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Preliminary energy audit of the historical building of the School of Engineering and Architecture of Bologna

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Abstract

Energy efficiency has become a common target for every building: the European Directive 2010/31 provides that by 2020 every new building must consume very little fossil energy (Nearly Zero Energy Building) and from 2018 also public buildings will have to meet this requirement. Although the objectives imposed by the new legislative references are very clear, modify the existing heritage in many cases is not easy. For example, many buildings, including public ones, in addition to consuming a lot of energy, are also constrained by the Superintendence for Architectural, Landscape, Historical and Artistic Assets; therefore it becomes difficult to improve their energy performance. This paper presents a preliminary energy audit of the historical building of the School of Engineering and Architecture in Bologna (Italy). It was built in the 30s, is one of several public buildings of particular historical and architectural interest for the city of Bologna and it is constrained architecturally. Special attention has been focused on the energy consumption for heating during the winter season. The audit was carried out taking into account the European standard EN 15603, using the method of energy signature based on actual consumption. The results of the energy analysis show an energy saving of about 15% with operations building management and over 30% with improvements of the heating system and the windows.

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Keywords: energy audit; energy signature; historical buildings.

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1. Introduction

During the last 50 years the theme of energy saving has increased its importance and nowadays it is one of the main strategic topics for all countries. In addition to concerns regarding the depletion of energy sources in the short term, energy saving can help to reduce the climate impact of the huge emissions of carbon dioxide linked to the combustion of fossil fuels.

In Europe, heating and cooling plants for buildings are responsible of about 40% of the total energy consumptions; the optimization of the thermal insulation of the building envelopes as well as the enhancement of HVAC systems can offer a good opportunity in order to save a significant amount of primary energy by means of the energy retrofitting of existing buildings, which have generally very low energy performance indeed, and the innovative energy design of new houses. Since in the European Union the new buildings constructed per year are less than 1.5% of the existing stock, the energy retrofit of existing buildings appears as a necessary tool to achieve a relevant energy saving in two or three decades. A considerable research activity aimed at improving the energy efficiency of European buildings has been performed in recent years and important research projects on this field, supported by UE funding are in progress [1].

By taking into account this situation, the European Directive 2002/91/CE, known as EPBD [2], and 2009/28/CE [3] have addressed their attention to the promotion in Europe of a series of actions with the aim to improve the energy efficiency especially of existing buildings. In Italy, where the number of historical buildings is significant, the enhancement of the energy performance of old buildings is always coupled with the theme of the artistic conservation and this introduces a series of constraints which can strongly limit the energy retrofitting actions. At the moment, energy retrofits are not mandatory for historical buildings [4] in Italy [5] but this theme is becoming strategic for a country which has about 70% of the historical and artistic heritage of the whole world [6].

The aim of this paper is to study the energy efficiency of the Rationalist building of the School of Engineering and Architecture of Bologna and to propose some retrofit techniques to improve its efficiency without modifying the external look of the enclosure. The first part of this paper describes the procedure followed for the implementation of an energy audit of the building using the Energy Signature Method (ESM) [7]. The aim of the analysis is to highlight, by means of the combined use of numerical simulations and the real energy consumption detection, the main critical points of the system in terms of energy use and, finally to propose a series of interventions able to improve the energy performance of the system, taking into account the main constraints existing on the building in order to preserve its historical and architectural meaning.

Nomenclature

BES	Building Energy Signature (-)
E_{avg}	annual average primary energy consumption for heating (kWh/y)
ESM	energy Signature Method (-)
H	global (transmission and ventilation) dispersion coefficient of the building (kW/K)
HDD	heating degree days (°C)
OAT	outdoor air temperature (°C)
OAT_{avg}	seasonal average outdoor air temperature (°C)
OAT_0	heating Limit External Temperature (°C)
P_{des}	design load (kW)
P_{th}	thermal power (kW)
S	heat exposed surface (m^2)
V	conditioned gross volume (m^3)
η	global seasonal efficiency of the heating plant (%)
$\Delta\tau$	duration of the heating period (days)
ΔE	energy variation (%)

2. Brief description of the historical building

The building analyzed in this work has been constructed by the architect Giuseppe Vaccaro between 1933 and 1935; this building is now the main site of the School of Engineering and Architecture of the University of Bologna and it is considered one the most important examples of the Italian Rationalist architecture.

Giuseppe Vaccaro (Bologna, April 31th 1896 - Roma, September 11th 1970) is considered one of the most important exponents of Italian Rationalism. Vaccaro crosses the development of the Italian architecture of 20th century with independence of thought and originality of language. He concentrates on the architectural shape rather than on ideological manifestos. In the years between the two world wars, the most important expressions of Vaccaro’s art are the School of Engineering and Architecture of Bologna (1933-35), the Post Palace in Naples (1928-36), the plans for Rome Auditorium (1935), and his masterpiece, namely the Agip colony in Cesenatico (1936-38). Vaccaro’s works are characterized by the systematic use of reinforced concrete and of wide windows with iron frame, by the preference given to flat roofs, by internal and external surfaces painted with several gray shades, according to the typical features of Rationalist architecture.

The School of Engineering and Architecture of Bologna (Fig. 1) is a relevant example of Vaccaro’s architectural style: in Fig. 1 there is a panoramic view of the School which nowadays hosts 5 departments, and 24 classrooms.

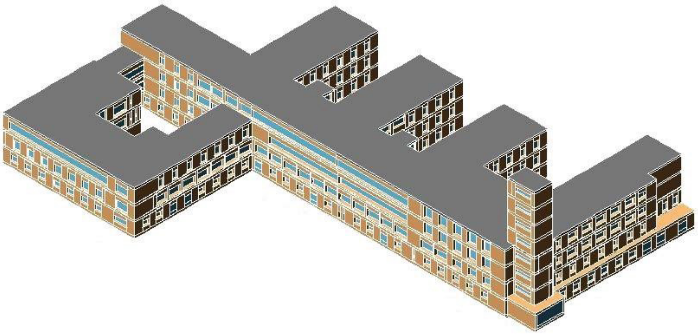

Fig. 1. Panoramic view of the historical building.

The building has a horizontal shape enriched by a vertical element: a tower (see Fig. 1), traditional in Bologna. The external surface is composed of wide windows and of a white Terranova plaster, while the tower has smaller windows and a brick shell. The main structure of the building, about 180 m long, is composed of four floors; it is straight and oriented in the East-West direction. The building is completed by wings orthogonal to the main structure which give to the complex a comb-like shape: four straight wings, each with four floors, are placed in the south side, while a lower U shaped wing, with three floors, is placed in the north side.

The building has a gross floor area and a total gross volume of 23’900 m^2 and 119’300 m^3 respectively. Unheated zones cover about 15% of the total area. The ratio between the gross heat exposed Surface (S) and the heated gross Volume (V) is about 0.25.

2.1. Building Envelope

The building envelope is made in reinforced concrete and pillars with an average thickness of 35 cm. Opaque vertical walls are characterized by a thickness between 60 and 80 cm and are basically in masonry brick with the presence of an unventilated air layer (10-30 cm). The total exposed vertical opaque area is about 9’311 m^2 with an average U-value of 1.10 W/m^2K [8].

Windows cover an area of about 4'160 m^2, which corresponds to 38% of the total vertical opaque surface. Most of windows are made with a single glass and a metal frame and they have an average U-value equal to 4.90 W/m^2K [9]. On the other hand, 14% of the windows have been recently (80s-90s) renewed; they are equipped with double glasses and their average U-value is about 2.90 W/m^{2}K [9]. As mentioned before, most of frames are made of metal and in many cases they are in the original condition. However, due to the renovations made without any coordination in the last thirty years, now in the building windows with the original frame in metal and windows with frames in wood, aluminum or PVC coexist together. In Table 1 typical U-values (W/m^{2}K) of the main envelope components, together with their area, are reported.

Table 1 – Overview of U-values (W/m^{2}K) and heat exposed Surface (m^2) for each building envelope component

Building envelope component	U-value (W/m^{2}K)	Exposed Surface (m^2)
Windows single pane	4.90	3'578
Windows double pane	2.90	582
Opaque walls	1.10	9'311
Ground floor	1.29	12'266
Roof	0.78	7'785

2.2. Heating system

The heating plant of the building has undergone several changes in different periods, as a consequence of technical evolution and National Standard requirements. The original heating plant employed a natural circulation system. The boiler is placed in the basement, in a central position with respect to heated spaces. The heated water flows in non-insulated iron pipes which first reach the top of the building and then go down to the heating devices, which are radiators (90%) and fan-coils (10%). The heating plant is composed of 3 boilers; each has a power of 1046 kW and is provided with a gas burner with a variable power between 400 kW and 1768 kW. The hot water temperature control is obtained through a thermal control unit, which allows 24 hours regulation on two temperature levels. This unit acts on 3 mixing three-way valves operating as a function of the Outdoor Air Temperature (OAT). In this way the hot water temperature can be adapted to the climatic conditions. Thermal control units for single spaces or thermal zones are not present. The hot water distribution is performed by 5 pumps, each with a power of 5 kW (80 m^3/h, 110 kPa).

3. Energy consumption analysis

The detection of the actual energy consumptions due to the heating of the building has been made by collecting the data of the gas bills; only the billing data of two years (from 2011 to 2013) were available; although the conventional heating period is 183 days [10], gas consumption of bills data concern a heating period of 217 days. Table 2 shows the yearly gas consumptions of the winter seasons 2011-12 and 2012-13.

Table 2 – Yearly gas consumption and Heating Degree-Days (HDD).

Winter season	Gas consumption (m^3)	Heating period (days)	Heating Degree-Days (°C)	Gas consumption/HDD (m^3/°C)
2011-2012	438'337	217	2242	196
2012-2013	473'237	217	2405	197

As it can be observed in Table 2, the yearly gas consumption is strongly influenced by the climatic conditions, characterized by introducing the Heating Degree Days (HDD): it is possible to demonstrate that the yearly gas consumption increases linearly with HDD. In Table 2 the values of HDD of the two winters considered in this analysis are shown; it is possible to observe that, in accordance with the HDD values, the gas consumption of the winter 2012-13 is slightly higher than the consumption of the previous winter (2011-12). Moreover, the ratio between the gas consumption and the HDD is basically the same for the two winters; this result confirms the linear relationship between gas consumptions and HDDs. In Figure 2 the monthly gas consumption (Nm^3) and the average monthly Outdoor Air Temperature (OAT) are reported. It is interesting to note that the gas consumption peak of the School is each winter in February.

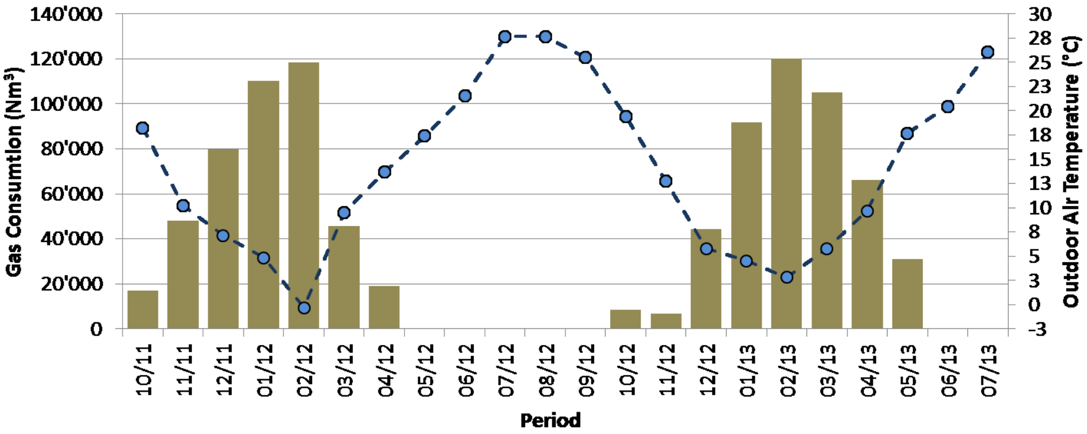

Fig. 2. Gas Consumption (Nm^3) of School of Engineering and Architecture versus Outdoor Air Temperature (from 2011 to 2013).

The relationship between the gas consumption versus HDD is represented in in Figure 3, where the cumulated gas consumptions have been correlated to the cumulated value of HDD by considering two years, starting from 16 September 2011 until 19 August 2013. The results shown in Figure 3 demonstrate clearly the linear dependence of the gas consumption of the School on the HDD.

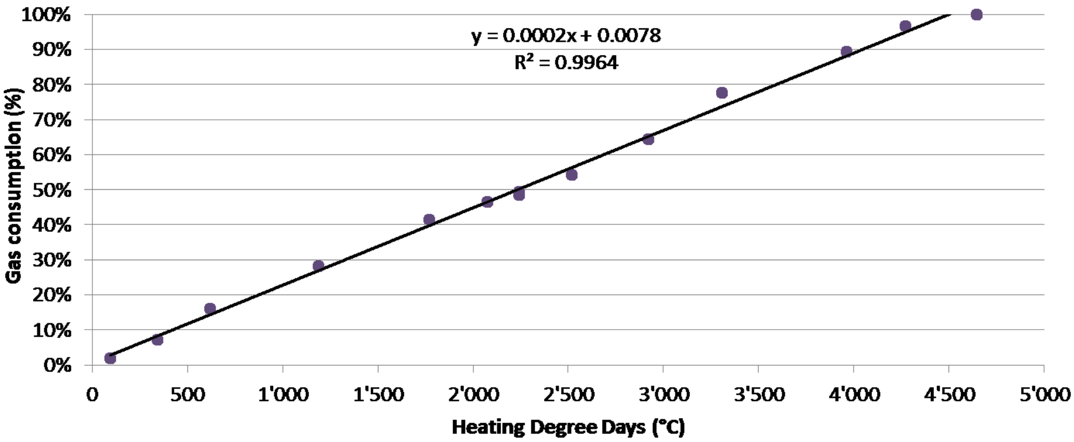

Fig. 3. Correlation between the Heating Degree Days and the gas consumption (from 2011 to 2013).

3.1. The Energy Signature Method

It has been demonstrated by many authors that for the analysis of the energy interaction between a building and its heating plant it is convenient to introduce the Building Energy Signature (BES), which is defined as the thermal power required by the building as a function of the outdoor air temperature (OAT). The methodology for the determination of the BES is introduced by Fels et al [11] and it is described in the standard EN 15603 [7]. The outdoor temperature in correspondence of which the building heating demand becomes zero is called Heating Limit External Temperature (OAT_0) or base temperature [12]. Generally, residential buildings are characterized by means of a linear BES curve; in this case, the value of (OAT_0) and the value of the design load (P_{des}) in correspondence of the outdoor design temperature are the only parameters which must be known in order to draw the "theoretical" BES associated to the building.

When the energy consumptions are measured, the BES curve can be obtained directly by using the measured consumptions; in this case BES is defined as "real".

It is always possible to compare the "theoretical" and the "real" BES of a building and this comparison can be used in order to identify different kind of anomalous behaviors of the "building-heating plant" system.

As an example, the presence of very scattered data points in a real BES can indicate an erroneous setup of the control system of the heating plant, and/or the presence of anomalous ventilation loads and so on. In this case, the R-squared value is a common metric to assess how well the data fit. In order to build the real BES, monthly and/or weekly and/or daily consumption measurements can be used; a discussion about the influence of the monitoring interval on the right determination of a BES, can be found in [13,14].

3.2. Energy Signature of the School of Engineering and Architecture of Bologna

By drawing the real BES of the School, elaborating the data about the real gas consumptions during the winter seasons 2011-12 and 2012-13 it is possible to obtain a series of important indicators. The average value of thermal power needed by the building as a function of the average outdoor temperature were obtained dividing the energy consumption recorded during a fixed period (value extracted by the gas bills) with the time interval between two consecutive gas consumption readings.

The average values of OAT in the same period were estimated by using the weather data recorded by a station located near the building.

The results obtained by collecting together the real gas consumption data and the weather data during the winter seasons 2011-12 and 2012-13 are shown in Figure 4. Each point of Figure 4 represents the average thermal power delivered to the building as a function of the average OAT during the monitored period; the typical time interval between two consecutive gas consumption readings is about one month.

Starting from the collected experimental data, a linear fit of the data has been made in order to obtain the real BES of the School. Real BES can be represented by means of the following equation:

$$P_{th} = \left(-\frac{H}{\eta} \cdot OAT + \frac{H}{\eta} \cdot OAT_0 \right) \tag{1}$$

In Eq. (1) H/η represents the slope of the real BES and OAT_0 is the heating limit external temperature. By means of Eq. (1) it is possible to estimate the thermal power (P_{th}) needed by the School as a function of the outdoor air temperature (OAT).

The slope H/η of the regression line can be linked to the value of the global (transmission and ventilation) dispersion coefficient of the building (H), while η is the global seasonal efficiency of the heating plant.

In Figure 4 the real BES obtained by using the data collected during the winter 2011-12 (dashed line) and the winter 2012-13 (continuous line), are shown. It is possible to observe that a good correlation ($R^2 = 0.8497$) exists among the collected points related to the winter 2011-12; on the contrary, the data related to the winter 2012-13 show a weak degree of linear correlation ($R^2 = 0.5998$). In addition, even if the dispersion of the data around the linear trend is different, the linear fitting of these two series of data gives the same BES (similar slope, similar heating limit external temperature OAT_0).

By considering a value of OAT equal to the outdoor design temperature (Bologna, -5°C) it is possible to obtain by Eq. (1) the indication of the design thermal power needed by the building (P_{des}).

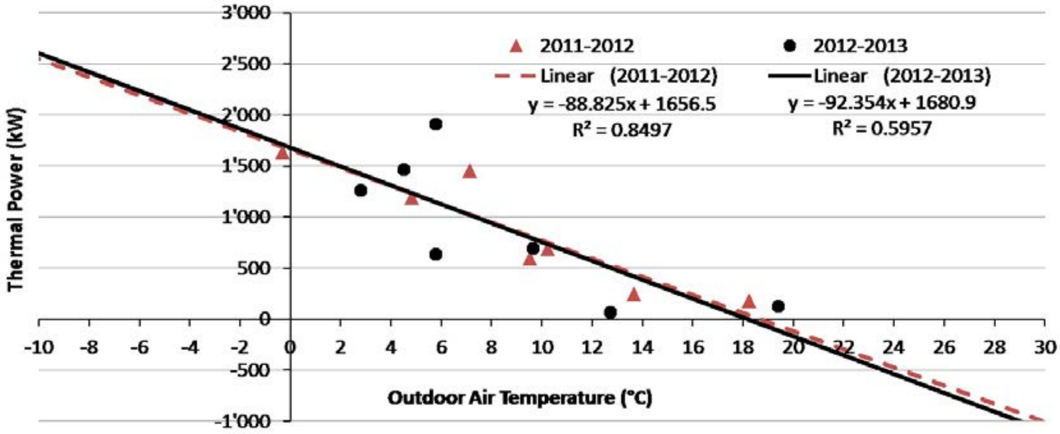

Fig. 4. Heating Building Energy Signatures of the School of Engineering and Architecture (data collected from 2011 to 2013).

In Table 3 are reported the values of the slope, of the design thermal power and of the heating limit external temperature obtained by considering the data collected during the winter 2011-12, the winter 2012-13 and by merging all the data available (2011-13).

Table 3 – Overview data of the real building energy signatures of the School building.

Winter season(s)	-(H/η) [kW/K]	P_{des} [kW]	OAT_0 [°C]
2011-2012	-88.825	2101	18.6
2012-2013	-92.354	2143	18.2
2011-2013	-90.504	2121	18.4

The data of Table 3 confirm that the slope of the real BES of the School is about -90 kW/K. Assuming a natural ventilation rate of 0.3 m^3/m^3h and using the data of Table 1, it is possible to estimate the value assumed by the dispersion coefficient of the school (H=63.2 kW/K). In this way, by the values of slope reported in Table 3 it is possible to estimate the value of the seasonal efficiency of the thermal plant (η) which is equal to 70% in this case.

The consumption data confirm that the heating limit external temperature OAT_0 of the School is about 18-18.5 °C and the value of the design thermal power needed by the School (P_{des}) in correspondence of a value of OAT=-5°C is about 2100 kW. This value is in agreement with the size of the gas boilers installed; two boilers are sufficient to cover the thermal loads during the winter (2092 kW) and the third boiler can be used as back-up. The scattered data obtained by using the measured gas consumption highlight that the control system of the heating plant is not optimized; this is mainly due to the compensation control system used in order to vary the temperature of the hot water as a function of the outdoor temperature. The results shown in Fig. 4 suggest that an improvement of the set-up of the existing control system can determine a significant reduction of the energy consumptions of the heating system without modifying the envelope components (i.e. thermal insulation) and/or the thermal plant (i.e. boiler replacement).

3.3. Energy saving improvements

BES can be used to assess the potential energy savings achievable by considering different building interventions.

Unfortunately, the historic building is subject to a series of constraints in order to preserve its architectural value, and for this reason the possibility to modify the envelope (and also the heating plant when the intervention has a non-negligible impact on the external aspect of the building) is very limited. However, some modifications having a negligible impact on the external aspect of the building can be considered for the energy retrofit of the School:

a) Improvement of the control system of the heating plant: this goal can be reached by placing thermostatic valves in each radiator in order to take into account the value of the indoor temperature during the control of the system. In this kind of intervention also the replacement of the existing hydraulic pump with an inverter driven pump is considered.
b) Improvement of the heat generation subsystem: this goal is fulfilled by replacing the existing 3 conventional gas boilers with 3 new condensing boilers. The transformation of the hydraulic circuit from open loop to closed loop and the cleaning operation of the whole distribution system are considered in this intervention.
c) Improvement of the thermal performance of the windows: all the windows having a single glass are replaced with ultra-thin vacuum insulating glass with the same thickness and restoring the frames – subject to constrains by the Superintendence. In this case the U-value of the windows can be reduced from 4.90 W/m^{2}K down to 1.40 W/m^{2}K.

Using the energy signature of the School, the energy savings of the proposed solutions can be easily evaluated by computing the energy consumption for heating by using the following formula [7]:

$$E_{avg} = P_{th,avg} \cdot \Delta\tau = \left(-\frac{H}{\eta} \cdot OAT_{avg} + \frac{H}{\eta} \cdot OAT_0 \right) \cdot \Delta\tau \tag{2}$$

where OAT_{avg} is the seasonal average outdoor air temperature and $\Delta\tau$ is the duration of the heating period. The slope (H/η) and the value of OAT_0 have been previously calculated by means of the linear fitting of the consumption data (see Table 3). By introducing in Eq. (2) the value of the average of outdoor air temperature calculated for instance by considering the two winter seasons monitored in this work (OAT_{avg}), which is equal to 9.1 °C, the value of OAT_0 (i.e. 18.4°C), the value of H/η (i.e. 90.5 kW/K), and the value of $\Delta\tau$ equal to 217 days, considering a 24-hour continuous operation of the heating system, it is possible to estimate the annual average primary energy consumption (E_{avg}) of the School.

By using Eq. (2) and the data of Table 3, the annual energy consumption for heating of the School has been estimated equal to 4'422'096 kWh/y, which confirms the gas consumption of the billing data.

Now, Eq. (2) can be used in order to estimate the expected reduction of the annual primary energy consumptions of the School when the energy retrofitting strategies described before are considered.

Three scenarios are considered here:

- Scenario a): by means of the thermostatic valves the control of the indoor temperature is strongly improved. This means that the value of the heating limit external temperature will be reduced by the presence of the thermostatic valves. If the average indoor temperature is maintained around 20°C the value assumed by OAT_0 can be imposed equal to 17°C [12,15,16]. Changing OAT_0 from 18.4 to 17 °C the energy consumption, using Eq. (2) becomes equal to 3'743'339 kWh/y, with an energy saving of 15%with respect to the current situation.
- Scenario a+b): the replacement of the gas boilers determines a change on the seasonal efficiency of the heating plant; as consequence BES changes its slope. The increase of the seasonal efficiency of the gas condensing boilers with respect the current conventional gas boilers has been estimated by using the analytical procedure described by UNI TS 11300/2 [17]. In this case it is possible to increase of the seasonal efficiency of the heating plant from 70% to 80%. Eq. (2) predicts an annual energy consumption equal to 3'284'971 kWh/y, with a decrease of 26% with respect to the current situation. In this case BES shifts to the left and changes its slope due to the lower design thermal power needed.
- Scenario a+b+c): this intervention has an impact on H, OAT_0 and η. H coefficient changes because the U-value of the windows decreases. By using the data of Table 1 and the new U-value of the windows (U=1.40 W/m^{2}K), it is possible to predict a reduction of H, which becomes equal to 50.7 kW/K after the replacement of the windows. The energy consumption becomes equal to 3'002'189 kWh/y, with an energy saving of 32% if compared to the current situation.

In Figure 5 it is possible to see the variation of BES for the three scenarios considered.

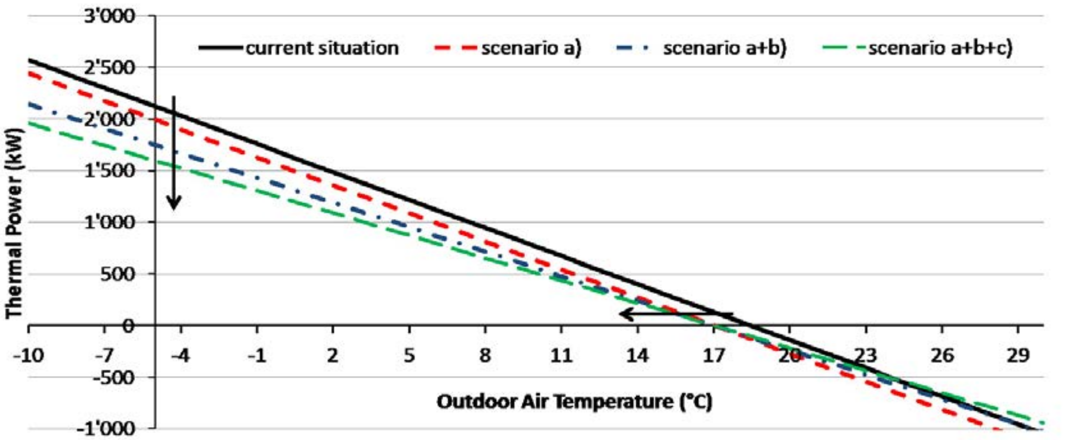

Fig. 5. Heating Building Energy Signatures of the proposed solutions for the School of Engineering and Architecture.

Table 4 summarizes the main results obtained by means of the Building Energy Signature method in terms of primary energy consumptions for all the scenarios considered in this paper.

Table 4 –Summary of results obtained from the energy audit

Building Energy Signature	$-(H/\eta)$ (kW/K)	P_{des} (kW)	OAT_0 (°C)	E_{avg} (kWh/y)	ΔE (%)
Current situation	-90.504	2121	18.4	4'422'096	-
Scenario a)	-90.504	1991	17.0	3'743'339	15%
Scenario a+b)	-79.422	1747	17.0	3'284'971	26%
Scenario a+b+c)	-72.585	1597	17.0	3'002'189	32%

4. Conclusion

The paper proposed a simple methodology tailored to predict, starting by the knowledge of the billing data, the impact of retrofit actions on the building energy demand. A simplified approach to the energy diagnosis has been presented in order to define a reliable energy audit. In this manner, the impact of several retrofit actions could be quickly evaluated; in particular, the case study is referred to School of Engineering and Architecture of Bologna (Italy) that hosts basically department, offices and classrooms. All the studies have been carried out with reference to the standardized method of energy signature reported in EN 15603:2008 in order to provide a correct building energy diagnosis. In particular, three different retrofit actions have been analyzed: (1) modification of the indoor temperatures in the heating season; (2) replacement of the old actual boilers with condensation gas heaters; (3) substitution of the actual fenestration systems (only the single glass panes). Each one of these actions concurred in reducing, significantly, the building energy requirement in terms of annual average primary energy consumption for heating, passing from -15%, due to the change of the indoor temperature set-point, to -26%, adding the boilers replacement, and to -32% considering also the substitution of fenestrations. Finally, in order to analyze more in depth these results it is recommended to perform a simulated energy audit in addition to an economic analysis of the retrofit actions.

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