Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 140 (2017) 252–264

Energy Procedia

www.elsevier.com/locate/procedia

AiCARR 50th International Congress; Beyond NZEB Buildings, 10-11 May 2017, Matera, Italy

Criticalities in the NZEB retrofit of scholastic buildings: analysis of a secondary school in Centre Italy

Daniele Testi*, Michele Rocca, Elena Menchetti, Simona Comelato

Dept. of Energy, Systems, Territory and Constructions Engineering (DESTEC), University of Pisa, Largo Lucio Lazzarino, 56122 Pisa, Italy.

Abstract

In Italy, the recast of the European Directive on Energy Performance of Buildings (2010/31/EU) is implemented with specific definitions and deadlines for Nearly Zero Energy Buildings. We focus our attention on schools, not only for their social importance and high visibility, but also because in the next future a significant share of these buildings is likely to undergo refurbishment for different purposes than the energetic one. We start to analyze the criticalities associated with the current Italian legislation on NZEBs by means of a bottom-up approach: we choose a benchmark secondary school (located in Pisa, hosting about 750 students) and perform an accurate energy audit of the building system, together with an energy and economic simulation of an NZEB retrofit. More in detail, we present the case study and explain its choice as an appropriate representative of the existing scholastic buildings in Centre Italy; besides, we build two concurrent energy models, based on tailored and asset rating methods, we propose technically-feasible actions for deep renovation, and simulate, for both models, the associated energy and economic savings after 20 years of use. We observe long payback periods of the retrofit measures, due to low yearly energy uses in the existing configuration. Based on these results, we attempt to extend to a more general level the considerations on strengths and weaknesses encountered in the present application of the Italian regulation on NZEBs.

Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings.

Keywords: NZEB; energy audit; energy retrofit; schools; cost-benefit analysis.

* Corresponding author. Tel.: +39 050 2217109; fax: +39 050 2217160.
E-mail address: daniele.testi@unipi.it

1876-6102
Peer-review under responsibility of the scientific committee of the AiCARR 50th International Congress; Beyond NZEB Buildings
10.1016/j.egypro.2017.11.140

1. Introduction

Nearly Zero Energy Building" (NZEB) is a definition that was introduced in legislation of EU Countries through European Directive 2010/31/EU [1], known as the EPBD recast. In particular, the EPBD recast instructed Member States to draw up plans for increasing the number of nearly zero-energy buildings, in order to increase the number of buildings which not only fulfill current minimum energy performance requirements, but are also more energy efficient, thereby reducing both energy consumption and carbon dioxide emissions. As well as giving a definition of NZEB, the Directive ordered Member States to ensure that: after December 31, 2020, all new buildings will be NZEBs and after December 31, 2018, new buildings occupied and owned by public authorities will be NZEBs. In Italy, the EPBD recast Directive has been adopted with the Government Decree 63/2013 (converted in Law n. 90/2013) [2,3]; the "NZEB" definition was introduced in Legislative Decree n. 192/05 [4], but it was implemented only by the Inter-Ministerial Decree of June 26, 2015 [5], which defined minimum requirements to the energy performance of buildings (both new and existing ones).

Nomenclature

Acronyms

BHE	Borehole ground heat exchanger
DHW	Domestic hot water
EPBD	Energy performance directive
IRR	Internal rate of return
NPV	Net present value
NZEB	Nearly energy zero building
PBT	Pay-back time
PI	Profitability index
PV	Photovoltaic system
SRI	Solar reflectance index

Symbols

$A_{sol,est}/A_{sol,utile}$	Ratio between the solar equivalent area and the useful area
$EP_{H,nd}$	Energy performance indicator for space heating need
EP_H	Energy performance indicator for heating
EP_W	Energy performance indicator for DHW production
EP_V	Energy performance indicator for ventilation
$EP_{C,nd}$	Energy performance indicator for space cooling need
H'_t	Global heat transfer coefficient
η_H	Seasonal energy efficiency ratio
Qp_H	Annual energy use for heating
Qp_W	Annual energy use for DHW
Qp_{ill}	Annual energy use for internal lighting
Qp_{tot}	Total annual energy use

Subscripts

ren	renewable share
nren	not renewable share
nd	need

Currently, according to the new energy requirements, every building must be compared with a "reference" building that has same geometry (shape, volume, net area, etc.), same orientation, same location, same use, and having thermal characteristics, energy parameters and requirements defined by law (Inter-Ministerial Decree

"Minimum Requirements") [5]. In order to be an NZEB, a building has to be compared to a reference building with the 2020 energy requirements. We point out that an NZEB with these requirements can be both a new one or an existing one. For this reason, we decided to focus our attention on an existing building, transformed in NZEB by major renovation, instead of a new one, because we decided to use the energy audit (that is possible only on existing buildings, with real consumptions) as a useful tool to expose limits and critical issues on new energy regulation and its application. We decided to study a school building, because this type of building allows environmental and energy considerations. Schools are the public buildings on which people pay more attention, because these buildings are used daily by children, teenagers, and also by their parents, consequently, people are very interested in themes like safety and psychophysical well-being inside schools.

In relation with the last series of earthquakes in our country and also for the above-mentioned reasons, an anti-seismic and anti-fire adjustment of buildings will be essential in the future, probably thanks to the support of national plans, economic incentives or funding (e.g., "Conto Termico 2.0" incentives and Law n. 107, July 13, 2015 [6-7]). We believe that schools will be considered priority and we hope that during anti-seismic and anti-fire adjustments, energy retrofit will be performed as well.

With the objective of analyzing the feasibility of NZEB retrofits of scholastic buildings, we followed a bottom-up approach. In other words, being unable to analyze a statistically significant share of the Italian school building stock, an alternative route is to identify types of constructions that are particularly common on the examined territory and perform a detailed energy audit of the buildings belonging to these classes. These reference buildings constitute the benchmarks for subsequent extension of the obtained results and drawn conclusions. Based on this strategy, in the next paragraphs we will thoroughly illustrate a specific case study, justifying its choice as a proper benchmark for schools in Centre Italy. For this reference building, we will report the results of the performed energy audit, with the thermal evaluation of the building envelope and the comprehensive analysis of the involved electric and thermal energy systems. We will then show the technical and economic feasibility of several proposed actions for deep renovation in terms of energy uses. Finally, we will point out some criticalities encountered in the application of the Italian legislation on NZEBs.

2. Description of case study

The official data by the Italian Ministry of Education show that 55% of existing school buildings have been built before 1976. Several national studies on the state of these buildings report the urgent need for deep refurbishment, not only for energetic purposes, but also for anti-seismic and anti-fire reasons. Among this broad stock and focusing on the climate of Centre Italy, we looked for an appropriate case study in the Province of Pisa. We decided to choose one of the secondary schools, because, with respect to schools of lower grades, they have a greater size, more students, more specialized classes and laboratories, and, in general, are more complex, typically constituted by a multi-functional cluster of buildings. In the Province of Pisa there are about 20 secondary schools. A prerequisite for our research was the availability of individual delivery points of both electric energy and natural gas, together with the associated historical data of energy uses. Among these schools, also considering the possible repeatability of the activity and the option to perform a monitoring campaign, we chose the Secondary School "G. Carducci" for economic sciences, humanities, linguistics and music, located in Pisa. The Secondary School has the following typical and functional characteristics: (1) it was built in the second half of the Sixties; in the Province of Pisa, about half of the school buildings have been built in the period 1960 – 1975; besides, the school is indeed representative of a distribution and construction style typical for those years, with reinforced concrete in sight and large windows, well suited for the internal volumes and specific uses; (2) it hosts a secondary institute of average size, with about 750 students; within the Province, the number of students varies from 300 to 1100 per school; (3) similarly to most Italian school buildings, it has already been subject to moderate renovations, necessary to comply with the occurred rules on safety and accessibility; (4) being located in the Centre of Pisa, it is easy to access, in order to perform inspections and monitoring activities. In addition, technicians of the Province of Pisa have shared with us all the available documentation on the building construction, energy systems and implemented refurbishment actions. Lastly, the School Headmaster ensured collaboration and support for the inspections and has shared occupation data and other useful information.

The School "G. Carducci" provides every year education for about 750 students. It is located inside the historic walls of Pisa and it was built in the second half of the seventies on an area of 11,530 m^2 of which 8078 m^2 used for parking and green areas. The School is composed by: the main building (object of the analysis), where classrooms, laboratories and administrative offices are located, and two gyms, where the physical education activities are carried out (Fig. 1).

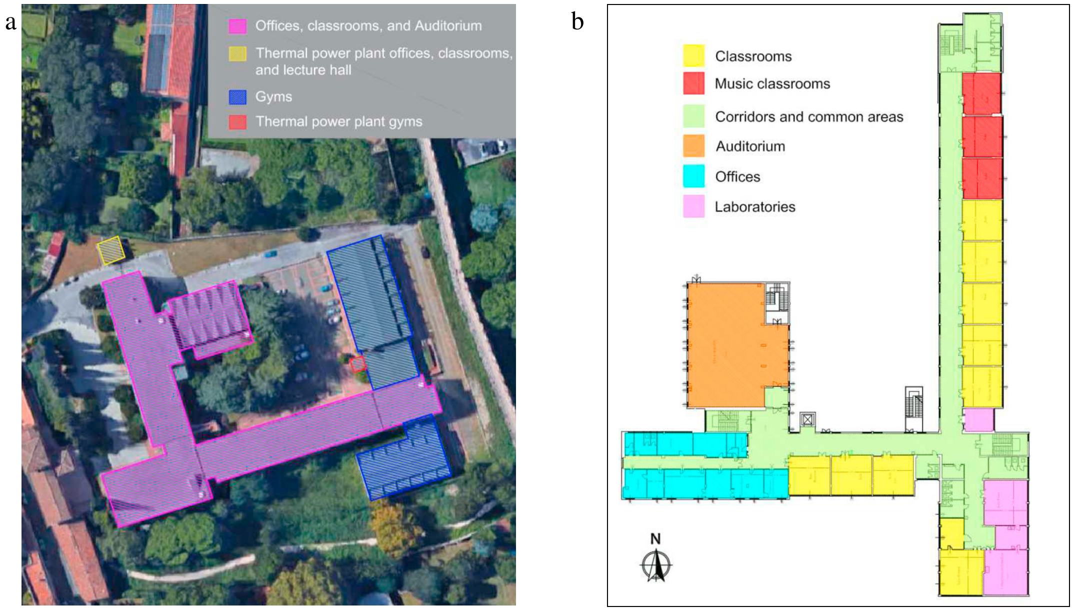

Fig. 1. (a) aerial view of School "G. Carducci"; (b) first floor plan with the division in thermal zones.

The main building is a three-story building with an overall area of about 6000 m^2. The building envelope is composed by reinforced concrete structures and masonry wall with face brick and a total thickness of 25 cm. The windows represent a very relevant part of the building envelope, because they cover over the 40% of the total external surface. They can be divided in two types: the original windows composed by single-glazed and aluminum frame and the new windows installed in 2009 during a partial refurbishment, with thermal break frame and low-emission double glass. The floor slabs are concrete and masonry slabs without acoustic or thermal insulated materials. A concrete and masonry slab, with a sloping screed (2-3%), a vapor control layer, and a thermal insulated screed on the top, composes the roof slab. The ground floor slab is in reinforced concrete and it is not placed directly on the ground, but on top of one ventilated basement space. As for the mechanical plant, the building is equipped with a unique centralized heating system and by a thermal power station located in a building detached from the rest of the school and placed in the green area (Fig. 1). In the thermal power station, there are two natural gas boilers in cascade. The primary boiler (named boiler 1) was installed in 2008, has a burner modulating on two stages, and nominal power of 448 kW; the other boiler was installed in 1986 and is a natural gas boiler with no modulating burner and nominal power of 250 kW. This second boiler works when peak power is required. For both boilers, a climate control system with a probe for the measure of the external temperature is installed. The hot water system is ensured by means of electric and automatic boilers and they are always turned on (nonstop service). The outdoor lighting systems are composed by floodlights with metal halide lamps and are controlled by a twilight switch. The indoor lighting systems are composed by suspended luminaires with linear fluorescent lamps. These luminaires are not equipped by automatic control systems, but are switched on/off by the school personnel. A mechanical ventilation system is not present.

To characterize the users' (students, employers, and teachers) behavior with regards to the thermal aspects, six zones have been created within the school building. Their main characteristics are summarized in Table 1. Another relevant aspect is the number of days the school is used. The 2015-2016 year is analyzed because of the available billing consumption in the same period. The ventilation of the rooms also depends on the users' behavior: the students open and close the windows to guarantee the minimum sanitary air exchanges. These exchanges are estimated based on interviews, but it is uncertain data (about 10 minutes bi-hourly, corresponding to the class change). On the contrary, in the hallway zone and in the auditorium the ventilation is exclusively based on the air permeability of the windows. Regarding the building energy services, the heating system management are provided by the Province of Pisa, with the schedule in Table 2, with a total amount of 34.5 hours per week. The two boilers (1 and 2) produce hot water from 45 °C to 70 °C, depending on the external air temperature (climate control).

Table 1. Main characteristics of each thermal zone: number of rooms, floors, net area (A), net volume (V), maximum nominal number of persons, set point temperature and time slot of use.

ZONES	Nr.	Floor	A (m^2)	V (m^3)	Nr. max persons	$T_{set\ point}$ (°C)	Use
Classrooms	19	0-1-2	1561	5697	851	18	Morning
Laboratories	5	0-1-2	482	1761	145	18	Morning
Auditorium	1	1	574	1882	190	16	Rarely
Corridors and common areas	-	0-1-2	2104	7726	1	17	All day
Offices	8	1	210	765	5	18	All day
Music classrooms	3	1	135	493	87	18	All day
TOTAL	-	-	5066	18,324	-	-	-

Table 2. Timetable of the use of pumps and boilers during the heating season.

		0:00 6:00	6:00 6:15	6:15 7:15	7:15 10:45	10:45 11:30	11:30 14:00	14:00 14:15	14:15 15:15	15:15 15:45	15:45 16:15	15:45 24:00
Boiler	Mon.-Fri.	0	0	1+2	1	0	0	0	1+2	1	0	0
	Sat.	0	0	1+2	1	0	0	0	0	0	0	0
Pumps	Mon.-Fri.	0	1	1	1	1	0	1	1	1	1	0
	Sat.	0	1	1	1	1	0	0	0	0	0	0

Natural gas consumption is measured by a gas meter positioned upstream of the boiler room that serves the main school building. Readings of the meter were performed twice a week, from February 16 to March 23, 2016. During the last week of monitoring, the measurements took place every morning, at half-hour steps. By means of the latter data, we could correlate natural gas consumption values to different external air temperatures, obtaining a statistically significant "energy signature" of the building (Fig. 2).

The obtained correlation curve was validated on biweekly readings of the first monitoring period, giving a 12% error in the prediction of gas consumption. Outdoor temperatures were measured by a weather station of the University of Pisa, located about 1 km away from the school building. To determine the energy signature, we imposed an upper limit consumption value of 36 standard cubic meters of gas per hour, corresponding to the maximum measured instantaneous consumption. All the other parameters of the curve were obtained by best fitting (in the least square sense) the measured data: starting temperature of the sloped segment: 9.5 °C, ending temperature of the sloped segment: 13.5 °C (also corresponding to the end of the modulating range of the climatic control curve of the boiler), lower limit of gas consumption: 12 Sm^3 (corresponding to the minimum modulation capability of the boiler: 30%). We observe that, due to the absence of a zone thermostat control in the building, there is gas consumption in the boiler even at high external temperatures. With the validated energy signature curve, we could extrapolate the gas consumption to the entire heating season (November 1 – April 15). In particular, the seasonal evolution of the external temperature, used as hourly input, was taken from the typical climatic year of the Province of Pisa, provided by the Italian Thermo-Technical Committee (CTI). For a correct prediction of the overall gas consumption, we have to take into account also boost conditions, occurring at switch-on of the heating system (every morning and every afternoon). In these cases, based on our monitoring, the second boiler works for about an hour and gas consumption at full load increases of about 50% (reaching 54 Sm^3/h), independently of the external temperature. In conclusion, also considering the school festivities, the calculated energy use for heating purposes is

243.7 MWh per year. As for the electric energy uses, based on actual readings of the energy meter, we estimate 75.0 MWh/yr.

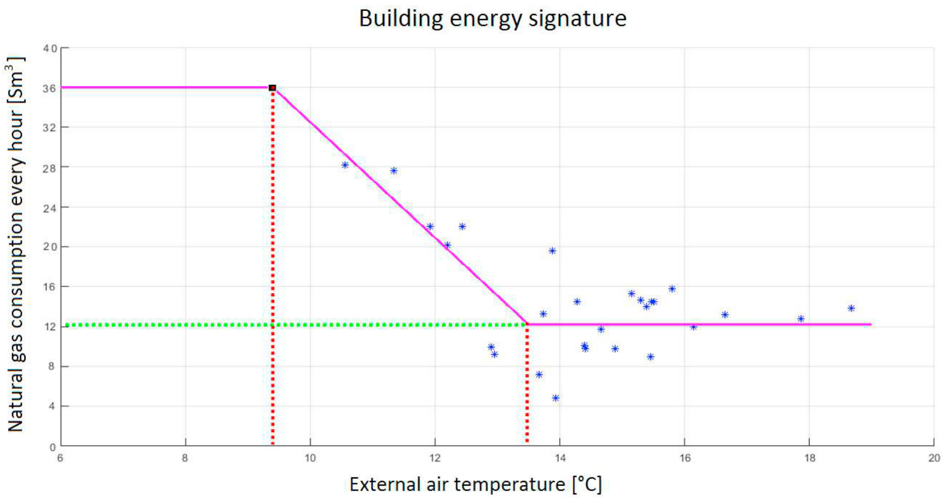

Fig. 2. Building energy signature and monitoring data.

3. Building models and simulation

The building energy simulation was performed by means of two concurrent energy models, developed on two applications: the commercial software EC700 (Edilclima) and the open access software SEAS 3 (ENEA – University of Pisa). The first software, being certified by the Italian Thermo-Technical Committee as conforming to the set of Italian technical standards UNI/TS 11300 [8] (asset rating method), is appropriate for evaluating the energy class and the fulfillment of NZEB requirements. Nevertheless, in a building with intermittent use such as a school and in the absence of room or zone thermostatic controls, a software specifically designed for energy audits such as SEAS is preferable. In particular, to get a more accurate estimate of the energy uses for heating (that should be comparable to the values based on measurements, obtained in the previous paragraph), SEAS allows to insert actual hourly schedules and users' profiles (tailored rating method). In addition, as far as electric energy uses are concerned, SEAS has a specific tool for considering the energy consumption of the office equipment of the school. Therefore, in the following paragraphs, we will use both approaches, depending on the specific goal: achieving the NZEB class, according to the definition of the Italian legislation, or identifying the best energy retrofit measures, in terms of costs and benefits. All tables should be numbered with Arabic numerals. Every table should have a caption. Headings should be placed above tables, left justified. Only horizontal lines should be used within a table, to distinguish the column headings from the body of the table, and immediately above and below the table. Tables must be embedded into the text and not supplied separately. Below is an example which the authors may find useful.

3.1. Building energy simulation with commercial software (Edilclima)

The energy model of the case study was developed by means of a validated commercial software (Edilclima). We underline that the asset rating method applies a standard use profile of the building, with energy services working 24/7; real use profile is not considered. So, final results on consumptions will be very different from real consumptions. Based on measured data and collected information, the energy model was entirely developed, defining each component (walls, floors, windows, thermal bridges, etc.) facing outward, facing unheated rooms, or facing heated rooms, but that have not been included in the energy model (gymnasium, nursery school). The building envelope was built floor by floor and the volume of each floor was divided into rooms; so, the specific features of each room were implemented in the model: indoor temperature, natural ventilation (according to the target use of the room and [9]), lighting (installed power, use features, lighting control systems, etc.). After modelling the envelope, all the energy services of the school (apart lift service) were developed, using the information collected during the inspection. We underline that the school does not have cooling or mechanical ventilation systems; so, the annual energy needs and use calculated do not include these energy services, but only heating, domestic hot water (DHW) production, and internal lighting. As for annual energy needs for heating, we notice that heat transfer by transmission through windows is the most important loss. Also, we observe that heat transfer by transmission is the 73.3% of the heat losses, while heat transfer by ventilation is the remaining 26.7%. Furthermore, we notice that solar heat gains through windows represent the 66.4% of total gains, while internal gains are the remaining 33.6%. The calculated annual energy use for heating is 1129 MWh/yr. The calculated annual energy use for DHW is 3.8 MWh/yr and the annual energy use for internal lighting is 157 MWh/yr (annual energy uses for each service are reported in Table 3). We observe that annual energy use for DHW represents only 1% of all the energy uses, while energy use for heating is 87.5% of the total energy use. Monthly distributions of energy uses are shown in Fig. 3.

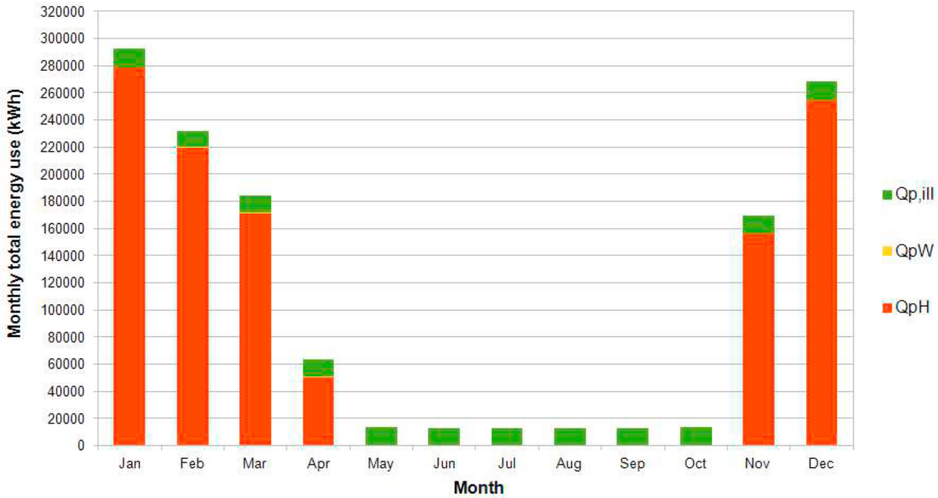

Fig. 3. Monthly energy use for heating, DHW, and internal lighting.

Table 3. Annual energy uses for heating, DHW, and internal lighting.

Period	Days	Qp_H (kWh)	Qp_H (%)	Qp_W (kWh)	Qp_W (%)	$Q_{p,ill}$ (kWh)	$Q_{p,ill}$ (%)	$Q_{p,tot}$ (kWh)	$Q_{p,tot}$ (%)
Year	365	1,129,386	87.5%	3805	0.3%	156,912	12.2%	1,290,103	100.0%

Annual energy consumptions were calculated separately for both energy vectors: electric energy and natural gas. As mentioned, in accordance with energy regulations, energy consumptions of the school were determined by the asset rating method, with energy services working 24/7. This "standard" energy uses are much higher than real consumptions provided by energy bills. In detail, natural gas annual consumption is 105,433 Sm^3/yr for the heating service, while electric energy consumption is 97,283 kWh_{el}/yr for internal lighting (83%), heating (15%), and DHW (2%). The existing building does not use renewable energy sources. Given the energy requirements of the Italian regulation on NZEBs, we defined a deep renovation of the school building, proposing several actions to turn the school into an NZEB. These actions were selected to verify all the energy requirements of the regulation. For this reason, we focused on these needs: 1) reduction of thermal transmittance of opaque and transparent components and important reduction of linear thermal transmittance of thermal bridges, to obtain a reduction of "H't" coefficient and of the energy losses in winter; 2) increase of windows shielding, by introducing internal curtains where they were absent, to reduce "$A_{sol,est}/A_{sup,utile}$" parameter; 3) increase of the efficiency of energy subsystems, to increase seasonal average performance of heating and DHW production and reduce total annual energy uses; 4) introduction of services powered by renewable energy sources, to satisfy almost 55% of annual energy needs for heating and DHW and also achieve the minimum installed photovoltaic (PV) power required by energy regulations. The corresponding actions that we introduced were: 1) external insulation of all the walls, using rock wool panels (thickness: 20 cm, thermal conductivity: 0.037 W/mK, density equal: 125 kg/m^3); external insulation of the roof, using EPS panels (thickness: 20 cm, density: 30 kg/m^3, thermal conductivity: 0.034 W/mK); application of a high solar reflectance index (SRI) coating ("cool-roof" effect); 2) substitution of the existing windows with PVC frame and double low-emissivity glazing ones (air permeability class: 4, thermal transmittance: 1.1 W/m^{2}K); internal venetian blinds at windows without shadings; 3) new heating generator: water-source heat pump; 4) installation of 4 natural circulation solar thermal panels, each one with a flat plate collector and a storage tank; installation of a PV plant on the roof (installed power: 37.4 kWp, south-oriented, tilt: 35°), to cover 32.2% of the annual electric energy consumption: 48.58 MWh$_{el}$/yr. With these last actions, the requirements on renewable energy installations of Legislative Decree n. 28/2011 [10] are met.

We employed the minimum retrofit measures needed to reach an NZEB configuration. We underline that we ignored every type of retrofit on internal lighting with LED sources, because they were not effective to achieve the NZEB target, even if they would reduce the energy consumption for lighting. Furthermore, we emphasize that every school should have a mechanical ventilation, for the air quality of the students and of all the people inside the building, even if the installation of this service is expensive. In our case study, being the school without a mechanical ventilation system, also the "reference" NZEB is considered without this service. So, since installation of this system did not help achieving the NZEB target, it was not included among the retrofit actions. Also, retrofit actions on the heating generation system were deeply conditioned by energy regulation requirements, in particular by [10]. In order to satisfy almost the 55% of annual energy needs and also achieve the minimum installed PV power required by energy regulations, we had to introduce a PV plant of 37.4 kWp. The annual energy needs to be reduced to 55% (according to [10]), do not consider internal lighting needs, but only heating, cooling, and DHW. Consequently, we chose a new heating generator able to use the electric energy produced by the PV system (for self-consumption), instead of natural gas. In accordance with the Inter-Ministerial Decree of June 26, 2015 [5], we selected a water-source heat pump, even if it was more expensive than the air-source one, because it was the only way to respect the target efficiency, in the case of a heat pump for the heating service. We also observe that the Italian regulations forced us to install solar thermal panels, even if the needs of DHW represent just 2% of the total electric energy uses. Concurrently simulating all these renovation measures, we showed that NZEB requirements were all satisfied, as illustrated in Table 4. As expected, we found a strong reduction in transmission losses with respect to the existing case and no difference in ventilation losses and internal gains (Fig. 4).

The energy needs for space heating in the NZEB model is 243 MWh/yr. The annual energy use for DHW is zero, thanks to the full contribution of solar thermal panels. Annual energy use for internal lighting is 157 MWh/yr, not considering the PV contribution. The annual electric energy produced by the PV system is 48.6 MWh/yr. In Table 5, we report annual energy uses for each energy service, calculated both for existing and NZEB models, showing both renewable and not renewable shares. We observe that in the NZEB model we obtain a reduction of the annual energy use of 75% with respect to the existing model. The NZEB does not use natural gas and the calculated annual electric energy consumption is 102 MWh$_{el}$/yr (only a 5% increase with respect to the existing system). Due to the asset rating method, the calculated energy savings between NZEB and existing model are significantly overestimated, making the economic feasibility of the proposed retrofit actions unreliable.

Finally, for evaluating the economic feasibility of the proposed retrofit measures, we estimated the cost of each action (Table 6). These costs include only supply and installation of materials and equipment; instead, they do not include charges for safety and design or possible discounts. These costs are just illustrative; in fact, they can change in a significant way, because they depend on many factors, such as geographic area and type of contract. The indicators of the economic analysis are payback time (PBT), net present value (NPV), profitability index (PI), and internal rate of return (IRR). The estimated lifetime of the renovated system is 20 years. The results are: a PBT of 13 years, a NPV of 239 k€, a PI of 0.23, and an IRR of 4.8%.

Table 4. Comparison between existing building and NZEB model results.

Efficiency, parameter, performance index	Unit	Existing building	NZEB model	"Reference" building
I.-M. D. 26/06/2015 "Minimum Requirements"		Calculated value		Limit value
H'_T	W/m^2K	2.11	0.49	≤ 0.53
$A_{sol,est} / A_{sup\ utile}$	-	0.46	0.25	≤ 0.40
$EP_{H,nd}$	kWh/m^2	145.87	48.01	≤ 56.22
η_H	%	65.0	61.3	≥ 56.7
EP_H	kWh/m^2	-	-	-
η_W	%	28.7	92.6	≥ 69.2
EP_W	kWh/m^2	-	-	-
EP_V	kWh/m^2	-	-	-
$EP_{C,nd}$	kWh/m^2	25.65	30.20	≤ 30.68
L. D. n. 28/2011		Calculated value		Limit value
Share of annual energy uses (heating, cooling, DHW) by renewable sources	%	0	70.1	≥ 55
Coverage of annual energy use for DHW by renewable sources	%	0	100	≥ 55
Minimum installed power of renewable sources plant	kW_{el}	0	37.40	≥ 36.7

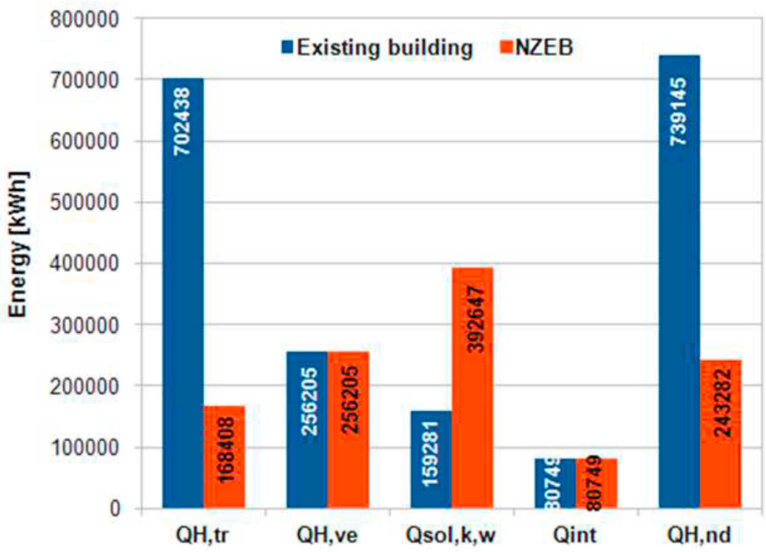

Fig. 4. Annual energy needs for space heating in the existing and NZEB models of the School.

Table 5. Annual energy uses for existing and NZEB models.

	$Qp_{H,nren}$ (kWh/y)	$Qp_{H,ren}$ (kWh)	$Qp_{W,nren}$ (kWh])	$Qp_{W,ren}$ (kWh)	$Q_{p,ill,nren}$ (kWh)	$Q_{p,ill,ren}$ (kWh)
Existing building	1,129,386	6986	3805	917	156,912	37,820
NZEB model	119,025	277,719	0	1463	80,687	58,539

Table 6. Unit price and total cost (labor included) of each retrofit action.

NZEB retrofit action		Value	Unit price (€)	Total cost (€)
Replacement of windows	m^2	1776	350.00	621,600.00
External insulation of walls	m^2	2393	67.00	160,331.00
External insulation of roof	m^2	2135.5	40.00	85,420.00
Installation of venetian blinds	n.	118	168.50	19,889.00
Installation of PV system	kWp	38	1500.00	57,000.00
Installation of solar thermal panels	n.	4	3000.00	12,000.00
Installation of water-source heat pump	n.	1	0.00	96,000.00
			TOTAL	1,052,240.00

3.2. Building energy simulation with SEAS

As for the energy simulation of the real consumption of the building (A3 or tailored rating, [11]), alternative to the one calculated in the previous section (A2 or asset rating), we chose to employ a validated quasi-steady state model. Full dynamic simulation models, such as the ones we developed and used in [12,13] are surely more accurate, but require further detailed input data and a yearly simulation is more time-demanding. We used the software SEAS (Simplified Energy Auditing Software), an open-access software developed by DESTEC, University of Pisa, in collaboration with ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development). SEAS performs simulations for energy audits of buildings, evaluating monthly energy requirements for space heating, DHW production, ventilation, lighting, and other electric uses. It has a multi-zone approach, useful for large and tertiary buildings as the one analyzed, and it also provides economic indexes for the cost-benefit analysis of retrofit actions. The input data are divided into four groups: 1) climatic and urban context data; 2) geometric data referred to the building envelope and the users' behavior schedule; 3) heating system data; 4) economic inputs. Wind velocity and solar energy radiation are provided by [14], while external air temperature is provided by CTI for a typical climatic year. The building has been divided into 6 thermal zones (as for the A2 rating), as described in section 2. Each zone has been characterized by the typology, the geometric data, and the thermal dispersion coefficient of each opaque or transparent element, including thermal bridges. Moreover, in each zone internal gains have been defined in terms of: week and bi-hourly schedules of students' presence, schedules of use of electric devices, week and bi-hourly schedules of school holidays, monthly and bi-hourly schedules of shutter and curtains use, monthly and bi-hourly schedules of windows openings. As for the on/off period of the heating system, the timetable is the same for each zone (Table 2). On the contrary, the values of the internal air temperature are different in the 6 zones. Despite they are not being monitored, they indicate a temperature of general discomfort (always lower than 20 °C, surely being an uncertain input). As for the internal lighting system, calculations are performed according to [15], using the evaluation of the real lighting device present in each room, considering the manual control and the users' behavior (lights often switched on also in daylight). With these inputs it is possible to calculate the net thermal energy need of the envelope of each thermal zone. The transmission losses are the largest ones for all the zones (about 30-35% of the total need, attributable to the high transmittance of opaque and transparent elements). Infiltration and ventilation losses are about 15% of the total need and are due to the high permeability of the windows. As for solar and internal gains, they are different for each zone, depending on the particular users' behavior (electric devices, use of curtains) or on the presence of glass windows: the classrooms zone has the largest window surface facing south and the highest number of users, so it needs the less amount of energy from the heating system. As for the heating system, all the data concerning the emission, control, distribution, and generation subsystems have been set (as in the A2 rating model). To validate the energy audit, we matched the simulation building energy requirements with the billing and measured energy consumptions, both for natural gas and electric energy. In particular, a tuning has been performed on the most uncertain input data (internal air temperatures and number of hours of internal artificial lighting). Table 7 shows the good agreement between the total energy consumptions, despite the unfavorable intermittency of the heating system and medium inertia of the envelope [16].

Table 7. Comparison between energy simulations and billings/measurements.

Thermal energy [kWh]			Electric energy [kWh_{el}]		
Simulation	Measurements	Deviation	Simulation	Billings	Deviation
251116	243700	+3%	74065	75042	-1.3%

To enhance the energy performance of the school building, independently of the NZEB definition, several medium retrofit actions have been modeled all in one, considering cost-optimality criteria and positive interaction among actions (e.g., windows substitution causes a lower heating demand and a smaller generation system in substitution of the boilers). Each action must respect the legislative minimum levels and no users' behavior improvement has been modeled, in order to correctly compare the energy audit retrofit actions with the ones needed for the reaching the NZEB performance. In this way, some criticalities of the building are noticed: 1) the absence of thermal local control, so that the internal air temperature fluctuates without control, depending on the gains (students, solar radiation); 2) strongly linked to the first problem, the absence of a mechanical ventilation system causes inefficient window openings by the students; 3) the geometry and typology of the building, associated to structural thermal bridges and relevant transparent surface (about 40% of the lateral surface), causes huge thermal losses; 4) the public function of the building implies a strong promotion of renewable energy installations that could partially cover the energy demand. According to these criticalities, the following retrofit actions were chosen: 1) upgrade of the control system: installation of thermostatic valves on the existing radiators with set point temperatures allowed by the standards (about 19.5 °C) and substitution of the existing circulators with variables-speed pumps; 2) substitution of all the old windows with new ones with the thermal performance required by current standards (thermal transmittance < 2 W/m^2K, air permeability class: 4, solar factor with curtains < 0.35); 3) substitution of the internal traditional lighting devices with LED lamps: 30 W LED tubes replace traditional 58 W fluorescent tubes, so that about 50% of the energy can be saved (as also demonstrated in [17,18]); 4) installation on the plane roof of a 24 kWp PV plant (polycrystalline modules, about 100 m^2); 5) substitution of the existing traditional boiler with a gas absorption heat pump with borehole ground-coupled heat exchangers (BHEs) and a thermal power coherent with the upgraded building (the sizing of the ground-source heat pump system, including the BHEs, was done according to [19,20]).

The calculated monthly energy uses of the existing building before and after the implementation of all the retrofit actions are reported in Fig. 5, showing a significant reduction of both electric (about 70%) and thermal energy. Electric energy use is partially covered by the PV plant (according to Evans model, implemented in SEAS, the annual electric production by the PV system is 24,391 kWh and the equivalent production hours are 1039). The annual consumption is 22,402 kWh_{el}. Thermal energy use is reduced of 48%, with an annual consumption of 129,454 kWh. The costs of each action (materials and installation) are shown in Table 8, deduced from market analyses, reference price lists for public installations, commercial prices of devices, and Edilclima costs database. The prices can differ, depending on many factors, such the geographic building localization or the applied discount. Safety costs and professional design costs are not included. For the economic analysis, we assumed a 5% inflation of electric energy costs and a 3% inflation of natural gas costs. We considered to get access to the national incentive on energy efficiency called "Conto Termico 2.0" [7]: it establishes that, in 5 years, 65% of the heat pump cost and 40% of windows and lighting system substitution costs are reimbursed. The results of the investment after 20 years of operation are positive and better of the NZEB refurbishment case: PBT is 13 years, NPV is 293 k€, PI is 0.44, and IRR is 6.0%.

Table 8. Retrofit action costs (overall cost: 819,987 €).

Retrofit action	Unit	Quantity	Unitary cost	Total costs
Windows substitution	m^2	1396	300 €	511,108 €
Local thermal control	n.	200	150 €	36,600 €
PV system installation	kWp	24	1500 €	43,920 €
LED internal lighting installation	n.	434	70 €	37,064 €
Absorption gas heat pump with BHEs	kWp	320	490 €	191,296 €

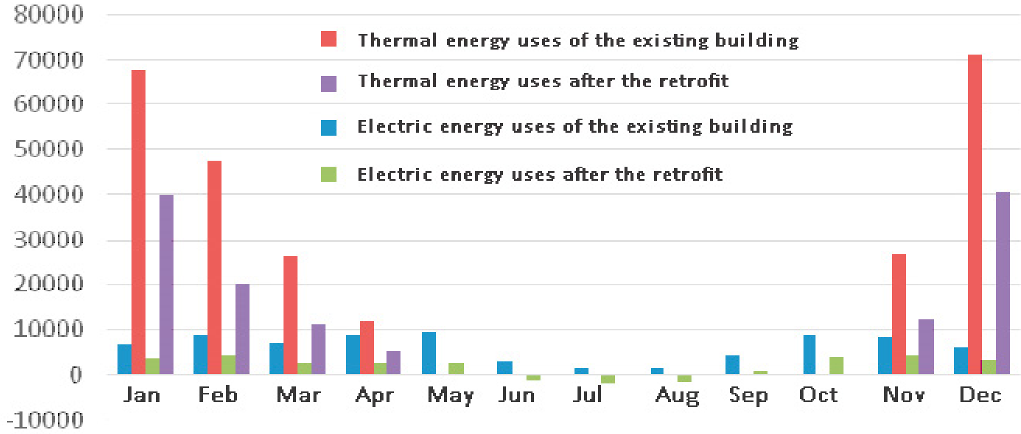

Fig. 5. Total monthly thermal and electric energy consumptions: existing versus renovated building.

4. Discussion of results and identification of criticalities

The main aim of this work is to apply the Italian NZEB regulation to a paradigmatic existing scholastic building in Centre Italy and evaluate the main criticalities of this approach. Two kinds of energy evaluation have been undertaken. With the first one, the A2 methodology, standard values of ventilation and internal gains are used and no matching with the real energetic consumption is needed, so that a very high thermal energy requirement is obtained as a result (more than 3 times the actual value). Particularly for school buildings, the asset rating causes overestimation of the real consumption for several reasons: 1) the building is characterized by an intermittent use, due to the students' presence and the heating system schedule, both in the whole year and during the day, so that the fixed internal gains and the heating systems switched on 24/7 are far from the real situation; 2) the absence of local thermal control causes internal air temperature to drop below standard values (20 °C) modeled in the A2 rating, with consequent minor consumption; 3) the absence of the ventilation system forces the simulation tool to apply the standard sanitary air exchanges imposed by [8] in A2 rating, provoking a further increase of the energy consumption. On the contrary, according to the A3 evaluation, the real situation has been simulated, with very good matching with the real billings and measurements. The final A3 energy requirements have been used to normalize the overestimated A2 results for the purpose of the economic analysis. To reach the NZEB performance level, the A2 evaluation should be adopted and a set of mandatory retrofit actions should be implemented. In this way, a big advantage is that a global action is designed, with positive interaction between each installation; on the contrary, it is not possible to apply a cost-optimality approach and many simple management actions (e.g., use of curtains, artificial lighting timers) are impossible to be simulated, due to the asset rating method. These changes in behavior are important to properly educate the users, especially in a school building, so that a priority scale of actions could be useful and should also be taken into account in the simulation. From the economic point of view, the large set of mandatory actions are economically sustainable only if national incentives are used (mostly "Conto Termico 2.0", which refunds, for an NZEB refurbishment, 65% of the total investment). Finally, the solar renewable energy installation, needed to achieve the NZEB performance, does not properly match the maximum electric energy production with the building energy use, because it occurs during the summer holidays. Advanced techniques for cost-optimal design of solar systems in NZEBs, such as the ones employed in [21,22], should be introduced, instead of rules based on a fixed minimum share of renewables.

In conclusion, generalizing from this case study, we can certainly suggest the national legislator to modify the current definition of NZEB, introducing correction coefficients for buildings with intermittent uses and high crowding such as schools, so that the measures needed to reach the NZEB level are also appropriate in terms of cost-benefits.

Acknowledgements

The research activity was funded by ENEA and the Italian Ministry of Economic Development (National Electric System Research). We gratefully acknowledge Alessandro Taverni and Valentina Vannucci, Province of Pisa, Luciano Terrinoni and Paolo Signoretti, ENEA, Prof. Walter Grassi and Davide Della Vista, DESTEC, University of Pisa, and the staff of School "G. Carducci" for their continuous and effective support.

References

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

[2] Italian Government Decree June 4, 2013, n. 63 "Disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia".

[3] Italian Law June 4, 2013, n. 90 "Conversione in legge, con modificazioni, del decreto-legge 4 giugno 2013, n. 63, recante disposizioni urgenti per il recepimento della Direttiva 2010/31/UE del Parlamento europeo e del Consiglio del 19 maggio 2010, sulla prestazione energetica nell'edilizia per la definizione delle procedure d'infrazione avviate dalla Commissione europea, nonché altre disposizioni in materia di coesione sociale.".

[4] Italian Legislative Decree August 19, 2005, n. 192 "Attuazione della direttiva 2002/91/CE relativa al rendimento energetico nell'edilizia".

[5] Italian Inter-Ministerial Decree June 26, 2015 "Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici".

[6] Italian Law July 13, 2015, n. 107 "Riforma del sistema nazionale di istruzione e formazione e delega per il riordino delle disposizioni legislative vigenti".

[7] Italian Inter-Ministerial Decree February 16, 2016 "Aggiornamento della disciplina per l'incentivazione di interventi di piccole dimensioni per l'incremento dell'efficienza energetica e per la produzione di energia termica da fonti rinnovabili (Nuovo Conto Termico)".

[8] UNI 11300-1, Prestazioni energetiche degli edifici – Parte 1: Determinazione del fabbisogno di energia termica dell'edificio per la climatizzazione estiva ed invernale. Milan (IT): Italian National Unification; 2014.

[9] UNI 10339, Impianti aeraulici ai fini di benessere. Generalità, classificazione e requisiti. Regole per la richiesta d'offerta, l'offerta, l'ordine e la fornitura. Milan (IT): Italian National Unification; 2003.

[10] Italian Legislative Decree March 3, 2011, n. 28 "Attuazione della direttiva 2009/28/CE sulla promozione dell'uso dell'energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE".

[11] CEN 2008. "Energy performance of buildings – Overall energy use and definition of energy ratings". EN 15603. Brussels: European Committee for Standardization.

[12] Testi D, Schito E, Menchetti E, Grassi W. Energy retrofit of an office building by substitution of the generation system: performance evaluation via dynamic simulation versus current technical standards. Journal of Physics: Conference Series 2014;547/012018:1-9.

[13] Testi D, Schito E, Tiberi E, Conti P, Grassi W. Building energy simulation by an in-house full transient model for radiant systems coupled to a modulating heat pump. Energy Procedia 2015;78:1135-1140.

[14] UNI 10349, Riscaldamento e raffrescamento degli edifici – Dati climatici. Milan (IT): Italian National Unification; 1994.

[15] EN 15193, Energy performance of buildings – Energy requirements for lighting. Brussels: European Committee for Standardization; 2007.

[16] Schito E, Testi D, Conti P, Grassi W. Validation of SEAS, a quasi-steady-state tool for building energy audits. Energy Procedia 2015;78:3192-3197.

[17] Salvadori G, Fantozzi F, Rocca M, Leccese F. The energy audit activity focused on the lighting systems in historical buildings. Energies 2016;9/998:1-13.

[18] Fantozzi F, Le Bail L, Leccese F, Rocca M, Salvadori G. General Lighting in Offices Building: Techno-Economic Considerations on the Fluorescent Tubes Replacement with LED Tubes. International Journal of Engineering and Technology Innovation 2017;7(3):143-156.

[19] Grassi W, Conti P, Schito E, Testi D. On sustainable and efficient design of ground-source heat pump systems. Journal of Physics: Conference Series 2015;655/012003:1-18.

[20] Conti P, Testi D, Grassi W. Revised heat transfer modeling of double-U vertical ground-coupled heat exchangers. Applied Thermal Engineering 2016;106:1257-1267.

[21] Testi D, Schito E, Conti P. Cost-optimal sizing of solar thermal and photovoltaic systems for the heating and cooling needs of a Nearly Zero-Energy Building: design methodology and model description. Energy Procedia 2016;91:517-527.

[22] Testi D, Schito E, Conti P. Cost-optimal sizing of solar thermal and photovoltaic systems for the heating and cooling needs of a Nearly Zero-Energy Building: the case study of a farm hostel in Italy. Energy Procedia 2016;91:528-536.