Integration of Rooftop Photovoltaics and Roof Retrofitting Strategies for Enhanced Energy Efficiency in Warm Climates

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Abstract

To forward renewable energy as a self-reliant option of energy production, the Government of India is promoting the extensive adoption of Rooftop Solar Photovoltaic (PV) in domestic buildings. Rooftop solar PV systems offer the dual benefit of being a clean energy source and serving as shading devices for roofs, reducing the impact of incident solar radiation. However, the effectiveness of PV shading in minimizing incident solar radiation on mounting surfaces depends on the urban context such as neighbouring building heights and distances between buildings, as well as on the mounting angle and geometry of the PV panels. This study investigates the potential of a roof-mounted PV as a shading element for a typical and retrofitted roof of a low-rise building in a warm and humid climate in Kharagpur, West Bengal. To identify the geometry of PV panels, a grid-connected PV system was first designed for the selected residential unit using PVSyst. The identified PV structure (with dimensions 5.5 m (l) X 4 m (w)) has been considered, mounted over the building at a height of 1.9 m with a tilt of 22° facing south (true azimuth). DesignBuilder, integrated with the EnergyPlus building energy simulation engine, is used to simulate the model to predict the heat transfer through the roofing structure and evaluate the change in the cooling demand associated with it. Three types of roofing structures were studied: an uninsulated roof, a cool roof retrofit, and a roof with mounted PV structure. The results show that the PV structure can provide additional shade to the roof, decreasing the conductive heat gained by incident solar radiation through the roofing assembly by 13.7 % and 9 % for the uninsulated and cool roof cases, respectively. Considering this study observes the Solar PV as a detached and mounted structure, focussing solely on its shading, the reduction in heat gain also resulted in a decrease in the annual cooling demand of the building, demonstrating the effectiveness of PV panels not only as an energy generation solution but also as a thermal management strategy for buildings in warm and humid climates.

1. Introduction

With one of the world's fastest-growing economies, India stands at a critical juncture with increasing urbanization and industrialization rates accompanied with increasing energy demand. According to reports, India is at present the third-largest global energy consumer in the world (U.S. Department of Commerce, 2024). India currently contributes to 3.4 % of the global energy consumption, with the energy demand expected to increase by 25 % by the year 2040 (International Energy Agency, 2021). Policy and technological transformations in the country have nearly electrified 97 % of households in the country, thus increasing the per household energy consumption (CEEW, 2020). The residential sector in India is responsible for 24 % of the total energy consumption (Ramapragada et al., 2022). Recognising this, India has embarked on various initiatives to integrate energy efficiency and sustainability in both the existing and up-coming building stock of the country.

India's goal to achieve 500 GW of non-fossil energy capacity by 2030 strengthens its aims to generate 50 % of its energy requirement through renewable sources and reduce the total projected carbon emissions by one billion tons by the year 2030 (PIB, 2023). India's geographical location endows it with significant solar potential, with most regions receiving between 4 to 7 kWh/m^2/day of solar radiation. Currently solar energy constitutes 37 % of the 179 GW installed renewable energy in the country (U.S. Department of Commerce, 2024). While solar photovoltaics represent an active strategy to provide alternative energy, reducing reliance on conventional fuels, it is equally important to investigate passive strategies to enhance the efficiency of buildings.

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Heat transfer through a building envelope has been cited as one of the main factors influencing buildings' cooling and heating loads (Lubis, 2018). Moreover, the heat gain through a roof is one of the major components of the building envelope that affects the thermal performance of buildings. The vast research on this subject has highlighted that the direct and diffuse solar radiations falling on the roof can raise the temperature of the roofs significantly, thus increasing the indoor temperature, causing discomfort and increased usage of cooling equipment (Bozonnet & Allard, 2011; Farhan et al., 2021). Thus, energy efficient roofs serve as a key factor in reducing building cooling loads whilst imparting thermal comfort, with daily peak roof surface temperature showing reductions of 10 to 20 °C in green roofs and 15 to 25 °C in cool roofs (Cavadini & Cook, 2021). While recent studies have focused on roof insulation technologies and retrofitting techniques based on concepts such as green roofs or cool roofs, the combined effect of building-applied photovoltaics and roof retrofitting strategies are also being investigated. Various studies have deliberated the differences in solar panel yield for different type of sustainable roofs by investigating the relationship between the roof surface temperature, albedo and the PV panel power output (Altan et al., 2019; Witmer & Brownson, 2011; Shafique et al., 2020; Lamnatou & Chemisana, 2015). Along with the analysis of the PV yield, a few studies have examined the shading effect of Rooftop Solar PV structure on indoor thermal conditions of the building (Dominguez et al., 2011; Pandiaraj et al., 2022; Wang et al., 2020; Ma et al., 2023; Albatayneh et al., 2022; Vakilinezhad & Ziaee, 2024).
Given this context, the objective of this study is to investigate the impact of the indirect shading of Rooftop Solar PV on the conductive roof heat gain for a residential building in a warm and humid climate for an uninsulated and retrofitted cool roof. The essential aim of the research is to investigate the passive role of the Solar PV in lowering the heat transfer from roof to indoors in the summer months, thus lowering the cooling load.

2. Methodology

This study employs field study and numerical simulations for data gathering and analysing purposes. A residential complex in Kharagpur is selected for the study. A field study was conducted to collect building envelope, occupancy, and household data. Next, a thermal simulation model of the building was constructed to run the analysis. A rooftop Solar PV that adequately serves the demand of the household is designed for the building using a solar simulator, which was then integrated into the whole-building simulation model. Cool roof retrofitting strategy integrated with Solar PV shading was studied to understand its effect on roof heat transfer into the building. The subsequent sections outline the research tools and techniques employed in this investigation.

2.1 Simulation Software and Engine

The simulations are performed using the whole-building simulation software DesignBuilder (Designbuilder Version v7), which incorporates the EnergyPlus engine used extensively for doing energy studies (Zhang, 2014; Bharath et al., 2016; Blanco et al., 2016; Choi et al., 2017; Bahri et al., 2024). To understand the structure and sizing of the PV system, a grid-connected roof mounted PV system (as described in Section 1.1) is constructed in PVSyst (PVSyst SA, Version v7), a solar simulation software used in scientific studies (Panicker et al., 2023; Alnoosani et al., 2019; Kandasamy et al., 2013). This PV system is integrated into the DesignBuilder environment for further analysis.

2.2 Specifications of Building Analysed in Study

The building chosen for the study is a typical single-family residence located in Kharagpur, West Bengal. Kharagpur (22°19′49″N 87°19′25″E) is a town located in West Bengal, in the eastern part of India. It is situated at an elevation of 49 m above mean sea level, exhibiting a tropical wet and dry climate, as classified under the Köppen climate classification. The mean annual temperature recorded in Kharagpur is 30.6 °C. The region accumulates an annual precipitation of roughly 157 mm and experiences an average of 144 rainy days per annum. Assumed climatic data for the region is extracted from Meteonorm database in PVSyst.
The building is a single storey residence with a floor area of 115 m^2. The entire roof area of 106.2 m^2 has been considered for the study. The window to wall ra-

tio is calculated as 0.36. The building has 2 bedrooms, a living room, kitchen, a semi-open porch area, and a common bathroom and toilet as seen in Figure 1. The floor-to-floor height is of 3.3 m, the window sill height is 1 m, and the lintel level is 2.2 m. A field study was conducted on site to assess the construction assemblies and materials of the building components of the existing building. The building has standard construction, with plaster finished 230 mm exterior brick masonry wall, 150 mm thick interior walls, 150 mm flat RCC concrete roof, polished concrete floor and wooden framed single glazed (multiple paned) windows with grilles.

Fig. 1 – Floor Plan (Ground Floor) of the residential unit

It is found that the house did not utilise any heating systems. The bedroom in the northern side is the only conditioned space (18.5 m²) in the house with a split AC system. Information on appliance purchase, ownership, usage and bi-monthly electricity bills for one year was collected from the household.

2.3 Building Simulation Model

2.3.1 Solar Simulation

To understand the sizing of the roof-mounted Solar PV, a grid-connected Photovoltaic plant connected to a power inverter has been designed for the analysed building with inputs presented in Table 1 fed into the PVSyst interface.

Table 1 – Inputs for design of Rooftop Solar PV on PVSyst

Parameter	Details
Module Technology Used	Monocrystalline Silicon
Module Dimension (l X w X d)	2 m X 1.1 m X 0.035 m
Cells	72
Nominal Operating Cell Temperature	45 °C
Modules in Series	5
Modules in Parallel	2
Module Peak Power (Pmax)	530 Wp
Open Circuit Voltage	49.32 V
Optimum Operating Voltage	41.36 V
Module Efficiency	20.54 %

Studies have shown that panels placed at tilt angles corresponding to the latitude of the location towards South (for northern hemisphere) perform well for the location being studied (Panicker et al., 2023). Thus, the panels are placed at a tilt of 22° facing South (true Azimuth).

2.3.2 Solar PV as a shading element

This study investigates the influence of the shading provided by solar structure on roof, and its impact on the conductive heat gain through the roof and thermal loads of the building. To evaluate the indirect effect of shading by installing PV panels on rooftop of buildings, factors such as the ideal tilt angle, design of the mounting structure for the PV, and the roof assembly need to be analysed (Albatayneh et al., 2022). Different methodologies to examine the same have been explored - Experimental (Dominguez et al., 2011; Pandiaraj et al., 2022), Numeric Model (Wang et al., 2020; Ma et al., 2023) and simulation-based studies (Albatayneh et al., 2022; Vakilinezhad & Ziaee, 2024) showcase the improved thermal comfort in the studied spaces through the shading effect of Solar PVs on the rooftop. In contrast to the above-mentioned studies, Zonato et al. (2021) states that parallelly placed photovoltaic panels on the roof help in reducing the roof temperatures during daytime by acting as a shield but cause warmer roof temperature during nighttime causing a positive heat flux into the building.

In an urban context, studies have also shown that the employment of large-scale cool roofs and photovoltaic deployment can lead to local cooling effect on the environment (Millstein et al., 2011). Various studies have reiterated that the deployment of solar panels reduce the near-surface air temperature as well as the citywide cooling energy demand (Salamanca et al., 2016; Masson et al., 2014). Another study (Tan et al., 2023) states that employment of city-wide solar panel roofs can reduce the cooling energy consumption. This is in contrast with studies stating that use of photovoltaic panels may lead to decreased thermal comfort and increase in local temperature (Gafford et al., 2016; Broadbent et al., 2019). These studies have been conducted for large scale PV systems, deployed on city-wide rooftops or on large fields.

Keeping these studies in mind, the current research presents a case of a small rooftop PV analyzed at building level, a schematic (side) section of which is shown in Fig. 2.

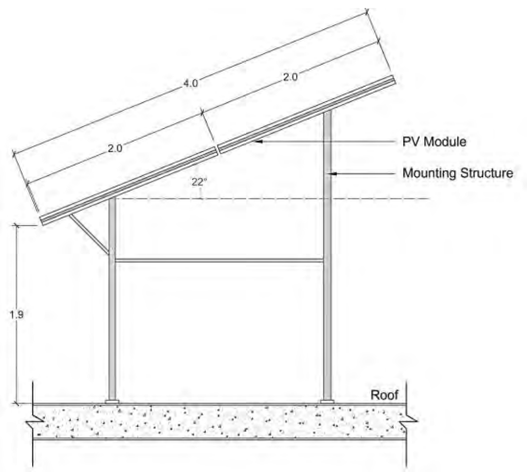

Fig. 2 – PV panel placed on a mounted structure on the roof

Each module measures 1.1 m x 2 m x 0.035 m (length, width, depth), with the entire PV structure with 10 modules covering an area of 22.5 m^2. The PV is kept detached from the roof, mounted on a steel MS frame, placed at an angle of 22° facing South, at a height of 1.9 m from the roof floor. Further, the PV panels are placed on the part of the roof that encases the non-sleeping areas (living, porch) where night-time cooling is not used, and no occupancy is recorded during the nighttime. Due to the significant space left between the PV structure and roof, this study does not discuss the heat flux exchanges in the zone between the PV panel and roof and focusses on the passive shading of the PV on the roof.

2.4 Roofing Assemblies as Cases

To select the most efficient roofing system, the existing roof structure is tested against two roofing options, cool roof and roof shaded by PV.

Cool roofing is a technique that offers better solar reflectance and thermal emittance compared to standard roofing materials (Coutts et al., 2013). Cool roofs specifically focus on the outer layer of the exterior roof surface being a highly reflective surface (BEE, 2018). Its adoption in the built environment is rapidly expanding as it presents itself as a viable resolution in mitigating the urban heat island effect, as well as improving indoor thermal comfort (Altan et al., 2019; Baik et al., 2022). A cool roof is designed to reflect more sunlight and absorb less heat compared to a standard roof, that may lead to lowering of indoor surface temperatures (Salamanca et al., 2016; Rawat & Singh, 2022) as well as near-surface air temperature (Song et al., 2016; Baik et al., 2022). As a result, the lower surface temperatures contribute to decreased heat transfer between the roof and the building, aiding in the management of cooling load (Rahmani et al., 2021).

The three parameters used to measure the efficiency of these roofs are 1) Albedo or solar reflectance (SR), 2) Thermal emittance (IE), and 3) solar reflectance index (SRI). Table 2 indicates the SR, IE and SRI for different roofing materials (Shakti Foundation, 2020). ECBC recommends materials for cool roofs like shingles, membranes, high albedo coating, broken glazed tiles, regular white paint, given a prescriptive requirement of minimum initial solar reflectance of 0.60, and an initial emittance no less than 0.90 (BEE, 2018).

Table 2 – Surface Radiative Properties of Roofing Materials

Material	Solar Reflectance (SR)	Thermal Emittance (IE)	Solar Reflectance Index (SRI)
White Cement tile	0.73	0.91	90
White EPDM	0.69	0.87	84
White Coating 8 mm (1 coat)	0.80	0.91	100
PVC White	0.83	0.92	104
White coating 20 mm (1 coat)	0.85	0.91	107

Here albedo refers to the ratio of the reflected solar energy to the incident solar energy and, emissivity points to the fraction of the absorbed solar energy that is radiated back to the sky as invisible infrared radiation. A cool roof can minimise the solar heat gain of a building by reflecting a significant amount of the incoming radiation and re-radiating a portion of the absorbed radiation before it is transferred through conduction. The third factor - Solar Reflectance Index (SRI) is calculated from the solar reflectance and the thermal emittance (ASTM, 2011). The SRI of a standard black surface is taken as 0 and for a standard white surface is taken as 100 (BEE, 2018).

For the current study, the RCC roof has been retrofitted with white coated cement tiles possessing an SRI of 90. This was assumed to be directly applied to the existing roof without addition of any insulation to the existing roof. Studies have shown that the application of cool roof in poorly or non-insulated residential buildings shows more energy savings than installations in well-insulated buildings (Synnefa et al., 2007). Four scenarios were created for comparison: R1 – Existing Uninsulated Roof, R1.1 – Uninsulated Roof with Rooftop PV, R2- Cool Roof, R2.1 – Cool Roof integrated with Rooftop PV. The details of the roof are given in Table 3 with thermophysical and surface properties of the roofing material guided from ECBC (BEE, 2017 and 2018).

Table 3 – Roof Assembly details

Parameters	Uninsulated Existing Roof (R1)	Cool Roof (R2)
Roof Area (m^2)	106	106
Albedo	0.4	0.8
Emissivity	0.85	0.91
U Value ($W/(m^2{\cdot}K)$)	3.8	3.2
	Top Layer	
	Cement Screed	White Coated Cement Tiles*
Thickness (mm)	20	10
Density (kg/m^3)	1648	2100
Thermal Conductivity (W/(m.K))	0.72	1.1
Specific Heat Capacity (kJ/(kg.K))	0.92	0.83
	Bottom Layer	
	RCC Slab	
Thickness (mm)	150	
Density (kg/m^3)	2288	
Thermal Conductivity (W/(m.K))	1.58	
Specific Heat Capacity (kJ/(kg.K))	0.88	

* New material created (Khan et al., 2016, EnergyPlus 24.1.0, IESVE, 2014)

3. Results and Discussion

This section first discusses the simulated performance of the designed rooftop PV that is integrated into the building simulation model. Next, for the four roofing cases the predicted value of roof surface heat conduction, surface temperature, and implications on the cooling demand are analysed and compared.

3.1 Rooftop Solar PV Generation

A 5.3 kW Rooftop PV consisting of 10 panels of 530 Wp (5 in series, 2 strings) is designed. PVSyst software expresses the simulation results as yield energies displayed as [kWh/kWp/day]. Here kWh represents the mean produced electrical energy, and kWp represents the array nominal installed power at Standard Test Conditions (STC). The reference System Yield (Yr) refers to the ideal array yield without considering for any loss, numerically equal to the incident energy in the array plane [kWh/m^2/day]. The System Yield (Yf) representing the system daily useful energy or the nominal power [kwh/kWp/day]. The Performance Ratio (PR) is the system efficiency with respect to the system yield and the incident energy [Yf/Yr]. The predicted monthly system yield, along with array and system losses for the designed PV system can be observed in Figure 3.

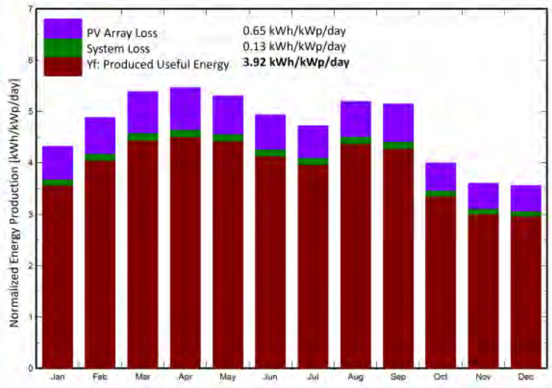

Fig. 3 — Predicted monthly System yield for the designed Solar PV

PVSyst accounts for array losses including shading, irradiance and thermal loss, as well as Inverter loss (PVSyst SA, Version v7). For this study, three parameters – the annual system production, the System Yield (Yf), and the Performance Ratio (PR) have been examined. The simulated on-site electricity production from the designed Solar PV after accounting for losses is calculated as 6158 kWh annually. The average system yield is 3.92 kWh/kWp/day, with a performance ratio of 0.8.

3.2 Surface Heat Conduction for Different Roofing Strategies

In the context of the study, the "Surface Inside Face Conduction Heat Transfer Rate" as defined by EnergyPlus quantifies the heat flow rate as measured by a heat flow meter. This includes the heat flow by conduction at the inside face of an opaque heat transfer surface. A positive value indicates net heat gain through the analysed opaque surface through conduction, and a negative value indicates the net heat loss from the building through conduction (Passerini et al., 2018). Figure 4 represents the roof surface inside face conduction heat transfer rate (in kWh) for a period of one year for the roofing assemblies.

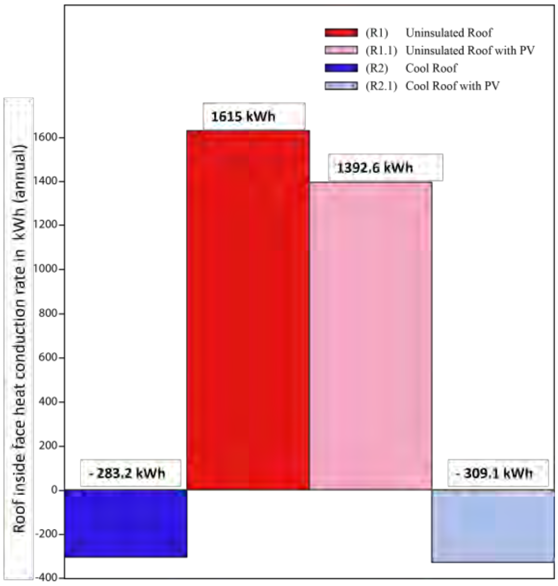

Fig. 4 — Simulated Roof surface inside face conduction heat transfer rate for the different roof strategies

The existing uninsulated roof (R1) demonstrates the highest annual heat gain at 1615 kWh, suggesting significant heat flow into the building. Introducing shade with solar panels (R1.1) reduces this to 1392.6 kWh, indicating that passive shading by solar panels can have a significant effect on heat intake in a building. A negative value of – 283.2 kWh for the Cool Roof (R2) indicates that over the year the cool roofs lead to net heat loss through conduction. Cool Roof with PV shading (R2.1) shows that this heat loss is amplified by PV shading by 9.5 %.

3.3 Indoor Roof Surface Temperature

As observed in Fig. 5, the predicted indoor surface temperature of the analysed roof surfaces was analysed through simulations for each day of the analysed year. Roof R1, the existing uninsulated variant, consistently showed the highest temperature readings, peaking at around 42 °C. This demonstrates the limited thermal resistance of a roof lacking insulation. Due to the absence of insulation, there is a significant temperature fluctuation, showing that the indoor surface temperature follows the external temperature variations.

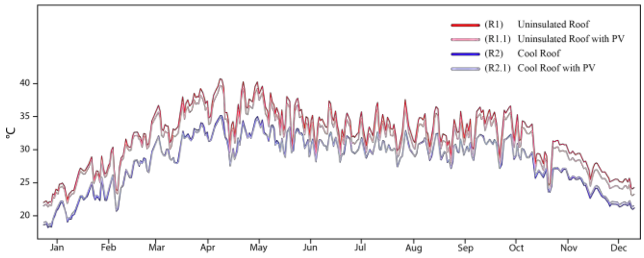

Fig. 5 — Predicted Indoor Roof Surface Temperature (Daily) for the different cases over a year

Both the Cool Roof (R2) and the Cool Roof with PV (R2.1) exhibit lower temperatures compared to the uninsulated roof. The Cool Roof maintains temperatures that generally remain below approximately 35 °C, even in the hottest months. During the peak of summer, the temperature differences between the roofing types are most pronounced, with the Cool Roof and Cool Roof with PV displaying better performance in reducing heat. During winter months, the inside surface temperature of the cool roof significantly decreases showing that cool roof is less effective at insulating and retaining heat during colder periods, especially when applied without insulation. For the PV installed roof variants, the uninsulated roof displays a temperature difference of 1 to 1.5 K, whereas a marginal change of 0.5 to 0.9 K is observed for the cool roof when compared with the cases without shading.

3.4 Implication on Cooling Demand

Fig. 6 shows the simulated cooling demand for the different roofing configurations annually. Here the generation from the PV has not been considered when estimating the cooling demand. The results only highlight the impact of the roofing retrofit and the shadowing effect of the PV on the cooling demand of the modelled residential building. The existing uninsulated roof (R1) registered the highest annual cooling demand at 4560 kWh, while the Cool roof (R2) retrofit by itself marked a substantial decrease in cooling demand to 3511 kWh, denoting a decrease of 23 % relative to the uninsulated roof. The integration of photovoltaic (PV) panels further reduces the roof affected cooling demand. The results show that the annual cooling demand is reduced from 4560 kWh to 4120 kWh for the uninsulated roof, and from 3511 kWh to 3396 kWh for the cool roof when the shading effect of PV is added. If the generation of the PV is added, then the PV production will be able to offset the cooling demand of the facility in addition to reducing the thermal loads for both the uninsulated and cool roof scenarios. However, this may require additional considerations of the heat flux calculations between the PV modules and the roof to estimate the energy benefits.

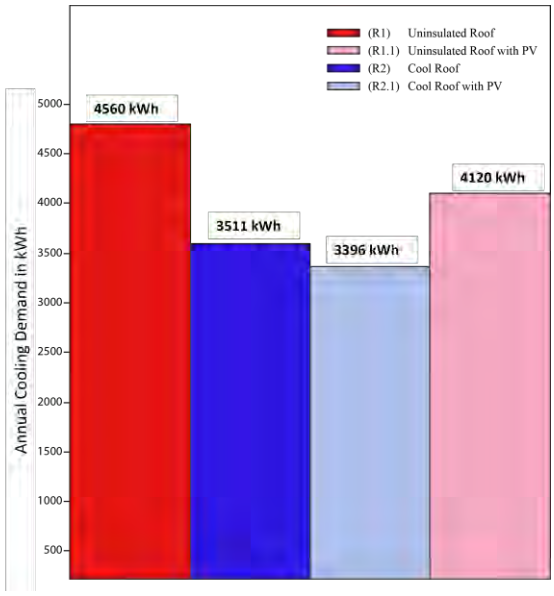

Fig. 6 — Predicted annual Cooling Demand for the Roof Variants

4. Future Work

The current study analyses a Rooftop Solar PV mounted at a height of 1.9 m in a building scale and does not detail out the convective and radiant heat transfer between the PV panel and the roof surface. Both the power generation of the PV and the energy balance of the entire roofing structure needs to be studied to evaluate the overall energy performance. Additionally, studies can benefit from the performance investigation of different types of Rooftop Solar PV (horizontal, attached, tilted) on roof coatings of different albedo values to identify the best performance for both, PV yield and building thermal load reduction. Furthermore, the possible heat island effect of large utility PV arrays in or close to urban settings (Gafford et al., 2016; Garshasbi et al., 2023) needs to be investigated further. Future studies can also be aided by experimental analysis to measure the actual effect of Solar PV to the building indoor environment, as well as changes to the urban micro-climate for building configurations in different climatic conditions.

5. Conclusion

The study described in this paper suggests that, for a single-storey residential building in a warm and humid climate, roof mounted Solar PV systems not only provides on-site renewable energy generation but also impart passive rooftop cooling due to roof shading thus enhancing indoor comfort as well as energy efficiency in buildings. The study concludes the following:

- The roof-mounted tilted Solar PV shading reduces the conductive roof heat gain of the uninsulated roof by 13.7 % when compared to the uninsulated roof alone for the single storeyed residence.
- By adding the mounted Solar PV to the cool roof, the conductive solar heat gain is reduced by 9 % compared to the cool roof alone.
- The predicted indoor surface temperatures of the roof show that during summer months shading by Solar PV can create a 1 to 2 K drop in indoor roof surface temperature for uninsulated roofs, while cool roofs show close to 0.5 to 1 K variation in temperature due to shading by the Solar PV.
- The shading effect of mounted and tilted Solar PV structures on uninsulated roof create more comfortable conditions indoors, reducing the cooling energy load by 440 kWh annually.
- Integration of Solar PV with cool roof further reduces the energy consumption of the building by providing shading effect to the roof, but this effect is greater for the uninsulated roof with no cool coating.
- The ease of retrofitting cool roofs, along with their complementary performance with Solar PV structures render them as a viable retrofitting option towards lowering the indoor temperature, proving more comfortable conditions indoor and thus reducing the cooling demand.
- For future studies in this area, the impact of the PV system's diurnal heat storage and release on local temperature variations, and subsequently on the building's cooling load, needs to be evaluated by considering a holistic heat balance of the PV system and building envelope. Additionally, the changes in microclimatic conditions resulting from large-scale deployment of PV systems over building surfaces must be examined to understand the broader implications on urban thermal environments and energy demands.

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