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Assessing the Climate Resilience of Passive Cooling Solutions for Italian Residential Buildings

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Abstract

One of the most significant repercussions of greenhouse gas concentration increase has been the global rise in temperature, resulting in drastic changes in the climate. According to this background, buildings are not only contributing to climate change, but they are also being affected by it, as climate change will raise the risk of overheating and cooling demand in buildings. Therefore, assessing and communicating resilient cooling and overheating protection solutions is inexorable. This paper aims to analyse the energy efficiency and climate resiliency of three passive cooling solutions for Italian residential buildings in future climates. Simulations have been performed using EnergyPlus for the pre-retrofitted condition (without insulation and conventional heating and cooling systems) and the retrofitted building (with insulation and a reversible heat pump for heating and cooling). Results show that buildings will be subject to an increase in cooling loads, electrical energy consumption for cooling, and overheating risk due to climate change. The ultra-selective double-glazed window is found to be more climate-resilient in comparison with roller blind and cool roof tiles. Besides, combining these three cooling technologies can guarantee the best future energy performance for each period. However, the overheating risk during the power outage still exists, especially for the post-retrofitted building. These findings have significant implications for understanding how analyzing multiple factors is essential to guarantee the climate resilience of cooling systems in a holistic way.

1. Introduction

Each of the last four decades since 1980 has been successively warmer than the preceding decade. According to the latest Assessment Report (6th A.R.) of the Intergovernmental Panel on Climate Change (IPCC), the concentration of greenhouse gases (GHG) in the atmosphere has continued to increase since 2011 (measurements in IPCC 5th A.R.) (Masson-Delmotte et al., 2021). Considering the fact that global CO_2 emissions from the building sector increased by 50 % from 1990 to 2019, making it the main contributor to GHG emissions, its impact on intensifying climate change is undeniable (Cabeza et al., 2022). Furthermore, climate change is already impacting many weather and climate extremes in all world regions. Due to methodological advances and new data sets, evidence of observed changes in climate-related hazards, such as heatwaves, has increased since the 5th A.R. (Symon, 2013). In this case, buildings are not only responsible for climate change but are highly affected by it. Accordingly, many published studies worldwide suggest a shift in building energy performance due to the impacts of climate change. For instance, Wan et al. (2012) analysed the heating and cooling energy use of an office building in different Chinese cities and reported an increase in cooling energy consumption of up to 24.2 %, implying a shift towards higher electricity demand. In the U.S. context, Shen (2017) demonstrated a rise in cooling energy use and a drop in heating energy use for office and residential buildings in four American cities. In addition, the inconsistency of energy use in residential buildings located in cold and hot regions of the U.S. is expected to decrease due to the impact of climate change. In Canada, an increase in cooling demand by up to 126 % and a decrease in heating demand by up to 33 % were predicted for several urban regions by Berardi & Jafarpur (2020).

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Besides the expected changes in energy needs, the overheating risk will also become a challenge in the future. For example, in southern regions of the U.K., overheating is expected to create a cooling problem for a third of the year, as Peacock et al. (2010) suggested. In the same vein, Dino & Akgül (2019) examined a typical mid-rise residential building in four different cities in Turkey, and found that inhabitants would experience overheating, particularly in naturally ventilated houses. In addition, other studies demonstrated that such changes in energy needs, and overheating risk are also predicted for retrofitted and energy-efficient buildings. In other words, due to the changing climate, meeting nearly zero-energy building (NZEB) requirements may not necessarily guarantee the energy performance and indoor environmental quality of buildings in the future. For example, as Tabatabaei Sameni et al. (2015) suggested, thermal discomfort during the cooling season is foreseen for 72 % of analysed social housing flats − built to Passivhaus standards − due to the impact of climate change. Attia & Gobin (2020) looked at a Belgian reference example of the NZEB and found that there would be overheating up to +43.5 % at the end of the century. In another study, Da Guarda et al. (2020) examined the influence of climate change on zero-energy buildings in 2020 (2011 to 2040), 2050 (2041 to 2070), and 2080 (2071 to 2100). It has been proved that energy consumption will rise, so further dimensioning of renewable energy installations is required to achieve zero net energy balance. Taken together, these studies suggest that to maintain energy efficiency, sustainability, and climate resilience of buildings over time, an assessment of the performance of energy-efficient buildings using future weather data is essential.

This paper is a part of research carried out in collaboration with the International Energy Agency (IEA) Energy in Buildings and Communities Programme (E.B.C) Annex 80 "Resilient Cooling of Buildings". This project develops, assesses, and communicates strategies for resilient cooling and overheating protection (Annex 80 IEA EBC, 2018). After creating reliable future weather data for Rome, the resilience of three passive cooling technologies was investigated using thermal comfort and energy performance metrics to assess and develop the adaptation and mitigation framework on a regional scale.

2. Materials and Methods

2.1 Generation of Future Weather Data

In synergy with the IEA-Annex 80 Weather Data Task Group, future typical meteorological years were created for Rome during the first step.

For this purpose, Regional Climate Models (GERICS-REMO 2015, MPI-M-MPI-ESM-LR) from Euro-CORDEX on a 0.11° grid in rotative coordinates (equivalent to a 12.5 km grid) were used. In detail, G.C.M.s (Global Climate Models) are mathematical models for forecasting climate change providing information on a global scale with a spatial resolution of 150–600 km (Symon, 2013). Since climate change effects and related weather extremes at the local level will not be considered using these models, they are not appropriate for energy simulations on the building scale. Therefore, it is necessary to downscale the models to applicable spatial (less than 100 km) and temporal resolution (less than monthly value). The dynamical technique employs regional climate models (R.C.M.s) to obtain finer spatial and temporal climate information; this is one of the downscaling methodologies. R.C.M.s can better capture the geographical and temporal variability of the local climate and provide physically consistent datasets (Soares et al., 2012). As mentioned above, this study employs the GERICS-REMO-2015 as the R.C.M. In addition, since being well-supported by the IPCC report on climate model evaluation (Flato et al., 2014), the MPI-M-MPI-ESM-LR is the study's driving model. Besides, the data source is the EURO-CORDEX entry point through the Earth System Grid Federation (ESGF) for the Europe domain on a 0.11° grid, in rotative coordinates (equivalent to a 12.5 km grid). NetCDF4, which is a file format for storing multi-dimensional scientific data, is the accessible format for this source. The hourly climatic data for Rome Fiumicino airport was extracted using the Cordex Data Extractor program, which enables the discovery of the data point on the grid closest to the specified latitude and longitude. These climatic data were extracted by adapting the RCP 8,5 (Representative Concentration Pathway) scenario from IPCC 5th A.R. for the 2041-2060 (2050s) and 2081-2100 (2080s) periods. These scenarios were the latest available projections of future climate at the time of the study.

Accordingly, the EN ISO 15927-4 (2005) methodology was applied to construct the future typical meteorological year from the 20 years of climatic data. This international standard addresses the selection of appropriate meteorological data for the assessment of the long- term mean energy use for heating and cooling. Twelve Best Months were picked by comparing the Cumulative Distribution Function of the single and reference years using the Finkelstein-Schafer (F.S.) statistics (Finkelstein & Schafer, 1971). This method was selected for this study because it includes the global solar irradiance, relative humidity, dry-bulb air temperature, and wind speed. The best representative 12 months were then employed to construct the T.M.Y. Historical (2001-2020), future medium-term (2041-2060), and future long-term (2081-2100) are the T.M.Y.s referred to in this study. Despite not being adjusted for bias, the results are reliable; since a relative comparison is applied in this study, and for confronting different technologies, this kind of future weather data is acceptable.

2.2 Cooling Strategies

In IEA EBC Annex 80, four categories of cooling strategies were created according to their approaches to cooling people or the indoor environment. They include strategies aimed at: a) reducing heat gains to indoor environments and people indoors, b) removing sensitive heat from indoor environments, c) enhancing personal comfort apart from cooling whole spaces, and d) removing latent heat from indoor environments.

For the present analysis, three cooling solutions were selected from the first category: ultra-selective double-glazed window, external roller blind, and cool roof tiles.

The ultra-selective double-glazed window is a static technology that incorporates low thermal-infrared emittance (low-E) coatings with spectral control to reduce the window heat loss (U-value ≤ 1.8 W/(m^2 K)) and solar heat gain ($g \leq 30$ %), while admitting most daylight ($\tau_v > 60$ %). The external roller blind is a dynamic technology with a low solar transmittance ($\tau_s < 15$ %) that strongly reduces the solar heat gain due to its external position and can be controlled to optimise both thermal and visual comfort and energy demands for heating, cooling and lighting. Cool roof tiles are a static technology that reduces net radiative heat gain at the envelope (solar + thermal infrared radiation) thanks to the high solar reflectance ($\rho_s > 0.30$ for pitched roofs, $\rho_s > 0.65$ for flat roofs).

2.3 Calculation Methods and Performance Indicators

The following three key performance indicators (KPIs) were used for the performance assessment of the selected cooling solutions:

- *HE* [%], i.e., hours of exceedance, which are the number of hours during June, July, and August in which the operative temperature of the zone is greater than the upper limit temperature,
- $EP_{C,nd}$ [kWh/m^2], which is the thermal energy need for space cooling in June, July, and August,
- $E_{el,C}$ [kWh/m^2], which is the electrical energy consumption (from the grid) for cooling in June, July, and August.

The above indicators were chosen from the list of KPIs officially adopted in IEA EBC Annex 80 to represent the summer performance of the building according to the following criteria: a) thermal discomfort in free-floating conditions (absence of cooling or power outage) or in case of power shortage, b) thermal performance of the fabric in cooling operation, and c) energy performance of the building (including HVAC system) in cooling operation.

All the adopted indicators are based on international standards. *HE* accounts for the number of weighted hours exceeding the acceptable range of the indoor operative temperature. For free-floating conditions, the adaptive comfort method is assumed according to the Annex-H of EN ISO 7730, 2005. $EP_{C,nd}$ reflects the basic energy needs of the building in ideal thermal conditions (uniform and ideally controlled indoor temperature) without interaction with specific technical building systems (EN ISO 52016-1, 2017). $E_{el,C}$ represents the energy delivered to the building for cooling by adding the effect of the energy losses of the cooling system (EN ISO 52000-1, 2017).

2.4 Case Study

With the aim of extending the research outcomes on a broader territorial scale, the case study was selected to be representative of a specific category, i.e., the Italian single-family house built in the period 1946-1960 (Ballarini et al., 2014). Among the Italian existing building categories, the one selected presents the lowest energy performance due to its highest shape factor and uninsulated envelope components (Ballarini et al., 2017). In a recent study (Tootkaboni et al., 2021), this type of building was found to be more sensitive to climate change due to its high shape factor. According to the IEE-TABULA project (Corrado et al., 2012), the building selected is an "archetype" (Fig.1), which means that it is characterised by average dimensional properties (gross heated volume, shape factor, conditioned net floor area, number of floors, number of apartments) of a representative building sample according to statistical analysis.

The main geometric data of the analysed archetype are listed in Table 1. The thermo-physical features of the building envelope components are provided in Table 2, assuming the building type both in the original pre-retrofit situation and in the retrofitted state. This double condition allows an assessment of the effect of the passive cooling strategies both on low energy-efficiency buildings and on already insulated buildings. The U-values of the envelope components in the pre-retrofit state refer to typical technologies of the construction period (solid brick masonry and single-glazing windows). The retrofitted state presents components insulated in accordance with the notional reference building for the climatic zone of Rome, as expressed by the Italian energy regulations (M.D 26 June, 2015), which also represents the nearly zero-energy building target. The post-retrofit windows present a low-E double-glazing. In addition, while the original building is not equipped with solar shading devices, these are provided for in the retrofitted building (external wooden Venetian blinds).

As far as the technical building systems are concerned, the building in the pre-retrofit state is equipped with a gas standard boiler and radiators for space heating and a split system for space cooling. In the post-retrofit phase, both heating and cooling are provided by a reversible air-to-water heat pump with fan coils as heat emitters.

Fig. 1 – Archetype of the Italian single-family house built in the period 1946-1960 (Corrado et al., 2012)

Table 1 – Geometric data of the case study

Parameter	Value
Conditioned gross volume, V_g [m^3]	584
Conditioned net floor area, A_{fl} [m^2]	162
Shape factor, A_{env}/V_g [m^{-1}]	0,73
Window-to-wall ratio, *WWR* [-]	0,09
Number of floors [-]	2
Number of apartments [-]	1

Table 2 – Thermo-physical parameters of the envelope components

Component	Parameter	Pre-retrofit	Post-retrofit
External wall	U [W·m^{-2}K^{-1}]	1.48	0.29
Roof	U [W·m^{-2}K^{-1}]	1.65	0.26
	α_s [-]	0.75	0.75
	ρ_s [-]	0.25	0.25
Bottom floor	U [W·m^{-2}K^{-1}]	2.00	0.29
Windows	U [W·m^{-2}K^{-1}]	4.9	1.30
Glazing	U [W·m^{-2}K^{-1}]	5.7	1.20
	g [-]	0.85	0.59
	τ_v [-]	0,90	0,80
Shading	τ_s [-]	N/A	0,40
	ρ_s [-]	N/A	0,12

The energy performance of the case study was assessed considering the behavior of a standard user. Hourly profiles of internal heat gains, which include occupants, electric lighting and appliances, and ventilation airflow rates were assumed in accordance with the Italian National Annex draft of the EN 16798-1 technical standard (2020).

A continuous operation mode of the technical building systems was adopted, considering heating and cooling temperature set-points equal to 20 °C and 26 °C, respectively. The heating season is included in the period from 1st November up to 15th April, while the cooling period was assumed for the months of June, July, and August. The operation of the solar shading devices was set in the function of a threshold value of the incident solar irradiance (300 W/m^2), in accordance with UNI/TS 11300-1 (2014).

3. Results and Discussion

The results obtained from the simulations are shown in Figs. 2 to 7. The first two refer to the thermal energy need for space cooling ($EP_{C,nd}$) during the months of June, July, and August in 2020, 2050, and 2080. Besides, Figs. 4 and 5 represent the electrical energy consumption (from the grid) for cooling ($E_{el,C}$) during the same period. An increase of up to 75 % for the pre-retrofitted and 35 % for the post-retrofitted case is shown in $EP_{C,nd}$ over time due to climate change. Furthermore, the increase in $E_{el,C}$ is up to 80 % for the pre-retrofitted and 30 % for the post-retrofitted building. For post-retrofitted building, the variations of $EP_{C,nd}$ and $E_{el,C}$ are less than the pre-retrofitted one. It can be argued that the post retrofitted building is less sensitive to the effects of climate change.

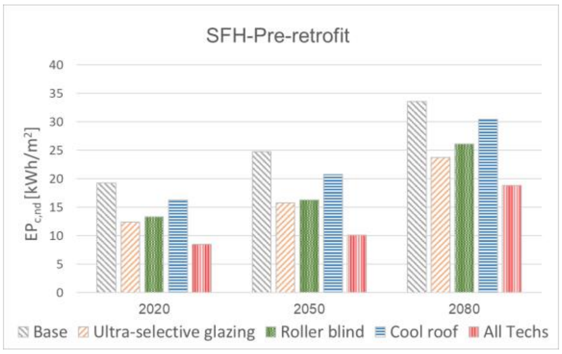

Fig. 2 – Thermal energy need for space cooling (June/July/August) in 2020, 2050, and 2080 for pre-retrofit building

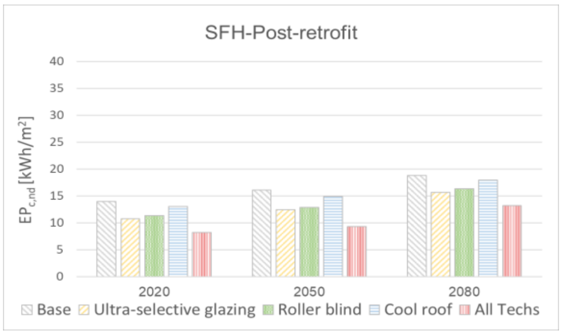

Fig. 3 – Thermal energy need for space cooling (June/July/August) in 2020, 2050, and 2080 for post-retrofit building

The reduction in the $EP_{C,nd}$ and $E_{el,C}$ caused by either of the cooling solutions is more significant in the pre-retrofitted building. In addition, it is shown that the most effective one is ultra-selective glazing in both conditions. The cool roof has a minor effect, as the building has a pitched roof with an attic. This effect is negligible for the electrical energy consumption in the post-retrofitted building in all three periods. If all cooling solutions are applied, the $EP_{C,nd}$ and $E_{el,C}$ can be reduced to the degree that in 2080 they are almost the same as the present base case. This result is valid for both building conditions.

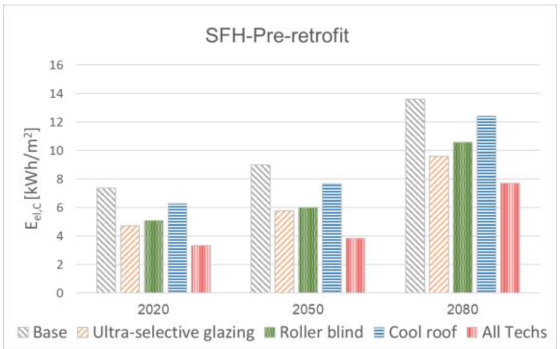

Fig. 4 – Electrical energy consumption (from the grid) for cooling (June/July/August) in 2020, 2050, and 2080 for pre-retrofit building

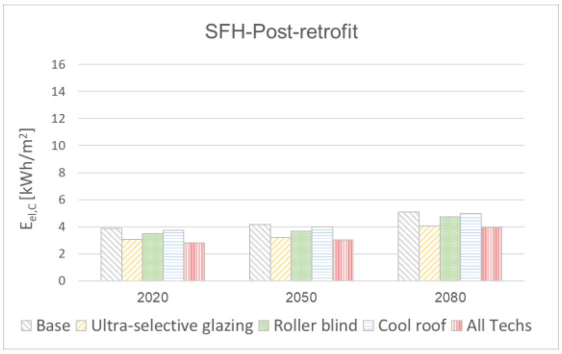

Fig. 5 – Electrical energy consumption (from the grid) for cooling (June/July/August) in 2020, 2050, and 2080 for post-retrofit building

As mentioned earlier, when it comes to the impact of climate change on buildings, it is necessary to take the overheating risk into account. For this purpose, by running free-floating simulations, weighted hours of exceedance for June, July, and August in 2020, 2050, and 2080 are calculated and presented in Figs. 6 and 7. Results report that the weighted hours of exceedance increase due to climate change in both conditions. However, in the post-retrofitted building, occupants will experience overheating equal to 5328 hours in the future scenarios, while this amount reaches a maximum of 2628 hours for the pre-retrofitted building in 2080. This result is due to the unwanted effect of insulation that causes a heat trap in the building in a free-floating regime. The results also show that the cooling solutions can reduce weighted exceedance hours. For the pre-retrofitted building, the effect of ultra-selective glazing and roller blind is almost the same and significantly higher than the cool roof. For post-retrofitted case, ultra-selective glazing has the most significant effect. The effect of the roller blind is diminished in this case since the post-retrofitted building was equipped with a Venetian blind in the base case. By applying all the cooling solutions, weighted hours of exceedance are reduced significantly for both cases. However, the weighted hours of exceedance in the pre-retrofitted building for the worst-case scenario (2080) equal 700 hours, which is much less than the post-retrofitted case (2600 h).

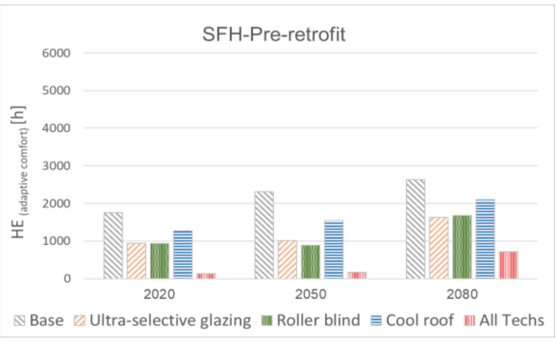

Fig. 6 – Weighted hours of exceedance (June/July/August) in 2020, 2050, and 2080 for pre-retrofit building, in free-floating condition

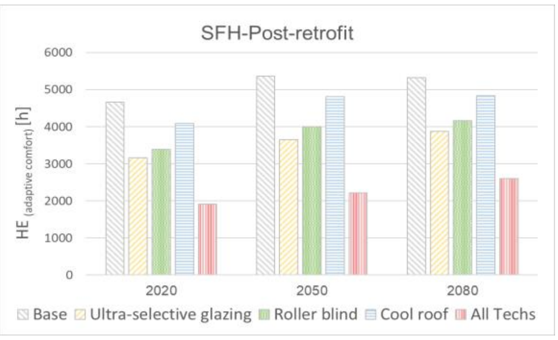

Fig. 7 – Weighted hours of exceedance (June/July/August) in 2020, 2050, and 2080 for post-retrofit building, in free-floating condition

4. Conclusion

The present research aimed to examine the climate resilience of three passive cooling solutions regarding the future performance of Italian residential buildings. To achieve this aim, the impact of the ultra-selective double-glazed window, external roller blind, and cool roof tiles was investigated on the thermal comfort and energy performance of an Italian single-family house built in 1946-1960. Two building conditions (pre-and post-retrofitted) and three periods (2020, 2050, and 2080) were considered. The current study results indicate that, among selected solutions, the ultra-selective double-glazed window has the most significant impact on reducing the effect of climate change on thermal energy needs for space cooling, electrical energy consumption from the grid for cooling, and weighted hours of exceedance in free-floating condition. The findings of this research also revealed that applying all three cooling solutions mentioned could significantly develop the energy performance of the buildings, so that in the worst-case future scenario (2080), the energy performance will be almost the same as the base case in 2020. This improvement is more considerable for the post-retrofitted building. However, in the absence of electrical energy (free-floating condition), although studied cooling solutions help to reduce the overheating, the risk is still present, specifically for the post-retrofitted building. These findings shed new light on the trade-off between energy efficiency and climate resiliency. In this case, it is necessary to identify cooling solutions that help to mitigate climate change and foster adaptation to it, to ensure both sustainability and climate resilience for the built environment.

Nomenclature

Symbols

A	Area (m^2)
E	Energy consumption (kWh/m^2)
EP	Energy performance (kWh/m^2)
HE	Hours of exceedance (h)
U	Thermal transmittance (W/(m^2·K))
V	Volume (m^3)
g	Total solar energy transmittance (solar factor) (–)
τ	Transmittance (%)
ρ	Reflectance (%)

Subscripts/Superscripts

C	Space cooling
el	Electrical energy
env	Envelope
fl	Floor
g	Gross
nd	Need
s	Solar
v	Visible

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