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Refurbishment of the residential building stock toward the nearly-zero energy target through the application of the building typology

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Abstract

Directive 2010/31/EU requires since 2019 the new public buildings and since 2021 all the new buildings to be nearly zero-energy (nZEB). In Italy, as in many geographical contexts, the existing buildings represent the majority of the building stock and equally the largest and most cost-effective energy saving potential. This study presents the energy performance calculations carried out by means of quasi-steady state method for some Italian reference buildings refurbished into nZEB. The results are presented in terms of "packages of measures" and potential energy reductions. The differences among measures depending on building type and climatic conditions are discussed.

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Keywords: nearly zero-energy buildings; residential buildings refurbishment; energy efficiency measures.

1. Introduction

The current Italian legislation, transposing the European Directive 2010/31/EU (EPBD recast) [1] on the energy performance of buildings, requires since 2019 the new public buildings and since 2021 all the new buildings to be nearly zero-energy. A nearly zero-energy building (nZEB) is defined as a building with very high energy performance where the nearly-zero or very low amount of energy required should be extensively covered by

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renewable sources produced on-site or nearby. Thus, the improvement of energy efficiency and the integration of renewable energy in buildings are the key elements of current European and national policies to reduce buildings' energy consumptions. In Italy, as in many geographical contexts, the existing buildings represent the majority of the building stock and equally the largest and most cost-effective energy saving potential [2]-[3]. For this reason an interesting challenge is to upgrade the existing building stock into nZEBs.

This study presents the energy performance calculations carried out for some Italian reference buildings refurbished into nearly zero-energy buildings. As regards the case studies, which are representative of the Italian residential building stock, different building types, construction periods and climatic zones are considered. For each building the packages of energy efficiency measures to apply in order to reach the nearly zero-energy target are identified and modeled. The energy performance is evaluated by means of the quasi-steady state method, according to the Italian technical specification UNI/TS 11300 [4]. The results are presented in terms of "packages of measures" and potential energy savings. The differences among measures depending on building type and climatic conditions are discussed.

Nomenclature

A	area	[m^2]
COP	coefficient of performance	[–]
EER	energy efficiency ratio	[–]
EP	energy performance	[$kWh\ m^{-2}$]
g	total solar energy transmittance	[–]
HDD	heating degree days	[°C d]
n	ventilation rate	[h^{-1}]
I	indicator	[–]
Q	quantity of heat	[kWh]
U	thermal transmittance	[$W\ m^{-2}K^{-1}$]
V	volume	[m^3]
W	power	[kW]
η	efficiency	[–]

Subscripts

C	cooling	n	normal
c	control (subsystem)	nd	need (energy)
d	distribution (subsystem)	nren	non-renewable (energy)
e	emission (subsystem)	P	primary (energy)
env	envelope	p	peak (PV system)
f	floor	PV	photovoltaic (system)
fl	slab	sh	solar shading
g	gross	u	unheated
gl	glass, global	up	upper
gn	generation (subsystem)	W	domestic hot water
H	heating	w	window
lw	lower	wl	wall

2. Method

2.1. Energy performance assessment

The aim of the work is to assess the energy performance of the residential buildings and the potential energy savings after refurbishment toward the nearly-zero energy target. The calculation is realized by means of a quasi-steady state method based on the standard EN ISO 13790 [5] and implemented in the Italian technical specification UNI/TS 11300.

According to ISO/DIS 52000-1 [6], the Energy Performance (EP) corresponds to the building global primary energy ($E_{\mathrm{P,gl}}$) divided by the conditioned floor area ($A_{\mathrm{f,n}}$). The global primary energy takes into account the energy demand to satisfy all the user's needs concerning heating, cooling, ventilation and domestic hot water. The global primary energy is obtained from the delivered energy split by energy wares, applying relevant primary energy factors. These conversion factors are specified at national level and they distinguish the renewable energy part from the non-renewable one. Thus, the EP can be expressed either as the non-renewable primary energy (EP_{nren}) or as the total (non-renewable plus renewable) primary energy (EP_{tot}). These couple of indicators, EP_{nren} and EP_{tot}, fully describe the building energy performance. Alternatively, the building energy performance can be expressed by EP_{nren} and the Renewable Energy Ratio (RER), which is the ratio of the renewable primary energy to the total primary energy.

$$EP = \frac{E_{\mathrm{P,gl}}}{A_{\mathrm{f,n}}} \tag{1}$$

$$EP_{\mathrm{tot}} = EP_{\mathrm{nren}} + EP_{\mathrm{ren}} \tag{2}$$

$$RER = \frac{EP_{\mathrm{ren}}}{EP_{\mathrm{tot}}} \tag{3}$$

2.2. The nZEB requirements

According to the methodological proposal included in ISO/DIS 52000-1, the Italian regulations [7] combine different requirements to a coherent assessment of a nearly zero energy building. They take into account indoor environmental conditions, thermal characteristics of the building, HVAC installation, DHW supply, built-in lighting installation, active solar systems and other systems based on energy, from renewable sources, district or block heating and cooling.

Two main requirements regarding the building envelope are defined:

- the maximum mean thermal transmittance of the envelope, the so called "global transmission heat transfer coefficient" (H'_{T}), which is set as a function of the heating degree days (HDD) and of the compactness factor of the building ($A_{\mathrm{env}}/V_{\mathrm{g}}$), as shown in Fig. 1a; and
- the maximum summer effective solar area per unit floor area ($A_{\mathrm{sol,summer}}/A_{\mathrm{f}}$) which is fixed to 0.03 for residential buildings and to 0.04 for commercial buildings. $A_{\mathrm{sol,summer}}$ is the sum of the effective solar collecting area of glazed elements, calculated for the month of July according to EN ISO 13790, multiplied by the monthly solar irradiance on each orientation divided by the average yearly solar irradiance on the horizontal plane in a reference location (Rome).

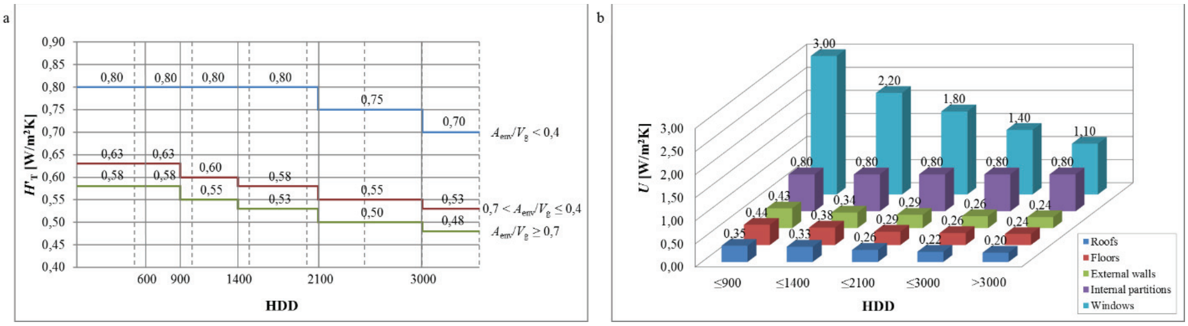


Fig. 1. (a) Required maximum value of the "global transmission heat transfer coefficient" (H'_T); (b) U-values of the reference building envelope components.

Furthermore, the nZEB target include the following requirements:

- the maximum value of the total global energy performance ($EP_{gl,tot}$);
- maximum values of energy needs for heating ($EP_{H,nd}$) and cooling ($EP_{C,nd}$);
- minimum values of seasonal efficiencies of heating, cooling and domestic hot water systems (η_H, η_C, η_W).

These requirements are calculated through the use of a *reference building*, considering a building with the same location, building function, geometry and boundary conditions as the design building, but with parameters such as insulation level, technical systems efficiency, etc. replaced by reference values. As regards the building envelope, the U-values of the reference building envelope components depend on the heating degree days (HDD) of the location as shown in Fig. 1b. Moreover, a total solar energy transmittance (g_{gl+sh}) of 0.35 is assumed for all the windows, including possible solar shadings, oriented to East, South and West.

Finally, a minimum value of the Renewable Energy Ratio for DHW and for heating, cooling and DHW are requested ($RER_W \geq 50\%$, $RER_{H+C+W} \geq 50\%$). Besides, the minimum electrical power from renewable sources produced on-site per unit footprint of the building area is set to 20 W/m^2.

3. Calculation

3.1. Case studies

In order to obtain results as general as possible, the energy performance calculations of refurbishment toward the nearly-zero energy target were performed on some Italian residential reference buildings.

The reference buildings are typical buildings able to represent the national building stock. They were selected from the Italian "National Building Typology" of the European IEE project TABULA [8].

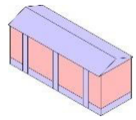
Four case studies are concerned in the analysis. They consist of two different building types with a fixed geometry, located in two different Italian climatic zones.

The first reference building is an apartment block, built in the period from 1946 to 1960; the second reference building is a single family house belonging to the age class ranging from 1961 to 1975.

The considered buildings are located in the following Italian cities: Palermo (PA, 751 HDD, climatic zone B) and Milan (MI, 2404 HDD, climatic zone E).

The main data of the case studies are shown in Table 1.

Table 1. Main data of the case studies.

Data		Parameter		Apartment block		Single-family house	
				PA	MI	PA	MI
Picture							
Geometry	Whole building	V_g	[m^3]	5949		679	
		$A_{f,n}$	[m^2]	1552		216	
		A_{env}/V_g	[m^{-1}]	0.46		0.70	
		A_w	[m^2]	217		19.54	
		no. of floors	[–]	4		2	
		no. of units	[–]	24		1	
Construction	Opaque envelope	U_{wl}	[W m^{-2}K^{-1}]	2.40	1.15	1.38	1.26
		$U_{wl,u}$	[W m^{-2}K^{-1}]	1.97	2.32		
		$U_{fl,up}$	[W m^{-2}K^{-1}]	1.63	1.65	1.63	1.65
		$U_{fl,lw}$	[W m^{-2}K^{-1}]	1.33	1.30	2.00	2.00
	Windows	U_w	[W m^{-2}K^{-1}]	4.90	4.90	4.90	4.90
		$g_{gl,n}$	[–]	0.85	0.85	0.85	0.85
Technical systems efficiency (mean yearly/ seasonal values)	Radiators	$\eta_{H,e}$	[–]	0.90	0.90	0.90	0.88
	Room temperature control	$\eta_{H,c}$	[–]	0.85	0.85	0.85	0.85
	Central distribution	$\eta_{H,d}$	[–]	0.901	0.901	0.901	0.901
	Natural gas standard generator	$\eta_{H,gn}$	[–]	0.85	0.85	0.73	0.73
	Electric water heater/Combined natural gas standard generator	$\eta_{W,gn}$	[–]	0.75	0.75	0.77	0.77
	Indoor units split systems	$\eta_{C,e}$	[–]	0.97	0.97	0.97	0.97

3.2. Energy efficiency measures

For each building the packages of energy efficiency measures to apply in order to reach the nearly zero-energy target are identified and modeled. The technologies consider both the building envelope and the technical systems.

The packages of energy efficiency measures applied to the case studies take account of the different building-systems type options and are listed in Table 2. In their current state the apartment block is characterized by centralised heating system and by individual DHW and cooling systems and the single-family house is provided with combined heating and DHW systems and cooling system.

The energy efficiency measures considered are those less onerous and invasive in order to avoid to force the people to leave the houses during the works. For this purpose, the retrofit measures don't admit the replacement of the single unit boilers with a centralized one or the replacement of radiators with appropriate emission systems like radiant panels. The target energy efficiency values comply with the requirements established by current legislation.

Table 2. Packages of energy efficiency measures applied to the case studies.

ID packages	Packages of energy efficiency measures	Apartment block	Single-family house
A	Thermal opaque envelope insulation	X	X
B	Transparent envelope – windows replacement	X	X
C	Installation of solar shading devices	X	X
D	Installation of ventilation heat recovery	optional	optional
E	Replacement of the old chiller with high efficiency chiller	X	
F	Replacement of the old space heating generator with high efficiency space heating generator*	X	
G	Replacement of the old DHW generator with high efficiency DHW generator	X	
H	Replacement of the old combined heating and DHW generator with high efficiency combined heating DHW generator*		
I	Installation of heat pump for heating, DHW and cooling*		X
L	Installation of thermal solar system		X
M	Installation of PV system	X	X
*plus improving heating system control			

3.3. Calculation options and boundary conditions

According to the quasi-steady-state calculation method, the following assumptions and simplifications were applied:

- climatic data of Milan and Palermo provided from the national technical standard UNI 10349-1:2016 [9],
- simplified approach to calculate internal heat gains, building internal heat capacity, temperature of unconditioned spaces, according to the assumptions defined in the Italian technical specifications UNI/TS 11300-1:2014,
- value of shading reduction factor for external obstacles fixed at 0.8,
- reduction factor for window frame (frame factor) fixed at 0.2,
- the thermal transmittance of opaque components includes the effect of thermal bridges,
- natural ventilation rate fixed at 0.3 h^{-1},
- a continuous operating mode during the conditioning period is considered, assuming a heating set point of 20 °C and a cooling set point of 26 °C according to the Italian regulations,
- primary energy factors fixed at 2.42 (1.95 non-renewable plus 0.47 renewable) for electricity, at 1.05 for fossil fuels (entirely non-renewable), at 1.00 for both electricity from photovoltaic system and heat energy from outdoor with heat pump (completely renewable in both cases). The thermal energy produced by solar collectors is considered as a reduction of the energy demand for the H and/or DHW. The electrical energy produced by PV panels is considered as a reduction of the electrical energy demand; the balance is within the month and the exported electrical energy is not considered.

4. Results

The packages of energy efficiency measures applied to the case studies are listed in Table 3 and the energy performance before and after refurbishment are shown in Fig. 2.

Table 3. Packages of energy efficiency measures to upgrade the case studies in nZEB.

ID packages	Energy efficiency measures	Parameter		Apartment block		Single-family house	
				PA	MI	PA	MI
A	External wall insulation	U_{wl}	[W m^{-2}K^{-1}]	0.43	0.24	0.43	0.24
	Wall vs unconditioned spaces insulation	$U_{wl,u}$	[W m^{-2}K^{-1}]	0.86	0.48		
	Roof/upper floor thermal insulation	$U_{fl,up}$	[W m^{-2}K^{-1}]	0.39	0.22	0.50	0.22
	Ground/lower floor thermal insulation	$U_{fl,lw}$	[W m^{-2}K^{-1}]	0.88	0.48	0.44	0.24
B	Window replacement	U_w	[W m^{-2}K^{-1}]	3.00	1.10	3.00	1.10
C	Solar shading devices	τ_s	[–]	0.35	0.57	0.39	0.57
D	Heat recovery unit	η_V	[–]	0.9	0.9	0.9	0.9
E	Chiller	EER	[–]	3.4	3.4		
F	Space heating generator*	$\eta_{H,gn}$ or COP_H	[–]	2.9	2.9		
G	DHW generator	$\eta_{W,gn}$ or COP_W	[–]	2.3	2.3		
H	Combined heating and DHW generator*	$\eta_{H+W,gn}$ or COP_{H+W}	[–]				
I	Heat pump for H, DHW and C*	EER COP_{H+W}	[–] [–]			3.4 2.4	3.4 2.4
L	Thermal solar system	A_{coll}	[m^2]				
M	PV system	$W_{PV,p}$	[kW]	10	10	2.5	2.5
*plus improving heating system control	Room temperature PI-controller	$\eta_{H,c}$	[–]	0.995	0.995	0.995	0.995

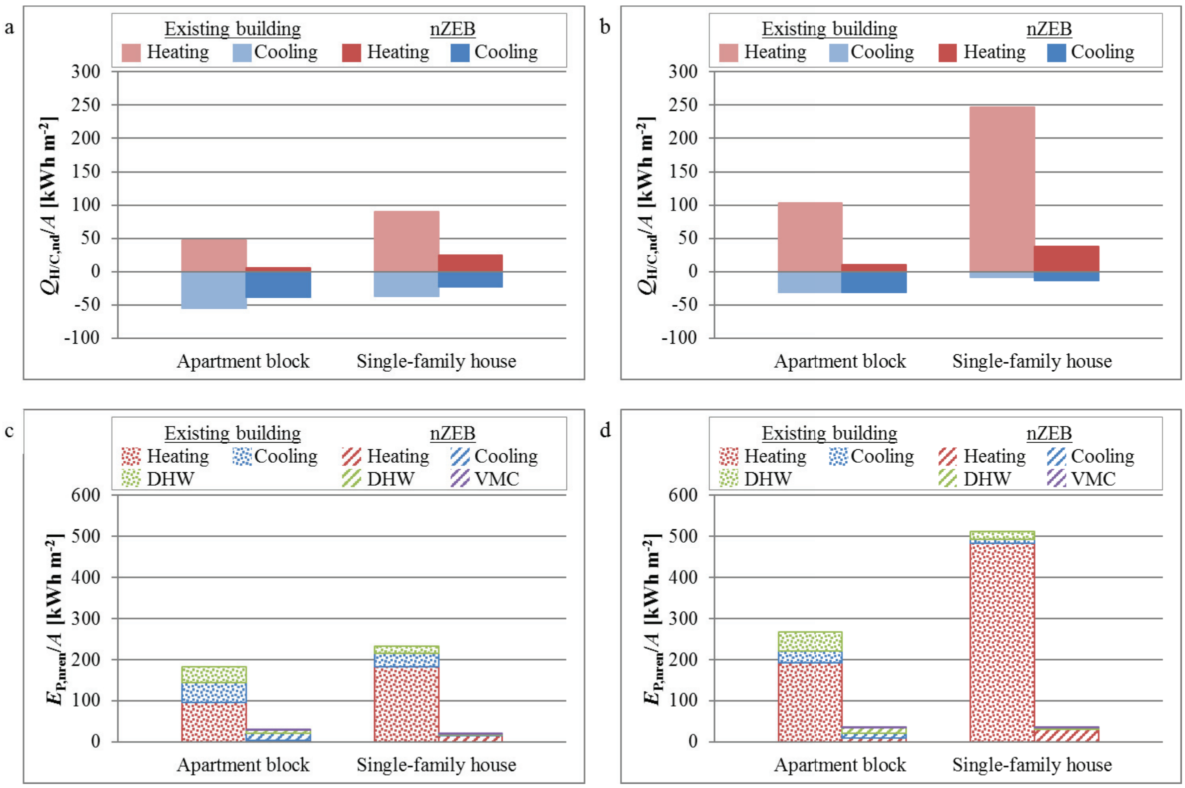


Fig. 2. Net energy need for heating and cooling normalized by the conditioned floor area for the cities of Palermo (a) and Milan (b). Non-renewable primary energy normalized by the conditioned floor area for the cities of Palermo (c) and Milan (d).

Firstly, the differences among measures regarding the building envelope depend on climatic conditions as the *U*-values increase by decreasing the HDD according to the Italian regulations. Secondly, the difference in thermal transmittance values for the same building envelope components in the same location are due to their different adjacent spaces exposure (external or different unconditioned spaces). The different technical system measures respect the existent different building-systems type which are typical for both the building type and the construction age, but they achieve the same level of high efficiency. Finally, the differences regarding the renewable technologies derive from different geometrical features and different building energy needs for the end uses considered.

The higher energy savings from the upgrade into nZEBs are spotted in net energy need for heating for both cities and building types. Particularly, the net heating energy savings are about 75-85% in climatic zone B and about 85-90% in climatic zone E, and they are 5-10% higher for the apartment block than for the single-family house.

As regards net energy need for cooling the energy savings vary from 30 to 40% for the buildings located in Palermo, whereas in Milan the cooling energy needs increase after envelope insulation increase, even redoubling for single-family house. These increases are anyway compensated by the replacement of the chiller and the installation of ventilation heat recovery.

Lastly the results reveal that the non-renewable global primary energy is reduced about from 85% to 95% and the energy savings are higher for both building types in climatic zone E and for both climatic zone for single-family house. The non-renewable heating primary energy savings are almost constant for all the case studies, while in contrast the non-renewable primary energy savings for cooling and DHW are highly different and are higher for single-family house in both cities. Independently of building types, the installation of ventilation heat recovery is more convenient in climatic zone E, whereas it is unfavourable in climatic zone B.

5. Conclusions

The results of the work show that the Italian transposition of the nZEB concept reduces the choice of technologies useful for the building refurbishment towards the nearly zero-energy target: the heat pump associated to a PV system seems to be the most effective solution. Moreover, the present work highlights the difficulties in the application of some requirements associated to the nearly zero-energy target achievement, especially in the hottest and coldest climatic zones.

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