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THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

From Rooftop PV Warming to Climate-Adaptive Design: Experimental Evidence from PV-Green Roof Systems

Liutao CHEN

Department of Civil & Environmental Engineering

Hong Kong University of Science and Technology

Sep 2025

Outline

1. Introduction

2. The Unintended Consequence: Local Climate Impacts of Rooftop PV

3. PVIGR as a Climate-Adaptive Solution: Experimental Evidence

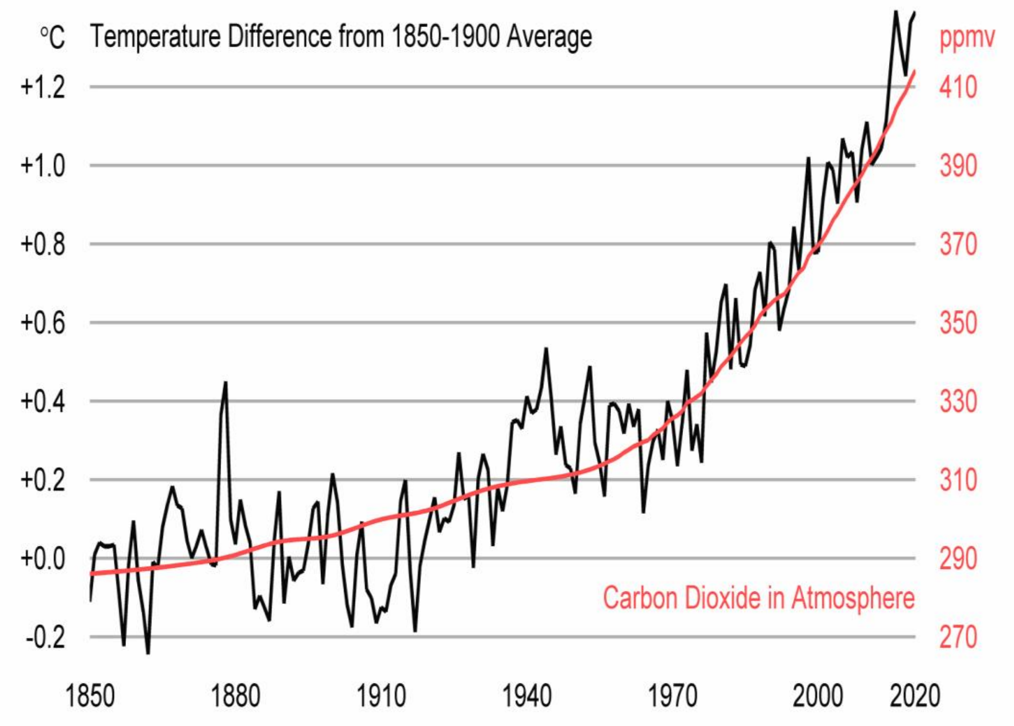
- Power output
- Thermal environment
- Building energy

4. Conclusions

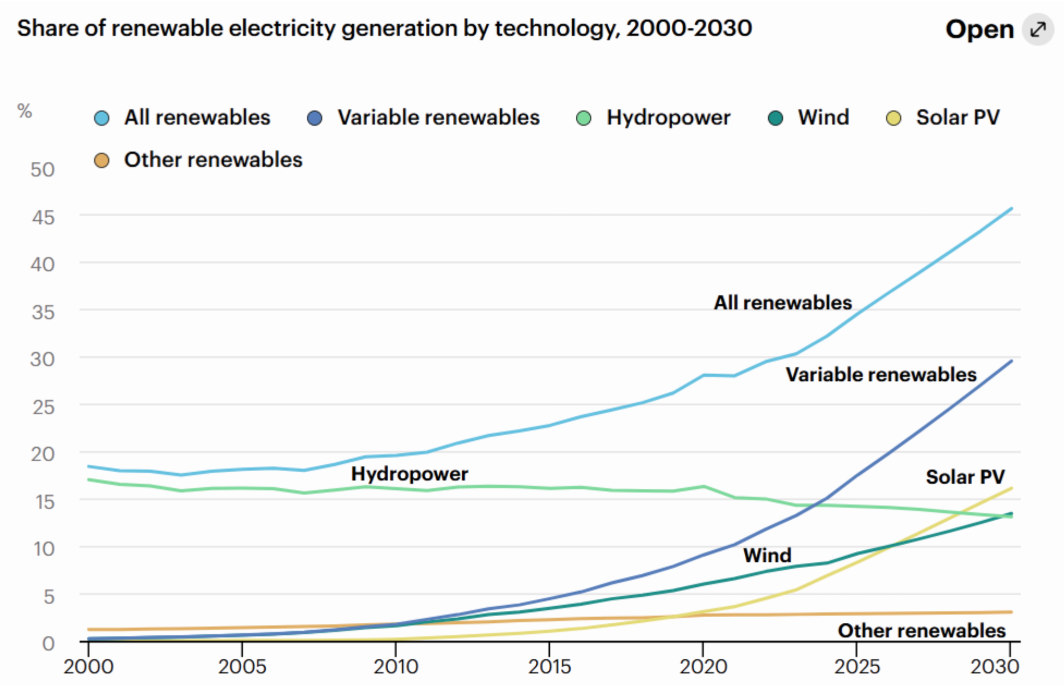
5. Ongoing and Future Works

1 Rapid expansion of solar PV

Global mean temperature & Carbon dioxide



Solar PV is set to become the largest renewable energy source by 2029

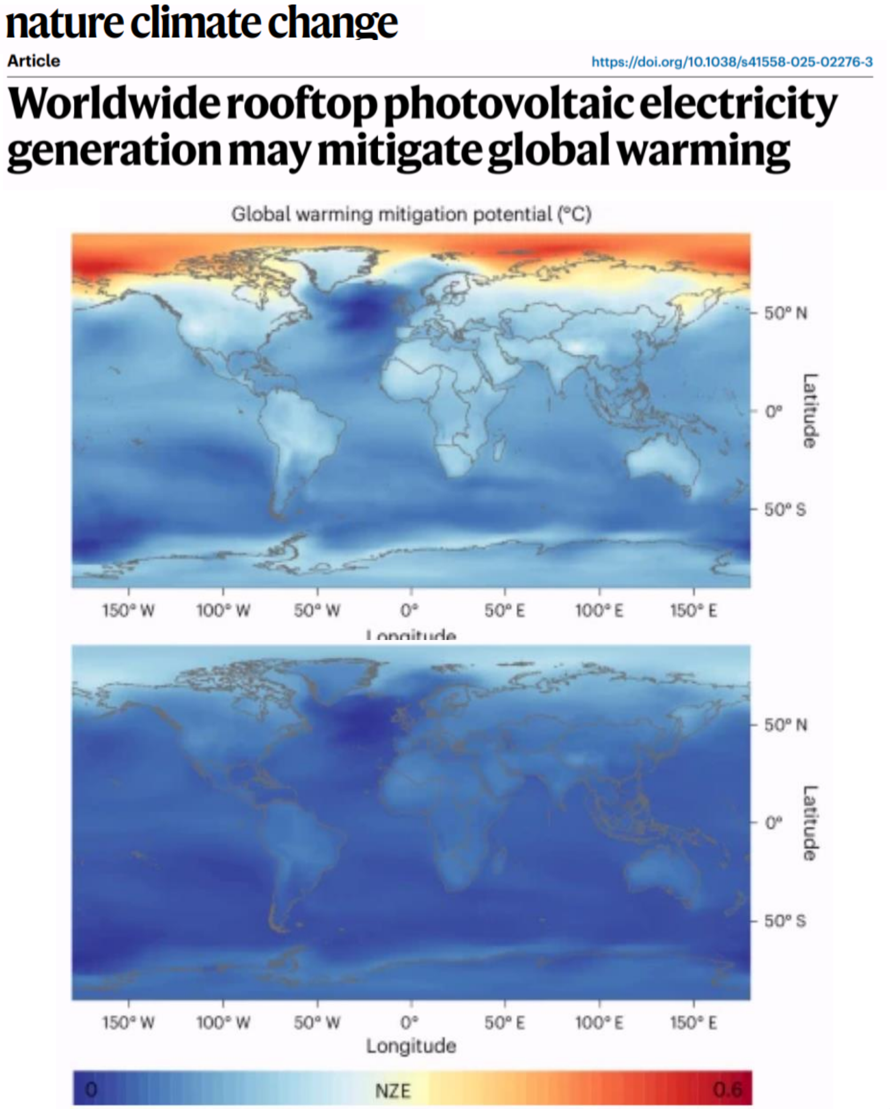


Cities are the major source of global greenhouse gas emissions (~70%).

Distributed systems (~43%) play an increasingly important role in global solar PV deployment.

Ref: (IEA, 2024)

1 Global benefits of PV deployment



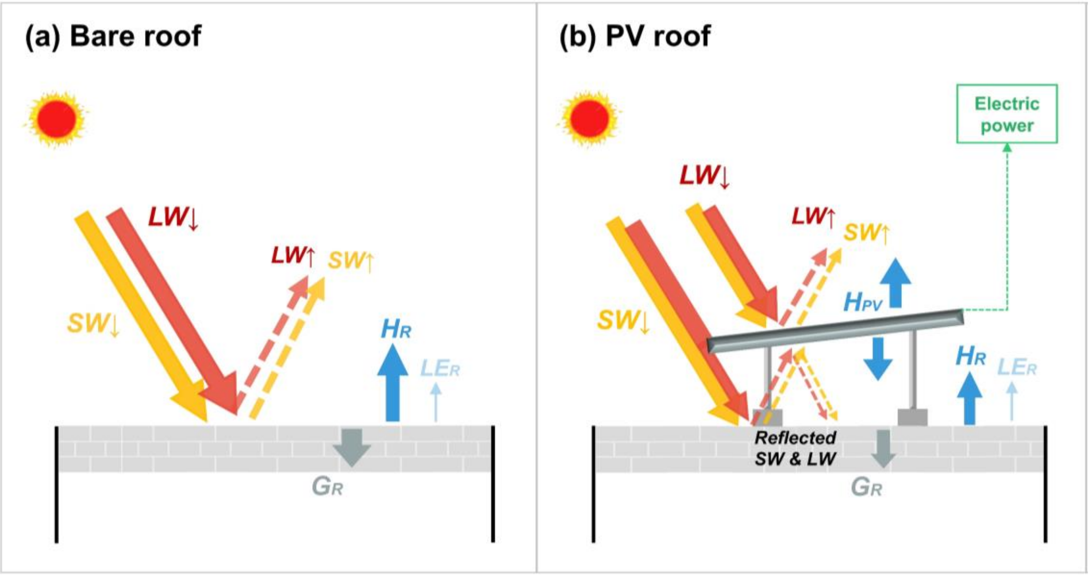
- PV panels produce clean electricity and reduce reliance on fossil fuels
- Carbon reductions mitigate global warming by 0.05 – 0.13 ℃.

1 Global benefits vs. Local climate impacts of PV deployment

Energy Balance Equation:

$$R_n = H + LE + G,$$

$$\text{where } R_n = SW\downarrow + LW\downarrow - SW\uparrow - LW\uparrow.$$



- PV panels produce clean electricity and reduce reliance on fossil fuels
- Carbon reductions mitigate global warming by 0.05 – 0.13 ℃.

- Thermal properties of PV: low albedo, low emissivity, and low heat capacity
- PV installations modify rooftop surface energy balance

1 Research question

Q1. What are the local climatic impacts of large-scale PV deployment?

P.s. This should be distinguished from the global cooling benefit of PV through carbon mitigation. Here, we focus on the direct local climatic effects of PV as an artificial surface.

Simulations

1 Effective albedo approach

2 Physics-based parameterization scheme

Effective albedo approach

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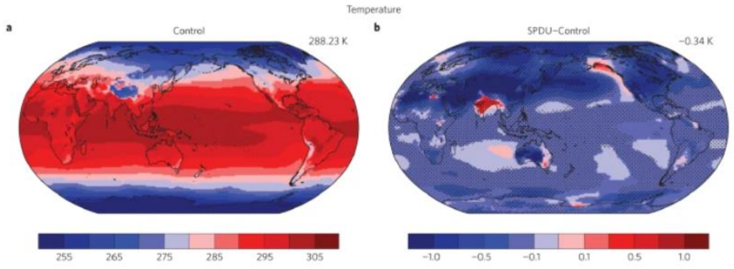
Letter | Published: 02 November 2015

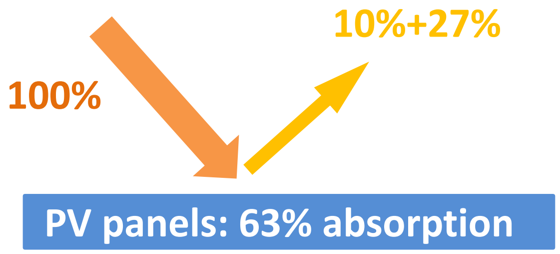
Impact of solar panels on global climate

Figure 1: Surface temperature. −0.26 °C cooling



How are PV panels parameterized in numerical climate models?

- **Reflection**: 10%;
- **Power conversion efficiency**: 27%;
- Remainder 63% conducted to substrate.



Equivalent of **"Effective albedo"** approach, which equals to **10%+27% = 37%**.

Control case albedo: 30%.

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REPORT

Climate model shows large-scale wind and solar farms in the Sahara increase rain and vegetation

YAN LI, EUGENIA KALNAY, SAFA MOTESHARREI, JORGE RIVAS, FRED KUCHARSKI, DANIEL KIRK-DAVIDOFF, EVIATAR BACH, AND NING ZENG

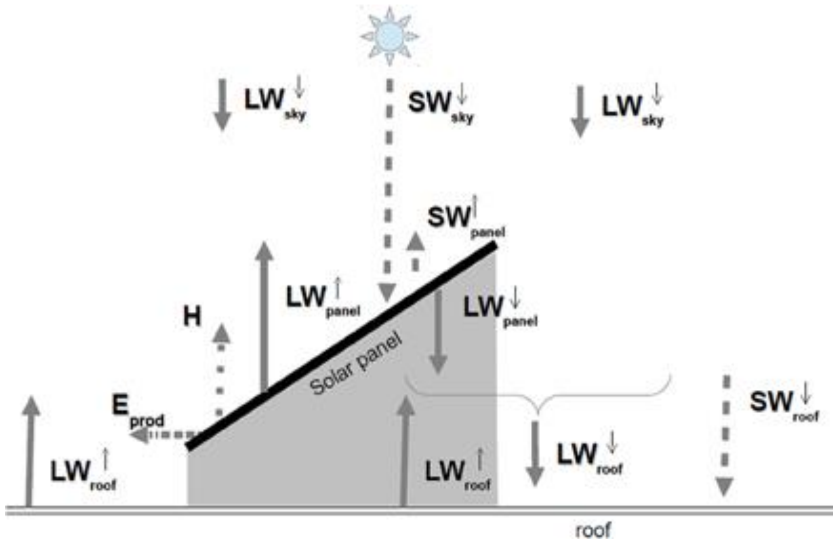
Authors Info & Affiliations

Li et al.: PV panels induces warming (**+1.28℃**) and intensified precipitation (+50%).

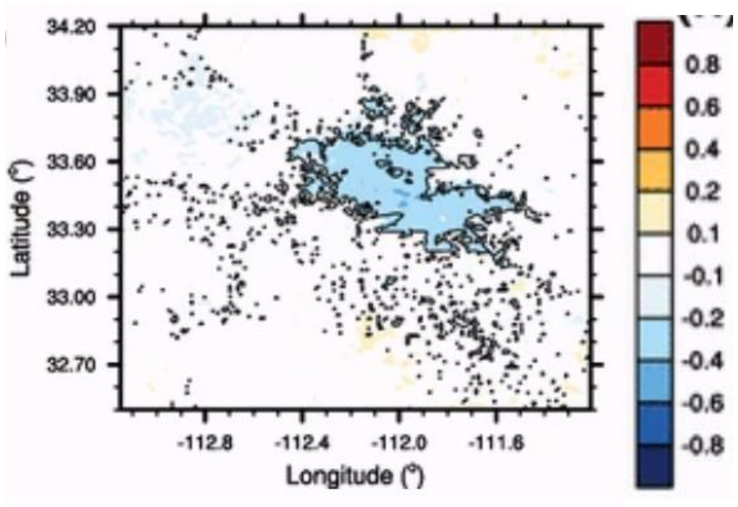
PV effective albedo: 10% + 13.5% = **23.5%**,
Control case albedo: 40%.

If control case albedo < effective albedo, PV deployment leads to **cooling**, vice versa.

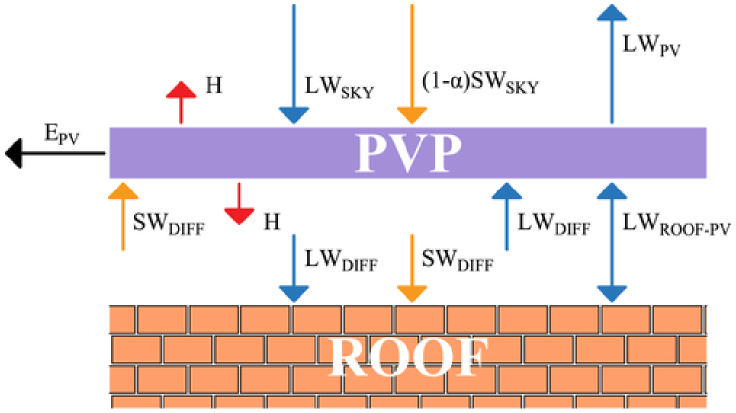
2 Physics-based parameterization scheme



Town Energy Balance Scheme
Paris: -0.2 ℃ (Masson et al, 2014)



WRF/BEP+BEM
Phoenix: -0.4 ℃ (Salamanca et al, 2016)



WRF/BEP+BEM
+1.5 ℃ (Zonato et al, 2021)

Assumptions:

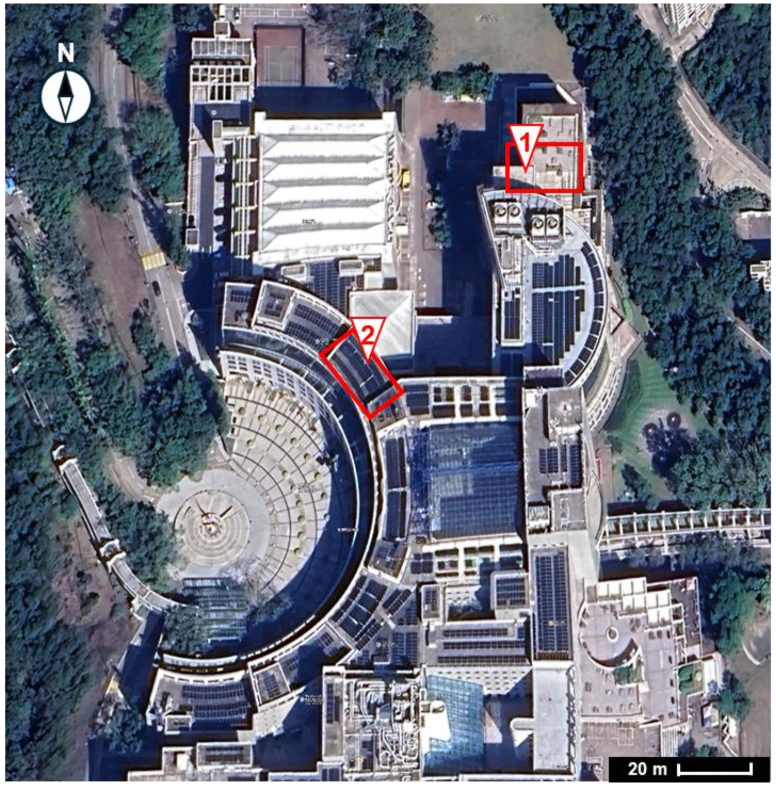
- $LW_{PV}^{\downarrow} = \varepsilon_{PV}\sigma TPV_{back}^{4} = \varepsilon_{PV}\sigma Ta^{4}$
- H= residue of energy budget
- $H = H^{\uparrow} + H^{\downarrow} = (h^{\uparrow}+h^{\downarrow})(TPV - Ta)$

⚠️ **Model validity must be evaluated against field measurement data.**

However, large-scale PV field experiments are still lacking.

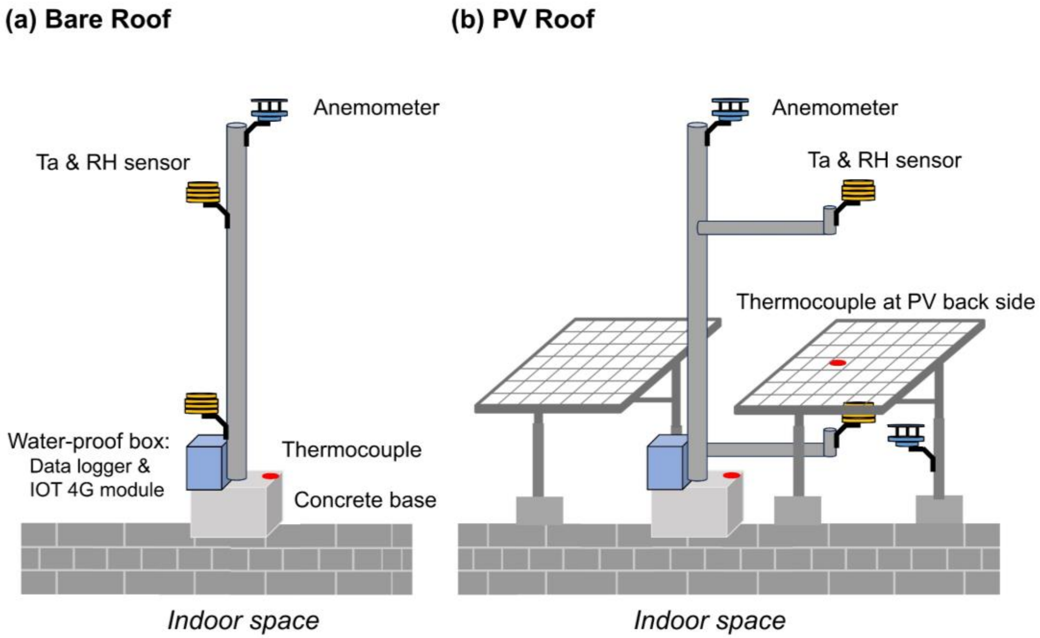
2 Site map of studied rooftops

(a)



(b)

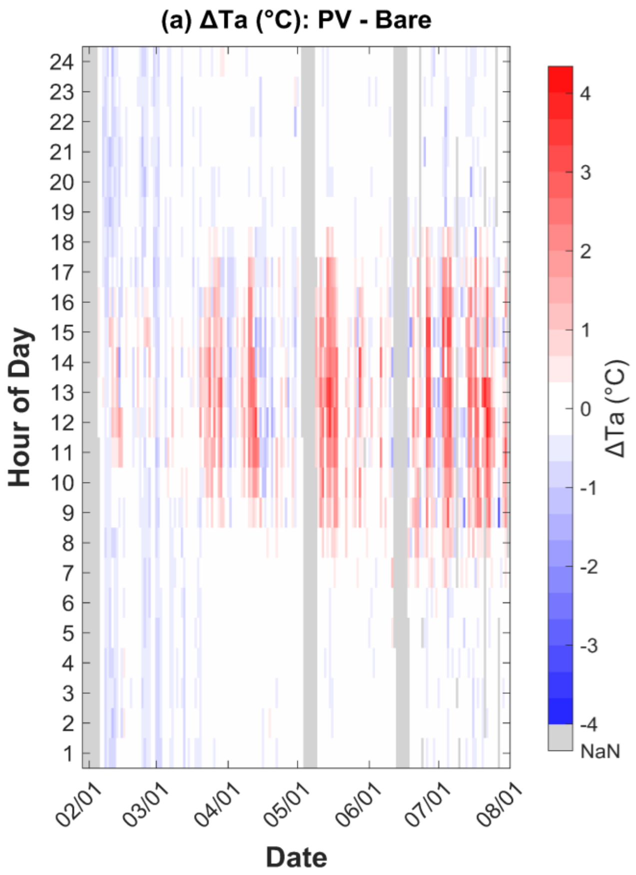
Location: Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR

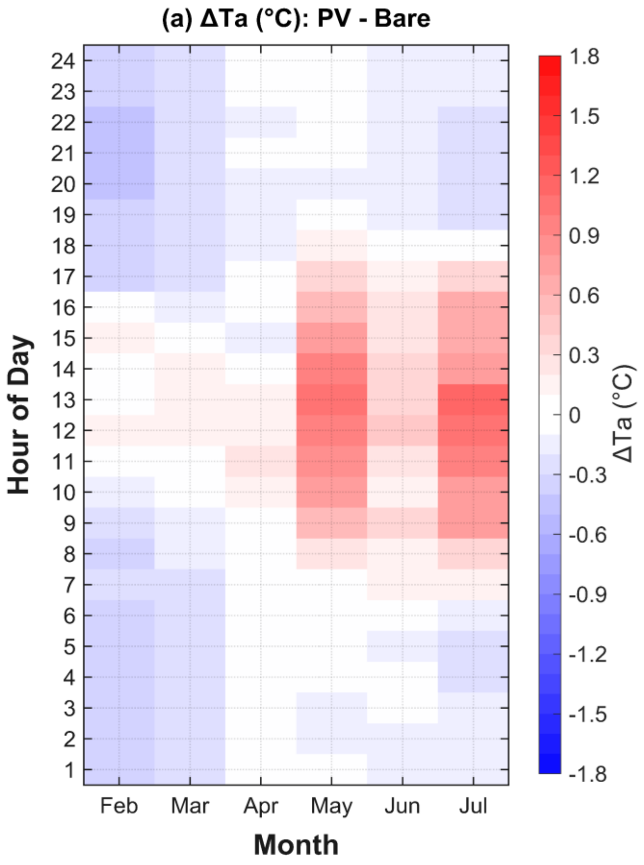


Campus rooftop: each 200 m²

Measurement period: Jan 19 to Aug 1, 2024

Results: PV heat island effect





Daily	PV-Bare
Max	Jul 21, 12 pm: 3.82 ℃
Min	Jul 27, 8 am: -2.72 ℃

Monthly	PV-Bare
Max	Jul 12 pm: 1.18 ℃
Min	Jan 8 pm: -0.46 ℃

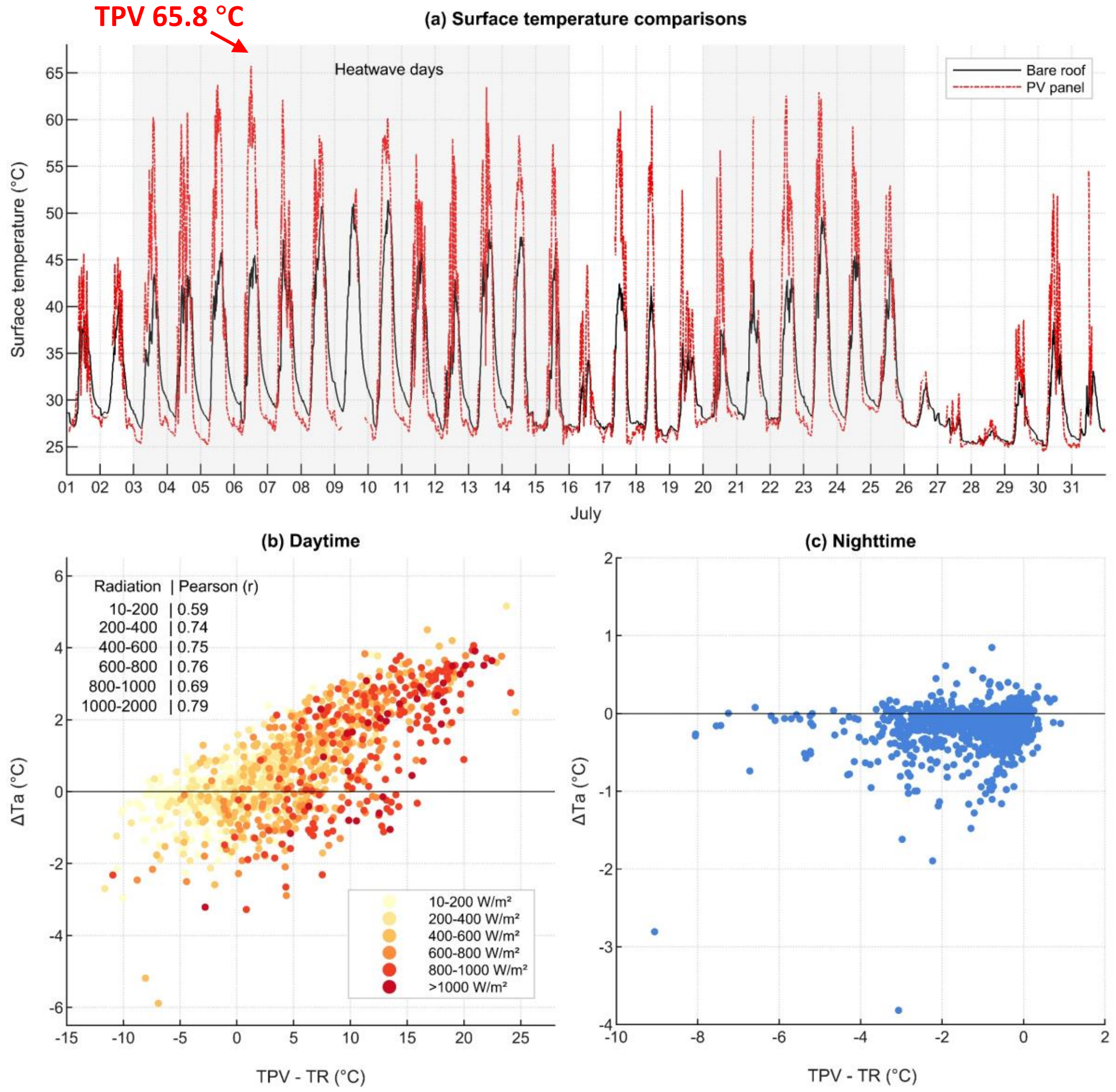
Daytime:

- PV heating effect is stronger in hotter months.

Nighttime:

- PV cooling effect is modest, but it is more evident in winter months.

2 Causes of PV heat island effect



Strong positive correlation between (TPV – TR) and (ΔTa) in daytime

PV properties:

low albedo, emissivity, and thermal inertia.

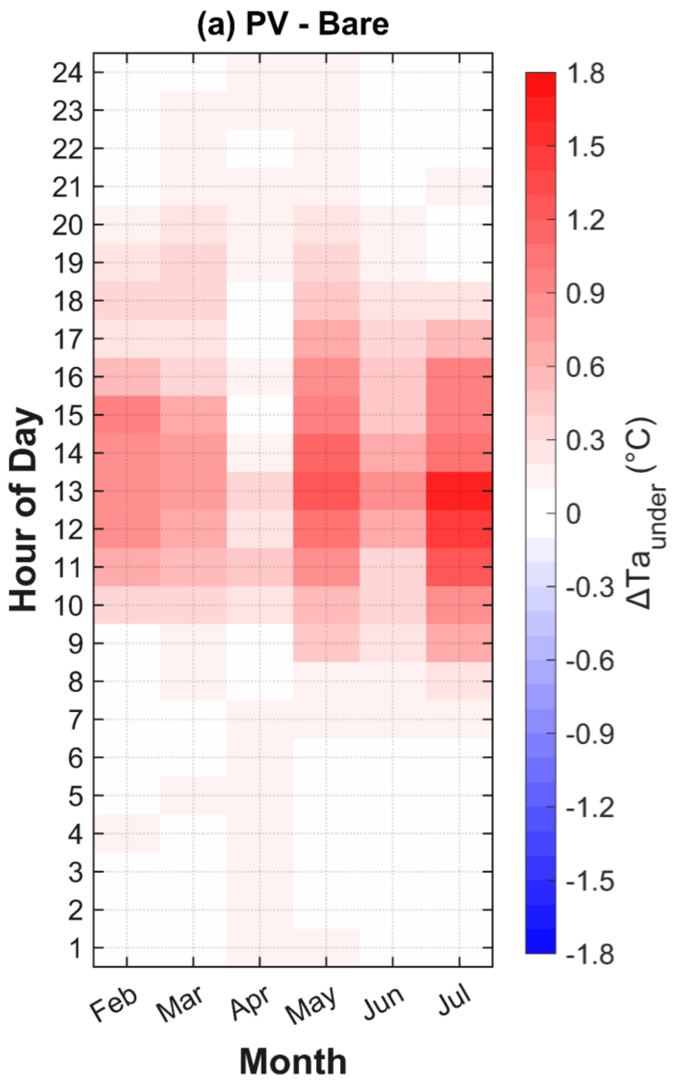
→ Reduced $SW_{PV}^{\uparrow}$ and $LW_{PV}^{\uparrow}$; Heat up and cool down quickly.

TPV – TR: up to 24.6 °C.

The warming of the surrounding air is primarily driven by convective heat transfer from the hot PV surface.

Results: PV canopy heating

PV-canopy heating effect:
up to **1.64 °C** at noon in July.



Causes:

(1) Heat released from heated PV panels, warming trapped air through convection and radiation;

(2) Reduced sky view factor, limiting longwave radiative cooling;

(3) Restricted airflow, inhibiting heat dissipation under the canopy.

Heat accumulation beneath the panels also limits panel self-cooling, thereby reducing electrical efficiency.

(Chen et al., 2025, Building and Environment)

2 Research questions

Q1. What are the local climatic impacts of large-scale PV deployment?

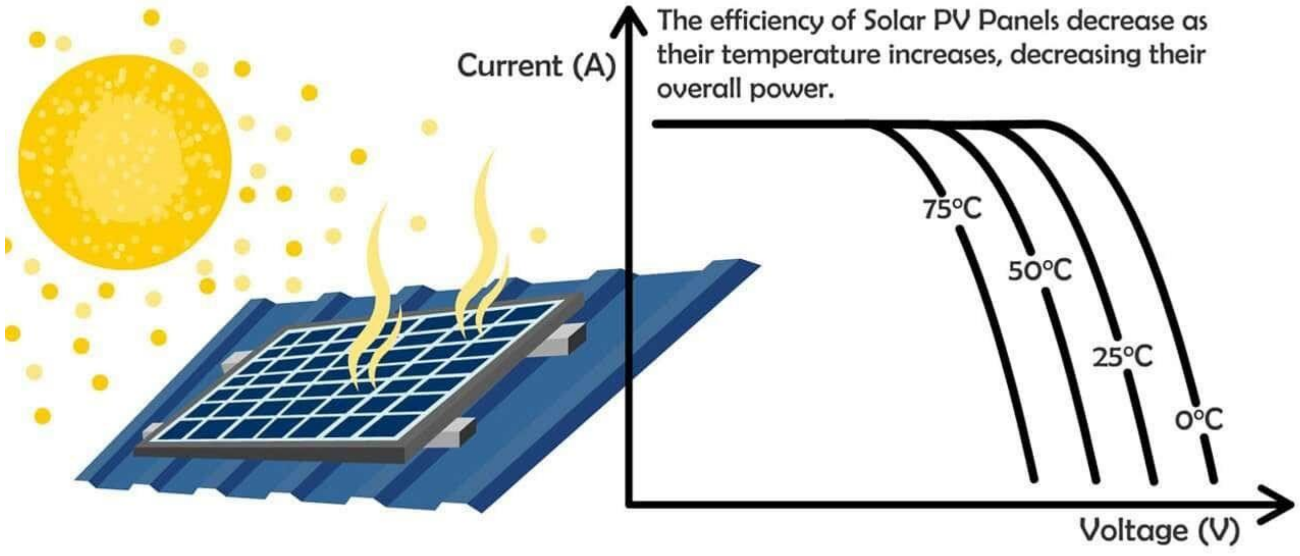
Key Finding: Rooftop PV creates a localized “PV heat island” and a pronounced “PV canopy heating” effect.

Significant daytime warming (monthly average up to +1.2 °C) and slight nighttime cooling (up to -0.5 °C).

Q2. How can we mitigate these effects through climate-adaptive PV design?

This motivates climate-adaptive PV systems that generate clean energy while also mitigating their local environmental impacts.

3 PV conversion efficiency decreases with increasing temperature



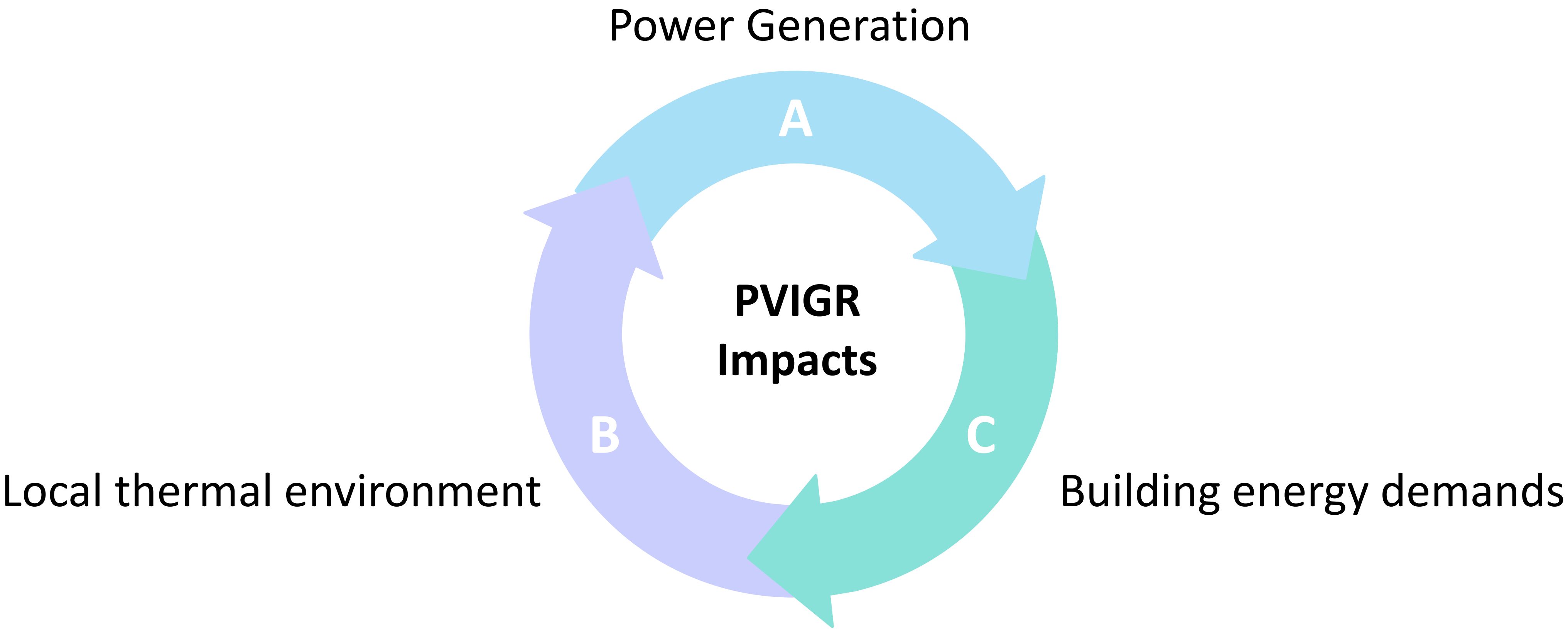
Temperature coefficient: -0.2 to -0.5%/℃

Köhler et al (2002):

Figure 4: General overview of the different types of roofs (July 2001)

PV integrated green roof (PVIGR) can cool panels and improve power output.

Framework of PVIGR benefits



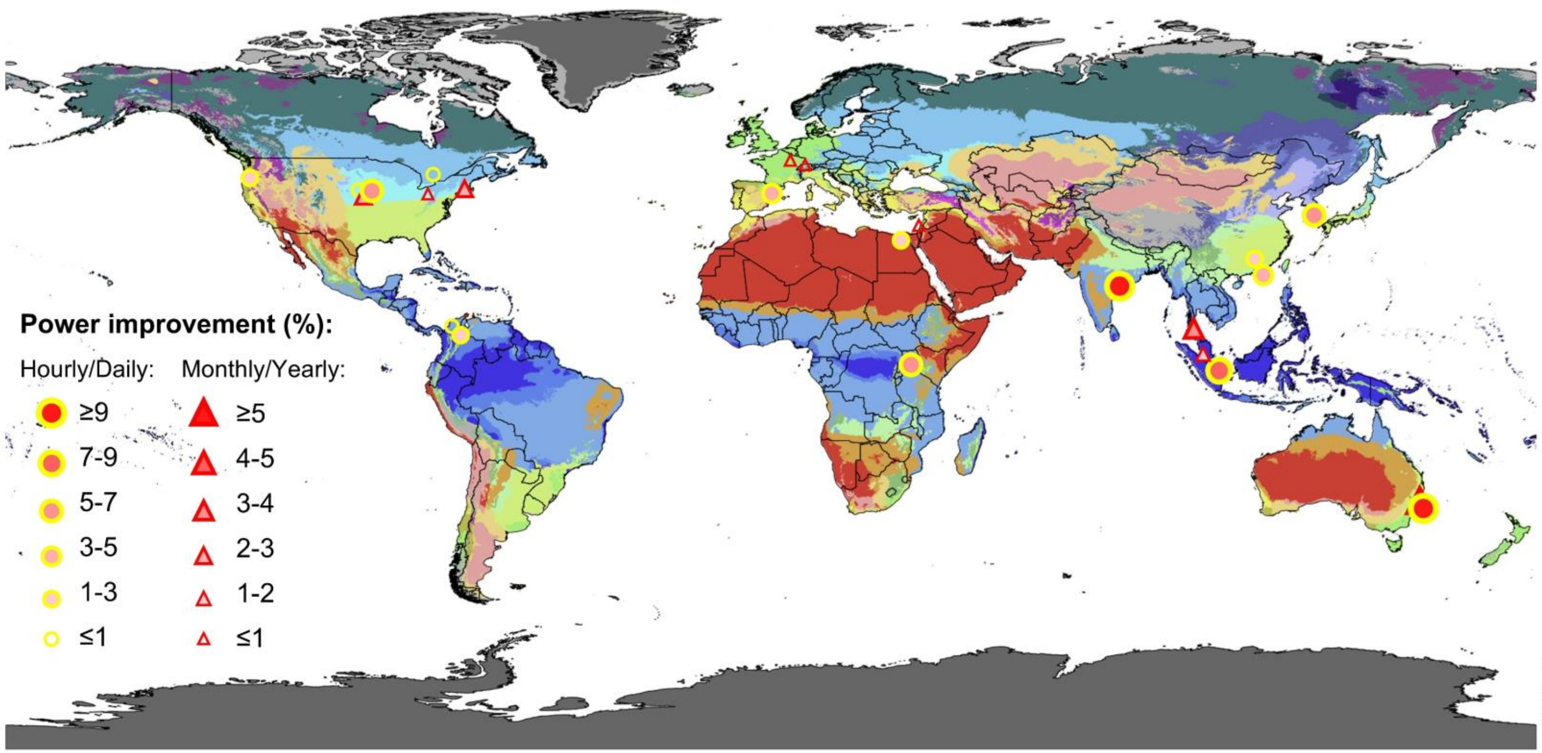
3 Few experimental studies have evaluated PVIGR power performance

PVIGR Power Enhancement across Köppen-Geiger Climate Zones

Climate classifications:

Af, Am, Aw, Csc, Cwa, Cwb, Dsc, Dsd, Dwa
BWh, BWk, BSh, Cwc, Cfa, Cfb, Dwb, Dwc, Dwd
BSk, Csa, Csb, Cfc, Dsa, Dsb, Dfa, Dfb, Dfc
Dfd, ET, EF

1st: Main climates	2nd: Precipitation	3rd: Temperature
A (Tropical)	f (Rainforest), m (Monsoon) w (Savanna, dry winter) s (Savanna, dry summer)	
B (Dry)	W (Arid desert), S (Semi-arid steppe)	h (Hot), k (Cold)
C (Temperate)	w (Dry winter), f (No dry season) s (Dry summer)	a (Hot summer) b (Warm summer) c (Cold summer) d (Very cold winter, for 1st D)
D (Continental)		
E (Polar)	T (Tundra), F (Ice cap)	



Only 6 studies examined > 1 year

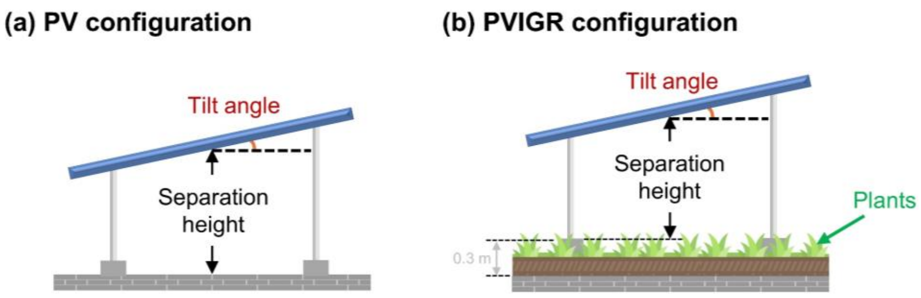
No improvement in **temperate** climates: France (Cfb), Switzerland (Cfb), Israel (Csa).

Cold climate (Dfa):
0.5% in Pittsburgh, 1.4% in Kansas.

Hot climate (Am):
1.97% in Thailand.

Overall, PVIGR systems perform better in **hot** climates compared to cooler regions.

3 We retrofitted existing PV arrays to establish PVIGR systems

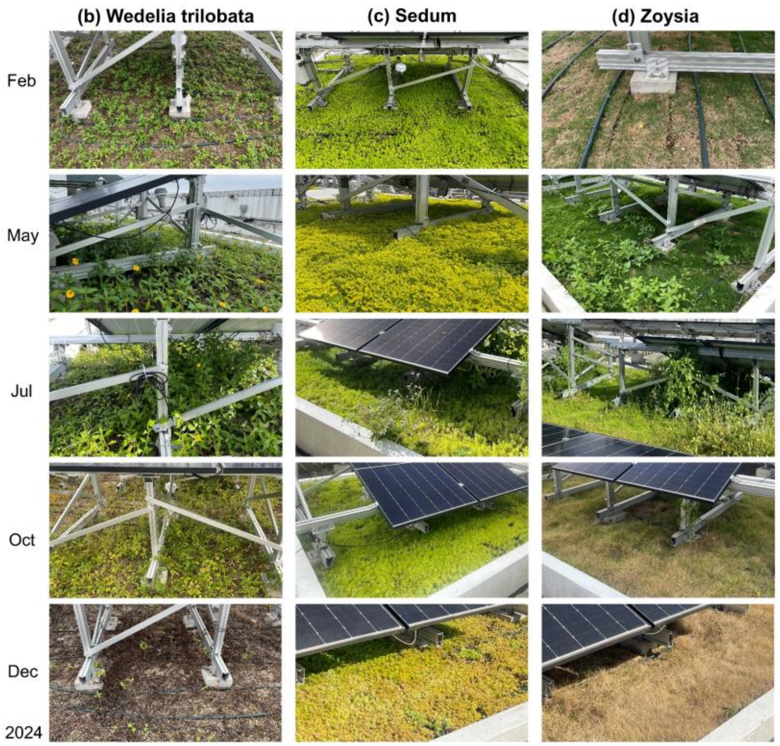


(c) Summary of all studied configurations

ID	Tilt angle (°)	Separation height (m)	Plant species
PV_12	12	0.9	N/A
PV_22	22	0.9	
WT_12	12	0.9	Wedelia trilobata
WT_22_060	22	0.6	
WT_22_075		0.75	
WT_22_090		0.9	
Sed_22_060	22	0.6	Sedum
Sed_22_090		0.9	
Zoy_22_060	22	0.6	Zoysia
Zoy_22_090		0.9	

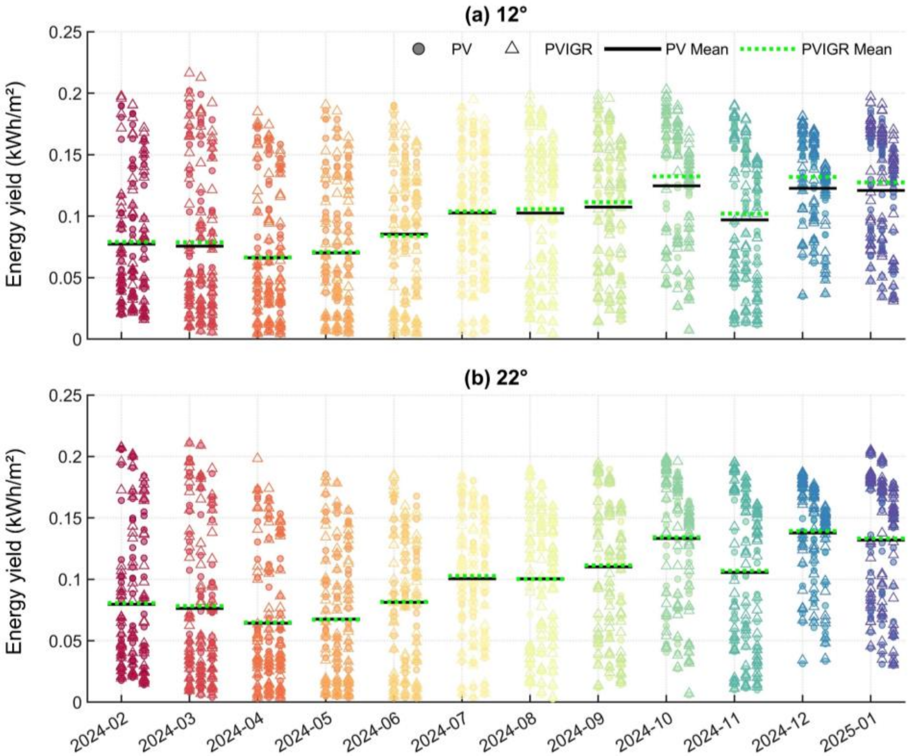
(a) Technical information of each plant species

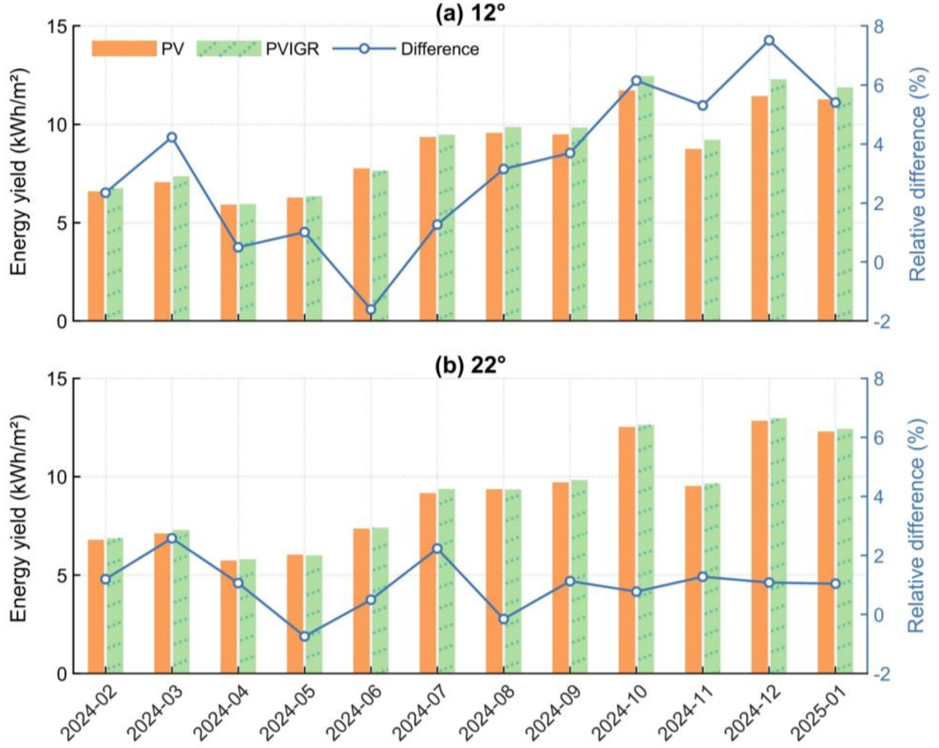
	Wedelia trilobata	Sedum lineare	Zoysia grass
Irrigation demand			
Pruning demand			
Tolerance	★	★★	★★★
Price	122 HKD/m² (≈ 15.6 USD)	344 HKD/m² (≈ 44.0 USD)	85 HKD/m² (≈ 10.9 USD)
Features	Fast ground cover with yellow daisy flowers from May–Sep	Dense yellow flowers from Apr-May	Fine textured turfgrass with inconspicuous little flowers



Two tilt angles · Three separation heights · Three plant species

3 PVIGR vs. PV: power enhancement at noon





(c) Monthly mean hourly relative difference between PVIGR and PV (%)

(%)	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
12°	1.41	2.74	2.51	2.17	0.73	1.84	3.19	3.76	6.13	4.50	7.08	4.66
22°	3.01	5.66	4.57	4.95	6.06	4.87	3.41	3.62	1.69	3.04	1.42	1.83

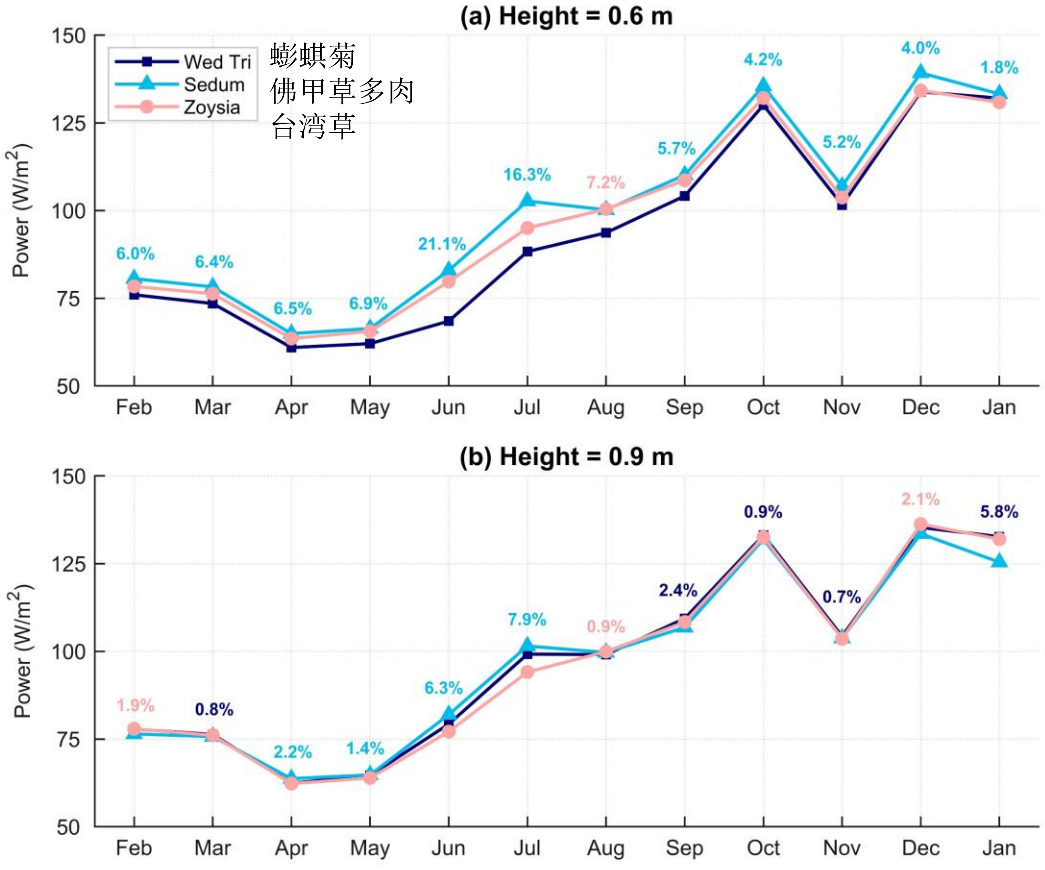
(c) Relative difference between PVIGR and PV (%)

(%)	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Year
12°	2.35	4.23	0.50	1.01	-1.61	1.27	3.15	3.69	6.15	5.31	7.51	5.41	3.66
22°	1.20	2.58	1.07	-0.74	0.50	2.23	-0.15	1.13	0.78	1.28	1.08	1.04	1.02

Hourly → Monthly → Yearly

Up to 7.08% | 7.51% | 3.66%

3 Optimal design analysis



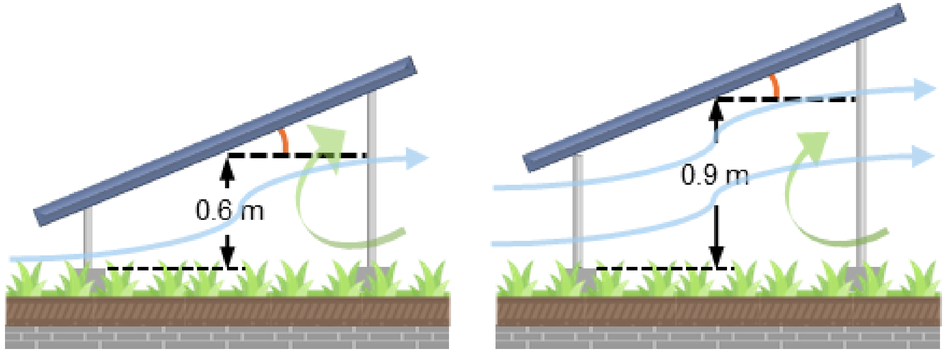
Sedum
(0.6 m)

Wed. Tri.
(0.75 m > 0.9 m)

109.28
(kWh/m^2)

107.84, 106.80
(kWh/m^2)

Separation height is the key regulator between convective cooling and evapotranspiration.



- **Optimal configuration**: *Sedum* (0.6 m) achieves peak power.
- **Height = 0.9 m**: vegetation benefits are significantly diminished.
- **Design warning:** suboptimal PVIGR designs can underperform conventional PV.

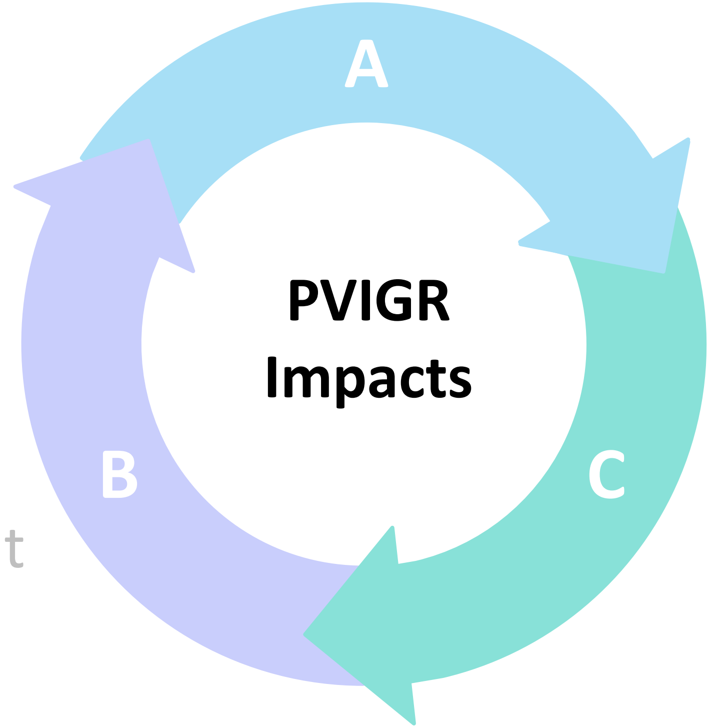
(Chen et al., 2026, Renewable Energy)

3 Framework of PVIGR benefits

Power generation

Modest annual gains: 1.0~3.7% (noontime)

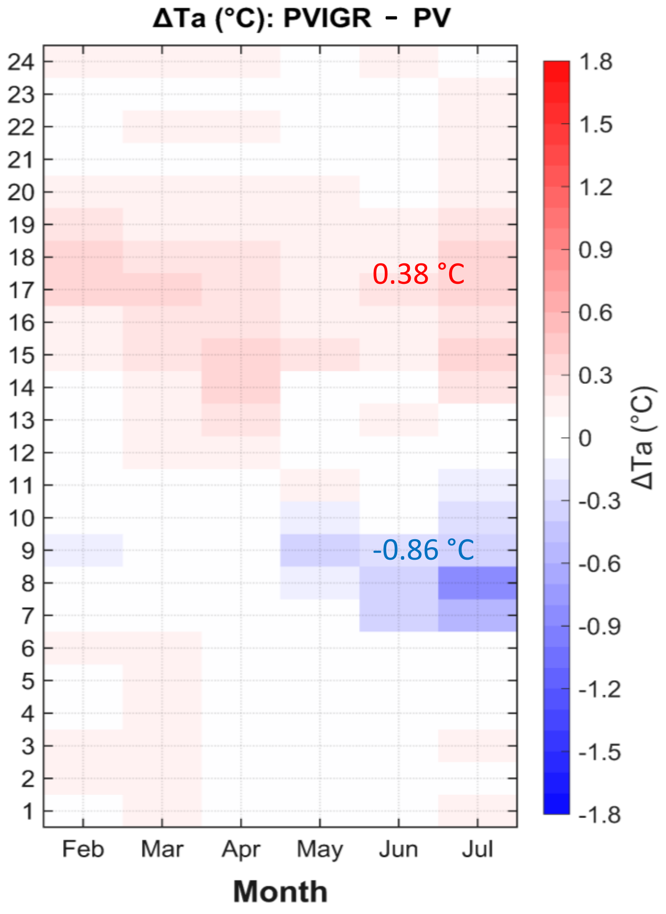
HOW?

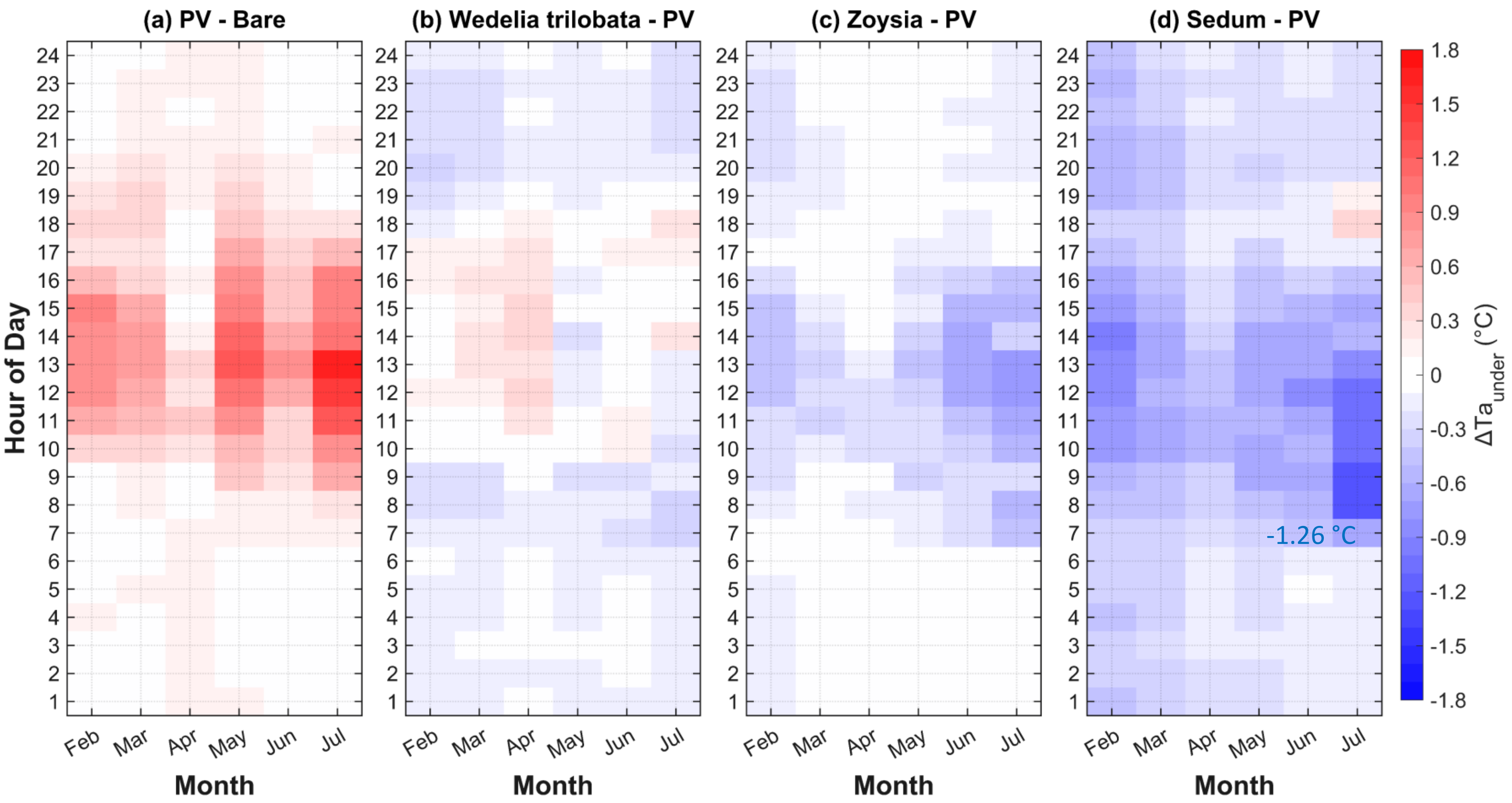


Local thermal environment

Building energy demands

3 PVIGR results: thermal environment

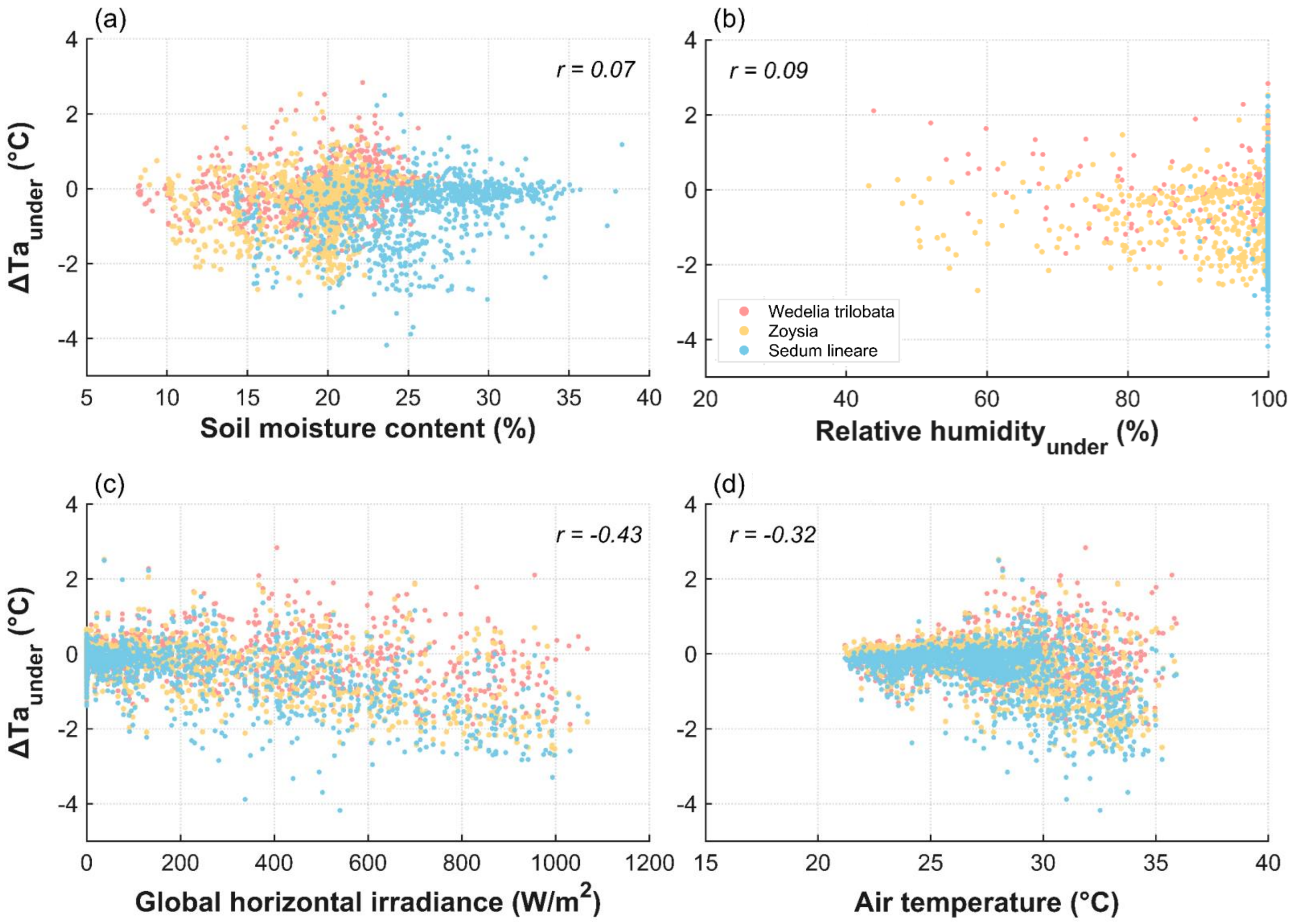




PVIGRs **do not** exhibit a cooling effect at 1.8 m height compared to PV roofs, except during the morning irrigation period.

PVIGRs can significantly **mitigate PV-canopy heating effect**, especially for Sedum (**-1.26 °C**).

3 Mechanisms of PVIGR's cooling effect

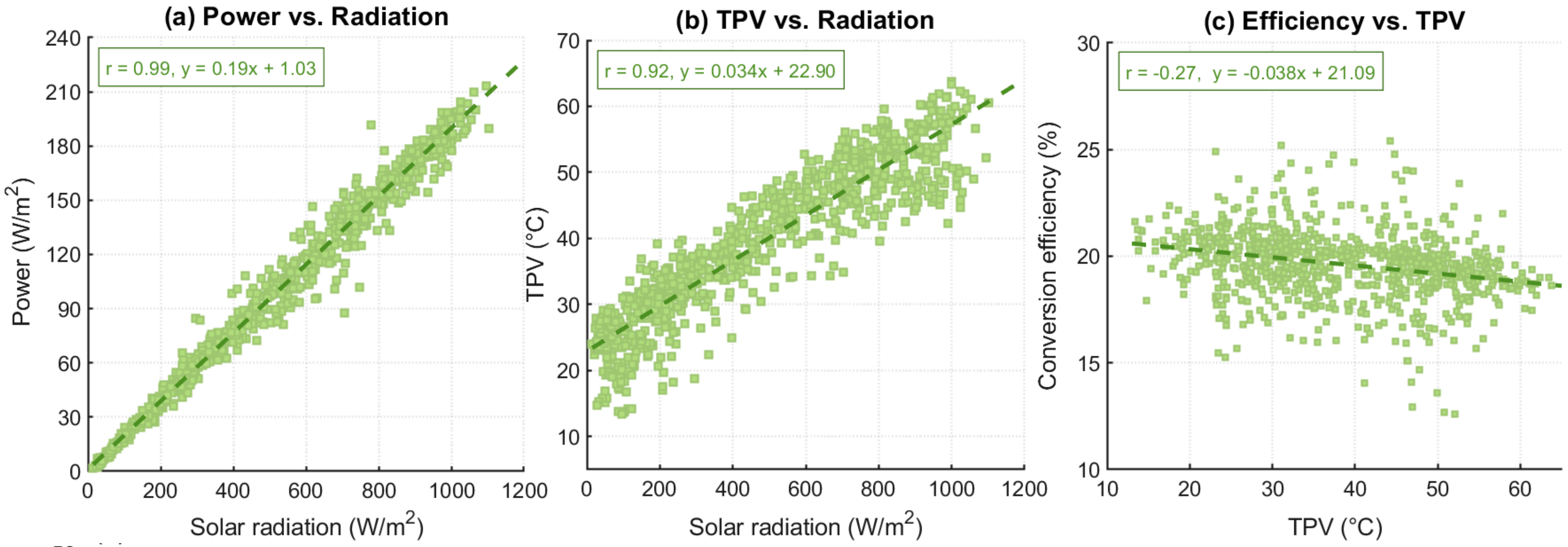


Weak correlation between soil moisture and cooling effects: In humid HK, cooling efficiency of green roofs relies less on water availability.

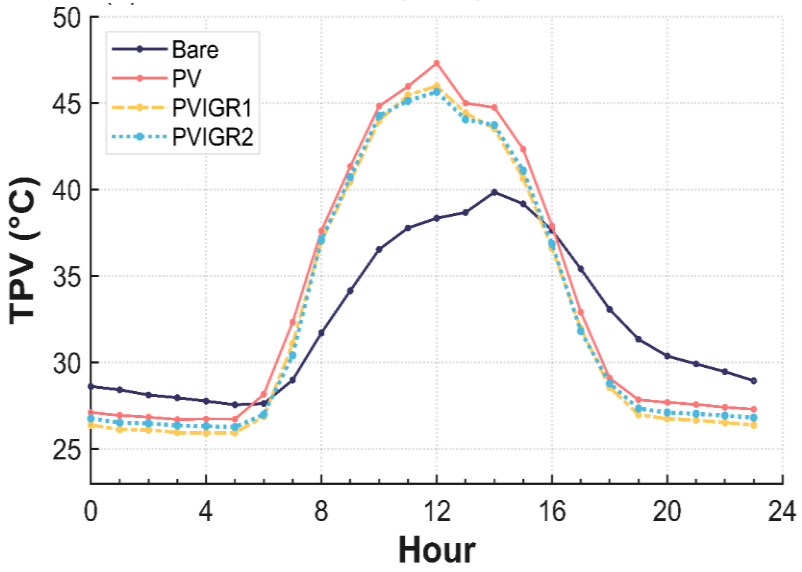
Stronger solar irradiance and **warmer** temperatures enhance the cooling effect.

(Chen, et al., 2025, Renewable and Sustainable Energy Reviews)

3 Mechanism linking PVIGR cooling to higher power generation



TPV ↓
Efficiency ↑



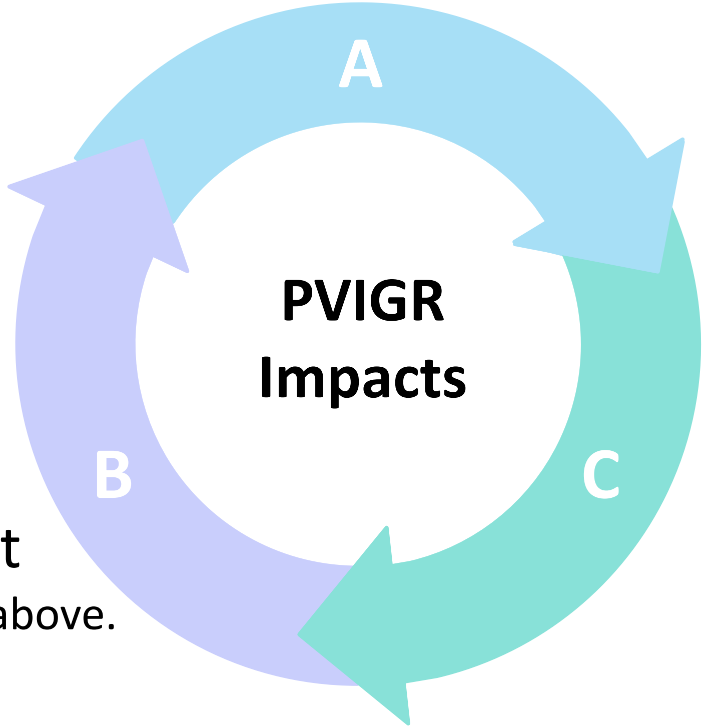
Under strong solar radiation, PV panels generate more electricity but also heat up rapidly, which lowers efficiency.

By cooling the air beneath the panels, PVIGR indirectly reduces panel temperature and helps recover part of this efficiency loss.

3 Framework of PVIGR benefits

Power generation

Modest annual gains: 1.0~3.7% (noontime)



Local thermal environment

Plants cool air beneath panels, but not above.

Building energy demands

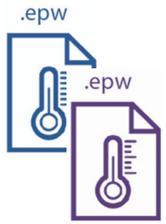
3 Impacts on building energy consumption

Climate impact: localized daytime warming, slight night cooling.
Shading impact: reduces underlying rooftop surface temperature and downward heat conduction.

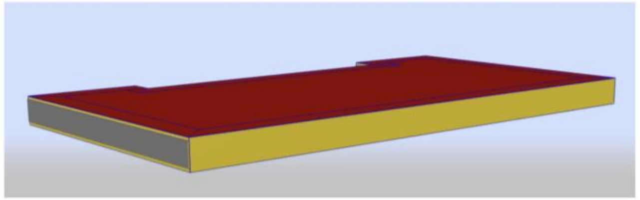
Which factor dominates?

Table 1. Designed simulation scenarios to investigate the impact of altered climate and PV shading on building cooling demand after installing rooftop PV.

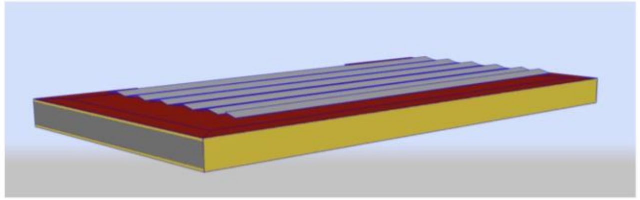
Scenario	Meteorological data	Building setting	Notes
A	Bare roof site $\mathbf{TMY_{Bare}}$	Control building with bare roof	B – A: Impact of altered climate
B	PV roof site $\mathbf{TMY_{PV}}$	Control building	C – B: Impact of PV shading effect
C	PV roof site $\mathbf{TMY_{PV}}$	Building with rooftop PV	C – A: Total impact of climate and shading



Control building with bare roof

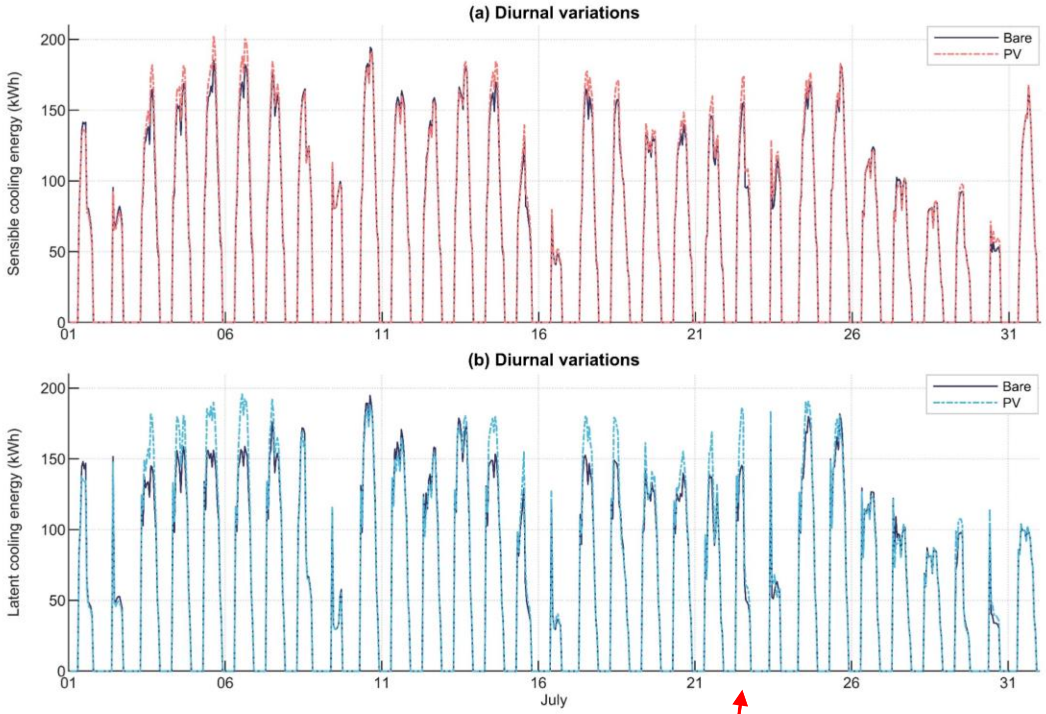


PV Building with 50% PV panels coverage

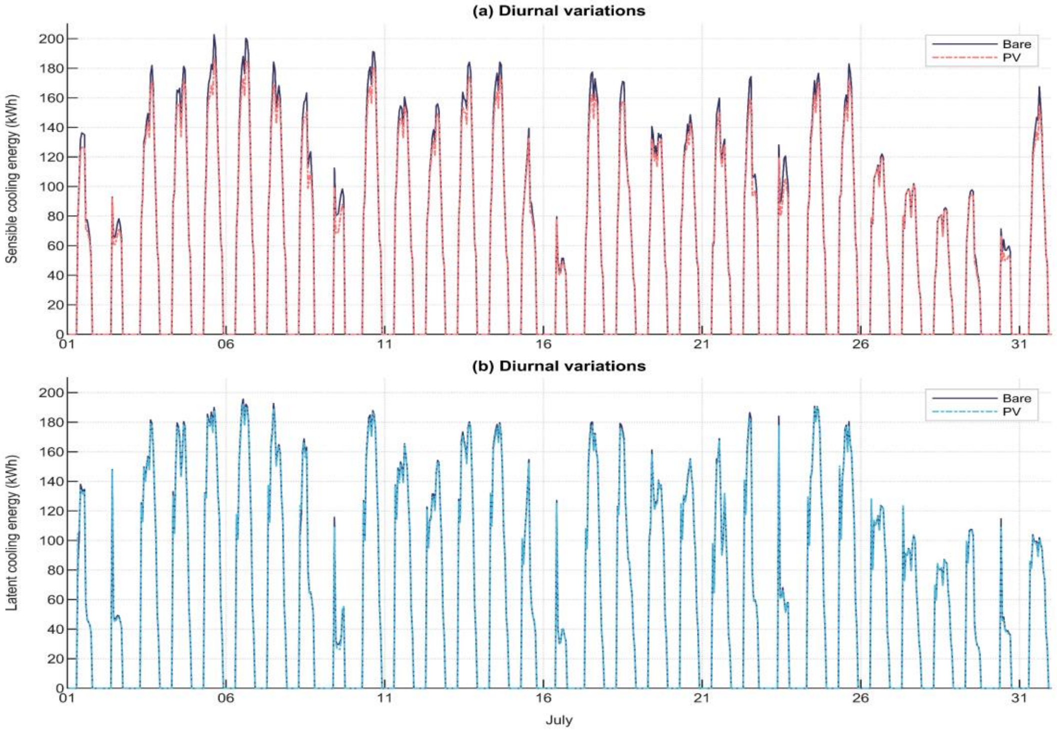


3 Impacts on cooling energy

Climate impact



Shading impact



Peak hour:

Hourly: Sensible +11%, latent +29%.

Monthly: Sensible +4%, latent +9%.

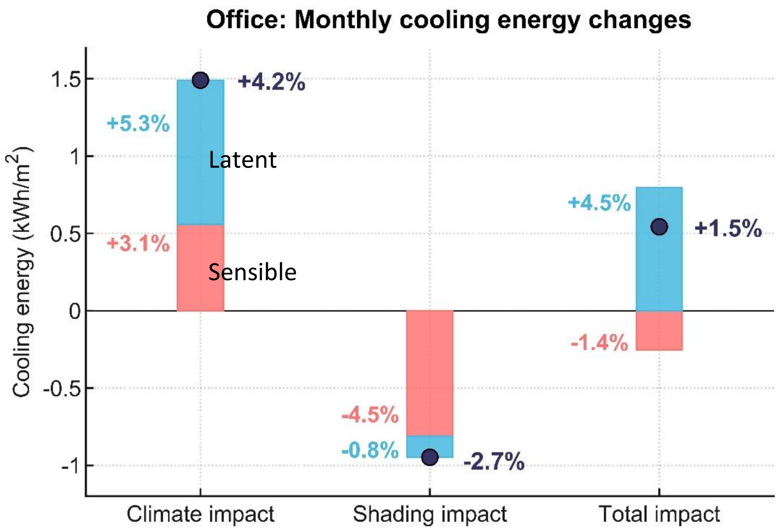
Peak hour:

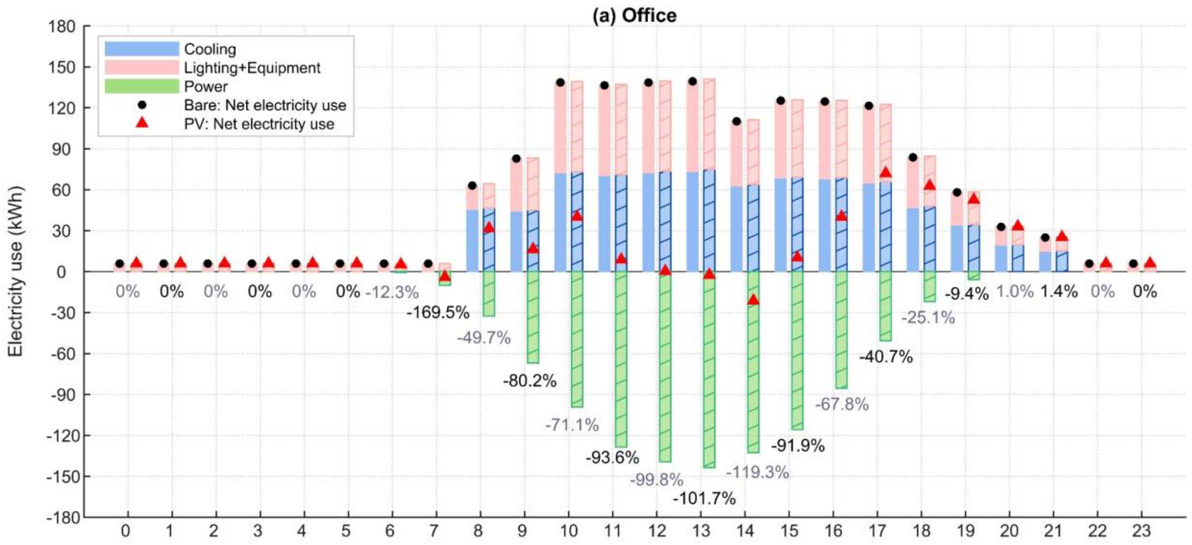
Hourly: Sensible -14%, latent -7%.

Monthly: Sensible -7%, latent -2%.

Warmer air at the PV site during midday can hold more moisture, leading to higher absolute humidity.
The office's dehumidification demand therefore produces a large latent cooling load.

3 Net changes in cooling energy per floor area





Daytime-dominant office floor: +1.5%.

Limitation: Using 1.8 m measurements as ambient forcing likely **overestimates** PV-induced warming, so the cooling-energy penalty may be smaller in reality.

Despite this slight cooling energy penalty, **PV electricity generation** still provides a clear net benefit.

PV systems contribute to reducing peak demand and alleviating energy burdens, especially around noon.

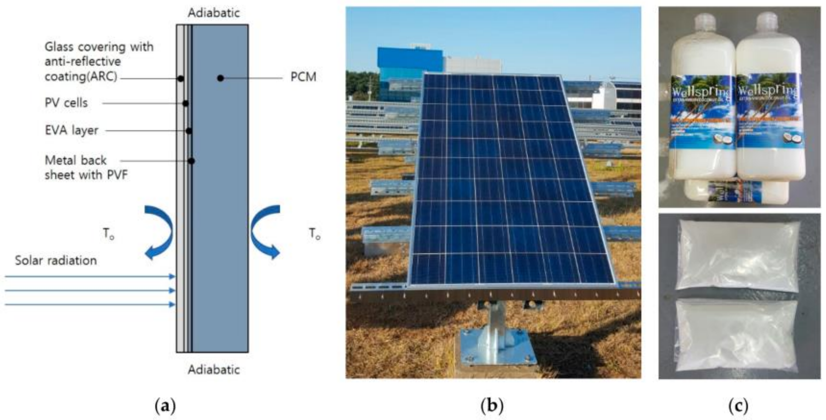
(Chen et al., 2025, Building and Environment)

4 Conclusions

1. Rooftop PV is not thermally neutral: it can create **localized daytime warming** and influence building energy performance.
2. PVIGR provides a climate-adaptive design strategy that can improve annual noontime power output by up to **3.7%**, although its benefits are strongly design-dependent.
3. These findings show that rooftop PV should be evaluated as **an integrated climate–energy system**, with joint consideration of electricity generation, microclimate, and building energy performance over annual timescales.

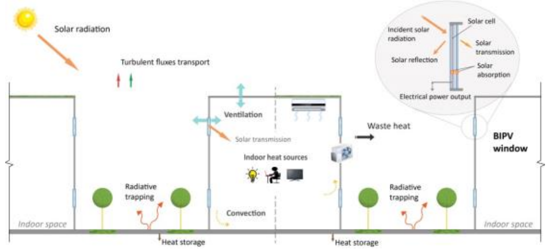
5 Future works

- Strategies could be developed and tested to mitigate the warming effects of PV panels, such as phase change materials or the reflective materials.



- How do the climate and energy impacts of large-scale PV deployment vary across climatic regions?

BEM-UCM: **B**uilding **E**nergy **M**odel coupled with **U**rban **C**anopy **M**odel



Develop BIPV schemes and incorporate into BEM-UCM

UBEM: **U**rban **B**uilding **E**nergy **M**odel

Apply single BEM concept to entire city

Cross-scale urban climate and building simulation framework

(Chen et al., 2026, Nexus)

Urban Building Energy Model

Weather Data + Geographic Information Systems (GIS) + Building Energy Modelling (BEM)

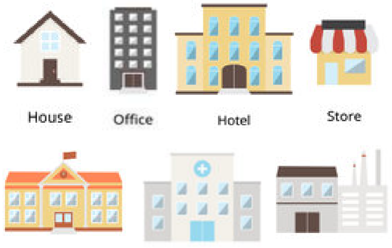
Real World

Hong Kong:
204393 buildings

GIS Layers

Geometric Data

- Building polygon
- Construction year
- Land use types
- Building types



Non-Geometric Data

- Construction material
- Indoor heat gains
- Occupant schedules
- HVAC settings

Simulation Engine

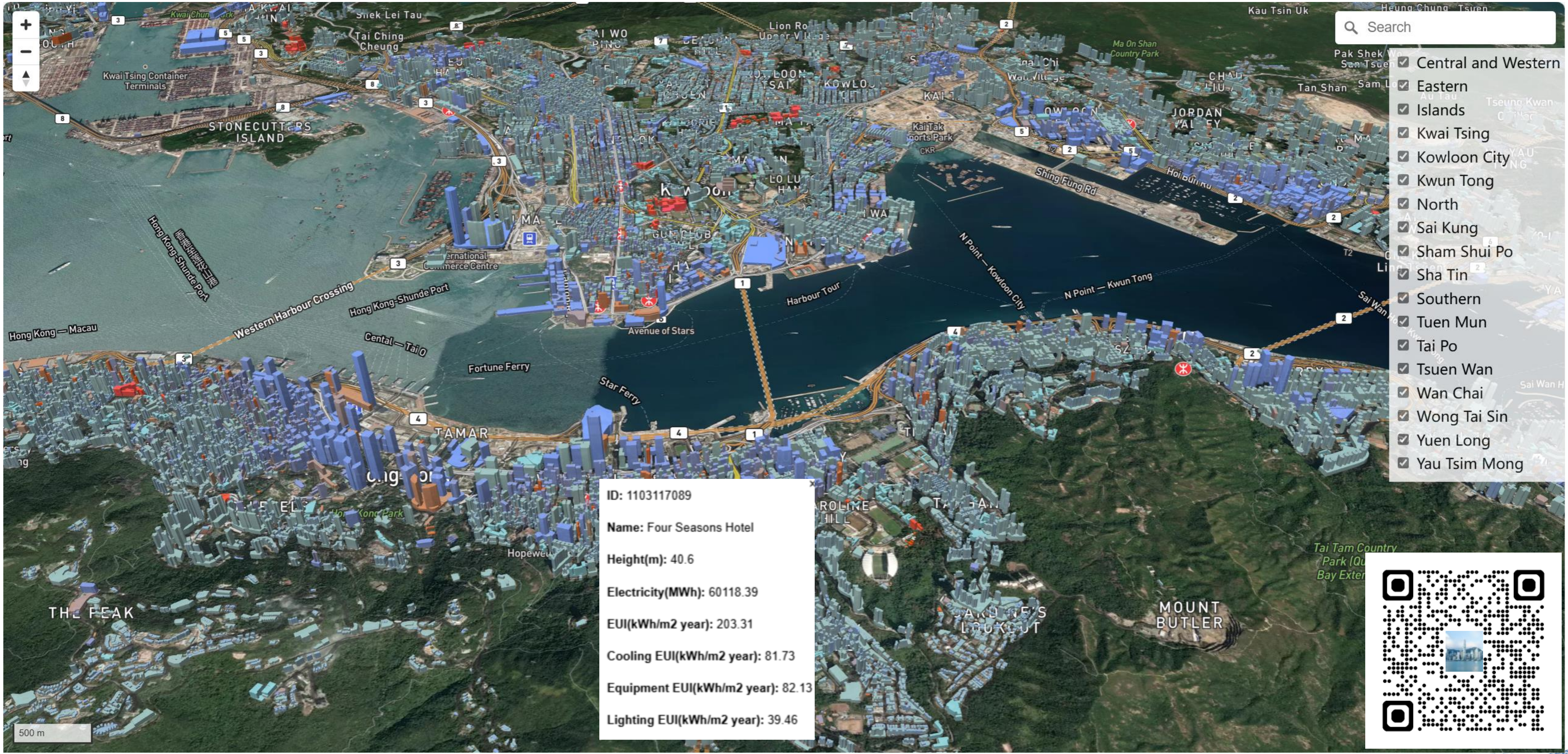
Python → IDF file → EnergyPlus (U.S. Department of Energy)

EPPY Script

1. Read input geo & non-geo data
2. Initialize Input Data File (IDF)
3. Divide thermal zone
4. Construct shading walls
5. Output IDF files for simulator

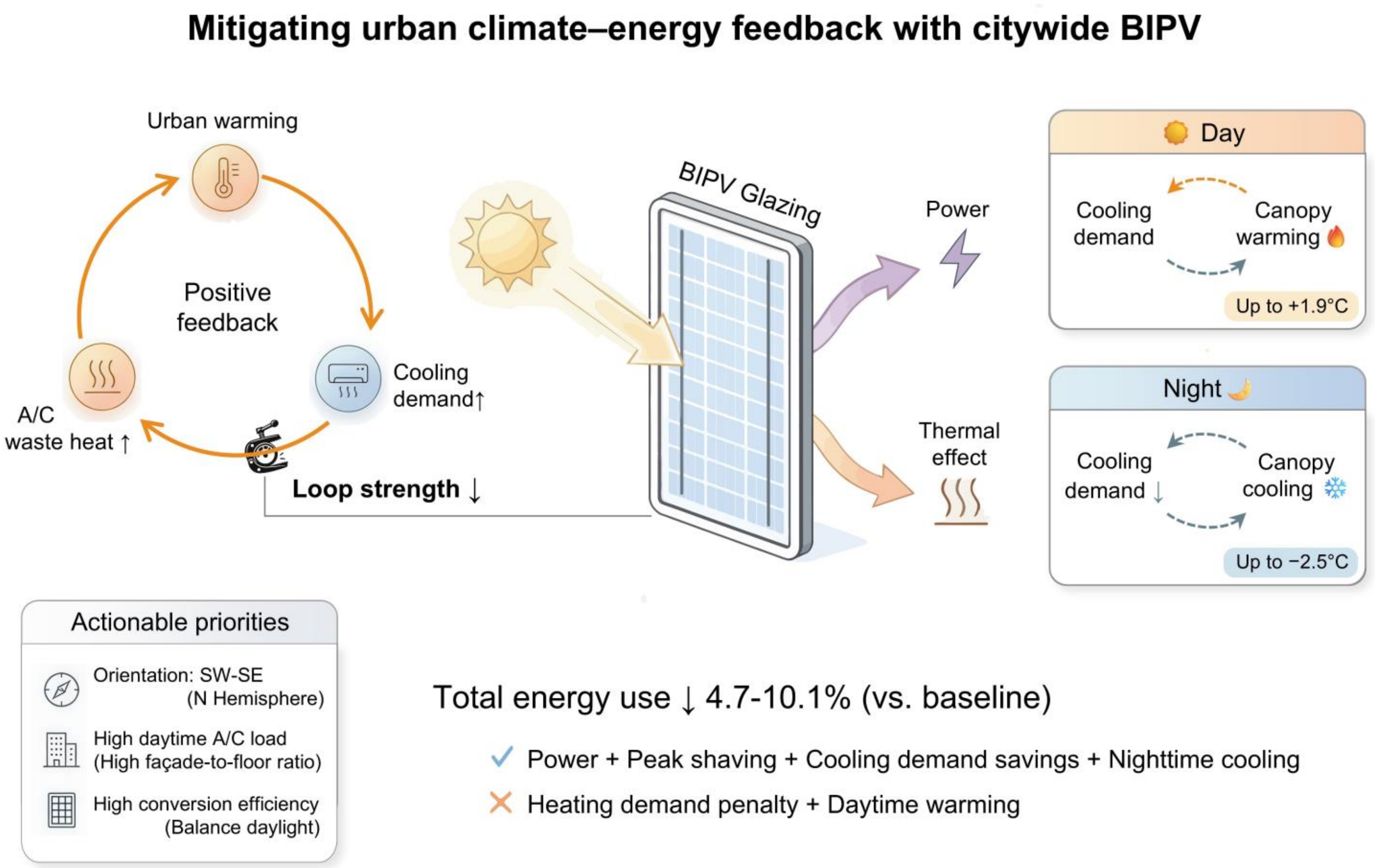
(Zhang, Chen et al., 2025, SCS)

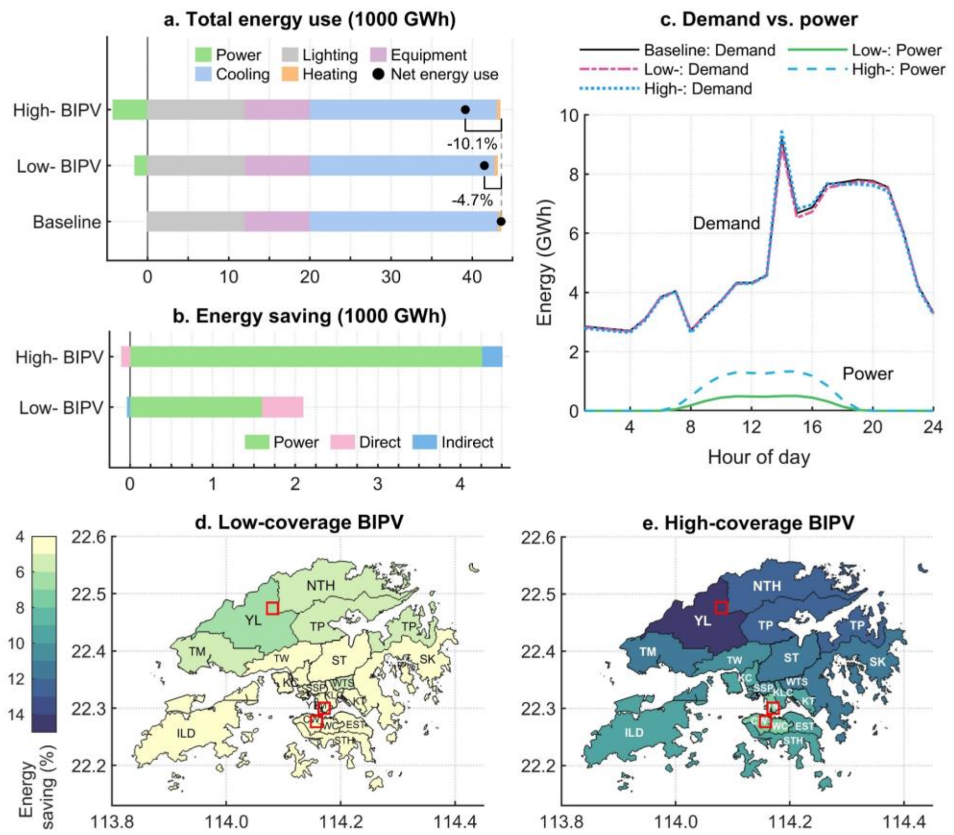
5 Hong Kong Digital Twin Platform



http://cez027.ce.ust.hk/HongKongUrbanEnergy/UrbanEnergy.html

5 UBEM applications: citywide climate–energy impacts of BIPV

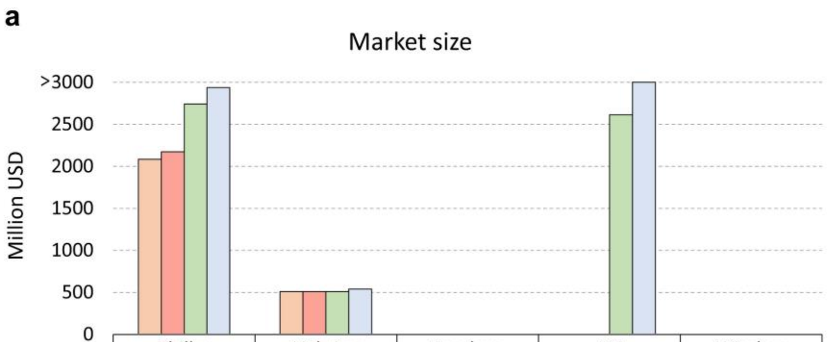




Citywide BIPV is not only a power-generation strategy, but also a regulator of urban climate–energy feedback.

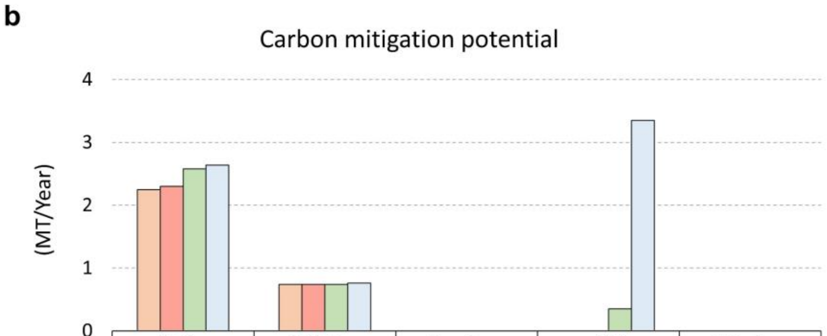
(Chen et al., 2026, Nexus)

UBEM applications: the potential of building retrofit strategies



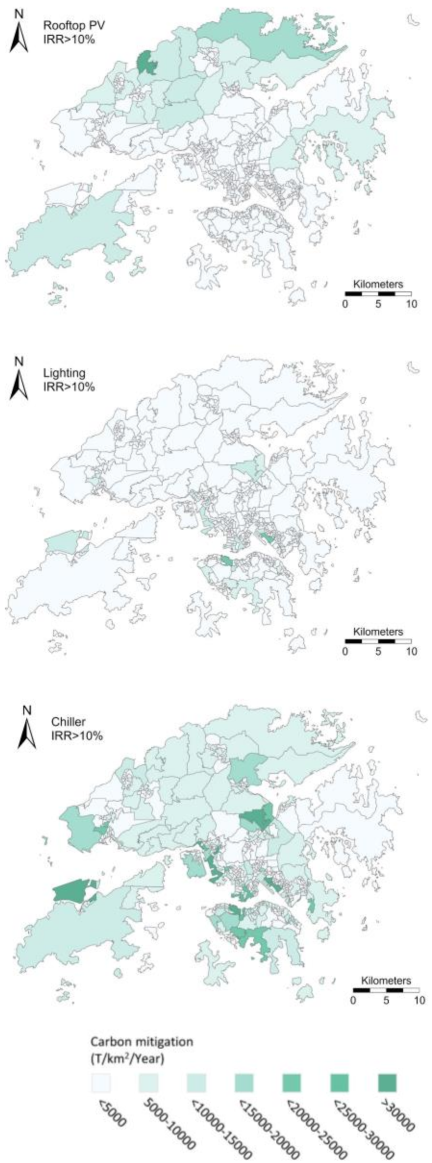
	Chiller	Lighting	Envelope	PV	Window
IRR>20%	2084.74	509.97	0.00	3.70^{-4}	0.00
IRR>15%	2172.07	509.97	0.00	0.07	0.00
IRR>10%	2743.65	510.00	0.00	2613.45	0.00
IRR>5%	2936.53	539.45	0.02	25242.85	0.00

IRR>20% IRR>15% IRR>10% IRR>5%



	Chiller	Lighting	Envelope	PV	Window
IRR>20%	2.25	0.74	0.00	6.80^{-7}	0.00
IRR>15%	2.30	0.74	0.00	2.20^{-5}	0.00
IRR>10%	2.58	0.74	0.00	0.35	0.00
IRR>5%	2.64	0.76	3.60^{-6}	3.35	0.00

IRR>20% IRR>15% IRR>10% IRR>5%



This framework provides insights into the market size and carbon-reduction potential of five retrofit measures under different investment criteria.

With government subsidies or other financing:

IRR from >10% to >5%	Chiller	Lighting	PV
Market size (Million USD)	193	29	22,629
Carbon mitigation (MT/Year)	0.06	0.02	3.00

(Zhang, Chen et al., Under Review in Apen)

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Thank you!

Liutao CHEN (chenlt@uw.edu)

Department of Civil & Environmental Engineering
Hong Kong University of Science and Technology

Sep 2025

Google Scholar

Linkedin

Relevant publications

[1] **Chen, L.**, Chang, H., Zhang, S., Li, M., Li, L., Karamanis, D., & Wang, Z. (2026). Comparing Designs for Photovoltaic-Green Roofs: A Year-Long Field Study in a Subtropical Climate. *Renewable Energy*, 125805.

[2] **Chen, L.**, Lin, Z., Zhou, Q, Zhang, S., Li, M., Wang, Z. (2025). Impacts of photovoltaics and integrated green roofs on urban climate: Experimental insights for urban land surface modelling, *Renewable and Sustainable Energy Reviews*, 217 (2025) 115709.

[3] **Chen, L.**, Zhang, S., Cheng, I., Chang, H., Chen, F., Li, M., Wang, Z. (2025). The Resilience Paradox of Rooftop PV: Building Cooling Penalties and Heat Risks. *Building and Environment*, 113233.

[4] **Chen, L.**, Zhang, S., Li, X. C., Chui, T. F. M., Yang, J., Wang, W., Hong, T., & Wang, Z. (2026). Mitigating Urban Climate-Energy Feedback with Citywide Building-Integrated Photovoltaics Implementation, *Nexus*, 3 (1).

[5] Zhang, S., **Chen, L.**, Xu, L., Wang, Z. (2025). GeoBEM: A geospatial computing empowered framework for urban-scale building energy modeling. *Sustainable Cities and Society*, 106203.

[6] Zhang, S., **Chen, L.**, Wang, Z. (2025) Decarbonizing the building sector through energy efficient retrofit measures: the cost and the benefits, *Applied Energy*, Under Review.

Costs of green roof systems installation

No.	Item Description	Price (in HK dollar)
1	Construct a planter (block wall) with waterproofing system	1,000 / sq.m
2	Design, Supply and install 100mm thick proprietary green roof planting system (includes multiple layers & accessories, plants excluded)	2,000 / sq.m
3	Automatic irrigation system (plumbing pipe works, pressure vessel with gauge, irrigation tank)	229,000
4	Corrugated sheet canopy with approved steel frame and necessary fixing accessories (to protect irrigation system)	60,000
5	E/M works for the irrigation system	240,000
6	Plants supply and planting works: Wedelia trilobata 南美蟛蜞菊	122 / sq.m
7	Plants supply and planting works: Sedum 佛甲草多肉	344 / sq.m
8	Plants supply and planting works: Zoysia 台湾草/结缕草	85 / sq.m
Sum (Fixed Cost + Cost per Square Meter)		529,000 + 3200 / sq.m

Note: Beyond technical performance, the economic feasibility and maintenance needs of PVIGR should also be considered in practice.