Climate change impact on the future performance of Nearly Zero Energy Buildings:
A case study base analysis

Mamak P.Tootkaboni, Giovanna De Luca, Ilaria Ballarini, Vincenzo Corrado
Politecnico di Torino, Turin, Italy

Abstract

Considering buildings large share of Europe's final energy consumption and CO_2 emissions, the concept of nearly zero-energy building (NZEB) has received considerable attention. However, the changes in the performance of an NZEB due to climate change has not been studied sufficiently. This paper investigates the effects of climate change on the energy performance of NZEBs in different climatic zones in Italy, for the mid-term (2050s) and the long-term (2080s) periods. The results indicate that climate change affects the energy balance of the NZEBs, while the extent varies among different climatic regions and time periods.

Key Innovations

- Contributing to the adaptation of NZEBs toward future needs coming from the inexorable trend of climate change.
- Verifying the importance of regional scale analysis for providing adaptation measures.
- Analysing the resilience of NZEBs on the road to become truly sustainable.

Practical Implications

Considering the issue of climate change is vital in building energy performance assessment. It is suggested to always perform such evaluation on regional scale. In addition, according to the long-life span of the buildings, analysis for different time periods is necessary.

Introduction

Effects of climate change on the building stock and on NZEBs

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850 (IPCC, 2014). The current pattern in the greenhouse gas emissions will lead to a 2,6-4,8 degrees Celsius (°C) increase in the global average temperature by the end of the 21st century (Collins et al., 2013). The most prominent target currently discussed is the 2 °C temperature target, that is, to limit global temperature increase relative to pre-industrial times to below 2 °C. By the way, even if we stop emissions today, much of the warming would persist for centuries (Symon, 2013). There are several impacts and risks associated with climate change, such as creating new or exacerbating natural hazards, provoking human discomfort, and causing negative consequences on human health (IPCC, 2018).

The largest driver of climate change is the emission of greenhouse gases, of which more than 90% are Carbon dioxide (CO_2) and Methane. Considering that the building sector contributes to 32% of global energy consumption − as the main driver of GHG emissions − its impact on intensifying climate change is undeniable (Lucon et al., 2014). Furthermore, buildings are not only responsible for climate change. Likewise, they are extremely affected by it in several ways considering their long-life span. Some of these impacts are the changes in building energy performance, thermal comfort conditions, and the grid interactions (Chai, 2019). For instance, the studies of Li et al. (2012) identified an estimated increase up to 24,2% in cooling energy demand of office buildings in five major representative cities in China, and consequently a shift towards more electricity demand. Besides, many studies revealed that an increase of the energy need for space cooling may happen even in existing energy efficient dwellings due to high insulation level. As an example, Murano et al. (2017) proved that the energy efficiency requirements determine an imbalance of opposite energy demands. Although reducing the heating energy need improves the energy performance of buildings, an increase of the cooling energy need occurs. In another article, Sameni et al. (2015) discussed that the standard of Passivhaus dwellings in the UK may provide thermal discomfort condition during cooling seasons. Therefore, the study of climate change effects in energy efficient buildings becomes more relevant compared to other traditional (scarcely insulated) ones. A recent study by Attia et al. (2015) analysed a Belgian reference case of nearly zero-energy building (NZEB), and a remarkable presence of overheating (up to +43,5% by the end of century) was demonstrated. In the same vein, a study by Summa et al. (2020) shows that a residential nearly zero-energy building located in Rome may meet an increase of 18% in the annual power consumption by 2050, due to protracted activation of the air conditioning system and enhanced peak power requirements. Consequently, energy efficient buildings like NZEBs – as efforts to reduce the contribution of the building sector on climate change – are also impacted by climate change like all building types in the same ways mentioned above. In the following section, the associated energy performance requirements, and the key targets of NZEBs are explained in more detail.

Energy performance requirements of NZEBs

According to Directive 2010/31/EU of the European Parliament (2010), 'nearly zero-energy building' means a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

As reported by the international standards, four classes of requirements are proposed for NZEBs: a) energy needs (building fabric), b) total (renewable + non-renewable) primary energy use, c) non-renewable primary energy use (without compensation between energy carriers), and d) non-renewable primary energy use (with compensation between energy carriers) (European Committee for Standardisation, 2017a). In addition, it is desirable that indicators for partial EP requirements related fabric and HVAC systems features are added in order to avoid performance unbalance between different systems and components of the building.

According to the Italian legislation, three main energy performance requirements are provided, namely the annual energy needs for space heating ($EP_{H,nd}$) and space cooling ($EP_{C,nd}$), and the overall annual total primary energy ($EP_{gl,tot}$), including space heating, space cooling, domestic hot water, mechanical ventilation, lighting, and transportation (the last two energy services only for non-residential buildings). The reference values of the performance indicators are obtained through the notional reference building approach (European Committee for Standardisation, 2017b). Strict requirements are also provided for renewable energy ratio, namely for domestic hot water (RER_W), and for heating, cooling, and domestic hot water (RER_{H+C+W}), respectively.

Electrical energy produced by PV system is allocated to different services (heating, cooling, DHW) according to their respective demands. The surplus energy, which includes exported energy and energy for non-EP uses (e.g., electrical appliances), is calculated on a monthly basis and is not accounted for in the EP assessment. Finally, partial requirements related to fabric include the envelope average U-value, the ratio of the envelope effective solar area to the floor area, thermal and solar properties of single envelope components. Specific requirements on the efficiency of generators and of other HVAC equipment are also provided.

Aim of the research

The performance of NZEBs in the future has not yet been investigated sufficiently. The climate is changing and the compliance with NZEB requirements may not be a guarantee of energy performance and indoor environmental quality. Considering the long-life span of buildings, the performance of NZEBs should be analysed using future weather data, to ensure energy efficiency, sustainability, and climate resilience over time.

This paper investigates the effects of climate changes on energy performance of a nearly zero-energy building in different climatic zones in Italy: Milan (2404 HDD), Rome (1415 HDD) and Palermo (751 HDD). The study is carried out by analysing the NZEB requirements under different scenarios. "Representative Concentration Pathways (RCPs)" 8,5 (business as usual) of emission, and concentration scenarios according to the fifth assessment report of the Intergovernmental Panel on Climate Change (Symon, 2013), have been applied in this study. Dynamically downscaled future hourly weather data from the regional climate models (GERICS-REMO 2015) are used in this work to create future typical metrological year (TMY). Energy simulations are carried out using EnergyPlus for the mid-term (from 2041 to 2060) and long term (from 2081 to 2100) periods.

Materials and Methods

Generation of future weather data

Global Climate Models (GCMs) are mathematical models for forecasting climate change. GCMs provide climate information on a global scale with a spatial resolution of 150–600 km^2 (Symon, 2013). Therefore, they cannot be used for building energy simulation, as 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 downscaling approaches is the dynamical method, which uses regional climate models (RCMs) to derive finer spatial and temporal climate information. This allows RCM to better represent the spatial and temporal variability of local climate and guarantee physically consistent datasets (Soares et al., 2012).

In this study, the utilized regional climate model is GERICS-REMO-2015 for which the data were downloaded from the EURO-CORDEX entry point through the Earth System Grid Federation (ESGF) for the Europe domain on a 0,11° grid, in rotative coordinates (equivalent to a 12,5 km grid). The available format for these data is NetCDF4, which is a file format for storing multidimensional scientific data.

The extraction of the data for the case-studies (cites of Milan, Rome and Palermo) was performed through the Cordex Data Extractor software, that allows finding the closest data point on the grid to the desired latitude and longitude. The RCP 8,5 scenario was adapted to extract these data for the 2041-2060 (2050s) and 2081-2100 (2080s) periods. MPI-M-MPI-ESM-LR is the driving model of this study since it is well-supported according to the IPCC report on Evaluation of climate models (Flato, Gregory, et al., 2014).

The methodology of the EN ISO 15927-4 (2005) standard was used, aiming to create future typical meteorological year out of the 20 years extracted data. Indeed, this international standard covers the selection of appropriate meteorological data for the assessment of the long term mean energy use for heating and cooling. TMY is constructed from 12 representative months (Best Months) from multi-year records. Best months are selected through the comparison of the Cumulative Distribution Function of the single and reference years, through the Finkelstein-Schafer (FS) statistics (Finkelstein & Schafer, 1971). This method was used in this study since the criteria for

selecting the 'best month' is not merely limited to dry-bulb air temperature, and it also takes global solar irradiance, relative humidity, and wind speed into account. In Figure 1, the box plots of outdoor air-dry bulb temperature for Milan, Rome, and Palermo TMYs in 2020, 2050 and 2080, are presented.
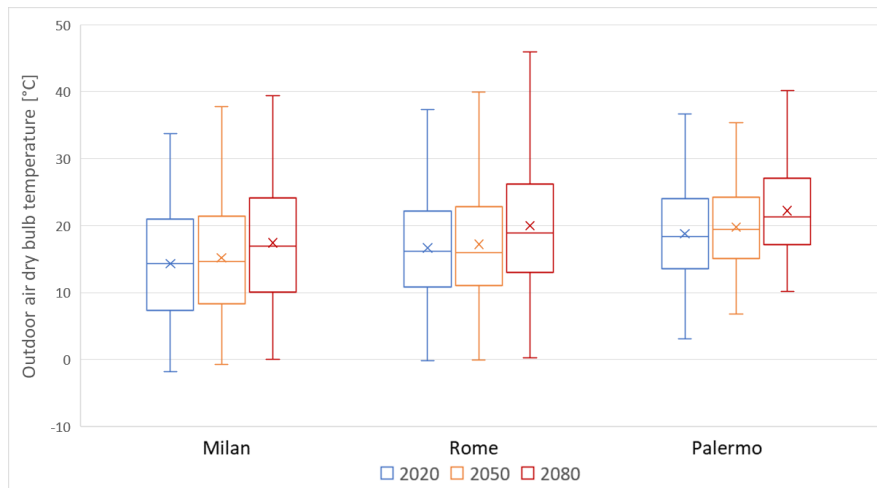

Figure 1: Box plot of outdoor air-dry bulb temperature for Milan, Rome, and Palermo in 2020, 2050 and 2080.

Performance indicators

The building energy performance indicators assessed in the present work are the annual energy needs for space heating and space cooling ($EP_{H,nd}$ and $EP_{C,nd}$, respectively), the overall annual total primary energy ($EP_{gl,tot}$), which includes space heating, space cooling and domestic hot water, the mean seasonal coefficient of performance (COP_m) and the mean seasonal energy efficiency ratio (EER_m) of the heat generators, and the renewable energy ratio (RER), under different climate change scenarios. The indicators refer to the NZEB requirements, as defined by the Italian energy regulations.

The performance indicators are assessed through detailed dynamic simulation using EnergyPlus. The primary energy conversion factors of the energy carriers applied in this study are those provided by the Italian Interministerial Decree (Inter.D.) of June 26th, 2015 (Italian Republic, 2015). Specifically, the total primary energy conversion factor of electricity from grid amounts to 2,42, split into non-renewable (1,95) and renewable (0,47) parts.

Case study

The analysis has been carried out assuming as a case study the "Vivaldi House" (Figure 2), described in the EN 12831:2003 standard (European Committee for Standardisation, 2003). The "Vivaldi House" is a residential building with one conditioned storey above ground and an unconditioned basement. The attic and the staircase are unconditioned too. The basement hosts the cellar and the garage, and a conditioned hobby room. The West-oriented building facade is in adherence to another residential building. The conditioned storey is 0,5 m above ground; part of the storey is on a ventilated suspended floor. The main geometric data of the conditioned space are listed in Table 1.

The building is assumed to be located in three different Italian climatic zones, Milan, Rome and Palermo. The technologies adopted in the case study represent the most widespread passive solutions in Italy. The opaque envelope components are thermally insulated on the external side. The transparent envelope components are low-e triple glazing windows for the building in Milan, low-e double glazing windows for the building in Rome, and uncoated double-glazing windows for the building in Palermo. The South- and East-oriented windows are equipped with external movable solar shading devices.

With the aim to verify the NZEB requirements in Italy, the thermal transmittance of the envelope components was set in accordance with the reference building, as defined in the Inter.D. of June 26th, 2015 (Italian Republic, 2015). The thermal transmittance values are listed in Table 2, for each climatic zone.

The parameters of the solar shading devices were set such that the total solar energy transmittance value of the glazing *plus* shading system is equal to 0,35, in agreement with the Italian reference building approach (Italian Republic, 2015).

Figure 2: Geometric model of the case study.

Table 1: Geometric data of the case study.

Quantity	Value	Unit
Conditioned gross volume, V_g	396	[m³]
Conditioned net volume, V_n	278	[m³]
Conditioned net floor area, $A_{f,n}$	103	[m²]
Compactness ratio, $A_{envelope}/V_g$	0,99	[m⁻¹]
Windows area, A_{win}	15,2	[m²]
Window-to-wall ratio, WWR	0,15	[-]

Table 2: Thermal transmittance of the building envelope components of the NZEB in the analysed climatic zones.

Component	U-value [W·m⁻²K⁻¹]		
	Milan	Rome	Palermo
External wall	0,26	0,29	0,43
Roof	0,22	0,26	0,35
Floor	0,26	0,29	0,44
Window	1,40	1,80	3,00

Space heating and space cooling are provided through fan coil units. In design conditions, the supply water temperature is set to 55 °C and 7°C, for heating and cooling, respectively. The return water temperature is set to 40°C for heating and 12°C for cooling. The emission system is characterized by a continuous operation of the heating and cooling systems, considering 20 °C and 26 °C temperature set-points, respectively.

Heat (for space heating and domestic hot water) and cold are provided by an electrical reversible air-to-water heat pump with multi-stage compressor. The sizing of the heat pump is based on the heating peak load for Milan and on the cooling peak load for Rome and Palermo. In the heating mode, the design inlet air dry bulb temperature is 7 °C and the outlet water temperature is 55 °C. For Milan and Rome, the rated *COP* is equal to 2,90 and the rated heating power is equal to 5,5 kW. For Palermo, the rated *COP* is equal to 2,90 and the rated heating power is equal to 4 kW. In the cooling mode, the inlet air dry bulb temperature is 35 °C and the outlet water temperature is 7 °C. For Milan, the *EER* is equal to 3,33 and the rated cooling power is equal to 6,5 kW. For Rome and Palermo, the EER is equal to 2,9 and the nominal power for cooling is equal to 9 kW.

The domestic hot water delivery is set to 40°C. To meet the need for domestic hot water, a 100 l hot water storage tank, at a temperature of 55 °C, is considered.

The efficiency of the heating/cooling/DHW utilization (including emission, control, and distribution) subsystems was assumed equal to 0,81 in compliance with the Italian Inter.D. of June 26th, 2015 (Italian Republic, 2015).

The photovoltaic system (235 W peak power) with crystalline silicon modules, installed on the South-oriented roof pitch, was considered as well. The Eckstein (1990) model for crystalline PV modules was employed, in which the electricity production (current voltage) of the circuit is a function of the module temperature. Besides, the cell temperature of modules is computed based on an energy balance relative to NOCT (Nominal Operating Cell Temperature) conditions (Duffie and Beckman, 1991).

For the simulation, a standard user behaviour was assumed for the quantification of the internal heat gains and the airflow rates by natural ventilation, according to the Italian National Annex of EN 16798-1 (Italian Thermotechnical Committee, 2020).

Results and Discussion

A set of comparative analysis is performed on different NZEB requirements in three Italian climate zones for the mid-term (2050s) and long-term (2080s) period, for the selected case-study. The aim is to assess the impact of climate change on the future performance of NZEBs.

The annual energy needs for space heating and space cooling ($EP_{H,nd}$ and $EP_{C,nd}$, respectively) are represented in Figure 3. The results show decreases in $EP_{H,nd}$ from 7,1% up to 99,3% for all the cities and for both time periods compared to 2020 as the reference case. On the other hand, $EP_{C,nd}$, increases from 4,5% to 94,1%. A closer analysis of these data shows that the NZEB compliance of annual energy needs for space cooling is not met in future for either cities or time periods. However, the magnitude of variation is not equal in different scenarios. As an example, the maximum increase in the cooling demand (94,1%) is expected to occur in 2080s in Rome, while the maximum decrease in heating demand (99,3%) is likely to happen in Palermo by the same period. It is also important to indicate that NZEBs in Milan are the least sensitive to climate change, which is due to buildings' lower cooling energy use at present.
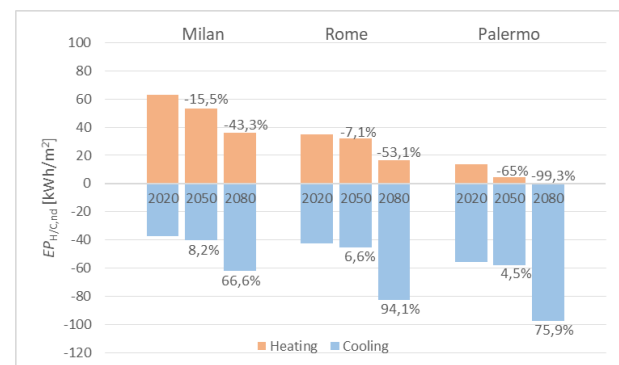

Figure 3: The annual energy needs for space heating and space cooling for Milan, Rome, and Palermo in 2020, 2050 and 2080.

The overall annual total primary energy ($EP_{gl,tot}$) is presented in the last set of columns in Figures 4, 5, and 6 for all cities. In addition, the splits of $EP_{gl,tot}$ for heating (H), domestic hot water (W), and cooling (C) are shown in the previous columns of the same Figures. It can be noticed that EP_H decreases, EP_w remains constant, and EP_C increases, regardless of the time period or the climatic zone. If we now turn into $EP_{gl,tot}$, it is seen that in 2050s it decreases for Milan and Palermo, while it increases for Rome. This is due to higher reduction of annual energy need for heating in 2050 for Milan and

Palermo. On the other hand, in 2080s $EP_{gl,tot}$ decreases for Milan and increases for Rome and Palermo. The change in Milan is slight (-1,9%), while for Rome and Palermo this change is more significant (36,3% and 45,6%, respectively). This is due to the fact that for Milan − unlike the two other cities − the energy for winter conditioning outweighs the cooling demand, which results in a slight alteration of the final total energy for the building in future. It can be concluded that in 2080s the NZEB compliance of $EP_{gl,tot}$ is not met for Rome and Palermo, while in 2050s it is not met only in case of Rome.

In Figures 4-6, the share of either non-renewable (EP_{nren}) or renewable (EP_{ren}) primary energy is also presented. The relative changes of these values are noted in Table 3 as well. EP_{nren} decreases for Milan and increases for Rome and Palermo for both periods. This might be associated with the dominance of the cooling energy need in Rome and Palermo, which leads to an increase in the electrical energy demand from grid. EP_{ren} in 2050s decreases for Milan and Palermo (4,2% and 8,8%, respectively) and slightly increases for Rome (1,2%). On the other hand, in 2080s, EP_{ren} increases for all cities. It can be suggested that by the end of century exploitation of renewable energy increases due to climate change.
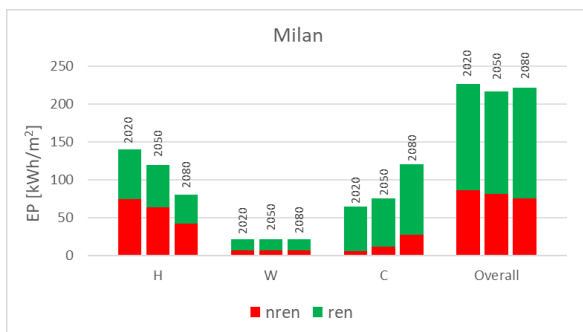

Figure 4: Annual primary energy for heating (H), domestic hot water (W), cooling (C), and overall, of the building in Milan, in 2020, 2050 and 2080.
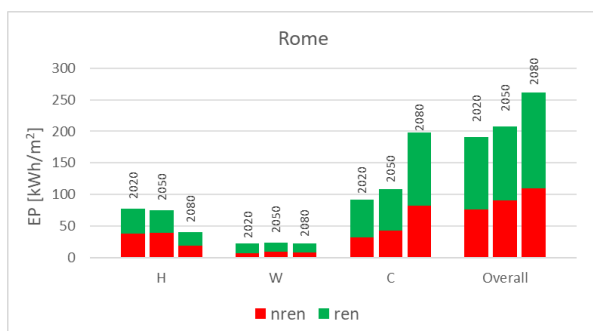

Figure 5: Annual primary energy for heating (H), domestic hot water (W), cooling (C), and overall, of the building in Rome, in 2020, 2050 and 2080.
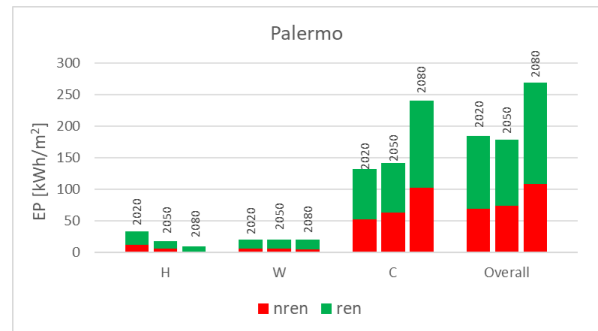

Figure 6: Annual primary energy for heating (H), domestic hot water (W), cooling (C), and overall, of the building in Palermo, in 2020, 2050 and 2080.

Table 3: Relative changes of non-renewable, renewable, and total primary energy for Milan, Rome, and Palermo, in 2050 and 2080 compared to 2020.

	Milan		*Rome*		*Palermo*	
	2050	*2080*	*2050*	*2080*	*2050*	*2080*
$EP_{gl,nren}$	−4,9%	−12,5%	19,2%	44,1%	5,8%	57,1%
$EP_{gl,ren}$	−4,2%	4,5%	1,2%	31,2%	−8,8%	38,7%
$EP_{gl,tot}$	−4,5%	−1,9%	8,3%	36,3%	−3,4%	45,6%

The annual delivered energy by each energy carrier (i.e., electricity from grid, on-site PV electricity, and on-site aerothermal energy), expressed by unit of conditioned net floor area, is shown in Figures 7, 8 and 9, for the building in Milan, Rome and Palermo, respectively. In addition, the PV surplus is shown in the last set of columns of the same Figures. The results show that the delivered energy decreases for heating, remains constant for domestic hot water, and increases for cooling for all the scenarios. Looking at the overall delivered energy it is apparent that electricity from grid increases in future for Rome and Palermo and decreases for Milan. The reason lies in the dominance of the heating energy need in Milan. The on-site aerothermal energy increases in all scenarios while this increase is more significant in 2080 and for Rome and Palermo. This comes from the fact that the higher outside temperature leads to more aerothermal energy extraction by the heat pump. Furthermore, the on-site PV electricity slightly decreases in all future scenarios. This may be associated with the reduction in the voltage that PVs can generate because of higher temperature. Besides, the amount of direct and diffuse radiation varies in the future due to the changes in cloud cover and atmospheric aerosol loadings. This leads to a lower efficiency of PVs. In addition, PV surplus decreases in every scenario (except in Palermo for 2050s) since not only the on-site PV electricity decreases, but also the electricity demand increases.
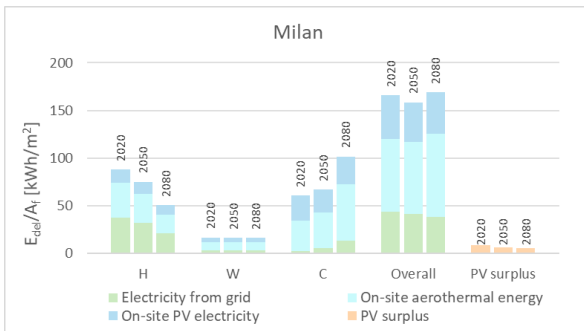
Figure 7: Annual delivered energy for heating (H), domestic hot water (W), cooling (C), overall, and PV surplus in Milan, in 2020, 2050 and 2080.
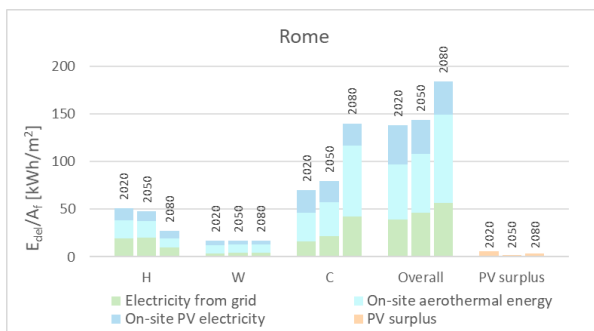

Figure 8: Annual delivered energy for heating (H), domestic hot water (W), cooling (C), overall, and PV surplus in Rome, in 2020, 2050 and 2080.
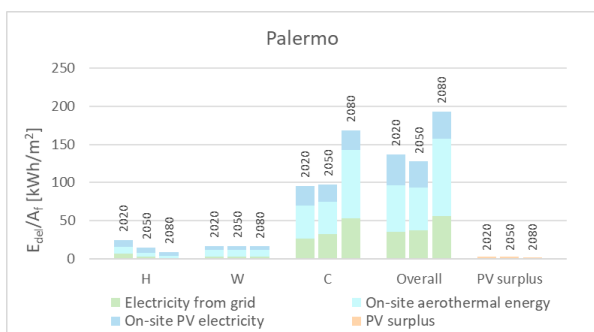

Figure 9: Annual delivered energy for heating (H), domestic hot water (W), cooling (C), overall, and PV surplus in Palermo, in 2020, 2050 and 2080.

Finally, in Table 4, the renewable energy ratio (RER_{H+W+C}), the mean seasonal coefficient of performance (COP_m), and the mean seasonal energy efficiency ratio (EER_m) are presented for each city in every period. In all scenarios, the compliance with the *RER* requirement for the NZEB is met (i.e. higher than 50%, according to the current Italian legislation). However, the changes in this value are not significant. In addition, COP_m increases for Rome and Palermo in all scenarios (except in Rome for 2050s), as the increase in temperature due to climate change makes the heat pump more efficient in winter. For Milan, the COP_m decreases in all scenarios because of the higher decrease in the heating load factor compared to the other two cities.

Besides, EER_m increases in all scenarios, except in 2050 for Palermo. This is due to the fact that by increasing the energy need for cooling in future the cooling load factor increases too.

It is important to indicate that the existence of exceptions in results and discussion may be due to the fact that the weather data have not been bias-adjusted to reduce long term bias associated with climate model data.

Table 4: Renewable energy ratio, mean coefficient of performance and mean energy efficiency ratio for Milan, Rome, and Palermo in 2020, 2050 and 2080.

	Milan			*Rome*			*Palermo*		
	2020	*2050*	*2080*	*2020*	*2050*	*2080*	*2020*	*2050*	*2080*
RER_{H+W+C}	62%	62%	66%	60%	56%	58%	63%	59%	60%
COP_m	1,96	1,91	1,89	1,90	1,87	1,94	2,10	2,18	2,32
EER_m	2,72	2,85	2,98	2,07	2,13	2,48	2,19	2,12	2,52

Conclusion

The aim of the present research was to investigate the energy performance of NZEBs in future scenarios of climate change. Three locations belonging to different Italian climatic zones were selected to perform the analysis: Milan, Rome, and Palermo. The NZEB energy performance requirements according to Italian regulations were compared for the mid-term and the long-term future periods with the present time. The main findings are summarized as follows:

1. The impacts of climate change on the NZEBs energy performance highly depends on the climatic zone. As an example, although in all scenarios the NZEB requirements are not met, it was demonstrated that the NZEBs in Milan are less sensitive to climate change compared to Rome and Palermo.

2. The studied period also affects the evaluation results significantly. For 2080, compared to 2050, the incompliance with the NZEB requirements is more severe. For instance, the annual energy needs for cooling in 2050 may increase up to 8,2% (Milan), while this value may raise up to 94,1% (Rome) in 2080.

3. The analysis performed on renewable and non-renewable primary energy showed that for renewable energy the changes depend on the type of energy source. More in detail, while the on-site aerothermal energy increases, the on-site PV electricity decreases for all scenarios. On the other hand, the non-renewable delivered primary energy increases for Rome and Palermo, which once more verifies the importance of the climatic zone for such analyses.

Overall, buildings will miss the target of meeting nearly zero-energy in the future so that a new configuration is needed to keep the NZEB goals in the future. These results highlight the significance of considering future weather for the energy performance assessment of NZEBs and establishing building adaptation measures for climate

change beside NZEB measures, as to ensure a holistic approach.

Acknowledgement

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