PV-COOL ROOFS Review

January 2022

Contents

Executive summary

Objectives:

This study is performed to review previous research concerning the effectiveness of the cool roof application on solar PV efficiency. Specifically, the purposes of this report are:

1. To review the benefit of using cool roof technology when implemented at different scales
2. To outlines the key findings of the integrated roof by highlighting a set of interrelated attributes and their impacts on the outdoor and indoor thermal environments, based on a literature review of existing research
3. To identify the most accurate method of measuring, examining and simulating PV panel efficiency
4. To classify effective criteria on the performance of PV systems and cool roof technologies

Data sources and study eligibility criteria:

Data sources, included Scopus, Web of Science and Google Scholar, were used in this review study. Snowballing was also used on full texts that met the inclusion criteria. Study eligibility criteria were included studies on “cool roof” OR “reflective roof “+ “PV” OR “solar panel” OR “photovoltaic”, focusing on the building or construction sector, in English and without time limitation.

Collectively, the following conclusions have been drawn:

1. The efficiency of solar PV integrated with cool roof application depends on different criteria, such as microclimatic conditions, local development context, building context, cool roof design and PV panel configurations **(Figure 1)**. Roof albedo was mentioned as the most important factor impacting on the efficiency of both cool roofs and PV panels. The inferences of the study are summarised in the following way:
    - For every 0.1 increments of roof albedo, the annual energy yield of PV increases by 0.71%-1.36%.
    - Every 0.1 increase in albedo leads to 14% cool roof improvement.
    - Every 0.1 increase in albedo creates a reduction in roof surface temperature by 3.1-5.2 °C. A decrease of 1 degree in roof surface temperature increases PV system efficiency by 0.2-0.9%.
    - Every 0.1 increment of roof albedo led to 0.58% surplus electricity.
    - For every 0.1 increments of roof albedo, heat flux decreases by 1.9%.

2. Integration of solar PV with cool roofs helps reduce peak electricity demand, and PV-cool roofs is able to generate more electricity than PV-green roofs. Green roofs can increase annual PV energy yield by 1.8%, and cool roofs, with higher albedo, can by 3.4%.
3. Although PV with a lower tilt angle have a higher performance during summer, and the systems with higher tilt angle have a higher performance during the winter season, the compensation of the cool roof paint can actually change the general understanding of the tilt angle of PV panels.
4. The higher albedo of the cool roofs can decrease roof surface temperature and increase the yield of PV and solar thermal systems.

Overall, existing literature suggests that the future improvement of PV-cool roofs could generate more electricity and decrease air temperature due to the significant reduction of excess heat release to the surrounding environment. The improvement could also result in a significant reduction of carbon emissions, reducing climate change on a larger scale. Hence, further research and government intervention options need to consider the specific microclimatic conditions, local development context, building context, cool roof design, and solar PV configurations when developing PV-cool roofs.

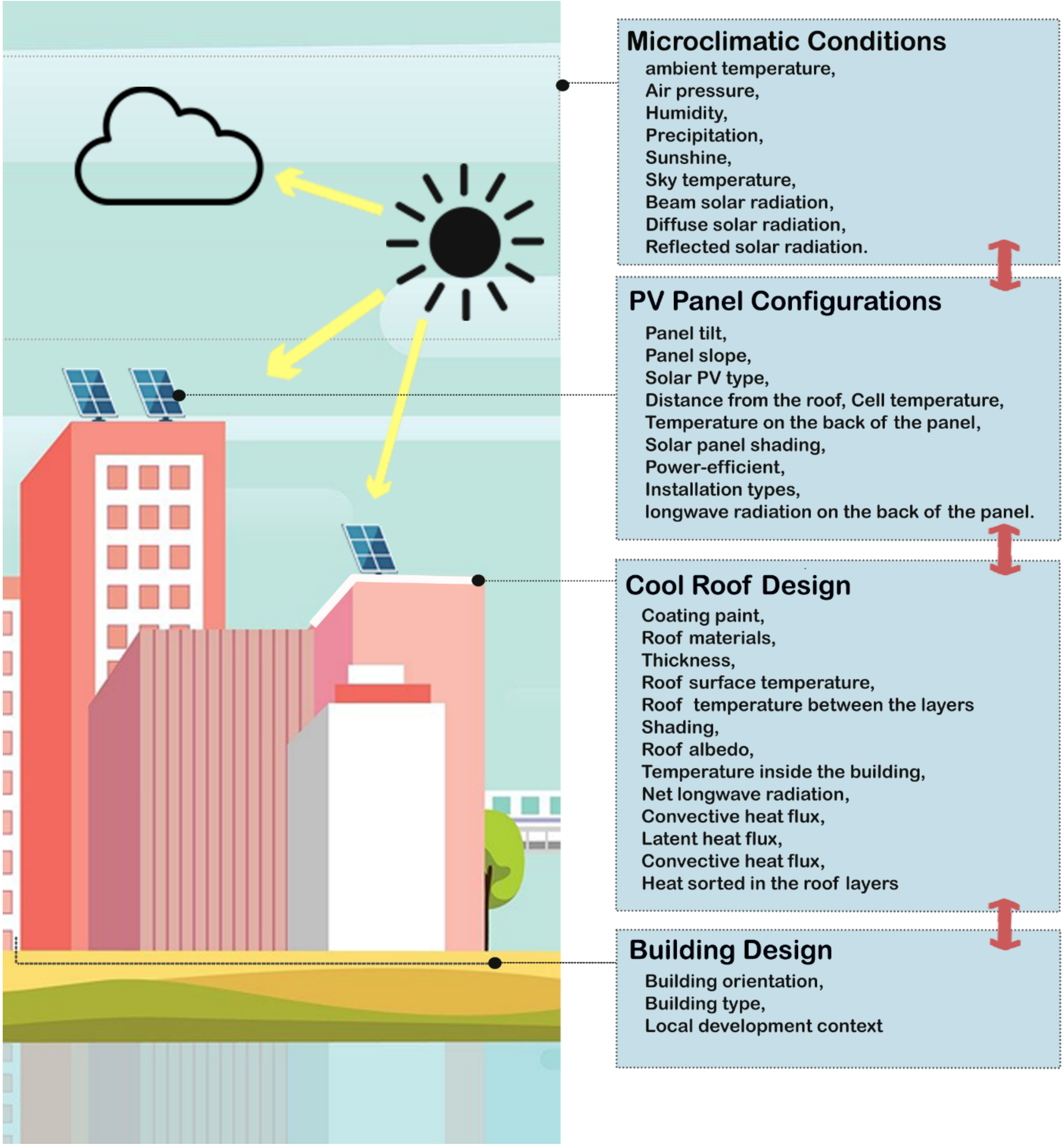

Figure 1 Criteria for evaluating the effectiveness of solar PV applications integrated with cool roofs application

1. Introduction

Currently, urban areas or metropolitan areas worldwide are significantly warmer than their surrounding rural areas because of the urban heat island (UHI) effect due to the increasing world's population and human activities. UHI is being exacerbated by local and regional climate change, which causes an increase in extreme temperatures, thermal distress, heat stress, and heat-related mortality and morbidity [1]. Overheating in urban areas is a well-documented phenomenon, occurring in more than 400 cities worldwide [2]. Urban overheating is largely caused by synoptic weather conditions, thermal properties of the materials (absorbing solar radiations or opaque surfaces that release heat), limited evaporative surfaces, lack of vegetation, anthropogenic heat released in the cities, reduction of wind penetration due to the urban texture, and the lack of heat sources or sinks in cities [1–5].

Several strategies have been studied to mitigate UHI and improve indoor thermal comfort (e.g. 6 and 7). [8] has reviewed several advanced cool materials systems used to mitigate urban overheating. Such materials could be implemented on roofs to reflect more heat to the sky (high albedo, high emissivity), reduce absorbed solar radiation, change the rate of long-wave radiation remit to the atmosphere and delay the heat transfer toward the inside the building (thermal mass and phase-change materials). This mitigation technology called cool roof techniques ((high solar reflective), also known as “albedo effect”, is a passive solution reducing the cooling load and energy consumption of a building envelope due to its modified surface properties, such as albedo and emissivity [9,10]. Cool roofs have also previously been shown to be a successful method for reducing summer overheating conditions to achieve global energy consumption reduction objectives. Research findings showed that daily peak surface temperature is 15 to 25 ◦C lower on cool roofs than darker roofs, which is even 5 ◦C lower than green roofs[11–13].

A study by [14] analysed the mitigation potential of the known mitigation technologies based on performance data from about 220 real scale urban rehabilitation projects. Regarding using of reflective materials installed on the roof of buildings or in pavements, the findings of the study showed that the average peak temperature reduction was close to 1.3 K for all the projects. Almost half of the projects experienced a peak temperature reduction below 1 K, and more than 80% fell below 2 K. Similarly, a recent study Study on the cool roofs mitigation potential in Australia by Santamouris et al. (2021) showed that the outdoor air temperature in major Australian cities could be reduced by 2.1- 2.5°C with solar reflective roofs – light coloured or cool coloured - which additionally reduce the cooling energy consumption of buildings. Likewise, [15] demonstrated that if white roof solutions spread worldwide in all cities, they could reach the targeted white reflective surface to eradicate the global warming effect. On the building scale, they found that it could save 10% on heating and cooling demand over a year.

In general, using cool roofs (by implementing retro-reflective materials and reflective coatings) gives a various level of benefits:

- On an urban scale, cool roofs reduce urban air temperatures by decreasing the quantity of heat transferred from roofs to the urban environment [5,14,16,17].
- On the building level, cool roof application improves indoor thermal comfort, and it decreases energy bills by decreasing the usage of mechanical air conditioning systems [18,19]. Cool roofs allow for the saving of electrical energy throughout the building and eliminate the threat of voiding warranty claims. According to [20] and [21], cool roof application can decrease ~10–40% in air conditioning energy.

- In the long run, a lower temperature on the roof reduces maintenance and, therefore, extends its lifespan [22].
- Cool roofs may also help improve the solar cells' efficiency in a Photovoltaic (PV) system for generating electricity [10,23].

Most studies focused on the impact of a cool roof on the indoor comfort in buildings, which is a critical factor for building environments; however, equally, it is essential to quantify the other benefits such as the benefits through other active systems, i.e., solar technologies. Moreover, Solar photovoltaic (PV) technology is a renewable energy technology that reduces greenhouse gas emissions, but little is known about how it affects UHI [24]. Therefore, there is a strong need to understand the interrelated attributes of cool roofs technologies integrated with solar PV and assess their impact in a holistic way to inform government policy and development assessment.

To support this need, the aim of this report is to review previous research concerning the effectiveness of the application of the cool roof on PV panels efficiency. The report is organised as follows: **Section 2** explains the methods that were carried out for this report. It is described into four sections: selected eligibility criteria, information sources, literature search and study records, and calculation methodology. The review results are discussed in **Section 3**, focusing on key findings extracted from relevant studies. Finally, the conclusion and research gaps are summarised in **Section 4**.

2. Methodology

2.1. Eligibility criteria

The following study characteristics were used as inclusion criteria for the review:

1. Studies on “cool roof” OR “reflective roof “+ “PV” OR “solar panel” OR “photovoltaic”,
2. Studies focused on the building or construction sector,
3. Studies published in English, and
4. Full text available.

2.2. Information sources

1. Search engines of Scopus, Web of Science and Google Scholar;
2. Snowballing from the included studies.

2.3. Literature search and study records

We used combinations of keywords and phrases related to cool roofs and PV solar panels to construct search strings:

- Search string for **SCOPUS** (search date 12/11/2021):
  (TITLE-ABS-KEY ("cool roof" OR "reflective roof") AND TITLE-ABS-KEY ("pv" OR "solar panel" OR "photovoltaic” OR “hpv”)) **[29 hits]**

- Search string for **Web of Science** (search date 12/11/2021):
  TS=("cool roof" OR "reflective roof") AND TS=("pv" OR "solar panel" OR " photovoltaic” OR “hpv”) **[16 hits]**

- Search string for **Google Scholar** (search date 01/12/2021):
  “cool roof” OR "reflective roof" AND "pv" OR "solar panel" OR " photovoltaic” OR “hpv” **[1,590 hits]**

Records from Scopus and Web of Science electronic databases were exported to Citavi reference management software. Reviewer screened the results of Google Scholar search by looking at the top 20 hits from each year between 2006 and 2021 (300 hits screened in total, 01/12/2021). After deleting duplicated records and the first screen, 35 articles were left, of which 30 of them was more relevant.

The majority of the studies were conducted in hot and warm climates, and there are few studies conducted on the cold, mild, mediterranean, and temperate climates. The top three continents were: North America, Europe, and Asia (**Figure 2**)

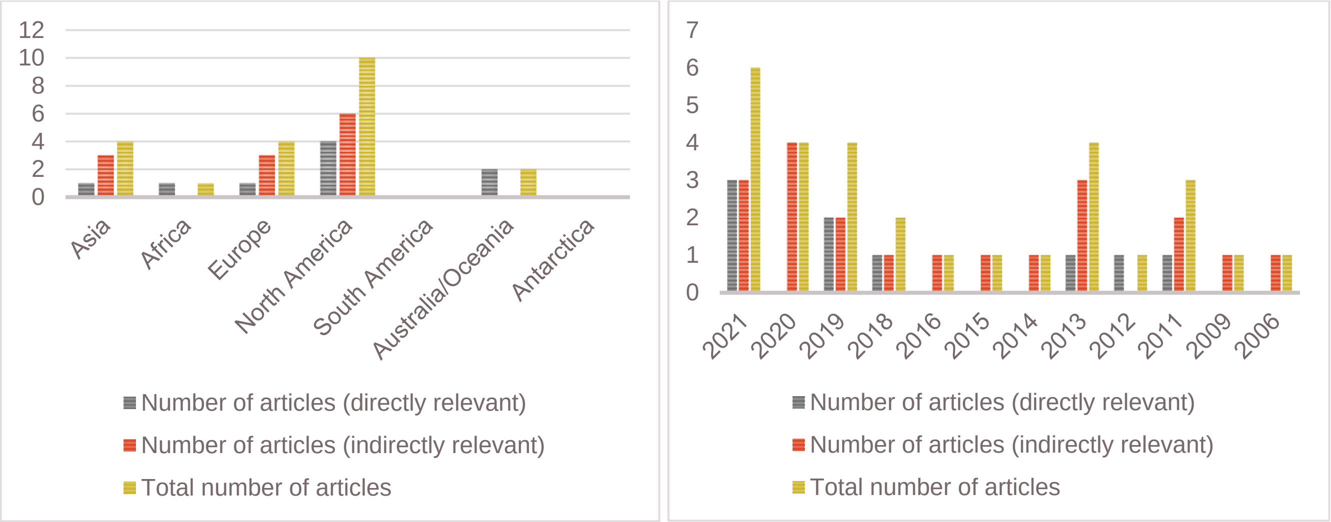

Figure 2 Number of papers from each continent and year

“Energy and Buildings” has been most active in this field by publishing almost 40% of selected papers, followed by “Applied Energy”, “Sustainable Cities and Society” and “Solar Energy” (**Figure 3**).

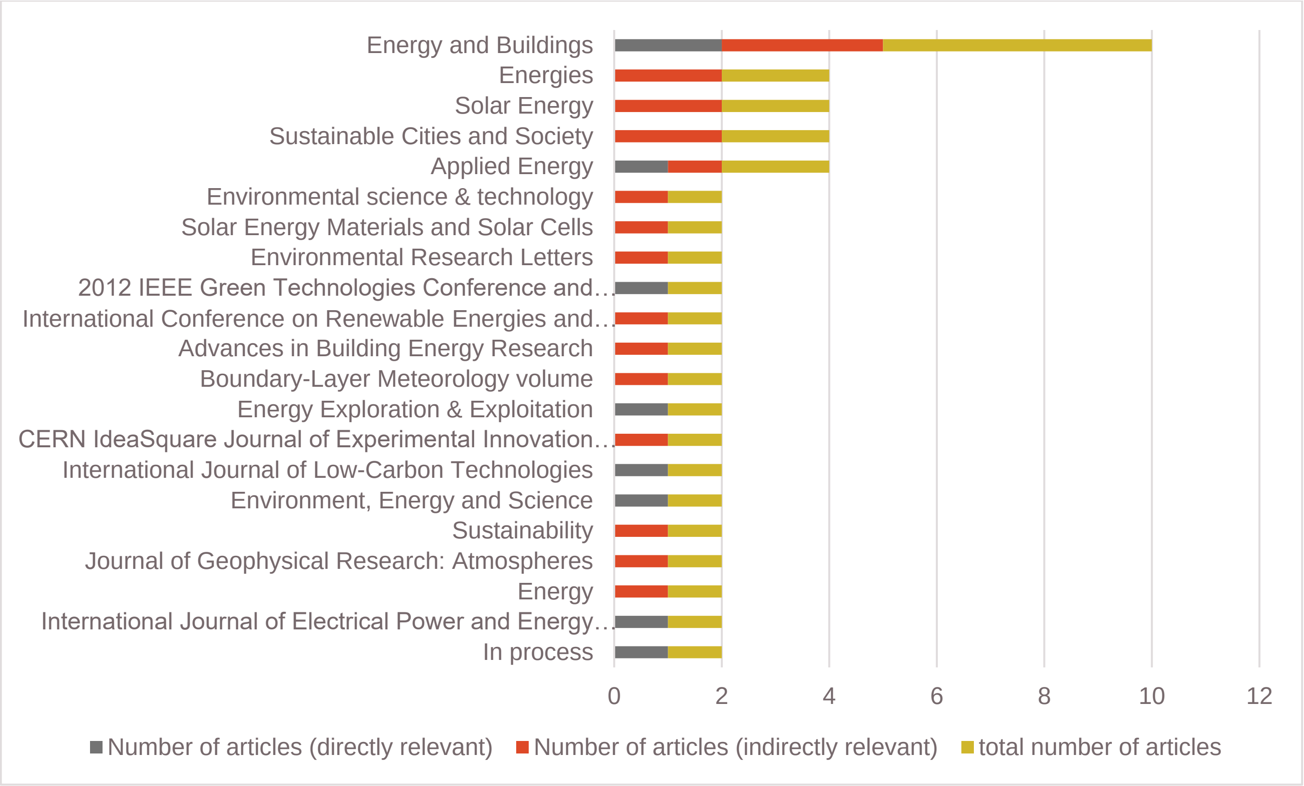

Figure 3 Number of papers published in relevant Journals or Conferences

More than two-thirds of selected papers provided case studies, experimental data, or simulation data, focusing on either cool roof technology or solar PV panels, but only 9 of them conducted a mix of cool roof and PV panels. **Table 1** shows characteristics (Article title, Country/climate type, Source title, Author/s, Year of publication, Research aim, Methods and finding) of the more relevant articles that were used in this review study. The articles were divided into “directly relevant” and “indirectly relevant”. Then, the calculation methods were explained for the most relevant articles.

Table 1 characteristics of the more relevant articles that were used in this review study (**Directly relevant**: blue sections, **Indirectly relevant**: green sections)

Article title	Country/climate type	Source Title	Author/s	Year of publication	Research aim	Methods	Findings
"Study on the Cool Roofs Mitigation Potential in Australia"	Australia	In process	Santamouris, M., M.Papadopoulos, A., Paolini, R., Khan, A., Bartesaghi Koc, C., Haddad, S., Garshasbi, S., Arasteh, S. and Feng, J	2021	▪ To evaluate the current climatic conditions in major Australian cities, understand the characteristics of urban overheating ▪ To evaluate the magnitude and spatial variation of the mitigation /cooling potential of cool roofs when implemented at the city scale ▪ To investigate the impact of cool roofs on the cooling/heating energy needs and indoor air temperature for different building types of buildings in all capital cities.	▪ Meso-scale climate modelling ▪ Building energy simulations ▪ Building modelling	▪ Mortality increased by 5% for every 1 degree increase in daily maximum temperature ▪ A city-scale deployment of cool roofs reduces the maximum peak ambient temperature by 2.1°C - 2.5°C, which means for every 0.1 increments of roof albedo, the ambient temperature increases by 0.3-0.35°C. ▪ In existing (pre-code) buildings without or with low insulation levels, the cooling energy savings achieved with cool roofs are significant. For instance, the annual energy savings in a low-rise office building without insulation are 22.2-39.9 kWh/m2 (34.7-42.3 %) in Sydney, 4.0-9.7kWh/m2 (12.3-27.6%) in Melbourne, and 34.2-52.2kWh/m2 (33.8-39.4%) in Brisbane. ▪ In new buildings with high level of insulation (NCC 2019 DtS levels), the cool roofs savings are relatively less than that in old buildings. For instance, the annual energy savings in a new low-rise office building is 1.6-8.3 kWh/m2 (4.6-18.2 %) in Sydney, 0.2-1.0 kWh/m2 in (1.2-4.6 %) Melbourne, and 3.4-5.2kWh/m2 (4.6-6.0%) in Brisbane. ▪ In residential buildings: Indoor air temperatures in houses are also reduced by up to 4°C in new houses with high insulation (NCC 2019 DtS), with the number of hours exceeding 26°C reduced by even 100 hours per month (summer only) compared with a conventional solar absorptive roof.
"Green and cool roof choices integrated into rooftop solar energy modelling"	Zurich, Switzerland	Applied Energy	Cavadini, GB; Cook, LM	2021	▪ To develop a calculation method that takes into account the characteristics of roof surface when simulating PV panel energy yield. ▪ comprehend how four roofing configurations (black membrane, white membrane, rock ballasted and vegetated) effect PV panel yield	▪ The modified System Advisor Model (SAM) ▪ Rooftop energy balance model to estimate the roof surface temperature, (this stage provides input to the modified SAM version)	▪ The adapted SAM model contribute planners and stakeholders to compare the benefits of different rooftop configurations ▪ The thickness and the thermal conductivity of the roof have a huge impact on surface temperature. ▪ A sustainable roofing configuration could increase the annual energy yield of PV panels in Zurich by 3.4% for a cool roof, on average. It shows that for every 0.1 increments of roof albedo, the annual energy yield of PV increases by 0.71%.

							▪ For green and cool roofs, respectively, surplus electricity could represent 15% and 28% of the annual household electricity consumption. ▪ Changing to cool roofs would produce, on average, 60 GWh more per year.
“Cool roof coating impact on roof-mounted photovoltaic solar modules at texas green power microgrid”	Texas, United States	International Journal of Electrical Power and Energy Systems	Rahmani, F., Robinson, M.A. and Barzegaran, M.R.	2021	▪ To analyse and present the impacts of cool roof coating on roof-mounted photovoltaic solar modules at texas green power microgrid	▪ Modeling thermal analysis by installing the THERMAX ▪ Analysing critical characteristics of the solar cells ▪ Installing Tigo power optimiser at each module ▪ Applying a power efficiency comparison between cool and hot surfaces ▪ Comparing the percentage of power generation by cool/hot module along with load and battery performances ▪ Comparing ENERGY STAR® certified cool roof by changing cool roof characteristics	▪ Sol-air temperature measurement showed an increase in system efficiency of 0.15% when cooling load was reduced by 0.5◦F/0.3 ◦C. ▪ A 14.9% increase in overall efficiency. ▪ An additional 10.41% of solar power and an extra 9.37% of current production when comparing cool and hot energy sources.
“Urban surface uses for climate resilient and sustainable cities: A catalogue of solutions”	-	Sustainable Cities and Society	Croce, S. and Vettorato, D	2021	▪ To explain the role of urban surfaces in developing climate resilient and sustainable cities ▪ To propose a catalogue of solutions for the urban surface use. The catalogue offers the main surface uses suitable for the built environment. It also discusses the potential conflicts and synergies among them in the view of a multiple and integrated utilisation of urban surfaces.	▪ Classification of urban surfaces ▪ Literature review: a collection of surface uses ▪ Categorisation and analysis of surface uses ▪ Identification of conflicts and synergies among surface uses	▪ The improvement of urban surfaces will provide opportunities to improve urban environments, social and economic resilience.
“Energy Performance of Integrated Adaptive Envelope Systems for	United States	Energy	Dehwah, A.H. and Krarti, M	2021	▪ To evaluate the energy performance of an integrated adaptive envelope system (AES) applied to detached houses in four US	▪ Analysis of two extreme scenarios to understand the impact of PV panels on heating thermal loads, when deployed on a static cool roof	▪ Residential buildings can save a significant amount of energy through integrated AES. With the AES installed in a US home, they can almost achieve net-zero energy designs, especially in hot and mild climates

Residential Buildings”					climates. AES includes three main technologies: cool roofs, switchable insulation systems (SISs), movable PV-integrated shading devices (MPVISDs)	▪ Estimation of PV electricity output using EnergyPlus accounting for the MPVISD position	▪ Depending on local climate, the integrated AES offers energy savings ranging from 234 kWh/year to 949 kWh/year.
“Exploring the Effects of Rooftop Mitigation Strategies on Urban Temperatures and Energy Consumption”	-	Journal of Geophysical Research: Atmospheres	Zonato, A.; Martilli, A.; Gutierrez, E.; Chen, F.; He, C.; Barlage, M.; Zardi, D.; Giovannini, L.	2021	▪ To describe and evaluate physical parameterisations accounting for the influence of “rooftop mitigation strategies (RMSs) *on* the urban environment in the context of the mesoscale model Weather Research and Forecasting (WRF)”	▪ Two-dimensional idealised simulations with the mesoscale WRF model in the urban environment	▪ During summer, cool and green roofs reduce near-surface air temperatures. ▪ A cool roof is the most efficient at reducing air temperature, followed by an irrigated green roof. ▪ Instead, photovoltaic panels cause a rise in temperature in the daytime and a slight decrease in the nighttime. ▪ Cool roofs are the most energy-efficient way to reduce the consumption of air conditioning. ▪ A green roof maintains a higher near-surface air temperature during the winter than clay tile roofs, thereby reducing energy consumption substantially. ▪ In the urban environment, the parameterisation schemes incorporated into the WRF model can be a valuable tool for evaluating mitigation strategies.
“Investigation of the impacts of microclimate on PV energy efficiency and outdoor thermal comfort”	Brampton, Ontario	Sustainable Cities and Society	Berardi U., Graham J.	2020	▪ To investigate the trade-offs between large-scale deployments of rooftop PV, cool roofs, and street trees. ▪ To compare each intervention by examining the impact on the PV efficiency and the Universal Thermal Climate Index (UTCI) values.	▪ Simulation by 3D CFD model ENVI-met to address outdoor thermal comfort and PV energy efficiency	▪ large adoptions of rooftop PV instead of cool roofs can make outdoor environment 0.5 °C hotter during heatwaves ▪ Depending on their height and location, street trees can decrease the output of rooftop PV significantly. This points to the need for solar access laws, which are currently missing in Ontario.
Thermo-optic durability of cool roof membranes: Effect of shape stabilised phase change material inclusion on building energy efficiency	-	Energy and Buildings	Fabiani, C.; Piselli, C.; Pisello, A. L.	Energy and Buildings	▪ To clarify whether PCM inclusions can help the membrane behave better over time due to the reduction of thermal stress.	▪ Experimental set up	▪ A 25% PCM increase in weight optimises the surface finishing characteristics of the prototype, enabling a more stable thermo-optical behavior, thus reducing both thermal-induced degradation and leakage.

“A materials perspective on radiative cooling structures for buildings”	-	Solar Energy	Li W., Li Y., Shah K.W.	2020	▪ To overview of the materials compositions and nano/microstructures of radiative cooling technology. ▪ To summarise morphologies, substrates, properties, and performances of the selective emitting material, back-mirror material reflecting material, insulation material, matrix material, and dynamic switching material, in terms of their.	▪ Systematic review	▪ Using a combination of multiple layers and nanostructures is better for design of radiative cooling composites from a materialistic perspective. ▪ An overview of nanomaterials and composite structures that can be used to optimise the design configuration for radiative cooling applications.
“Energy Savings on an Industrial Building in Different Climate Zones: Envelope Analysis and PV System Implementation”	Mexico	Sustainability	Espino-Reyes, CA; Ortega-Avila, N; Rodriguez-Munoz, NA	2020	▪ To analyse the typical envelope of industrial buildings in Mexico as well as the impact of industrial rooftop photovoltaic systems on annual energy consumption.	▪ Simulation using TRNSYS 17 USA to evaluate the thermal behavior of the building over a year on an hourly basis.	▪ Cool roof application on a non-insulated layer or to simply insulate the roof is the best option for cities with warm climates. ▪ In warmer climates, rooftop PV systems would be most beneficial for industrial buildings with metallic roofs.
“Assessing the Impact of Solar Photovoltaics and Air Conditioning Waste Heat on Urban Heat Island Effects”	Australia	Environment, Energy and Science	Lan Ding, Baojie He, Henry Petersen, William Craft, Jinda Qi, Mattheos Santamouris, Deo Prasad	2019	▪ To assess the impact of solar PV and a/c Waste heat on urban heat island effects’ along with an extension of the microclimate and Urban heat island mitigation decision-support tool	▪ Review of existing research ▪ Using advanced software including PALM (Parallelised Large Eddy Simulation (LES) Model) and TRNSYS ▪ Using CRCLCL UHI-DS Tool to incorporate solar PV and A/C options for the UHI scenario analysis	▪ Solar PV and A/C waste heat can contribute to increased temperatures in the outdoor air ▪ A combination of UHI mitigation strategies, such as cool roofs, contributes to reducing outdoor air temperatures within cities and precincts.
“An experimental study of the impact of cool roof on solar PV electricity generations on building rooftops in Sharjah, UAE”	Sharjah, UAE	International Journal of Low-Carbon Technologies	Altan, H; Alshikh, Z; Belpoliti, V; Kim, YK; Said, Z; Al-chaderchi, M	2019	▪ To investigate the impact of cool roof applications integrated with solar PV panels for the Middle East climatic conditions	▪ Developing and modifying System Advisor Model (SAM) ▪ A rooftop energy balance model used to estimate the roof surface temperature, as input to the modified SAM model	▪ There is a possible impact of 5–10% improvement with the cool roof applications. ▪ Mainly climatology, geographical region and PV configrations affect the performance of PV systems ▪ A PV panel with a cool coating generate more power at angle 45, largely due to the greater amount of reflection and solar radiation generated by the cool coating ▪ “Cool Carpet” case performe more effectively at 45 and 35 degrees as can be seen in the difference between the average of power

							difference. The average power difference at angle 45 is 2.9%, and at angle 35 it is 4.0%.
“Evaluating the Operational Potential of LRV Signatures Derived from UAV Imagery in Performance Evaluation of Cool Roofs”	South Korea	Energies	Park, S.I., Ryu, T.H., Choi, I.C. and Um, J.S.	2019	▪ To evaluate and compare white and black roof with different Light Reflectance Value (LRV) and surface temperature	▪ Using Unmanned Aerial Vehicles (UAVs) to evaluate the energy-saving performance of a cool roof.	▪ Whitish roof had LRV: 91.36, and rooftop surface temperature: 38.03 degrees C, and blackish color roof had LRV: 18.14, and rooftop surface temperature: 65.03 degrees C ▪ There was a strong negative correlation between the LRV and the surface temperature, implying that a higher LRV (e.g., a white color) is important in lowering the surface temperature.
“White roof as a multiple benefits low-cost technology: a state of the art”	-	CERN IdeaSquare Journal of Experimental Innovation (CIJ)	FrancescGiordano, Zeynep Tulumen , Raphaël Sanchez, Giovanni Magnacca	2019	▪ To explores the potentiality of white roof as an effective solution to address global warming, urban heat island effect and energy consumption in buildings	▪ Literature review and prototyping	▪ Literature findings are used to investigate the effects of white roof technology on building energy efficiency.
“A review of roofing methods: Construction features, heat reduction, payback period and climatic responsiveness”	-	Energies	Abuseif, M. and Gou, Z	2018	▪ To review studies about roofing methods for flat roofs. Ten roofing methods are reviewed in this paper.	▪ Systematic literature review using the Web of Science database	▪ Suggestion of basic principles for selecting appropriate roofing methods. The right choice and the right implementation of these methods can eliminate the need for HVAC systems, while others can achieve a high degree of heat reduction. ▪ A wrong selection could result in mild to severe energy penalties.
“Combination effects of roof coating and solar photovoltaic system in the tropical region of Ghana: A case study”	Ghana	Energy Exploration & Exploitation	Wisdom Opare - Can Kang - Yiping Gu - Ning Mao	2018	▪ To investigate the combination effects of roof coating and solar PV system in tropical region of Ghana	▪ Computational fluid dynamics simulation	▪ A coated roof reduces the building's temperature considerably, enhancing thermal comfort. ▪ A total of 427.670 MW h/year could be fed into the national grid with the participation of the solar photovoltaic module. ▪ The reduction in power generation costs can be achieved by combining a solar photovoltaic system with the roof coating.
“Citywide impacts of cool roof and rooftop solar photovoltaic deployment on near-surface air temperature and	United States	Boundary-Layer Meteorology volume	Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui,	2016	▪ To investigate the summertime regional impacts of cool roofs and rooftop solar PV deployment on cooling energy demand and near-surface air temperature and (for the two major	▪ Modelling system using the non-hydrostatic (V3.4.1) version of theWeather Research and Forecasting (WRF) model joined to the multilayer building energy (BEP+BEM) system	▪ A deployment of cool roofs and rooftop photovoltaic panels reduces near-surface air temperatures across the diurnal cycle and decreases daily citywide cooling energy consumption. ▪ At daytime, cool roofs provide better cooling than rooftop solar photovoltaic systems,

cooling energy demand.”			M. and Martilli, A		Arizona cities of Phoenix and Tucson).		but at night, solar panels are better at reducing the UHI effect. ▪ The maximum coverage rate deployment of cool roofs reduced citywide cooling energy demand by 13–14 %, while the rooftop deployment of solar photovoltaic panels reduced energy usage by 8–11 %. ▪ Deployment of both roofing technologies, cool roof and photovoltaic roof, have multiple benefit for the cities and urban environment.
“On the effect of roof added photovoltaics on building’s energy demand”	Greece	Energy and Buildings	Kapsalis, V.; Karamanis, D.	2015	▪ To investigate the PV roof effect annually on building’s energy demand (reducing the cooling and heating building loads) during different seasons	▪ Simulation by TRNSYS ▪ Experimental set up	▪ Based on the simulation results, seasonal heating loads increase by 6.7% and cooling loads decrease by 17.8% in the top floor under typical energy management considerations. The BAPV roof external flow is dominated by complex and time-dependent conditions and strongly influenced by the temperature difference between the surface and the fluid. ▪ the top floor of the building's energy performance improves due to a decrease in total weighted heating and cooling load demands by 3.2% on an annual basis. ▪ In order to achieve efficient design and enhanced net zero energy operations, the effect of roof added PV panels needs to be taken into consideration for seasonal strategies.
“Simulation of the cooling effect of the roof-added photovoltaic panels”	Greece	Advances in Building Energy Research	Kapsalis, Vasilis C.; Vardoulakis, Eftychios; Karamanis, Dimitris	2014	▪ To examine the shading and cooling effects of roof-mounted photovoltaics (PV)	▪ TRNSYS simulation ▪ Experimental study	▪ PV panels have a significant effect on roof surface temperature between shaded and exposed portions of the roof during the summer. ▪ As well as generating electricity, the rooftop PV system can passively reduce the daily rooftop cooling energy and peak load during the hot summer days.
“Electricity production and cooling energy savings from installation of a building-integrated photovoltaic roof on an office building”	Yuma, AZ	Energy and Buildings	Ban-Weiss, G; Wray, C; Delp, W; Ly, P; Akbari, H; Levinson, R	2013	▪ To demonstrate the impact of building-integrated photovoltaic roof on electricity production and cooling energy saving in office buildings.	▪ Experimental study ▪ Building energy simulations	▪ After installation of the BIPV, the roof's solar absorption decreased to 0.38 from 0.75, lowering summertime upper surface temperatures by about 5 degrees C. ▪ During summertime, the roof deck has a daily heat flux of +/- 0.1 kWh/m2 as opposed to 0.3-1.0 kWh/m2. ▪ BIPV significantly reduced daily heat flux from the ventilated attic to the conditioned space in the summer, suggesting a decoupled roof.

“Evaluation of Renewable Energy Technologies in a net Zero Energy Office Building in Germany”	Germany	International Conference on Renewable Energies and Power Quality (ICREPQ’13) Bilbao (Spain)	Spitalny, L., Unger, D., Maasmann, J., Schwerdt, P., Van Reeth, B., Thiemann, A. and Myrzik, J.M.A.	2013	▪ To analyse the operation in a daily office routine and to organise building's power supply and demand ▪ To analyse the impact of high reflecting roof coating on the photovoltaic efficiency and yield	▪ Experimental study	▪ A HR-coating (high reflecting coating) can increase the efficiency of building air conditioning and the benefit of renewable energy technologies. ▪ HR coatings have a higher albedo, increasing the yield of solar PV and solar thermal systems. ▪ A lower temperature on the roof surface has a positive effect on HVAC systems.
“A new design of metal-sheet cool roof using PCM”	Taiwan	Energy and Buildings	Chou, Huann-Ming; Chen, Chang-Ren; Nguyen, Vu-Lan	2013	▪ To present an improved design strategies for metal sheet roofing in order to increase its thermal resistance ▪ To investigate Phase Change Materials (PCM) properties to absorb the downward heat flow and release it back to the environment	▪ Experimental and numerical analyses ▪ Mathematic equation system ▪ solar simulation system	▪ Through the new design, it is possible to effectively reduce the downward flow of heat in the house from the roof. ▪ It was found that the phase change property of PCM could be utilised not only to store thermal energy, but also to enhance the thermal insulation effect of the combined PCM structure. ▪ This will result in a lower cooling load for the house and a reduction of the amount of electricity required for cooling.
“The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas”	United States	Solar Energy	Taha, H	2013	▪ To evaluate the potential atmospheric impacts of solar PV deployment in meteorological modeling	▪ Simulation	▪ The simulations show that large-scale PV deployment has no adverse impact on air temperature or urban heat islands.
“Thermal Comparison of Reflective (White) and Non-reflective (Black) Roofs Using Thin-Film Solar Panels”	Edwardsville, Illinois	2012 IEEE Green Technologies Conference and master thesis	Irvine, G., Celik, S.	2012	▪ To illustrates an experimental and comparative thermal analysis of two types of roofing membranes (reflective and non-reflective roofing membranes) matched with thin-film photovoltaic (PV) panels.	▪ Experimental study	▪ There is a difference in interface temperatures between thermoplastic olefin (TPO) and ethylene propylene diene monomer (EPDM)/PV assemblies, which could affect the degradation of the roofing material as well as the performance of the solar panels depending on the material used in fabrication.
“Modeling impacts of roof reflectivity, integrated photovoltaic panels and green roof systems on sensible heat flux	Portland Oregon	Energy and Buildings	Scherba, A; Sailor, DJ; Rosenstiel, TN; Wamser, CC	2011	▪ To explore the impacts of sustainable roofing technologies on the rooftop energy balance, and sensible heat flux with a focus on the summertime urban heat island.	▪ Energy balance models were developed ▪ Simulation with EnergyPlus ▪ Experimental measurements	▪ Black roofs and black-PV roofs have the highest sensible heat flux to the environment, ranging from 331 to 405 W/m. ▪ An average of 11% less flux was produced by PV panels on black roofs compared to a white roof.

into the urban environment”							▪ The total sensible flux was substantially reduced when a black roof was replaced with a white or green roof. ▪ Compared to a black membrane roof, a PV-covered white or green roof reduced the total sensible flux by 50%
“Regional climate consequences of large-scale cool roof and photovoltaic array deployment”	United States	Environmental Research Letters	Millstein, D; Menon, S	2011	▪ To investigate the impacts of modifying surface albedo on regional climate and radiative effects produced by mass deployments of cool surfaces and photovoltaic arrays across the United States.	▪ Weather Research and Forecasting (WRF) model version ▪ Experimental measurements ▪ Installation of solar generating systems in the desert (SOL)	▪ Implementing and using cool roofs and pavements resulted in domain-wide yearly average outgoing radiation to increase by 0.16 +/- 0.03 W/m(-2) (meaning +/- 95% C.I.) and afternoon summertime temperature in urban places was reduced by 0.11-0.53 degrees C. ▪ In reply to increased urban albedo, some rural locations demonstrated summer afternoon temperature rise of maximum +0.27 degrees C and these areas were closely connected with less cover of cloud and lower precipitation. ▪ Solar arrays had an impact on local and regional wind patterns within a 300 km radius.
“Effects of solar photovoltaic panels on roof heat transfer.”	United States	Environmental Research Letters	Millstein, D; Menon, S	2011	▪ To measure the thermal conditions across a roof profile partially covered with solar photovoltaic (PV) panels in San Diego, California	▪ Weather Research and Forecasting (WRF) model version ▪ Experimental measurements ▪ Installation of solar generating systems in the desert (SOL)	▪ A thermal infrared image taken on a clear April day showed the PV arrays to be 2.5 K cooler than the exposed roof during the day. ▪ Under the PV array, daytime roof heat flux was significantly reduced. ▪ During the night, the solar arrays were warmer than the exposed roof, indicating that they acted as insulators. ▪ A PV covered roof did not reduce the annual heating load but did reduce annual cooling load by 5.9 kWh m2 or 38%. ▪ As a result of having reduced daily variation in rooftop surface temperatures under the PV array, energy savings and/or human comfort benefits are realised, particularly on older warehouse buildings with rooftop PV.
“Optimised cool roofs: Integrating albedo and thermal emittance with R-value”	-	Solar Energy Materials and Solar Cells	Gentle, A. R.; Aguilar, J. L.C.; Smith, G. B.	2011	▪ To systematically analysis the contribution of roof design to avarage cooling load and to peak load reduction. ▪ To demonstrate the importance of high albedo, while sensitivityto R-value and E drops away as albedo rises.	▪ Systematic analysis	▪ The peak cooling load can be dramatically reduced by switching to high albedo (low A_{sol}) regardless of R-value, but especially at Rr1.63. ▪ As roof albedo and emittance rise, lower R-values offer little or no penalty in peak load benefits or overall energy savings associated with reduced cooling demand.
“Net radiative forcing from widespread	-	Environmental	Nemet, Gregory F.	2009	▪ To understand the impact of radiative forcing and land use change	▪ Using a series of equations to do comparision	▪ The avoided radiative forcing due to the substitution of PV for fossil fuels is

deployment of photovoltaics”		science & technology			▪ To compare the amount of radiative forcing avoided by substituting PV with fossil fuels		approximately 30 times larger than the forcing caused by the modification of albedo. ▪ Albedo effect significantly reduces the climatic benefits of PV ▪ It is important that we know how to deploy solar PV, not how much to deploy
“Influence of a building's integrated-photovoltaics on heating and cooling loads”	Tianjin, China	Applied Energy	Wang, Y., Tian, W., Ren, J., Zhu, L., Wang, Q.	2006	▪ To assess the impacts of BIPV on the building's heating-and-cooling loads, by applying on four different roofs: namely ventilated air-gap BIPV, non-ventilated (closed) air-gap BIPV, closeroof mounted BIPV, and the conventional roof with no PV and no air gap.	▪ Modeling and Simulation	▪ PV roofs with ventilated air gaps are suitable for the application in summer due to the low cooling load and high PV conversion efficiency. ▪ Comparing PV roofs with ventilation air-gaps, the PV roof with ventilation air-gap has a long time lag and a small decrement factor, and it has an absorption coefficient of 0.4, the same as a cool roof. ▪ BIPV with a non-ventilated air gap can be more appropriate in winter because the PV roof has less heating load and the PV output is higher.

3. Calculation methods

This section elaborates calculation methods for the three most relevant articles:

3.1. “Green and cool roof choices integrated into rooftop solar energy modelling”: by [13]

Currently, there are different solar energy models such as System Advisor Model[1] [25], PVlib [26], and PVSYST [27] that use energy and mass equations to simulate a range of PV configurations and climatic systems. These models, however, do not take the contribution of rooftop type into account in predicting surface temperatures. For instance, to assess the feasibility of solar PV installations, stakeholders widely use the System Advisor Model (e.g., 28 and 29), which assumes that the rooftop surface temperature is equal to the ambient temperature. Such assumptions make it impossible to compare the energy yield of PV systems on green and reflective roofs. Due to this gap, a study by [13] have developed a method that “can be used by stakeholders to compare the energy yield of PV installations on different rooftop configurations, including traditional (black membrane or rock ballasted) and sustainable (green and reflective) roofs” [13]. They used two models to quantify the influence of the roofing configuration on rooftop PV energy yield, including: 1) A modified version of the SAM to simulate PV panel energy yield, and 2) A rooftop energy balance model to estimate the roof surface temperature, which is given as input to the modified SAM version

3.1.1 A modified version of the SAM to simulate PV panel energy yield

Standard SAM assumes that the rooftop surface temperature is equal to ambient temperature. The following equations were used to SAM calculation:

$$P_{out} = I_t * A_m * \eta_{OC} \qquad (1)$$

Where (I_t) is solar radiation, P_{out} is the power output and refer to the product of available I_t, A_m is module area, and η_{OC} is the panel conversion efficiency at operating conditions which depends on the panel cell temperature.

$$\eta_{OC} = (\eta_{ref} * \ 1 - \beta * (T_{cell} - T_{ref})) \qquad (2)$$

“Where η_{OC} is the panel conversion efficiency at operating conditions [-], η_{ref} is the panel conversion efficiency at reference conditions (usually an irradiance of 1000 $W\,m^{-2}$ and an ambient temperature of 25 $^{\circ}C$) [-], β is the temperature coefficient of the cell [$^{\circ}C^{-1}$], T_{cell} is the cell temperature [$^{\circ}C$] and T_{ref} is the ambient temperature at reference conditions [$^{\circ}C$].” [13]

As discussed above, Standard SAM heat transfer model assumes that both the surface temperature and the temperature on the back of the panel are equal to the ambient temperature. However, the roof's surface

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[1] “System Advisor Model (SAM), developed by Neises et al. (2012) , is an open source software, is widely used to evaluate the technical and economic feasibility of renewable energy installations. To model rooftop solar energy installations, SAM implements a set of physically-based equations to consider the heat fluxes between the PV modules and the roof surface, which accounts for the influence of roof surface temperature and albedo on PV panel power output” [13].

temperature is higher than the ambient temperature, and heat is released from the ground beneath the panel, leading to an increase in the air temperature below. Additionally, the air on the back of the panel can be poorly ventilated and mixed with the ambient air. Because the roof surface temperature can be higher than the ambient temperature, this assumption misestimates the amount of radiant and conductive heat flow towards the solar panel, especially during the radiation peak at noon. Consequently, it might lead to an overestimating PV power output due to the underestimation of PV cell temperature.

In order to address this gap, rather than using the conventional assumption that the roof's surface temperature equals the ambient temperature, a time series of surface temperatures is given as the input to the modified version of SAM. The following equations were used to the modified SAM calculation:

$$T_{back} = (T_{amb} - T_s) * f_{conv} + T_s \qquad (3)$$

Where T_{back} is the air temperature on the panel back [◦ C] used to compute the adapted convective heat flux. T_{amb} is the ambient air [◦C], T_s is the roof surface temperature [◦ C], and f_{conv} is the temperature factor [-], quantified how well the air behind the panel is mixed, which is specific to the PV installation.

According to temperature factor f_{conv}, it is assumed that the air temperature behind the panel (T_{back}) lies somewhere between the ambient temperature and the surface temperature of the roof. f_{conv} is an empirical factor that need to be adjusted for each PV installation. This factor depends on the slope of the panels, the distance between the panels and the roof and the ventilation on the roof. According to an example, [13], if f_{conv} is equal to 0, T_{back} is equal to T_s , signifying no mixing. Instead, if f_{conv} is equal to 1, it means that the back of the panel is well ventilated and the temperature is in equal to ambient air, similar to the standard SAM assumption. **Figure 4** illustrates an overview of the heat exchange on a rooftop with PV panels.

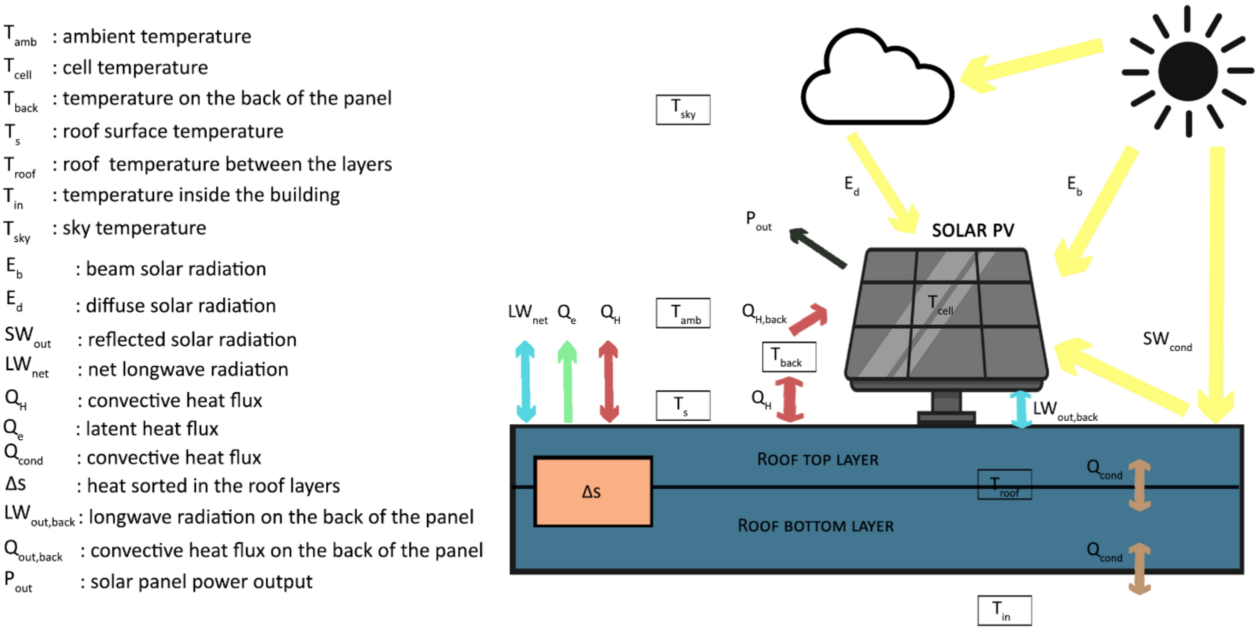

Figure 4 Overview of the heat exchange on a rooftop with PV panels. Source: Adapted from [13]

3.1.2 A rooftop energy balance model, used to estimate the roof surface temperature: as input to the modified SAM version.

A roof energy balance model, used for simulation of roof surface temperature, provides input for the modified SAM model. To provide input for the modified SAM, we need 6 general parameters, describing roof characteristics and material proprieties: Roof area [m2], Albedo [α], emissivity [ε], Roof view factor, Ponding factor, Crop coefficient, and 4 specific parameters to each roof layer, and therefore considered for both top and bottom layers: Thickness (z), thermal conductivity (λ), heat capacity (C_p), and density (ρ).

[13] started model calibration and validation by modelling two same layers, including a bottom concrete layer and a top covered layer with different materials: either membrane (black or cool roofs), gravel (rock ballasted), or soil (green roof). Roof surface temperature were measured with a FLIR C3 infrared camera in August 2020 in Dübendorf, Switzerland. A visual observation, assessment and comparison of the simulations of the roof surface temperature align with an evaluation of several goodness of fit measures (GOF) was used to calibrate the roof energy balance model. [13] also quantified the error by computing GOF measures which included “root mean square error” (RMSE), “mean biased error” (MBE), “squared correlation coefficient” (r2) and total error. They found 7.8% as total error for the adapted SAM version in their study, which was +/- 3% larger than the model accuracy of the SAM validation report by [30]. According to [13], the distance between the PV installation (in Dübendorf) and the weather station (in Kloten) , lack of calibration for shading, energy losses and module degradation rate can be one of the reasons for this difference. An improved calibration may reduce this overestimation; however, the adapted SAM version simulates the power output of the rooftop PV installation more accurately than the standard SAM model. The Adapted SAM model reduced the total error from 12.0% to 7.8% in this study.

In summary, the result of the above study showed that the adapted SAM model contribute to planners and stakeholders to compare the benefits of different rooftop configurations. Further work needs to be done to determine which sustainable roofing configurations should be implemented based on the climate zone and building type.

3.2. “An experimental study of the impact of cool roof on solar PV electricity generations on building rooftops in Sharjah, UAE”: by [10]

An experimental method was used for this study by conducting a test on the laboratory rooftop of the University of Sharjah (UOS), in the UAE. In addition, PV-Analysator and PROFITEST PV were used to record the generation of electricity and to compile the analysis report for PV modules. Different type of cool coating paint was used to run experimental test (see Appendix 1).

This experiment consisted of two scenarios, and each scenario had two cases. The first scenario compared two cases, one with the cool coating paint and the other one without the cool coating paint. As with the first scenario, the second scenario involves a black carpet.

In order to understand the impact of cool roof strategies on solar PV electricity generation and to test the potential improvement of PV yield and performance, different strategies were used in this study:

- Raising the diffused radiation onto the PV surface
- Choosing different tilt angles and giving one day for each tilt angle (45°,35°,25°, and 15°)
- Designing and fabricating a tailored panel’s rack (in this study, they used a nylon sheet which was coated with special reflective paint (cool coating) and combined with the PV panels support rack).

- Measuring increased solar radiation onto the PV surface by sensors and storing digitally with a data logger and workstation

Seven parameters were applied to compare the readings, including Irradiance difference in W/m2, Power difference in %, Energy production difference assuming 16% efficiency, Energy in WH without cool painted carpet (or with black carpet), Energy in WH with cool painted carpet, and Energy difference in WH.

Overall, these experiments confirmed that:

- There is a possible impact of 5–10% improvement with the cool roof applications.
- Mainly climatology, orientation, latitude, azimuth angles, tilt angle, and in a particular geographical region and usage over a period of time, affect the performance of PV systems [31,32]. As previous studies showed, the systems with higher tilt angles have a higher performance during the winter season, and the systems with lower tilt angles have a higher performance during summer [31,33].
- The higher the tilt angle, the higher the irradiance levels. A PV panel with a cool coating generate more power at angle 45, largely due to the greater amount of reflection and solar radiation generated by the cool coating, particularly at the experiment’s timeframe.
- “Cool Carpet” case perform more effectively at 45 and 35 degrees as can be seen in the difference between the average of power difference. The average power difference at angle 45 is 2.9%, and at angle 35 it is 4.0%.

3.3. “Cool roof coating impact on roof-mounted photovoltaic solar modules at texas green power microgrid”: by [34]

[34] did comprehensive thermal analyses for residential buildings in this study, focusing on the analysis of the cool roof-mounted solar photovoltaic system. They apply 186 solar photovoltaic 330-W modules on a metal roof with a white silicone coating. They also used “DC-coupled system that features nine 5 kW inverters each with maximum system input of 600Vdc and 92 batteries with 225.216 kWh energy storage”. The daily/monthly voltages produced by the inverters, as well as the battery energy storage, have been monitored and authenticated through thermal modelling calculations. Further, the cool-roof effect on reducing the solar cell thermal voltage and module/roof heat flux was evaluated based on the conductive coefficient. More specifically, they used the following methodological approaches in their study:

- Modelling thermal analysis by installing the THERMAX under the individual modules in order to observe the impact of the cool roof technology on the performance of the solar arrays. THERMAX technique also formed and calculated the sol–air temperature and energy balance equations **(Figure 5)**

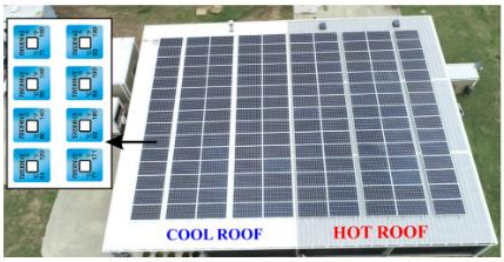

Figure 5 THERMAX technique (Thermax®) for thermal evaluation of the Rubicon buildings’ roofs. [34]

- Analysing critical characteristics of the solar cells, such as the heat flux and the solar photovoltaic cell equations, so that modules can be arranged on the cool/hot roofs of case studies.
- Installing Tigo power optimiser at each module to observe the instantaneous performance of each solar module.
- Applying a power efficiency comparison between cool and hot surfaces, taking into consideration the maximum expected generation for each string, to verify the cooling load hypothesis.
- Comparing the percentage of power generation by cool/hot module along with load and battery performances.
- Comparing ENERGY STAR® certified cool roof by changing cool roof characteristics

Generally, this study had the following achievements:

- Sol-air temperature measurement showed an increase in system efficiency of 0.15% when the cooling load was reduced by 0.5◦F/0.3 ◦C.
- All critical characteristics of the module cell, such as voltage, current, power, and fill factor, were monitored and compared to the experimental B-grade modules. Using the aforementioned data, the diode, load, shunt, and reverse saturation currents of the cell were calculated.
- A 14.9% increase in overall efficiency was found from monitoring and verifying the weekly conversion efficiency with the theoretical equation.
- Project performances showed that 156.63 kWh of battery storage is enough to be able to continuously consume electricity for 5.55 hours or more after a blackout. The study shows an additional 10.41% of solar power and an extra 9.37% of current production when comparing cool and hot energy sources.
- The findings also compared ENERGY STAR® certified cool roof by changing cool roof characteristics and showed:
  - 26% improvement for cool roof by using initial Solar Reflectivity 0.87 versus 0.69
  - 23% improvement for cool roof by using aged Solar Reflectivity 0.80 versus 0.65
  - 9 times more heat retained by galvalume roof by Emissivity 0.10 versus 0.90
  - 77% improvement for cool roof by Initial SRI 110 versus 62,

4. Results and Discussion

As discussed before, cool roof technology reduces urban air temperatures by decreasing the quantity of heat transferred from roofs to the urban environment [16,17].

Cool roof application also improves indoor thermal comfort, and it decreases energy bills by decreasing the usage of mechanical air conditioning systems [18]. A recent study by [35] evaluated physical parameterisations in order to understand the effect of rooftop mitigation strategies (RMSs) on the urban context and environment. Their study's results show that cool roofs are the most efficient in decreasing air temperature and decreasing energy consumption by air conditioning systems. In extrapolating and analysing previous studies, [20] estimated that replacing dark roofs with cool roofs can save 1013 Wh per year, which would be about 0.5% of all building electricity usage.

Sustainability of PV-cool roofs:

In recent years, the consciousness of renewable energy and built environments have been attracting Photovoltaic scientists, and the renewable and low-carbon solar energy resource has been strongly considered due to its availability, scalability, and technological maturity [36]. The direct effects of PV systems include providing local power, while the indirect ones include reducing reliance on fossil fuels which lead to reduced emissions of greenhouse gas and other pollutants such as ozone precursors [37].

Deployment of both roofing technologies, cool roof and photovoltaic roof, have multiple benefits for the cities and urban environment. A deployment of cool roofs and rooftop photovoltaic panels reduce near-surface air temperatures across the diurnal cycle and decreases daily citywide cooling energy consumption. The maximum coverage rate deployment of cool roofs reduced citywide cooling energy demand by 13–14 %, while the rooftop deployment of solar photovoltaic panels reduced energy usage by 8–11 %.

In terms of potential atmospheric effects of solar PV deployment in cities, [37] demonstrate that the installation of solar PV systems has no negative effects (considering that the average albedo of, e.g. 0.18, and even at low solar conversion efficiencies (e.g., 10%)). However, modelling showed that in hypothetical cool cities with higher density solar PV array deployment, solar conversion efficiencies of 10% can lead to warming of up to 0.1°C.

Roof Integrated Solar Systems:

[38] also did a systematic literature review about roofing systems by comparing ten different roofing methods. They concluded that the integration of a variety of roofing systems could lead to the development of new roofing methods that would be worth further investigation; for example, photovoltaic panels can be integrated with other roofing systems like cool roofs and used as a secondary slab for double-skin roofs [38]. Similarly, [39] recommended the combination of the solar PV system with roof and said that a reduction of 30% in total heat gain is possible with this combination. In another review paper of different roof applications, [40] demonstrated that using a combination of multiple layers and nanostructures is better for the design of radiative cooling composites from a materialistic perspective. However, [41] referred to the possible conflict between the application of reflective materials with the presence of active solar systems, which need further investigation.

The application of building-integrated photovoltaics[2] (BIPVs) as a roofing system has received more attention for their dual function [42]. BIPV acts as an additional layer to the building element and generates on-site electricity. A BIPV roofing system was assumed as another alternative to cool roof systems, for summer applications, due to their indirect shading impact and ability to produce electricity, especially with decreasing PV costs.

Effects of PV-cool roofs on building energy demand and sensible heat flux:

As a result of the BIPV system installation, the building produces significant amounts of energy. According to a study by [43], a PV module produced 0.15 kWh/m2 of daily energy in winter and 0.4 kWh/m2 in summer. Summer PV energy production was about 2.5 times higher than in winter. Overall, the BIPV system provided about 25% of the building's electrical energy use in summer and 20% in winter. Similarly, [44] compared the conventional roof with PV panels in a Mediterranean climate and concluded that an integrated roof could increase heating loads by 6.7% in winter and heating load by 17.8% in summer. However, the produced energy depends on day to day variation due to temperature fluctuation, clouds, or precipitation events. [45] also conducted measurements of the thermal conditions through a roof profile on a building partially covered by PV panels. Thermal infrared images taken on a clear April day showed the PV arrays to be 2.5 K cooler than the exposed roof during the day. The roof heat flux under the PV array also reduced significantly during the day. Their study showed that PV-covered roofs reduce annual cooling load by 5.9 kWh m2 or 38%.

In 2010, 23 [23] developed a low-cost method to passively cool roof-mounted photovoltaics to improve electricity production. Their original system consisted of an aluminium plate in thermal contact with the module back and a fin extension exposed to the open air. They found that both fin systems, which differed by the length of the exposed fin, provided an average 0.12°C cooling effect when the temperature gradient between the modules and the ambient was greater than 1°C. The study proved that the concept of a plate with an exposed fin could effectively cool a roof-mounted photovoltaic module. Similarly, 46 [46] stated that the effect of PV ventilated roofs on cooling load reduction is the same as cool roofs with a reflectance of 0.65. However, the impact of installing PV on top of a cool roof system on heating energy has not been fully investigated in the literature [42].

Shading by solar panels also impacts building energy demand. As [47] showed, the roof shaded by solar panels increases domestic heating needs by 3% in the winter. The roof shading, however, results in a 12% reduction in the energy needed for air conditioning during summer. It also reduces the UHI effect and reduces surrounding temperatures by 0.2 K on summer days and up to 0.3 K at night.

Summertime heat flux through the roof deck can also be reduced after the installation of PV panels on cool roofs. PV has resulted in a substantial reduction of sensible flux, about 50%, requiring the replacement of black roofs with PV-cool roofs or PV-green roofs. [48] showed 60–63% heat flux reductions due to applying photovoltaic panel roof. The preliminary simulation results by [49] indicate that for a reference conventional roof (U value = 2 kJ/h m2 K, gray $\rho = 0.2$), the BAPV can reduce the heat flux by 37%, whereas a cool roof with $\rho = 0.9$ can reduce the heat flux by about 50%.

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[2] In the BIPV system, thin films of PV are laminated to a white membrane layer, which is covered by a layer of 3.8 cm of insulation

Effect of tilt angle on the performance of PV-cool roofs”

The optimum performance of a PV panel depends on the amount of incident solar radiation on it. So, a panel needs to be inclined in such an angle that maximum sunrays intercept its top surface vertically. So, Tilt angle has impact on the performance, efficiency and electrical parameters of a PV module because PV panels' performance depends on the amount of received solar radiation. [50] concluded that With every 5^o increment in module tilt, indoor power output decreases by 2.09 W and outdoor power output decreases by 3.45 W. Similarly, [10] showed that the higher the tilt angle, the higher the irradiance levels. A PV panel with a cool coating generate more power at angle 45, largely due to the greater amount of reflection and solar radiation generated by the cool coating, particularly at their experiment’s timeframe. However, PV solar panels can act differentl in winter and summer. PV with a lower tilt angle have a higher performance during summer, and the systems with higher tilt angle have a higher performance during the winter season. Though, the compensation of the cool roof paint can also change the general understanding of the tilt angle of PV panels [10].

Albedo concept in PV-cool roofs:

An increase in roof albedo (solar reflectance) can contribute to energy saving and reduce the cooling load in building, especially in hot climates. The installation of reflective roof membranes can save energy by 40-60%, depending on the climate zone [45]. However, energy savings will be based on how well the roof is insulated. For example, as [51] showed, the increase in roof albedo from 0.09 to 0.75 on a building without insulation resulted in a 28% savings in energy, but the increase from 0.30 to 0.75 on a building with R-30 insulation (a 5.28 Km2 W_1 increase in thermal resistance) only resulted in a 5% savings in energy. [52] showed that raising albedo by 0.4 typically reduces total cooling demand by two to three factors but raises heating demand by only 10% or less. It is because light coloured roof with a high albedo maintains a lower temperature in the sun as compared to dark coloured roofs. The black bitumen coating reached a temperature of 70°C, whereas the temperature of the cool roof is less than 30°C.

Few studies have explored the impact of roof albedo on urban climate and mostly focused on building scale. Despite this limitation, some studies modelled and quantified the possibility of urban air temperatures reduction. A very early study by [53] found that as much as 1.5°C could be saved by raising the albedo of Los Angeles, California by 0.14. A recent study by [19] evaluated the current climatic conditions in major Australian cities and showed that a city-scale deployment of cool roofs with higher albedo reduces the maximum peak ambient temperature by 2.1°C - 2.5°C in Australia.

Impact of cool roof on solar PV efficiency

The albedo factor also impacts on the efficiency of solar panels. A recent study by [13] used an updated SAM model (see Section 3.1) to identify how four roofing designs (white membrane, black membrane, rock ballasted, and vegetated) impact PV panel yield, which is currently not well understood in cooler climates. Their case studies were located in Zurich, Switzerland. They demonstrated that green roofs can increase annual PV energy yield by 1.8%, while cool roofs, with higher albedo can do so by 3.4%. The 95th-quantile roof surface temperature is inversely correlated with PV energy yield in the case study installation; an increase of 1°C results in a 71 kWh decrease in yearly energy output.

In the same vein, [34] did comprehensive thermal analyses texas residential buildings, focusing on the cool roof-mounted solar photovoltaic system (see Section 3.3). They compared solar electric generation on both cool and hot roofs and found that the cool roof's performance was 1.31% higher. They also found that solar power efficiency in cool roofs increased by 10.4%, producing 294.6 kWh of solar power despite system losses and a 3.82◦F reduction in roof temperatures, resulting in a 1.91% increase in output power. Their study also proved that cool-roof application considerably enhances sustainable energy development, safety, and building comfort when applied worldwide. While the above studies have emphasised the combination effects of roof coating and solar PV systems, the effect of cool roof’s materials on PV panel efficiency and the impacts of roof coating and solar PV systems are poorly understood [40].

As discussed above, most studies until now have either focused exclusively on cool roof technology or PV systems. This is a result of siloed industries that tend to focus on selling each system to the customer. That is, solar roof installers do not have expertise in cool roof applications, and cool roof experts do not tend to focus on the benefits associated with photovoltaics. This presents an opportunity for research into the combined field of cool roof and PV systems, since there exists a natural overlap in the space. If more research on the benefits of this combination is conducted, government and industry partners may become motivated to increase incentives or establish mandates for such technology.

5. Conclusion and Future Work

According to the structural review of previous literature, cool roofs as a booster can increase solar panel yield by increasing solar radiation and, in general, means better PV performance. Although most studies have either focused exclusively on cool roof technology or PV systems, a few studies showed the impact of cool roof technology on PV efficiency.

The efficiency of solar PV integrated with cool roof application depends on different criteria, such as microclimatic conditions (ambient temperature, air pressure, humidity, precipitation, sunshine, sky temperature, beam solar radiation, diffuse solar radiation, reflected solar radiation), local development context, building context (building orientation, type, and design), cool roof design (roof surface temperature, roof temperature between the layers, shading, roof albedo, temperature inside the building, net long-wave radiation, convective heat flux, latent heat flux, convective heat flux, heat sorted in the roof layers), PV panel configurations (panel tilt, panel slope, Solar PV type such as bi-facial or perovskite, distance from the roof, cell temperature, temperature on the back of the panel, solar panel shading, long-wave radiation on the back of the panel, power-efficient and installation types such as land-based solar farms or floating PV panels). In the present report, the effect of cool roofs on PV solar panels' performance has been investigated through reviewing previous studies. Roof albedo was mentioned as the most important factor impacting on the efficiency of both cool roofs and PV panels. The inferences of the study are summarised in the following way:

1. For every 0.1 increments of roof albedo, the annual energy yield of PV increases by 0.71%-1.36%.
2. Every 0.1 increase in albedo leads to 14% cool roof improvement.
3. Every 0.1 increase in albedo creates a reduction in roof surface temperature by 3.1-5.2 °C. A decrease of 1 degree in roof surface temperature increases PV system efficiency by 0.2-0.9%.
4. Every 0.1 increment of roof albedo led to 0.58% surplus electricity.
5. For every 0.1 increments of roof albedo, heat flux decreases by 1.9%.

Overall, the following conclusions have been drawn:

1. The traditional retrofitting roofs with cool roofs would lead to relevant gains in PV output and additional environmental benefits, including building energy savings and urban heat mitigation.
2. Integration of solar PV with cool roofs helps reduce peak electricity demand, and PV-cool roofs is able to generate more electricity than PV-green roofs. Green roofs can increase annual PV energy yield by 1.8%, and cool roofs, with higher albedo, can by 3.4%.
3. Although PV with a lower tilt angle have a higher performance during summer, and the systems with higher tilt angle have a higher performance during the winter season, the compensation of the cool roof paint can actually change the general understanding of the tilt angle of PV panels.
4. The higher albedo of the cool roofs can decrease roof surface temperature and increase the yield of PV and solar thermal systems.

In summary, results from previous studies, especially in warmer regions, supported the need for integrated PV with sustainable roof evaluation methods such as cool roofs. However, there are several limitations that could be improved in future work:

1. There is a need to reduce the number of necessary input parameters of a rooftop energy balance model so that stakeholders can more easily integrate the energy balance model with the SAM model. [13]. Therefore, more significant efforts are needed to design a more user-friendly model for the industry.
2. The modified SAM model was only tested for limited climate conditions, for a single PV type, and for a limited installation types. The results may change in other climate regions and other PV and cool roof configurations. Then, continued efforts are needed to test the model in different countries and climate zones.
3. Additional studies will be conducted to demonstrate seasonal variations in the results as well as different angles of usage of PV panels on building rooftops.
4. Further research would be needed to identify different f_{conv} values (quantifies how well the air behind the Pv panel is mixed) in order to consistently compare the output of PV installations with different design characteristics [13].
5. The majority of studies have focused on the impact of cool coating paint on building indoor comfort and environment. Very little is currently known about the effects of integrated roof systems on the urban scale.
6. As the microclimatic conditions and geography conditions may change the efficiency of both PV panels and cool roof application, there is a need for testing the effectiveness of cool roof application on the efficiency of PV panels in different climate zone, including Australia. In addition, the current review study showed that there are few studies conducted on the cold, mild and mediterranean and temperate climates, most of which are conducted in hot and warm climates.
7. Previous studies examined limited PV types such as mono-crystallised PV cells, and therefore, there is a need for further studies using different PV panel configurations (panel tilt, slope, distance from the roof, cell temperature, temperature on the back of the panel, solar panel shading, power-efficient and installation type such as land-based solar farms, agrivoltaics, floating PV panels) integrated with cool roof application.

Overall, existing literature suggests that the future improvement of PV-cool roofs could generate more electricity and lead to air temperature decrease due to the significant reduction of excess heat release to the surrounding environment. The improvement could also result in a significant reduction of carbon emissions, reducing climate change on a larger scale. Hence, further research and government intervention options need to consider the specific microclimatic conditions, local development context, cool roof design and solar PV configurations when developing PV-cool roofs.

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