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Potential effect of mechanical ventilative cooling on the climate resilience of the Italian residential building stock

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Abstract

According to the 5th and 6th Assessment Reports of the Intergovernmental Panel on Climate Change, there has been a continuous increase in the concentration of greenhouse gases (GHG) in the atmosphere since 2011. Buildings, responsible for 32% of global energy consumption, contribute not only to climate change but are also influenced by its effects, including increased risk of overheating and cooling demands. Consequently, there is a need to evaluate and implement resilient solutions to address cooling and overheating issues. This paper investigates the energy efficiency and climate resilience of mechanical ventilative cooling in the Italian residential building sector under future climate conditions. Both existing buildings (without insulation and with conventional heating/cooling systems) and retrofitted buildings (with insulation and heat pumps for heating and cooling) were analysed. The findings indicate that due to climate change, buildings will require more energy for cooling. The use of mechanical ventilative cooling can, at best, reduce annual energy needs for space cooling and related electrical energy consumption up to 20% by 2050 in pre-retrofitted buildings. Besides, this change will have a considerable impact on post-retrofit buildings (up to 55% by 2050). In the case of a free-floating condition, findings demonstrate the cooling strategy's adaptability to the negative impacts of insulation in retrofitted buildings (decreases of up to 92% in the 2090s). These results shed new light on the trade-off between climate resilience and energy efficiency.

Highlights

- Analysing the effect of climate change on building energy performance by creating accurate and high resolution future weather data
- Assessment of the resilience of mechanical ventilative cooling strategy
- Contributing to the adaptation of Italian residential buildings to the inexorable trend of climate change

Introduction

In the sixth Assessment Report (A.R.) of the Intergovernmental Panel on Climate Change (IPCC), evidence of observed changes in climate-related hazards, such as heatwaves, has grown stronger (Masson-Delmotte et al., 2021). This is due to methodological advancements and additional data sets since the 5th A.R. (Symon et al., 2013). The building sector is the primary CO₂ emissions

contributor, and its impact on intensifying climate change is undeniable. Specifically, between 1990 and 2019, the building sector's global CO₂ emissions increased by 50%. (Cabeza et al., 2022). At the same time, the impacts of climate change can significantly affect the building energy performance showing that there is a reciprocal relationship between climate change and the energy performance of buildings. In light of this, many published researches point to the importance and urgency of a shift in building energy performance in correspondence to climate change impacts. Accordingly, researchers investigated the changes in the energy performance of buildings – in relation to climate change – by exploring various energy-related indicators such as heating and cooling energy use and overheating risk. Such analyses are performed in the case of both existing pre-retrofitted and post-retrofitted (energy-efficient) buildings.

In terms of energy use, in four American cities, Shen (2017) discovered an increase in cooling energy use and a decrease in heating energy use for office and residential buildings. Besides the decreased variability of energy consumption of residential buildings located in cold and hot regions of the U.S., Berardi and Jafarpur (2020) expected a rise in cooling demand of up to 126% and a decrease in heating demand of up to 33% for numerous urban areas in Canada. In another study in different Chinese cities, Wan et al. (2012) analysed the heating and cooling energy use of an office building. The results show a 24,2% increase in cooling energy need, indicating a move toward increased electricity demand.

Regarding overheating risk, Dino and Meral Akgül (2019) explored the climate change impacts in a typical mid-rise residential building in four Turkish cities. The findings indicate that overheating will occur in structures, particularly naturally ventilated ones. Another study by Peacock et al. (2010) shows that cooling will become a challenge in U.K. southern regions for a third of the year due to increased overheating.

The impacts of climate change are also expected to affect the energy performance of retrofitted and energy-efficient buildings. Some studies show that further dimensioning of renewable energy installations is necessary to meet the energy efficiency criteria, such as NZEB requirements. Da Guarda et al. (2020), for instance, studied the impact of climate change on zero-energy buildings at various time scales and showed that the anticipated increase in energy consumption makes it necessary to reassess the

performance of energy-efficient buildings using future weather data. Another study, which used a Belgian NZEB reference example, predicted an overheating of up to +43,5% by the end of the century (Attia et al. 2020). According to Tabatabaei Sameni et al. (2015), due to the effects of climate change, thermal discomfort is anticipated for 72% of studied social housing apartments that were built to Passivhaus standards during the cooling season.

In the present paper, after producing accurate future weather data for Rome, the resilience of mechanical ventilative cooling technology was examined using thermal comfort and energy performance criteria to analyse and develop the adaptation and mitigation measures on a regional scale. Two typical Italian residential buildings (single-family house and apartment block) from the 1946–1960 construction period were studied. This research is part of a project in conjunction with 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 (IEA EBC Annex 80, 2018).

Materials and Methods

Generation of future weather data

The first phase of this study was the creation of the future typical meteorological years for Rome using 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).

Global Climate Models (G.C.M.s) – having a spatial resolution of 1-600 km – are inappropriate for energy simulations on the building scale since they do not account for climate change effects and related weather extremes at the local level (Symon, 2013). Regional Climate Models (R.C.M.s) can produce physically consistent datasets and better capture the spatial and temporal variability of the local climate (Soares et al., 2012). Accordingly, in this study, to create a reliable basis for building scale simulation, it is necessary to downscale G.C.M.s to less than 100 km spatial scale and increase

their temporal resolution to less than monthly value. One of the downscaling methodologies is the dynamical technique that employs regional climate models (R.C.M.s) to obtain finer spatial and temporal climate information. As previously noted, the GERICS-REMO-2015 is used as the R.C.M. in this investigation. The MPI-M-MPI-ESM-LR is also the study's driving model because it is well-supported by the IPCC report on climate model evaluation (Flato et al., 2014). Additionally, the information is derived from the EURO-CORDEX entry point via 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). The accessible format for this source is NetCDF4, a file format for multi-dimensional scientific data. Using the Cordex Data Extractor tool, the hourly meteorological data for Rome Fiumicino airport were extracted, allowing for the discovery of the data point on the grid closest to the desired latitude and longitude. The RCP 8,5 (Representative Concentration Pathway) scenario from IPCC's Fifth Assessment Report – which is the most recent available climate projection at the time of the study – was used to derive these climatic data for the time periods of 2001-2020 (2010s), 2041-2060 (2050s) and 2081-2100 (2090s). In addition, by using quantile delta mapping (Q.D.M.) (Cannon et al., 2015) and multivariate bias correction using N-dimensional probability density function transform (MBCn) (Cannon, 2018), the bias of raw climate variables was corrected on observations of 2008-2017 from Rome Fiumicino airport weather station. Afterward, the bias correction was technically validated by comparing the observational and bias-corrected data. The validation period refers to the overlapping period of observational and contemporary one (2008-2017). In this way, the whole length of the available observational data is utilised to validate the bias correction. After being validated, it is seen that for both Q.D.M. and MBCn methods, the R.C.M. simulation biases are significantly reduced. These results are presented in Table 1, in which mean climate statistics from observations (OBS), raw R.C.M., and bias-corrected (bc) R.C.M. are presented for the validation period. The findings demonstrate a considerable bias in the projected temperature, solar irradiance, wind speed, and relative humidity from R.C.M.s.

Table 1: Mean temperature, solar irradiance, wind speed, and relative humidity in Rome over the validation time-period

Temperature [°C]			Solar irradiance [W/m²]			Wind speed [m/s]			Relative humidity [%]		
OBS	R.C.M. (raw)	R.C.M. (bc)	OBS	R.C.M. (raw)	R.C.M. (bc)	OBS	R.C.M. (raw)	R.C.M. (bc)	OBS	R.C.M. (raw)	R.C.M. (bc)
16,3	16,5	16,3	187,8	161,8	187,8	3,6	2,7	3,6	72,5	70,7	72,5

In the next step, the future typical meteorological year was constructed from the 20 years of bias-adjusted climatic data and using the EN ISO 15927-4 (2005) methodology, which is an international standard that enables appropriate select the meteorological data for the assessment of the

long-term mean energy use for heating and cooling. By comparing the Cumulative Distribution Function of the single and reference years using Finkelstein-Schafer (F.S.) statistics, the twelve best months were chosen (Finkelstein & Biometrika, 1971). Since it takes into

account global solar irradiance, relative humidity, dry-bulb air temperature, and wind speed, this technique was chosen for this investigation. The T.M.Ys of this study – historical (2001-2020), future medium-term (2041-2060), and future long-term (2081-2100) – are constructed using the best representative 12 months.

Mechanical ventilative cooling

Ventilative cooling can be provided using mechanical technologies (fans), natural solutions (wind- or buoyancy-driven flows), or a combination of both (mixed mode or hybrid ventilation). The cooling potential of the outside air is used in all cases for ventilative cooling. There is a difference between ventilation for direct cooling during the day and ventilation for nighttime cooling or an indirect one. Ventilation for daytime comfort allows for the direct removal of heat gains by letting outside air circulate through the building during the day. Through convective heat transmission, enhancing the evaporative cooling impact on the occupants' skin, and lowering the interior air temperature, the thermal comfort of the occupants is increased. The effects of night cooling are twofold: first, they employ the building thermal mass, which serves as a heat sink during the day when it is used, and second, they lower the inside air temperature overnight.

The strategy adopted in the analysis considers an air exchange rate calculated using the VC Tool (Venticool, 2018), developed within the IEA EBC Annex 62 project (Heiselberg et al., 2018), which allows for evaluating the potential effectiveness of cooling with ventilation strategies, considering the thermal properties of the building envelope, occupancy profiles, internal heat gains, and ventilation needs. VC Tool applies the method derived from the energy balance of a single well-mixed area delimited by heat exchange surfaces. It is assumed that it is possible to determine a thermal equilibrium point of the external air temperature, below which it is necessary to heat the environment in a way that maintains the internal air temperature at its set point value. Therefore, when the outdoor dry bulb temperature exceeds this equilibrium temperature, direct ventilation is useful to keep the indoor conditions within the comfort zone. At or below the heating equilibrium temperature, cooling with ventilation is no longer useful. Instead, ventilation with heat recovery must be used to meet the minimum air exchange rates for heat control, indoor air quality, and reduced heat losses.

In the VC Tool, five ventilative cooling modes (0–4) have been identified (Belleri & Chiesa, 2018). Mode [0]: “When the outdoor temperature is below the heating balance point temperature, no ventilative cooling is required since heating is needed”; Mode [1]: “Direct ventilation with airflow rate maintained at the minimum required for indoor air quality can potentially ensure comfort when the outdoor temperature exceeds the balance point temperature, yet it falls below the lower temperature limit of the comfort zone”; Mode [2]: “Direct ventilative cooling with increased airflow rate can potentially ensure comfort when the outdoor temperature is within the range of comfort”; Mode [3]: “direct

evaporative cooling (DEC) can potentially ensure comfort even if direct ventilation alone is not useful because the outdoor temperature exceeds the upper-temperature limit”; Mode [4]: “Direct ventilative cooling is not useful when the outdoor temperature exceeds the upper-temperature limit of the comfort zone, and furthermore this limit is also overtaken from the expected DEC outlet temperature.” Mode 2 was used in this study. In addition to dividing the total number of hours the building is occupied into the defined groups, the tool determines the required airflow for ventilation cooling mode 2. In this way, cooling with direct ventilation with an increased airflow can potentially ensure comfort when the outdoor temperature is within a range equal to the temperature range of the comfort zone. In this case, the instrument calculates the airflow necessary to maintain the internal air temperature within the temperature ranges of the comfort zone.

Calculation Methods and Performance Indicators

Simulations were run using EnergyPlus 9.0. The key performance indicators (KPIs) used for the performance assessment of the selected cooling solutions in this study are:

- 1) HE [%], i.e., percentage hours of exceedance, which are the number of hours in which the operative temperature of the zone is greater than the upper limit temperature,
- 2) $EP_{C,nd}$ [kWh/m²], annual thermal energy need for space cooling per unit cooled floor area,
- 3) $EP_{el,C}$ [kWh/m²], annual electrical energy consumption (from the grid) for cooling and ventilation per unit cooled floor area.

All of these indicators are based on international standards, and according to the following criteria, the aforementioned KPIs were selected from the list of KPIs included in IEA EBC Annex 80 to represent the summer performance of the building:

- Thermal discomfort in free-floating situations (such as when there is no air conditioning or when there is a power outage) or in the event of a power shortage;
- The thermal performance of the fabric during cooling operation;
- The building energy performance during cooling operation, including the HVAC system.

Regarding HE determination, turning to international standards, according to Annex-H of EN ISO 7730, 2005, the adaptive comfort approach is assumed for the free-floating condition.

The $EP_{C,nd}$ measures the basic energy requirements of the building under ideal thermal conditions (a uniform and ideally controlled interior temperature) without interacting with particular technical building systems (EN ISO 52016-1, 2017).

$E_{el,C}$ represents the energy delivered to the building for cooling, considering the effect of the energy losses of the cooling system (EN ISO 52000-1, 2017).

Case Studies

In the present research, the simulated cases were chosen from the IEE-TABULA research project with the intention of analysing the future energy performance and thermal comfort of the Italian residential building stock (Ballarini et al., 2014). The goal of TABULA was to harmonise the definition of the residential building typology across Europe. The representative building types of the existing residential building stock and proper national building typologies were identified by each participating country. Each building type has typical geometrical and thermal characteristics for the cluster of the building stock it represents. Each cluster in TABULA is distinguished by a certain climatic zone, building size, and construction period. By using the ability to scale up the findings from the representative building type to the building stock cluster, the building typology may be efficiently used to create bottom-up energy models.

Consequently, the building typology approach can be used to predict the energy performance of building stocks (Ballarini & Corrado, 2017), assess effective energy-saving potentials, and develop reliable refurbishment scenarios for the stock. Two building types from the 1946–1960 construction period have been chosen from the Italian residential building typology: the single-family home (SFH) (Figure 1) and the apartment block (AB) (Figure 2). These types were picked because they had more significant potential for energy savings than structures from other construction periods (Corrado & Ballarini, 2016). Tables 2 and 3 display, respectively, the main geometric and thermal features of the building types studied in this research. The building sizes span various window-to-wall ratios (W.W.R.) and shape factors (A_{env}/V_g).



Figure 1: Photograph of the building type of the Italian single-family house (SFH) built in the period 1946-60



Figure 2: Photograph of the building type of the Italian apartment block (AB) built in the period 1946-60

Both the original pre-retrofit scenario and the retrofitted state were taken into consideration when analysing these building types since this double assessment enables evaluating the impact of passive cooling solutions on both low energy-efficiency buildings and already-insulated buildings. The U -values of the envelope components in the pre-retrofit state relate to conventional construction-era technology (solid brick masonry and single-glazing windows). According to the Italian energy regulations (M.D. 26 June 2015), which also reflect the goal of nearly zero-energy buildings, the retrofitted state considers insulated components in line with the national reference building for the climatic zone of Rome, whose thermal features are listed in Table 3 as well. Accordingly, the post-retrofit buildings have windows with low-E double glazing. Additionally, the retrofitted building has external wooden Venetian blinds as solar shading devices are installed, while the original building does not favor such devices. Both heating and cooling are provided by a reversible air-to-water heat pump with fan coils as heat emitters in post-retrofit conditions, while in its pre-retrofit form, the building has a split system for space cooling and a gas standard boiler and radiators for space heating.

Table 2: Geometric data of the case studies

Parameter	SFH	AB
Conditioned gross volume V_g [m ³]	584	5949
Conditioned net floor area A_{fl} [m ²]	162	1552
Shape factor A_{env}/V_g [m ⁻¹]	0,73	0,46
Window-to-wall ratio W.W.R. [-]	0,09	0,23
Number of floors [-]	2	4
Number of apartments [-]	1	24

Table 3: Thermal transmittance of the building envelope components Pre and Post- retrofit

Component	U-value [W·m ⁻² K ⁻¹]		
	SFH	AB	Post-retrofit
External wall	1,48	1,15	0,29
Roof	1,65	1,65	0,26
Floor	2,00	1,30	0,29
Window	4,90	4,90	1,30

The energy performance of the case studies was evaluated in light of typical user behavior. According to the draft Italian National Annex of EN 16798-1 (Comitato Termotecnico Italiano, 2022) technical standard, hourly profiles of internal heat gains were considered, including those from occupants, electric lights, and appliances. The heating and cooling temperature set-points of 20 °C and 26 °C were applied, respectively, considering a continuous operation mode of the technical building systems. The period from 1st November to 15th April is regarded as the heating season, and the months of June, July, and August represent the cooling period.

According to UNI/TS 11300-1 (2014), a threshold value of the incident solar irradiance (300 W/m^2) was used to determine how the solar shading devices would operate. Using the VC Tool, an air exchange rate of 2,8 and 3,1 volumes per hour was assumed for the ventilation cooling strategy for SFH and AB, respectively. The mechanical ventilation modeled in Energyplus is active when the outdoor air temperature is lower than the internal temperature by at least 2°C . The strategy is available for 24 hours. 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 on average by 0.4°C .

Results and Discussion

The results obtained from the simulations are shown in Figures 3 to 14. Figures 3 to 7 show the annual thermal energy need for space cooling ($EP_{C,nd}$) in the 2010s, 2050s, and 2090s for both SFH and AB. Besides, Figures 7 to 10 represent the annual electrical energy consumption from the grid ($E_{el,C}$) during the same period. Both indicators are normalised regarding the conditioned net floor area. Each graph compares the base case and the case with the mechanical ventilative cooling strategy.

As a result of climate change, there is an increase in the values of $EP_{C,nd}$ and $E_{el,C}$, and this increase is most significant in the case of the existing condition of SFH, which reaches 50% and 67%, respectively. The reason why these changes in the case of AB are less significant results from its lower shape factor. For both energy indicators, the increases over the years are smaller for the refurbished building than the existing one. It can be argued that the post-retrofitted building is less sensitive to the effects of climate change. This is because of the higher insulation level, thanks to the reduction of heat gains from the outdoor sol-air temperature.

In the presence of mechanical ventilative cooling in the case of pre-retrofitted building $EP_{C,nd}$, and $E_{el,C}$ decrease less significantly (in the best case, up to 18% for the 2050s, in SFH and 20% for 2050s in AB) than the post-retrofitted building (up to 50% for 2050s, in SFH, and 55% for 2050s in AB). The reduction of $E_{el,C}$ happens despite considering the electrical energy consumption due to the mechanical ventilation. In general, the positive effect of mechanical ventilative cooling solution will diminish over time as this solution works in relation to the outside air temperature, which will increase due to climate change in the future.

It should also be emphasised that, for the building that has already been partially renovated, the effect of the chosen strategy significantly compensates the effect of climate change. Mainly, electricity consumption in the presence of the cooling strategy in the 2090s is even less than the value of the base case in the 2010s for both building types.

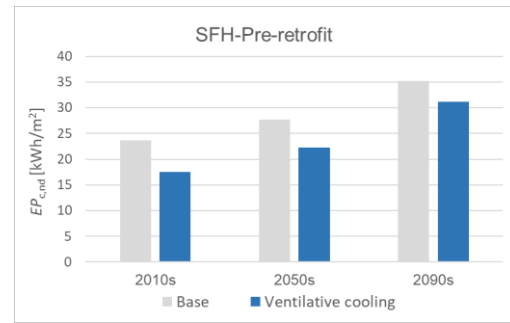


Figure 3: Thermal energy need for space cooling in the 2010s, 2050s, and 2090s for pre-retrofit SFH

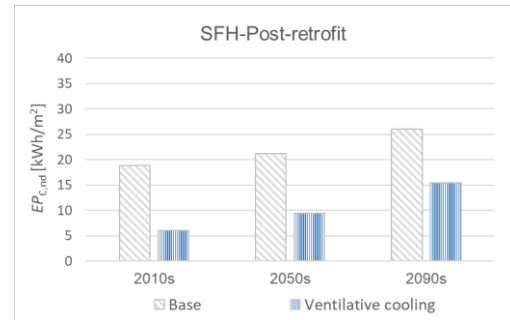


Figure 4: Thermal energy need for space cooling in the 2010s, 2050s, and 2090s for post-retrofit SFH

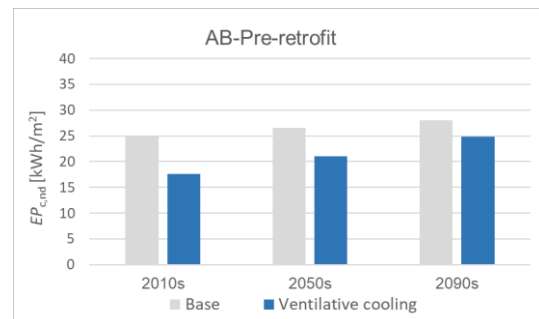


Figure 5: Thermal energy need for space cooling in the 2010s, 2050s, and 2090s for pre-retrofit AB

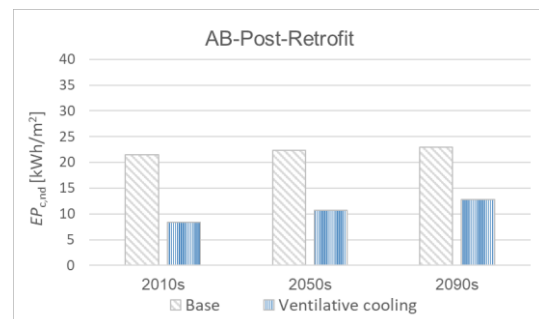


Figure 6: Thermal energy need for space cooling in the 2010s, 2050s, and 2090s for post-retrofit AB

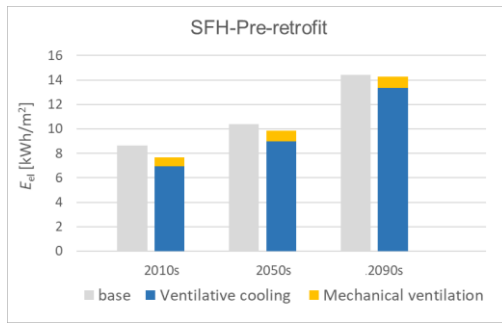


Figure 7: Electrical energy consumption (from the grid) for cooling and ventilation. in 2010s, 2050s, and 2090s for pre-retrofit SFH

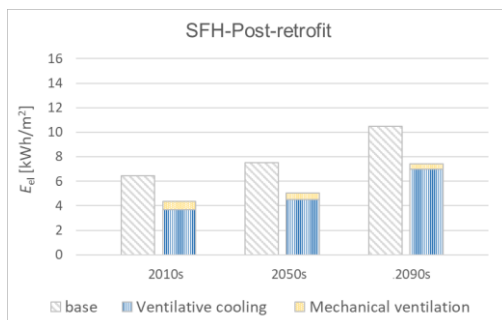


Figure 8: Electrical energy consumption (from the grid) for cooling and ventilation. in 2010s, 2050s, and 2090s for post-retrofit SFH

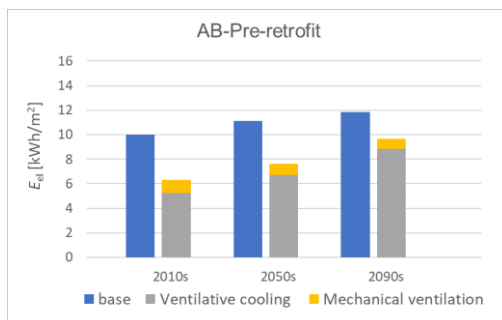


Figure 9: Electrical energy consumption (from the grid) for cooling and ventilation. in 2010s, 2050s, and 2090s for pre-retrofit AB

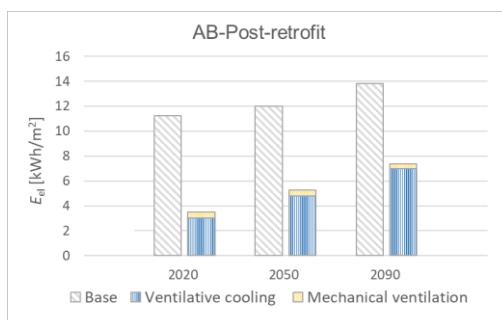


Figure 10: Electrical energy consumption (from the grid) for cooling and ventilation. in 2010s, 2050s, and 2090s for post-retrofit AB

Figures 11 to 14 show the HE indicator, representing the number of hours of exceedance of the acceptable internal operative temperature range in free-floating condition. Results report that the hours of exceedance increase due

to climate change in both states and for both building types. However, in post-retrofitted buildings, occupants will experience overheating up to 4924 hours for SFH and 8162 for AB in future scenarios. This amount reaches a maximum of 1603 hours for SFH and 3165 hours for AB in the case of pre-retrofitted buildings. This result is due to the unwanted effect of insulation that causes heat traps in the building in a free-floating regime.

Hours of exceedance in the AB -in both pre and post-retrofitted conditions- are more significant because of the higher W.W.R. ratio compared to SFH. By applying mechanical ventilative cooling to the SFH building, the exceedance hours reduce up to 46% for the pre-retrofitted and up to 83% for the post-retrofitted building in the worst-case scenario (the 2090s). In the case of the AB, this reduction reaches a maximum of 70% for the pre-retrofitted building and 92% for the post-retrofitted building. This reduction is to the degree that the exceedance hours in the 2090s are even less than the present base case. The findings show the capacity of this cooling solution to adapt to the unwanted effects of insulation in the post-retrofitted building, demonstrating its resilience. This is valid even considering the overmentioned fact that the positive effect of mechanical ventilative cooling solution will diminish due to climate change. In addition, the COP of the system was calculated as the ratio of the ventilation sensible heat loss to the electrical consumption of the fan. Although the COP-value of 22 in the 2010s decreases to 19 in the 2090s, results show that the performance of the ventilation strategy is still high.

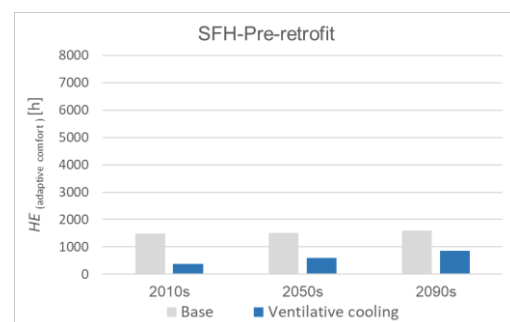


Figure 11: Hours of exceedance in 2010s, 2050, and 2090s for pre-retrofit SFH, in free-floating condition

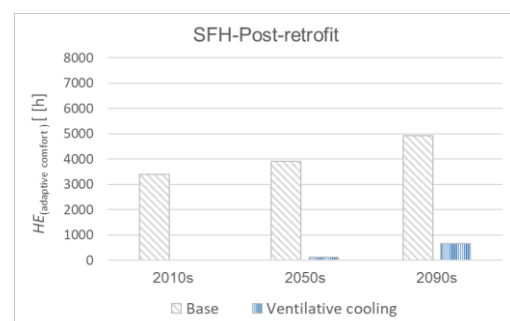


Figure 12: Hours of exceedance in 2010s, 2050, and 2090s for post-retrofit SFH, in free-floating condition

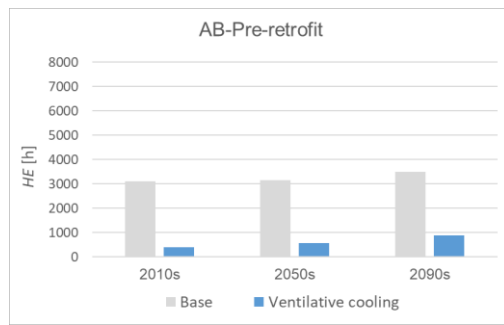


Figure 13: Hours of exceedance in 2010s, 2050, and 2090s for pre-retrofit AB, in free-floating condition

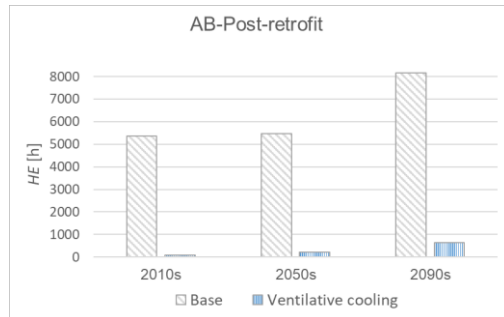


Figure 14: Hours of exceedance in 2010s, 2050, and 2090s for post-retrofit AB, in free-floating condition

Conclusion

The present research aimed to examine the climate resilience of mechanical ventilative cooling solution regarding the future performance of Italian residential buildings. To reach this aim, the impact of this solution on the thermal comfort and the energy performance of two Italian residential building types built in the 1946-1960 period was investigated. Two building conditions (pre- and post-retrofitted) and three periods (the 2010s, 2050s, and 2090s) were considered. The results indicate that mechanical ventilative cooling's impact on reducing the effect of climate change on thermal energy need for space cooling, electrical energy consumption from the grid, and hours of exceedance in the absence of mechanical cooling, depends on the building type and especially its retrofit condition. It should be pointed out that the effectiveness is much higher in the already refurbished building than in its original condition and in the apartment block due to its lower sensitivity to climate change.

Particularly in the case of the free-floating condition, the overheating risk in the insulated building reduces to the level below the present base case. 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 (active and passive) that help to mitigate climate change and foster adaptation to it to ensure both sustainability and climate resilience for the built environment.

Acknowledgement

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