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Building and Urban Cooling Performance Indexes of Wetted and Green Roofs—A Case Study under Current and Future Climates

Madi Kaboré ^{1,2,*}, Emmanuel Bozonnet ¹, and Patrick Salagnac ¹

- ¹ LaSIE (UMR CNRS 7356), La Rochelle University, Av. M. Crépeau, 17042 La Rochelle, France; ebozonne@univ-lr.fr (E.B.); patrick.salagnac@univ-lr.fr (P.S.)
- ² DE/IRSAT/CNRST, Ouagadougou 03 BP 7047, Burkina Faso
- * Correspondence: madi_kabore@outlook.com

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Abstract: We developed and studied key performance indexes and representations of energy simulation heat fluxes to evaluate the performance of the evaporative cooling process as a passive cooling technique for a commercial building typology. These performance indexes, related to indoor thermal comfort, energy consumption and their interactions with their surrounding environments, contribute to understanding the interactions between the urban climate and building for passive cooling integration. We compare the performance indexes for current and future climates (2080), according to the highest emission scenario A2 of the Special Report on Emission Scenario (SRES). Specific building models were adapted with both green roof and wetted roof techniques. The results show that summer thermal discomfort will increase due to climate change and could become as problematic as winter thermal discomfort in a temperate climate. Thanks to evapotranspiration phenomena, the sensible heat contribution of the building to the urban heat island (UHI) is reduced for both current and future climates with a green roof. The performance of the vegetative roof is related to the water content of the substrate. For wetted roofs, the impacts on heat transferred to the surrounding environment are higher for a Mediterranean climate (Marseille), which is warmer and drier than the Paris climate studied (current and future climates). The impact on indoor thermal comfort depends on building insulation, as demonstrated by parametric studies, with higher effects for wetted roofs.

Keywords: evaporative passive cooling; passive building key performance index; summer thermal comfort; urban heat island; climate change

1. Introduction

The expected consequences of global warming [1–3] will be more acute within dense cities where buildings and their surroundings are the origin of microclimatic disturbances. This effect, known as urban heat island (UHI), is quantified by a temperature increase in urban areas. This is a critical health issue during extreme summer events (such as the 2003 heatwave episode [4]), especially due to thermal discomfort, and also to atmospheric pollutants such as tropospheric ozone. In addition, buildings are often an increasing factor of vulnerability to heatwave events. Climate change in mid-latitude countries will expose buildings and occupants to drier and warmer conditions. This climate evolution and its consequences have to be taken into account for the design of new buildings today for future conditions, as well as for the renovation of existing building stock [5]. As the construction and refurbishment rates remain quite low regarding future challenges, the impacts of climate change and cooling strategies have to be considered in the design of tools nowadays, as well as in urban planning strategies.

The development of building energy simulation (BES) is essential in the building design processes. These tools use climate data in relation to materials, energy systems and building operation data to predict the performance of buildings. The accuracy of the simulations and outcome evaluations (comforts, health, economic) that result depends on the availability of these data. Most of the weather data currently used in building and even renewable energy is historical or current. It is necessary to consider the prospects of climate change, including extreme events, i.e., the impact of heatwaves on the design of indoor environments and on outdoor conditions in complex urban environments. The climate change scenario is considered here from the data on the variability of the climate system given by the Special Report on Emission Scenario (SRES) and radiative forcing [6], both used in climate simulations. Climate models provide an opportunity to anticipate how the climate system may be affected by human activities. The climate simulations are made from numerical models called General Circulation Models (GCMs), which cut the surface of the Earth into meshes about 150 km-wide. These data, coming directly from GCMs, do not fit the needs of the engineering sector such as building, energy and urban planning [7]. To refine the diagnosis, models and method downscaling have been developed [8–10]. A well-known "statistical" method of descending ladders is the "Morphing" method, which makes it possible to obtain usable data for the building sector from the climate data of GM models [7]. Morphing combines observed or current weather data from a site (realizing changes in spatial and temporal scales) with the results of climate change models. Nowadays, it is the most accessible method for authors who carry out investigations on theme building and the future of the climate.

Reducing the vulnerability of buildings to the climate requires the establishment of urban planning and a built environment that is adapted to high temperatures as much as possible. In recent decades, the scientific community studied the phenomenon of the urban microclimate, in order to better understand the factors affecting the UHI intensity and adaptation strategies [11–13]. Passive cooling solutions for building envelopes can be developed at the neighborhood and urban scale as well. They constitute a global strategy for action that prepares communities to deal with climate impacts and helps to avoid future effects that are even more harmful. Focused on building and the immediate built environment scale, mitigation and adaptation techniques are strongly correlated. Some well-known passive techniques to limit the cooling needs and overheating of buildings can be extended to the built environment in an urban context and vice versa. It is then necessary to consider the different levels of cooling techniques and to identify the different transfer phenomena to mitigate temperatures and heat fluxes at both scales: evaporative, radiative, related to inertia and thermal insulation, and related to ventilation and heat transfer. Figure 1 gives an overview of typical or innovative passive cooling techniques with some examples per physical phenomenon for building design and urban environment planning.

For radiation-based phenomena solutions, passive techniques such as cool coatings (roof, façade, and pavement) and occultation techniques exist. The cool coating solution mitigates roof surface temperatures, temperature gradients in the roof, and thus cooling energy demand [14–16]. Akbari et al. [17] have assessed that the cooling effect of an increased albedo of 0.01 per square meter is equivalent to a CO_2 emission decrease of around 7 kg in the long term (decadal to centennial).

Ventilation and heat transfer are mainly developed at the building scale as a passive solution through natural ventilation, free cooling, or heat recovery ventilation. These ventilation techniques are used as a heat flush system, but daytime ventilation is also a common passive cooling technique since increased air velocity gives a cooling sensation due to evapotranspiration. Natural ventilation of buildings can be achieved through multiple or single forms of exposure to winds. The potential is mainly related to the prevailing wind flows. The design of natural ventilation can be compromised in urban areas by confinement and weakened ventilation potential within dense urban tissue.



Figure 1. Building and its surrounding environment—passive cooling techniques through various heat transfer phenomena.

High thermal inertia may improve summer thermal comfort as buildings store heat and restitute it some hours later [18], at a time of the day when it is possible to bring cooler air into buildings. This phenomenon also exists in winter when a building stores energy during the day (solar gain) to return it in the form of heat in the evening or night when it is coldest. Note that it is important to find a balance between the thermal comfort of summer and winter. Phase Change Materials (PCM) have been tested by Kong et al. [19] and the PCM technique can limit and phase out energy inputs in the summer and thus contribute to a reduction in discomfort. Building insulation can also have an important role in reducing summer discomfort. However, increased insulation commonly used for passive buildings in winter can have opposite consequences on the internal comfort in summer or even periods between seasons.

Mineral urban areas tend to trap solar radiation and restore this heat during nighttime due to the lack of vegetation, the thermal storage of urban surfaces, and the solar absorptance of construction materials. This mineralization of urban surfaces and rainwater evacuation infrastructure reduce the natural evaporation of urban surfaces. One of the challenges of urban design is to restore the natural cooling phenomena such as evaporation and evapotranspiration.

The cooling effect of water in an urban climate results mainly from evaporation, and then the limitation of surface overheating and air cooling through convective transfers. Water sprayed in public spaces also has a strong cooling effect. Large water bodies such as rivers can cool the environment both by evaporation [20] and heat transfer out of the zone by the flow of the river [21]. The phase change consumes energy that is taken from the environment. Considering 5 mm/m² summer rainfall (for a 24 h period), 4 mm is evaporated in rural areas (permeable surfaces), compared to only 0.5 mm in urban areas. A study carried out in Bucharest demonstrated a cooling effect of approximately 1 °C, 1 m above and 30 m away from the surface of the experimental reservoir [22].

Urban vegetation is another UHI mitigation strategy. The evapotranspiration of vegetation is characterized by the phase change from liquid to the vapor phase of water during photosynthesis and the thermal regulation of plant tissues. In addition, we notice the occultation capacity of certain types of plants and the low albedo of the vegetation. Beyond the cooling aspect, the vegetation has a positive impact through other aspects such as the production of oxygen and CO₂ capture. Green spaces absorb and hold water and can be an effective strategy for reducing stormwater runoff in urban areas. In the city, greening can be implemented at the street level by green spaces, and on buildings by green roofing technologies and facades. In this paper, we studied vegetation at the building scale. Under certain

favorable climatic conditions, evapotranspiration can generate an oasis that is 2 to 8 $^{\circ}$ C cooler than the surrounding environment [23]. In the summer, the revegetation of the surfaces leads to a reduction in overheating periods, particularly in street canyons [24] and a significant drop in indoor temperatures, from around 4 to 6 $^{\circ}$ C.

In this article, a commercial building with a large footprint is used as a reference to study the relation between building surfaces and the immediate environment. Specific models have been adapted to focus on the evaporation process and its cooling performance. A key performance index method and a representation of BES outputs [25] are applied to this generic commercial building with evaporative-based passive cooling solutions (namely a flat green roof and s roof pond) in order to evaluate the performance for the current climate and the future climate of 2080 according to SRES scenario A2.

2. Methodology

The proposed case study described in the following sub-section is a typical application of the studied passive cooling techniques, based on latent heat transfer on roofs. Then, the physical processes and the proposed key performance indicators for the studied passive cooling techniques are developed. The equations and physical models are also detailed for green and wetted roofs.

2.1. Description of the Building Model

Our case study (Figure 2) is a low-rise commercial building with a floor area of 1296 m² and a 6 m ceiling height. These types of buildings contribute 7% of the total world energy consumption [26]. The slab is made of 160 mm of concrete on sandy ground. The radiative properties and the composition (material and thickness in mm) of the walls and roof, from the inside to the outside layers, are presented in Table 1. The roof has skylights (8% of the roof area). The windows (a total of 30 m² of glass surfaces) are located on each facade except the north one.



Figure 2. View of the building.

Surface Type	Plaster	Mineral Wool	Steel Cladding	Thermal Emissivity (ε)	Solar Reflectance (α)
Walls	13	140	2	0.9	0.3
Roof	13	120	2	0.9	0.3

Table 1. Composition and radiative properties of the reference building's walls and roof.

The furniture and partitions have been taken into account as internal mass. The infiltration is considered with an air permeability level of 2 cm²/m² [27]. The occupancy schedule is 07:00 a.m.– 10:00 p.m. for only weekdays and Saturdays, with an occupation rate of 11.6 m²/person [28]. The use of lighting depends on the availability of daylight (lights are off when the daylight exceeds 300 lux). Here, no active cooling system is considered. The heating system exists in order to maintain an indoor temperature of 19 °C during occupied periods and 5 °C otherwise. The fresh air (0.5 air changes per hour) is provided using heat recovery ventilation (HRV) when the building is occupied.

For these investigations, we located a building in two urban areas of France. The location of Paris is subjected to a temperate climate. The weather of Marseille is a Mediterranean type. TMY3 weather data are used for these simulations. The TMY3 standard allows us to take into account the rain data

and this is useful for green envelope investigations. Current and future weather data are generated using Meteonorm© [29]. For future weather data, the SRES A2, which is one of the higher emission scenarios, is used [9].

2.2. Sankey Diagram of the Heat Quantities and Cooling Performance Indexes

The energy flows between the building and its environment are represented by a percentage Sankey diagram (Figure 3). This is a simulation output representation method proposed in [25].



Figure 3. Sankey diagram (% of solar irradiance) for the cooling season in Marseille.

For the total cooling period (mainly during summer), Figure 3 highlights that the heat transmitted to the urban canopy from the building as sensible heat (Q^O) represents 39.3% of the total solar radiant exposure. This is the contribution of the building to the UHI effect and the main heat source is the solar radiation. The other terms account for solar gains from windows (G_{solar}), internal gains (G_{int}), and thermal losses toward the sky (D_{rad}) and the ground (D_G); these terms are detailed in this section.

These terms aggregate various fluxes for a simplified representation to highlight the exchanges with the surrounding environment. Two thermal balances are performed initially for the entire building: for the building envelope and for the indoor air node.

The first balance (Equation (1)) concerns the building envelope and the internal wall heat exchanges, separately integrating heat gains (index +) and heat losses (index -). Heat quantities (Q) are indexed in relation to their nature and are computed from the integrated heat fluxes for the entire cooling season and for the living space area, i.e., expressed in J/m².

$$\begin{pmatrix} Q_{SW} - Q_{SW}^{refl} \end{pmatrix} - Q_{LW}^{o} - \begin{pmatrix} Q_{C-}^{o} - Q_{C+}^{o} \end{pmatrix} - Q_{G} = \\ Q_{SW}^{win} + Q_{LW}^{ohters} + Q_{LW+}^{i} - Q_{LW-}^{i} + Q_{C+}^{i} - Q_{C-}^{i} + (\Delta Q_{W+} - \Delta Q_{W-}) \end{cases}$$
(1)

where the various heat quantities are outside the building envelope. The definitions of the different terms (Equation (1)) are described in Table 2.

Then, considering indoor air node energy balance:

$$Q_{V+} + Q_{I+} + Q_{C+}^{i} + Q_{C}^{heat} + Q_{C}^{others} - Q_{I-} - Q_{V-} - Q_{C-}^{i} = 0$$
⁽²⁾

where $(Q_{V+} - Q_{V-})$ and $(Q_{I+} - Q_{I-})$ are, respectively, ventilation and infiltration heat gains; $(Q_{C+}^i - Q_{C-}^i)$ is the convective heat gain from walls; Q_C^{heat} and Q_C^{others} are, respectively, the heat from the HVAC system, and from occupants and lighting by convective heat transfer.

However, the integrated solar irradiance Q_{SW} for the cooling season may vary in various locations or for a specific hot or cold year. So, the benefit of the cooling strategy cannot be assessed precisely as it gives variable results for thermal balance terms. To get an intrinsic comparison reference for various case studies, we expressed heat quantities as a ratio of Q_{SW} , like in the Sankey diagram (Figure 3). The main heat source is the incident solar irradiance Q_{inc} (Equation (3)) and all the other ratios are expressed relatively by the following equations:

$$Q_{\rm inc} = \frac{100}{Q_{\rm SW}} Q_{\rm SW} \tag{3}$$

$$Q^{\rm o} = \frac{100}{Q_{\rm SW}} \left(Q^{\rm o}_{\rm C+} - Q^{\rm o}_{\rm C-} - Q_{\rm I-} - Q_{\rm V-} \right) \tag{4}$$

$$D_{\rm rad} = \frac{100}{Q_{\rm SW}} \left(Q_{\rm SW}^{\rm refl} + Q_{\rm LW}^{\rm o} + Q_{\rm Latent}^{\rm o} \right) \tag{5}$$

$$D_{\rm G} = \frac{100}{Q_{\rm SW}} Q_{\rm G} \tag{6}$$

$$G_{\rm solar} = \frac{100}{Q_{\rm SW}} Q_{\rm SW}^{\rm win} \tag{7}$$

$$G_{\rm int} + Q_{\rm inc} = Q^{\rm o} + D_{\rm rad} + D_{\rm G} \tag{8}$$

where D_{rad} (Equation (5)) represents the heat dissipation ratio from the building to the external environment, except sensible heat to ambient air: solar reflected heat (SW), net longwave (LW) heat losses and dissipated latent heat. D_G and G_{solar} (Equations (6) and (7)) represent the ratio of heat dissipated to the ground and shortwave radiation through the openings. Finally, two heat sources related to those heat dissipations (Equation (8)) are given from both internal gains G_{int} and Q_{inc} . G_{int} is the ratio of net gains for the indoor volume and surfaces. The proportion of heat released to the surrounding environment (Q^o , Equation (4)) is the ratio of the sum of heat from convection between the outdoor surfaces and ambient air, and the heat dissipated by ventilation and air leakage. These parameters are entries for the Sankey diagram. One can observe that, for the climate of Marseille (Figure 3), the anthropogenic heat released to the surroundings is 39.3% of Q_{inc} .

Table 2. Description of Equation (1) terms.

Expression	Description
$Q_{\rm SW} - Q_{\rm SW}^{\rm refl}$	the absorbed solar irradiance by the building envelope
$Q^o_{ m LW}$	the net longwave (LW) heat loss radiated to the sky and the environment
$Q_{\rm C-}^{\rm o} - Q_{\rm C+}^{\rm o}$	the net convective heat transmitted by the envelope to the ambient air
QG	the net conducted heat to the ground
$Q_{ m SW}^{ m win}$	the indoor solar gains (SW) through windows and skylights
$Q_{\rm LW}^{\rm others}$	the radiative internal gains
Q^{i}_{LW+} – Q^{i}_{LW-}	the net longwave heat gains from indoor surfaces radiation
$\Delta Q_{W+} - \Delta Q_{W-}$	the net heat stored within the building envelope and internal walls

Moreover, the passive cooling efficiency depends on the building's cooling needs, the design or use of the building (e.g., a non-occupied school during summer will have fewer gains compared to a permanently occupied building). Then, we assessed these strategies as an improvement of the reference building (index "ref" in the following) without a passive cooling technique. We proposed the following three efficiency indexes to assess the cooling strategies (Equation (9)):

Cooling efficiency for the indoor environment (η_{FRin}): mitigation potential of thermal discomfort during the cooling season. The cooling season is the period in which the building presents cooling needs and may vary according to the climate and the passive solution implemented. For the reference building in Marseille, the cooling season represents 59% of the year. This efficiency is computed only for the occupied periods and based on the degree-hours (DH) according to the adaptive thermal comfort standard EN15251 [23] limits;

- Cooling efficiency of the external environment (η_{FRout}): UHI mitigation potential during the cooling season;
- Energy efficiency (η_{CEP}): energy consumption benefits for the full year, including the heating system. This is especially important when studying the impacts of a passive cooling solution on heating needs in moderate climatic areas. It is based on the primary energy consumption C_{EP} .

$$\eta_{\rm FRin} = 100 \ \frac{\rm DH_{ref} - \rm DH}{\rm DH_{ref}}; \ \eta_{\rm FRout} = 100 \ \frac{Q_{\rm ref}^{\rm o} - Q^{\rm o}}{Q_{\rm ref}^{\rm o}}; \ \eta_{\rm CEP} = 100 \ \frac{C_{\rm EP,ref} - C_{\rm EP}}{C_{\rm EP,ref}}$$
(9)

where η_{FRout} , η_{FRin} and η_{CEP} are percentages and can be positive (meaning improvements due to the design option) or negative (meaning negative impacts). η_{FRout} expresses the reduction or increase in the anthropogenic heat released toward the immediate environment regarding the transmitted heat to the urban environment Q° . η_{FRin} shows the capacity of a given passive cooling solution to decrease or increase summer indoor heat stress. η_{CEP} helps us to understand the impacts of the cooling strategy in terms of energy consumption. In the following sections, this methodology will be applied to evaporative-based passive solutions.

2.3. Wetted Roof Model

Wetted roofs are considered here as impermeable, so the water partially evaporates (latent heat flux) and the other part flows towards the evacuation. The phase change consumes energy from the environment (Figure 4).



Ballangelac

Figure 4. Heat balance of wetted surface.

Here, the roof surface is considered permanently wetted with a water supply [30,31]. The heat flux balance for this wetted roof surface can be written as follows (Equation (10)):

$$\alpha_{\rm SW}E_{\rm SW} - \varepsilon_{\rm LW}\left(\sigma T_{\rm s}^4 - E_{\rm LW}\right) + h_{\rm C}\left(T_{\rm air} - T_{\rm s}\right) + \phi_{\rm T} - L\frac{\rho_{\rm air}}{R_{\rm a}}\left[q_{\rm sat}(T_{\rm w}) - q(T_{\rm air})\right] = 0 \tag{10}$$

where:

 $\alpha_{SW}E_{SW}$ the solar irradiance absorbed by the wetted roof;

 $\varepsilon_{\rm LW}(\sigma T_{\rm s}^4 - E_{\rm LW})$ the net longwave radiative loss from the wetted roof surface to the sky;

 $h_{\rm C}(T_{\rm air} - T_{\rm s})$ the convective heat gains from the ambient air;

 $\phi_{\rm T}$ the heat flux transmitted by conduction to the roof layer.

The evaporation process is conditioned by the evaporative demand of the air [31]. R_a is the sensible heat thermal resistance for air; ρ_{air} the air density; *L* the specific latent heat for the vapor; q(T) the specific humidity at a given temperature. These equations are implemented directly in TRNSYS© and couple with the type 56 building model. The inputs of the model are the weather data and the roof heat flux ϕ_T from the building model.

Similarly to the wetted surface model, the heat and mass process have been modelled for a green roof model with a component developed and validated by Djedjig et al. [32,33]. This model is also integrated into TRNSYS© [33]. The vegetated roof model is composed of two separate layers: the foliage canopy and the substrate [32]. Both heat balances are established for these two layers, considering simultaneously radiative, sensible, latent and conductive heat transfer at the foliage and substrate levels. The model parameters include the average leaf thickness, the leaf area index and the specific thermal capacity of the foliage; the substrate's thermal properties are simultaneously calculated given the water content. The vegetative roof model is coupled to the building envelope with the roof temperature and the heat flux under the substrate. At each time step for the given meteorological data, an iterative process allows the convergence of both building and green roof models. Detailed outputs are given, especially sensible and latent heat fluxes for the substrate and the foliage, which are used in the following Sankey analysis, and the indicator computations.

3. Results

3.1. Simulation Results of the Reference Building—Current and Future Climates

Figure 5 shows the behavior of the reference building during the summer period without a cooling strategy. The diagrams at the top show the results obtained for the current climate and those at the bottom of a climate projection in 2080 with one high-emission scenario (SRES: A2) in order to take into account the average lifespan of a building.



Current weather data

Figure 5. Sankey diagram (% of solar irradiance) for the reference building—impacts of current and future climates in Marseille and Paris.

Regarding the anthropogenic contributions of the building, there are slight decreases for the studied location. For Paris, Q° represents 42.3% for the historical climate and 40.8% for the future. This observation reflects a warmer future climate. The degree-hours of thermal discomfort increase by a factor of 400% for Paris (1017 °Ch and 4340 °Ch, respectively, for historical and future) and about 50% for Marseille. These observations show the trend of increasing summer thermal discomfort in buildings for future climates. So, summer thermal comfort could become as problematic as winter thermal comfort for a more temperate climate.

3.2. Impacts of Green Roof

3.2.1. Comparison of Current and Future Climates

Figure 6 shows the results considering the fact that the water needs for the green roof are provided by rainfall only and according to the weather data of Marseille and Paris. These results were obtained for the summer period and the rainfall data come from TMY3 weather files of the location. The efficiency indexes are related to the respective reference buildings (current and future weather data presented in the previous section).



Figure 6. Sankey diagram (% of solar irradiance) of the green roof case with water needs provided by rainfall—impacts of current and future climates in Marseille and Paris.

Compared to the respective reference cases, the cooling potential for an ambient urban environment η_{FRout} is 18.3% and 27.6%, respectively, for Marseille and Paris, reflecting the ability of this solution to have an impact on the UHI under current climates. For the 2080 climates (Figure 6), the UHI cooling efficiency increases (19.12%) in Marseille and decreases in Paris (26.4%). Thanks to the vegetation, a part of the non-reflected solar radiation is transmitted in the form of latent heat during the photosynthesis and the thermal regulation of the plant tissues. In the same way, the part of the soil not occulted by the foliage heats up less quickly due to evaporation. There is a reduction in summer thermal

discomfort by about 4.6% and 4.3%, respectively, for historical and future weather data in Marseille (Figure 7). The same trend is also observed in Paris. Indeed, rainfall is higher in Paris than in Marseille (Mediterranean climate), and the evaporation process becomes more important, which explains the differences observed for the indexes between the two locations.



Figure 7. Cooling potentials of green roof for urban environment η_{FRout} , indoor environment η_{FRin} and impact on the heating season η_{CEP} obtained for two French cities.

Climate change leads to a reduction in indoor cooling potential (Figure 7) compared to the corresponding reference cases, especially for Paris where the number of degree-hours is four times higher compared to the historical climate.

It should be noted that absolute values of discomfort (degree-hours) decrease significantly compared to the current climate; this denotes the ability of this solution. However, the thermal comfort indexes are relatively low as the roof is highly insulated with limited effects due to outside modifications. The green roof in this case is an additional insulation layer and helps to reduce the primary energy consumption index η_{CEP} , which includes heating consumption (Figure 7). We can observe that η_{CEP} values decrease for the future climate due to the fact that it is warmer.

3.2.2. Watering Effect on Green Roof Performances

Figure 8 shows the impacts of the water content of the substrate on the green roof performance. The water content is maintained at different fixed values by watering.

The UHI effect through the heat transmitted to the ambient air Q° drops from 39.3% for the reference building to only 2.5% of the total solar irradiance for the water content of the substrate 150 kg water/m³. This highlights the watering benefits compared to the obtained value of 32.1% (Figure 6) when the rainfall for the current climate in Marseille ensures the water requirement. When the substrate is saturated (maximum water content of the model used), we can even observe the heat sink effect of the building in this urban context (Q° is taken from the environment, Figure 8), so the building heat contribution is negative and its cooling performance η_{FRout} is above 100%. The indoor cooling efficiency (thermal comfort) also increases with water content, as the cooling index η_{FRin} increases from 4.6% without watering to 24.3% when the substrate is permanently saturated (Figure 8). In the case of rainfall, the water content of the substrate depends on the amount of water collected and the rainfall distribution throughout the summer period. This explains the improvements observed in the

cases of regular watering, thus allowing greater evapotranspiration. This evapotranspiration helps to dissipate some of the heat from indoors and reduces the thermal discomfort. The cooling provided by the evapotranspiration of plants and their substrates works well when they are properly irrigated [24].



Figure 8. Sankey diagram (% of solar irradiance)—case of a green roof in Marseille (current climate) depending on the water content of the substrate.

3.2.3. Impacts of Roof Insulation on Green Roof Performances

A parametric study was carried out on the roof insulation layer for the climate of Marseille. The results obtained by varying the thermal resistance of the roof are presented in Table 3.

Insulation's Thermal Resistance R (m ² ·K/W)	η_{FRin}	$\eta_{\rm CEP}$	η_{FRout}
1.25	13%	1%	18.3%
2.25	7%	3%	18.3%
2.75	6%	4%	18.3%

Table 3. Parametric study of the performance of a green roof (water needs are provided by rainfall) according to the thermal insulation of the roof.

One can observe that the thermal comfort index η_{FRin} increases as the insulation decreases. This is because a high level of insulation does not allow for the dissipation of indoor heat through the roof. On one hand, the impact on energy consumption (mainly for heating) η_{CEP} is slightly less favorable because of the weakly insulated roof. On the other hand, η_{FRout} remains almost constant. The green roof performed very well to reduce the heat transferred to the surrounding environment and this index depends strongly on water content. For indoor thermal comfort, the impact of green roofing depends on the roof insulation. These results give hints as to the potential design of this solution in future warm climates as the insulation requirements would have to be adapted.

3.3. Impacts of Wetted Roof

3.3.1. Comparison of Current and Future Climates

The wetted roof as a cooling technique is based on evaporation phenomena, nocturnal radiative exchange, and the thermal inertia of the water body. During the day, solar energy can heat and evaporate the water. At night, the heat stored in the roof and water is evacuated by natural convection with the colder ambient air and radiative cooling to the sky. We can observe in Figure 9 that the heat released from the building to the outdoor environment mainly occurs via D_{rad} , i.e., radiative cooling and latent heat. The building does not contribute much to the local warming of the surrounding urban environment.



Figure 9. Sankey diagram (% of solar irradiance) of wetted roof case—impacts of current and future climates in Marseille and Paris.

The evaporation phenomenon is higher when the air is hot and dry; this explains the higher η_{FRout} in Marseille (93.4%) than in Paris (75.7%) for the current climate. The same trend is observed for the 2080 climates (SRES A2). The impacts of global warming lead to a decrease in thermal comfort indexes. As with green roofs, the obtained thermal comfort indexes are relatively low due to the well-insulated roof, which is detailed in the following section. It should be noted that the wetted roof causes a slight increase in heating needs here (Figure 10), expressed by low but negative values of η_{CEP} .



Figure 10. Cooling potentials of wetted roof for urban environment η_{FRout} , indoor environment η_{FRin} and impact on the heating season η_{CEP} obtained for two French cities.

3.3.2. Impacts of roof insulation on wetted roof performances

The results of our parametric study of insulation thermal resistance for a wetted roof are summarized in Table 4. These results have been established for a building located in Marseille and for the current weather data. We observe that outdoor cooling indexes are quite constant for all roof insulations studied here. The indoor thermal comfort index is higher when the roof is weakly insulated ($\eta_{FRin} = 25.1\%$ for R = 1.25 m².K/W against $\eta_{FRin} = 9.5\%$ for R = 2.75 m².K/W). As previously observed, penalties on heating consumption drive the observed negative values of η_{CEP} .

Table 4. Parametric study of the performance of a wetted roof according to the thermal insulation of the roof.

Insulation's Thermal Resistance R (m ² ·K/W)	η_{FRin}	$\eta_{ ext{CEP}}$	η_{FRout}
1.25	25.1%	-10.7%	92.11%
2.25	12.5%	-3.1%	92.85%
2.75	9.5%	-2.01%	92.11%

4. Conclusions

In this study, we focused on thermal comfort and heat distribution during the cooling season between a building and its immediate environment by applying a methodology (Kaboré et al. [25]) to compare cooling strategy designs. This methodology allows for the comparison of the performances of different buildings, climates, and design options, with the same normalized indicators for indoor thermal comfort η_{FRin} , primary energy consumption η_{CEP} , and outdoor anthropogenic contribution η_{FRout} . We illustrated this for a typical commercial building located in both a temperate and a Mediterranean climate. First, the obtained indoor overheating (°Ch) of the reference building (without passive cooling) is much more amplified with climate change (factor 4) for the temperate climate of Paris (France) than (factor 0.5) for the Mediterranean climate of Marseille (France). Then, we focused on the performance evaluation of evaporative cooling (green roof and wetted roof) for both indoor and outdoor environments, in current and future climatic contexts. Compared to various existing parametric studies, the normalized results presented here provide a brand new approach to the performance and design strategies of evaporative solutions, which were compared here in a normalized approach in relation to the building and the climate conditions.

The well-known advantages of wetted and green roofs for passive cooling can be observed in the results for both indoor thermal discomfort and UHI mitigation. Evapotranspiration processes contribute to reducing the anthropogenic heat contribution of the building to the UHI for both historical and future climates. As the reference building is well insulated, the results highlight the increased cooling efficiency of the evaporative cooling outdoors in an urban climate compared to indoor thermal comfort.

It is interesting to note that the cooling efficiency is very much the same under the current and future climates for both locations, except for the Mediterranean climate, where climate change reduces by a factor of two the indoor cooling efficiency for both wetted and green roofs.

The comparison of these cooling technique efficiencies is also interesting in order to differentiate their relative impacts on indoor thermal comfort and UHI mitigation. Indeed, we observed that the anthropogenic contributions of the building to the UHI decreased greatly with the wetted roof (cooling efficiency between 75.7% and 93.4%), while a much weaker effect is observed for the green roof (from 18.1% to 27.7%). The performance is higher for Marseille than Paris for both studied periods because the climate is warmer and drier in the Mediterranean context of Marseille. The impact on indoor thermal comfort is weak, but stronger than the green roof. It is possible that current insulation recommendations need to be updated by considering future climates, which could increase the benefits of these evaporative cooling techniques, especially in relation to indoor thermal comfort.

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Nomenclature

C _{EP}	Primary energy consumption, Wh/m ²	Others	Internal loads
<i>c</i> _p	Specific heat, J/(kg·K)	refl, R	Reflected
Ď	Dissipated part,% or drainage kg/(m ² ·s)	win	Openings
DH	Discomfort degree-hours, °C·h		Subscripts
Е	Incident radiation, W/m ²	air	Air
G	Gain part,%	С	Convective
h	Heat transfer coefficient, $W/(m^2 \cdot K)$	FRin, FRout	Cooling indoor and outdoor
L	Specific latent heat of water vaporization, J/kg	G	Ground
q	Specific humidity kg/kg	i, int	Indoor
Ra	Aerodynamic resistance, s/m	inc	Incident solar radiation
t	Time, s	Ι	Infiltration
Т	Temperature, °C	LW	Longwave
	Greek symbols	rad	Radiative
α	Solar absorptance	ref	Related to the reference case
ε	Long wave emissivity	S	Surface
η	Index,%	sat	Saturate
ρ	Density, kg⋅m ⁻³	SW	Shortwave
σ	Stefan–Boltzmann coefficient, W/(m ² ·K ⁴)	V	Ventilation
	Superscripts	W	Water
i	Indoor	(+)	Positive value
heat	Heating system	(-)	Negative value
0	Outdoor		

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