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Winter climate–energy trade-offs of rooftop photovoltaics under green, cool, and super cool roofs in cities



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Urban rooftop photovoltaic systems are increasingly integrated with green, cool and super cool roofs to simultaneously support renewable energy generation, building energy efficiency and climate adaptation. However, whether these objectives remain aligned during winter is poorly understood. Here we show that winter atmospheric stability largely confines rooftop thermal effects to the near-roof environment, resulting in only modest reductions in ambient temperature (−0.2 to −1.0 °C). In contrast, substantial cooling occurs at roof and photovoltaic panel surfaces, with panel temperatures decreasing by up to 14.7 °C. These cooler operating conditions increase photovoltaic electricity generation by 2.1–6.1%. However, the same cooling processes enhance nocturnal heat loss through building envelopes, increasing winter heating load by 1.1–3.48%. These findings reveal a previously overlooked winter climate–energy trade-off, emphasizing the need to balance photovoltaic efficiency with building thermal performance in urban energy transitions.

Rooftop photovoltaic solar panels (RPVSPs) have emerged as a key component of urban decarbonization and distributed energy systems, transforming underutilized building surfaces into productive renewable energy assets^{1–3}. Because RPVSPs conversion efficiency decreases with increasing module temperature, considerable attention has been directed toward passive roof technologies capable of regulating rooftop thermal conditions while simultaneously providing climate and energy co-benefits^{4,5}. Among these approaches, evaporative green roofs (GRs) and reflective cool roofs (CRs) have attracted increasing interest because they modify the rooftop energy balance, reduce module temperatures, and mitigate urban heat exposure^{6–9}. Integrating RPVSP systems with these roof technologies offers opportunities to enhance electricity generation while lowering building cooling demand and improving urban energy resilience^{10–12}. Consequently, GR + RPVSP and CR + RPVSP systems have been extensively investigated across diverse climatic regions over the last two decades^{12–14}. Understanding the interactions among rooftop materials, atmospheric processes, and RPVSP systems is therefore becoming increasingly important for

maximizing renewable electricity generation and accelerating net-zero transitions under a warming climate^{15,16}.

Extensive studies have demonstrated that GR + RPVSP can enhance electricity generation through evaporative cooling and reductions in module operating temperatures^{10–12,17–25}. The highest gains of approximately 6.0% have been reported in Berlin¹⁷, whereas enhancements of around 4.3% have been documented in Hong Kong¹⁸. Improvements of approximately 3.0% have been observed in Lleida¹⁰ and Winterthur¹¹, while electricity gains of around 2.0% have been reported in New York¹⁹ and Colombia²⁰. More moderate increases ranging from 0.8 to 1.8% have been documented in Zurich¹², Kansas²¹, Portland²², and San Diego²³. Average gains of approximately 0.55% across various regions of the United States²⁴ and the smallest enhancement of approximately 0.4% in Bucaramanga, Colombia²⁵ have also been reported. Collectively, these findings indicate that GR + RPVSP systems can increase electricity generation by approximately 0.4–6.0%, depending on local climate, vegetation characteristics, substrate properties, and roof configuration. In addition to improving RPVSP performance, GRs

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provide multiple co-benefits through reduced rooftop temperatures, enhanced evapotranspiration, lower cooling demand, and improved urban environmental quality^{6–9,12}. These findings report the important role of evaporative cooling in enhancing RPVSP performance while simultaneously contributing to urban climate adaptation.

Similarly, extensive studies have shown that reflective CR technologies can substantially improve RPVSP performance by reducing module operating temperatures and modifying rooftop radiative conditions^{12,26,27}. Previous studies have reported electricity gains ranging from approximately 1.9 to 7.0%, with the highest enhancements observed in Shanghai²⁶ and more moderate increases documented in Zurich¹² and Texas²⁷. Specifically, electricity generation improvements of approximately 7.0% and 6.0% have been reported in Shanghai²⁶, whereas gains of 3.4% and 1.9% have been observed in Zurich¹² and Texas²⁷, respectively. Together, these findings suggest that CR + RPVSP can enhance electricity generation by approximately 1.9–7.0%. In addition to improving RPVSP output, reflective CRs reduce rooftop temperatures, lower building cooling energy demand, and mitigate urban heat^{12,26,27}. Therefore, extensive evidence demonstrates that both evaporative and reflective roof technologies can substantially improve CR performance while simultaneously generating climate and energy co-benefits. However, despite the extensive literature on GR + RPVSP and CR + RPVSP systems, virtually all reported investigations have focused on summer conditions, when cooling effects are expected to be strongest^{10–12,17–27}. To our knowledge, no previous studies have systematically examined winter RPVSP gains under hybrid roofing technologies.

This pronounced summer bias represents a critical limitation because RPVSP performance depends not only on solar irradiance but also on module temperature, radiative forcing, atmospheric stability, cloud conditions, and surface energy exchanges^{28,29}, all of which exhibit substantial seasonal variability. Consequently, conclusions derived exclusively from summer experiments cannot necessarily be extrapolated to annual performance. The absence of winter assessments limits understanding of year-round electricity gains and hinders the development of climate-sensitive design strategies for hybrid rooftop systems. Moreover, most previous investigations have been conducted at building or neighborhood scales, thereby limiting representation of city-scale atmospheric feedbacks and climate–energy interactions^{10–12,17–27,30}. Seasonal differences in radiation, ambient temperature, and atmospheric conditions may substantially alter the effectiveness of roof-mediated cooling and consequently influence RPVSP efficiency. Therefore, the annual benefits of integrated roof technologies may have been underestimated by existing summer-based studies. Addressing these limitations requires seasonally explicit frameworks capable of representing the coupled interactions among rooftop materials, RPVSP modules, and the urban atmosphere across different climatic conditions. Such understanding is essential for improving RPVSP reliability and optimizing climate-responsive urban energy systems.

Another important knowledge gap concerns advanced radiative cooling materials^{31–33,34}. Recent developments in super cool roofs (SCRs) characterized by exceptionally high solar reflectance and strong infrared emissivity have demonstrated remarkable capabilities for reducing roof surface temperatures and lowering building energy consumption^{35–39}. Compared with reflective CRs, these roofs can maintain substantially lower temperatures through enhanced radiative cooling and therefore offer additional opportunities for regulating RPVSP module temperatures⁴⁰. Despite their promising thermal properties, interactions between SCRs and RPVSP systems remain largely unexplored. To date, studies evaluating SCR + RPVSP systems are virtually absent from the literature, and no investigations have examined their seasonal behavior or winter performance. Consequently, the potential of advanced radiative cooling materials to enhance RPVSP electricity generation and improve energy resilience remains unknown. Resolving these uncertainties requires integrated climate–energy frameworks capable of quantifying the seasonal response of RPVSP systems to emerging rooftop technologies. Such assessments are essential for identifying previously overlooked opportunities to maximize renewable electricity generation and strengthen the climate adaptation

benefits of urban rooftops. These advances also offer new opportunities for integrating passive cooling technologies with distributed renewable energy systems.

Here, we investigate the seasonal climate–energy interactions of urban RPVSP under evaporative, reflective, and radiative-cooling rooftops, with particular emphasis on winter conditions, using a climate-informed urban modelling framework. During summer, GR + RPVSP systems increased electricity generation by 1.9%, which falls within the previously reported range of 0.4–6.0%, while CR + RPVSP systems produced gains ranging from 3.6 to 5.3%, comparable to values reported for Zurich¹² and Shanghai²⁶. More importantly, winter simulations reveal that cooling-induced benefits persist and, in some cases, become more pronounced. Electricity generation increased by 2.1% under GR + RPVSP systems and by 4.3% under CR + RPVSP systems during winter. Furthermore, SCR + RPVSP systems achieved a 6.1% increase in winter electricity generation, representing the highest enhancement among all scenarios considered. To our knowledge, these findings provide one of the first seasonal evaluations of roof–panel interactions and the first assessment of winter RPVSP performance under SCRs. These results demonstrate that roof-mediated thermal regulation is not exclusively a summer phenomenon but a year-round process, extending the predominantly summer-based literature into winter conditions and revealing previously overlooked climate–energy interactions that are important for enhancing SCR reliability, improving urban energy resilience, and accelerating net-zero transitions under current climate normal.

Results

Winter atmospheric limits on rooftop thermal effects

Wintertime urban meteorology is characterized by low solar elevation, reduced incoming shortwave radiation, weakened turbulent exchange, and persistent stable boundary-layer conditions, which collectively constrain the vertical propagation of surface thermal signals. Rooftop modifications during winter influence the partitioning of turbulent energy fluxes under stable atmospheric conditions. Generally, sensible heat flux responses remain moderate and generally decrease under reflective and shaded roofs, while vegetated configurations (GR + RPVSP) show relatively larger daytime exchanges compared with CR + RPVSP and SCR + RPVSP. In contrast, latent heat flux exhibits stronger enhancements primarily over vegetated roofs due to evapotranspiration, whereas reflective and shaded roofs produce comparatively small changes. These results indicate that winter atmospheric stability limits turbulent heat exchange, while vegetation-driven moisture fluxes play a more prominent role in modifying the surface energy balance. Detailed analyses of sensible and latent heat flux responses across all scenarios are presented in Supplementary Fig. S1 and in Supplementary Fig. S2.

Within this framework, ambient air temperature exhibits the weakest sensitivity to rooftop modification. Relative to conventional roofs, daytime maximum ambient temperature increases slightly by +0.6 °C under GR + RPVSP but decreases by −0.6 °C and −1.0 °C under CR + RPVSP and SCR + RPVSP (Fig. 1a–c). Daytime minimum ambient temperature responses remain small, ranging from +0.1 °C to −0.2 °C, producing daytime mean anomalies of +0.4 °C, −0.4 °C, and −0.7 °C for GR + RPVSP, CR + RPVSP and SCR + RPVSP, respectively. At night, when radiative cooling dominates and mechanical turbulence is suppressed, ambient temperature maxima decline by −1.4 °C, −1.6 °C, and −1.9 °C, while nighttime mean reductions reach −0.9 °C, −1.1 °C, and −1.3 °C for GR + RPVSP, CR + RPVSP and SCR + RPVSP, respectively (Fig. 1a'–c'). Daily mean ambient temperature decreases remain limited at −0.2 °C, −0.7 °C, and −1.0 °C (Table S1) for GR + RPVSP, CR + RPVSP and SCR + RPVSP, respectively. These muted responses align with boundary-layer theory, indicating that winter atmospheric stability restricts the feedback of roof-level cooling to the urban canopy air, isolating surface and building-scale processes.

Surface temperatures represent the first level at which winter rooftop modification effects become amplified, reflecting direct control by radiative

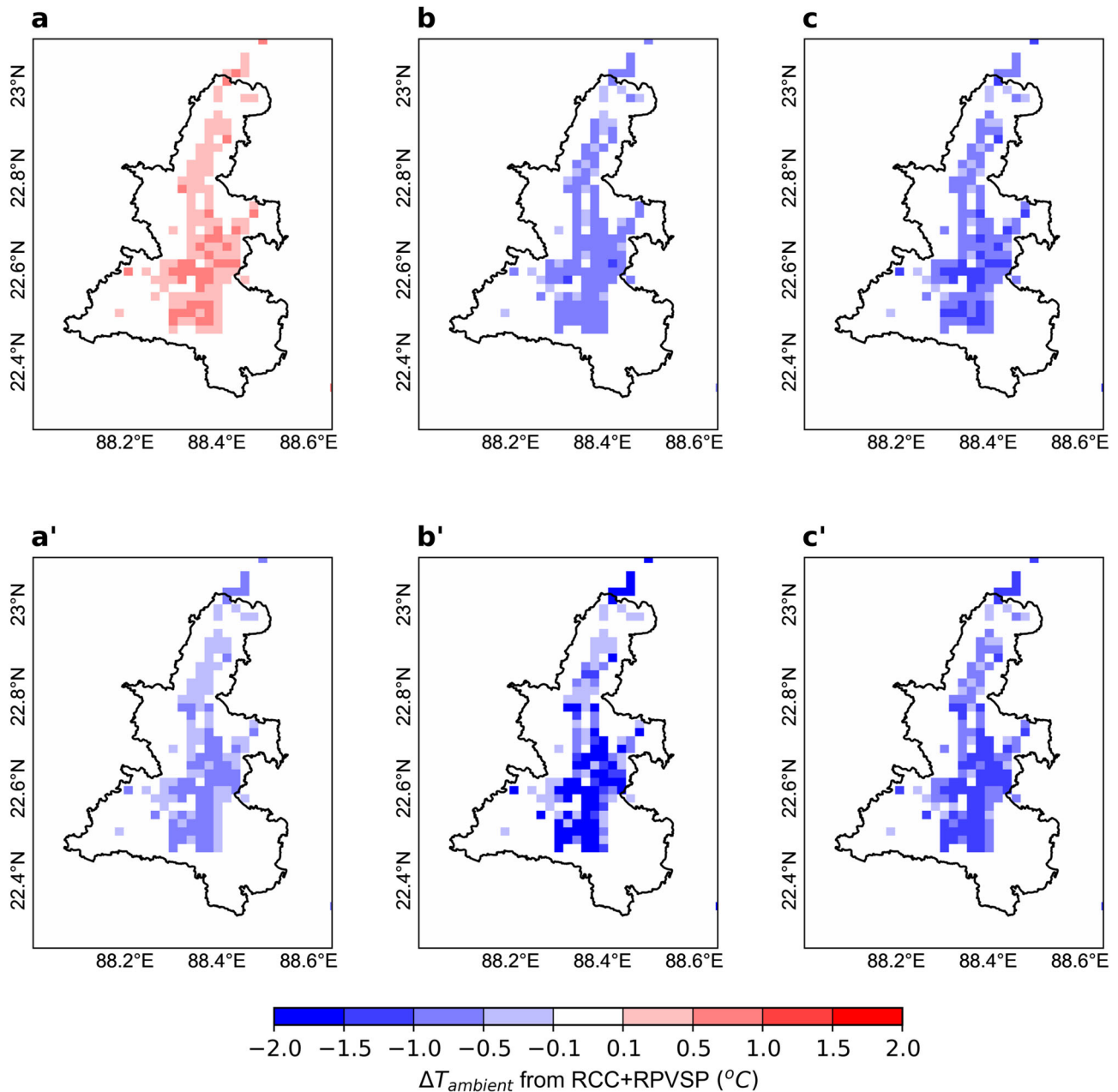


Fig. 1 | Wintertime ambient temperature differences under optimized RPVSP scenarios. Differences (experiments minus RCC + RPVSP) in simulated ambient temperature (T_{ambient}) under various optimized rooftop scenarios during the winter month- **a**, **a'** GR + RPVSP, **b**, **b'** CR + RPVSP, and **c**, **c'** SCR + RPVSP,

corresponding to peak daytime **a–c** and nighttime **a'–c'** conditions. All results are spatially averaged over urban grid cells across the Kolkata urban region. The baseline RCC + RPVSP represents conventional RCC rooftops integrated with RPVSP.

balance and surface thermal properties. During daytime, surface temperature maxima increase slightly by $+0.7^{\circ}\text{C}$ under GR + RPVSP, indicating partial insulation-driven heat retention, but decrease by -1.8°C and -2.2°C under CR + RPVSP and SCR + RPVSP, respectively (Fig. 2a–c). Daytime minimum surface temperatures decline by -0.5°C for both CR + RPVSP and SCR + RPVSP, yielding daytime mean surface temperature anomalies of $+0.5^{\circ}\text{C}$, -1.2°C , and -1.5°C (Table S1). These responses reflect reduced net shortwave absorption and suppressed sensible heat flux under reflective and shaded surfaces. At night, surface temperature maxima decrease by -2.8°C , -4.2°C , and -5.4°C , while nighttime mean reductions reach -1.9°C , -2.8°C , and -3.8°C , consistent with enhanced longwave radiative loss under stable winter conditions (Fig. 2a'–c'). Daily mean surface temperature reductions intensify from -0.6°C to -2.0°C and -2.5°C , demonstrating increasing sensitivity relative to ambient air and

confirming that winter surface thermodynamics are governed by material properties rather than atmospheric mixing.

Roof surface temperatures show the strongest winter response, reflecting their dominant role in urban heat storage and release within the building energy balance. Daytime roof surface maximum temperatures decrease substantially by -4.4°C under GR + RPVSP, -10.8°C under CR + RPVSP, and -19.2°C under SCR + RPVSP (Fig. 3a–c). Corresponding daytime minimum reductions of -1.5°C , -3.6°C , and -6.3°C produce daytime mean roof surface cooling of -3.0°C , -7.3°C , and -12.8°C (Table S2). These large reductions arise from increased albedo, reduced absorptivity, added insulation layers, and diminished thermal mass, which collectively suppress conductive heat storage during winter. At night, roof surface maximum temperatures decline further by -4.5°C , -9.1°C , and -11.7°C , while nighttime mean reductions reach -3.2°C , -6.3°C ,

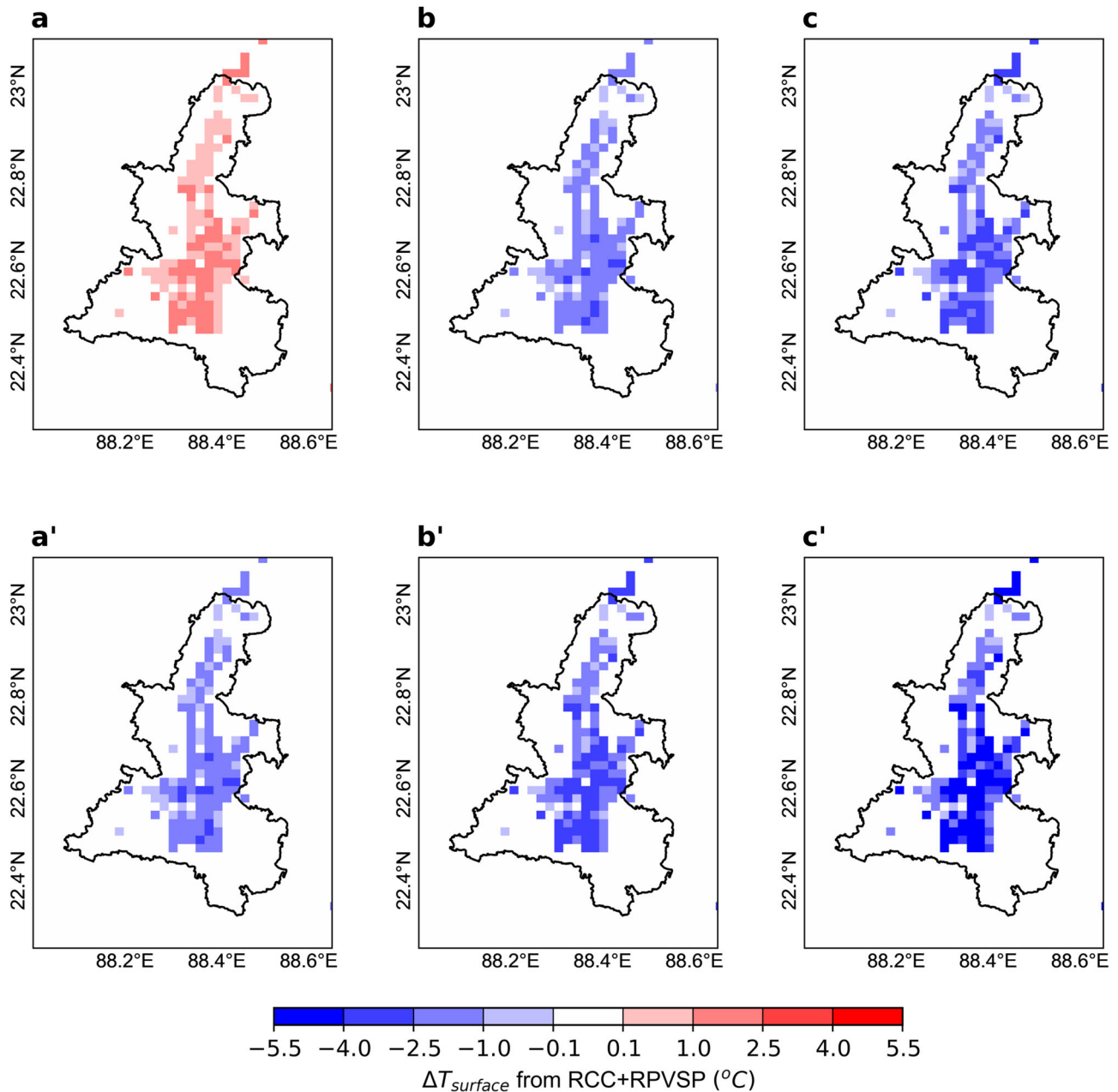


Fig. 2 | Wintertime urban surface temperature differences under optimized RPVSP scenarios. Same as Fig. 1, but for urban surface temperature (T_{surface}).

and -7.9°C , indicating enhanced longwave emission and weakened heat release from roof slabs (Fig. 3a'–c'). Daily mean roof surface temperature reductions intensify from -3.1°C to -6.8°C and -10.6°C , establishing a persistent cold roof boundary that directly constrains upward heat transfer to overlying RPVSP systems.

RPVSP temperatures respond directly to roof surface cooling through combined conductive, radiative, and convective pathways, completing the winter thermal cascade at the city scale. During daytime, RPVSP surface maximum temperatures decrease by -6.8°C under GR + RPVSP, -14.1°C under CR + RPVSP, and -22.6°C under SCR + RPVSP, while daytime minimum reductions range from -2.3°C to -7.6°C . These yield daytimes mean RPVSP temperature decreases of -4.7°C , -9.5°C , and -15.2°C , which closely mirror roof surface cooling rather than ambient air temperature changes. At night, RPVSP surface temperatures decrease further, with nighttime mean reductions of -5.7°C , -10.2°C , and -14.2°C , reflecting dominant longwave radiative exchange under stable conditions (Table S2). Although nocturnal cooling does not directly enhance electricity

generation, it establishes a colder initial thermal state at sunrise, delaying temperature-driven efficiency losses during subsequent daylight hours. Daily mean RPVSP surface temperatures decline by -5.2°C , -9.8°C , and -14.7°C , confirming that winter RPVSP behavior is controlled primarily by building-scale thermal physics rather than atmospheric temperature modulation.

Figure 4 illustrates the relationship between changes in winter ambient air temperature and the simulated rooftop thermal responses across the Kolkata urban region under different optimized rooftop configurations. Winter conditions are characterized by lower background temperatures and reduced solar elevation, which modify the surface–atmosphere energy exchange and influence rooftop thermal dynamics and RPVSP operating temperatures. This relationship highlights how wintertime atmospheric variability interacts with rooftop material properties and surface energy balance processes. Cooling responses are particularly pronounced in reflective and vegetated roof systems, where enhanced radiative losses and reduced heat storage amplify the sensitivity of roof surfaces to ambient

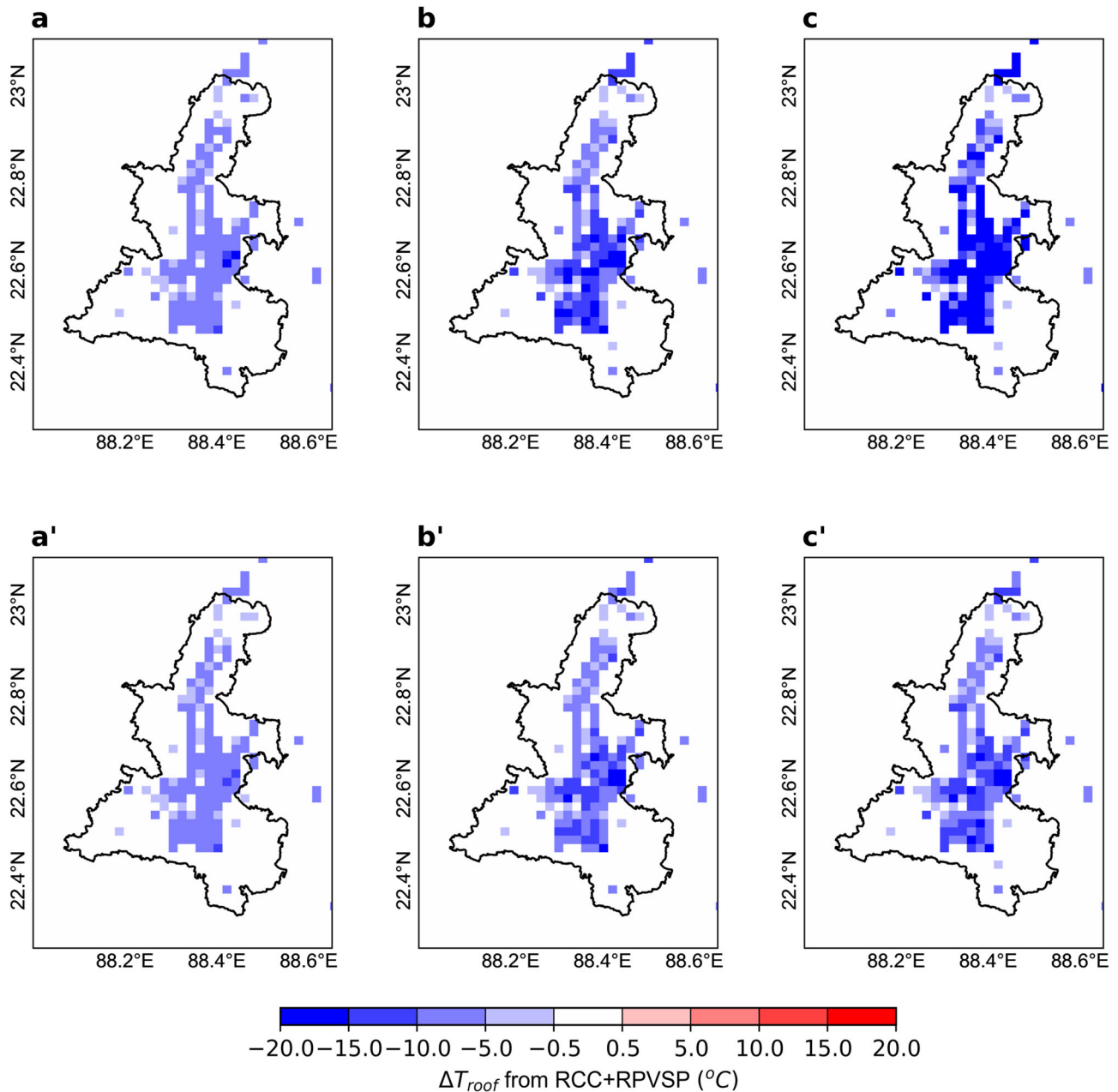


Fig. 3 | Wintertime roof surface temperature differences under optimized RPVSP scenarios. Same as Fig. 1, but for roof surface temperature (T_{roof}).

temperature fluctuations. As a result, RPVSP temperatures closely track these rooftop thermal adjustments, reflecting the coupling between RPVSP operating temperature and the underlying roof environment. Such responses indicate that optimized rooftop configurations not only influence summertime heat mitigation but also modulate winter rooftop thermal regimes. These interactions are important for understanding seasonal urban energy dynamics, as lower roof and RPVSP temperatures can affect building heating demand and RPVSP performance under winter climate conditions.

Temperature-mediated winter control of building energy consumption

During winter daytime, building energy consumption responds weakly despite pronounced cooling at surface, roof, and RPVSP levels, reflecting strong atmospheric constraints. Ambient air temperature variations remain small, with daytime mean changes limited to $+0.4^{\circ}\text{C}$, -0.4°C , and -0.7°C , indicating shallow boundary layers and restricted turbulent heat exchange. Under these conditions, daytime maximum building energy consumption

reaches 6.52 W m^{-2} for GR + RPVSP, 6.51 W m^{-2} for CR + RPVSP, and 6.61 W m^{-2} for SCR + RPVSP, corresponding to relative increases of 0.87%, 1.04%, and 3.66% and absolute increases of 0.05 W m^{-2} , 0.04 W m^{-2} , and 0.14 W m^{-2} . Daytime minimum consumption remains low at 0.97 W m^{-2} for both GR + RPVSP and CR + RPVSP and increases marginally to 0.99 W m^{-2} for SCR + RPVSP, with relative increases of 0.57%, 0.60%, and 2.12%. These modest penalties persist despite daytime mean roof surface cooling of -3.0°C , -7.3°C , and -12.8°C and RPVSP cooling of -4.7°C , -9.5°C , and -15.2°C , demonstrating partial compensation by winter solar gains, indoor heat storage, and reduced daytime heating sensitivity.

Daytime mean building energy consumption integrates surface cooling and limited atmospheric feedback under reduced winter insolation. Mean consumption stabilizes at 2.53 W m^{-2} for both GR + RPVSP and CR + RPVSP and increases marginally to 2.58 W m^{-2} for SCR + RPVSP. These values correspond to relative increases of 0.76%, 0.85%, and 3.00% and absolute increases of 0.02 W m^{-2} , 0.02 W m^{-2} , and 0.07 W m^{-2} , respectively (Fig. 5 and Table S3). The muted daytime response contrasts sharply with

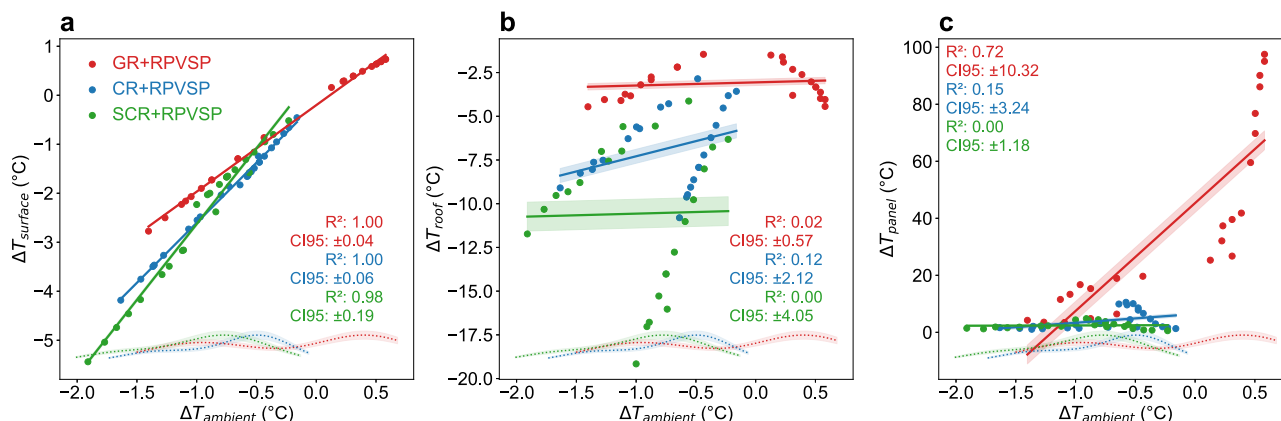


Fig. 4 | Relationship between ambient temperature change ($\Delta T_{\text{ambient}}$) and simulated urban thermal responses under different optimized rooftop configurations during winter month over the Kolkata urban region. Panels show **a** changes in surface temperature ($\Delta T_{\text{surface}}$), **b** roof temperature (ΔT_{roof}), and **c** RPVSP temperature (ΔT_{panel}) relative to the RCC + RPVSP baseline. Points represent hourly mean values of the 24-hour mean diurnal cycle averaged over the 62-day simulation period ($n = 24$) for GR + RPVSP, CR + RPVSP, and SCR +

RPVSP scenarios; solid lines and shaded bands indicate linear regressions and their 95% confidence intervals, respectively. Dotted curves denote the probability density distribution of $\Delta T_{\text{ambient}}$. Reported coefficients of determination (R^2) values quantify the strength of the temperature-response relationships. Negative $\Delta T_{\text{ambient}}$ reflects colder conditions associated with potential increased in winter heating load, whereas values closer to zero or positive indicate relatively warmer ambient states influencing rooftop thermal behaviour and RPVSP temperature responses.

stronger cooling observed at surface, roof, and RPVSP levels. Daytime mean surface temperatures vary between $+0.5^\circ\text{C}$ and -1.5°C , while roof surface temperatures decrease by -3.0°C , -7.3°C , and -12.8°C , and RPVSP temperatures decline by -4.7°C , -9.5°C , and -15.2°C . This decoupling reflects winter meteorological control, where stable stratification and weak mechanical mixing limit the transmission of surface cooling into indoor thermal loads. Building thermal inertia further moderates heat loss during daylight hours, delaying the response of heating systems to roof and RPVSP temperature suppression. As a result, daytime heating demand increases nonlinearly, remaining small relative to the magnitude of surface and roof cooling.

Nighttime conditions reveal a pronounced amplification of winter cooling impacts on building energy consumption, driven by enhanced radiative losses and suppressed convective exchange. Ambient air temperature reductions remain limited, with nighttime mean decreases of -0.9°C , -1.1°C , and -1.3°C , confirming weak atmospheric control. In contrast, roof surface nighttime mean temperatures decline sharply by -3.2°C under GR + RPVSP, -6.3°C under CR + RPVSP, and -7.9°C under SCR + RPVSP, while RPVSP surface temperatures decrease further by -5.7°C , -10.2°C , and -14.2°C . These reductions intensify conductive heat loss across the roof envelope, directly increasing indoor heating demand. Consequently, nighttime maximum building energy consumption rises to 9.97 W m^{-2} for GR + RPVSP, 10.01 W m^{-2} for CR + RPVSP, and 10.13 W m^{-2} for SCR + RPVSP, corresponding to relative increases of 2.34%, 3.18%, and 6.06% and absolute increases of 0.23 W m^{-2} , 0.31 W m^{-2} , and 0.32 W m^{-2} . Nighttime minimum consumption increases to 3.50 W m^{-2} , 3.51 W m^{-2} , and 3.55 W m^{-2} , with relative increases of 1.02%, 1.37%, and 2.61%, confirming dominant nocturnal winter energy penalties (Fig. 6).

Nighttime mean building energy consumption reaches 7.37 W m^{-2} for GR + RPVSP, 7.42 W m^{-2} for CR + RPVSP, and 7.56 W m^{-2} for SCR + RPVSP, corresponding to relative increases of 1.53%, 2.12%, and 4.04% and absolute increases of 0.11 W m^{-2} , 0.15 W m^{-2} , and 0.29 W m^{-2} . These elevated nighttime demands persist into daily means because short winter days provide limited opportunity for thermal recovery. Daily mean surface temperatures decrease by -0.6°C , -2.0°C , and -2.5°C , while roof surface temperatures decline by -3.1°C , -6.8°C , and -10.6°C across GR + RPVSP, CR + RPVSP, and SCR + RPVSP. The RPVSP surface daily mean temperatures exhibit the strongest cooling, decreasing by -5.2°C , -9.8°C , and -14.7°C , respectively. These sustained reductions suppress upward heat flux from conditioned indoor spaces, maintaining elevated heating

demand throughout the diurnal cycle. As a result, daily mean building energy consumption increases to 4.75 W m^{-2} for GR + RPVSP, 4.77 W m^{-2} for CR + RPVSP, and 4.86 W m^{-2} for SCR + RPVSP. These correspond to relative increases of 1.11%, 1.43%, and 3.48% and absolute increases of 0.06 W m^{-2} , 0.08 W m^{-2} , and 0.17 W m^{-2} , confirming a robust city-scale winter cooling penalty.

Winter modulation of urban photovoltaic energy generation

Wintertime RPVSP energy generation responds nonlinearly to rooftop cooling despite strong atmospheric constraints on ambient temperature. Daytime generation shows clear sensitivity to roof modification, while nighttime generation remains zero across all scenarios due to the absence of solar irradiance. Relative to the conventional roof baseline, daytime maximum energy generation increases by 18.2 W m^{-2} under GR + RPVSP, 19.0 W m^{-2} under CR + RPVSP, and 20.1 W m^{-2} under SCR + RPVSP, corresponding to percentage increases of 5.3%, 10.1%, and 16.5%, respectively. Daytime minimum generation enhancements are smaller, increasing by 6.2 W m^{-2} , 6.3 W m^{-2} , and 6.4 W m^{-2} , with associated percentage gains of 1.7%, 3.2%, and 4.9% (Table S4). These gains reflect improved module operating conditions under reduced RPVSP temperatures, rather than changes in incoming radiation, confirming that winter RPVSP performance is thermally constrained rather than irradiance-limited alone.

Daytime mean RPVSP energy generation provides a robust metric for evaluating winter performance improvements. Under GR + RPVSP, daytime mean energy generation increases by 14.4 W m^{-2} , corresponding to a 3.8% enhancement. Stronger responses are observed for CR + RPVSP and SCR + RPVSP, where daytime mean generation rises by 14.9 W m^{-2} (7.5%) and 15.5 W m^{-2} (11.2%), respectively. Absolute increases of 0.6 W m^{-2} , 1.1 W m^{-2} , and 1.6 W m^{-2} further indicate progressively stronger thermal control with increasing roof reflectance and emissivity. These patterns closely follow the magnitude of RPVSP surface cooling reported earlier, demonstrating that daytime RPVSP gains scale with rooftop-induced reductions in module temperature rather than ambient air temperature. The nonlinear amplification from GR to SCR scenarios highlights that winter RPVSP performance is particularly sensitive to roof-level radiative control, where enhanced cooling reduces temperature-driven efficiency losses during peak daytime operation.

In contrast to daytime behavior, nighttime RPVSP energy generation remains zero across all scenarios, with no measurable differences in

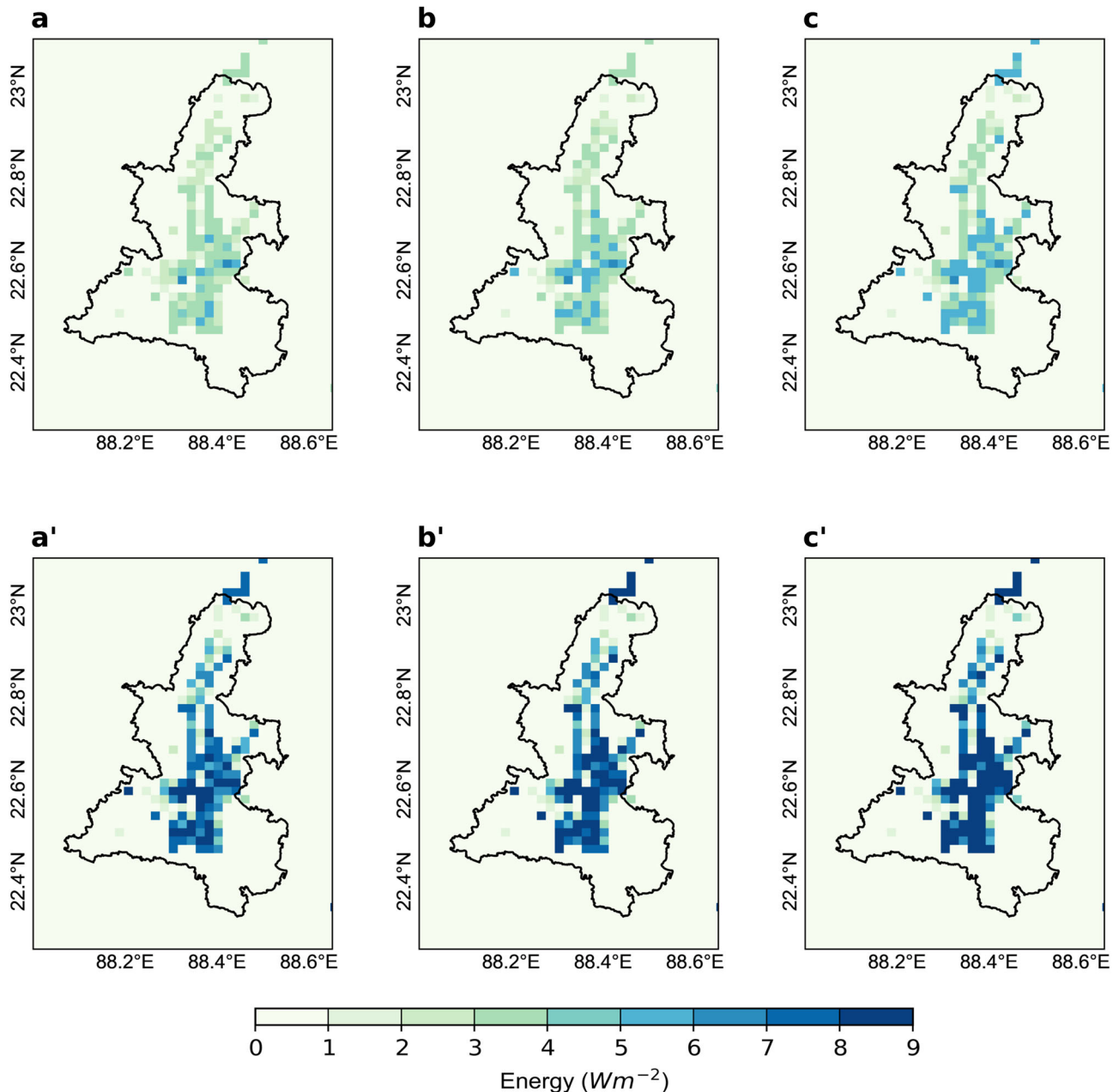


Fig. 5 | Spatial distribution of winter building heating load and RPVSP energy generation under optimized roof top scenarios. Spatial distribution of **a–c** daily mean building energy (heating load) consumption and **a'–c'** RPVSPs energy

generation under various optimized rooftop scenarios during the winter month: **a, a'** GR + RPVSP, **b, b'** CR + RPVSP, and **c, c'** SCR + RPVSP. Values are averaged over urban grid cells across the Kolkata urban region.

percentage increase, absolute increase, or energy generation for GR + RPVSP, CR + RPVSP, and SCR + RPVSP. Nighttime maximum, minimum, and mean values are uniformly 0.0 W m^{-2} , reflecting the absence of solar input during winter nights. However, the absence of nocturnal generation does not imply an absence of thermal influence. Substantial nighttime RPVSP cooling, reported previously, establishes colder initial conditions at sunrise, indirectly shaping subsequent daytime performance. This carry-over effect is particularly relevant under SCR + RPVSP, where enhanced longwave emission produces the strongest nighttime cooling but no immediate electrical output. Thus, winter RPVSP performance is governed by a delayed thermodynamic response, where nocturnal cooling modifies the starting thermal state of the RPVSPs rather than producing instantaneous energy gains. This distinction underscores the importance of separating thermal conditioning effects from direct radiative generation when interpreting winter RPVSP performance.

Daily mean RPVSP energy generation integrates both daytime gains and nighttime inactivity, providing a conservative measure of winter performance. Daily mean energy generation increases by 8.1 W m^{-2} under GR + RPVSP, 8.4 W m^{-2} under CR + RPVSP, and 8.6 W m^{-2} under SCR + RPVSP, corresponding to percentage increases of 2.1%, 4.3%, and 6.1%, respectively (Fig. 5d–f). Absolute daily mean increases of 0.3 W m^{-2} , 0.6 W m^{-2} , and 0.9 W m^{-2} confirm a systematic intensification of winter RPVSP gains with increasing rooftop cooling strength. Although daily mean enhancements are smaller than daytime maxima, they remain substantial given the limited winter photoperiod and reduced solar elevation. The persistence of these gains despite strong atmospheric stability and low ambient temperatures demonstrates that rooftop radiative modification can partially offset winter climate constraints. Moreover, these results establish that winter RPVSP performance in cities is governed by a balance between atmospheric limitation and roof-induced thermal optimization.

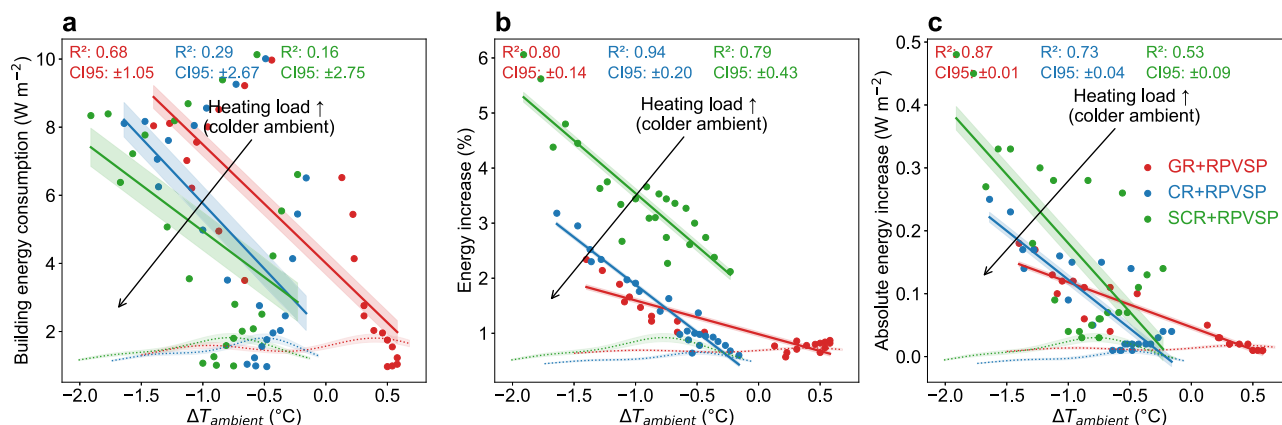


Fig. 6 | Relationships between ambient temperature change ($\Delta T_{\text{ambient}}$) and wintertime building energy responses across the Kolkata urban region under various optimized rooftop scenarios (GR + RPVSP, CR + RPVSP, and SCR + RPVSP). Panels show (a) building energy consumption, (b) percentage increase in energy demand, and (c) absolute increase in energy use as functions of $\Delta T_{\text{ambient}}$. Points represent hourly mean values of the 24-hour mean diurnal cycle averaged over the 62-day simulation period ($n = 24$), solid lines denote least-squares linear regressions, and shaded envelopes indicate the corresponding 95% confidence

intervals. Dotted curves at the bottom of each RPVSP show the probability density distribution of $\Delta T_{\text{ambient}}$. Reported R^2 values quantify the strength of the fitted relationships. Negative $\Delta T_{\text{ambient}}$ values correspond to colder ambient conditions associated with increased space-heating requirements (winter heating load), resulting in higher building energy consumption. The negative slopes across all scenarios indicate a systematic increase in winter heating load with decreasing ambient temperature, with the strongest sensitivities observed for the CR + RPVSP and SCR + RPVSP configurations.

Discussions

We demonstrate that winter climate imposes a hierarchical constraint on urban RPVSP performance, with atmospheric stability limiting ambient air temperature responses while amplifying thermal contrasts at the surface, roof, and RPVSP levels. The weak sensitivity of ambient air temperature to rooftop modification, despite substantial reductions in roof and RPVSP temperatures, is consistent with stable winter boundary-layer conditions in which suppressed turbulence restricts vertical heat exchange and weakens atmospheric mixing^{41,42}. Similar decoupling between surface cooling and near-surface air temperature has been reported in previous winter urban thermal studies^{43,44}. Our results further show that these atmospheric constraints do not inhibit strong thermal responses at the roof and building scales, emphasizing the importance of scale-dependent interpretation when assessing winter rooftop mitigation strategies. As illustrated in Fig. 7, thermal processes dominate winter rooftop thermodynamics, producing substantial roof and RPVSP cooling that modifies conductive or convective heat transfer across the roof envelope and enhances nocturnal heat losses, thereby increasing nighttime heating demand.

Despite the increase in nighttime heating requirements, RPVSP energy generation exhibits consistent gains owing to reduced RPVSP operating temperatures. The increase in daytime RPVSP output across all modified roof scenarios demonstrates that thermal optimization remains effective even under lower winter irradiance conditions. The results further indicate that RPVSP performance is governed primarily by roof-induced RPVSP cooling rather than changes in ambient air temperature, emphasizing the dominant role of rooftop thermodynamics. The absence of nighttime electricity generation, coupled with pronounced nocturnal cooling, suggests that winter RPVSP performance is partly influenced by the thermal state established during the preceding night. As shown in Fig. 6, lower RPVSP temperatures are consistently associated with enhanced daytime electricity production across all rooftop configurations. These results indicate that winter RPVSP responses arise from coupled atmosphere–surface–building–panel interactions and exhibit strong diurnal variability. Consequently, assessments based solely on daily or seasonal averages may overlook important processes controlling photovoltaic efficiency, highlighting the need to explicitly resolve diurnal climate–energy interactions when evaluating winter RPVSP strategies.

The enhancement in RPVSP performance obtained during summer is broadly consistent with previous city-scale studies conducted under different climatic conditions, although the magnitude of improvement varies

with climate and cooling strategy. As shown in Figs. 6 and 8, CR + RPVSP configurations produced larger reductions in roof and RPVSP temperatures and consequently larger increases in RPVSP output than GR + RPVSP systems. Previous city-scale studies reported summer RPVSP output enhancements of 7% and 6% in Shanghai²⁶, 3.4% in Zurich¹², and 1.9% in Texas²⁷ for CR + RPVSP systems. In comparison, the present study produced summer increases of 3.6% and 5.3% in Kolkata. Although lower than the maximum values reported for Shanghai²⁶, these results indicate that reflective roofs remain effective for improving photovoltaic performance under tropical climatic conditions. The variability among studies likely reflects differences in atmospheric humidity, radiation availability, and background climatic conditions affecting roof and module temperatures.

For GR + RPVSP systems, previous investigations reported summer RPVSP performance improvements ranging from 0.4% in Bucaramanga²⁵, 0.55% across various U.S. regions²⁴, 0.8% in San Diego²³, 1.2% in Portland²², 1.4% in Kansas²¹, and 1.8% in Zurich¹², to 2.0% in Colombia²⁰ and New York¹⁹, 3.0% in Lleida¹⁰ and Winterthur¹¹, 4.3% in Hong Kong¹⁸, and 6.0% in Berlin¹⁷. The present study produced a summer enhancement of 1.9% in Kolkata, which lies within the range reported in the literature (Table S5). Such variability reflects differences in vegetation characteristics, substrate moisture, irrigation conditions, and local meteorological environments. Under humid tropical conditions, relatively high atmospheric moisture may reduce evaporative cooling efficiency and moderate RPVSP temperature reductions, resulting in smaller increases in RPVSP output. This behavior is consistent with the smaller roof and RPVSP temperature reductions observed for GR + RPVSP relative to reflective roof configurations (Fig. 5). Furthermore, the comparison presented here is restricted to city-scale studies because building-scale investigations resolve individual roof geometries and microscale processes that are not directly comparable with spatially averaged urban-scale responses.

Winter responses exhibit a distinct pattern from those observed during summer. As shown in Figs. 5d–f and 6, winter RPVSP output increased by 2.1% under GR + RPVSP, 4.3% under CR + RPVSP, and 6.1% under SCR + RPVSP. Direct comparison with previous studies remains limited because most existing investigations have focused on summer conditions, and city-scale assessments of winter RPVSP–climate interactions are scarce. Available winter studies are predominantly performed at the building scale and therefore cannot be directly compared with the present city-scale simulations. Nevertheless, the present results demonstrate that reductions in roof and RPVSP temperatures continue to

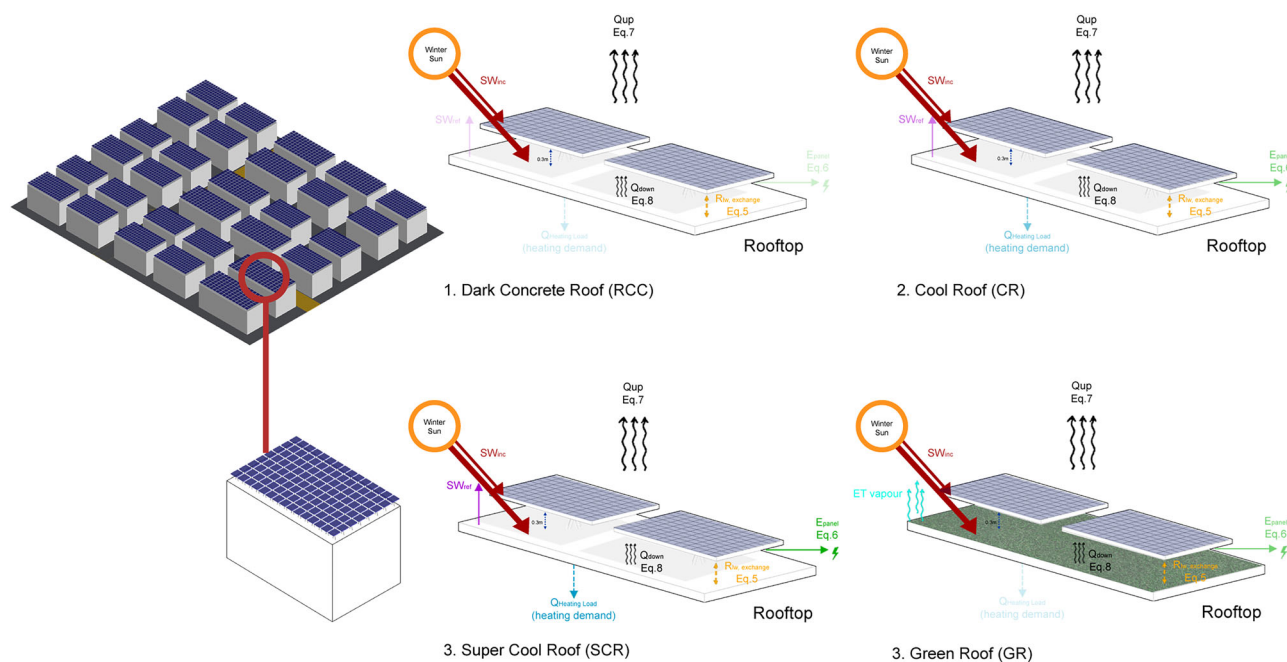


Fig. 7 | Conceptual framework of RPVSPs configurations and associated energy exchanges. The RPVSPs are coupled with four roof types: conventional RCC, CR, SCR, GR. The schematics illustrate the partitioning of incoming shortwave radiation (SW_{inc}), outgoing longwave radiation ($LW_{out,panel}$), net longwave radiative exchange ($R_{lw,exchange}$), conductive heat transfer (h_{up} , h_{down}), sensible heat flux (Q_{up} , Q_{down}),

and building heating demand ($Q_{heating load}$). Relative to the reference RCC configuration, CRs enhance solar reflection, SCRs promote radiative cooling, and GRs increase evapotranspiration (ET_{vapour}), thereby modifying rooftop thermal conditions and RPVSPs module temperatures. These coupled winter climate–energy interactions regulate electricity generation (E_{panel}) and building energy demand.

enhance RPVSP conversion efficiency even under lower winter irradiance. Among the investigated configurations, SCR + RPVSP produced the maximum increase in electricity generation, corresponding to the strongest reductions in roof and RPVSP temperatures, while CR + RPVSP generated larger gains than GR + RPVSP, indicating that radiative cooling exerts a stronger influence on RPVSP performance than evaporative cooling under winter conditions.

We also show that the magnitude of RPVSP performance enhancement is strongly influenced by climatic conditions and the type of rooftop cooling strategy employed. While GR + RPVSP systems generally provide moderate improvements, CR + RPVSP and SCR + RPVSP configurations produce larger gains through stronger reductions in roof and RPVSP temperatures. The results shown in Figs. 6, 8 indicate that roof-induced thermal regulation is the principal mechanism governing RPVSP performance and that these responses exhibit pronounced seasonal dependence. The present simulations further suggest that evaluation of rooftop technologies should consider multiple climate–energy metrics and seasonal variability rather than relying exclusively on summertime performance. However, the analysis presented here is limited to atmosphere–surface–building–panel interactions resolved by the coupled WRF–BEP + BEM framework. Figure 8 further summarizes the potential seasonal performance trade-offs associated with reflective, radiative and evaporative rooftop technologies, including radiative modification, water–energy implications, and RPVSP–climate interactions within urban environments.

We demonstrate that winter urban climate–energy interactions are governed by a hierarchical thermal response in which the influence of rooftop interventions progressively strengthens from the urban atmosphere to the building envelope and RPVSP. Unlike summer conditions, stable winter boundary layers largely suppress the vertical propagation of rooftop thermal perturbations, limiting their influence on ambient air temperature despite pronounced cooling at roof and RPVSP surfaces. This decoupling reveals that the principal winter impacts of GRs, CRs and SCRs arise through modifications of the local surface energy balance rather than city-

scale atmospheric cooling. By altering radiative exchange, conductive heat transfers and near-roof thermodynamic conditions, rooftop materials or vegetative coverage fundamentally regulate building heat exchange and RPVSP operating temperatures. These findings challenge the conventional assumption that the effectiveness of rooftop renewable technologies should be assessed primarily through reductions in ambient temperature, demonstrating instead that their greatest winter influence occurs at the building–energy interface, where coupled radiative, conductive and convective processes govern thermal storage, heat transfer and RPVSP performance. Collectively, our results establish a mechanistic framework linking rooftop interventions, urban surface thermodynamics and renewable energy systems under winter conditions.

We further reveal a previously overlooked winter climate–energy trade-off associated with integrating RPVSP with GRs, CRs and SCRs. Cooler rooftop environments substantially reduce RPVSP operating temperatures, improving module efficiency and increasing electricity generation. However, the same thermal processes enhance nocturnal heat losses through the roof envelope, increasing winter building energy demand despite only minor changes in city-scale ambient temperature. This demonstrates that improvements in RPVSP performance do not necessarily coincide with improvements in building thermal performance, indicating that rooftop interventions influence urban energy systems through competing physical pathways. Consequently, evaluating rooftop technologies solely on the basis of RPVSP electricity generation, roof cooling or ambient temperature reduction may overlook important interactions among buildings, rooftop materials and renewable energy systems. Instead, these technologies should be considered as components of an integrated climate–energy system in which seasonal changes in surface energy partitioning determine whether rooftop interventions produce complementary benefits or unintended trade-offs. This perspective provides a more comprehensive framework for evaluating rooftop technologies under seasonally varying climatic conditions.

Although our analysis represents an idealized assessment of complete rooftop deployment and direct city-scale winter observations of

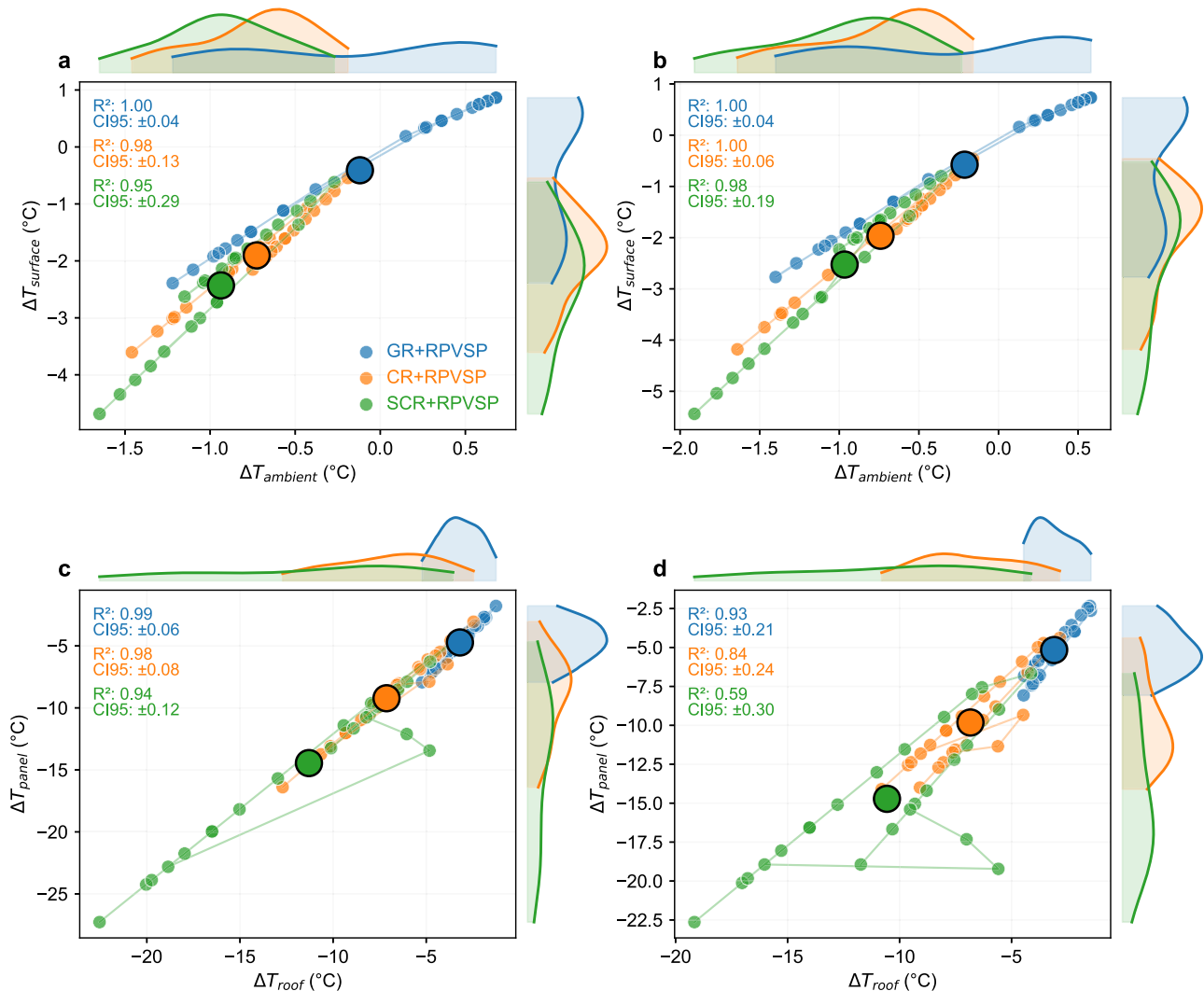


Fig. 8 | Seasonal thermal interaction between atmospheric cooling response and photovoltaic operating environment under rooftop-integrated RPVSP scenarios. **a, c** and **b, d** represent the coupled thermal behaviour of different rooftop configurations integrated with RPVSP during summer and winter conditions, respectively. **a, b** show the relationship between ambient thermal response ($\Delta T_{\text{ambient}}$) and surface thermal response ($\Delta T_{\text{surface}}$), while **c, d** represent the interaction between roof thermal conditions (ΔT_{roof}) and RPVSP operating temperature (ΔT_{panel}). Solid

trajectories indicate the temporal evolution of the coupled thermal states, whereas enlarged markers represent the centroid (mean) thermal condition of each scenario. Marginal kernel density distributions along the upper and right axes characterize the statistical distribution and variability of the thermal responses. Reported R^2 values and 95% confidence intervals quantify the strength and uncertainty of the fitted relationships. Points represent hourly mean values of the 24-hour mean diurnal cycle averaged over the 62-day simulation period ($n = 24$).

roof surface temperature, photovoltaic module temperature and building energy demand remain unavailable, the identified trade-offs arise consistently from physically based representations of coupled radiative, conductive and convective energy exchanges. Because all rooftop strategies were evaluated within an identical modelling framework using the same meteorological forcing, urban morphology and physical parameterizations, the relative differences among scenarios and the underlying physical mechanisms are expected to be more robust than the absolute magnitudes of the simulated responses. While the quantitative responses will inevitably vary with climate, urban form, building characteristics and deployment extent, the governing mechanisms identified here are likely to be broadly applicable to cities where RPVSP are integrated with reflective, radiative or vegetated roofing systems. We therefore anticipate that these findings will provide a robust physical basis for developing seasonally adaptive rooftop strategies that jointly optimize renewable energy generation, building thermal performance and urban climate resilience, supporting more integrated approaches to low-carbon urban energy transitions.

Method

Rooftop photovoltaic model

The RPVSP temperature and electricity generation were prognostically simulated using the physically based rooftop photovoltaic parameterization developed and implemented within the WRF-BEP + BEM framework⁴⁵. The model explicitly resolves the coupled exchanges of shortwave and longwave radiation, sensible heat, and electricity between the RPVSP, the underlying roof surface, buildings, and the urban atmosphere. The RPVSP temperature was calculated by solving a transient energy-balance equation that accounts for absorbed solar radiation, atmospheric and surface longwave radiation exchanges, convective heat transfer from the upper and lower RPVSP surfaces, and temperature-dependent electricity generation. The scheme further incorporates panel-roof radiative interactions through a view-factor approach and parameterizes convective heat exchange using both natural and wind-driven convection, enabling physically consistent simulations of photovoltaic thermal behavior, electricity production, and their interactions with the urban surface energy balance and building energy demand.

The temporal evolution of the RPVSP temperature (T_{panel}) was determined by solving the energy balance equation⁴⁵ in the WRF-BEP + BEM framework (unit $W\ m^{-2}$):

$$C_p \frac{dT_{panel}}{dt} = (R_{sw,in} + R_{lw,in} - R_{lw,out,panel} + R_{lw,exchange} - E_{panel} - Q_{up} - Q_{down}) \quad (1)$$

where C_p is the equivalent areal heat capacity of the RPVSP, $R_{sw,in}$ is the absorbed shortwave radiation, $R_{lw,in}$ is the incoming atmospheric longwave radiation, $R_{lw,out,panel}$ is the emitted longwave radiation, $R_{lw,exchange}$ is the longwave radiative exchange between the RPVSP and roof surface, E_{panel} is the electricity generated by the RPVSP, and Q_{up} and Q_{down} are the sensible heat fluxes from the upper and lower RPVSP surfaces, respectively.

Absorbed shortwave radiation was calculated as:

$$R_{sw,in} = (1 - \alpha_{panel}) \times SW_{inc} \quad (2)$$

where $\alpha_{panel} = 0.11$ is the RPVSP albedo⁴⁶ and SW_{inc} is the incident solar radiation.

The incoming atmospheric longwave radiation was calculated as:

$$R_{lw,in} = \epsilon_{panel}^U LW_{sky,down} \quad (3)$$

where $\epsilon_{panel}^U = 0.79$ is the emissivity of the upper glass surface^{4,47} and $LW_{sky,down}$ is the downward longwave radiation emitted by the atmosphere.

The outgoing longwave radiation emitted by the RPVSP was calculated using the Stefan-Boltzmann law.

$$R_{lw,out,panel} = \epsilon_{panel}^U \sigma T_{panel}^4 \quad (4)$$

The net longwave radiative exchange between the underside of the RPVSP and the roof surface was represented as:

$$R_{lw,exchange} = \frac{1}{\frac{1-\epsilon_{panel}^D}{\epsilon_{panel}} + \frac{1}{VF} + \frac{1-\epsilon_{roof}}{\epsilon_{roof}}} \sigma (T_{roof}^4 - T_{panel}^4) \quad (5)$$

where $\epsilon_{panel}^D = 0.95$ is the emissivity of the lower RPVSP surface, ϵ_{roof} is the roof emissivity, and VF is the panel-roof view factor.

The electricity generation by the RPVSP was calculated as a function of the incident solar radiation, RPVSP conversion efficiency, and RPVSP temperature:

$$E_{panel} = \eta_{panel} SW_{inc} \left[1 - 0.005 (T_{panel} - 298.15) \right] \quad (6)$$

where E_{panel} is the electrical power output, η_{panel} is the reference RPVSP conversion efficiency (0.19)⁴⁵ to represent contemporary mono-crystalline and polycrystalline silicon RPVSP., SW_{inc} is the incident shortwave solar radiation flux, and T_{panel} is the RPVSP temperature (K). The coefficient $0.500\ K^{-1}$ represents the temperature sensitivity of RPVSP efficiency, while 298.15 K (25°C) corresponds to the standard reference temperature^{4,48}.

The sensible heat fluxes from the upper (Q_{up}) and lower (Q_{down}) surfaces of the RPVSP were calculated as the product of the corresponding convective heat transfer coefficient and the temperature difference between the RPVSP and the ambient air temperature ($T_{panel} - T_{air}$). These fluxes represent the convective exchange of sensible heat between the RPVSP and the surrounding atmosphere.

$$Q_{up} = h_{up} (T_{panel} - T_{air}) \quad (7)$$

and

$$Q_{down} = h_{down} (T_{panel} - T_{air}) \quad (8)$$

where the overall convective heat transfer coefficients for the upper (h_{up}) and lower (h_{down}) RPVSP surfaces were calculated by combining the natural convection coefficient (h_c) and the forced convection coefficient (h_f) using a root-sum-square formulation. This approach accounts for the concurrent effects of buoyancy-driven and wind-driven heat transfer processes.

$$h_{up} = \sqrt{h_c^2 + h_f^2} \quad (9)$$

and

$$h_{down} = \sqrt{h_c^2 + h_f^2} \quad (10)$$

For the upper RPVSP surface, the natural convective heat transfer coefficient (h_c) was calculated as a function of the panel-to-air temperature difference (ΔT) and the RPVSP tilt angle (θ), following the empirical formulation⁴⁵:

$$h_c = \frac{9.842 |\Delta T|^{1/3}}{(7.283 - |\cos(\theta)|)} \quad (11)$$

The forced convective heat transfer coefficient (h_f) was parameterized as a function of roof-level wind speed (U_{roof}), following an empirical square-root relationship. This formulation accounts for the enhancement of convective heat exchange between the surface and ambient air under increasing wind conditions:

$$h_f = 2.5(0.4 \times U_{roof})^{0.5} \quad (12)$$

where the roof-level wind speed (U_{roof}) was calculated as the magnitude of the horizontal wind vector using the zonal (U_{out}^2) and meridional (V_{out}^2) wind components.

$$U_{roof} = \sqrt{U_{out}^2 + V_{out}^2} \quad (13)$$

And, the panel-to-air temperature difference (ΔT) was calculated as the difference between the RPVSP temperature (T_{panel}) and the ambient temperature ($T_{ambient}$). This temperature gradient governs the magnitude and direction of sensible heat exchange between the RPVSP surface and the surrounding atmosphere.

$$\Delta T = T_{panel} - T_{ambient} \quad (14)$$

For the lower RPVSP surface,

$$h_c = \frac{1.810 |\Delta T|^{1/3}}{(1.382 + |\cos(\theta)|)} \quad (15)$$

These empirical formulations were adopted from the EnergyPlus model⁴⁹, which has been evaluated against measurements⁵⁰. The convective heat-transfer coefficients depend on the surface material properties (glass in this case), RPVSP orientation, whether the surface faces upward or downward, and the sign and magnitude of the panel-air temperature difference. Wind speed was obtained from the first atmospheric level above the rooftop within WRF, and the absolute wind speed was assumed to be identical for both the upper and lower RPVSP surfaces. This framework enables physically consistent simulations of RPVSP temperature, electricity generation, roof-panel interactions, and their

coupled impacts on building energy demand and the urban surface energy balance.

Model configuration

The numerical experiments were conducted using the WRF-BEP + BEM v4.6.0^{51–53}. A three-level nested configuration was employed, with horizontal grid spacings of 18 km, 6 km, and 2 km for domains d01, d02, and d03, respectively. The corresponding domain dimensions were 75 × 75, 91 × 91, and 121 × 121 grid cells, with the innermost domain encompassing the Kolkata (Supplementary Fig. S3). The model was configured with 40 vertical levels, including a lowest atmospheric layer thickness of approximately 15 m to better resolve urban boundary-layer processes. The winter simulations were integrated from 30 November 2025 to 1 February 2026. Following a 24-h spin-up period, analyses were performed for 1 December 2025–31 January 2026. This simulation window captures the core winter season over eastern India, when air temperatures, solar elevation, and surface–atmosphere coupling differ markedly from other seasons. Focusing on this period enables robust evaluation of rooftop thermal behavior and RPVSP performance under cold-season meteorological constraints. To place the winter climate–energy responses within a broader seasonal context, an additional summer simulation was conducted from 31 March 2025 to 1 June 2025, with a 24-h spin-up period and an analysis period of 1 April–31 May 2025. The same rooftop configuration experiments (Table S6) were performed to evaluate seasonal climate–energy trade-offs associated with RPVSP. However, the main focus of this study is on winter climate–energy interactions.

Physical parameterizations followed configurations that have been extensively evaluated and applied in urban climate simulations over tropical and subtropical environments. Cloud microphysical processes were represented using the WRF Single-Moment six-class (WSM6) scheme, which predicts the mixing ratios of water vapor, cloud water, rain, cloud ice, snow, and graupel⁵⁴. Land–atmosphere interactions were simulated using the Noah land surface model⁵⁵ coupled with the BEP + BEM, which explicitly represents urban geometry, surface energy exchanges, and building energy consumption^{52,53}. Turbulent transport within the urban canopy and atmospheric boundary layer was represented using the turbulent kinetic energy (TKE) closure scheme⁵⁶. Shortwave and longwave radiative transfer were calculated using the Dudhia⁵⁷ and Rapid Radiative Transfer Model⁵⁸ schemes, respectively. Planetary boundary-layer processes were represented using the Bougeault–Lacarrère (BouLac) scheme⁵⁹, while sub-grid-scale convective processes were parameterized using the Kain–Fritsch scheme⁶⁰. Together with the RPVSP parameterization⁴⁵, this modelling framework explicitly resolves coupled exchanges of radiation, heat, moisture, momentum, and energy between urban surfaces, buildings, rooftop technologies, and the atmosphere. The framework provides a physically consistent representation of urban climate processes and enables robust assessment of the climatic and energy impacts of rooftop photovoltaic systems, GRs, CRs, and SCRs across city scales.

Accurate representation of Kolkata's land surface characteristics and urban morphology was achieved using multiple high-resolution geospatial datasets (Table S7). Land-use and land-cover information for the innermost

model domain (d03) was derived from 10-m Sentinel-2 imagery, providing detailed characterization of urban, vegetation, water, and impervious surface distributions across the metropolitan region⁶¹. Urban morphological parameters required by the BEP + BEM scheme were obtained from the University of Texas Global Building Heights for Urban Studies (UT-GLOBUS) dataset at 1 × 1 km spatial resolution⁶². These parameters included (a) urban fraction (f_u) (b) area averaged building height (h_a), (c) plan area fraction (λ_p) and (d) building surface to plan area ratio (λ_b). Together, these variables characterize the three-dimensional urban structure governing radiative trapping, turbulent exchange, and building–atmosphere interactions within the urban canopy. Across Kolkata, mean building heights typically range from 6–11 m and increase to 12–14 m within densely developed urban cores. The λ_p generally varies between 0.25 and 0.35 and exceeds 0.5 in highly compact urban districts, whereas the λ_b ranges from 0.5 to 0.75 across much of the metropolitan area and exceeds 2.5 in the most intensely developed zones⁶³. Initial and lateral meteorological boundary conditions were prescribed from the National Centers for Environmental Prediction Global Forecast System (GFS) analyses⁶⁴, available at 0.25° spatial resolution with 3-hourly temporal updates. These datasets provide a robust representation of both regional atmospheric conditions and local urban morphology, enabling realistic simulations of urban climate processes and rooftop energy interventions across Kolkata.

Numerical experiments

The CRs were represented by modifying rooftop radiative and thermal properties within the urban parameter tables. Roof shortwave reflectance (ρ) was increased to values near 0.80, consistent with field measurements and modelling studies demonstrating that advanced reflective roof coatings can achieve solar reflectance of ~0.8 and effectively reduce roof heat gains and building energy demand^{65–68}. Corresponding longwave emissivity and thermal parameters were adjusted to represent reflective roofing assemblies, while urban geometry and building morphology were held constant to isolate thermodynamic effects. Partial deployment of CRs was represented using an area-weighted effective albedo, allowing mixed rooftop conditions within individual grid cells. The GRs were parameterized⁴⁵, ensuring consistent treatment of vegetated surfaces within the urban canopy. To account for the spectral selectivity of SCRs, effective broadband solar reflectance (ρ) and hemispherical longwave emissivity (ϵ) were derived from reported spectral measurements and implemented within the urban canopy and land-surface schemes^{35–39}. This approach preserves the essential wavelength-dependent radiative behavior of advanced reflective materials within a broadband modelling framework, enabling physically consistent assessment of their performance under realistic urban climates and compound extreme conditions^{38,39}.

The numerical experiments were designed to quantify the influence of winter climate conditions on RPVSP performance in Kolkata through interactions between rooftop surface properties and building energy processes (Table 1). A conventional reinforced cement concrete roof with rooftop RPVSP deployment (RCC + RPVSP) was used as the control scenario, representing present-day urban rooftops with low solar reflectance

Table 1 | Numerical design used in the present study

Scenarios	Types of roof surface	Building roof surface properties					Purpose
		Albedo	Emissivity	GR fraction	CR or SCR coverage	RPVSP fraction	
RCC + RPVSP	Conventional roofs with urban photovoltaic	0.15	0.90	-	-	1.0	Control
GR + RPVSP	Green roofs with urban photovoltaic	0.15	0.90	1.0	-	1.0	Experimental
CR + RPVSP	Reflective roofs with urban photovoltaic	0.80	0.90	-	100%	1.0	Experimental
SCR + RPVSP	Radiative roofs with urban photovoltaic	0.96	0.97	-	100%	1.0	Experimental
Current urban with RCC roofs	Conventional roofs	0.15	0.90	-	-	-	Model validation

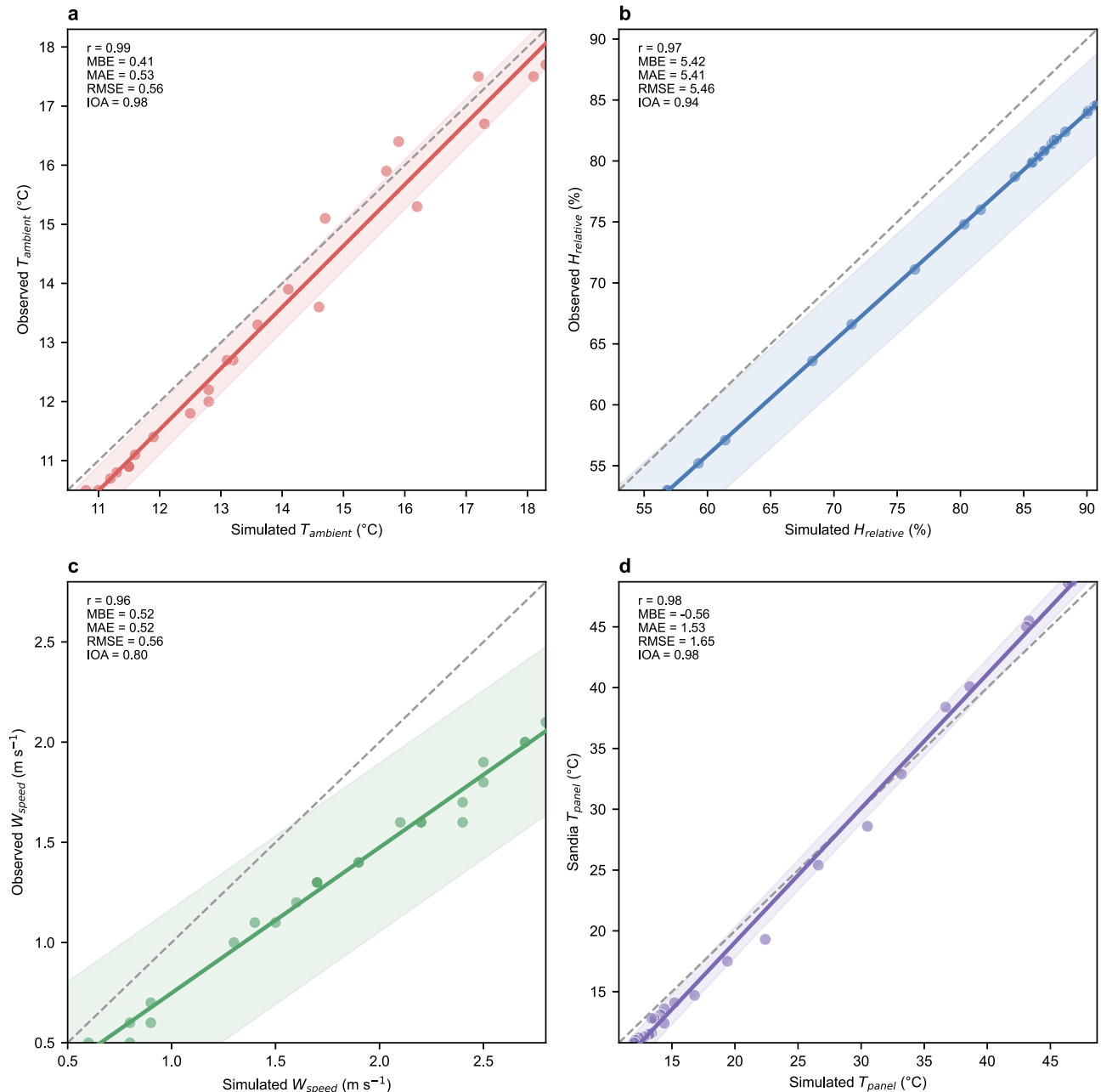


Fig. 9 | Evaluation of winter meteorological conditions and RPVSP temperature. Comparison between simulated and observed wintertime: **a** ambient air temperature (T_{ambient}), **b** relative humidity (H_{relative}), **c** wind speed (W_{speed}), and **d** RPVSP temperature (T_{panel}). Meteorological observations (T_{ambient} , H_{relative} , and W_{speed}) were obtained from CPCB monitoring stations, whereas simulations represent urban-grid-cell-averaged values. RPVSP temperature (T_{panel}) was calculated using

the Sandia Module Temperature Model based on T_{ambient} , W_{speed} , solar irradiance, and RPVSP materials properties. Solid lines show linear regressions, dashed lines indicate the 1:1 relationship, and shaded regions denote RMSE-based uncertainty bands. Statistical performance metrics (r , MBE, MAE, RMSE, and IOA) are shown in each RPVSP. Points represent hourly mean values of the 24-h mean diurnal cycle averaged over the 62-day simulation period ($n = 24$).

(albedo = 0.15) and typical longwave emissivity (0.90). This configuration serves as the reference for assessing wintertime rooftop thermal and RPVSP responses. Three experimental scenarios were constructed by modifying rooftop radiative and thermophysical properties while keeping urban morphology, building geometry, and RPVSP coverage identical, thereby isolating winter surface-atmosphere-panel interactions. The GR with rooftop RPVSP (GR + RPVSP) scenario represents complete vegetative rooftop coverage (GR fraction = 1.0) beneath RPVSPs and isolates evapotranspirative and thermal inertia effects. The CR with rooftop RPVSP (CR + RPVSP) scenario applies full rooftop coverage (100%) of high-reflectance materials (albedo = 0.80, emissivity = 0.90). The SCR with

rooftop RPVSP (SCR + RPVSP) scenario further enhances radiative control using spectrally selective materials with very high solar reflectance (albedo = 0.96) and elevated longwave emissivity (0.97), representing the upper bound of rooftop cooling under winter conditions.

Model validation and limitations

The modelling framework was evaluated against wintertime observations from six urban monitoring stations across Kolkata operated by the Central Pollution Control Board (CPCB), India (Supplementary Fig. S3). For domain-scale validation, hourly observations of ambient temperature (2-m air temperature), relative humidity and wind speed from all six stations were

averaged to generate a single city-wide observational time series representative of urban conditions across Kolkata. This observational dataset was compared with the corresponding spatially averaged output from the innermost model domain (d03). Simulated ambient temperature showed excellent agreement with observations (correlation coefficient, $r = 0.99$; mean bias error (MBE) = 0.41°C ; mean absolute error (MAE) = 0.53°C ; root mean square error (RMSE) = 0.56°C ; and index of agreement (IOA) = 0.98). Relative humidity was also reproduced with high fidelity ($r = 0.97$, MBE = 5.42% , MAE = 5.41% , RMSE = 5.46% , IOA = 0.94), while wind speed showed strong agreement with observations ($r = 0.96$, MBE = 0.52 m s^{-1} , MAE = 0.52 m s^{-1} , RMSE = 0.56 m s^{-1} , IOA = 0.80) over the 62-day simulation period (Fig. 9a–c and Table S8). To further evaluate model performance at the local scale, simulated and observed diurnal cycles of 2-m air temperature were compared separately at each monitoring station. The model successfully reproduced the magnitude and timing of temperature variations across all six sites, demonstrating its ability to capture local thermal variability within heterogeneous urban environments (Supplementary Fig. S4).

Direct observations of RPVSP temperature representative of an entire urban area are unavailable for the study region and remain exceptionally rare worldwide. Existing measurements are typically obtained from individual rooftop installations, experimental facilities or dedicated monitoring sites and therefore represent site-specific conditions rather than the grid-cell-averaged conditions resolved by urban climate models. To address this limitation, city-wide reference RPVSP temperatures were independently estimated using the Sandia Module Temperature Model⁶⁹ (T_{Panel}), driven by the city-wide hourly observational time series of ambient temperature (T_{ambient}) and wind speed (W_{speed}) together with coincident solar irradiance (E_{POA}) on the RPVSP.

$$T_{\text{Panel}} = E_{\text{POA}}(e^{a+b \cdot W_{\text{speed}}}) + T_{\text{ambient}} \quad (16)$$

The model was parameterized using the glass-sheet close-roof-mount configuration ($a = -2.98$; $b = -0.0471$), representative of RPVSP with limited rear-surface ventilation. Simulated domain-averaged RPVSP temperatures were then compared with the corresponding Sandia-based city-wide reference estimates over the same 62-day simulation period. Simulated RPVSP temperatures showed excellent agreement with the independent estimates ($r = 0.98$, MBE = -0.56°C , MAE = 1.53°C , RMSE = 1.65°C , IOA = 0.98 ; Fig. 9d). The strong agreement between simulated and independently estimated RPVSP temperatures, together with the accurate reproduction of the underlying meteorological drivers, provides confidence that the modelling framework realistically captures the coupled radiative, aerodynamic and thermodynamic processes governing urban-scale RPVSP operation.

Data availability

The urban land-use data have been updated in the Kolkata from the European Space Agency (ESA) World Cover data is available at <https://worldcover2021.esa.int/>. The Kolkata region building shapefile along with the urban morphological parameters has been obtained from the University of Texas – Global Building heights for Urban Studies (UT-GLOBUS) dataset (<https://zenodo.org/records/11156602>). The meteorological input data to create the initial and boundary conditions for the WRF model domains were obtained from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) datasets (<https://rda.ucar.edu/datasets/d084001/>). For Kolkata, meteorological observational data for model validation can be obtained from the Central Control Room for Air Quality Management – All India (<https://airquality.cpcb.gov.in/ccr/#/caaqm-dashboard-all/caaqm-landing/caaqm-data-repository>), maintained by the Central Pollution Control Board (CPCB). Hourly data on temperature and humidity were retrieved using the station-wise dropdown in the CPCB data repository. As direct links are often unstable, the data can be located by searching “2025/2026 Kolkata and Howrah station-wise

meteorological data” on the CPCB portal. These datasets were used to serve as reference observations for model evaluation and validation.

Code availability

The source code of WRF model version 4.6.0 is available at <https://github.com/wrf-model/WRF/releases/tag/v4.6.0>.

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References

1. Amaripadath, D., Sailor, D. J., Bertini, A., Barker, M. & Attia, S. Are net zero energy buildings necessarily also net zero emission buildings? Time-integrated analysis using dynamic grid emission factors. *Build. Environ.* **283**, 113367 (2025).
2. Amaripadath, D., Sailor, D. J., Khan, A., Bertini, A. & Attia, S. Achieving low-carbon electricity operations in net zero energy residential buildings through plug-in battery energy storage systems. *J. Energy Storage* **153**, 120964 (2026).
3. Kapsalis, V. et al. Critical assessment of large-scale rooftop photovoltaics deployment in the global urban environment. *Renew. Sustain. Energy Rev.* **189**, 114005 (2024).
4. Skoplaki, E. & Palyvos, J. A. On the temperature dependence of photovoltaic module electrical performance: A review of efficiency/power correlations. *Sol. Energy* **83**, 614–624 (2009).
5. Dubey, S., Sarvaiya, J. N. & Seshadri, B. Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world—a review. *Energy Procedia* **33**, 311–321 (2013).
6. Khan, A. et al. Exploring the Meteorological Impacts of Surface and Rooftop Heat Mitigation Strategies Over a Tropical City. *J. Geophys. Res. Atmospheres* **128**, e2022JD038099 (2023).
7. Khan, A. et al. Urban cooling potential and cost comparison of heat mitigation techniques for their impact on the lower atmosphere. *Comput. Urban Sci.* **3**, 26 (2023).
8. Santamouris, M. Cooling the cities—a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. *Sol. Energy* **103**, 682–703 (2014).
9. Khorat, S. et al. Cool roof strategies for urban thermal resilience to extreme heatwaves in tropical cities. *Energy Build* **302**, 113751 (2024).
10. Chemisana, D. & Lamnatou, C. hr Photovoltaic-green roofs: An experimental evaluation of system performance. *Appl. Energy* **119**, 246–256 (2014).
11. Baumann, T. et al. Photovoltaic systems with vertically mounted bifacial PV modules in combination with green roofs. *Sol. Energy* **190**, 139–146 (2019).
12. Cavadini, G. B. & Cook, L. M. Green and cool roof choices integrated into rooftop solar energy modelling. *Appl. Energy* **296**, 117082 (2021).
13. Wang, W., Yang, H. & Xiang, C. Green roofs and facades with integrated photovoltaic system for zero energy eco-friendly building—A review. *Sustain. Energy Technol. Assess.* **60**, 103426 (2023).
14. Vasilakopoulou, K., Ulpiani, G., Khan, A., Synnefa, A. & Santamouris, M. Cool roofs boost the energy production of photovoltaics: Investigating the impact of roof albedo on the energy performance of monofacial and bifacial photovoltaic modules. *Sol. Energy* **265**, 111948 (2023).
15. Jerez, S. et al. The impact of climate change on photovoltaic power generation in Europe. *Nat. Commun.* **6**, 10014 (2015).
16. Crook, J. A., Jones, L. A., Forster, P. M. & Crook, R. Climate change impacts on future photovoltaic and concentrated solar power energy output. *Energy Environ. Sci.* **4**, 3101–3109 (2011).
17. Kohler, M., Feige, R. & Wiartalla, W. Interaction between PV-systems and extensive green roofs. <https://www.osti.gov/etdweb/biblio/20926951> (2007).

18. Hui, S. C. & Chan, S.-C. Integration of green roof and solar photovoltaic systems. in *Joint symposium* 1–12 (2011).
19. Perez, M. J., Wight, N., Fthenakis, V. & Ho, C. Green-roof integrated PV canopies—an empirical study and teaching tool for low income students in the South Bronx. in *ASES* **4**, 6 (2012).
20. Osma-Pinto, G. & Ordóñez-Plata, G. Measuring factors influencing performance of rooftop PV panels in warm tropical climates. *Sol. Energy* **185**, 112–123 (2019).
21. Alshayeb, M. J. & Chang, J. D. Variations of PV panel performance installed over a vegetated roof and a conventional black roof. *Energies* **11**, 1110 (2018).
22. Ogaili, H. & Sailor, D. J. Measuring the effect of vegetated roofs on the performance of photovoltaic panels in a combined system. *J. Sol. Energy Eng.* **138**, 061009 (2016).
23. Nagengast, A., Hendrickson, C. & Matthews, H. S. Variations in photovoltaic performance due to climate and low-slope roof choice. *Energy Build* **64**, 493–502 (2013).
24. Witmer, L. T. Quantification of the passive cooling of Photovoltaics using a green roof. <https://etda.libraries.psu.edu/catalog/11242> (2010).
25. Osma, G., Ordóñez, G., Hernández, E., Quintero, L. & Torres, M. *The Impact of Height Installation on the Performance of PV Panels Integrated into a Green Roof in Tropical Conditions*. vol. 205 (WIT Press Southampton, UK, 2016).
26. Gu, W., Ma, T., Li, M., Shen, L. & Zhang, Y. A coupled optical-electrical-thermal model of the bifacial photovoltaic module. *Appl. Energy* **258**, 114075 (2020).
27. Rahmani, F., Robinson, M. A. & Barzegaran, M. R. Cool roof coating impact on roof-mounted photovoltaic solar modules at texas green power microgrid. *Int. J. Electr. Power Energy Syst.* **130**, 106932 (2021).
28. Rehman, T. et al. Global perspectives on advancing photovoltaic system performance—A state-of-the-art review. *Renew. Sustain. Energy Rev.* **207**, 114889 (2025).
29. Bamişile, O., Acen, C., Cai, D., Huang, Q. & Staffell, I. The environmental factors affecting solar photovoltaic output. *Renew. Sustain. Energy Rev.* **208**, 115073 (2025).
30. Sailor, D. J., Anand, J. & King, R. R. Photovoltaics in the built environment: A critical review. *Energy Build* **253**, 111479 (2021).
31. Liu, R. et al. Materials in Radiative Cooling Technologies. *Adv. Mater.* **37**, 2401577 (2025).
32. Li, Z., Chen, Q., Song, Y., Zhu, B. & Zhu, J. Fundamentals, Materials, and Applications for Daytime Radiative Cooling. *Adv. Mater. Technol.* **5**, 1901007 (2020).
33. Zhang, Q. et al. Recent Progress in Daytime Radiative Cooling: Advanced Material Designs and Applications. *Small Methods* **6**, 2101379 (2022).
34. Hossain, M.d.M. & Gu, M. Radiative Cooling: Principles, Progress, and Potentials. *Adv. Sci.* **3**, 1500360 (2016).
35. Ma, Y. The super-cool materials that send heat to space. *Nature* **577**, 18–20 (2020).
36. Santamouris, M. & Yun, G. Y. Recent development and research priorities on cool and super cool materials to mitigate urban heat island. *Renew. Energy* **161**, 792–807 (2020).
37. Baniassadi, A., Sailor, D. J. & Ban-Weiss, G. A. Potential energy and climate benefits of super-cool materials as a rooftop strategy. *Urban Clim* **29**, 100495 (2019).
38. Feng, J., Khan, A., Doan, Q.-V., Gao, K. & Santamouris, M. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale. *Cell Rep. Phys. Sci.* **2**, (2021).
39. Khatun, R. et al. Urban scale rooftop super cool broadband radiative coolers in humid conditions. in *Building Simulation* 17 1629–1651 (Springer, 2024).
40. Li, H., Zhang, J., Liu, X. & Zhang, T. Comparative investigation of energy-saving potential and technical economy of rooftop radiative cooling and photovoltaic systems. *Appl. Energy* **328**, 120181 (2022).
41. Oke, T. R. *Boundary Layer Climates*. (Routledge, 2002).
42. Barlow, J. F. Progress in observing and modelling the urban boundary layer. *Urban Clim* **10**, 216–240 (2014).
43. Li, D. & Bou-Zeid, E. Synergistic interactions between urban heat islands and heat waves: The impact in cities is larger than the sum of its parts. *J. Appl. Meteorol. Climatol.* **52**, 2051–2064 (2013).
44. Chakraborty, T. C., Sarangi, C. & Lee, X. Reduction in human activity can enhance the urban heat island: Insights from the COVID-19 lockdown. *Environ. Res. Lett.* **16**, 054060 (2021).
45. Zonato, A. et al. Exploring the Effects of Rooftop Mitigation Strategies on Urban Temperatures and Energy Consumption. *J. Geophys. Res. Atmospheres* **126**, e2021JD035002 (2021).
46. Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X. & Lemonsu, A. Solar panels reduce both global warming and urban heat island. *Front. Environ. Sci.* **2**, (2014).
47. Gentle, A. R. & Smith, G. B. Is enhanced radiative cooling of solar cell modules worth pursuing? *Sol. Energy Mater. Sol. Cells* **150**, 39–42 (2016).
48. Best Research-Cell Efficiency Chart | Photovoltaic Research | NLR. <https://www.nlr.gov/pv/cell-efficiency>.
49. Energy, U. D. O. Engineering Reference (2010).
50. Scherba, A., Sailor, D. J., Rosenstiel, T. N. & Wamser, C. C. Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux into the urban environment. *Build. Environ.* **46**, 2542–2551 (2011).
51. Skamarock, W. C. et al. *A Description of the Advanced Research WRF Model Version 4*
52. Martilli, A., Clappier, A. & Rotach, M. W. An Urban Surface Exchange Parameterisation for Mesoscale Models. *Bound.-Layer Meteorol.* **104**, 261–304 (2002).
53. Salamanca, F. & Martilli, A. A new Building Energy Model coupled with an Urban Canopy Parameterization for urban climate simulations—part II. Validation with one dimension off-line simulations.
54. Hong, S.-Y. H. ongandlim-J. KMS-2006. *J. Korean Meteorol. Soc.* **42**, 129–151 (2006).
55. Chen, F. & Dudhia, J. Coupling an Advanced Land Surface–Hydrology Model with the Penn State–NCAR MM5 Modeling System. Part I: Model Implementation and Sensitivity. https://journals.ametsoc.org/view/journals/mwre/129/4/1520-0493_2001_129_0569_caals_2.0.co_2.xml (2001).
56. Janjić, Z. I. The Step-Mountain Eta Coordinate Model: Further Developments of the Convection, Viscous Sublayer, and Turbulence Closure Schemes. https://journals.ametsoc.org/view/journals/mwre/122/5/1520-0493_1994_122_0927_tsmecm_2_0_co_2.xml (1994).
57. Dudhia, J. Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model. https://journals.ametsoc.org/view/journals/atsc/46/20/1520-0469_1989_046_3077_nsocod_2_0_co_2.xml (1989).
58. Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J. & Clough, S. A. Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res. Atmospheres* **102**, 16663–16682 (1997).
59. Bougeault, P. & Lacarrere, P. Parameterization of Orography-Induced Turbulence in a Mesobeta-Scale Model. https://journals.ametsoc.org/view/journals/mwre/117/8/1520-0493_1989_117_1872_pooiti_2_0_co_2.xml (1989).
60. Kain, J. S. The Kain–Fritsch Convective Parameterization: An Update. https://journals.ametsoc.org/view/journals/apme/43/1/1520-0450_2004_043_0170_tkcpau_2.0.co_2.xml (2004).
61. Zanaga, D. et al. ESA WorldCover 10 2021 v200. Zenodo (2022).
62. GLOBAL Building heights for Urban Studies (UT-GLOBUS) for city- and street- scale urban simulations: Development and first applications | Scientific Data. <https://www.nature.com/articles/s41597-024-03719-w>.

63. Khorat, S. et al. Quantifying outdoor heat stress potential due to city-wide installation of rooftop photovoltaic solar panels. *Energy Build* **344**, 115996 (2025).
64. Commerce, N. C. for E. P. W. S. S. D. of. NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive. NSF National Center for Atmospheric Research (2015).
65. Akbari, H., Damon Matthews, H. & Seto, D. The long-term effect of increasing the albedo of urban areas. *Environ. Res. Lett.* **7**, 024004 (2012).
66. Pisello, A. L. State of the art on the development of cool coatings for buildings and cities. *Sol. Energy* **144**, 660–680 (2017).
67. Khan, A. et al. Compound urban extremes weaken the cooling efficacy of super cool broadband materials in cities. *Urban Clim* **65**, 102761 (2026).
68. Khan, A. et al. Rooftop photovoltaic solar panels warm up and cool down cities. *Nat. Cities* **1**, 780–790 (2024).
69. King, D., Boyson, W. & Kratochvil, J. *Photovoltaic Array Performance Model*. SAND2004-3535, 919131 <https://www.osti.gov/servlets/purl/919131/> (2004).

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Author contributions

A.K. conceived the study, designed the methodology, performed the numerical simulations and analysis, and led the original manuscript writing. S.K. and R.K. contributed to data processing, figure preparation, and interpretation of results. T.A. assisted with model setup, sensitivity analysis, and validation of RVPSP performance. K.V. and D.A. supported data curation, conceptual framework, and methodological refinement. R.H. and

X.Y. contributed to scientific discussion, interpretation of results, and manuscript review and editing. D.N. provided conceptual guidance on urban climate processes and contributed to critical revisions. M.S. contributed to the theoretical framing of urban heat–energy interactions and refinement of the discussion. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare that they have no known competing financial or non-financial interests that could have influenced the work reported in this paper.

Additional information

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