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Research Paper

Analysing the future energy performance of residential buildings in the most populated Italian climatic zone: A study of climate change impacts

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ABSTRACT

There is growing concern that global warming will change the building's performance pattern in the future. This paper investigates the effects of climate changes on the heating and cooling energy demand, the overall energy performance and the overheating risk of typical residential buildings (existing and refurbished) in the biggest city of the most populated Italian climatic zone, Milan. The widely used morphing methodology was adapted for creating future weather data for different scenarios. Energy performance analysis was carried out using dynamic simulation for the near term (2021–2040) and the long term (2081–2099) periods. The results show decreases in heating energy demand up to 30.9%, intense increases in cooling energy demand, up to 255.1% and significant increases of overheating risk up to 155%. In addition, the effect of refurbishment on each parameter is also analysed and reported. The research demonstrates that climate change causes a paradigm shift in the building energy performance, while the magnitude of climate change impact is not equal for different building types, time periods, insulation levels, and future weather scenarios. Therefore, climate change must be considered for future energy performance assessment of buildings.

1. Introduction

Recently, the issue of climate change has received considerable attention. According to the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC), if the emissions continue to rise, the global average temperature will be 2.6–4.8 degrees Celsius (°C) higher than the present, by the end of 21st century. Even supposing the immediate stop of the greenhouse gas emissions, the temperature increase will endure as a result of already present greenhouse gases in the atmosphere. Furthermore, global warming can increase the frequencies of extreme weather events. Recent studies reveal that this phenomenon has doubled the probability of the European heatwaves and longer heatwaves are more than 90% definite as the climate pattern has been disrupted (Symon, 2013). Heatwave is defined as a singular microclimate condition with temperatures over a specific percentile and characterized by more than three consequent hot days. This event is associated with drastic physiological impacts on human health. For instance, the August 2003 heatwave contributed to around 45,000 excess deaths across 12 European countries (Zuo et al., 2015). In addition to such consequences, heatwave causes uncertainty regarding performance of the built environment. In this context, due to the long-life span, buildings will be subjected to a warmer climate, which can affect their thermal comfort condition. One of the major problems caused by climate change is the building overheating which leads to a significant rise in cooling energy consumption and energy shortage. There is a growing body of literature that analyses the effect of climate change on building energy performance (BEP), which is summarized in the following paragraphs.

In China, Wan et al. (2012) estimated the changes in the energy use for heating and cooling of an office building in five major representative cities with different climates, using MIROC3.2-H for weather projection. The authors identified that the estimated increase in cooling energy use is up to 24.2% for low forcing scenario and argue that there would be a shift towards more electricity demand. To determine the effect of climate change on U.S building energy performance, Shen (2017) used the morphing method for downscaling the global climate models and analysed residential and office buildings in four cities. He identified that there is a rise in cooling energy use and a decrease in heating energy use in both office and residential buildings for all the cities. However, the extent of variation is different, and Shen concluded that climate change is diminishing the inconsistency of energy use in residential buildings located in cold and hot regions

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Nomenclature

Quantities

A	Area (m^2)
CDD	Cooling degree days (°C d)
EER	Energy efficiency ratio (–)
EP	Energy performance (indicator) (kWh m^{-2})
f	Factor, coefficient (–)
g	Total solar energy transmittance (solar factor) (–)
H	Heat transfer coefficient (W K^{-1})
HDD	Heating degree days (°C d)
HE	Hours of exceedance (h)
RH	Relative humidity (–)
SI	Solar irradiance (W m^{-2})
T	Temperature (°C)
U	Thermal transmittance (W m^{-2} K^{-1})
V	Volume (m^3)
WWR	Window to wall ratio (–)

Greek symbols

6	efficiency (–)

Subscripts

C	Space cooling
cond	Condenser
el	Electrical energy
env	Envelope
evap	Evaporator
ext	External
f, fl	Floor
g	Generation
gl	Overall
gr	Gross
H	space heating
hor	horizontal
lw	Lower
n	Normal
nd	Nren
nren	Non-renewable (energy)
P	Primary (energy)
tr	Thermal transmission
u	Utilization
unc	Unconditioned
up	Upper
w	Window
wl	Wall

Acronyms

AB	Apartment Block
AR	Assessment Report
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BEP	Building Energy Performance
CIBSE	Chartered Institution of Building Services Engineers
GCM	Global Climate Model
IPCC	International Panel for Climate Change
IWEC	International Weather for Energy Calculation
LT	Long Term
MFH	Multi Family House
NT	Near Term
RCM	Regional Climate Model
RCPs	Representative Concentration Pathways
SFH	Single Family House

in the U.S. In another article, Shen and Lukes (2015) measured the impact of climate change on the efficiency of a ground source heat pump, for office and residential buildings in the U.S., using TRNSYS and eQuest simulation software. They estimated that global warming decreases the efficiency of the ground source heat pump, in all the studied cities, due to the rise in inlet and outlet water temperature of the heat pump. However, this negative impact is not significant for office buildings. Berardi and Jafarpur (2020) demonstrated the need to perform analysis of the future energy performance of buildings, by assessing the heating and cooling demand of 16 ASHRAE building prototypes using future weather data of populated urban regions in Canada. They point out that there would be an increase in cooling demand up to 126% and a decrease in heating demand up to 33%. It was also highlighted that higher insulation layer, higher zone ratios, lower window-to-wall ratio and smaller outdoor air supply can scale down the negative effect of climate change on building energy performance. In Argentina, Flores-Larsen et al. (2019) analysed a typical mid-income house for medium and long-term climate change using the A2 scenario of global model HadCM3, for four different cities. The authors concluded that cooling loads increase 360%–790% and heating loads decrease up to 59% in 2080. They also argued the effect of present bioclimatic strategies on the future performance of buildings towards global warming. The same studies were carried out for countries with colder climate like Nordic countries. Nik and Sasic Kalagasidis (2013) discussed the future energy performance of residential building stock in Stockholm and its uncertainties, by analysing 153 buildings for 12 climate scenarios and with three cooling solutions. The authors found out that the heating demand will decrease, and the cooling demand will increase. However, the variation in cooling demand is more sensitive to different climate scenarios, and in most cases, it can be covered by natural ventilation in the Swedish climate.

There is also research being conducted on overheating risk. Peacock et al. (2010) investigated overheating risk in UK dwellings by studying occupant thermal discomfort indicator (CIBSE, 2006) and the number of "cooling nights" in a year. The authors considered near term period (by the year 2030) for their analysis and concluded that overheating appears mostly in the south of the UK, which can cause the cooling problem for a third of a year. This increase of cooling demand and overheating risk was also predicted for Mediterranean countries. Dino and Meral Akgül (2019) investigated the impact of climate change on a typical mid-rise residential building in four cities in Turkey, considering three space cooling scenarios. They concluded that the occupants would experience overheating risk, especially in naturally ventilated dwellings. For air-conditioned buildings, they found out that the increase in the annual mean temperature increases the cooling load up to 177%, varied for different cities. Cartalis et al. (2001) simulated the climate change in 2030 in Greece. They pointed out the increase in cooling degree days and cooling demand, with various magnitude in different cities, and discussed the importance of modification of energy management in the country. This change in the energy use pattern was also identified by Zachariadis and Hadjinicolaou for Cyprus (Zachariadis and Hadjinicolaou, 2014). An increase of 6% in the country annual electricity demand was estimated. Besides, the authors also ran economic analysis and argued that the country may need to forsake up to two years of economic growth to cope with extra electricity needs. Pérez-Andreu et al. (2018) analysed a typical Mediterranean residential building in Valencia (as the representative city for Mediterranean climate) under various scenarios for the mid and the end of the 21st century. The authors concluded that the heating demand decreases, while cooling demand and overheating risk increase considerably. Moreover, they discussed a range of passive improvement measures for the building (up to reaching nearly zero-energy building), and found out that the expected energy consumption changes are not going to happen after the major retrofit. Rodrigues and Fernandes (2020) performed a similar series of analyses by considering 16 different Mediterranean cities. They demonstrated that the extent of the cooling demand increase varies for different locations and must be analysed further.

Besides, several studies show that overheating risk and energy need for space cooling may increase also in existing retrofitted and energy-efficient dwellings due to high insulation levels. As an example, Tabatabaei Sameni et al. (2015) discussed the overheating risk in social housing flats built to Passivhaus standards. The results highlight that 72% of all monitored flats experience thermal discomfort condition during cooling season under current climatic conditions. In another article, an imbalance of heating and cooling energy demands is determined by energy efficiency requirements (Murano et al., 2017). It was concluded that, although the energy performance of buildings improves by reducing the heating energy need, an increase of the cooling energy need is inevitable. Considering this context, studying the effect of climate change on the performance of retrofitted and energy-efficient buildings is significantly important. A recent study by da Guarda et al. (2020) analysed the impact of climate change in 2020 (2011 to 2040), 2050 (2041 to 2070) and 2080 (2071 to 2100) for a zero-energy building (ZEB). It was demonstrated that the energy demand will increase and renewable energy installation with adequate dimensioning is vital to reach zero net energy balance. In the same vein, the study done by Attia and Gobin (2020) for a Belgian reference case of nearly zero energy building shows that the presence of overheating reaches up to +43.5% by the end of century. In another study, an increase of 18% in annual power consumption by 2050 was demonstrated for a residential nearly zero energy building located in Rome (Summa et al., 2020). It was concluded that the increase is due to protracted activation of the air conditioning system and enhanced peak power requirements.

In summary, review of the reported literature verifies the increasing concern about the effect of climate change on the future energy performance of buildings. However, there is little research on analysing the Italian building stock towards this issue. Although a paradigm shift in the BEP is likely to happen, there is a need to perform quantitative analysis on a regional scale. The goal of this paper is to draw a clearer picture of the future performance of Italian residential buildings until the end of the 21st century. This study can form the basis for future actions towards the climate resiliency of the built environment. It evaluates the heating and cooling demand, the overall energy performance in the presence of heating and cooling systems with continuous operation, and the overheating risk in free floating regime, of three building types, representative of the existing residential building stock in Italy, under different scenarios, using Energy Plus simulation engine. The effect of building refurbishment related to the increase of the thermal insulation level of the building envelope components – which is the energy efficiency measure commonly applied in Italy – were also analysed. "Representative Concentration Pathways (RCPs)" 4.5 (stabilization) and 8.5 (business as usual) (Symon, 2013) have been applied in this study, using WeatherShift^{TM} tool. The analysis was carried out for Milan, as it is the main city of the Italian middle climatic zone ($2100 < HDD \leq 3000$), which includes 4250 Italian municipalities on a total amount of 8100.

This paper aims to contribute to prepare Italian residential buildings for the future. In a changing climate, to avoid problems like overheating and power outage, which brings health risks for the occupants, regional scale analysis considering different scenarios is necessary. The study offers some important insights into the climate resiliency of Italian residential building stocks, which is not sufficiently investigated in literature.

2. Materials and methods

2.1. Future weather data generation

To study the impact of climate change on BEP in the future, the fundamental step is the increase of knowledge about the external boundary conditions that the building will face. The analysis of future climate is based on future scenarios and the projections of climate models. The newest future scenarios were adopted by AR5 of IPCC, and are expressed in terms of greenhouse gas concentrations instead of emission levels (Symon, 2013). Representative Concentration Pathways (RCPs) are established using hypotheses about economic growth, choices of technology and land-use which are identified by their associated warming effect (radiative forcing; measured in units of watts per metre squared) in the year 2100 (Symon, 2013). In this study, two RCPs have been considered. First, the RCP 4.5, in which "CO_2 emissions fall below current levels by 2070 and atmospheric concentrations stabilize by the end of the century at about twice those of the pre-industrial period". Second, the RCP 8.5, which "assumes a 'business-as-usual' approach in which by 2100 atmospheric concentrations of CO_2 are three to four times higher than pre-industrial levels" (Symon, 2013).

These scenarios are the input data used to provide initial conditions for General Circulation Models or Global Climate Models (GCMs). This climate model is a mathematical model that simulates the state and evolution of the atmosphere, including the atmospheric circulation and energy exchanges in terms of radiation, heat, and moisture. They also take into account the interaction with the ocean and the land (Symon, 2013). GCMs cannot be used for building energy simulation as they provide climate information on a global scale with a spatial resolution of 150–600 km ^{2}. Therefore, the climate change effect and related weather extremes at the local level will not be considered in the simulations. In this case, they should be downscaled to applicable spatial (less than 100 km^2) and temporal resolution (less than monthly value).

One of the most widely used methods for downscaling is the "Morphing" methodology, originally developed by Belcher et al. (2005). The approach preserves real weather sequences (as a base scenario) and modifies it for the future, using climate change signals given by GCMs or regional climate models (RCMs). This is called morphing procedure and it includes (1) shifting which is applied when an absolute change to a variable is expressed, (2) stretching or scaling factor when the change is projected relatively, and (3) a combination of both shifting and scaling when both mean and variance of the variable change over time. A major advantage of the morphing method is the low computational time so that various climate change scenarios can easily be applied (Ramon et al., 2019).

Table 1
Annual average value of Milan climate variables for different scenarios.

	Base	NT-RCP 4.5		NT-RCP 8.5		LT-RCP 4.5		LT-RCP 8.5	
			Relative change		Relative change		Relative change		Relative change
T [°C]	11.8	13.3	12.7%	13.7	16.1%	14.3	21.2%	16.6	40.7%
SI_{hor} [W m^{-2}]	147	154	4.7%	156	5.6%	155	5.6%	171	16%
RH [%]	75	73.1	−2.5%	73.1	−2.5%	72.8	−2.9%	70.8	−5.6%

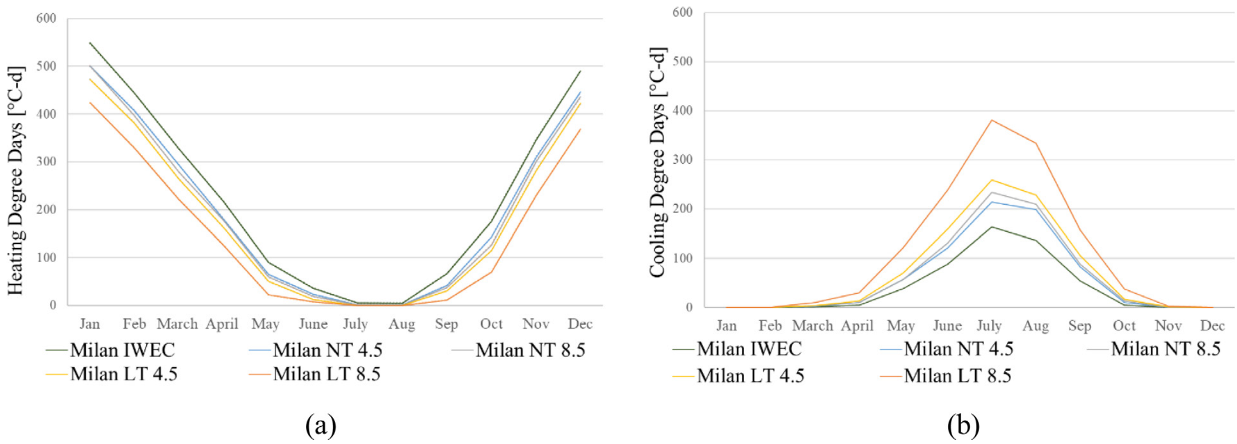


Fig. 1. Monthly heating (a) and cooling (b) degree days for Milan under different scenarios.

This study uses the WeatherShift TM tool tool, which is developed upon morphing methodology, for creating future weather data. "The tool blends 14 of the more recently simulated GCMs (BCC-CSM1.1, BCC- CSM1.1(m), CanESM2, CSIRO- Mk3.6.0, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, NorESM1-M) into cumulative distribution functions (CDF). Creating CDFs allows a percentile distribution (called warming percentile factor) and "smooths out" the inter-modal uncertainty and stochastic climate behaviour" (Troup and Fannon, 2016). Herein four weather data set were generated for Milan: referring to a near term period (NT) from 2026 till 2045 and a long-term period (LT) from 2080 till 2099, considering RCP 4.5 and RCP 8.5 and the median (50%) warming percentile. The Milan International Weather for Energy Calculation (IWEC) was used as the base scenario (Huang et al., 2014). In Table 1, the annual average of climate variables (dry bulb temperature, T, solar irradiance on horizontal plane, SI_{hor}, and relative humidity, RH), for four developed future weather data are presented. As shown, the dry bulb temperature is more likely to change compared with other variables and LT-RCP 8.5 scenario is associated with the most significant variation. It is important to indicate that wind speed has not been morphed by the WeatherShift tool.

Subsequently, Heating Degree Days (HDD) and Cooling Degree Days (CDD) have been calculated for different scenarios. HDD and CDD reflect the heating and cooling energy demand for a building. In this calculation, base 18 °C heating and cooling degree-days have been considered (ASHRAE, 2017). Fig. 1 presents the monthly HDDs and CDDs for Milan base and future scenarios. It can be seen in Fig. 1, that HDDs increase, CDDs decrease, while changes in CDDs are more severe. However, degree days give a primary insight of changes on BEP, and for more deep analysis, BEP simulations must be run.

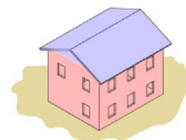
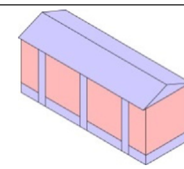
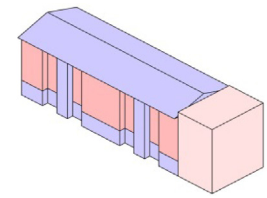
2.2. Building performance and thermal comfort evaluation metrics

The investigation of the climate change effect on building performance in the future is done based on the comparison of different indexes. The BEP was evaluated for all the scenarios by comparing the annual net energy need for space heating and space cooling of the building normalized by the net conditioned floor area ($EP_{H,nd}$ and $EP_{C,nd}$). Besides, the overall energy performance (EP_{gl}), expressed as the ratio of the annual non-renewable primary energy for space heating and space cooling to the net conditioned floor area, was calculated and analysed for different scenarios according to Eq. (1). The Italian most common technical building system technologies are considered in this study: centralized gas standard boilers for heat generation, and radiators as heat emitters, while space cooling is provided by individual direct expansion air conditioners (split systems).

$$EP_{gl}=\frac{EP_{H,nd}\cdot f_{P,nren,gas}}{\eta_{H,u}\cdot\eta_{H,g}}+\frac{EP_{C,nd}\cdot f_{P,nren,el}}{\eta_{C,u}\cdot\eta_{C,g}} \quad (1)$$

where, $EP_{H/C,nd}$ is the annual energy need for space heating/cooling, $f_{P,nren,gas/el}$ is the non-renewable primary energy conversion factor for natural gas (1.05) and electricity (1.95) respectively, $\eta_{H/C,u}$ is the mean seasonal efficiency of the heating/cooling utilization (including emission, control, and distribution) subsystems, which is equal to 0.81 for heating and 0.83 for cooling, and $\eta_{H/C,g}$ is the mean seasonal efficiency of the heating and the cooling generation subsystem. The reference mean seasonal efficiency values of the thermal subsystems were assumed in compliance with the Italian Interministerial Decree of June 26th, 2015 (Italian Republic, Interministerial Decree of June 26th, 2015). The mean seasonal efficiency of the heating generation was considered equal to the reference value (0.95), while the current mean seasonal efficiency of the cooling generation subsystem was assumed equal to the reference value of 2.5. As regards the future mean seasonal efficiency ratio of the cooling generation subsystem, it was obtained by assuming proportionality between the efficiency energy ratio (EER) of the chiller and its maximum theoretical efficiency (EER_{Carnot}) over different temperatures, according to EN 16798-13 (CEN. EN 16798-13, 2017). The future seasonal mean seasonal efficiency ratio of the cooling

Table 2
Data of the building-types.

		Building type		
		Single-family house (SFH)	Multi-family house (MFH)	Apartment block (AB)
Thermal zones and boundary conditions: conditioned space; unconditioned space; adjacent building; ground				
Geometric parameters:	Symbol:			
Gross conditioned volume	V_{gr} [m^3]	584	3076	5949
Net floor area	$A_{f,net}$ [m^2]	162	827	1552
Thermal envelope area	A_{env} [m^2]	424	1576	2740
Shape factor	A_{env}/V_{gr} [m^{-1}]	0.73	0.51	0.46
Window to Wall Ratio	*WWR* [–]	0.09	0.20	0.23
Number of floors	–	2	3	4
Number of units	–	1	12	24
Thermo-physical parameters:	Symbol:			
External wall thermal transmittance	$U_{wl,ext}$ [W m^{-2} K^{-1}]	1.48	1.48	1.15
Wall thermal transmittance to adjacent unconditioned space	$U_{wl,unc}$ [W m^{-2} K^{-1}]	–	1.70	2.32
Upper floor thermal transmittance	$U_{fl,up}$ [W m^{-2} K^{-1}]	1.65	1.65	1.65
Lower floor thermal transmittance	$U_{fl,lw}$ [W m^{-2} K^{-1}]	2.00	1.30	1.30
Windows thermal transmittance	U_w [W m^{-2} K^{-1}]	4.90	4.90	4.90
Total solar energy transmittance of glazing for normal incidence angle	$g_{gl,n}$ [–]	0.85	0.85	0.85

generation subsystem is calculated as:

$$\eta_{C,g,future} = \eta_{C,g,ref} \cdot \frac{\sum_{currentcoolingseason}\left(\Phi_{C,j}\frac{T_{evap,out}}{T_{cond,in,j}-T_{evap,out}}\right)}{\sum_{currentcoolingseason}\Phi_{C,j}} \cdot \frac{\sum_{futurecoolingseason}\Phi_{C,j}}{\sum_{futurecoolingseason}\left(\Phi_{C,j}\frac{T_{evap,out}}{T_{cond,in,j}-T_{evap,out}}\right)} \quad (2)$$

where, is the reference value of the cooling generation subsystem efficiency (equal to 2.5), $\Phi_{C,j}$ is the thermal energy load for cooling at time *j*, $T_{evap,out}$ is the evaporator air outlet temperature (equal to 280 K) and $T_{cond,in,j}$ is the condenser air inlet temperature at time *j*.

For analysing the thermal comfort and overheating risk, the adaptive comfort model of EN 16798-1:2019, was implemented in free floating condition. The main driving force behind the adaptive approach is the pattern of outside weather conditions and exposure to them. This allows to predict likely comfort temperatures or ranges of comfort temperature, from the outdoor running mean temperature, to capture the occupant's thermal sensation in a situation that they can be in comfort by taking adaptive adjustments (Italian National Annex of the EN 16798-1 technical standard). In this model, the optimal operative temperature ($\theta_{o,c}$, in °C) is calculated as:

$$\theta_{o,c} = 0.33 \cdot \theta_{r,m} + 18.8 \quad (3)$$

where $\theta_{r,m}$ is the outdoor running mean temperature, which is defined as an exponential running mean of the daily mean outdoor air temperatures over the last seven days.

In this study, the second category of indoor environmental quality, corresponding to a medium level of occupant expectation, is applied. In this category the range of comfort is between $\theta_{o,c}$ +3 °C (highest limit) and $\theta_{o,c}$ −4 °C (lowest limit). For assessing whether the building is overheated or not, the hours of exceedance (*HE*) indicator was calculated. *HE* is equal to the number of hours during the cooling period, in which the operative temperature of the zone is greater than the upper limit temperature. In the following sections, the results regarding the above-mentioned measures for the selected case study and for all developed future weather data are presented and discussed.

3. Calculation

3.1. Description of the case study

3.1.1. Existing buildings

For the purpose of analysing the future performance of Italian residential building stock, the buildings simulated in the present paper have been selected from the IEE-TABULA research project (Ballarini et al., 2014). TABULA was aimed at creating a harmonized definition of the residential building typology at the European level. Each participating country developed its national building typology and identified representative building-types of the existing residential building stock. Each building-type has average geometrical and thermo-physical features of the building stock cluster that represents. In TABULA, each cluster is characterized by specific climatic zone, building size and construction period. The building typology can be effectively applied to develop bottom-up energy models, by taking the advantage to scale 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 (Ballarini and Corrado, 2017), to assess effective energy saving potentials, and to develop reliable refurbishment scenarios of the stock (Corrado and Ballarini, 2016). Three building-types of the Italian residential building typology have been selected: single-family house (SFH), multi-family house (MFH) and apartment block (AB), all belonging to the climatic zone of Milan (zone E, 2100 < HDD ≤ 3000) and to the construction period 1946–1960. These buildings have been chosen as they present the highest energy saving potential among the building-types of the Italian residential building typology. The main geometric and thermo-physical features of the building-types are shown in Table 2. The

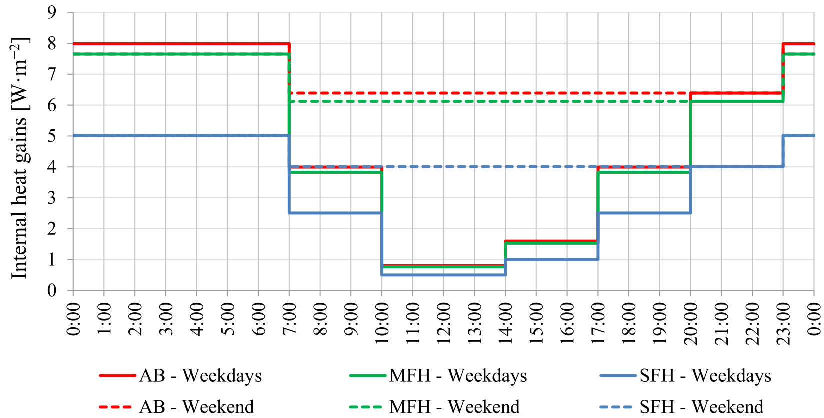


Fig. 2. Hourly profile of the internal heat gains per unit of net floor area.

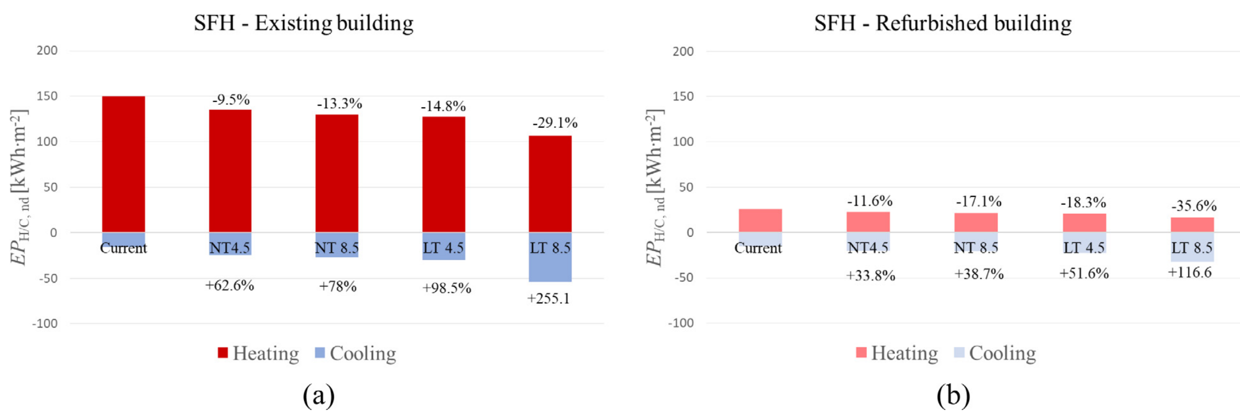


Fig. 3. Thermal energy need for heating and cooling normalized by the conditioned floor area for single-family house (SFH) existing building (a) and after refurbishment (b) under different future scenarios in Milan.

building sizes cover a significant range of shape factors (A_{env}/Vgr) and window-to-wall ratios (WWR).

The buildings have uninsulated envelope components, as the construction period predates the first Italian law on energy savings issued in 1976. The opaque external wall is a solid brick masonry, while the horizontal envelope components are reinforced brick-concrete slabs. The transparent envelope components are single-glazing and wood-frame windows with exterior wooden Venetian blinds.

3.1.2. Refurbished buildings

To assess the impact of climate changes in case of refurbished buildings, an insulated fabric of the existing buildings has been assumed. For the three building-types described in Section 3.1.1, the insulation level of the envelope components was set as to match with the U-values of the reference building currently adopted to verify compliance with the nearly zero-energy building (NZEB) requirements in Italy. For each envelope component, in accordance with the Italian Interministerial Decree June 26th, 2015 (Italian Republic, Interministerial Decree of June 26th, 2015), the U-values of the reference building are listed in Table 3 for the climatic zone of Milan. Whereas the replacement of the existing windows has been assumed, no modification of the solar shading devices has been considered, because of the already high performance of the existing devices ($g_{gl+sh} = 0.12$).

Since the energy efficiency increase due to the refurbishment actions might differ in the future from that hypothesized in the present, the assumption to adopt the current reference U-values of the Italian NZEB can be considered a reasonable starting point to carry out the analysis.

Table 3
Thermal transmittance values of the building envelope components assumed for the refurbished buildings in Milan Italian Republic, Interministerial Decree of June 26th (2015).

Building envelope component	U-value [W m^{-2} K^{-1}]
External wall	0.26
Upper floor (roof)	0.22
Bottom floor	0.26
Windows	1.40

3.2. Boundary conditions and simulation

The buildings have been simulated using dynamic simulation engine Energy Plus (Energyplus 9.0.1) for all future scenarios. The energy performance of the building-types was assessed considering a standard user behaviour. Hourly profiles of internal heat gains and ventilation airflow rates were set up under the Italian National Annex draft of the EN 16798-1 technical standard Comitato Termotecnico Italiano (2020). An example of the hourly profile is shown in Fig. 2 for the internal heat gains of each building-type; the heat gains take into account occupants, electric lighting and appliances, and follow a typical residential hourly occupancy profile. The variability of the heat gains among the building-types is due to a different occupancy density in the building unit, as specified in EN 16798-1.

Standard energy assessment considering continuous operation mode of technical building systems has been adopted according to Italian legislation (Italian Republic, Interministerial Decree of June 26th, 2015) to verify compliance with the minimum

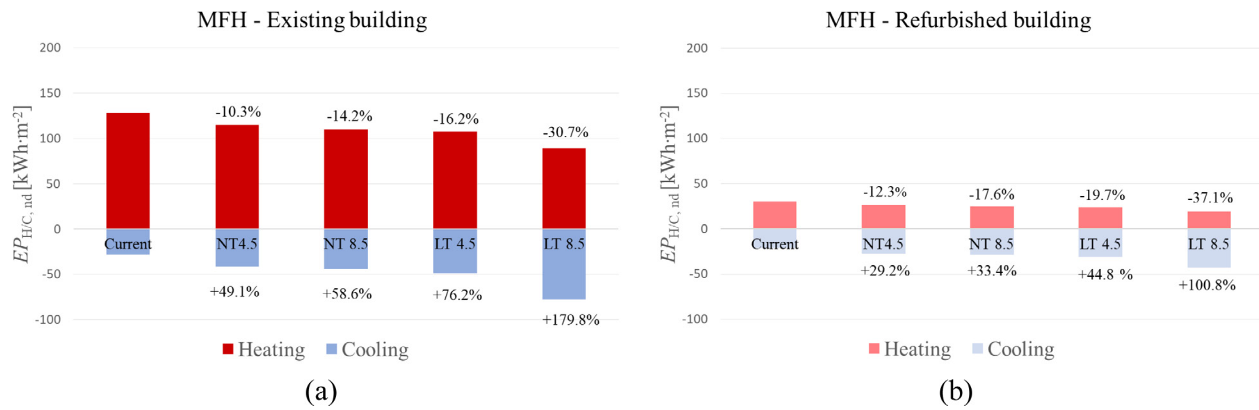


Fig. 4. Thermal energy need for heating and cooling normalized by the conditioned floor area for multi-family house (MFH) existing building (a) and after refurbishment (b) under different future scenarios in Milan.

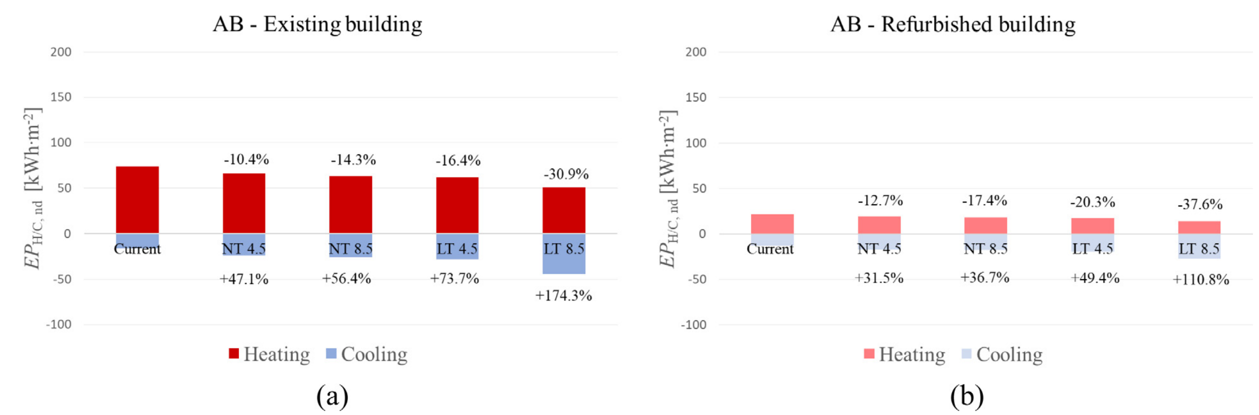


Fig. 5. Thermal energy need for heating and cooling normalized by the conditioned floor area for apartment block (AB) existing building (a) and after refurbishment (b) under different future scenarios in Milan.

energy performance requirements. Heating and cooling temperatures set-points were assumed equal to 20 °C and 26 °C, respectively. The heating period was set between October 15th till April 15th as indicated in UNI/TS 11300-1 for climatic zone E and fixed by the Italian energy regulations. The cooling period was assumed from April 16th till October 14th. To carry out the energy simulation, the blinds are considered under operation if beam *plus* diffuse solar irradiance incident on the window exceeds 300 W/m^2 Ente Italiano di Normazione, UNI/TS 11300-1, 2014.

4. Results and discussion

The results obtained from the simulations of the selected building types are shown in Figs. 3 to 11 and in Tables 4 and 5.

Figs. 3a to 5a, which refer to the buildings before refurbishment, indicate that the thermal energy need for heating ($EP_{H,nd}$) decreases up to 29% for SFH and up to 31% for MFH and AB. On the opposite, when the thermal energy need for cooling ($EP_{C,nd}$) is compared to the base scenario, increases up to 255% for SFH, 180% for MFH, and 174% for AB, are obtained. As regards the refurbished buildings, which are represented through Figs. 3b to 5b, the thermal energy need for heating ($EP_{H,nd}$) decreases up to 36% for SFH and up to 38% for MFH and AB. On the contrary, the thermal energy need for cooling ($EP_{C,nd}$) increases till 117% for SFH, 101% for MFH, and 111% for AB. The comparison between the thermal energy needs for heating and cooling before and after refurbishment shows that the relative variations of $EP_{H,nd}$ due to climate change increase after refurbishment for the same building while changes of $EP_{C,nd}$ decrease. This is due to the positive effect of the insulation when a cooling system is considered. In addition, the thermal energy need for cooling in SFH – especially before refurbishment of the building – is found to be more sensitive to climate change. This result is due to the fact that SFH has a higher shape factor in comparison with MFH and AB, which means it has a larger surface area in proportion to its volume and will be more sensitive to the warming weather. It is also important to indicate that relative changes in cooling demand for either existing or refurbished buildings in all case studies are more dramatic in comparison with variation in their heating demand, and this can be associated with their lower cooling energy use in the present days.

Figs. 6 to 8 present the breakdown of the adaptive comfort analysis. The graphs show the distribution of hours of the cooling period (April 16th till October 14th — 4368 h) in three ranges: comfort, warm discomfort, and cold discomfort. Figs. 6a to 8a refer to the buildings before refurbishment and Figs. 6b to 8b represent buildings after refurbishment. Results report that for all analysed cases before refurbishment, occupants will experience overheating up to 50% of the times by the mid-century (NT), and up to 80% of the times by the end of the century (LT). The overheating hours after refurbishment for the same building types reach 79% of the times by the mid-century (NT), and 92% of the times by the end of the century (LT). It is apparent that for all the scenarios and case studies, the period of warm discomfort increases due to climate change. This issue is more significant for buildings after refurbishment due to the negative effect of insulation that causes heat trap in the buildings in a free-floating regime. This trend can be also revealed from Figs. 9 to 11, which present the hourly operative temperature in the upper floor of the analysed buildings in free floating condition, for the second

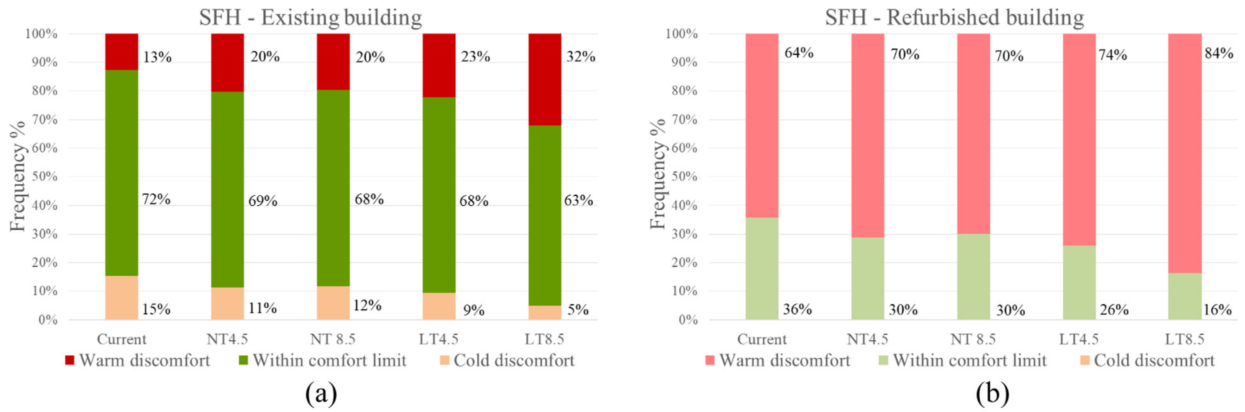


Fig. 6. Adaptive comfort analysis for single-family house (SFH) existing building (a) and after refurbishment (b) under different future scenarios in Milan.

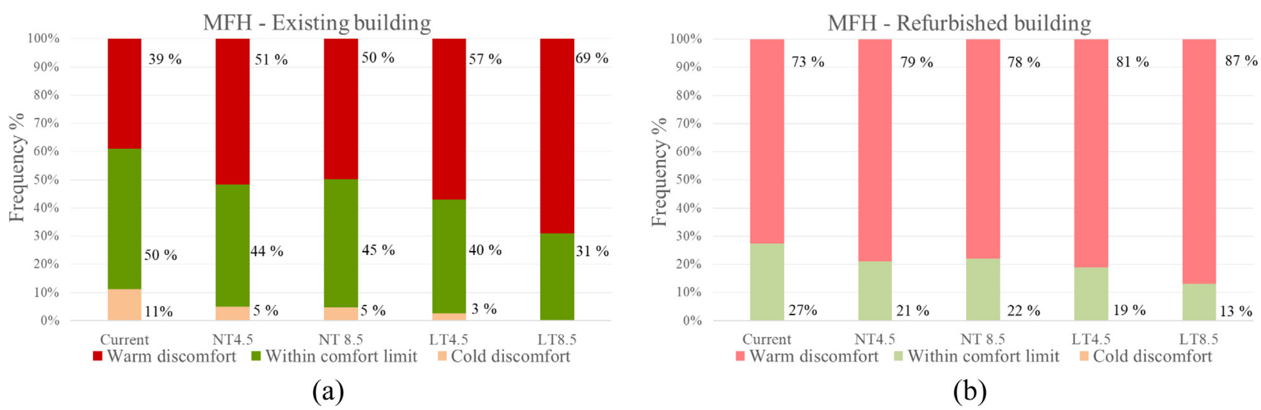


Fig. 7. Adaptive comfort analysis for multi-family house (MFH) existing building (a) and after refurbishment (b) under different future scenarios in Milan.

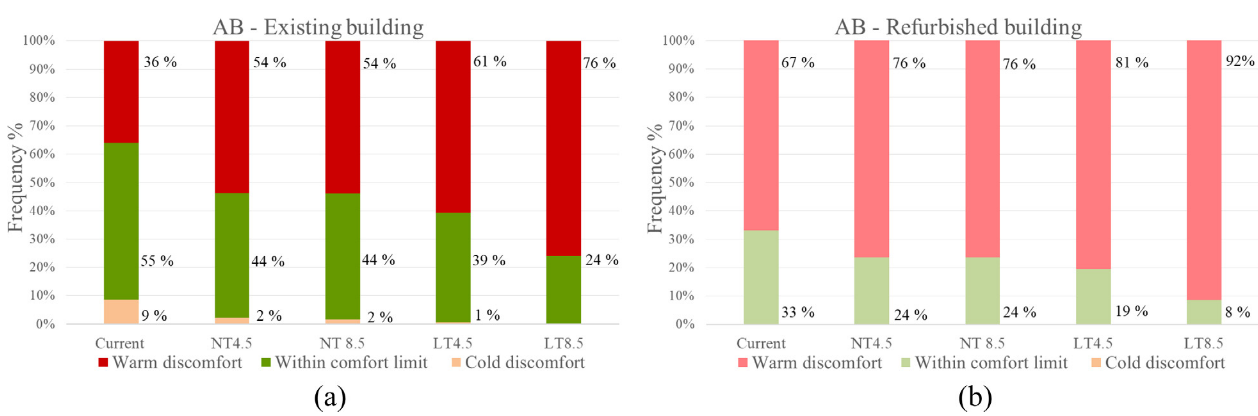


Fig. 8. Adaptive comfort analysis for apartment block (AB) existing building (a) and after refurbishment (b) under different future scenarios in Milan.

week of May under different future scenarios. By comparing the hourly temperature profile for after refurbishment (Figs. 9b to 11b) and existing buildings (Figs. 9a to 11a), although the changes in temperature is steadier after refurbishment, its average value is higher. In addition, MFH and AB are found to be more sensitive to overheating risk and the reason is that MFH and AB buildings have larger windows in comparison to SFH, as their *WWR* is higher (see also Table 2). Likewise, this issue can be seen in the hourly temperature profiles (Figs. 9 to 11). As an example, for the worst case scenario (LT 8.5) after refurbishment, temperatures of the upper floor reach up to 31 °C for MFH and AB while they reach up to 29 °C for SFH. Besides, hours of exceedance (*HE*) for all the scenarios are presented in Tables 4 and 5. It can be seen that although *HE* increase after refurbishment, as mentioned earlier, the relative change in *HE* due to climate change for buildings will be less compared to buildings before refurbishment.

Tables 4 and 5 also provide the results of the overall energy performance calculation. The analysis of this factor is crucial for the interpretation of the energy usage of case studies under the impact of global warming. Before refurbishment, the EP_{gl} increases for MFH and AB in all scenarios. However, the degree of change is not so significant, except for the pessimistic scenario (LT.8.5). This illustrates that the reduction in the energy for winter conditioning outweighs the cooling demand, which results in a slight alteration of the final total energy for the building. The reason is that the analysis has been done for a city in the Italian

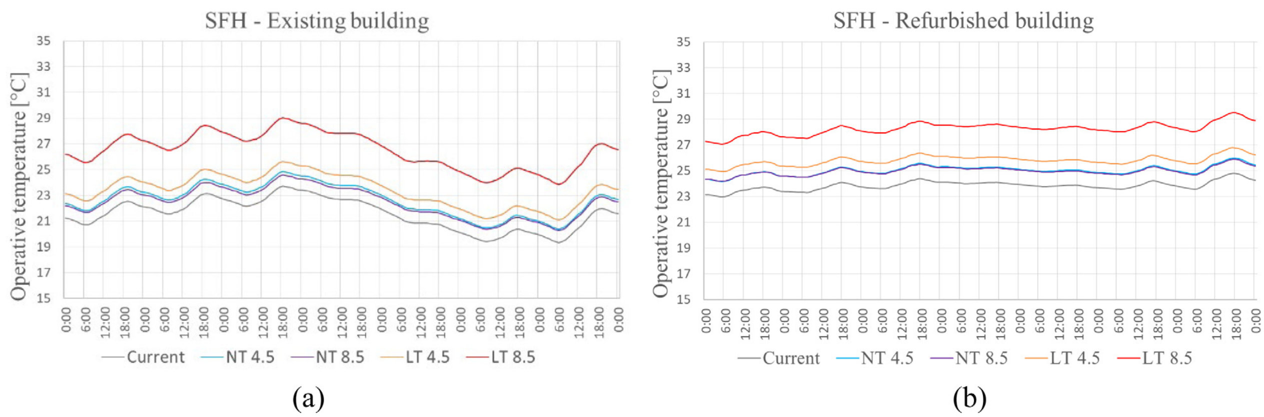


Fig. 9. Hourly operative temperature in the upper floor of single-family house (SFH) existing building (a) and after refurbishment (b), for the second week of May under different future scenarios in Milan.

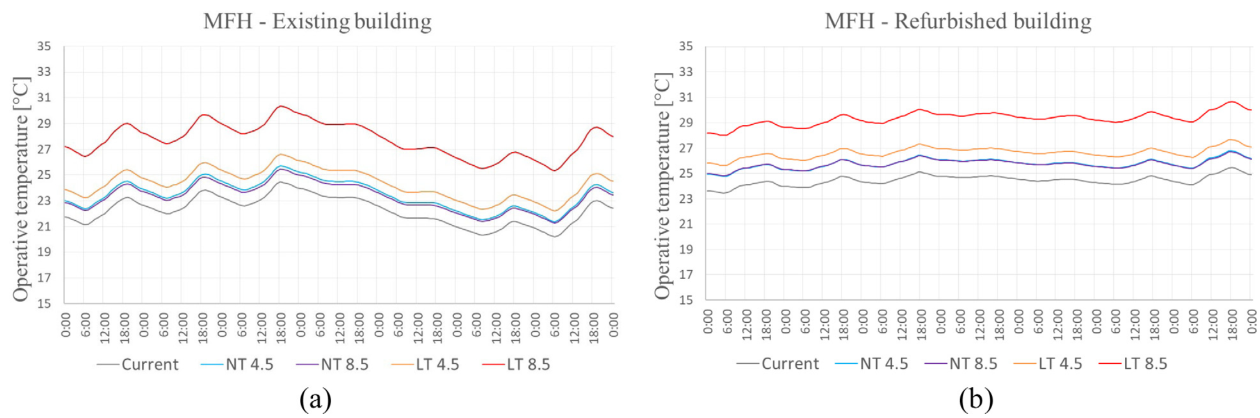


Fig. 10. Hourly operative temperature in the upper floor of multi-family house (MFH) existing building (a) and after refurbishment (b), for the second week of May under different future scenarios in Milan.

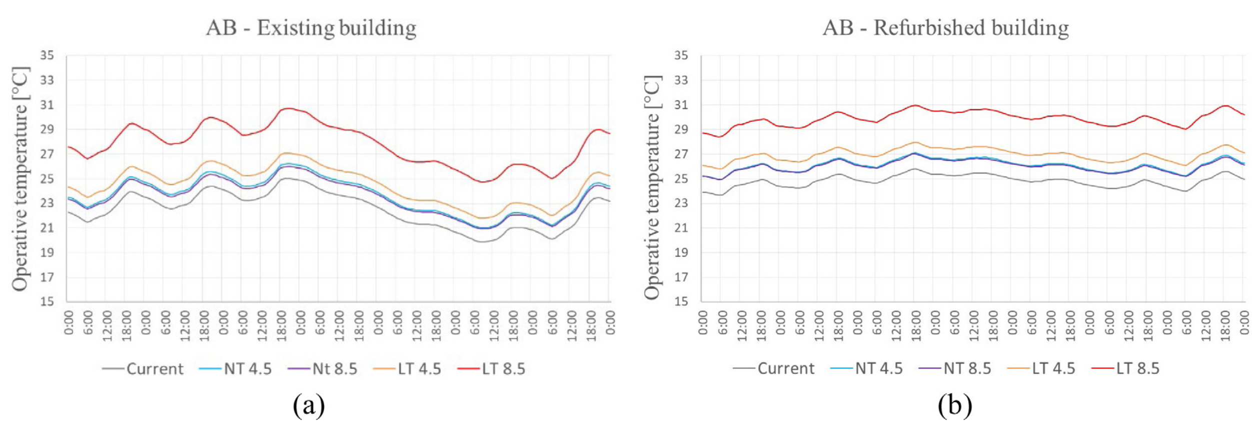


Fig. 11. Hourly operative temperature in the upper floor of apartment block (AB) existing building (a) and after refurbishment (b), for the second week of May under different future scenarios in Milan.

middle climatic zone, having HDDs from 2100 to 3000, in which the energy usage of the building is more biased towards heating. Besides, it is also important to consider that electricity has a higher primary energy factor than natural gas. Nonetheless, the EP_{gl} for SFH in all scenarios decreases except the LT.8.5. This is associated with the higher shape factor of SFH, which skews the energy usage of it more towards the heating regime. It results in a very limited decrease in the total primary energy.

After refurbishment, the EP_{gl} increases for all the building types in all scenarios, and the degree of change is significant. Besides, the relative changes of EP_{gl} for refurbished buildings are higher comparing to existing buildings. As an example, in the pessimistic scenario (LT.8.5), the relative change of EP_{gl} for SFH before refurbishment is equal to 9.1%, while after refurbishment it reaches 70%. The reason is that the heating demand is not dominant any more for any case study after the refurbishment. In other words, these results show that the effect of refurbishment on EP_{gl} will reduce due to climate change.

Overall, comparing $EP_{H,nd}$, $EP_{C,nd}$, EP_{gl}, and *HE* of all building types, for the near-term period scenarios presents a slight difference between RCP 4.5 and 8.5, while changes become more

Table 4
Overall energy performance and hours of exceedance for SFH, MFH and AB, existing buildings under different scenarios in Milan.

		Base	NT-RCP 4.5		NT-RCP 8.5		LT-RCP 4.5		LT-RCP 8.5	
				Relative change		Relative change		Relative change		Relative change
SFH	EP_{gl} [kWh m^{-2}]	219	213	*−2.5%*	210	*−3.9%*	214	*−2.4%*	239	*9.1%*
	HE [h]	550	884	*60.6%*	884	*60.6%*	965	*75.2%*	1405	*155.3%*
MFH	EP_{gl} [kWh m^{-2}]	202	205	*1.7%*	204	*1.4%*	211	*4.9%*	258	*28%*
	HE [h]	1709	2228	*30.4%*	2184	*27.8%*	2490	*45.7%*	3014	*76.4%*
AB	EP_{gl} [kWh m^{-2}]	116	118	*1.5%*	117	*1.2%*	121	*4.5%*	147	*26.9%*
	HE [h]	1571	2346	*49.3%*	2346	*49.3%*	2650	*68.7%*	3315	*111%*

Table 5
Overall energy performance and hours of exceedance for SFH, MFH and AB, after refurbishment under different scenarios in Milan.

		Base	NT-RCP 4.5		NT-RCP 8.5		LT-RCP 4.5		LT-RCP 8.5	
				Relative change		Relative change		Relative change		Relative change
SFH	EP_{gl} [kWh m^{-2}]	49.1	54.8	*11.6%*	55.5	*13.1%*	59.9	*22%*	83.6	*70.2%*
	HE [h]	2808	3057	*8.8%*	3057	*8.8%*	3232	*15.1%*	3652	*30%*
MFH	EP_{gl} [kWh m^{-2}]	60.9	68.8	*13%*	70.1	*15.2%*	75.7	*24.3%*	107.2	*76.1%*
	HE [h]	3172	3442	*8.5%*	3442	*8.5%*	3538	*11.5%*	3798	*19.7%*
AB	EP_{gl} [kWh m^{-2}]	42	46	*9.6%*	46.7	*11.2%*	49.8	*18.6%*	68.1	*62.6%*
	HE [h]	2917	3338	*14.4%*	3338	*14.4%*	3518	*20.6%*	3997	*37%*

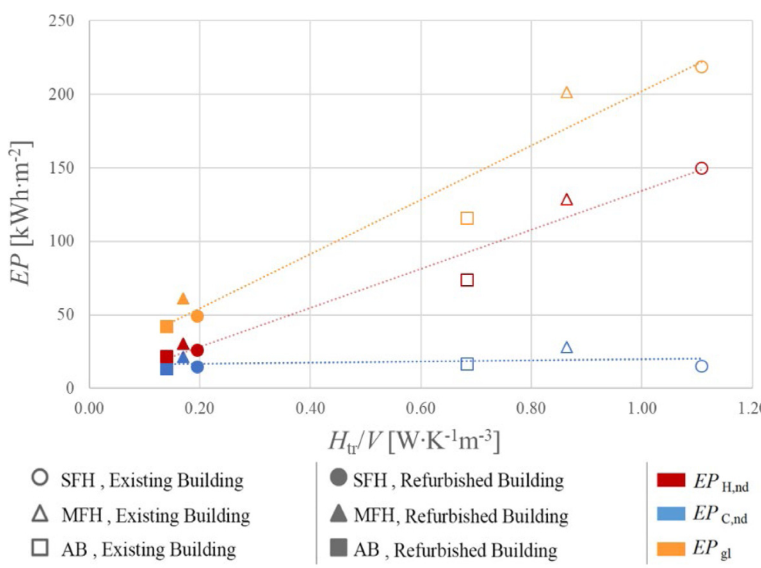


Fig. 12. Energy Performance (*EP*) vs. H_{tr}/V.

significant considering the long-term period. This finding represents that the effect of climate change on the Italian residential buildings from 2026 till 2045 does not alter a lot whether the CO_2 emission level stabilized or continue to grow. As an example, warm discomfort hours for all the case studies are almost the same in both NT scenarios, anhed thermal energy need for cooling differs up to 2 kWh/m^2. Although climate change exacerbates the performance of the buildings even in NT period, the impact of reducing the emission levels will be significant for the long-term period assessment.

Finally, in order to generalize the results for different building types and insulation levels, a new parameter was introduced to express the outdoor temperature sensitivity of the building, expressed as the ratio of the overall transmission heat transfer coefficient (H_{tr}) to the gross conditioned volume (V). H_{tr} is calculated according to the EN ISO 13789 standard (CEN. EN ISO 13789, 2017), as in Eq. (4):

$$H_{tr} = H_D + H_g + H_U + H_A = \sum_i b_i \cdot A_i \cdot U_i + \sum_k b_k \cdot l_k \cdot \psi_k \quad (4)$$

where, H_D is the direct heat transfer coefficient between the heated or cooled space and the exterior through the building envelope, H_g is the steady-state ground heat transfer coefficient, H_U is the transmission heat transfer coefficient through unconditioned spaces, and H_A is the transmission heat transfer coefficient to adjacent buildings. For each ith component, b_i is the adjustment factor for the temperature difference, A_i is the area, and U_i is the thermal transmittance. For each kth linear thermal bridge, b_k is the adjustment factor for the temperature difference, l_k is the length of the linear thermal bridge, and ψ_k is the linear thermal transmittance.

In Fig. 12, the relation between $EP_{H,nd}$, $EP_{C,nd}$, and EP_{gl} versus H_{tr}/V is presented. As can be seen from the trend lines, all three energy performance indicators increase when H_{tr}/V grows. This trend is significantly slighter for $EP_{C,nd}$ as the refurbishment in this study is applied by merely increasing the insulation level of the envelope, which makes it less effective on thermal energy need for cooling. In Figs. 13 and 14, the relation between the variation of all three energy performance indicators versus H_{tr}/V for NT (2021–2040) and LT (2081–2099) periods based on RCP

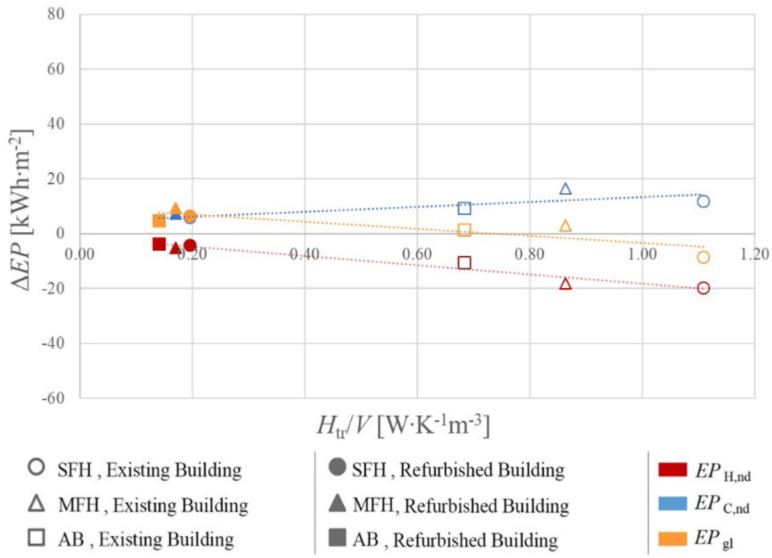


Fig. 13. *EP* variation vs. H_{tr}/V for NT (2021–2040) RCP 8.5 scenario.

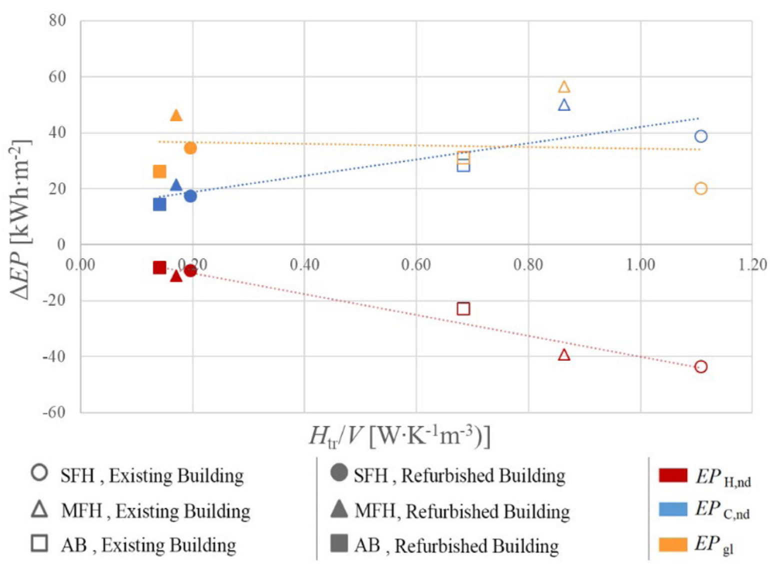


Fig. 14. *EP* variation vs. H_{tr}/V for LT (2081–2099) RCP 8.5 scenario.

8.5 scenario are presented. RCP 8.5 scenario is selected as there is evidence that it is already late for more optimistic scenarios, so RCP 8.5 is the most probable scenario. Results show a decrease in $EP_{H,nd}$ and an increase in $EP_{C,nd}$ in both time periods. These changes are slighter in NT (2021–2040) period and greater in LT (2081–2099) period expectedly. In addition, EP_{gl} decreases with the slightest variation in both time periods. In other words, the sensitivity of EP_{gl} variations to the outdoor temperature after climate change is less than the other two indicators' variations.

A general consideration is that the EP_{gl} variation after climate change mainly depends on the outdoor temperature sensitivity of the building and on the heating to cooling need ratio that, in turn, is a function of the outdoor temperature sensitivity. Consistently with this consideration, the performed analysis confirms that the EP_{gl} is not biased towards heating after refurbishment. In addition, the most striking result to emerge is that after refurbishment the effect of building typology on the energy performance, and also its variations due to climate change, will significantly decrease.

5. Conclusions

This study sets out to analyse the impacts of climate change on Italian residential buildings' performance. While the changes in energy need pattern are well studied, the impacts of future scenarios on the Italian building stock, on a regional scale is neglected. To fill this gap, three representative building-types of the existing residential building stock were simulated under two future scenarios (RCP 4.5 and RCP 8.5) for the city of Milan (representative of the Middle Climatic zone). In addition, the effect of adding insulation level of the envelopes in all these conditions is analysed to incorporate the influence that the refurbishment has on the future performance of buildings, especially considering the measures that are commonly applied in the country. This analysis lays the foundation for future actions towards the resiliency of the built environment. To quantify and better present the impact of climate change, even considering the significant long-life span of buildings in Italy, both near-term (2026–2045) and long-term (2080–2099) periods were assessed.

For different residential building-types, the results clearly show that there is a drastic rise in cooling energy use and a moderate decrease in heating energy use, as expected. The cooling and heating demand is demonstrated to change from 47.1% (AB) to 255% (SFH) and from −9.5% (SFH) to −31% (AB), respectively in existing buildings. For refurbished buildings, the changes in the cooling demand varies between 29% (MFH) to 117% (SFH), and in the heating demand varies between −12% (SFH) to −38% (AB). In addition, the overheating risk for existing buildings increases significantly, as the warm discomfort hours raise between almost 30% (MFH) to 155% (SFH). After refurbishment, this increase varies between 8.5% (MFH) to 37% (AB). Likewise, it is shown that the overall energy performance for different scenarios changes from −3.9% (SFH) to 28% (MFH) for the existing and between 9.6% (AB) to 76% (MFH) for refurbished buildings. It was also concluded that buildings with higher shape factor are more sensitive to climate change and this sensitivity is reduced by applying refurbishment. However, it is crucial to point out that the effect of refurbishment – despite being always positive – reduces in future compared to current situation. This illustrates the need to consider climate change for re-identifying refurbishment actions. Besides, it was confirmed that the effect of different scenarios on the Italian residential buildings is more severe in the long term. Therefore, the climate change impact magnitude is not equal for different future weather scenarios and case studies, so that in a changing climate, it becomes absolutely necessary to perform a regional and localized analysis. These findings point out the urgent need to establish building adaptation measures for climate change.

In future works, it is suggested to also analyse the representative building-types for other climate zones of Italy, like Mediterranean Zone (having up to 2100 heating degree-days), in order to reach a more holistic overview of the impact of climate change on the residential buildings in the region.

CRediT authorship contribution statement

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

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.

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