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A new procedure of energy audit and cost analysis for the transformation of a school into a nearly zero-energy building

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Abstract

The article presents the fundamental steps of building refurbishment toward the nZEB target; it is based on a detailed energy audit and on a financial analysis. The methodology starts from the set-up of a numerical model of the building, calibrated through actual data on operation, climate and energy consumption. Then, a cost-optimisation procedure is applied to identify the energy efficiency measures that determine the minimum global cost in 30 years lifetime. Finally, the measures are improved as to comply with the nZEB requirements and to be cost-effective as well. The methodology was applied to a high school in Torino.

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Keywords: building refurbishment; public building; school; nZEB; energy audit; cost-optimisation; building energy performance; model calibration; energy signature; energy efficiency measures.

1. Introduction

1.1. Energy audits of educational buildings

The Directive 2010/31/EU specifies that the public sector should lead the way in the field of energy performance of buildings and the national plans should set more ambitious targets for the buildings occupied by public authorities [1]. Among the public buildings, the educational buildings account 17% of the built area and 12% of the final energy use of the non-residential sector in Europe [2].

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Energy consumption benchmarks of existing schools are provided by several studies in the EU countries and high potentials for energy savings are generally revealed. The highest values of energy consumption occur in the schools of southern Finland; according to Sekki et al. [3], the yearly mean final energy consumption is 214 kWh·m^{-2} and 229 kWh·m^{-2} for primary schools and universities, respectively. In Slovenia, Butala and Novak [4] analysed a sample of 24 school buildings and found out an average total final energy consumption of 192 kWh·m^{-2} per year. Similar results, but considering space heating only, were got by Bull et al. [5], which simulated school building archetypes in United Kingdom. In Luxemburg, a sample of 68 schools showed thermal and electricity yearly consumptions of 93 and 32 kWh·m^{-2}, respectively [6]. The energy consumption data of schools in southern Europe are comparatively lower. For example, studies conducted in Cyprus show average yearly energy consumption of 63 kWh·m^{-2} including electricity and fuel [7].

The educational buildings in Italy are 51 000 units, with a built surface of 73.2 million m^2 and a volume of 256 million m^3. According to reports from CRESME [8] and ENEA [9], most of the schools were built in the period 1960-80, and 48% of the schools are located in the climatic zones E and F ($HDD > 2100$). The average yearly energy consumption amounts to 130 kWh·m^{-2} (thermal energy) and 20 kWh·m^{-2} (electricity) [10].

The knowledge of the building energy performance through effective energy assessment methodologies is necessary to set-up suitable retrofit measures able to increase the building energy efficiency. Energy and environmental audits allow to identify the building weaknesses and to provide potential improvements. Thus, the implementation of effective energy audits on educational buildings is crucial to identify suitable solutions aimed at reducing their high energy consumption.

Studies on the development of energy audits for educational buildings were conducted throughout Italy. In the north of Italy, a field survey was carried out to collect and process data on the actual energy consumption of 120 high schools in the district of Torino. The average yearly energy consumption for space heating of the sample revealed to be about 115 kWh·m^{-2} [11]. Other studies were conducted in the centre of Italy; Desideri and Proietti [12] presented two applications of energy audit for schools of the province of Perugia, and determined potential thermal and electrical energy savings. Studies in the south of Italy were carried out by Rospi et al. [13] for different typologies of schools in Matera. They carried out measurements and monitoring activities for energy audit and assessed the energy performance before and after the application of retrofit measures to the building envelope and to the technical building systems.

Several methodologies for the energy audit of educational buildings have been developed and applied. For instance, following the procedure of the EN 16247-2 Standard, Magrini et al. [14] applied the quasi-steady-state calculation method of the EN ISO 13790 Standard to carry out the energy audit of the University of Pavia. A simplified approach to the energy diagnosis has been followed for the School of Engineering and Architecture of Bologna; the standardized method of the energy signature reported in EN 15603 was applied by Marinosci et al. [15]. Other studies compared the actual energy consumption of school buildings with the energy performance estimated through dynamic and quasi-steady-state calculation methods [13]. Finally, some researchers developed tools that support local administrators to assess the energy performance of educational buildings through simple data input and to identify the most convenient energy efficiency measures easily [16].

Nomenclature

A	area	[m^2]
$b_{\mathrm{tr,U}}$	adjustment factor for heat transfer through unheated spaces	[-]
C	cost	[€]
COP	coefficient of performance	[-]
E	energy	[Wh]
EP	energy performance indicator	[kWh·m^{-2}]
F_{O}	occupancy dependency factor	[-]
GC	global cost	[€·m^{-2}]

H'	mean overall heat transfer coefficient	[$W \cdot m^{-2}K^{-1}$]	
HDD	heating degree-days	[°C]	
U	thermal transmittance	[$W \cdot m^{-2}K^{-1}$]	
V	gross conditioned volume	[m^3]	
W	power	[W]	
Greek symbols			
η	efficiency	[-]	
τ	transmission coefficient	[-]	
Subscripts			
C	space cooling	PV	photovoltaic (system)
c	heat control (subsystem)	ren	renewable (energy)
coll	solar collectors	sh	shading
del	delivered (energy)	sol	solar
env	building envelope	sum	summer
f, fl	floor	T	transport
fp	footprint on ground	tot	total
gl	global	tr	thermal transmission
gn	heat generation (subsystem)	U	unconditioned (space)
H	space heating	up	upper
L	lighting	V	ventilation
lw	lower	W	domestic hot water
nd	need (energy)	w	windows
nren	non-renewable (energy)	wl	wall
Pn	nominal power		
Acronyms			
CTER-SC	Calibrated Tailored Energy Rating with Standard Climate	nZEB	nearly Zero-Energy Building
DHW	Domestic Hot Water	OER	Operational Energy Rating
EEL	Energy Efficiency Level	PV	photovoltaic
EEM	Energy Efficiency Measure	RER	renewable energy ratio
EP	Energy Performance	SER	Standard Energy Rating
MD	Ministerial Decree	TER	Tailored Energy Rating

1.2. Nearly zero-energy schools: requirements and issues

The Italian Ministerial Decree (MD) 26/06/2015 [17], which implements the Law No. 90/2013 transposing the Directive 2010/31/EU, specifies minimum energy performance requirements for new buildings and buildings subject to renovation. The decree provides requirements differentiated in function of the extent of the building retrofit. For instance, the retrofit action that affects more than 50% of the building envelope area and includes the thermal system upgrading should meet stricter requirements. These requirements concern the energy performance of the building and the global efficiency of the technical building systems, and are determined through the notional reference building approach [18].

The thermo-physical parameters of the notional reference building are provided by the MD. The requirements for a public building subject to major renovation are listed in Table 1. A building is considered a nZEB when it complies with requirements obtained by adopting for the notional reference building the values enforced from 1st January 2019.

Due to the very low energy performance of the average Italian educational buildings, the transformation into nZEBs requires strong efforts. A study by Zeiler and Boxem [19] highlighted advantages and disadvantages of high efficiency schools compared with traditional educational buildings. Among the advantages there are increased energy efficiency and thermal comfort, and reduced total cost for the owner; for against, the very high investment cost is a drawback. According to de Santoli et al. [20], the energy performance of school buildings, as well as of public buildings in general, should be assessed taking into account not only energy implications but also economic and environmental aspects; first of all, it is necessary to quantify how many resources the government and local administrations need to undertake energy refurbishment of schools. As large funds are required and the Italian public sector is still limiting direct investments, a third party financing is usually necessary to promote energy retrofits provided that the investments are cost-effective [21].

Table 1. Requirements of nearly zero-energy public buildings according to MD 26/06/2015 [17].

Parameter	Limit value	Condition
H'_{tr} [W·m^{-2}K^{-1}]	Variable, in function of HDD and compactness factor	$H'_{tr} < H'_{tr,limit}$
$A_{sol,sum}/A_f$ [-]	Variable, in function of the building category	$(A_{sol,sum}/A_f) < (A_{sol,sum}/A_f)_{limit}$
$EP_{H,nd}$ [kWh·m^{-2}] $EP_{C,nd}$ [kWh·m^{-2}] $EP_{gl,tot}$ [kWh·m^{-2}]	Variable, to be determined by means of the notional reference building	$EP_{H,nd} < EP_{H,nd,limit(2019)}$ $EP_{C,nd} < EP_{C,nd,limit(2019)}$ $EP_{gl,tot} < EP_{gl,tot,limit(2019)}$, $EP_{gl,tot}=EP_H+EP_C+EP_W+EP_V+EP_L+EP_T$
η_H [-] η_C [-] η_W [-]	Variable, to be determined by means of the notional reference building	$\eta_H > \eta_{H,limit}$ $\eta_C > \eta_{C,limit}$ $\eta_W > \eta_{W,limit}$
RER_{H+C+W} [-] (1,2)	Fixed	$RER_{H+C+W} > 0.55$
RER_W [-] (1,2)	Fixed	$RER_W > 0.55$
W_{PV} [kW] (1)	Variable, in function of the building footprint area	$W_{PV} > (A_{fp}/50)\cdot 1.10$

(1) According to Legislative Decree No. 28/2011, Annex 3.

(2) The requirements do not apply in case of district heating for space heating and domestic hot water.

1.3. Objective of the work

The article presents a new energy audit methodology that complies with the guidelines provided by the EN 16247-2 Standard. The purpose is to propose a detailed energy diagnosis procedure as to identify cost-effective and feasible technical solutions that meet the nZEB requirements and are based on cost-optimal analysis as well. The process consists of the following main activities: 1) set-up of a numerical model of the building and calibration of the model; 2) choice of a set of energy efficiency measures feasible for a major renovation; 3) identification of the cost-optimal package of energy efficiency measures; and 4) improvement of the cost-optimal solution to comply with the nZEB requirements, if needed.

The methodology was applied to a technical high school in Torino built in the ‘40s. The final aim is to provide public administrators with an effective and manageable instrument useful to find out weaknesses in the building energy behaviour and to identify cost-effective retrofit actions for transforming low energy efficiency schools into nZEBs.

2. Method

2.1. New detailed energy diagnosis procedure

The EN 16247-2 Standard [22] provides requirements, methodology and deliverables for the energy audits of buildings. The overall process flow of an energy audit includes the following activities: preliminary contact, start-up meeting, collection of data, field work, analysis, report and final meeting. The present work aims at deepening the phase of analysis by providing a detailed procedure for the building energy modelling, the energy performance assessment and the identification of cost-effective and technically feasible energy efficiency measures fit to reach the nZEB target. The flowchart of the proposed methodology is shown in Fig. 1.

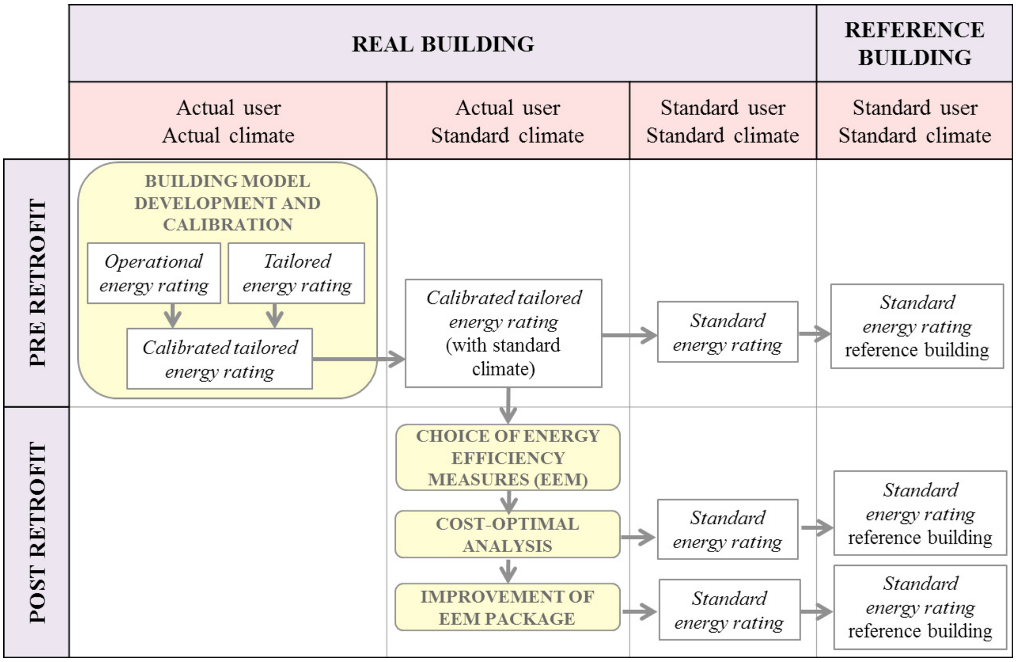


Fig. 1. Flowchart of detailed energy audit procedure.

The analysis is divided into two phases: pre retrofit and post retrofit. According to the object of evaluation, each phase includes different energy ratings, as shown in Fig. 1 (white boxes). The differences between the energy ratings concern the types of user and climate, which can be either actual or standard.

The whole analysis activity includes four steps, which are shown in the yellow boxes of Fig. 1. The building model development and calibration refer to the pre retrofit phase and to the actual boundary conditions. An operational energy rating (OER) and a tailored energy rating (TER) are carried out to assess the building energy performance (EP) in the current state. The OER includes the collection and processing of real energy consumption data. The TER consists in the creation of a building model and in the calculation of the EP considering real occupancy and climate. A good matching between the results of these two energy ratings should be assured, through the model calibration. Once the model is calibrated, further energy rating is carried out considering the actual user data but a standard climate (CTER-SC); in this way, the energy saving potential is not affected by specific weather data. Finally in the pre retrofit phase, a standard energy rating (SER), with standard user and climatic data, can be performed if the issue of the energy performance certificate is needed. In addition, the standard energy rating of the notional reference building is carried out to complete the EP classification scheme.

The choice of the energy efficiency measures, the cost-optimal analysis, and the improvement of the package of energy efficiency measures are included in the post retrofit phase analysis and are carried out on the CTER-SC model. The choice of the energy efficiency measures (EEMs) to be applied to the existing building should consider technical feasibility and other criteria established by the energy auditor. The cost-optimal analysis allows to find out the cost-effective package of EEMs that determines the lowest global cost in the building lifecycle. Carrying out a SER with the cost-optimal EEMs package, the compliance with the nZEB requirements is verified. In case the optimal solution does not comply, an improvement of the EEMs package can be done by selecting specific EEMs and then assessing the building EP again and verifying the compliance with the requirements. Economic evaluations to determine global cost and payback period of the selected packages are carried out by the same tool used for cost-optimisation.

The standard energy ratings are performed both to verify the requirements and to determine the energy performance class of the building transformed into nZEB.

2.2. Calculation methods

The following energy and cost evaluation methods have been applied in the energy audit procedure described in Section 2.1:

- quasi-steady-state EP calculation, as specified in the UNI/TS 11300 Standards series [23], which mainly refers to the calculation procedure of EN ISO 13790 [24] and EN 15316 series [25]. The renewable and non-renewable primary energy factors were derived from MD 26/06/2015;
- calculation of economic parameters, such as global cost and payback period, according to the EN 15459 Standard [26], considering a building lifespan of 30 years and a real interest rate of 3%;
- cost-optimal analysis based on a sequential search-optimisation technique that considers a discrete number of options, as described in Corrado et al. [27].

3. Case study

3.1. Description of the building

The case study (see Fig. 2) is a technical high school in Torino built in the '40s; the school gym, separate from the main building, was erected in a more recent period. The building is representative of more than 80% of the educational buildings located in the climatic zone E ($2101 \leq HDD \leq 3000$) as concerns the construction features and the characteristics of the thermal systems. The main geometrical data and the U-values of the building envelope components are listed in Table 2.

a

b


Fig. 2. Pictures of the building: (a) façade with the main entrance of the school; (b) façade on the internal court and the gym (on the left).

Table 2. Main geometric and construction data of the case study.

Geometric data						Building envelope components U-values [W·m^{-2}K^{-1}]					
V [m^3]	A_f [m^2]	A_{env} [m^2]	A_{env}/V [m^{-1}]	A_w [m^2]	No. of storeys	$U_{wl,school}$	$U_{wl,gym}$	$U_{fl,up}$	$U_{fl,lw}$	$U_{w,1}$	$U_{w,2}$
47223	8935	11549	0.24	1399	4	1.41	1.04	1.65	1.25	4.25	2.80

The opaque envelope of the main building has solid brick cavity walls, while the external walls of the gym are made of hollow bricks. The main building has unconditioned underground and attic spaces. The floors facing the unconditioned spaces have uninsulated reinforced brick-concrete slabs. Two types of windows are in the school: single glazing with wood frame (w,1) and double glazing with metal frame (w,2). Most of the windows have external wood shutters and internal solar shading devices.

Two gas standard heat generators with a total power of 1860 kW are installed in the building. The heat distribution subsystem is composed by six different circuits that operate independently each with its own heat control system. The heat emitters are radiators, located on the walls facing outdoor; just a limited number of rooms present convectors. The gym and the conference room are equipped with a mechanical ventilation system with an air handling unit and a heat recovery unit. The building is not provided with space cooling and DHW systems. The most used lighting devices are fluorescent lamps.

All data concerning the building construction and systems were derived from technical documents of the building and in field surveys.

3.2. Data on occupancy, climate and actual energy consumption

Hourly profiles of occupants' presence for each weekday and room category were set up by means of surveys and documents providing information about the number of students and school staff. Five different rooms categories were considered in function of the activity: classrooms, laboratories, offices, gym and unoccupied rooms. For each category, the hourly occupancy profiles of a typical week were used to model the internal heat gains and the operation of the lighting system. The opening schedule of windows and the operation of shutters and shading devices were detected through questionnaires.

An intermittent schedule was assumed for the space heating system, according to the users presence. The set-point temperature is 20 °C in all conditioned spaces.

The climatic data were derived from the weather database of the Regional Agency for Environmental Protection - ARPA Piemonte. Three heating seasons were considered, 2012/13, 2013/14 and 2014/15, consistently with the available data on the real energy consumption.

3.3. Modelling options

The building was divided into 20 thermal zones, in such a way as to separately model the different room categories, the heat distribution circuits, the types of heat emitters and the ventilation modes (natural or mechanical). According to UNI/TS 11300-1:

- the linear thermal transmittance values of thermal bridges were derived from a catalogue based on numerical calculation carried out in accordance with EN ISO 10211 [28];
- the internal heat capacity was determined as in EN ISO 13786 [29];
- the heat transfer through unheated spaces was calculated by means of the adjustment factor $b_{\mathrm{tr,U}}$, according to EN ISO 13789 [30];
- the mean monthly ventilation flow rate was assessed taking into account the actual users presence and the opening schedule of windows;
- the sensible heat flow from occupants, electric equipment and lighting devices was derived from scientific literature and modelled according to the hourly profiles of users' presence (see Section 3.2).

3.4. Energy efficiency measures for refurbishment and related costs

The chosen energy efficiency measures (EEMs) are listed in Table 3. They concern both the building envelope (EEM1-EEM6) and the technical building systems (EEM7-EEM12). For each EEM, up to four efficiency levels (EELs) quantified through suitable parameters are considered. They include different *U*-values of the envelope components, which correspond to typical thermal insulation levels of common retrofit actions up to advanced renovations. In case of heat generator replacement (EEM7), the levels refer to different technologies, such as gas condensing boiler (EEL1), biomass boiler (EEL2), district heating (EEL3) and air-to-water heat pump (EEL4). The DHW production is partially covered by thermal solar system in EEM8 from EEL1 to EEL3, while DHW plus space heating are considered in EEL4. EEM11 refers to the installation of thermostatic valves. Finally, EEM12 concerns the lighting system upgrading (fluorescent or LED lamps plus automatic control). The related investment costs are reported in Table 3; they come from a market survey and include design, purchase, installation and commissioning, excluding VAT. The energy costs and their trend scenarios, the maintenance costs and the technical lifespan of the components were derived from previous studies [27,31].

Table 3. Energy efficiency measures (EEMs) and related levels (EELs).

No	EEM	Parameter	EEL1	EEL2	EEL3	EEL4
1	External wall thermal insulation	U_{wl} [$W\cdot m^{-2}K^{-1}$]	0.30	0.26	0.20	
		C/A [€$\cdot m^{-2}$]	43	49	75	
2	Unheated spaces wall thermal insulation	$U_{wl,U}$ [$W\cdot m^{-2}K^{-1}$]	0.60	0.52	0.40	
		C/A [€$\cdot m^{-2}$]	12	15	18	
3	Upper floor thermal insulation	$U_{fl,up}$ [$W\cdot m^{-2}K^{-1}$]	0.25	0.22	0.20	
		C/A [€$\cdot m^{-2}$]	46	53	44	
4	Lower floor thermal insulation	$U_{fl,lw}$ [$W\cdot m^{-2}K^{-1}$]	0.30	0.26	0.20	
		C/A [€$\cdot m^{-2}$]	20	27	44	
5	Window replacement	U_w [$W\cdot m^{-2}K^{-1}$]	1.90	1.80	1.40	1.16
		C/A [€$\cdot m^{-2}$]	114	120	124	150
6	Solar shading system	τ_{sh} [-]	0.40	0.25		
		C/A [€$\cdot m^{-2}$]	50	70		
7	Heat generator replacement	$\eta_{gn,Pn}$ or COP [-]	1.10	0.90	0.99	4.30
		$C^{(1)}$ [k€]	85.0	197.5	43.7	174.0
8	Thermal solar system	A_{coll} [m^2]	6	10	16	100
		C [k€]	6.79	6.92	10.2	133
9	PV system	W_{PV} [kW]	20	40	60	80
		C [k€]	19.8	54.7	122	151
10	Heat recovery	η_V [-]	0.90			
		C [k€]	35.5			
11	Heating control system	$\eta_{H,c}$ [-]	0.995			
		C [k€]	43.7			
12	Lighting system	W/A_f [$W\cdot m^{-2}$]	7.91	7.91	4.34	4.34
		F_O [-] $^{(2)}$	1	0.90	1	0.90
		C [k€]	26.7	26.7	120	120

$^{(1)}$ Cost variable in function of the nominal power: the reported values refer to 800 kW.

$^{(2)}$ EN 15193. Energy performance of buildings – Energy requirements for lighting [32].

4. Results

4.1. Calibrated energy model

The operational energy rating (OER) was performed considering the real consumption data of natural gas for space heating over 3 heating seasons (2012/13, 2013/14, 2014/15) collected from energy bills. The calibration of the model did not include the annual electricity consumption as no real data were provided. The calibration was carried out through the energy signature, which consists of a correlation between heating energy use and average outdoor temperature, according to EN 15603 [33]. The energy signatures obtained by the tailored energy rating (TER) and by the OER were compared. In Figs. 3a and 3b, the results before and after the calibration process are reported. Some refinements of the model were needed, as follows:

- the HDD and the outdoor mean air temperature were corrected in such a way as to not consider the unoccupied periods (e.g. holidays, weekends);
- the set-point temperature was reduced to 19.5 °C to consider the non-ideal heat control system that causes variations of ±0.5 °C around the prefixed set-point of 20 °C;
- more accurate evaluation of the sensible thermal emission of the occupants, according to ISO 18523-1 [34];
- an adjustment of the operational schedule of the distribution subsystem.

At the end of the calibration process, an average deviation of 2% between the OER and the TER is revealed.

As described in Section 2.1., a tailored energy rating with standard climate was performed on the calibrated model (CTER-SC). This represent the baseline to carry out the subsequent post retrofit phase analysis. Fig. 4 shows the renewable (in green) and the non-renewable (in red) energy performance of the building, for the different energy services, resulting from the CTER-SC. The total global energy performance of the building, defined as the ratio of the yearly primary energy use to the conditioned floor area, is about 160 kWh·m^{-2}, and the related global cost over 30 years is 349 €·m^{-2}, of which 335 €·m^{-2} is energy cost. According to the national methodology for the energy classification of buildings [35] the school is classified as D, with 249 kWh·m^{-2} of yearly non-renewable primary energy use.

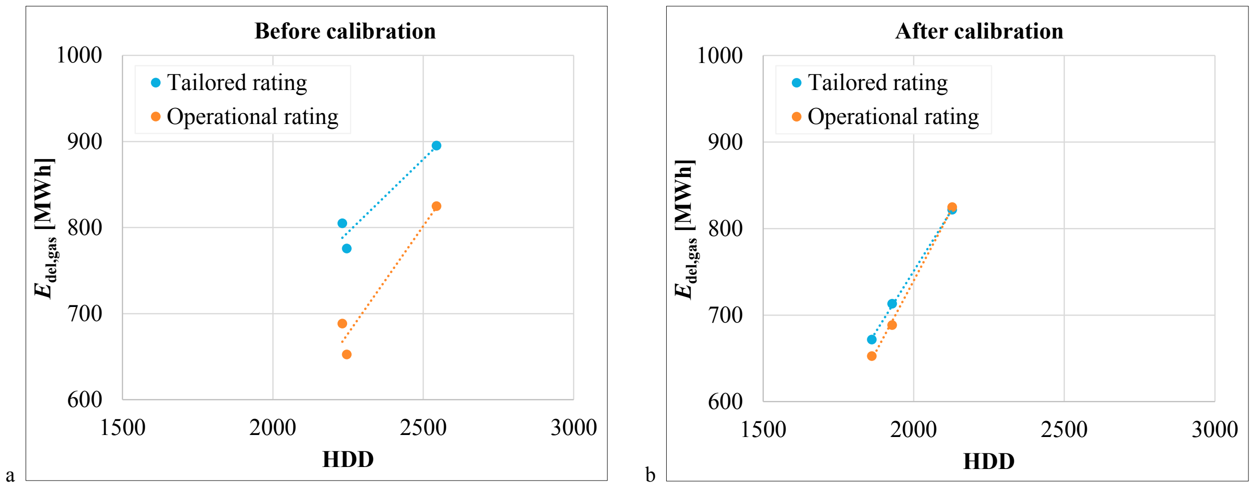


Fig. 3. Energy signature of tailored and operational ratings before (a) and after (b) model calibration.

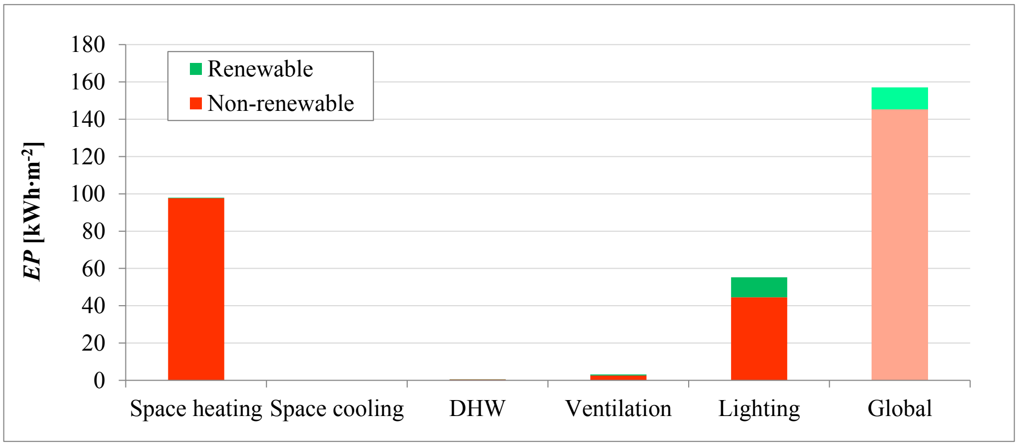


Fig. 4. Renewable and non-renewable primary energy performance of the building by energy service and global. Results of the calibrated tailored rating with standard climatic data.

4.2. Cost-optimal and nZEB solutions

Table 4 shows the package of EEMs resulting from the cost-optimal analysis, i.e. the set of EEMs that determines the lowest global cost in the building lifecycle, and the choice of up to three technical solutions aimed at achieving the nZEB target. Indeed, the cost-optimal solution does not imply a major renovation and does not meet some requirements (see the values in bold in Table 5).

The nZEB solution No. 1 differs from the cost-optimal one for an increased thermal insulation of both opaque and transparent components. Moreover, it is proposed the substitution of the luminaire with high efficient LED lamps, an increased peak power of the PV system, the replacement of the heat generator with a heat pump and the installation of external movable shadings. The solar collectors, the heating control system and the heat recovery ventilation system are maintained with respect to the cost-optimal solution. The nZEB solution No. 2 differs from the previous one for the replacement of the heat generation with a heat exchanger suitable for the connection with the district heating. The solar collectors are still considered for the DHW production. Anyway this solution could not be considered nearly zero-energy as it does not satisfy the 55% of RER required by law; nevertheless, according to the Legislative Decree No. 28/2011, in case of district heating use, the RER requirements are already satisfied. The nZEB solution No. 3 takes into account the use of a biomass heat generator coupled with a storage tank of 5800 liters, while the other EEMs are the same of the previous retrofit solutions.

Fig. 5a shows the global EP index of the existing building (CTER-SC model) compared to the cost-optimal and the nZEB retrofits. The most efficient solution is the nZEB3, which greatly increases the EP of the building and the share of renewable primary energy. Fig. 5b illustrates the overall cost related to the proposed solutions. The less convenient solution is the nZEB3, which on the contrary is the most energy performant. This is due to the high cost of the biomass system, that includes the installation of the generator and the replacement costs during the whole life cycle (e.g. filters). Instead, the solution nZEB1 deeply reduces the energy cost, even if it involves an increased cost of investment. Of the three nZEB solutions proposed, the No. 2 has the lowest global cost, but provides for the use of district heating, currently not present in situ.

While the nZEB1 and nZEB2 solutions are cost-effective, the nZEB3 is not cost effective over 30 years building lifespan. In terms of energy classification, all the nZEB solutions allow to move from class D to class A (classes A3, A2 and A4, respectively).

Table 4. Cost-optimal and nZEB retrofit measures.

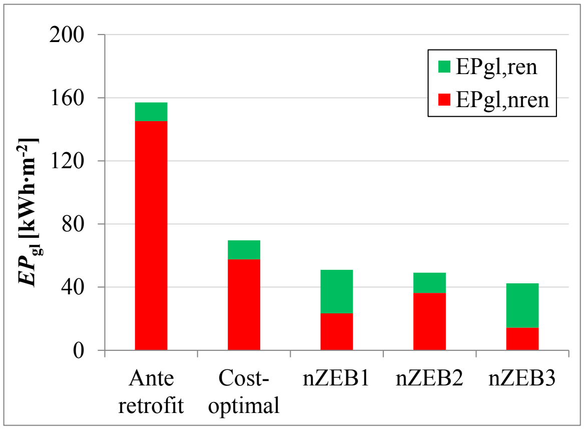
No.	EEM Parameter	Cost-optimal	nZEB1	nZEB2	nZEB3
1	U_{wl} [W·m^{-2}K^{-1}]	0.30	0.20	0.20	0.20
2	$U_{wl,U}$ [W·m^{-2}K^{-1}]	0.40	0.40	0.40	0.40
3	$U_{fl,up}$ [W·m^{-2}K^{-1}]	0.20	0.20	0.20	0.20
4	$U_{fl,lw}$ [W·m^{-2}K^{-1}]	-	0.20	0.20	0.20
5	U_{w} [W·m^{-2}K^{-1}]	-	1.40	1.40	1.40
6	τ_{sh} [-]	-	0.25	0.25	0.25
7	$\eta_{gn,Pn}$ or COP [-]	-	4.3	0.99	0.90
8	A_{coll} [m^2]	-	6	6	6
9	W_{PV} [kW]	40	80	80	80
10	η_V [-]	0.9	0.9	0.9	0.9
11	$\eta_{H,c}$ [-]	0.995	0.995	0.995	0.995
12	W/A_f [W·m^{-2}]	7.91	4.34	4.34	4.34
	F_O [-]	0.9	1.0	1.0	1.0

Table 5. Check of nZEB requirements.

Technology	Parameter	*Limit value*	Cost-optimal[(1)]	nZEB1	nZEB2	nZEB3
-	H'_{tr} [W·m^{-2}K^{-1}]	*0.75*	0.64	0.33	0.33	0.33
-	$A_{sol,sum}/A_f$ [-]	*0.04*	**0.13**	0.03	0.03	0.03
-	$EP_{H,nd}$ [kWh·m^{-2}]	*26.7*	23.0	25.9	25.9	25.9
-	$EP_{C,nd}$ [kWh·m^{-2}]	*19.0*	**39.0**	13.4	13.4	13.4
Heat pump	$EP_{gl,tot}$ [kWh·m^{-2}]	*81.0*	-	71.0	-	-
	η_H [-]	*1.24*	-	1.37	-	-
	η_W [-]	*0.51*	-	0.55	-	-
District heating	$EP_{gl,tot}$ [kWh·m^{-2}]	*83.0*	-	-	68.3	-
	η_H [-]	*1.15*	-	-	1.41	-
	η_W [-]	*0.52*	-	-	0.55	-
Biomass boiler	$EP_{gl,tot}$ [kWh·m^{-2}]	*78.0*	-	-	-	57.5
	η_H [-]	*1.27*	-	-	-	1.85
	η_W [-]	*0.52*	-	-	-	0.55
-	RER_{H+C+W} [-] [(2)]	*0.55*	**0.02**	0.55	0.04	0.74
-	RER_W [-] [(2)]	*0.55*	**0.40**	0.60	0.60	0.60
-	W_{PV} [kW]	*49*	**40**	80	80	80

(1) The values in bold refer to the requirements not met.

(2) The requirements do not apply in case of district heating for space heating and DHW.



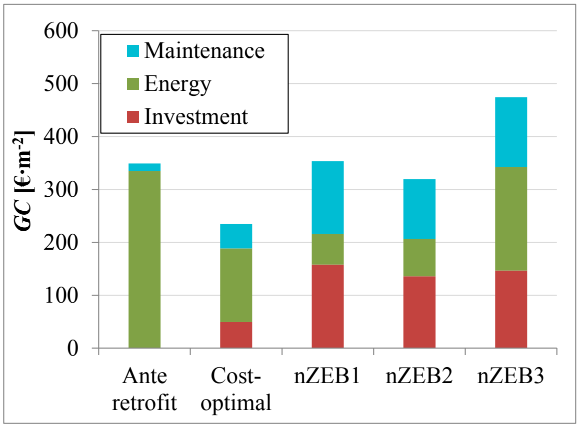


Fig.5. Comparisons between existing building, cost-optimal and nZEB solutions: global energy performance (a) and global cost (b).

5. Conclusions

The activity involved the energy audit of a building in Torino, which is representative of the school building stock in the Italian climatic zone E. The purpose of the article is to propose a detailed energy audit framework that allows to meet the current energy requirements as well as to assess the economic feasibility. The proposed approach starts from a tailored energy rating and from the calibration of the model through the comparison with the outcomes of an operational rating. The further calculations are referred to the actual user and to a standard climate. The energy efficiency measures, which can be adopted in a major renovation, are chosen by applying the cost-optimal procedure and then by upgrading the chosen packages of measures as to meet the nearly zero-energy target.

The analysis shows the feasibility of the transformation of the school in nearly zero-energy building, through the adoption of advanced technology systems that exploit renewable energy sources, such as heat pump or biomass generator. It is also essential to carry out a financial analysis, in order to choose between the available energy measures, ones that ensure acceptable payback period. Among the cases analysed, the adoption of the heat pump associated with PV panels, mechanical ventilation with heat recovery and high efficiency lighting system, can satisfy both the energy requirements by law and the economic feasibility. In case of presence of a district heating network, this solution is a possible alternative to the heat pump. The adoption of a biomass heat generator is a valid solution in terms of energy efficiency, but the costs are still too high.

A possible solution to the challenges of the high costs for the building renovation towards nZEBs, especially for public buildings, is reported in the national action plan for the nZEBs: structural funds will be provided during the period 2014-2020 for measures that will increase the energy efficiency and that will reduce the consumption in buildings and public facilities or public use. Specifically, in order to increase the incidence of the nZEBs, buildings or groups of buildings belonging to the central government and occupied by it will be identified by means of energy auditing, giving priority to the refurbishment of the buildings with the lowest energy performance, if the renovation is efficient in terms of costs and technically feasible. To this end, the presented methodology can be a valid instrument and easily replicable on a large scale.

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References

[1] European Parliament. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union, 18 June 2010.

[2] Atanasiu B, Despret C, Economidou M, Maio J, Nolte I, Rapf O. *Europe's buildings under the microscope. A country-by-country review of the energy performance of buildings*. Brussels: Buildings Performance Institute Europe (BPIE); 2011.

[3] Sekki T, Airaksinen M, Saari A. Measured energy consumption of educational buildings in a Finnish city. *Energy Build* 2015; 87:105-115.

[4] Butala V, Novak P. Energy consumption and potential energy savings in old school buildings. *Energy Build* 1999; 29:241-246.

[5] Bull J, Gupta A, Mumovic D, Kimpian J. Life cycle cost and carbon footprint of energy efficient refurbishments to 20th century UK school buildings. *Int J Sustain Built Environ* 2014; 3:1-17.

[6] Thewes A, Maas S, Scholzen F, Waldmann D, Zürbes A. Field study on the energy consumption of school buildings in Luxembourg. *Energy Build* 2014; 68:460-470.

[7] Katafygiotou MC, Serghides DK. Analysis of structural elements and energy consumption of school building stock in Cyprus: Energy simulations and upgrade scenarios of a typical school. *Energy Build* 2014; 72:8-16.

[8] Italian Economic Social Market for Construction and Land Research Centre (CRESME). *RIUSO03. Ristrutturazione edilizia, riqualificazione energetica, rigenerazione urbana*. Rome: CRESME; 2014 (in Italian).

[9] Citterio M, Fasano G. *Indagine sui consumi degli edifici pubblici (direzionale e scuole) e potenzialità degli interventi di efficienza energetica*. Rome: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA); 2009 (in Italian).

[10] Italian Ministry of Economic Development. *STREPIN - STrategia per la Riqualificazione Energetica del Parco Immobiliare Nazionale*; 2015 (in Italian).

[11] Corgnati SP, Corrado V, Filippi M. A method for heating consumption assessment in existing buildings: A field survey concerning 120 Italian schools. *Energy Build* 2008; 40:801-809.

[12] Desideri U, Proietti S. Analysis of energy consumption in the high schools of a province in central Italy. *Energy Build* 2002; 34:1003-1016.

[13] Rospi G, Cardinale N, Intini F, Cardinale T. Analysis of energy consumption of different typologies of school buildings in the city of Matera (Southern Italy). *Energy Procedia* 2015; 82:512-518.

[14] Magrini A, Gobbi L, d'Ambrosio FR. Energy audit of public buildings: the energy consumption of a University with modern and historical buildings. Some results. *Energy Procedia* 2016; 101:169-175.

[15] Marinosci C, Morini GL, Semprini G, Garai M. Preliminary energy audit of the historical building of the School of Engineering and Architecture of Bologna. *Energy Procedia* 2015; 81:64-73.

[16] Zanni D, Righi A, Dalla Morra T, Peron F, Romagnoni P. The Energy improvement of school buildings: analysis and proposal for action. *Energy Procedia* 2015; 82:526-532.

[17] Italian Ministry of Economic Development. Ministerial Decree 26/06/2015. Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici. Official Journal of the Italian Republic, 15 July 2015 (in Italian).

[18] Corrado V, Ballarini I, Dirutigliano D, Murano G. Verification of the new Ministerial Decree about minimum requirements for the energy performance of buildings. *Energy Procedia* 2016; 101:200-207.

[19] Zeiler W, Boxem G. Net-zero energy building schools. *Renew Energy* 2013; 49:282-286.

[20] de Santoli L, Fraticelli F, Fornari F, Calice C. Energy performance assessment and a retrofit strategies in public school buildings in Rome. *Energy Build* 2014; 68:196-202.

[21] Dall'O' G, Sarto L. Potential and limits to improve energy efficiency in space heating in existing school buildings in northern Italy. *Energy Build* 2013; 67:298-308.

[22] European Committee for Standardisation (CEN). EN 16247-2:2014. Energy audits - Part 2: Buildings.

[23] Italian National Organisation for Standardisation (UNI). UNI/TS 11300 series (2010-2016). Energy performance of buildings.

[24] European Committee for Standardisation (CEN). EN ISO 13790:2008. Energy performance of buildings - Calculation of energy use for space heating and cooling.

[25] European Committee for Standardisation (CEN). EN 15316 series (2017). Energy performance of buildings - Method for calculation of system energy requirements and system efficiencies.

[26] European Committee for Standardisation (CEN). EN 15459:2007. Energy performance of buildings - Economic evaluation procedure for energy systems in buildings.

[27] Corrado V, Ballarini I, Paduos S. Assessment of cost-optimal energy performance requirements for the Italian residential building stock. *Energy Procedia* 2014; 45:443-452.

[28] European Committee for Standardisation (CEN). EN ISO 10211:2007. Thermal bridges in building construction - Heat flows and surface temperatures - Detailed calculations.

[29] European Committee for Standardisation (CEN). EN ISO 13786:2007. Thermal performance of building components - Dynamic thermal characteristics - Calculation methods.

[30] European Committee for Standardisation (CEN). EN ISO 13789:2007. Thermal performance of buildings - Transmission and ventilation heat transfer coefficients - Calculation method.

[31] Corrado V, Murano G, Paduos S, Riva G. On the Refurbishment of the Public Building Stock Toward the Nearly Zero-energy Target: Two Italian case studies. *Energy Procedia* 2016; 101:105-112.
[32] European Committee for Standardisation (CEN). EN 15193:2007. Energy performance of buildings - Energy requirements for lighting.
[33] European Committee for Standardisation (CEN). EN 15603:2008. Energy performance of buildings - Overall energy use and definition of energy ratings.
[34] International Organisation for Standardisation (ISO). ISO 18523-1:2016. Energy performance of buildings - Schedule and condition of building, zone and space usage for energy calculation - Part 1: Non-residential buildings.
[35] Italian Ministry of Economic Development. Ministerial Decree 26/06/2015. Adeguamento linee guida nazionali per la certificazione energetica degli edifici. Official Journal of the Italian Republic, 15 July 2015 (in Italian).