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NZEB, cost- and comfort-optimal retrofit solutions for an Italian Reference Hotel

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Abstract

Building upon the implementation of EBPD recast in the large majority of EU Member States, this paper studied how far cost-optimality is from the Nearly Zero Energy Building (NZEB) performance level for an Italian Reference Hotel (RH) undergoing major renovations. The energy performances of retrofit options for the RH were compared with the Italian NZEB requirements. Simulations results confirmed that the Italian NZEB target is reachable. However, the financial analysis of these retrofit options denounced a worrying gap between financially interesting solutions and NZEB ones.
Then, through a novel comfort-optimal approach, the comfort-related consequences of the proposed retrofit options were investigated.

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Keywords: NZEB; Hotel; Cost-optimal; Thermal Comfort.

1. Introduction

In 2010, the EPBD recast [1] introduced the NZEB concept and by January 2021 all over Europe new private buildings will have to comply with nationally defined NZEB standards. Accordingly, most of MSs have now endorsed EU requirements in their regulations and set numerical indicators for new and existing buildings aiming to

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reach the NZEB level [2]. In the EU view, these national figures should also represent the cost-optimal level of energy performance from 2021 on, meaning that NZEB design options should be those leading to the lowest global cost during the estimated lifecycle of buildings. Indeed, EPBD recast also introduced cost-optimal methodology as the guiding principle for setting building energy requirements.

However, the envisaged full match between cost-optimal and NZEB energy performance level remains an open issue. Studies investigating the possible energy/financial performance gaps between the two levels can inform policy-makers about how demanding the forthcoming market transition towards an energy efficient building stock will be. To serve the cause, in the present paper the matter was investigated for the proposal of retrofit solutions for a Reference Hotel located in Italy, where NZEB minimum requirements are available since June 2015.

Several reasons led the authors to deal with hotel buildings. Primarily, hotels well represent a wide spectrum of non-residential buildings where multiple functions are in place. While cost-optimal and NZEB studies have flourished in recent years for residential (e.g. [3]) and office buildings (e.g. [4]), other non-residential categories have been rarely investigated. Nonetheless, the mixed energy uses of multi-functional non-residential buildings represents an interesting challenge for the simultaneous achievement of cost-optimal and NZEB performances. Additionally, hotels are highly regarded by the international community for their role in the transition towards a low-carbon society. This building category ranks third for specific energy uses of the non-residential EU stock [5]; given the drastic reduction in CO_2 emissions that is expected for the building sector by 2050 in Europe [6], high performing design solutions for hotel buildings have been strongly promoted by the European Commission in the last years, for instance through the neZEH project [7]. The role of tourism accommodations in sustainable development gained further attention in 2017, which was nominated “International Year of Sustainable Tourism for Development” by the United Nations General Assembly. Accommodation structures are accounted to be responsible for more than 20% of the total tourism-related emissions [8] and a drastic shift in the management of these businesses could significantly contribute the economic, social and environmental dimensions of sustainable development [9]. In this framework, the focus of the paper on the retrofit of an Italian Reference Hotel can represent an interesting case study at a broad scale, as Italian hotels represent 18% of the EU hotel stock [5].

Finally, the specific nature of hotels, buildings and businesses at once, gives the chance of coupling cost-optimal analysis with investigations on comfort conditions. Indeed, in order to run a successful accommodation business, reduced operational costs (e.g. energy costs) must be coupled with guests’ satisfaction, which chiefly requires comfortable indoor conditions [10]. Moreover, indoor comfort is widely recognized as an important co-benefit of energy efficient buildings from the macroeconomic perspective as well [11].

Building upon these premises, in the followings of the paper the Reference Hotel is introduced and investigation methods and results are presented for the performed energy, financial and comfort analyses.

Nomenclature

U	Thermal transmittance, W/(m^{2}K)
H'_T	Transmission heat transfer coefficient, W/(m^{2}K)
$A_{sol,est}/A_{net\ area}$	Normalized summer effective solar collecting area of glazed elements, ND
$EP_{H,nd}$	Heating energy need index, kWh/(m^{2}y)
$EP_{C,nd}$	Cooling energy need index, kWh/(m^{2}y)
$EP_{gl,tot}$	Total global primary energy index, kWh/(m^{2}y)
η_H	Heating plant and system efficiency, %
η_W	Hot water production plant and system efficiency, %
η_C	Cooling plant and system efficiency, %
RES_{DHW}	Share of renewable energy sources for DHW production, %
$RES_{DHW+H+C}$	Share of renewable energy sources for DHW, heating and cooling energy uses, %
PMV	Predicted Mean Vote, ND
PPD	Percentage of People Dissatisfied, %

2. Case Study

Cost-optimal and comfort analyses were carried out for a fictional Reference Hotel, modelled following the EPBD recast's precepts. In the European Commission's view, Reference Buildings (RBs) are models based on a solid understanding of the building stock and representative of the typical and average building typologies across Europe [12]. Developing energy and economic analysis for these models allow the results to be relevant for a wide pool of buildings.

The RH portrays a 3-star, medium-size, urban hotel, open all year, built between 1921 and 1945 and located on the Italian Middle Climatic zone (Heating Degree Days (HDD) = 2100-3000). This building sub-category was selected because of its statistical relevance in the Italian hotel stock; its representative building was modeled based on statistical data and experts' assumptions, in accordance with Corgnati et al.'s RB modeling approach [13]. The main features of the obtained Italian RH, extensively described by Buso et al. [14] are recalled in Table 1. The RH energy performances were simulated in EnergyPlus 8.3, selecting Turin (HDD = 2842, Cooling Degree Days = 287) as representative location.

Table 1. RH main features for form, envelope, system and operation.

Class of parameters	Parameter	Unit	Value
Form	Gross conditioned area	m^2	1700
	Number of floors	ND	5 (4 + basement)
	Orientation	ND	S-N
	Aspect ratio (S/V)	ND	0,28
	Window/Wall ratio	ND	0,17
	Number of guestrooms	ND	49
	Number of beds	ND	95
Envelope	Opaque envelope average U-value	$W/(m^2K)$	1,17
	Glazed envelope average U-value	$W/(m^2K)$	5,46
System	Ventilation	ND	Natural
	Heating system	ND	Centralized, with radiators
	Heating energy source	ND	Natural gas
	DHW system	ND	Centralized
	DHW energy source	ND	Natural gas
	Cooling system	ND	Centralized, with split
Operation	Schedules	ND	UNI 10339:2009, EN15251, EN15232

3. Method

The research was developed through the following steps:

I. Definition of the minimum and NZEB level of energy performance requirements for the RH, according to the Italian regulation.
II. Cost-optimal analysis oriented to meet the NZEB target for the retrofitted RH.
III. Thermal comfort analysis assessing the effects of retrofit solutions on the comfort level in guestrooms, in view of developing a comfort-optimal graph.

3.1. (I) Definition of minimum and NZEB energy performance requirements

The inter-ministerial decree (d.i.) "Requisiti Minimi" [15] came into force in October 2015 as the regulatory tool announced in Law 90/2013 [16], which, in turn, transposed the EPDB recast to the Italian context. The decree defines the requirements for NZEBs and sets up-dated minimum energy standards, differentiated for new buildings, degree of renovation and for target year. The main characterizing feature of the d.i. is the performance-based approach proposed to verify the compliance with energy requirements for new buildings and major renovations. Indeed, they are based on the concept of baseline building. The baseline building is as a fictional building having the same geometry, orientation, geo-graphic location, purpose of use and type of systems than the building object of the evaluation, but implementing pre-defined thermal and energy features (e.g. envelope U-values and plants efficiency). The limit values for the building under evaluation refer to envelope thermal properties (H'_T, $A_{sol,est}/A_{net\ area}$), heating and cooling energy needs ($EP_{H,nd}$ and $EP_{,nd}$) and total primary energy use ($EP_{gl,tot}$), that in non-residential buildings includes energy uses for heating, cooling, domestic hot water (DHW), ventilation, artificial lighting and lift systems. Coming to the minimum share of Renewable Energy Sources (RES) to be exploited on-site, the d.i. refer to D.lgs.28/2011 [17]. While envelope-related and RES requirements are established with a traditional prescriptive approach, the energy-related ones are obtained through the calculation of the energy performance of the baseline building. Based on the decree's dispositions, it is possible to derive 2 levels of minimum energy requirements, mandatory for private buildings from 2015 and from 2021, and the NZEB requirements. The building under evaluation can meet these requirements through any suitable combination of Energy Efficiency Measures.

In this paper, baseline models of the RH were built in EnergyPlus, in order to easily spot the performance gap between the RH in its original configuration and the baseline building.

3.2. (II) Cost-optimal analysis towards the NZEB target

The well-established steps of cost-optimal analysis foresee (a) the definition of several Energy Efficiency Measures (EEMs) to be combined and hypothetically implemented in the building object of investigation and the (b) energy and (c) financial analysis of the so-obtained models. In particular, primary energy and global cost have to be calculated for the creation of the cost-optimal graph (d). Results highlight retrofit options whose primary energy uses lead to the minimum life cycle cost, i.e. the cost-optimal retrofit options.

a. EEMs. In the present paper, EEMs were implemented in the RH model with the aim of reaching the NZEB level. To this purpose, packages of EEMs were assembled in order to verify by subsequent steps the NZEB requirements. First, envelope-related EEMs and packages (PE) were created to verify compliance with envelope-related NZEB requirements. PEs meeting these requirements were the basis for the implementation of artificial lighting measures (PEL). PE and PEL were analyzed in terms of heating and cooling energy needs and the packages satisfying the related requirements were the baseline models for the implementation of systems, plants and renewable energy measures. Table 2 summarizes and describes the selected EEMs and Table 3 reports the created packages of envelope EEMs (PE). Other packages of EEMs were created by adding lights, system, plants and RES measures to the PEs in line with NZEB requirements. In the followings of the paper, these packages will be named according to the features they implement: e.g. in package PE10L1.2S1.1S4.2R1.1R2.2, envelope is upgraded as foreseen by PE10, lights are substituted according to L1.2, system and plants are replaced as described by S1.1 and S4.2 respectively and renewables are installed according to R1.1 and R2.2.

Table 2. Energy Efficiency Measures (EEMs) applied to the RH.

EEM type	EEM code	Description	
Envelope	E1.1	External walls insulation level 1	U < 0,30 W/(m^{2}K)
	E1.2	External walls insulation level 2	U < 0,26 W/(m^{2}K)
	E2.1	Ground floor insulation level 1	U < 0,30 W/(m^{2}K)
	E2.2	Ground floor insulation level 2	U < 0,26 W/(m^{2}K)
	E3.1	Semi-exposed ceiling insulation level 1	U < 0,25 W/(m^{2}K)
	E3.2	Semi-exposed ceiling insulation level 2	U < 0,22 W/(m^{2}K)
	E4.1	Windows substitution level 1	U < 1,80 W/(m^{2}K)
	E4.2	Windows substitution level 2	U < 1,40 W/(m^{2}K)
	E5.1	Fixed shading	
	E5.2	Automated shadings	
Lights	L1.1	Substitution of all CFLs with LED lights	
	L1.2	Substitution of CFLs with LED lights in common and working areas	
System	S1.1	Substitution of heating and cooling terminals with four-pipes fancoils	
	S1.2	Substitution of heating and cooling terminal devices with radiant floor	
	S1.3	Substitution of heating and cooling terminal devices with radiant ceiling	
Plant	S4.1	Substitution of condensing boilers with an air-to-water heat-pump	
	S4.2	Substitution of condensing boilers with District Heating	
RES	R1.1	Installation of 11 Solar Thermal (ST) Panels	
	R1.2	Installation of 22 Solar Thermal (ST) Panels	
	R2.1	Installation of 56 Solar Photovoltaic (PV) Panels	
	R2.2	Installation of 84 Solar Photovoltaic (PV) Panels	

Table 3. Packages of envelope-related EEMs (PE).

Code	Description	Code	Description
PE1	E1.1+E2.1+E3.1	PE10	E1.2+E2.2+E3.2+E4.2+E5.1
PE2	E1.2+E2.2+E3.2	PE11	E1.1+E2.1+E3.1+E4.2
PE3	E4.1+E5.1	PE12	E1.2+E2.2+E3.2+E4.1
PE4	E4.2+E5.1	PE13	E1.1+E2.1+E3.1+E4.2+E5.1
PE5	E1.1+E2.1+E3.1+E4.1	PE14	E1.2+E2.2+E3.2+E4.1+E5.1
PE6	E1.2+E2.2+E3.2+E4.2	PE15	E1.2+E2.2+E3.2+E4.1+E5.2
PE7	E1.1+E2.1+E3.1+E5.1	PE16	E1.2+E2.2+E3.2+E4.2+E5.2
PE8	E1.2+E2.2+E3.2+E5.1	PE17	E1.1+E2.1+E3.1+E4.2+E5.2
PE9	E1.1+E2.1+E3.1+E4.1+E5.1	PE18	E1.2+E2.2+E3.2+E4.1+E5.2

b. Energy analysis. The energy analysis was performed with the two-folded aim of satisfying the minimum and NZEB requirements and of finding the cost-optimal level of energy performance for the RH. In view of scoring the first goal, envelope thermal properties, space heating and cooling energy needs, energy produced from RES and delivered energy were obtained through EnergyPlus simulations. Then, the share of renewables was calculated according to the Italian standards UNI-TS 11300-4 [18] recommendations and the delivered energy data were converted into primary energy by applying the Italian conversion factors given in the d.i.. The obtained total global primary energy index ($EP_{gl,tot}$) was used to score the second goal of the energy analysis, i.e. as the primary energy indicator in the cost-optimal graph.

c. Financial analysis. Global cost was calculated as shown in equation (1):

$$C_G(\tau) = C_I + \sum_j \cdot [\sum_{i=1} (C_{a,i}(j) \cdot R_d(i)) - V_{f,\tau}(j)] \tag{1}$$

where $C_G(\tau)$ represents the global cost referred to starting year τ_0, C_I is the initial investment cost, $C_{a,i}(j)$ is the annual cost for component j at the year i (including running costs and periodic or replacement costs), $R_d(i)$ is the discount rate for year i, $V_{f,\tau}(j)$ is the final value of component j at the end of the calculation period (referred to year τ_0). The discount rate R_d is used to refer the costs to the starting year τ_0; it is expressed in real terms, hence excluding inflation.
For the RH and for each model implementing EEMs all the data were defined and the global cost was calculated adopting a microeconomic (i.e. private investors') perspective. The calculation period τ was set as 20 years; 4% discount rate was used [12]; investment costs were taken from Piedmont Price List 2015 [19] and they were increased by the Italian VAT (22%) and professional fees, while possible subsidies were excluded from the calculations; replacement and maintenance costs were derived from EN 15459:2007 Appendix A [20]; energy costs were calculated by applying to EnergyPlus simulation results the following energy tariffs (including taxes), derived from real hotels bills: natural gas = 0,077 €/kWh; electricity = 0,231 €/kWh; district heating = 0,092 €/kWh (space heating), 1679 € + 0,071 €/kWh (domestic hot water).

d. Cost-optimal graph. Final outcome of the cost-optimal analysis was a scattered dots graph, where global costs were plotted versus the corresponding primary energy indexes, in order to identify the cost-optimal retrofit solutions and to spot the existing energy and financial gap between these solutions and the ones meeting the NZEB target.

3.3. (III) Thermal comfort analysis

The Reference Hotel is a mechanically heated and cooled building whose main users (guests) have high level of expectations in terms of comfort. Here-hence, the RH thermal environment operative conditions were set according to EN15251 I Comfort Category (CC) [21]; thus, operative temperature set-points for space heating and cooling were respectively 21°C during occupied hours from October 15th to April 15th, and 25,5°C during occupied hours from April 15th to October 15th. Aim of this section of the study was to verify if the envisaged building/system retrofit configurations were able to guarantee the RH design thermal comfort conditions (I CC) to guests.

EN15251 Standard [21] recommends *PMV-PPD* indexes [22] as the most suitable indicators of the thermal comfort level of a mechanically conditioned building. It also suggests that thermal performances can be evaluated by calculating the number of occupied hours (those during which the building is occupied) when the comfort criteria are met. Comfort criteria (i.e. Comfort Categories) expressed as a function of *PMV* are reported in Table 4.

Based on these recommendations, the hourly *PMV* values for a standard guestroom were retrieved from the dynamic simulations outputs and compared with the *PMV* comfort category limits. Additionally, these thermal comfort performance indicators were plotted versus the primary energy indexes in order to put in relation comfort and energy performances of the investigated retrofit options and to spot comfort-optimal solutions.

Table 4. EN15251 [21] Indoor Environmental Quality categories for thermal comfort requirements for spaces with sedentary activities.

Category	Applicability	PMV limit values
I	High level of expectation	-0,2 < PMV < + 0,2
II	Normal level of expectation	-0,5 < PMV < + 0,5
III	Moderate level of expectation	-0,7 < PMV < + 0,7
IV	Values outside the above categories	PMV < -0,7 or PMV > + 0,7

4. Results and discussion

Results are presented separately for each of the research steps listed in Section 3.

4.1. (I) Definition of minimum and NZEB energy performance requirements

In accordance with the d.i. "Requisiti Minimi", Table 5 summarizes the minimum requirements for 2015, 2021 and NZEBs, as well as the RH original performances.

Starting from January 2017 the 2021 and NZEB requirements fully overlap. This is in line with EPBD recast dispositions', which envisage all new buildings to be NZEB from 2021. Moreover, it can be noticed how 2015 mandatory requirements just slightly differ from the NZEB ones. In view of these facts, only NZEB requirements were selected for comparison with the energy performances of the proposed retrofit options.

EEMs are required to fill the gap between the Reference Hotel original performances and its NZEB *baseline* counterpart. In particular, the transmission heat transfer coefficient H'_T must be lowered by almost 2 times, a 32% reduction is required for the primary energy index $EP_{gl,tot}$ and a 65% reduction is necessary to meet the heating energy need requirements $EP_{H,nd}$. Conversely, cooling energy need limit slightly increased due to the better thermal envelope properties of the *baseline* RH.

Table 5. Minimum and NZEB requirements for the RH vs. RH performances.

Requirement	Limit values			RH
	2015	2021	NZEB	
H'_T		≤0,75		2,22
$A_{sol,est}/A_{net\ area}$		≤0,04		0,03
$EP_{H,nd}$	27,6	24,1		69,3
$EP_{C,nd}$	25,72	27,5		20,9
$EP_{gl,tot}$	182,9	180,2		265,3
$\eta_{H,}$		0,81 (u); 0,95 (g)		0,84 (u); 0,97 (g)
η_W		0,70 (u); 0,85 (g)		0,70 (u); 0,97 (g)
η_C		0,81 (u); 2,50 (g)		0,70 (u); 2,61 (g)
RES_{DHW}		50%		0%
$RES_{DHW+H+C}$		50% *		0%

Notes: * from January 2017, 50% is the minimum $RES_{DHW+H+C}$ for all new buildings and major renovations; (u) = use efficiency; (g) = generation efficiency

4.2. (II) Cost-optimal analysis towards the NZEB target

EEMs and Energy analysis. The creation process of packages of EEMs went along with the energy analysis towards the fulfilment of the NZEB level. Only packages meeting the envelope and energy needs performance requirements were further investigated in terms of primary energy performance and share of renewable energy. Figures 1, 2 and 3 display this combined energy analysis and packages selection procedure; in each figure the horizontal dotted line highlights the NZEB limit for the analyzed requirement and the yellow rectangles identify the retrofit solutions complying with it.

Figure 1 reports H'_T values of models implementing envelope related EEMs and shows that only packages envisaging an overall envelope upgrade (opaque + glazed surfaces) can satisfy minimum/NZEB requirements.

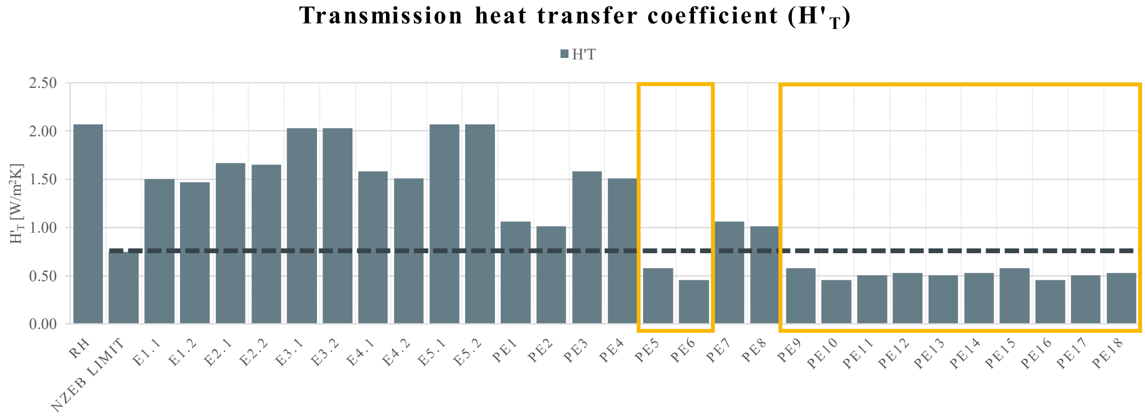

Figure 1. Heat transmission coefficient (*H'T*) of models implementing envelope EEMs and Packages of envelope EEM, in comparison with the NZEB limit value (dotted horizontal line). The yellow rectangles identify the retrofit solutions complying with the NZEB requirements.

Figure 2 reveals that only PE10L1.2, in which the combination of high level of insulation, fixed shadings and partial lights substitution was tested, is able to simultaneously meet the $EP_{H,nd}$ and $EP_{C,nd}$ requirements. In Figure 3, $EP_{gl,tot}$ and RES share of packages of EEMs including systems and plants measures are shown. It can be noticed that none of the retrofit options complies with both Primary Energy and Renewables limit values. Even if 10 packages are able to outperform the $EP_{gl,tot}$ and RES_{DHW} requirements, $RES_{DHW+H+C}$ is always below the mandatory minimum share.

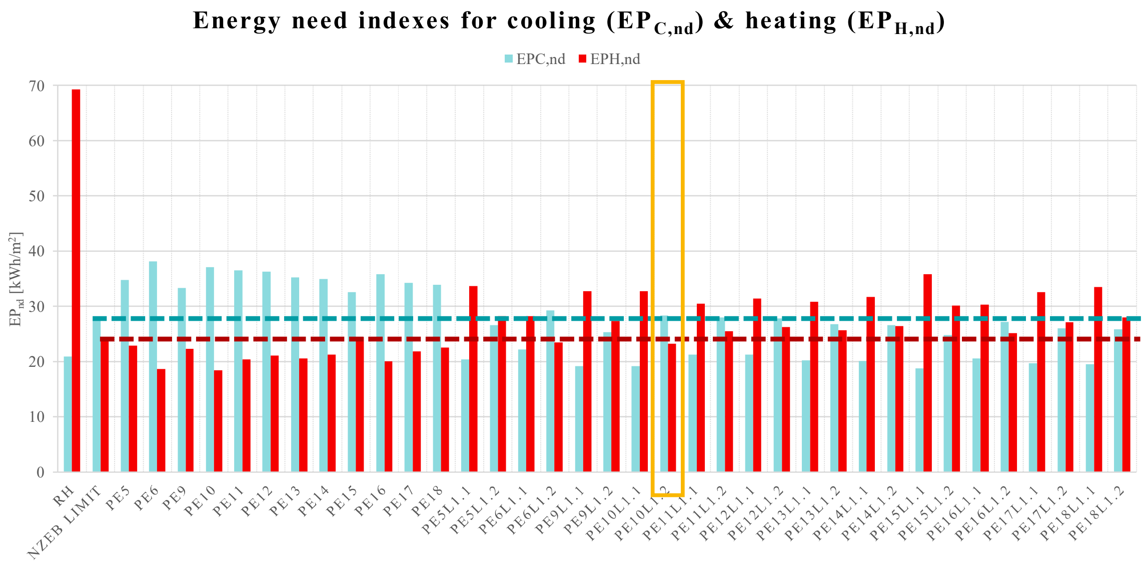

Figure 2. Cooling and Heating energy needs of models implementing packages of envelope EEM and packages of envelope&lights EEMs, in comparison with the NZEB limit value (dotted horizontal line). The yellow rectangle identifies the retrofit solution complying with the NZEB requirements.

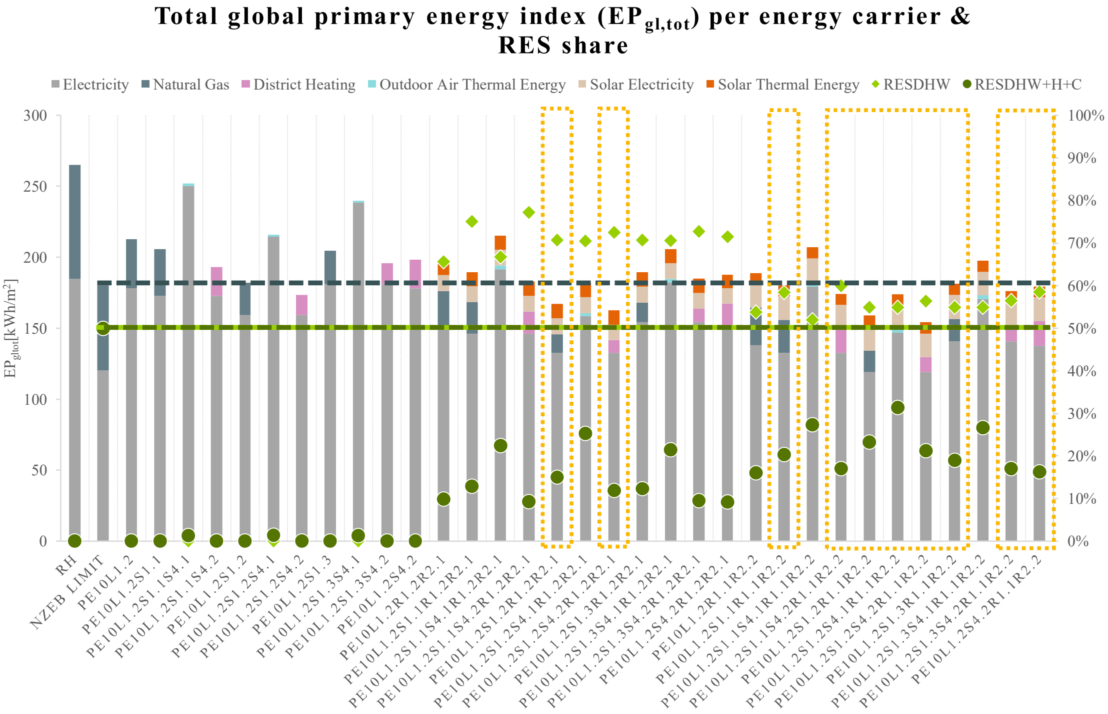

Figure 3. Total global primary energy index ($EP_{gl,tot}$) per energy carrier (on the left y-axis) and RES share (on the right y-axis) of models implementing packages of envelope, lights, systems, plants and RES EEMs, in comparison with the NZEB limit values (dotted horizontal lines). The yellow dotted rectangles identify the retrofit solutions complying with the NZEB primary energy requirements.

Reasons for the disappointing share of renewable energy sources may be found in the high electricity energy use for climatization purposes (fans and pumps, cooling and heating in case of heat-pump installation), that Photovoltaic (PV) panels on roof south slope cannot compensate. Additionally, the air-to-water heat-pump, when present, was not able to exploit the outdoor air thermal energy to produce heat. Despite the considered retrofit options are not able to formally reach the NZEB level, simulations results provide encouraging perspectives for the retrofit of existing hotels. The object of analysis is an energy-intensive building located in a densely-built context. These factors prevent the effective exploitation of RES. Nonetheless, the implementation of standard retrofit options allows the compliance with NZEB primary energy requirements.

Financial analysis and cost-optimal graph. In Figure 4 the primary energy and global cost data for all the simulated packages of EEMs are summarized in a scattered plot, from which the cost-optimal curve (red dotted line in the graph) is derived.

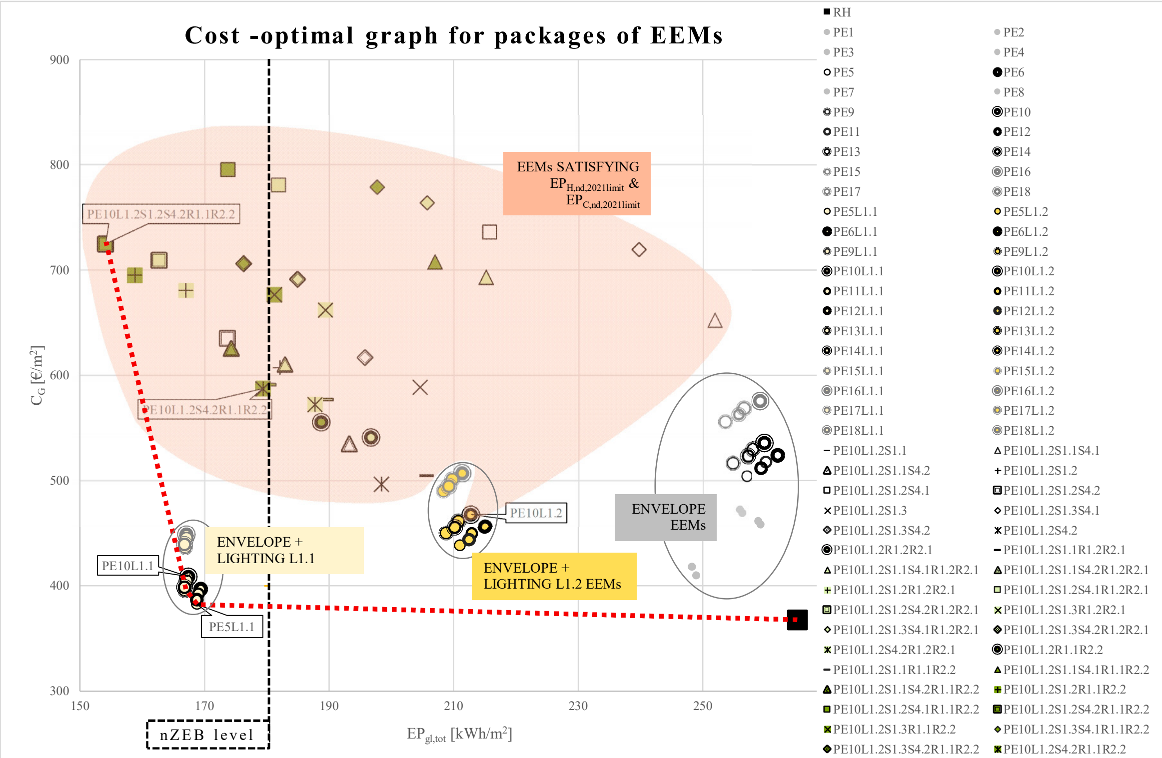

Figure 4. Cost-optimal graph, in comparison with NZEB primary energy requirements.

Results deceptively show that the cost-optimal option is represented by the RH without retrofit, as it has the lowest global cost. In general, the missing balance between investment costs and energy costs reduction is the reason for the recorded disappointing financial performances. However, undertaking an overall envelope and artificial lighting upgrade can significantly decrease the primary energy use of the hotel with an irrelevant increase in global cost. In particular, package PE5L1.1 shows the best combination of energy and financial performance. It entails a 4% increase in C_G and a significant -36% in the $EP_{gl,tot}$ with respect to the RH. Unfortunately, the promising primary energy performances of PE5L1.1 and similar packages do not allow to define them as NZEB retrofit options. Indeed, packages envisaging the overall substitution of artificial lights have too high heating energy needs, when compared to the NZEB limit (see Figure 2). Conversely, the top point of the cost-optimal curve – PE10L1.2S1.2S4.2R1.1R2.2 - meets the NZEB energy performance requirements (climatization needs and primary energy), with a 42% $EP_{gl,tot}$ reduction. Unfortunately, its C_G almost doubled (+97%) the RH's C_G. Other retrofits option meet both the energy needs and the primary energy requirements, presenting slightly higher $EP_{gl,tot}$ and lower C_G. Among them, PE10L1.1S4.2R1.1R2.2 shows the lowest global cost.

Based on Figure 4, it is possible to quantify the energy and financial performance gap between cost-optimal and NZEB retrofit options. The cost-optimal level of energy performance can be identified in the $EP_{gl,tot}$ of PE5L1.1 (169 kWh/m^2), while the NZEB $EP_{gl,tot}$ is fixed at 180 kWh/m^2. Therefore, in terms of Primary Energy, cost-optimal and NZEB level do overlap. However, the energy needs of the cost-optimal package of EEMs does not comply with the NZEB requirements. To evaluate the financial gap, the C_G of the cost-optimal package PE5L1.1 (382 €/m^2) is compared with the C_G of package satisfying the EP NZEB requirements with the lowest C_G (587 €/m^2), PE10L1.2S4.2R1.1R2. The important cost difference – 205 €/m^2 – stresses the existence of market barriers towards the market up-take of NZEB renovations. Additionally, it must be noted that package PE10L1.2S4.2R1.1R2.2, here identified as representative of an NZEB renovation, in fact cannot be considered a NZEB renovation, as it is not able to cover the minimum $RES_{DHW+H+C}$ (see Figure 3). To satisfy this requirement, additional PV or ST panels may be installed, entailing on the one hand decreased energy costs, on the other hand an increase in the initial investment costs. It is licit to infer that, in order to fully satisfy NZEB requirements, the financial gap will further widen.

4.3. (III) Thermal comfort analysis

The analysis aimed at investigating the thermal comfort conditions of a typical south-oriented guestroom during its occupied hours for all the analysed simulation models. The imposed operative conditions were based on the I Comfort Category, therefore the study focused on verifying the frequency of occupied hours during which the *PMV* values lied in the (-0,2)/(+0,2) range (i.e. the I CC limits) during the annual simulations.

Figure 5 is a Tukey box-and-whisker plot depicting the statistical distribution of hourly *PMV* values throughout the year. In the graph, each box represents the *PMV* values distribution for a specific simulation model. Models implementing RES EEMs were omitted, since these measures did not influence the comfort level with respect to the corresponding models without RES. For every box in the graph, bottom and top indicate the minimum and maximum *PMV* values within which 50% of the hourly data is included. The upper and lower whiskers specify the *PMV* variability outside the upper and lower quartiles. The dotted horizontal lines represent the Comfort Category limits. Using this type of graph, the most thermally comfortable solutions are represented by compact box-and-whisker elements (which stand for reduced *PMV* variations), with all values (i.e. the whiskers limits) comprised within the I Comfort Category *PMV* range.

Based on these considerations, results show that:

- an overall thermal envelope retrofit (PE5, PE6, from PE9 to PE18) reduces the *PMV* variability with respect to the RH and shifts the *PMV* distribution to higher values (i.e. warmer thermal sensations);
- reducing artificial lighting internal gains in thermally efficient models causes an increase in PMV values variability, with values out of the acceptability range (i.e. in IV CC) both towards hot and cold thermal sensations. Packages envisaging an overall lights replacement with LEDs show the wider distributions;
- system-related measures are the only ones able to maintain I CC *PMV* values for 50% of the time (i.e. the corresponding boxes are placed between the I CC limits) and to keep acceptable *PMV* values for the whole year (i.e. the whiskers limit are placed below or nearby the III CC limits). Among these packages, radiant ceiling (measure S1.3) shows the best comfort performances.

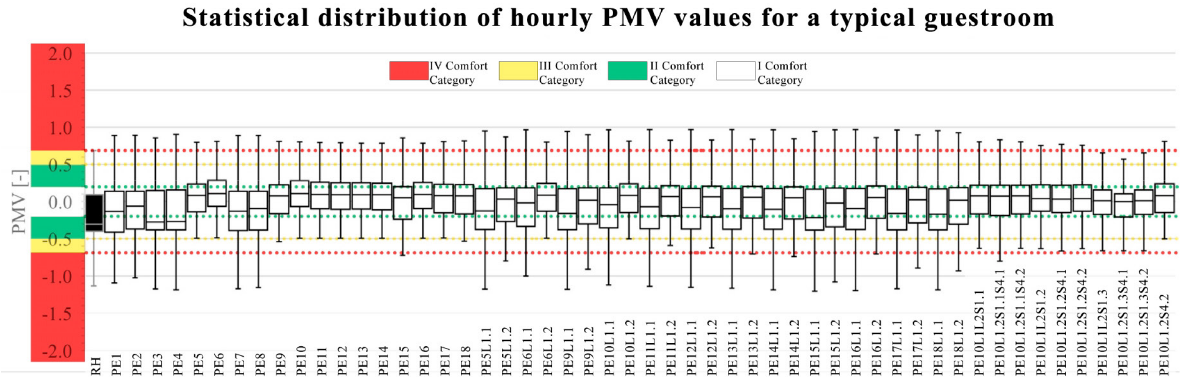

Figure 5. Statistical distribution of hourly PMV values in a typical RH guestroom in annual simulations of RH models implementing packages of envelope, lights, systems and plants EEMs.

In order to relate energy and thermal comfort performances, a comfort-optimal graph was built, as shown in Figure 6. It depicts a scattered plot where $EP_{gl,tot}$ of each simulated package of EEMs is plotted versus the corresponding percentage of time during which *PMV* values lie within the I CC limits.

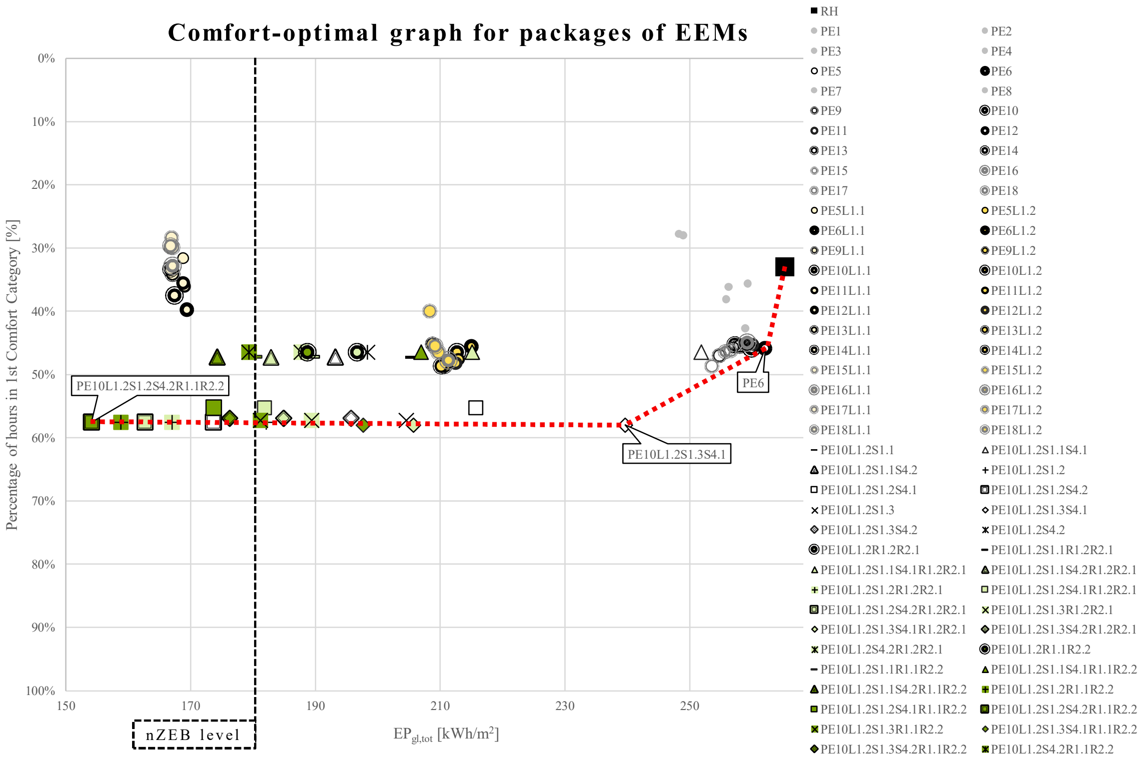

Figure 6. Comfort-optimal graph in comparison with NZEB primary energy requirements.

The comfort-optimal curve (red dotted line in Figure 6) identifies the comfort-optimal retrofit options as the packages implementing radiant floors/ceilings. Since internal comfort conditions disregard the installation of RES, the range of primary energy values included in the comfort-optimal range is wide. Among them, the lowest value is represented by PE10l1.2S1.2S4.1R1.1R2.2, which was the higher point of the cost-optimal curve (Figure 4). The comparison between Figures 4 and 6 highlights that packages of EEMs complying energy needs and primary energy NZEB requirements have contrasting economic and comfort performances. Packages with lower global costs (i.e. with better economic performance), such as PE10L1.2S4.2R1.1R2.2, have lower percentages of *PMV* values in the I Comfort Category (i.e. worst thermal comfort performance) and vice-versa. This combined analysis suggests that for a hotel building, where guests' comfort is a priority, financial convenience should not be considered as the only leading parameter to evaluate retrofit options.

5. Conclusions

This research was committed to investigate the existing performance gap between cost-optimal and NZEB retrofit options for a Reference Hotel and to the test indoor thermal quality of the considered design solutions. On the one hand, the goal was to inform policy-makers about the existence of technological and/or market barriers towards the market up-take of energy efficiency projects for multi-functional buildings, as hotels are. On the other hand, the study wanted to highlight that financial performances alone are not enough to guide investors towards the most successful retrofit intervention. For better informed investment choices, non-tangible co-benefits, such as users' comfort, should to be included in the evaluation. A comfort-optimal analysis was the solution here proposed to embody these considerations in the analysis of the RH.

The comparison between NZEB limit values and retrofit options energy performances provided encouraging perspectives for the existing non-residential building stock. Indeed, the implementation of business-as-usual retrofit options allowed the fulfilment of envelope, energy needs and primary energy requirements.

Conversely, the match between energy and financial performances for the simulated retrofit options gave disappointing results. Maintaining the original RH configuration turned out to be the most convenient option. It must be noted that a group of retrofit options showed a consistent energy use reduction together with a very slight increase in global cost with respect to the RH. In this cluster of models, an overall lighting upgrade played the leading role in the drop in energy use. Due to the minor technical interventions and the short-term return of the investment, lights substitution could be a favorite measure among hoteliers. Nonetheless, these retrofit options did not satisfy mandatory nor NZEB energy requirement. Any envisaged solution in line with NZEB limits had a global cost at least 50% higher than the cost-optimal solutions.

Coming to considerations on comfort, the study highlighted that only design solutions including systems-related measures were able to constantly maintain acceptable conditions. Additionally, models implementing packages of EEMs showed contrasting economic and comfort performances. Generally speaking, retrofit options with better economic performances showed worse comfort values.

Generalizing the obtained results, it may be inferred that there is still a significant mismatch between cost-optimal and NZEB retrofit solutions for Italian non-residential buildings. In these buildings, where electricity uses (lighting and appliances) are major responsible of the overall energy performances, the fulfilment of nZEB requirements does not allow to fully exploit the energy saving potential. On the other hand, however, the inclusion of comfort analysis could support the implementation of climatization-oriented retrofit measures, such as systems replacement, as they are able to improve indoor comfort conditions.

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