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Façade retrofitting: from energy efficiency to climate change mitigation

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Abstract

Since climate changes are now evident, it is not only important to achieve high level of energy efficiency, but also to think about retrofit actions in order to mitigate the natural hazard impacts and to make buildings resilient. The paper focuses on climate change effects in summer and investigates how it is possible to reduce them through façade retrofitting solutions (external insulation, PCM, green wall, cool materials) in Mediterranean climate. The goal is to develop a set of climatic resilience indicators for opaque envelopes in order to consider resilience ability against climate change, both inside and outside of buildings.

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Keywords: Energy efficiency; energy refurbishment; sustainable energy development; resilience; climate change mitigation; green wall; cool materials

1. Introduction

The European Directive 31/2010 and its targets for 2020 has become effective through the enactment of national laws and regulations. However, they impose complex obligations for existing buildings towards NZEB and do not take into account other actual problems. It is not only important to achieve high level of energy efficiency, but also to think about retrofit actions in order to mitigate the impacts of natural hazard. This issue has been neglected for several years, especially in building sector, but these events are becoming more and more influential and frequent. For this reason, the idea of resilience in buildings is developing [1] and represents the measure of their ability to recover from or adapt to an unfavourable condition, event or change in building use [2]. Resilience is a complex challenge at any

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scale, including the scale of building systems. In other words, buildings have to be able to survive and maintain their own functionality [3] and performances even in an uncertain future. Moreover, environmental degradation is accelerated by climate changes and global warming and by increasing frequency and severity of the linked disruptive events. Buildings are highly responsible for the global and local climate change [4] but, at the same time, they have to withstand to these events in terms of performances and dynamic reaction.

As regards the study focuses on climate change effects in summer and on how it is possible to reduce them through façade system retrofit (in particular opaque envelope) in Mediterranean climate. Indeed, the facades play an important role in urban context because the surface area of facades overcome roof and, sometimes, street area for huge amounts of square meters. Moreover, each side of a building façade should perform for the environment that it faces: inside and outside [5]. Most of the facades in the existing building stock need retrofit, but current practices do not require enough attention in de-signing systems that adapt to changing external conditions. Therefore, it is desirable to predict the needs for future retrofit, satisfying principles of resilient design. In particular, facades have to mitigate increasing or decreasing temperatures in the future, even if it is obviously that this function has to be supported by the whole building - plant system. The influence of facades needs particular analysis both at building and pedestrian level.
The aim of the research is to create an assessment tool thanks to a set of climatic resilience indicators for different building facades in order to take into account resilience ability against climate change, both inside and outside of building. This new holistic approach integrates both the energy efficiency requirements of buildings and resilience to climate effects at urban and building level.

2. Method

Since facades are crucial elements to ensure energy efficiency and indoor comfort, but also to mitigate urban heat island phenomenon, it is studied a methodological approach that takes into account these two different dimensions and allows to analyse how the facade system can contribute to enhance resilience in both buildings and urban neighbourhood. In particular, the opaque building envelopes are studied considering different solutions also with dynamic behaviour to withstand and react to very hot temperatures.

Therefore, it is important to define a set of climatic resilience indicators in order to evaluate the degree of increase in resilience and to tackle the reciprocal interactions between existing buildings and urban climate. In fact, the interaction between buildings and the atmosphere is not limited to the wind field and shading: technological solutions and materials chosen for façade affect the radiative behaviour towards neighbourhood and the heat stored in walls or transferred between the inside of a building and the outside atmosphere. The characteristics of facades define also the external surface temperature of walls, which consecutively influences the external air temperature [6]. Moreover, the envelope behaviour in summer can increase or decrease the use of air-conditioning systems that affects energy consumption in buildings and urban pedestrian comfort.

The comparative analysis of different technological solutions concerns the assessment of summer resilience to climate change of buildings in relation to urban effects. In this field of study, it is identified the need: to reduce the inside and outside temperature in summer. Hence, in relation to this goal (criterion), an index about resilience to the increase in temperatures is defined through multi-indicators. Therefore, resilience indicators for opaque envelope are singled out. They can be divided into direct performance indicators and indirect ones. The direct indicators have a direct effect on neighbourhood microclimate; the indirect indicators have effect on reducing energy consumption and on the heat rejected by air conditioning system to external environment. The performance indicators with urban indirect effect are: Operative Temperature, Wall Heat Gains, Sensible Cooling. The performance indicator with urban direct effect is External Surface Temperature. These indicators are chosen in order to evaluate the dynamic behaviour of building in summer. The performance measure for each indicator (with the relative unit) is defined in relation to a base case that can be a traditional retrofit solution (Table 1).

The methodological approach is validated on a case study of residential building in an urban context of a Mediterranean city. Different retrofitting actions regarding building facades are applied: XPS, XPS+PCM, cool finishing layers, green wall. These solutions are chosen because they can be responsive to the disruption event linked to the hot peaks of temperature in summer. At the same time, they have to comply with the energy efficiency regulations: in fact, the energy improvement is a prerequisite for the comparative evaluation of retrofit solutions. The dynamic simulations are carried out through the software DesignBuilder/Energy Plus in the hottest period of the year.

Finally, they are compared respect a traditional thermal insulation solution using the defined resilience indicators for opaque facades in order to understand the influence of different building skin typologies on buildings and neighbourhood microclimate changes and their different resilient behaviour.

Table 1. Performance indicators to quantify the reduction of the inside and outside temperature in summer and the increase of climatic resilience

	Performance Indicators for opaque envelope	Measure of performance	Unit
Urban indirect effect	Operative Temperature (T_{op})	$\Delta T_{op} = T_{op}$ of the solution - T_{op} of the base case	°C
	Wall Heat Gains (WHG)	ΔWHG = WHG of the solution - WHG of the base case	kWh
	Sensible Cooling (SC)	ΔSC = SC of the solution - SC of the base case	kWh
Urban direct effect	External Surface Temperature (Ts)	ΔTs = Ts of the solution – Ts of the base case	°C

3. The case study

In order to validate the described theoretical approach, it is studied a multi-storey building in the city of Bari, in the South of Italy (Fig. 1).

The city is located in Mediterranean climatic zone that belongs to group C in the Köppen climate classification (1350dd according to Italian standards). The climate is characterized by hot summers and mild winters, but the climate change and pollution are causing temperature below zero in winter and peak temperatures also during autumn and spring, especially in urban area. The building (Fig. 2) is representative of one of the most common construction typologies in Bari, built before 1960s [7].

Fig. 1. Identification of the studied building in its urban context.

Fig. 2. Orthophoto of the building front façade.

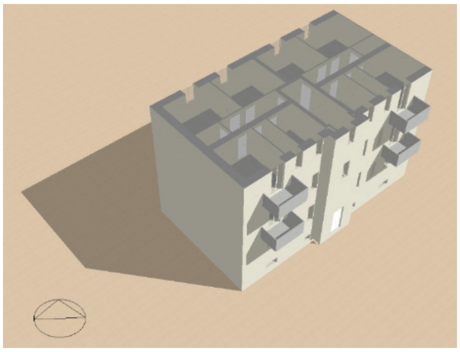

Fig. 3. Axonometric horizontal section of the analysed building.

The considered block has two central staircases, with three floors above ground and a basement, but the study is focused on the south staircase unit. Each floor is divided into two apartments of about 58 m^2 (Fig. 3).

The building was built in load-bearing masonry with 60 cm thick external wall (U=0.867 W/(m^2 K)) made of calcarenite stone (tufo). The flat slab floors and the roof have a mixed structure of reinforced concrete hollow-tile (U=1.583 W/(m^2 K) and U=1.195 W/(m^2 K) respectively). The single-glazed windows have aluminum frame (U_w=5.778 W/(m^2 K)) without thermal break. The heating system is autonomous, separated for each apartment. The majority of boilers is installed outside and their efficiency values are higher than 80%.

The building is analysed through dynamic simulations during the hottest week in summer, from 20th to 26th July.

The dynamic method takes into account the temporal variation of the boundary conditions, such as the external climatic data and the users' profiles. Thanks to the thermal inertia of the building envelope (for external walls: thermal lag φ=19.74 h, periodic thermal transmittance Yie=0.03 W/(m^2 K), attenuation factor f_a=0.04, areic mass M_a=840 Kg/m^2), the trend of the indoor temperature is obviously more regular than the outdoor one, but it is higher than the optimal temperature value (26°C) for the indoor thermal comfort (Fig. 4).

During the hottest days of the simulated week, the average daily values of operative temperature reach 28.73°C and 29.18°C on 24th and 25th July respectively (Fig. 5).

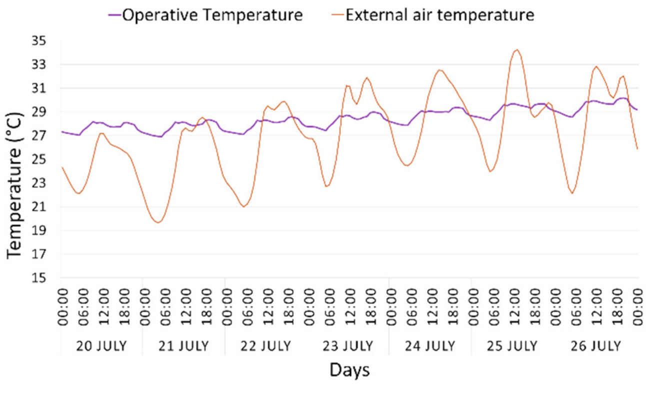

Fig. 4. Trend of temperature during the hottest summer week in the studied building.

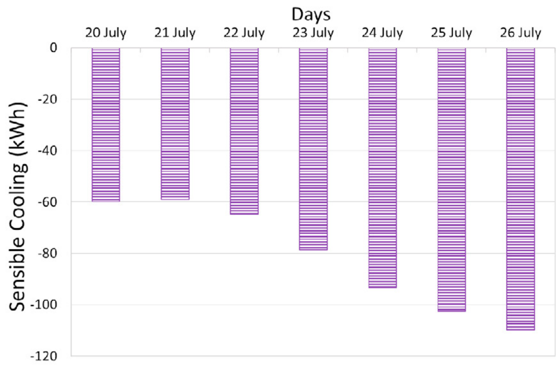

Fig. 5. Daily sensible cooling during the hottest summer week in the studied building.

In order to evaluate the amount of heat that might be rejected in the surrounding area for the summer comfort, it is hypothesized a system of cooling according to Italian standard [8] with a COP = 3.5. The sensible cooling reaches high peak values during the hottest days of the summer week. In particular, it results equal to 93.49 kWh on 24^{th} and 102.64 kWh on 25^{th} July. Even if 26^{th} July is not the hottest day in the week, the sensible cooling is greater (109.92 kWh) than the other days because it is affected by the thermal lag of the building envelope.

The analysis of the existing buildings reveals that not only it is poor in the point of view of the energy efficiency but also it fails to face the hot summer conditions, caused by climate change. Subsequently the need to enhance resilience of the building envelope is evident.

4. The retrofit solutions

The improvement of building energy performance is the first step of the case study analysis in order to comply with energy standards. Since we want to investigate how walls influence the thermal and adaptive behaviour of building, the other features remain unchanged. In accordance with EU nearly zero building strategy, we do not consider a cooling system as an improvement strategy, giving much more importance to building envelope. The thermal insulation solutions, placed on wall external side, are chosen in order to perform according to Italian energy standards for that climate zone, introducing at the same time a better external shading system (shade roll – light opaque – solar transmittance equal to 0.05) respect to the existing one. In fact, a highly insulated envelope causes an inside overheating and therefore it is assumed that the activation of shading system is always on when it is necessary during the daylight hours [9].

In order to reach the compulsory threshold of transmittance, the base technological solutions chosen for the walls (on the external side) are XPS with 40% albedo and wood fibers layer for insulation layer.

The thermal characteristics are:

- with XPS layer (thickness equal to 6 cm) U=0.335 W/(m^2 K), M_a=890 kg/m^2, φ=22.86h, f_a=0.01 and Yie= 0.003 W/(m^2 K).

- with wood fibers layer (thickness equal to 8 cm) U=0.336 W/(m^2 K), M_a=897 kg/m^2, φ=23.15h, f_a=0.01 and Yie= 0.003 W/(m^2 K).

Since they are almost equal and, after the dynamic simulations, the results are almost the same, the solutions are very similar from an energy point of view for the case study. The differences are mainly the environmental compatibility and the durability and the solution with XPS and 40% albedo is assumed as the base case because durability is very important in terms of resilience to extreme events.

The results for this case demonstrate that the action of insulation on building envelope is useful to achieve better energy performance in summer, if it is combined with the use of adequate shading system and ventilation rate.

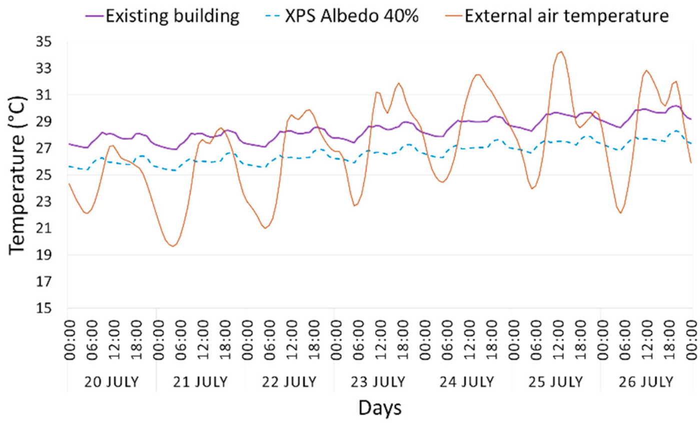

Fig. 6. Comparison between trends of operative temperature in the studied building and the XPS Albedo 40% solution (base case) during the hottest summer week.

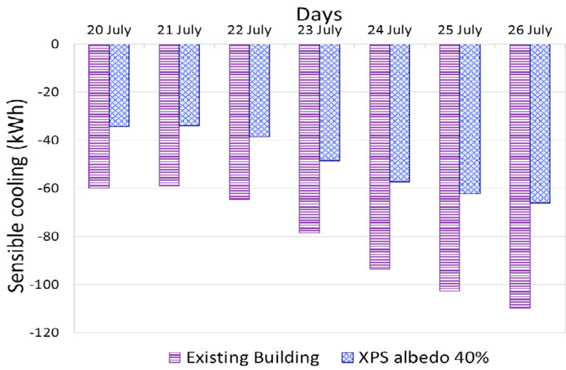

Fig. 7. Comparison between daily sensible cooling in the studied building and in the base case during the hottest summer week.

The distribution of temperature follows the same trend of the existing building one (Fig. 6), but the average value decreases of about 1.78°C.

Thanks to the reduction of temperature, even the sensible cooling decreases in the base case (Fig. 7) with a saving up to 39% in the hottest days in the week.

After the base case analysis, it is necessary to consider alternative solutions that are addressed to have potential influence on UHI mitigation and not only on the improvement of buildings thermal characteristics. Hence, the different solutions are compared respect to the chosen resilience indicators: wall heat gains, sensible cooling, operative temperature and external surface temperature

First of all, the base case solution is combined with finishing layers characterized by different solar reflectance (albedo) that can affect the external surface overheating of the walls exposed to sunlight. The albedo of materials, that is, the ratio of the reflected solar radiation and the incident one (between 0 and 1) is often underestimated in design phase although it is of extreme importance. In fact, a wrong choice of materials contributes to the heat island effect, which characterizes urban areas. The improved albedo values considered for finishing materials are: 65% (that comes from the minimum compulsory value for roof and is used here as representative value for facades) and 85%.

Secondly, the adding of PCMs (Phase Change Materials) layer is explored as a new passive solution applied to the wall. These materials are able to store and release heat during the state transition phase when they reach the melting/solidification temperature. The heat supplied upon melting is called latent heat.

The PCMs can be inorganic (engineered hydrated salt solution made from natural salts with water), organic (paraffin and fatty acid), eutectic (mixture of more PCMs) and Bio-based PCM (materials extract from renewable plant). The applied typology is the last one because they are environmentally friendly: in particular the BIO-PCM M27Q25 with a peak melting temperature equal to 25 °C is used. The other features are thermal conductivity equal to

0.20 W/(m K), specific heat equal to 1970 J/(kg K) and density equal to 235 kg/m^3. In the studied configuration, BIO-PCM M27Q25 is placed between the external side of the existing wall and the added insulation layer of XPS, taking into account its melting temperature and temperature distribution within the wall [10]. In this way, it is possible to analyze if PCMs reduce thermal fluctuations and allow a more rational use of the heat gains.

Also for PCM solution, the albedo of finishing layers is changed (XPS+PCM with 40% albedo, XPS+PCM with 65% albedo and XPS+PCM with 85% albedo).

The other investigated strategy is the use of vertical greening systems on facades because they can change not only the building energy consumption but also the interaction between building and neighborhood environment. In fact, plants absorb a significant amount of solar radiation for their growth and biological functions. Both the evapotranspiration process and the shading effect of plants leaves can contribute to cool facades, which are very useful in Mediterranean urban area [11].

These systems can be classified into green facades and living wall systems. Green façades are based on climbing plants planted directly at the base of the façade or supported by cables or meshes in order to attach themselves directly on the facades. Living wall systems, also called green walls and vertical gardens, are constructed through the use of modular panels, each of which contains its own soil or other artificial growing mediums and irrigation systems [12].

The solution of green wall (average thickness equal to 10 cm) is placed on an external XPS layer in order to achieve the same transmittance of base case. For the simulation we use the roofVegetation module modelled in Energy Plus and integrated in Design Builder as a material. This model takes into account several physic and technical parameters in order to consider the complex behavior of vegetation linked to several interacting phenomena. The input parameters (Table 2) are chosen according to some researches on green wall dynamic simulation using roofVegetation model [13,14].

We consider a high leaf area index (LAI), which represents the ratio of leaf area per soil surface area, because we want to maximize the solar shading by foliage and cooling by evapotranspiration in order to mitigate the peak hot temperatures in summer. Concerning the irrigation schedule, the maximum rate is 0.04 m/hr and it is simulated a daily schedule from 6:00-8:00.

It is chosen a saturation threshold (30%) that is lower in comparison with the value used for roof, because green wall is not able to retain a lot of water.

Table 2. Performance indicators to quantify the reduction of the inside and outside temperature in summer and the increase of climatic resilience

Height of plants (m)	0.070
Leaf area index (LAI)	5.000
Leaf reflectivity	0.300
Leaf emissivity	0.800
Minimum stomatal resistance (s/m)	180.000
Max volumetric content at saturation	0.300
Min residual volumetric content	0.100
Initial volumetric moisture content	0.300
Conductivity of dry soil (W/mK)	0.2

5. Results and discussion

The comparison among all the adopted wall retrofit solutions provides interesting results in terms of summer energy performance and climate change resilience. This is highlighted by the analysis of the indirect performance indicators.

The operative temperature follows the same trend in all the solutions (Fig. 8), but the lowest temperature is obtained through the green wall use. Instead, the solutions of PCM across its albedo variations give results almost equal to the XPS ones.

As it is known, PCM solutions can be effective for improvement of flat roof performance during summer [15]. In fact, the solar radiation hits the flat surface throughout the day; in this way, the PCM absorbs large amount of heat until it reaches the melting temperature and changes phase. Instead, if PCM is applied on vertical building envelope, the solar radiation is not constant during the day but depends on the facades orientation. That causes a decrease of their performance.

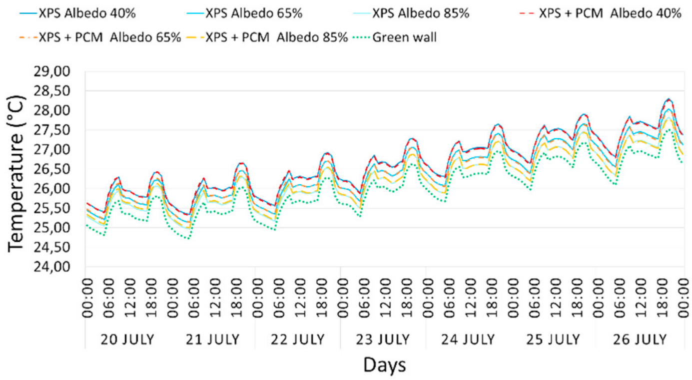

Fig. 8. Comparison between trends of operative temperature in the different retrofit solutions during the hottest summer week.

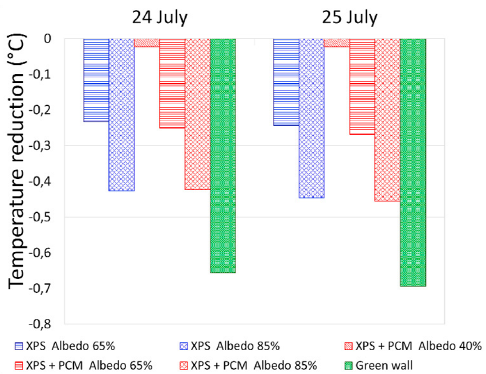

Fig. 9. Average reduction of daily operative temperature obtained by the different retrofit solutions during the hottest days of the week, related to the base case (XPS Albedo 40%).

Analysing in detail the evolution of daily operative temperature during the hottest days of the week, these considerations are confirmed (Fig. 9). The XPS with 65% and 85% albedo are almost equal to the relative PCM solutions and the greatest operative temperature reduction is achieved in both cases by XPS and PCM with 85% albedo on 25th July. In fact, the temperature is 0.45°C (XPS with 85% albedo) and 0.46°C (PCM with 85% albedo) less than the operative temperature achieved in the base case (XPS with 40% albedo). However, the best solution is the green wall with an average reduction of 0.7°C on 25th July, respect to the base case.

The wall heat gains confirm the previous result (Fig. 10): the best performance is achieved by the green wall and by the solutions with the 85% albedo, with PCM prevailing slightly above XPS. In fact, considering 24th July, the wall heat gains of green wall are 64% less than the base case (XPS with 40% albedo), followed by PCM with 85% albedo (drop of 62%) and XPS with 85% albedo (drop of 52%). On 25th July, the hottest day of the week, the reduction of the wall heat gains is even more evident and it is of about 78%, 67% and 55% for green wall, PCM with 85% albedo and XPS with 85% albedo respectively. Obviously, the increasing of the reflectance reduces the difference between the other solutions and the green wall.

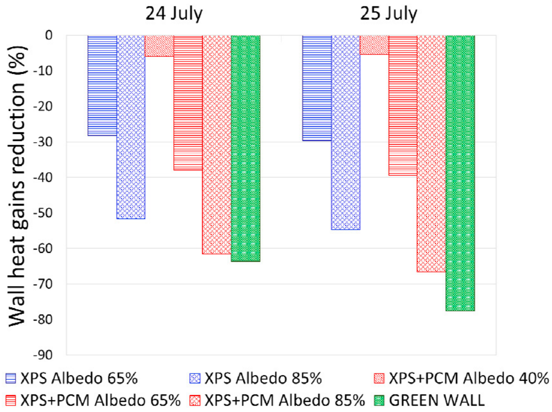

Fig. 10. Wall Heat Gains reduction over the base case, obtained by the different retrofit solutions during the hottest days of the week (24th and 25th July).

Finally, the XPS and PCM solutions with same reflectance require almost the same sensible cooling in order to obtain comfort conditions (Fig. 11). On 24th July, the sensible cooling decreases of 9.45% and 9.50% in the case of XPS and PCM with 65% albedo and of 16.47% and 16.88% in the cases of XPS and PCM with 85% albedo over the base case.

Instead, the sensible cooling in the green wall retrofit is lower of 25.14% than the XPS with 40% albedo, 17% than the XPS and PCM with 65% albedo and 10% than the XPS and PCM with 85% albedo. On 25th July, the percentage is almost the same.

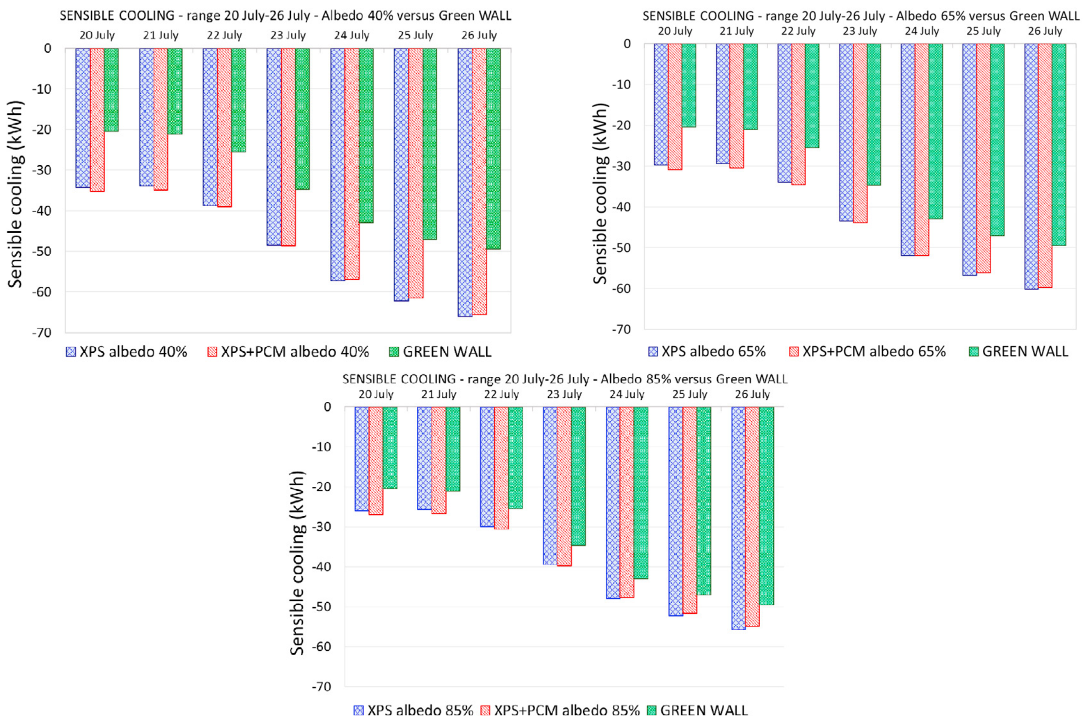

Fig. 11. Sensible cooling: comparison between XPS and XPS+PCM versus Green wall, varying the albedo and during the hottest summer week.

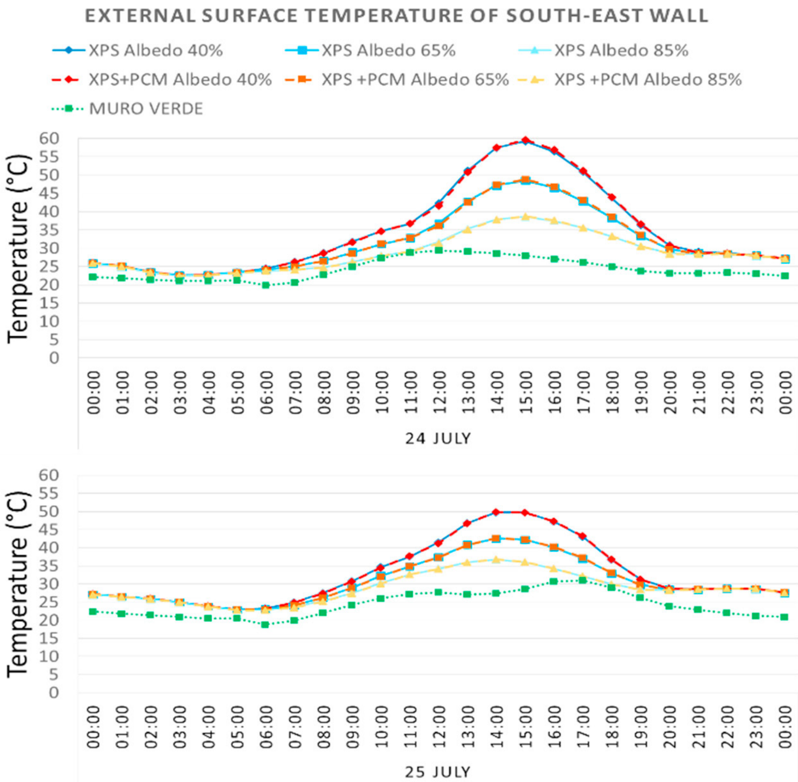

Fig. 12. External surface temperature of south-east wall for the different applied solutions, during the hottest day of the week (24th and 25th July).

Thanks to the green wall and solutions with 85% albedo, the amount of heat rejected in the surrounding area decreases, improving indoor and outdoor microclimate. The benefit of these strategies also on urban areas is furthermore confirmed by external surface temperature, that is the direct performance indicator. The walls and the finishing layers are usually made of materials with high emissivity (plaster, paints) so that we need to drop surface temperature increasing shading, reflectance or evapo-traspiration in order to reduce the emission of infrared radiations that, in urban canyons, are amplified for multiple reflections between buildings and street surfaces. This contributes to the phenomenon commonly known as the Urban Heat Islands, more frequent also for rising external temperatures.

For brevity, the results are presented only for the South-East façade (at pedestrian level), the mostly affected by the incident solar radiation, and for 24th and 25th July (Fig. 12).

The maximum external surface temperature is reached obviously by the solutions with 40% albedo, followed by 65% and 85% albedo. As the graphs show, the PCM solutions do not influence this parameters because of its intermediate position in the wall.

As regards to the green wall, when the irrigation is activated (between 6:00 and 8:00 a.m. every day) the external surface temperature is lower. Then, the water evaporates and the surface temperature increases, even if its trend remains the best one of all the solutions.

At 14:00 of 24th July, the external surface temperature decreases of 31.25°C, 20.49°C and 10.63°C over the XPS with 40%, 65% and 85% albedo respectively. At 14:00 of 25th July, it reduces of 22.35°C, 15.18°C and 9.31°C.

In the last step of the study, in order to evaluate the best climate change resilient solution in summer conditions, all the performance indicators for opaque envelope are calculated and the reductions respect to the base case are explicitated. The Table 3 clearly shows that green wall prevails on the other retrofit interventions, according to all the indicators. The second best solutions are the XPS and PCM with 85% albedo.

Table 3. Performance Indicators for climate change resilience Index related to opaque envelope on 25th July, the hottest day of the week.

Urban Effect	Performance Indicators for opaque envelope	Analysed solutions	Measure of performance (Daily average values)	Reduction (%)
Indirect	Operative Temperature (°C)	XPS Albedo 65%	- 0.24	0.89
		XPS Albedo 85%	- 0.45	1.63
		XPS + PCM Albedo 40%	- 0.02	0.08
		XPS + PCM Albedo 65%	- 0.27	0.98
		XPS + PCM Albedo 85%	- 0.46	1.67
		Green Wall	**- 0.69**	**2.54**
Indirect	Wall Heat Gains (kWh)	XPS Albedo 65%	- 6.19	29.69
		XPS Albedo 85%	- 11.41	54.71
		XPS + PCM Albedo 40%	- 1.12	5.35
		XPS + PCM Albedo 65%	- 8.23	39.48
		XPS + PCM Albedo 85%	- 13.88	66.60
		Green Wall	**- 16.19**	**77.65**
Indirect	Sensible Cooling (kWh)	XPS Albedo 65%	- 5.49	8.83
		XPS Albedo 85%	- 9.88	15.88
		XPS + PCM Albedo 40%	- 0.71	1.15
		XPS + PCM Albedo 65%	- 6.10	9.80
		XPS + PCM Albedo 85%	- 10.61	17.05
		Green Wall	**- 15.18**	**24.40**
Direct	External Surface Temperature South-East façade (°C)	XPS Albedo 65%	- 2.12	6.46
		XPS Albedo 85%	- 3.84	11.74
		XPS + PCM Albedo 40%	- 0.02	0.05
		XPS + PCM Albedo 65%	- 2.13	6.50
		XPS + PCM Albedo 85%	- 3.86	11.80
		Green Wall	**- 8.59**	**26.23**

5. Conclusions

The overheating in buildings and surrounding area associated with climate change and dense urbanization is a challenge that requires adaptive and responsive capacities of facades because they are close to pedestrian level and have a more extended area in comparison with roof and other urban surface.

The dynamic simulation are essential to assess the chosen retrofit actions on building facades towards energy efficiency as a prerequisite.

From the comparative analysis, green wall results the best solution respect to the improvement of the building performance and at the same time of UHI mitigation for all the performance indicators. Facades with integrated plants can effectively reduce operative temperatures (2.54%), wall heat gain (77.65%), sensible cooling (24.40%) and exterior surface temperature (26.23%) in the hottest week of year. Additionally, it is very significant the daily surface temperatures distribution of green wall: they are much lower during the hottest hours of the day (the maximum difference in relation to base case is from 22.35 °C up to 31.25 °C at 14:00 on the hottest days).

The increasing of albedo is an effective strategy, in fact, for the XPS solution with maximum albedo (85%) it is performed a reduction of operative temperatures (1.63%), wall heat gain (54.71%), sensible cooling (15.88%) and exterior surface temperature (11.74%). Since the finishing layers are usually made of materials with high emissivity (plaster, paints) the increase of reflectance has a positive effect in reduction of infrared emission of external wall and then of multiple reflections between buildings and street surfaces.

PCM has a nearly negligible influence on wall surface temperature but we have a further improvement in operative temperature, wall heat gains and sensible cooling (e.g. for solution with albedo 85% their reductions are 1.67%, 66.60% and 17.05% respectively) thanks to its position under the external insulation layer and especially to the albedo increase of external finishing.

As the case study analysis highlights, the defined resilience indicators are useful parametric tools to evaluate the various retrofit wall solutions in relation to the mitigation of climate change in summer. Different indicators mean to have the possibility to compare various solutions in order to choose the best strategy in terms of adaptability and mitigation based on local climate risk.

The study is going on with the implementation of the applied methodology, assigning a suitable weight to each indicator and introducing a scale of priorities, in relation to different weather conditions and urban context. Moreover, further researches are necessary to extend the method to the other building components to monitor the feedback between the buildings and their neighborhood.

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