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On the compliance of thermal performance requirements for highly insulated building units

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ABSTRACT
The target of the nearly zero-energy building (nZEB), stated by the European Union, represents one of the most strenuous challenges to reduce energy consumptions and greenhouse gas emissions in the building sector. In Italy, the nZEB concept refers to a set of energy performance requirements, fixed at national level and establishing a maximum allowable mean thermal transmittance value of the building envelope, as a function of the heating degree-days and of the shape factor. The building envelope is becoming more and more thermally insulated; this determines the reduction of the energy need for heating, but on the other hand it can cause the indoor overheating and the resulting increase of the energy need for cooling. In the design of highly energy efficient buildings, the different energy needs should be kept in balance as to increase the overall energy performance.
The article aims to investigate the conditions and extent for which the envelope insulation is beneficial for containing overall energy needs. A sensitivity analysis that involves different insulation levels of the building envelope is performed on some apartments of a typical residential building, located in three different Italian climatic zones. The energy performance calculations are carried out by means of a detailed dynamic simulation tool (*EnergyPlus*). The results point out that, whereas the effect of increasing the thermal insulation causes a stable reduction of the energy need for heating, the energy need for cooling is very sensitive to the apartment storey; specifically, it increases in ground-floor apartments, and decreases for top-floor building units. Its reduction becomes progressively more consistent at the decrease of the heating degree-days. Considering the annual imbalances between the energy needs for cooling and heating due to the hyper-insulated envelope, reference values of thermal transmittance can be derived as to maximise the overall energy performance of the building.

KEYWORDS
Nearly zero-energy building; thermal insulation; building energy performance; building envelope; dynamic simulation.

INTRODUCTION
Directive 2010/31/EU (European Union, 2010) promotes the energy performance improvement of buildings and enforces the Member States to draw up national plans for increasing the number of nearly zero-energy buildings (nZEBs). In Italy, the detailed application of the definition of nZEB has been specified by the Ministerial Decree (M.D.) 26/06/2015 (Italian Republic, 2015): a set of provisions concerning the building envelope, the technical building systems and the use of renewable energy sources must be complied with to achieve the nZEB target. In particular, the national strategy focuses on the building envelope (Zinzi et al., 2017), enforcing restrictive mean thermal transmittance values. In addition, the adoption of adequate insulation thickness as to meet winter energy requirements could lead to indoor overheating and, consequently, to an increase of the energy need for space cooling. Guaranteeing the best

trade-off between energy performance for heating and cooling is of crucial importance to minimize the overall energy needs.
Several studies investigated the role of the building envelope in achieving the nZEB target and demonstrate the discrepancy between the envelope requirements and the building energy behaviour in summer. Ballarini and Corrado (2012) proposed a methodology to investigate the effect of thermal insulation in summer. They underlined that transparent envelope and shading devices have a greater influence on summer energy needs than the opaque envelope. Murano et al. (2017) demonstrate the imbalance of nZEB energy need for heating and cooling by evaluating the effects of the reduction of the *U*-values of the envelope components and of the improvement of solar shadings on the energy needs of three reference buildings. Applying the two measures simultaneously, they proved that the influence of the thermal insulation on the energy needs for heating is greater than the effect of solar shading on the energy needs for cooling. Chvatal and Corvacho (2009) and Chvatal et al. (2005) investigated the summer overheating in buildings as a consequence of thermal insulation and thermal inertia of the building envelope; when solar and internal gains are not adequately controlled, there is a tendency towards more discomfort as the envelope insulation increases. Sameni et al. (2015) highlighted the risk of overheating in a hyper-insulated social housing, identifying the most critical flats on the basis of both occupants' behaviour and geometrical characteristics.
Within this framework, the choice of an optimal insulation level would prevent overheating and ensure the lowest overall energy consumption. The present research focuses on a typical Italian residential building and carries out a sensitivity analysis including different insulation levels and climatic zones. The imbalance of the energy needs and its effect on the overall primary energy for heating and cooling are discussed for four representative apartments, highlighting the different behaviour for storey location and climatic condition.

METHODS

Theory

The dynamic numerical simulation of the building was performed by means of *Energy Plus*. Each apartment has been modelled as a single thermal zone. The code solves a convective heat balance equation on the internal air node of the building thermal zone. As the analysis of technical building systems is out of the scope of the work, an infinite heating and cooling capacity was adopted to determine the net energy needs for space heating and space cooling.
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 determined as the weighted sum of the thermal energy needs for heating and for cooling:

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

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 utilisation subsystems (i.e. heat emission, control and distribution, equal to 0.81) and $\eta_{H/C,g}$ is the mean seasonal efficiency of the heating (0.95) and the cooling (2.50) generation subsystem, respectively. The reference mean seasonal efficiency values of the thermal subsystems were assumed in compliance with M.D., and the most used energy carriers in Italy were adopted. Gas condensing boiler and chiller were used as reference generators for heating and cooling.

Case study

The case study is a 4-storey multi-family house, studied in a previous work (Murano et al., 2016). It is not a real building but an "archetype", which is a "virtual" building characterised by a set of properties detected though statistical analysis of a large building sample. It is supposed to be located in Palermo (Southern Italy), Rome (Central Italy), and Turin (Northern Italy). The main climatic data (UNI, 2016) are listed in Table 1. The building consists of 12 units; its main facades are North-South oriented. Four representative apartments were chosen as to cover a wide range of the shape factor values (i.e. ratio of the envelope surface to the conditioned volume) and kinds of adjacent spaces (e.g. ground, conditioned spaces). The main geometric data are reported in Table 2. The sensitivity analysis took into account six levels of thermal insulation, from highly (level no. 1) to scarcely insulated (level no. 6). Each level is a combination of the *U*-values of the opaque and transparent envelope components (Table 3); the same *U*-value is assumed for each opaque component (walls, roof and ground floor) and the insulating material is placed on the exterior side. The areal thermal mass is about 270 kg·m^{-2} for the external walls and the ground floor, and 400 kg·m^{-2} for the roof. For each insulation level, the *U*-value of windows varies accordingly, while the total solar energy transmittance of glazing at normal incidence is kept constant ($g_{gl,n}$=SHGC$_n$=0.67). A solar shading (τ=0.15, ρ=0.70) is supposed to be placed on the external side of all windows. The external opaque surfaces are intermediate coloured (solar absorption coefficient equal to 0.6).

Table 1. Main climatic data of the analysed locations.

Cities	Heating period		Cooling period		
	Duration [h]	HDD $_{20\ °C}$	Duration [h]	CDD $_{26\ °C}$	$H_{sol,gl,hor,C}$
Palermo (PA)	5 034	1 121	1 446	166	3 830
Rome (RM)	5 789	1 643	1 084	143	4 004
Turin (TO)	6 604	2 648	809	84	3 511

HDD = heating degree-days [°C·d], CDD = cooling degree-days [°C·d], $H_{sol,gl,hor,C,}$ = global solar irradiation on a horizontal surface in the cooling period [MJ·m^{-2}]

Table 2. Main geometric characteristics of the building and of the analysed units.

Pictures	Building unit code	Storey	Building unit	V_g	V_n	A_f	A_{env}	A_w	A_{env}/V_g	WWR
	BU0C	0	C	389	320	118	246	18.0	0.63	0.18
	BU1C	1	C	389	320	118	116	18.0	0.30	0.18
	BU3A	3	A	285	230	85	201	11.1	0.71	0.14
	BU3B	3	B	184	153	57	108	8.7	0.58	0.29
	Building	-	-	3 401	2 788	1 033	1 653	151	0.49	0.18

V_g = gross conditioned volume [m^3], V_n = net conditioned volume [m^3], A_f = net conditioned floor area [m^2], A_{env} = envelope area [m^2], A_w = windows area [m^2], WWR = windows-to-wall ratio [-]

Table 3. Thermal properties of the building envelope components.

Insulation level	External walls			Flat roof			Ground floor			Windows
	U	κ_i	$\|Y_{ie}\|$	U	κ_i	$\|Y_{ie}\|$	U	κ_i	$\|Y_{ie}\|$	U
1	0.10	48.9	0.009	0.10	64.8	0.006	0.10	56.6	0.015	1.00
2	0.20	49.3	0.031	0.20	65.1	0.021	0.20	56.9	0.049	1.50
3	0.30	49.6	0.053	0.30	65.3	0.034	0.30	56.7	0.081	2.00
4	0.40	50.0	0.076	0.40	65.5	0.048	0.40	56.6	0.115	2.50
5	0.50	50.4	0.104	0.50	65.7	0.064	0.50	56.5	0.151	3.00
6	0.60	50.9	0.138	0.60	66.0	0.081	0.60	56.5	0.191	3.50

U = thermal transmittance [W·m^{-2}K^{-1}], κ_i = internal areal effective heat capacity [kJ·m^{-2}K^{-1}], Y_{ie} = periodic thermal transmittance [W·m^{-2}K^{-1}]

The weather data were derived from the CTI database (CTI, 2017). Hourly profiles of the internal heat sources and the ventilation flow rate were determined according to UNI/TS 11300-1 (UNI, 2014). As specified by the Italian regulations, a continuous thermal system operation is considered during the heating and cooling seasons. The set-point temperature was fixed at 20 °C and 26 °C for heating and cooling, respectively. The solar shading devices are considered in function when the hourly value of solar irradiance exceeds 300 $W \cdot m^{-2}$.

RESULTS AND DISCUSSION

The results of the sensitivity analysis are reported in Figures 1-2. For each location, Figure 1-a) shows annual cooling energy need vs. annual heating energy need of the whole building for different insulation levels. Figure 1-b) shows cooling peak power vs. heating peak power for the same insulation levels. Figure 2 shows the same outcomes both for the whole building and for each building unit. In addition, Figures 2-a), 2-c) and 2-e), for different location, also show the annual overall primary energy vs. the annual energy needs for heating and cooling. The dotted grey lines represent the *iso*-EP_{gl} lines, calculated as described in "Methods" section.

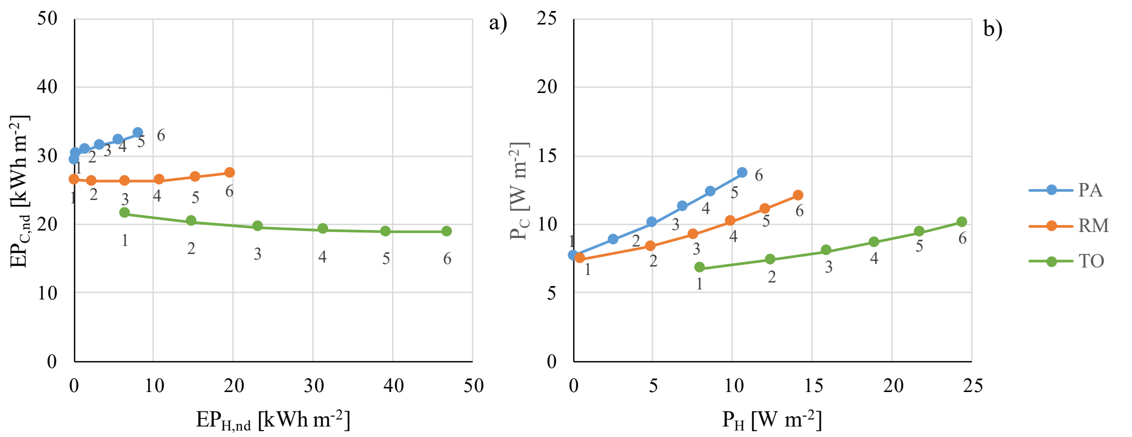

Figure 1. Net energy need (EP_{nd}) and peak power (P) for heating (H) vs. cooling (C) for the whole building and for six insulation levels.

Analysing the whole building (Figure 1), the sensitivity of the heating energy need to the insulation level is higher in the zones with higher HDD, like Turin, and generally it is more sensitive than the cooling energy need. Anyway, in Turin a reduction of heating energy need by progressively reducing the U-values corresponds to an increase of need for cooling.

Differences in the energy behaviour between the apartments are noticeable, above all in Rome and Palermo (Figure 2). In Palermo, where the CDD are higher, the influence of thermal insulation is more evident in summer than in winter and an opposite effect is revealed between the units at ground floor and those at the highest floor. Specifically, by reducing the thermal transmittance of the envelope, at ground floor the reduction of heating corresponds to an increase of the energy need for cooling, while at the highest floor the reduction of cooling is higher than the reduction of the energy need for heating.

The difference between apartments is less evident moving from Palermo to Turin, even if the hyper-insulation of the ground floor units always determines a higher energy need for cooling regardless of the climatic zone. For instance, considering a medium insulation level (level no. 4) in Turin, the difference between the cooling energy needs of the ground floor and the third floor units is greater by 68% than the difference between the respective heating needs. In Palermo, switching from insulation level no. 6 to no. 1, the cooling need is reduced by 31% for BU3B and increases by 32% for BU0C. This is due to a greater value of the solar-air temperature on the upper units, where a high level of insulation has a favourable effect. On the other hand, the hyper-insulation of the ground floor does not allow the discharge of the accumulated heat, thus leading to an increase of the cooling need. For intermediate floors above all in Palermo, the sensitivity to the insulation level is negligible, due to a very low shape factor.

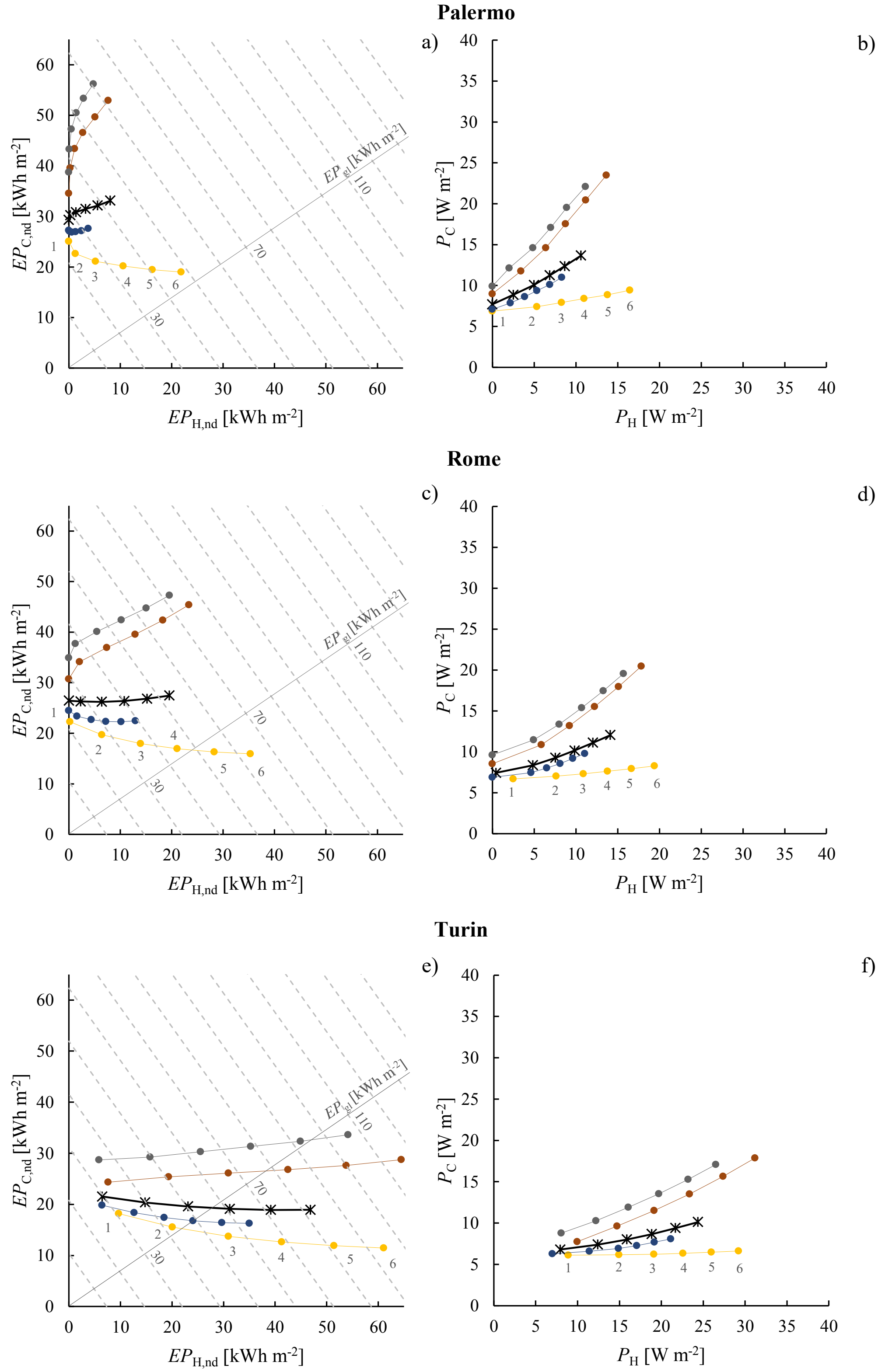

Figure 2. Net energy need (EP_{nd}) for heating vs. cooling, and overall primary energy for the whole building and for different building units, for six insulation levels.

The high differences of the energy needs between units at different storeys are also evident in the overall primary energy (EP_{gl}), so that the same EP_{gl} can be achieved by insulating the units differently. For instance in Palermo, BU3B and BU0C have the same EP_{gl} with $U = 0.1$ W·m^{-2}K^{-1} in the former case and $U = 0.4 \div 0.5$ W·m^{-2}K^{-1} in the latter case.

Due to the imbalances between annual energy needs for heating and cooling and in the ground floor units, it would be possible to identify limit *U*-values below which EP_{gl} tends to increase. An example is BU0C in Palermo; by switching from level no.2 to level no.1, the same EP_{gl} is obtained (24 kWh·m^{-2}). Level no.2 would consist in a limit *U*-value for this unit.

The thermal transmittance decrease generally causes the reduction both of heating and cooling peak powers. A higher power for heating than for cooling occurs in Turin rather than in Palermo, where in addition the cooling peak power is more sensitive to the insulation level.

CONCLUSIONS

To improve the energy design of buildings, the findings of the work pointed out that, where possible, it would be desirable to differentiate the envelope requirements for each building unit in function of the geometrical properties, storey location and exposure. In such a way, the imbalances between energy needs for heating and cooling on the building energy performance due to the hyper-insulation of the envelope can be controlled and the overall *EP* minimised.

The analysis will be widened by investigating more use categories, glazing properties and shading positions, and assessing the primary energy through detailed models of the technical building systems, as to take into account the temporal variability of system efficiencies.

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