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Original
Towards climate resilient and energy-efficient buildings: A sensitivity analysis on building components and cooling strategies / Pourabdollahtootkaboni, Mamak; Ballarini, Ilaria; Corrado, Vincenzo. - In: BUILDING AND ENVIRONMENT. - ISSN 0360-1323. - ELETTRONICO. - 270:(2025), pp. 1-13. [10.1016/j.buildenv.2024.112473]

Availability:
This version is available at: 11583/2996310 since: 2025-01-07T12:59:13Z

Publisher:
Elsevier

Published
DOI:10.1016/j.buildenv.2024.112473

Building and Environment 270 (2025) 112473

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Towards climate resilient and energy-efficient buildings: A sensitivity analysis on building components and cooling strategies

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ARTICLE INFO

Keywords:
Climate change
Building energy performance
Overheating risk
Resilient cooling technologies

ABSTRACT

Climate change is a major global challenge with significant impacts that have been studied across various research fields. The building sector, being a major contributor to global energy consumption and greenhouse gas emissions, plays a crucial role in climate change. However, buildings not only contribute to climate change but are also negatively impacted by it due to their long lifespans. This paper presents a quantitative analysis of building energy performance and thermal comfort within the context of climate change, focusing on long-term assessment at a regional scale and examining the effectiveness of resilient cooling solutions. Besides, it employs a global sensitivity analysis to explore the impact of building types and retrofit conditions on energy performance and thermal comfort, enabling the tailoring of regional approaches accordingly. The study focuses on a representative building in Rome, Italy, before and after energy-efficient refurbishment across three periods: 2010s, 2050s, and 2090s. Findings indicate a significant increase (up to 55 %) in the annual thermal energy need for cooling and a substantial rise (up to 155 %) in the risk of overheating. Mechanical ventilative cooling and ultra-selective double-glazed windows emerge as impactful solutions, mitigating climate change effects. Combining these solutions could help to keep the trade-offs of energy efficiency. Results also demonstrate the crucial contribution of retrofit measures and building typology to buildings' climate resilience. After refurbishment, the cooling solutions become more effective. Energy-efficient buildings with adequate ventilation show greater resilience to climate change compared to non-retrofitted buildings.

1. Introduction

Recently, the issue of climate change and its associated impacts has received considerable attention in a wide range of disciplines. The most significant driver of climate change is the emission of greenhouse gases, of which more than 90 % are carbon dioxide (CO_2) and methane. As outlined in the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) [1], until at least the mid-century, the global surface temperature is very likely to continue increasing. It might exceed 1.5 °C and 2 °C above pre-industrial levels during the 21st century unless there is a huge cut in greenhouse gas emissions in the coming years and decades. According to the European Commission's recent report on the energy sector [2], the building sector contributes to 32 % of energy-related greenhouse gas emissions. Countries worldwide are implementing policies and strategies to reduce the energy consumption of buildings and promote reductions of greenhouse gas emissions and energy utilisation. Furthermore, buildings are not solely responsible for climate change; they are also profoundly affected by it in various ways, particularly given their long lifespan, which necessitates the implementation of adaptation solutions. With the 2024 revision of the Energy Performance of Building Directive (EPBD) [3], Europe should achieve a decarbonised building stock by 2050. Besides, measures to enhance the energy performance of buildings should consider climatic conditions, including adaptations for climate change.

One major impact of climate change on buildings is overheating, leading to a significant rise in cooling energy consumption and potential energy shortages. An analysis by Larsen et al. [4] on future climate impacts on space heating and cooling requirements in European buildings shows a decline in heating demand and a rise in cooling demand across Europe. These trends become more apparent when examining extreme events over ten-year intervals. By 2050, the heating demand is expected to decline moderately in most European states, except Cyprus and Malta, while the cooling demand could more than double in several countries. In the same vein, Berardi and Jafarpur [4] evaluated the heating and cooling needs of 16 ASHRAE building prototypes using future weather data from populous metropolitan zones. Their analysis demonstrated the necessity of considering future energy performance,

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https://doi.org/10.1016/j.buildenv.2024.112473
Received 20 August 2024; Received in revised form 25 November 2024; Accepted 17 December 2024
Available online 31 December 2024

Nomenclature

Acronyms

AR	Assessment Report
BEP	Building Energy Performance
EBC	Energy in Buildings and Communities
EPBD	Energy Performance of Building Directive
ESGF	Earth System Grid Federation
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KPI	Key Performance Indicator
NZEB	Nearly Zero Energy Building
PV	Photovoltaic
RCP	Representative Concentration Pathway
SFH	Single Family House

Quantities

A	area (m^2)
ACH	air changes per hour (h^{-1})
CDD	cooling degree day (°C·d)
d	dimensional thickness (m)
E	energy consumption (kWh)
EP	energy performance ($kWh \cdot m^{-2}$)
g	total solar energy transmittance (solar factor) (-)
HDD	heating degree day (°C·d)
U	thermal transmittance ($W \cdot m^{-2}K^{-1}$)
V	volume (m^3)
WHE	weighted hours of exceedance (h)
WWR	window-to-wall ratio (-)
τ	transmittance (%)
ρ	reflectance (%)
α	absorptance (%)

Subscripts

C	space cooling
el	electrical energy
env	envelope
fl	floor
g	gross
gl	glazing
ins	insulation material
nd	need
s	solar
sh	shading
v	visible
w	window

projecting up to a 126 % rise in cooling demand and a 33 % decrease in heating demand. Further emphasising this trend, a recent study conducted by Jalali et al. [5] investigated the impact of climate change on energy usage and thermal loads in residential buildings across New Zealand. Using different climate change scenarios, including RCP4.5 and RCP8.5, the authors predicted increased cooling energy and reduced heating energy demands over the next 70 years. This shift varied among the six climatic zones, with warmer zones expected to transition from dominant heating to dominant cooling. Examining the trade-offs between energy efficiency and heat resilience, Baniassadi and Sailor [6] analysed the indoor comfort of residential buildings during power outages in extreme heat in Houston and Phoenix in the United States. Older buildings face extreme indoor temperatures during such events. Different energy-saving strategies affect survivability and energy use differently, with insulation and airtightness proving beneficial in hot climates. Additionally, Waddicor et al. [7] used building energy simulations to explore how climate warming and building ageing affect the energy performance of a library in Turin, Italy. In line with other studies, they found that while climate change reduced heating energy usage, it raised cooling energy demand. The research emphasised the significant impact of building ageing, particularly HVAC system degradation, which could offset the energy savings from the warming climate. The findings of these studies highlight the growing importance of adapting building design and energy strategies to address the changing demands caused by climate change. As building resilience and energy efficiency become crucial, it is necessary to integrate current and future climate conditions into building design and implement measures to enhance building resilience in the face of climate change.

Accordingly, several studies have tried to analyse the climate resilience of different cooling solutions. Varying insulation levels, window-to-wall ratios, and ventilation air flow rates significantly affect a building's energy efficiency under climate change. Parametric analysis on the wall thermal transmittance values, orientation, ventilation rates, and window-to-wall ratios of a three-story, multi-family concrete structure in the sub-Himalayan region of eastern India [8] revealed that using autoclaved aerated concrete bricks, reducing the infiltration rate and decreasing the window-to-wall ratio, can improve the building's thermal performance under predicted climate change conditions, where an increase of 467.0 % in annual cooling energy use is anticipated. Similarly, Fosas et al. [9] examined how increased insulation in buildings could affect overheating risks. They found that while insulation can impact overheating, its overall influence is limited to about 5 %. However, improved insulation, coupled with purge ventilation, can actually enhance indoor comfort by reducing overheating severity and duration, aligning with findings from the 2003 European heat wave. The effect of extreme climates on buildings is also studied by Baba et al. [10] to develop strategies for adapting Canadian school buildings using optimisation techniques. They identified seven building design solutions that meet objectives like reducing overheating, minimising energy use, and maximising daylighting. Key factors included energy-efficient building envelopes, window characteristics, and natural ventilation. Furthermore, a study by Hamdy et al. [11] focused on Dutch dwellings built from 1964 to 2013, identifying vulnerable buildings, particularly those with poor ventilation and solar protection. It suggests that well-insulated buildings without adequate shading and ventilation face higher overheating risks in the future. While ventilative cooling can mitigate overheating, it may become less effective as global warming progresses. The study proposes new metrics to guide policymakers in adapting buildings to climate change. Finally, De Masi et al. [12] analysed a residential single-family home from the 1980s in Benevento (Italy) using medium and long-term climatic projections for the 2050s and 2080s. They found that passive retrofit solutions such as double-glazed low-emissive windows and insulation were ineffective, resulting in a 62 % increase in cooling energy requirements and a 56 % decrease in heating energy requirements by the 2080s.

Other studies have delved into the impacts of climate change on energy-efficient buildings. Attia et al. [13] analysed a Belgian nearly zero-energy building (NZEB), measuring the increase in overheating hours due to climate change by 2050 and 2100. They found up to a 43.5 % increase in overheating by the end of the century and a failure to mitigate the overheating risk by 2050. Another study on NZEBs was performed by D'Agostino et al. [14], who analysed both the energy balance and the changes in photovoltaic (PV) outputs, considering a future climate change scenario for 2060 in eight European climate zones. They noted a 38 % to 57 % reduction in heating and a 99 % to 380 % increase in cooling across different cities. The productivity of PV in NZEBs also increased up to three times compared to baseline buildings, indicating that energy efficiency is a viable strategy against climate change impacts. Additionally, Baba et al. [15] compared high energy-efficient buildings to old buildings using sensitivity analysis to assess how individual building envelope parameters impact indoor temperature changes in Canada. They found ventilation rates crucial: with inadequate ventilation, old buildings exhibit lower risks of overheating compared to high-energy-efficient buildings. Mitigation strategies like natural ventilation and solar control were suggested for managing overheating in high-energy-efficient buildings under various climates.

Shifting the focus to the effects of climate change on energy-efficient buildings within the Italian context, which is the primary focus of this study, [16] et al. conducted an assessment of the energy performance of an NZEB multi-family residential building in Lecce across weather scenarios projected for 2020, 2050, and 2080. They reported up to a 75 % increase in cooling requirements between 2020 and 2080 and a 16 % increase in hours with indoor temperatures above 26 °C, corresponding with an 11 % rise in outdoor temperatures. Similarly, Summa et al. [17] evaluated the yearly performance changes of a residential NZEB in Rome, comparing current energy consumption to projections for 2050. They concluded that air conditioning usage would increase significantly, resulting in an 18 % rise in annual power consumption by 2050 and heightened peak electricity demand. The study highlights the need for resilient NZEB designs to minimise future air conditioning requirements. Furthermore, Tootkaboni et al. [18] examined the impact of climate change on nearly zero-energy buildings (NZEBs) in three Italian climatic zones: Milan, Rome, and Palermo. The study focused on analysing NZEB requirements for the mid-term (2050s) and long-term (2080s) periods to ensure energy efficiency, sustainability, and climate resilience over the buildings' lifetimes. Emphasising regional-scale assessments and the utilisation of future weather data to evaluate NZEB energy performance, the research highlighted variations across different climatic zones. It was found that NZEBs in Milan are less affected by climate change compared to the hotter climates of Rome and Palermo.

In a nutshell, the review of the relevant literature shows that climate change impacts the functionality and habitability of buildings, and this effect, in turn, causes the misuse of resource consumption. This lack of understanding tarnishes the existing energy efficiency and sustainability criteria, highlighting the need to incorporate the concept of resilience in this context. Here, climate resilience involves the implementation of mitigation measures to support sustainable development and reduce the building's contribution to emissions. Additionally, it encompasses adaptation scenarios that carefully consider future risks. Although many studies have been carried out on this topic, there is still a need to perform quantitative analysis on a regional scale. Herein, the term "regional level" pertains to the territorial context, distinguished by factors such as population, climate, and building typology.

This paper traces the development and application of a method to investigate and optimise the building stock climate resilience at the regional scale. The method involves evaluating the energy performance and thermal comfort of buildings in a changing climate over the long term, using future typical meteorological years (TMYs) and a set of key performance indicators (KPIs). This selection is done considering the fact that the impacts of climate change on buildings include not just acute events like heat waves but also long-term chronic stresses [19].

The approach deploys reference buildings at a regional level and takes into account several building components through a parametric analysis. According to current devolved energy efficiency regulations, various building components can enhance energy efficiency and indoor environmental quality in the present and future. Their impact on Building Energy Performance (BEP) fluctuates with changing climate conditions. To accurately analyse the relative contribution of each building's component and cooling technology to the variation of KPIs, a variance-based sensitivity analysis (Sobol) is performed. Through this process, the variances of the KPIs are considered as model outputs and are decomposed into fractions, which can be attributed to the parameters referring to the building's components and cooling strategies as model inputs.

The methodology was subsequently employed to assess a representative building in Italy (Rome) both before and after undergoing energy-efficient refurbishment during three distinct periods: 2010s (2001–2020), 2050s (2041–2060), and 2090s (2081–2100). The investigation focused on four cooling technologies: advanced glazing and solar shading, cool envelope materials, and ventilative cooling. KPIs concern the weighted hours of exceedance outside the thermal comfort, the thermal energy need for space cooling, and the electrical energy consumption from the grid for cooling.

This research is part of a project carried out in conjunction with IEA-EBC Annex 80, "Resilient Cooling of Buildings" of the Energy in Buildings and Communities Program (EBC) of the International Energy Agency (IEA). This initiative creates, evaluates, and disseminates methods for fostering resilience against overheating and analysing the resilience of cooling solutions in the future climate [20].

2. Materials and methods

For evaluating the future energy performance of buildings and the resilience of the cooling technologies, the methodology to create weather files aligns with the outcomes of the IEA-EBC ANNEX 80 Weather Data Task Group [21]. The description of the procedure, along with a graphical summary (Fig. A.1), is presented in Appendix A.

2.1. Key performance indicators

The following three key performance indicators (KPIs) were used for the assessment of the building energy performance and thermal comfort in a changing climate:

- Weighted hours of exceedance, which are the number of hours in which the operative temperature of the zone is greater than the upper limit temperature of the indoor thermal comfort range. This measure is weighted by a factor that reflects the extent of temperature deviation from the comfort range, as defined in EN ISO 7730 (Method B) [22], *WHE* (h),
- Thermal energy need for space cooling, $EP_{\mathrm{C,nd}}$ ($\mathrm{kWh{\cdot}m^{-2}}$), and
- Electrical energy consumption (from the grid) for cooling, $E_{\mathrm{el,C}}\,/A_{\mathrm{fl}}$ ($\mathrm{kWh{\cdot}m^{-2}}$).

The above indicators were chosen from the list of KPIs officially adopted in IEA-EBC Annex 80 to represent the building's summer performance. They comply with the following criteria: a) thermal discomfort in free-floating conditions (absence of space 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 definitions and assessment methods derived from international technical standards. Weighted hours of exceedance measure the duration and severity of temperature exceeding the acceptable range of the indoor operative temperature. For free-floating condition, the adaptive comfort method is assumed according to Annex H.2 of ISO 17,772–1 [23]. Thermal energy need for space cooling 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 [24]. Electrical energy consumption (from the grid) for cooling is the electrical energy delivered to the building for cooling, which also takes into account the energy losses of the cooling system and the chiller efficiency [25].

2.2. Resilient cooling technologies

In IEA-EBC Annex 80, four categories of cooling strategies were created according to their approaches to cooling the occupants 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. This study explicitly analyses cooling solutions from the first and second categories. The first category includes an examination of ultra-selective double-glazed windows, external roller blinds, and cool roof tiles. On the other hand, the second category explores mechanical ventilative cooling.

The characteristics of glazing and shading technologies, the way they are combined, and the relevant functional classification – static and dynamic, besides manual and automatic – could determine the resilience of the cooling solution. 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 and solar heat gain while admitting most daylight. In addition, the external roller blind is a dynamic technology with a low solar transmittance 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. Besides, cool envelope materials are solar-opaque surfaces using a reflecting product to minimise the net radiative heat gain and have a less radiative heat gain compared to traditional envelope materials. This helps to lessen heat flow into the occupied space. 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.

The other analysed cooling solution is ventilative cooling, which has the advantage of outdoor air-cooling potential through wind airflow, buoyancy forces, or fans. It is also possible to use a combination of these techniques. A distinction can be made between ventilation aimed at daytime comfort (or direct cooling) and night cooling (or indirect). Daytime comfort ventilation introduces the flow of outside air through the building during the day to directly remove heat gains. It aims to improve the thermal comfort of the occupants through the transport of convective heat, increasing the evaporative cooling effect on the occupants' skin and decreasing the internal air temperature. Night cooling has a double effect: on the one hand, it uses the thermal mass of the building during the night, which acts as a heat sink during the busy period, and on the other hand, it reduces the indoor air temperature during the hours [26].

2.3. Sensitivity analysis

Sensitivity analysis is categorised into two main types: local and global. Local sensitivity analysis examines how a specific input affects a particular output, often using derivatives. It is computationally efficient but limited when dealing with uncertain or nonlinear models and does not account for interactions between inputs. In contrast, global sensitivity analysis is better suited for uncertain inputs, involving the consideration of a broader range of data points to assess sensitivity comprehensively. In this study, Sobol's variance-based method [27], which is a commonly used global sensitivity analysis, has been applied. The method is explained in Appendix B. Variance-based sensitivity analysis can measure sensitivity across the entire input space and compute the sensitivity of interaction between inputs. The basic idea is to use variance to describe uncertainty in the model output. The variance of output is decomposed to variances of inputs and their interactions.

In this study, the sensitivity analysis aims to determine the contribution of variances in building features (insulation level of envelopes) and cooling technologies to the variances in building energy performance and thermal comfort. Accordingly, the outputs (Ys) are the KPIs that are dependent on the parameters (X_s), representing the cooling technologies and the building's conditions. These parameters are thermal transmittance (U_w) W·m^{-2}K^{-1}, total solar factor (g) %, and light transmittance (τ_v) % for ultra-selective double-glazed windows, solar transmittance ($\tau_{s,blind}$) and solar reflectance ($\rho_{s,blind}$) for the external roller blind, solar absorbance ($\alpha_{s,roof}$) and solar reflectance ($\rho_{s,roof}$) for the cool roof tiles, the air exchange rate for mechanical ventilative cooling, and the thickness of insulation materials across various envelopes for considering the building's conditions.

3. Application

3.1. Case study

In order to broaden the research findings to the building stock, the case study has been selected from Italian reference buildings developed in the CIP-IEE-2008 -TABULA research project [28]. TABULA aimed to create a harmonised definition of the residential building typology at the European level. Every building type embodies the typical geometric and thermal characteristics of the corresponding cluster within the building stock. The building typology can be effectively applied to develop bottom-up energy models by taking advantage of scaling up the results of the representative building type to the building stock cluster. Consequently, the building typology approach can be used to predict the energy performance of building stocks [29] to assess effective energy-saving potentials and to develop reliable refurbishment scenarios for the stock [30]. The single-family house (SFH) was selected for analysis due to its heightened sensitivity to climate change, attributed to its high shape factor, as identified in a recent study [31]. Furthermore, buildings from this construction period offer substantial energy-saving potential when compared to those built in other periods [30,32], making this building type crucial for examining climate resilience and energy efficiency improvements. The main geometric data of the analysed archetype is listed in Table 1. The buildings have uninsulated envelope components, as the construction period predates the first Italian law on energy savings issued in 1976.

For all stages of analysis performed in this study, the retrofitted state of the building has been considered accordingly. The thermal 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 for an assessment of the effect of passive cooling strategies on low energy-efficiency buildings and 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 [33], which also represents the nearly zero-energy building target. The post-retrofit windows present a low-E double-glazing. In

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 ($W \cdot m^{-2}K^{-1}$)	1.48	0.29
Roof	U ($W \cdot m^{-2}K^{-1}$)	1.65	0.26
	$\alpha_{s,roof}$ (-)	0.75	0.75
	$\rho_{s,roof}$ (-)	0.25	0.25
Bottom floor	U ($W \cdot m^{-2}K^{-1}$)	2.00	0.29
Windows	U ($W \cdot m^{-2}K^{-1}$)	4.90	1.30
Glazing	U ($W \cdot m^{-2}K^{-1}$)	5.70	1.20
	g (-)	0.85	0.59
	τ_v (-)	0.90	0.80
Shading	$\tau_{s,blind}$ (-)	N/A	0.40
	$\rho_{s,blind}$ (-)	N/A	0.12

addition, while the original building is not equipped with solar shading devices, these are provided for in the retrofitted building ($g_{gl+sh} = 0.35$). The external wooden Venetian blinds are considered under operation if the beam plus diffuse solar irradiance incident on the window exceeds 300 $W \cdot m^{-2}$[34]. The buildings have been simulated using the dynamic simulation engine Energy Plus (Version 9.0). The energy performance of the building types was assessed considering standard user behaviour. Hourly profiles of internal heat gains and ventilation airflow rates were set up under the Italian National Annex draft of EN 16,798–1 technical standard [35].

Regarding the technical building systems, the building in the pre-retrofit state is equipped with a standard gas boiler and radiators for space heating and a split system for space cooling. In the post-retrofit phase, heating and cooling are provided by a reversible air-to-water heat pump with fan coils as heat emitters. The air conditioning is auto-sized to design days according to each weather condition. Since passive cooling technologies are simulated, the auto-sizing of the HVAC system will produce energy savings or improvements in thermal comfort that are not solely attributable to passive cooling technologies but rather to the compound effect of cooling technologies, plus changes in HVAC system sizing. As a result, the baseline model should be used to estimate the HVAC capacities for heating and cooling coils, and these fixed capacities should be applied throughout the performance assessment of passive cooling technology. According to Italian standards [34], heating and cooling temperature set points were assumed to be equal to 20 °C and 26 °C, respectively. Moreover, the heating season and cooling periods were assumed on the base of the climatic zone. The heating season is included in the period from 1st November to 15th April, while the cooling period was assumed for the months of June, July, and August. The cooling season was predetermined to improve comparability among the analysed cases.

3.2. Modelling assumptions and parameters of cooling technologies

Simulations are performed for the city of Rome with latitude 41.81° N and longitude 12.25° E. It has a Mediterranean climate and belongs to the climate zone 3A (Warm Humid) of the ASHRAE classification [36]. Mediterranean areas are particularly prone to the impacts of climate change [37], making them critical regions for studying climate resilience. Typical Meteorological Year (TMY) for three distinct periods – 2010s (2001–2020), 2050s (2041–2060), and 2090s (2081–2100) – are used in the simulations to assess the climate resilience of buildings over time. The future weather files indicate a temperature increase in both the short and long term, as shown by the heating and cooling degree days in Table 3. This trend is further illustrated in Fig. 1, which presents the mean monthly dry bulb air temperature across the three periods.

Table 3
Heating and cooling degree-days for Rome across different future periods.

Period	HDD_{18} [°C·d]	CDD_{18} [°C·d]
2010s (2001–2020)	1207	757
2050s (2041–2060)	948	1042
2090s (2081–2100)	610	1523

For each of the selected technologies described above, a range of relevant parameters was defined and used to perform the sensitivity analysis. Subsequently, a configuration was chosen to run the simulations for all these parameters. Table 4 presents all the values, ranges of parameters, and the selected configurations used in the simulations. All parameters follow a uniform distribution. For the resilient cooling solutions, the procedure for defining these ranges is explained in the "Way of Determination" column in Table 4.

For mechanical ventilative cooling, the air exchange rate was calculated using the ventilative cooling potential tool (VC Tool) developed within the IEA-EBC Annex 62 project [38]. The VC Tool estimates the energy contribution of ventilative cooling by analysing a single-zone energy balance, where all air within the space is assumed to be well-mixed. This calculation considers the thermal properties of the building envelope, internal heat gains, ventilation requirements, and occupancy patterns. By evaluating these factors, the tool assesses the potential for ventilative cooling to offset cooling loads, providing insight into the cooling energy reduction achievable through mechanical ventilation strategies. The Ventilative Cooling mode, in which "direct ventilative cooling with increased airflow rate can potentially ensure comfort when the outdoor temperature is within the range of comfort", was employed in this study. It is active when the outdoor air temperature is lower than the internal temperature by at least 2 °C. This choice was made based on the Ventilative Cooling Design Guide [39] developed in the IEA-EBC Annex62 project. The strategy is available 24 h a day to enhance nighttime cooling and support transitional seasons. It was considered that the heat corresponding to the electrical energy consumed by the fan is added to the entering air stream. In this case, the inlet air temperature increases by 0.4 °C on average. The Specific Fan Power (SFP) is set at 1.08 $kW/(m^3/s)$, consistent with Italian energy regulations for reference buildings [33]. A lower SFP reduces fan energy use, thereby enhancing the overall efficiency of the cooling strategy, as underscored by recent studies [40,41].

The simulations were performed as presented in Fig. 2. In total, 90 simulations were run. For sensitivity analysis, the smallest sample size for the Sobol indices (including first and total-order indices) is $n(2k+2)$, where n is the least number of model evaluations needed to estimate a single effect; n can range from 16, 32, 64…1024; and k is the total number of variables [42]. In this study, considering the computational cost, a sample size of 3000 is chosen, which is between 2048 (128 $(2k+2)$) and 4096 ($256(2k+2)$). A smaller sample size might fail to achieve convergence in the computation of indices, and a larger one would be unfeasible. In this study, the convergence of the indices has been controlled and verified. The number of simulations equals 27,000 for three time periods and three outputs. The Sensobol package in *R* [43], which provides a set of combinations of first, second, and total order indices, is utilised. The analysis is limited to first and total-order indices. Besides, JEPlus [44] was used to run the parametric simulations and generate the output vector (Y).

4. Results and discussion

4.1. Performance assessment

The findings from the initial phase of analysis, which assessed the resilience of cooling technologies, are illustrated in Figs. 3–5. Fig. 3 shows the thermal energy need for space cooling ($EP_{C,nd}$) in the 2010s, 2050s, and 2090s for the case study before and after the retrofit. Fig. 4 represents the electrical energy consumption (from the grid) for cooling ($E_{el,C}$). In each graph, comparisons are made between the base case, individual cases with different cooling strategies activated, and the case where all discussed cooling technologies are applied. An increase of up to 55 % for the pre-retrofitted and 40 % for the post-retrofitted case is shown in $EP_{C,nd}$ over time due to climate change. Furthermore, the

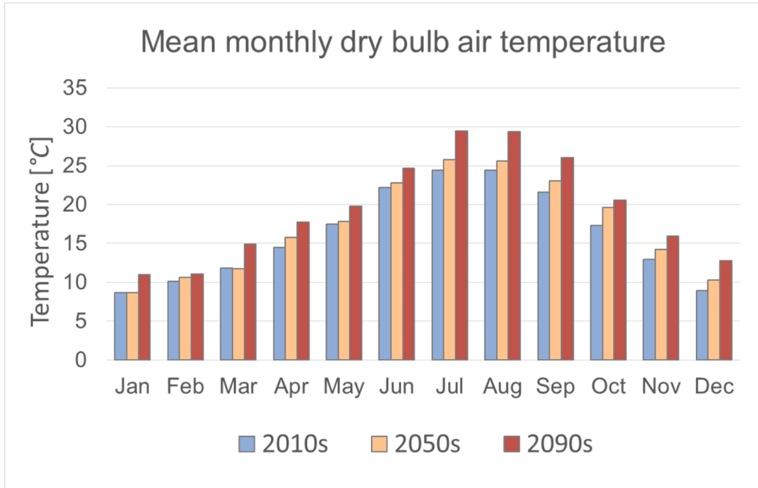


Fig. 1. Mean monthly dry bulb air temperature for Rome across different future periods.

increase of $E_{el,C}$ is up to 70 % for the pre-retrofitted and 60 % for the post-retrofitted building. For post-retrofitted buildings, the variations of $EP_{C,nd}$, and $E_{el,C}$ are less than the pre-retrofitted ones. Accordingly, it can be argued that the post-retrofitted building is less sensitive to the effects of climate change.

The decrease in $EP_{C,nd}$, and $E_{el,C}$ achieved through either cooling solutions is notably greater in the pre-retrofit building. Among the options, ultra-selective glazing emerges as the most effective solution for reducing $EP_{C,nd}$, and $E_{el,C}$, under pre-retrofit conditions. However, in post-retrofit conditions, ventilative cooling becomes more effective in reducing $EP_{C,nd}$ although its impact on $E_{el,C}$, considering the fan's electrical consumption, is comparable to that of ultra-selective glazing. Overall, the results indicate that the effectiveness of mechanical ventilative cooling will diminish over time as its performance depends on the outside air temperature, which is expected to increase due to future climate change. The cool roof shows a minor impact because the building has a pitched roof with an unconditioned attic, making its effect on electrical energy consumption negligible in the post-retrofit building across all three periods. Besides, if all cooling solutions are implemented, $EP_{C,nd}$, and $E_{el,C}$ can be reduced to a level that, by 2090, are even lower than the present-day base case. This result is valid for both pre-and post-retrofit building conditions.

As mentioned earlier, the impacts of climate change on buildings require consideration of the overheating risk. To this purpose, free-floating simulations were conducted to calculate weighted hours of exceedance (*WHE*) for the 2010s, 2050s, and 2090s, with results shown in Fig. 5. The results indicate an increase in *WHE* due to climate change in both building conditions. In post-retrofit buildings, occupants are projected to experience 9695 *WHE*, reflecting both the duration and severity of temperature exceedances in future scenarios. In contrast, pre-retrofit buildings are expected to reach a maximum of 2600 *WHE*. This discrepancy arises from the unintended effect of insulation in retrofitted buildings, which traps heat under a free-floating regime.

Cooling solutions demonstrate the potential to mitigate *WHE,* with ventilative cooling emerging as the most effective strategy in both building conditions. For pre-retrofit buildings, ventilative cooling reduces *WHE* to 1240 h in the 2090s. In post-retrofit buildings, the impact is even more pronounced, lowering *WHE* to 834 h in the 2090s. The disparity in effectiveness between ventilative cooling and other solutions is notably greater in post-retrofit conditions. While the positive impact of mechanical ventilative cooling may diminish due to climate change, the results highlight its capacity to mitigate the unwanted effects of insulation in retrofitted buildings. By enhancing indoor-outdoor air exchange and leveraging cooler nighttime temperatures to dissipate accumulated heat, ventilative cooling proves especially beneficial for highly insulated buildings prone to heat retention. This alignment with passive cooling principles underscores its value as a resilient, low-energy solution, even in a warming climate.

Turning to the other solutions, the impact of ultra-selective glazing and roller blind is almost the same and significantly higher than that of the cool roof. By applying all cooling solutions, the *WHE* were reduced significantly for both cases. However, in the worst-case scenario (2090s), the *WHE* for the post-retrofitted building are reduced to 80 h, which is substantially lower than the 278 h observed in the pre-retrofitted case.

Findings in this phase indicate that, depending on the building's condition, both mechanical ventilative cooling and ultra-selective double-glazed windows have a substantial impact on mitigating the effects of climate change in terms of thermal energy needs for space cooling, electrical energy consumption from the grid for cooling, as well as reducing weighted hours of exceedance in free-floating conditions. Additionally, it was revealed that the combined application of all four cooling solutions could significantly enhance the energy performance of buildings, even under the most adverse future scenarios (by 2090s), with a more pronounced improvement observed in post-retrofitted buildings.

4.2. Sensitivity analysis

The results from the Sobol sensitivity analysis are reported for all three KPIs, considering three time periods (2010s, 2050s, and 2090s). Figs. 6–8 represent the Sobol indices of input variables. Fig. 6 represents the Sobol first (red) and total (green) indices of window thermal transmittance (U_w) W·m^{-2}K^{-1}, shading solar transmittance ($\tau_{s,blind}$)%, roof solar absorbance ($\alpha_{s,roof}$) %, air change rate by mechanical ventilative cooling (ACH) h^{-1}, the thickness of wall insulation material ($d_{ins,wall}$) m, the thickness of roof insulation material ($d_{ins,roof}$) m, and thickness of floor insulation material ($d_{ins,floor}$). These indices reflect each parameter's contribution to the variance of thermal energy need for space cooling ($EP_{C,nd}$) for the 2010s, 2050, and 2090s. The data presented in the figures reveal a consistent trend across all three time periods.

Table 4
Input parameters and their distribution ranges.

Technology	Parameter	Value		Way of determination
		Selected configuration	Range and distribution	
Window (ultra-selective double-glazed)	Thermal transmittance, U_w, ($W·m^{-2}K^{-1}$) Solar factor of glazing, g, (%) Light transmittance of glazing, τ_v, (%) Solar transmittance of glazing, τ_s, (%)	1.2 30 64 21	U (0.9, 1.8) 30 64 21	• Upper limit for U_w according to Italian energy regulations [33] for Rome's climatic zone. • Lower limit for U_w according to the European AGC glass configurator. dataset [45], based on available market products • Values of g and τ_v based on the limits defined for advanced glazing technology in IEA-EBC Annex 80 [26].
Shading (external roller blind)	Solar transmittance, $\tau_{s,blind}$, (%) Solar reflectance, $\rho_{s,blind}$, (%)	13 42	U (1, 25) U (10, 34)	• Upper limit for $\tau_{s,blind}$ according to Italian energy regulations [33] for Rome's climatic zone to guarantee g_{gl+sh} equal to 0.35. • Lower limit for $\tau_{s,blind}$ according to the European Solar Shading Organisation [46], based on available market products. • The value of $\alpha_{s,blind} = 0.65$ to achieve an acceptable range of $\rho_{s,blind}$, based on available market products.
Cool roof	Solar absorbance, $\alpha_{s,roof}$, (%) Solar reflectance, $\rho_{s,roof}$, (%)	50 50	U (30, 70)	• Upper limit for $\rho_{s,roof}$ for a pitched roof according to EN ISO 22,969 [47]. • Upper limit for $\rho_{s,roof}$ for a pitched roof according to the Cool Roof Rating Council database [48], based on available market products. • The value of $\alpha_{s,roof}$ consistently with the range of $\rho_{s,roof}$.
Ventilative cooling	Air change rate by mechanical ventilative cooling, *ACH,* (h^{-1})	2.8	U (1, 5)	• The standard deviation equal to 1.75, defined by the VC tool [38].
Wall thermal insulation	Thickness of insulation material, $d_{ins,wall}$, (m)	0.40	U (0, 0.40)	• Upper limit for d_{ins} according to Italian energy regulations [33] for Rome's climatic zone.
Roof thermal insulation	Thickness of insulation material, $d_{ins,roof}$, (m)	0.35	U (0, 0.35)	• The lower limit for d_{ins} refers to the absence of insulation material.
Bottom floor thermal insulation	Thickness of insulation material, $d_{ins,floor}$, (m)	0.40	U (0, 0.40)	

Specifically, the difference between the first and total order remains relatively insignificant, suggesting that interactions among the parameters do not significantly impact the $EP_{C,nd}$. Notably, in each of the three periods, the variance in wall insulation thickness emerges as the dominant contributor to output variance, underscoring the critical role of the building's condition. For the 2010s, following wall insulation thickness, the variance in air change rate through mechanical ventilation cooling becomes more substantial. However, this pattern undergoes a shift in the 2050s and 2090s, with roof insulation thickness taking on greater significance. This shift is likely attributed to the decreasing influence of ventilative cooling over time, as its effectiveness is closely tied to external temperature conditions, which are expected to rise due to climate change. This further underscores the growing importance of the building's condition as time progresses. Now, focusing on parameters related to cooling solutions, air change rate via mechanical ventilative cooling (measured in h^{-1}) consistently stands out as the primary contributor across all three time periods.

Turning now to the electrical energy consumption (from the grid) for cooling ($E_{el,C}$), the variance of ACH is the most effective on the output variance in the 2010s, as shown in Fig. 7. This result is due to the fact that more electrical energy is consumed when ACH is higher. However, the contribution of ACH was reduced in the 2050s and more significantly in the 2090s. The reason is the same as mentioned before and refers to the rise of outside temperature due to climate change. In the 2050s and 2090s, the variance of wall insulation thickness was more effective, and in the 2090s, the roof insulation thickness became the second significant contributor in the variation of $E_{el,C}$. This reaffirms the pivotal role of a building's condition in shaping its response to future climatic conditions.

The last set of results refers to weighted hours of exceedance -on the second floor- which is the number of hours in which the operative temperature of the zone is greater than the upper limit temperature, weighted by a factor that reflects the extent of temperature deviation from the comfort range (*WHE*); they are presented in Fig. 8. First, it is evident that there is a substantial discrepancy between the first-order and total-order Sobol indices for the parameters. This discrepancy highlights that when assessing the building under free-floating conditions, the interplay between parameters significantly contributes to the *WHE* variance. These results align with findings that mechanical ventilative cooling, even under future climate conditions, demonstrates resilience in mitigating overheating risk, particularly in retrofitted buildings. This is due to the fact that, in free-floating conditions, indoor temperature variation is strongly influenced by interactions between parameters related to different passive strategies. In all three periods, the variation of ACH has the most contribution to the variation of hours of warm discomfort, and even its effect reduces over time. The second significant contributor in the 2010s and 2050s was the thickness of floor insulation, while in the 2090s, the importance of roof insulation thickness became greater. It has also been discovered that the parameters representing the cooling solutions, solar absorbance of roof tiles, and solar transmittance of the blinds contribute more to the variation of *WHE* if we compare them to their contribution to the variations of $EP_{C,nd}$, and $E_{el,C}$. The analysis of the last set of results, which focuses on weighted hours of exceedance on the second floor, sheds light on the operative temperature of the zone when it surpasses the upper limit temperature (*WHE*). It is important to note that these findings reveal a considerable divergence between the first-order and total-order Sobol indices for the various parameters involved. This discrepancy

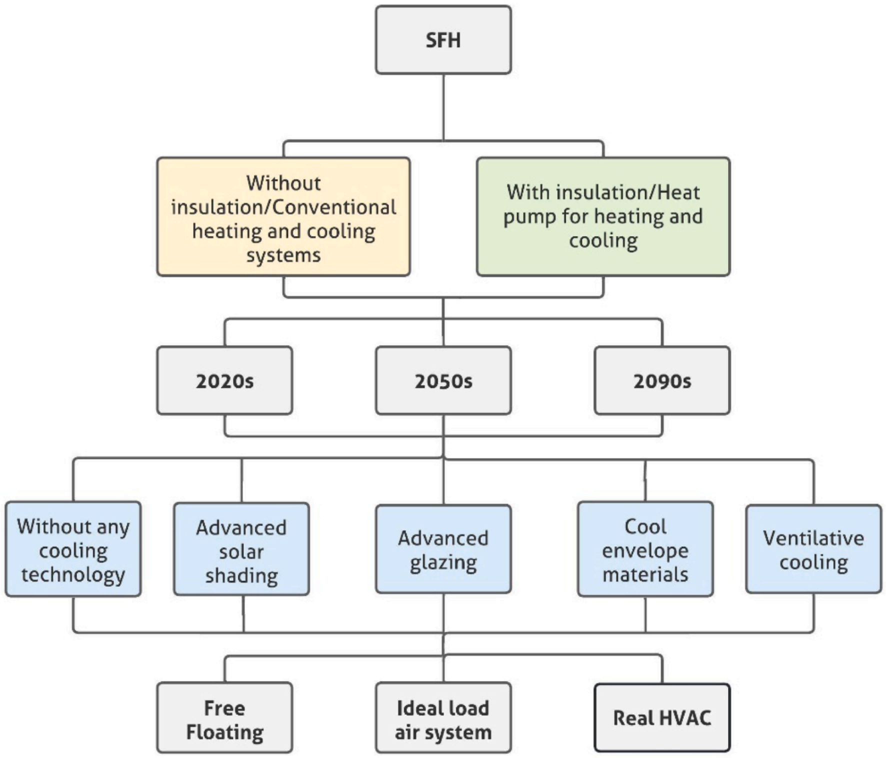


Fig. 2. Simulation flow chart of analysing the resilience of cooling technologies.

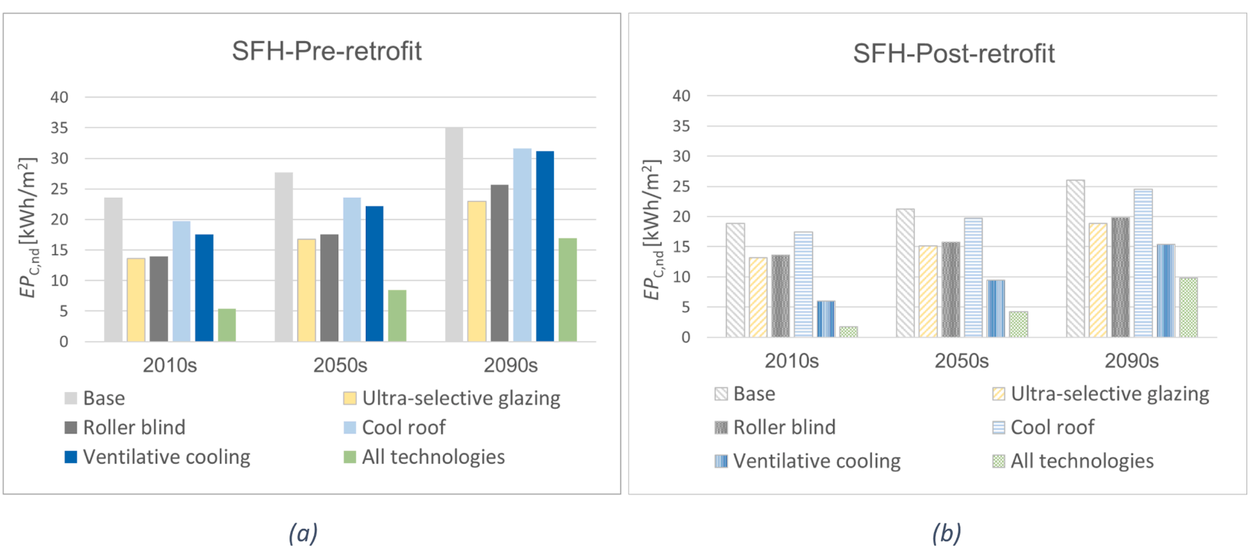
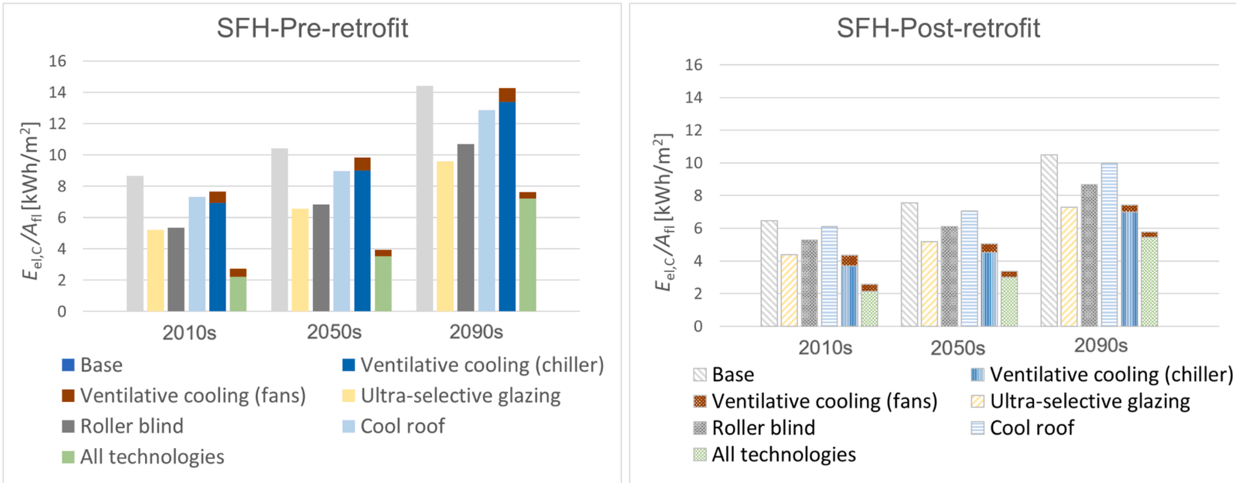


Fig. 3. Thermal energy need for space cooling in the 2010s, 2050s, and 2090s for pre-retrofit building (a) and post-retrofit building (b).

underscores the complex interplay between these parameters in the context of assessing a building's performance under free-floating conditions, where many factors come into play and significantly contribute to the variance in *WHE*.

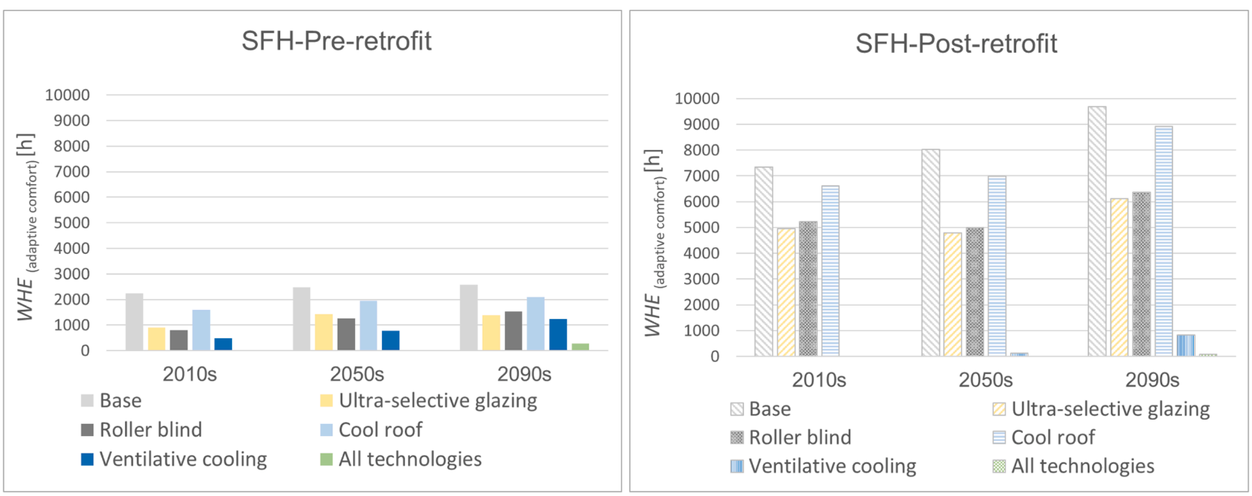
5. Conclusion

Climate change significantly affects buildings, particularly in terms of overheating, which increases cooling energy demand and contributes to energy scarcity. Given this context, it is imperative to provide cooling technologies that are energy-efficient and effective not only at present but also in the future. This study aimed to investigate energy efficiency, energy performance, and thermal comfort in buildings under the influence of a changing climate, with a focus on long-term assessment. The research is inquiring into the regional building stock in Italy. A set of cooling solutions regarding the future performance of Italian residential



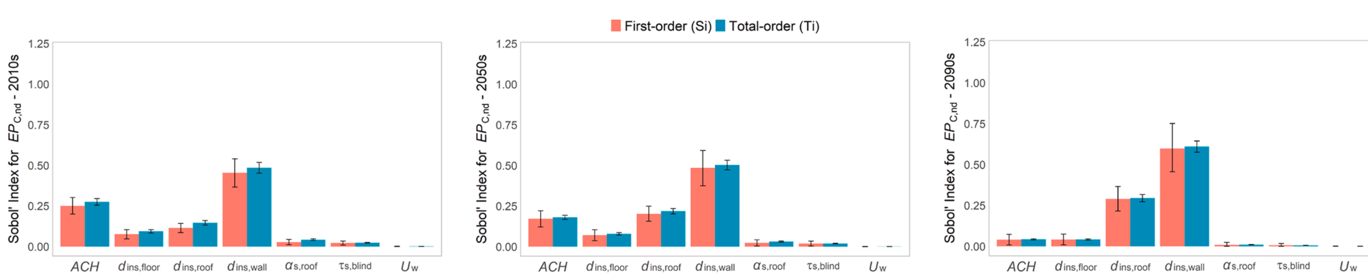
(a) (b)

Fig. 4. Electrical energy consumption (from the grid) for cooling in the 2010s, 2050s, and 2090s for pre-retrofit building (a) and post-retrofit building (b).



(a) (b)

Fig. 5. Weighted hours of exceedance in 2010s, 2050s, and 2090s for pre-retrofit building (a) and post-retrofit building (b) in free-floating condition.



(a) (b) (c)

Fig. 6. First and total order of the Sobol indices of the input parameters for thermal energy need for space cooling in the 2010s (a), 2050s (b), and 2090s (c).

buildings for a representative case study in Rome was assessed: ultra-selective double-glazed windows, external roller blinds, cool roof tiles, and mechanical ventilative cooling. Both pre-retrofit and post-retrofit buildings were analysed for three time periods (2010s, 2050s, and 2090s). The study considers future projections based on the Representative Concentration Pathway (RCP) 8.5, the highest baseline scenario, which assumes emissions will continue to rise throughout the twenty-first century. The findings show that the mechanical ventilative cooling and ultra-selective double-glazed windows -depending on the building's condition - have the most significant impact on reducing the impact of climate change on the thermal energy need for space cooling, the electrical energy consumed from the grid for cooling, and weighted

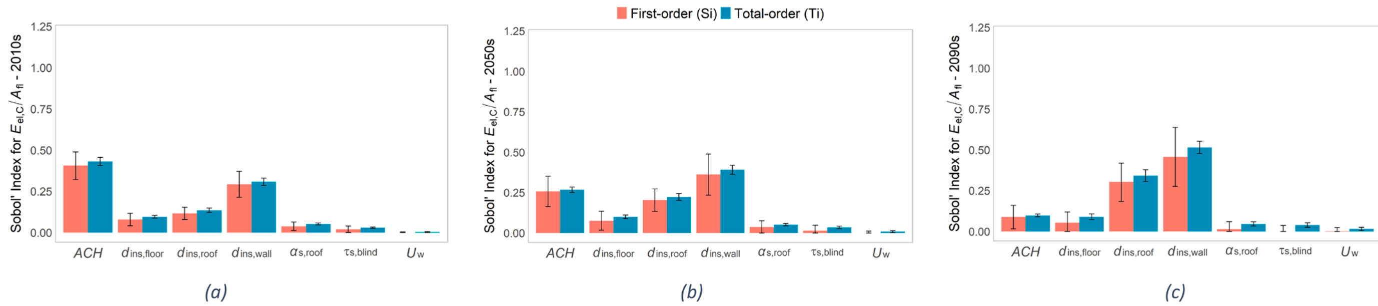


Fig. 7. First and total order of the Sobol indices of the input parameters for electrical energy consumption (from the grid) for cooling in the 2010s (a), 2050s (b), and 2090s (c).

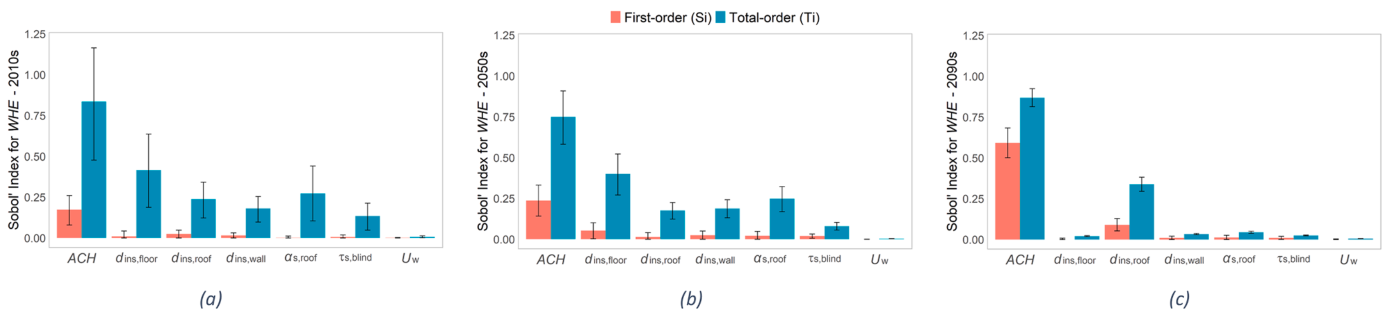


Fig. 8. First and total order of the Sobol indices of the input parameters for weighted hours of exceedance in the 2010s (a), 2050s (b), and 2090s (c).

hours of exceedance in the free-floating condition. This analysis also shows that using all the considered cooling strategies might significantly improve a building's energy efficiency, resulting in a significant improvement even in the worst-case scenario (2090s).

Subsequently, a global sensitivity analysis (Sobol method) was conducted to assess the effect of variations in building conditions (insulation level of envelopes) and cooling technologies on variations in building energy performance and thermal comfort precisely. It is noticeable that, for all three periods (2010s, 2050s, and 2090s), the variation in wall insulation thickness has the most contribution to the variation in the thermal energy need for space cooling, which demonstrates the critical role of the building's condition in relation to retrofit measures. Turning now to the electrical energy consumption (from the grid) for cooling, it was confirmed once more that in the future climate, the building's condition plays a crucial role. In addition, for both of these key performance indicators, the first and total orders do not differ much, indicating that interactions between the parameters do not contribute a large amount of variance. Unlikely, the difference between the first and the total order of Sobol indices is more considerable when analysing the weighted hours of exceedance, and this indicates that the interactions between factors are a substantial source of output variance when analysing the building in a free-floating condition. Even though its impact decreases with time, the variance of the mechanical ventilative cooling air flow rate in all three periods contributes the most to the variation of the warm discomfort period.

The findings of this study not only add to the rapidly expanding field of built environment climate resilience and establish the urgency of providing building adaptation measures for climate change but also present a practical and robust adaptable regional method. A source of limitation in this study was the high computational cost of performing building simulations with adequate size for applying the sensitivity analysis. Although a relatively large sample size was created in this research, more simulations could help to study further scenarios. For example, fixing the parameters regarding the building condition and analysing more cooling solutions or comparing the active and passive resilient cooling solutions to widen the analysis of the resilient cooling solutions could be helpful.

Taken together, these findings offer recommendations for future policies. Resilient cooling strategies should be assessed in future whole-building performance assessment tools and calculation methods. All thresholds/recommendations/input data should be revised based on the impacts of climate change. Climate resilience policies should not be developed as standalone policies but fully integrated with policies concerning indoor environmental quality, energy efficiency, fuel poverty, decarbonisation, environmental sustainability, etc. It is recommended that climate resilience key performance indicators should also be standardised and inserted into official reports, such as energy performance certificates and energy audit reports. Ultimately, given the placed-based nature of climate change impacts, further studies could be performed for more climate zones since the importance of regional and local analysis was demonstrated.

CRediT authorship contribution statement

Mamak P. Tootkaboni: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Ilaria Ballarini:** Writing – review & editing, Validation, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Vincenzo Corrado:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

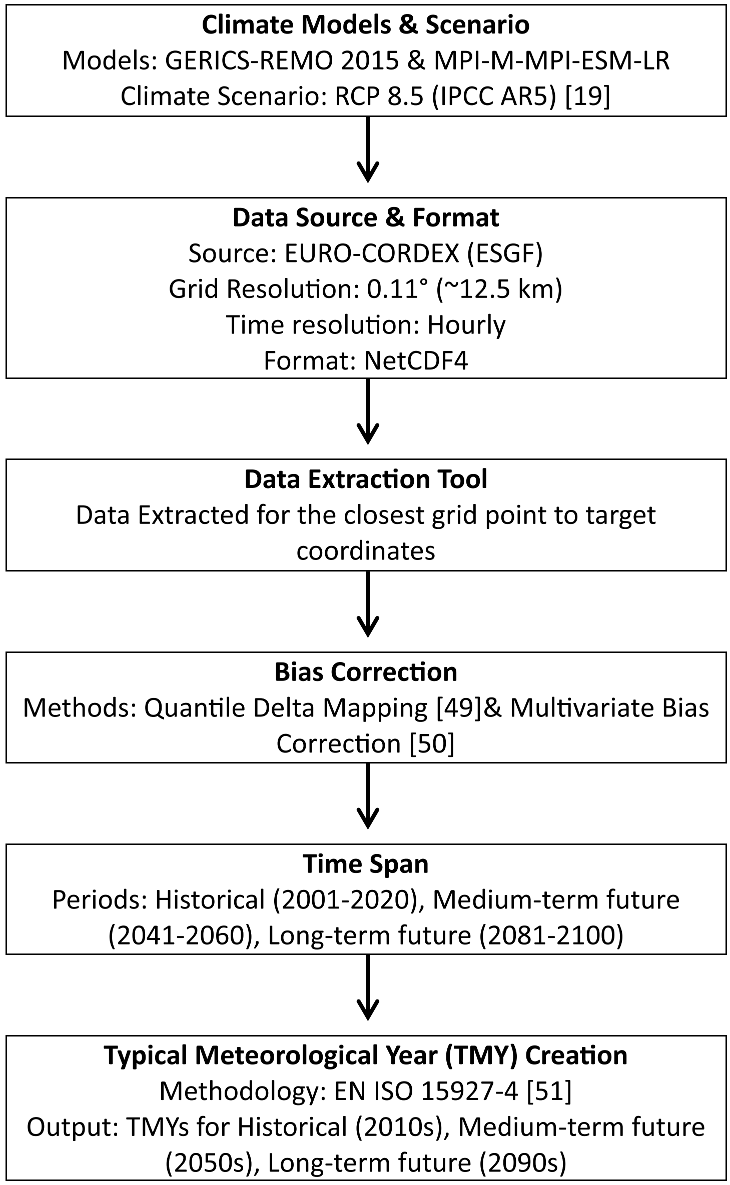


Fig. A.1. Graphical summary of the methodology for creating future weather data [49–51].

Appendix B

For applying the Sobol sensitivity analysis, the model is in the format $Y = f(X)$, where X is a vector of "k" inputs and Y is a scalar output. $X_{1\ldots}X_k$ are independent inputs, each defined by a probability distribution. It is assumed that $f(X)$ is square-integrable. Y can be defined in the following format:

$$\begin{aligned} Y &= f(X) \\ &= f_0 + \sum_i f_i(x_i) + \sum_i \sum_{i<j} f_{ij}(x_i, x_j) + \ldots + f_{1,2,\ldots,k}(x_1, x_2, \ldots, x_k) \end{aligned} \tag{B.1}$$

Where:

$$f_0 = E(Y), \qquad f_i(X_i) = E(Y|X_i) - f_o, \qquad f_{ij}(X_i, X_j) = E(Y|X_i, X_j) - f_o - f_i - f_j, \ldots \tag{B.2}$$

The variance of Y can be decomposed in the following way:

$$V(Y) = \sum_i V_i + \sum_i \sum_{i<j} V_{ij} + \ldots + V_{1,2,\ldots,k} \tag{B.3}$$

Where:

$$V_i = V_{x_i}\left(E_{x_i}(Y|X_i)\right), \qquad V_{ij} = V_{x_i,x_j}\left(E_{x_{ij}}(Y|X_i)\right) - V_{x_i}\left(E_{x_i}(Y|X_i)\right) - V_{x_j}\left(E_{x_j}(Y|X_j)\right) \tag{B.4}$$

Based on these variances, Sobol's indices are defined as follows:

$$S_i = \frac{V_i}{V(Y)}, \qquad S_{ij} = \frac{V_{ij}}{V(Y)}, \ \ldots \tag{B.5}$$

Where S_i are first-order indices, S_{ij} are second-order indices, and similarly for higher-order indices.

S_i is the fraction of V(Y), which could be reduced if X_i were fixed. Similar interpretations hold for higher-order indices. By dividing two sides of equation (A.3) by V(Y), we have:

$$\sum_{i=1}^{k} S_i + \sum_i \sum_{i<j} S_{ij} + \ldots + S_{1,2,\ldots,k} = 1 \tag{B.6}$$

In the case of no interaction between inputs $\sum_{i=1}^{k} S_i = 1$. This is rarely the case, and first-order indices are not enough to explain the output variance [43]. It can be seen that with an increase in the number of inputs, the number of interaction terms will increase exponentially (there are 2^{k-1} terms in equation (A.6)). This makes the computation of second and higher-order indices difficult. To tackle this issue, Homma and Saltelli [52] introduced the total-order index $T_{i:}$

$$T_i = 1 - \frac{V_{x_i}\left(E_{x_i}(Y|X_i)\right)}{V(Y)} \tag{B.7}$$

A (quasi) Monte Carlo method is used to compute these indices.

Data availability

No data was used for the research described in the article.

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