1.964 kWh/m², with the high-performance region concentrated in the parameter space characterized by high Em, moderate CCR, and medium-to-high DD. Q_{total} is primarily driven by Q_{gain} , and the two follow similar trends.

Fig. 13(d) presents the effects of the construction parameters on the energy performance of the V-PVVG system, as analyzed using a hierarchical regression model. Detailed results are presented in Table S5.

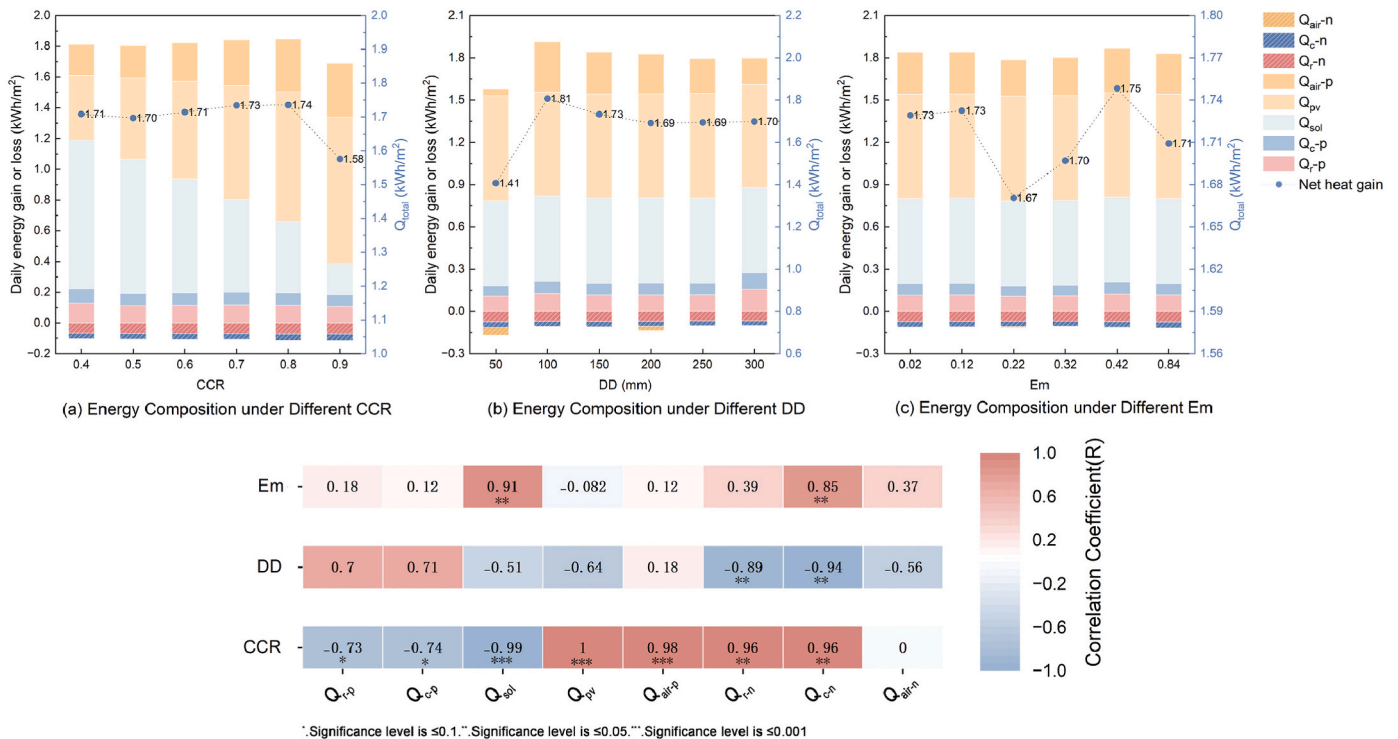
Main effects show CCR reduces and Q_{total} and Q_{gain} , as higher coverage blocks solar gain and amplifies nocturnal loss. Conversely, DD and Em enhance energy gain. For Q_{loss} , DD has a strong reducing effect, while CCR increases heat loss.

A significant negative CCR-Em interaction indicates that increasing both synergistically reduces Q_{total} and Q_{gain} , as high CCR restricts solar access and high Em accelerates radiative heat loss, jointly suppressing gain. The CCR-Em interaction is the only significant two-way interaction affecting energy acquisition, consistently reducing the system's energy gain. For Q_{loss} , both the CCR-DD and DD-Em interactions effectively lower heat loss, whereas the CCR-Em interaction increases it. All third-order interactions are statistically non-significant.

Therefore, optimizing the V-PVVG system should leverage the beneficial effects of DD and Em, control CCR's adverse impact, exploit DD's interactions to suppress heat loss, and avoid the high CCR and high Em combination.

5.2.3. Optimization of construction parameters

The top 10% configurations in terms of Q_{total} are presented in Fig. 14. The global maximum Q_{total} (1.965 kWh/m²) was achieved with CCR = 0.5, DD = 250 mm, and Em = 0.84, representing a 13.32% increase in total energy gain relative to the baseline model. The Q_{total} for these optimal configurations ranged from 1.85 to 1.97 kWh/m², and their parameter distributions revealed distinct patterns. CCR was predominantly concentrated in the 0.5–0.6 range (~68%), DD was widely distributed between 100 mm and 250 mm (90% of the top configurations, with 200 mm and 250 mm jointly accounting for 65%), and Em was primarily distributed above 0.22, with concentrations at 0.84 and



(d) Correlations between Construction Parameters and Energy Performance

Fig. 12. Impact of individual parameter variations on energy components.

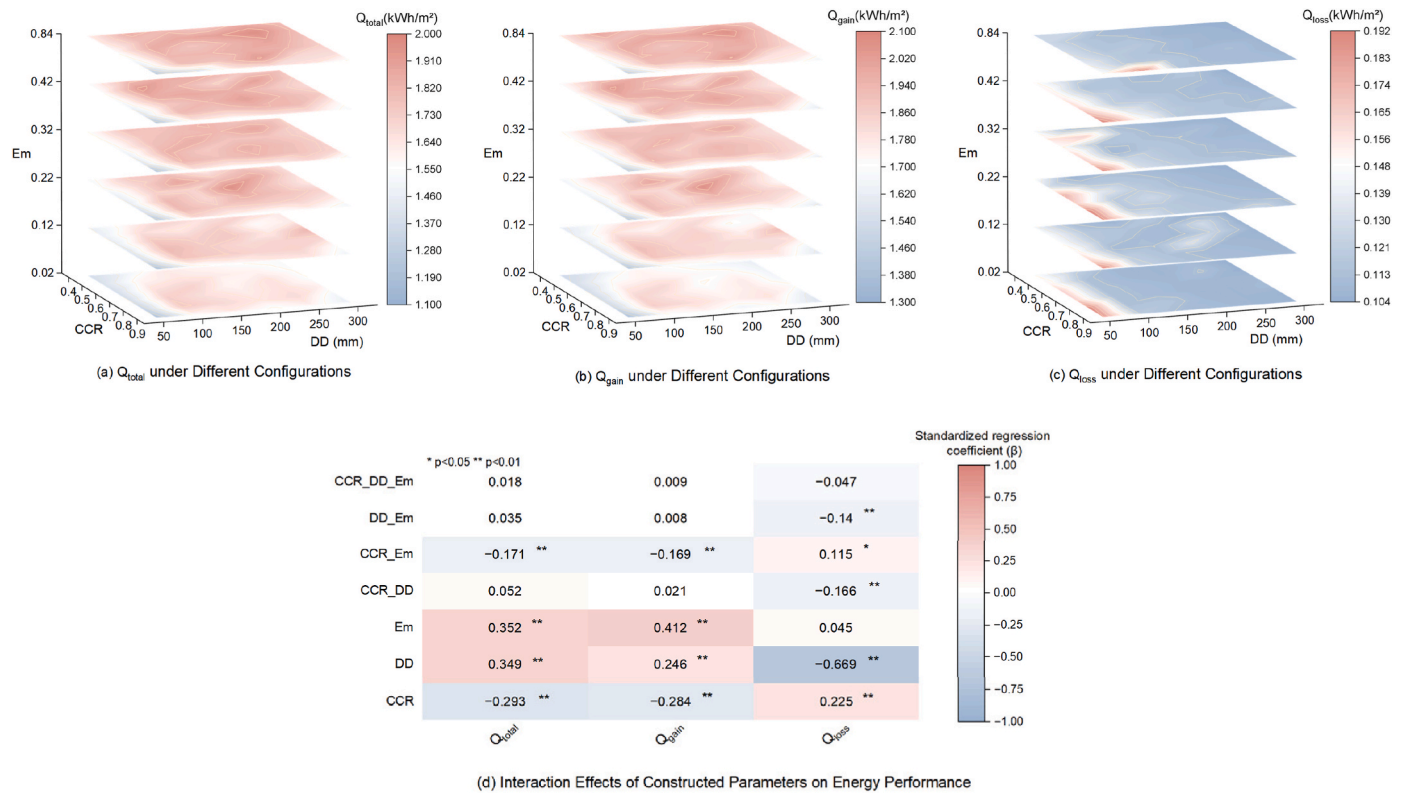


Fig. 13. Effects of construction parameters on the energy performance.

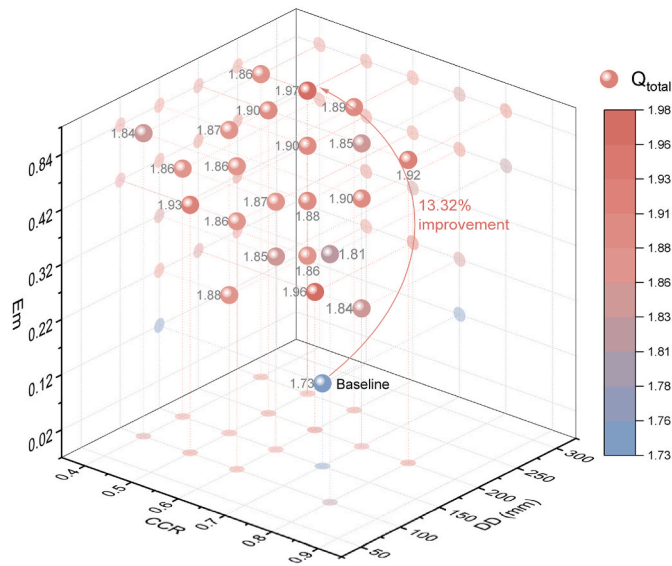


Fig. 14. Comparison of the top 10% parameter configurations with the baseline.

0.42. Therefore, to maximize the comprehensive energy gain in cold climates, the optimized design of the V-PVVG system should prioritize a lower CCR (0.5–0.6), a higher DD (≥ 200 mm), and a combination with a higher Em (0.22–0.42/0.84).

5.3. Discussion

This study demonstrates that the V-PVVG system offers a viable window solution for high-altitude, cold-climate environments. Through experimentally validated simulations, the seasonal energy performance

of its three ventilation modes was evaluated, leading to an annual ventilation strategy that maximizes energy gain. Further optimization of the V-PVVG's construction parameters was undertaken to maximize winter energy acquisition. This work provides a theoretical foundation for the practical application of the system in extreme climates.

5.3.1. Heat loss disparities

This study further identified diurnal variations in heat loss between modes, with notable seasonal dependence. In summer and the transitional season, the indoor air circulation mode incurred higher losses in the early evening (e.g., 19:30–3:00 in the transitional season) because the system and cavity remained warm after sunset, leading to greater heat dissipation via Q_{air} . Conversely, the outdoor air circulation mode showed greater losses late at night/early morning, as introducing colder outdoor air increased the temperature difference between the cavity and the indoor space, thereby intensifying Q_c and Q_r losses. In winter, however, the outdoor air circulation mode consistently exhibited more severe heat loss throughout the night, since the cavity and the adjacent glass panes remained at low overall temperatures.

5.3.2. Ventilation strategy

In cold, severe cold, hot-summer/cold-winter, hot-summer/warm-winter, and hot climates [25], ventilation strategies for V-PVVG are often based on fixed monthly schedules and fixed operating hours (e.g., 9:00–17:00), lacking systematic performance comparisons and climatic adaptability analysis. In contrast, the ventilation strategy proposed in this study is based on simulated and analyzed hourly performance of different ventilation modes. While the seasonal division (winter: October to March; summer: June to August) and the basic ventilation approach align with those for cold plains [25], a key difference lies in how the transitional season is treated. In cold plains, the V-PVVG system operates in insulation mode throughout the transitional season [25], whereas in high-altitude cold climates, where daytime temperatures during this season still feel cold (Fig. 1), the indoor air circulation mode

is employed to utilize the heat energy effectively. The activation and deactivation times for indoor and outdoor air circulation modes in this high-altitude cold region are delayed by 1–2 h compared to the plains [25], due to later sunrise and slower temperature rise at high altitudes. For example, the winter indoor air circulation period is set to 10:15–19:15. Furthermore, extending the daytime ventilation window allows fuller use of the more abundant solar radiation, thereby increasing energy gain by over 53%. These findings underscore the importance of region-specific, climate-adaptive design for optimizing V-PVVG system performance.

5.3.3. Construction parameters

This study recommends a parameter set of moderate CCR (0.5–0.6), relatively high DD (200–250 mm), and high Em (>0.22) for the V-PVVG in high-altitude cold climates.

The recommended CCR differs from values suggested for other climates—e.g., 0.6 in cold/Mediterranean [26,37], 0.4 in hot-summer/cold-winter [33], and 0.9 in hot regions of China [25]. In contrast, the strong solar radiation and high heating demand make Q_{sol} especially valuable in high-altitude cold climates. A high CCR increases electricity generation but severely reduces Q_{sol} (Fig. 12), lowering overall winter efficiency, whereas a low CCR fails to harness the region's significant PV potential. The proposed 0.5–0.6 CCR thus represents a climate-specific trade-off between power output and direct solar heat gain.

For DD, the results align with findings for other system types, where a moderate depth (0.15–0.3 m) promotes airflow and ventilation-heat exchange [35,36]. Excessive DD can reduce ventilation efficiency, potentially leading to a situation where the increase in Q_{air-p} is less than the increase in Q_{air-n} (Fig. 12), ultimately lowering Q_{total} .

A higher Em on the inner vacuum-cavity surface was found to enhance winter total heat gain by strengthening radiative transfer. This contrasts with common practice in hot-summer/cold-winter regions, where the low-E coating is often placed externally or a very low Em is used [24,33]. In the high-radiation plateau climate, a higher Em increases winter Q_{sol} , albeit at the expense of increased nighttime loss.

A significant negative interaction exists between CCR and Em (Fig. 13). High CCR severely reduces Q_{sol} without sufficient electrical compensation, while high Em increases nighttime loss, together lowering total gain. Therefore, the combination of high CCR and high Em must be avoided in the design.

6. Conclusion

This study investigated the performance of a V-PVVG system in high-altitude cold climates. A simulation model that accounts for the effects of low pressure on convection was developed in COMSOL and validated with experimental data obtained from a test platform installed in Kangding (3457 m a.s.l.). Based on the system's seasonal energy characteristics for Lhasa (3650 m a.s.l.), an annual ventilation strategy was formulated. Under this strategy, the influence of three key design parameters on the total energy gain was analyzed under typical winter conditions. The main findings are summarized as follows:

- (1) A ventilation strategy was developed for the V-PVVG system in Lhasa. Compared with the insulation mode alone, implementing the indoor air circulation mode during the daytime in winter and the transitional season increased Q_{total} by 53.48% and 55.84%, respectively. During summer, daytime use of the outdoor air circulation mode reduced heat gain by 13.22% while increasing power generation by 6.35%.
- (2) CCR exerted a significant negative influence on both Q_{total} and Q_{gain} , whereas DD and Em showed significant positive effects. A significant negative interaction between CCR and Em was identified, indicating that simultaneous increases in both parameters

synergistically reduce Q_{total} . No significant third-order interactions were observed.

- (3) The high-performance parameter space for the heating season was concentrated in combinations featuring moderate CCR (0.5–0.6), relatively high DD (200–250 mm), and high Em (>0.22). The maximum Q_{total} was achieved with CCR = 0.5, DD = 250 mm, and Em = 0.84, representing a 13.32% increase in total energy gain relative to the baseline model.

This study systematically analyzed the performance, ventilation strategies, and construction parameter optimization of the V-PVVG system, though some limitations remain. First, the pressure correction in the model was validated through experimental data, supporting its overall reliability, though the individual contribution of low-pressure effects to system performance remains unquantified and warrants further investigation. Second, the analysis focused on the system's own energy gain under typical winter conditions using typical monthly days derived from 8760-h TMY data. While this approach captures average seasonal characteristics and is computationally feasible for coupled CFD simulations, it may not fully reflect daily weather variability or extreme events, nor the impact on whole-building energy use. Future work could develop a system energy model to enable full-year hourly simulations, while also accounting for indoor temperature variations under realistic occupancy and Heating, Ventilation, and Air Conditioning operation. Third, life-cycle cost analysis could be introduced to evaluate the economic viability of different parameter sets and control strategies, supporting cost-optimal designs.

CRediT authorship contribution statement

Luyang Zhong: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dan Wu:** Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Jing Tong:** Writing – review & editing, Visualization. **Lixing Chen:** Writing – review & editing, Validation, Data curation. **Yibing Xie:** Writing – review & editing, Validation. **Yingzi Zhang:** Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Soukanh Chithpanya:** Resources.

Declaration of competing interests

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2026.142241>.

Data availability

Data will be made available on request.

References

- [1] Tian X, Zhang H, Liu L, Huang J, Liu L, Liu J. Establishment of LCZ-based urban building energy consumption dataset in hot and humid subtropical regions through a bottom-up method. *Appl Energy* 2024;368:123491. <https://doi.org/10.1016/j.apenergy.2024.123491>.

- [2] China urban and rural construction carbon emissions research report n.d. https://cpnn.com.cn/news/ydylnyh/202501/t20250121_1768366.html. [Accessed 10 July 2025].
- [3] Tiwari T, Kaur GA, Singh PK, Balayan S, Mishra A, Tiwari A. Emerging bio-capture strategies for greenhouse gas reduction: navigating challenges towards carbon neutrality. *Sci Total Environ* 2024;929:172433. <https://doi.org/10.1016/j.scitotenv.2024.172433>.
- [4] Bosu I, Mahmoud H, Ookawara S, Hassan H. Applied single and hybrid solar energy techniques for building energy consumption and thermal comfort: a comprehensive review. *Sol Energy* 2023;259:188–228. <https://doi.org/10.1016/j.solener.2023.05.006>.
- [5] Biyik E, Araz M, Hepbasli A, Shahrestani M, Yao R, Shao L, et al. A key review of building integrated photovoltaic (BIPV) systems. *Eng Sci Technol Int J* 2017;20: 833–58. <https://doi.org/10.1016/j.jestech.2017.01.009>.
- [6] Tibet: facts and figures (Part 1) — Beijing review n.d. http://www.beijingreview.com.cn/2009news/wenjian/2008-04/25/content_199571_3.htm. [Accessed 22 March 2026].
- [7] Global solar atlas n.d. <https://globalsolaratlas.info/map> (accessed March 22, 2026)..
- [8] Energyplus n.d. <https://energyplus.net/weather> (accessed July 24, 2026)..
- [9] Peng J, Curcija DC, Thanachareonkit A, Lee ES, Goudey H, Selkowitz SE. Study on the overall energy performance of a novel c-Si based semitransparent solar photovoltaic window. *Appl Energy* 2019;242:854–72. <https://doi.org/10.1016/j.apenergy.2019.03.107>.
- [10] Musameh H, Alrashidi H, Al-Neami F, Issa W. Energy performance analytical review of semi-transparent photovoltaics glazing in the United Kingdom. *J Build Eng* 2022;54:104686. <https://doi.org/10.1016/j.jobe.2022.104686>.
- [11] Sivaraaj S, Rathanasamy R, Kaliyannan GV, Panchal H, Jawad Alrubai A, Musa Jaber M, et al. A comprehensive review on current performance, challenges and progress in thin-film solar cells. *Energies* 2022;15:8688. <https://doi.org/10.3390/en15228688>.
- [12] Liao W, Xu S. Energy performance comparison among see-through amorphous-silicon PV (photovoltaic) glazings and traditional glazings under different architectural conditions in China. *Energy* 2015;83:267–75. <https://doi.org/10.1016/j.energy.2015.02.023>.
- [13] Han J, Lu L, Yang H. Numerical evaluation of the mixed convective heat transfer in a double-pane window integrated with see-through a-Si PV cells with low-e coatings. *Appl Energy* 2010;87:3431–7. <https://doi.org/10.1016/j.apenergy.2010.05.025>.
- [14] Bilal K, Erdoğan İ. Effects of cooling on performance of photovoltaic/thermal (PV/T) solar panels: a comprehensive review. *Sol Energy* 2023;262:111829. <https://doi.org/10.1016/j.solener.2023.111829>.
- [15] Ahmed M, Radwan A, Serageldin A, Memon S, Katsura T, Nagano K. Thermal analysis of a new sliding smart window integrated with vacuum insulation, photovoltaic, and phase change material. *Sustainability* 2020;12:7846. <https://doi.org/10.3390/su12197846>.
- [16] Ghosh A. Investigation of vacuum-integrated switchable polymer dispersed liquid crystal glazing for smart window application for less energy-hungry building. *Energy* 2023;265:126396. <https://doi.org/10.1016/j.energy.2022.126396>.
- [17] Mohammad AK, Garrod A, Ghosh A. Do building integrated photovoltaic (BIPV) windows propose a promising solution for the transition toward zero energy buildings? A review. *J Build Eng* 2023;79:107950. <https://doi.org/10.1016/j.jobe.2023.107950>.
- [18] Jarimi H, Lv Q, Ramadan O, Zhang S, Riffat S. Design, mathematical modelling and experimental investigation of vacuum insulated semi-transparent thin-film photovoltaic (PV) glazing. *J Build Eng* 2020;31:101430. <https://doi.org/10.1016/j.jobe.2020.101430>.
- [19] Ghosh A, Sundaram S, Mallick TK. Investigation of thermal and electrical performances of a combined semi-transparent PV-vacuum glazing. *Appl Energy* 2018;228:1591–600. <https://doi.org/10.1016/j.apenergy.2018.07.040>.
- [20] Qiu C, Yang H. Dynamic coupling of a heat transfer model and whole building simulation for a novel cadmium telluride-based vacuum photovoltaic glazing. *Energy* 2022;250:123745. <https://doi.org/10.1016/j.energy.2022.123745>.
- [21] Huang J, Chen X, Peng J, Yang H. Modelling analyses of the thermal property and heat transfer performance of a novel composite PV vacuum glazing. *Renew Energy* 2021;163:1238–52. <https://doi.org/10.1016/j.renene.2020.09.027>.
- [22] Huang J, Wang Q, Chen X, Xu S, Yang H. Experimental investigation and annual overall performance comparison of different photovoltaic vacuum glazings. *Sustain Cities Soc* 2021;75:103282. <https://doi.org/10.1016/j.scs.2021.103282>.
- [23] Zhong L, Wu D, Zhang B, Chen L, Xie Y, Zhang Y, et al. Study on the impact of design parameters of photovoltaic combined vacuum glazing (PVCVG) on the energy consumption of buildings in Lhasa. *Buildings* 2025;15:649. <https://doi.org/10.3390/buildings15040649>.
- [24] Zhang C, Ji J, Wang C, Ke W, Xie H, Yu B. Experimental and numerical studies on the thermal and electrical performance of a CdTe ventilated window integrated with vacuum glazing. *Energy* 2022;244:123128. <https://doi.org/10.1016/j.energy.2022.123128>.
- [25] Zhang C, Ji J, Wang C, Ke W. Annual analysis and comparison of the comprehensive performance of a CdTe PV ventilated window integrated with vacuum glazing in different climate regions. *Renew Energy* 2024;223:120029. <https://doi.org/10.1016/j.renene.2024.120029>.
- [26] Peng J, Curcija DC, Lu L, Selkowitz SE, Yang H, Zhang W. Numerical investigation of the energy saving potential of a semi-transparent photovoltaic double-skin facade in a cool-summer mediterranean climate. *Appl Energy* 2016;165:345–56. <https://doi.org/10.1016/j.apenergy.2015.12.074>.
- [27] Zhu L, Zhang J, Li Q, Shao Z, Chen M, Yang Y, et al. Comprehensive analysis of heat transfer of double-skin facades integrated high concentration photovoltaic (CPV-DSF). *Renew Energy* 2020;161:635–49. <https://doi.org/10.1016/j.renene.2020.07.045>.
- [28] Wu Z, Zhang L, Su X, Wu J, Liu Z. Experimental and numerical analysis of naturally ventilated PV-DSF in a humid subtropical climate. *Renew Energy* 2022;200: 633–46. <https://doi.org/10.1016/j.renene.2022.09.108>.
- [29] Xu C, Shi X, Ni Y, Su H, Lei X, Kong D, et al. Comparative study of dynamic thermal performance of photovoltaic double skin facades influenced by glass transmittance and natural ventilation. *Energy Build* 2023;294:113220. <https://doi.org/10.1016/j.jenbuild.2023.113220>.
- [30] Tan Y, Peng J, Luo Y, Luo Z, Curcija C, Fang Y. Numerical heat transfer modeling and climate adaptation analysis of vacuum-photovoltaic glazing. *Appl Energy* 2022;312:118747. <https://doi.org/10.1016/j.apenergy.2022.118747>.
- [31] Lei W, Gastro O, Wang Y, Felicien NH, Hui L. Intelligent modelling to predict heat transfer coefficient of vacuum glass insulation based on thinking evolutionary neural network. *Artif Intell Rev* 2020;53:5907–28. <https://doi.org/10.1007/s10462-020-09837-2>.
- [32] Yang S, Fiorito F, Prasad D, Sproul A, Cannavale A. A sensitivity analysis of design parameters of BIPV/T-DSF in relation to building energy and thermal comfort performances. *J Build Eng* 2021;41:102426. <https://doi.org/10.1016/j.jobe.2021.102426>.
- [33] Tan Y, Peng J, Luo Y, Li H, Wang M, Zhang F, et al. Daylight-electrical-thermal coupling model for real-time zero-energy potential analysis of vacuum-photovoltaic glazing. *Renew Energy* 2023;205:1040–56. <https://doi.org/10.1016/j.renene.2023.01.116>.
- [34] Chengdu zhongjian building materials optoelectronic materials Co., Ltd. n.d. <http://b2b.cdbaidu.com/company/index.php?homepage=cdzjc> (accessed March 22, 2026)..
- [35] Tao Y, Zhang H, Huang D, Fan C, Tu J, Shi L. Ventilation performance of a naturally ventilated double skin facade with low-e glazing. *Energy* 2021;229: 120706. <https://doi.org/10.1016/j.energy.2021.120706>.
- [36] Tao Y, Zhang H, Zhang L, Zhang G, Tu J, Shi L. Ventilation performance of a naturally ventilated double-skin facade in buildings. *Renew Energy* 2021;167: 184–98. <https://doi.org/10.1016/j.renene.2020.11.073>.
- [37] Liu X, Yang H, Wang C, Shen C, Bo R, Hinkle L, et al. Semi-experimental investigation on the energy performance of photovoltaic double skin facade with different facade materials. *Energy* 2024;295:131049. <https://doi.org/10.1016/j.energy.2024.131049>.
- [38] Liu X, Shen C, Bo R, Wang J, Ardabili NG. Experimental investigation on the operation performance of photovoltaic double skin facade in winter. *Energy* 2023; 283:129040. <https://doi.org/10.1016/j.energy.2023.129040>.
- [39] Lin Y. Theoretical and experimental study on the performance of PV–Trombe wall systems with different configurations. University of Science and Technology of China; 2019. <https://doi.org/10.27517/d.cnki.gzkju.2019.000019>. PhD dissertation.
- [40] Luo Y, Zhang L, Su X, Liu Z, Lian J, Luo Y. Improved thermal-electrical-optical model and performance assessment of a PV-blind embedded glazing facade system with complex shading effects. *Appl Energy* 2019;255. <https://doi.org/10.1016/j.apenergy.2019.113896>.
- [41] Design code for heating, ventilation and air conditioning of civil buildings (GB 50736-2012) n.d. <https://www.soujianzhu.cn/NormAndRules/NormContent.aspx?id=275>. [Accessed 22 March 2026].
- [42] Lhasa's heating season commences on November 15th n.d. <http://xz.people.com.cn/n2/2024/1024/c138901-41018600.html>. [Accessed 22 March 2026].
- [43] Ju Z, Zhang X, Xie J, Xu X, Yin K. Field measurement and analysis of the impact of buffer spaces on indoor thermal environment in hotel buildings in Lhasa. *Build Sci* 2026;42(2):39–45. <https://doi.org/10.13614/j.cnki.11-1962/tu.2026.02.05>.
- [44] Li Z, Lu S, Zhao Q, Xu Y, Xie Y, Si Y. Summer indoor thermal environment of sunspace in traditional residential buildings in Lhasa. *Building Energy Efficiency* 2019;47(9):6–10.
- [45] COMSOL China | Multiphysics simulation software n.d. <https://cn.comsol.com/>. (accessed March 22, 2026).
- [46] Pasut W, De Carli M. Evaluation of various CFD modelling strategies in predicting airflow and temperature in a naturally ventilated double skin facade. *Appl Therm Eng* 2012;37:267–74. <https://doi.org/10.1016/j.applthermaleng.2011.11.028>.
- [47] Fallahpour M, Khorshidi IM, Ghasempour F, Davari DD, Khoei ET, Tamimi M. A multi-objective optimization framework for designing a double-skin facade in hot-arid climate: central composite design and CFD simulation. *Results Eng* 2025; 25. <https://doi.org/10.1016/j.rineng.2025.104288>.
- [48] Melgaard SP, Nikolaïsson IT, Zhang C, Johra H, Larsen OK. Double-skin facade simulation with computational fluid dynamics: a review of simulation trends, validation methods and research gaps. *Build Simulat* 2023;16:2307–31. <https://doi.org/10.1007/s12273-023-1052-y>.
- [49] Iso 6946:2017. ISO n.d. <https://www.iso.org/standard/65708.html>. [Accessed 22 March 2026].
- [50] Handbook n.d. <https://www.ashrae.org/technical-resources/ashrae-handbook>. [Accessed 22 March 2026].
- [51] Wang L, Zhou J, Zhong W, Ji Y, Yuan Y. Analysis of factors affecting the performance of a novel micro-channel heat pipe PV-trombe wall system for space heating. *Sustain Energy Technol Assessments* 2023;58:103347. <https://doi.org/10.1016/j.seta.2023.103347>.
- [52] Chandrika V, Talib MM, Karthick A, Sathyamurthy R, Manokar AM, Subramaniam U, et al. Performance assessment of free standing and building integrated grid connected photovoltaic system for southern part of India. *Build*

- Serv Eng Res Technol 2021;42:237–48. <https://doi.org/10.1177/0143624420977749>.
- [53] IGDB downloads | windows & daylighting n.d. <https://windows.lbl.gov/igdb-downloads> (accessed March 22, 2026)..
- [54] Gao Y, Huang Z-W, Huang Z-Y, Huang L, Kuang Y, Yang X. Multi-scale broad collaborative filtering for personalized recommendation. Knowl Base Syst 2023; 278:110853. <https://doi.org/10.1016/j.knosys.2023.110853>.