

Article

# Assessment of Energy Sustainable Operations on a Historical Building. The *Dante Alighieri* High School in Florence

Carla Balocco \*  and Alessandro Colaianni

Department of Industrial Engineering, University of Florence, via Santa Marta 3, 50139 Florence, Italy; alessandro.colaianni@unifi.it

\* Correspondence: Carla.balocco@unifi.it; Tel.: +39-055-2758739

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**Abstract:** Italy has a huge cultural heritage, most of which consists of historical buildings that have changed their original function and use over time. The complex question of building and plant system refurbishment and retrofitting mainly derives from this crucial aspect. The aim of this paper is to provide a simple provisional tool useful for the assessment of efficient, energy sustainable refurbishment solutions for historical buildings and their plant systems. The Dante Alighieri high school (with an important music department) in Florence was the case study. We proposed a method based on dynamic simulations that allows plant design guarantying indoor air quality (IAQ) and thermal comfort, as well as energy efficiency, but, at the same time offering reversibility and mobility as well as ease of management and maintenance. Transient simulations of building-plant system were specifically addressed dynamic control and adaptive proportional regulation, so as to ensure that the plant adapts to the change of building and indoor environment thermo-physics and thermo-hygrometric parameters. Results showed that important refurbishment and retrofitting operations for energy saving are possible and effective for historical buildings if they are oriented to sustainability—i.e., low environmental impact, indoor thermo-hygrometric conditions, ventilation, air quality, and user wellbeing improvement—in compliance with preventive protection constraints.

**Keywords:** cultural heritage; school building; energy sustainability; energy refurbishment; dynamic simulation

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## 1. Introduction

About 40% of energy consumption in Europe is due to building energy needs much of which is for summer and winter air conditioning. The position of the European Union (EU) increasingly focuses on energy saving and the efficient use of energy resources. This objective has been defined by means of the issue of the Energy Performance Buildings Directive (EPBD [1–3]) and with nearly zero energy buildings concept (nZEB).

Energy efficiency has become a common target for buildings and plant systems: European Directive 2010/31 specifies that every new building must consume less and less fossil energy and reach the nZEB goal by 2020 [2]. This directive [2] also refers to the cost-optimal method for fixing building energy requirements. The deadline for public buildings is the end of 2018.

Nevertheless, it has been widely demonstrated that refurbishment and retrofitting operations on the existing building heritage is a complex task, especially when it consists of school buildings [4–8]. This is particularly true for historical public buildings of our cultural heritage, because many energy solutions in the field of renovation are not always compatible with historic constructions, and preservation of historical value, authenticity, and integrity [8,9]. In many cases, operations for

improving the building envelope, usually consisting of massive walls in heavy masonry, single-glazed wooden window frames, and wooden shutters cannot always be carried out. The main risks for user health and comfort and historical building preventive protection, derive from the thermo-hygrometrics and air quality of the indoor environments. The annual variations of indoor and outdoor thermal and hygrometric parameters, characterized by slow stresses spread over time, can lead to fewer negative changes compared with the most rapid daytime and seasonal impulsive variations (e.g., the effects due to strong, uncontrolled artificial lighting, or uncontrolled heating and cooling).

Recent studies on this subject have built up complete, integrated databases useful for the identification and checking of possible intervention strategies to reduce energy consumption in this sector [8,9]. In particular, the authors have foregrounded the fact that a significant item regarding losses (i.e., energy, money, and costs) is due to inefficiencies in the management of building-plant systems that can be easily overcome by simple, low cost actions [8]. Educational buildings in Europe account for 20% of the entire non-residential floor space where good indoor comfort and air quality are essential for efficient educational development, but also increase of knowledge on how energy is used and consumed to enhance the awareness of school managers of the importance of improving energy efficiency and reducing energy costs [10–15].

Some authors have also demonstrated that the application of cost-optimal measures for retrofitting can be useful for assessing the priority and urgency, cost-optimality, energy efficiency, energy management, and effective energy saving of different refurbishment operations in school buildings [7,8,15]. Much of the relevant literature has proposed integrated methodologies for helping to identify major energy consuming plants/equipment in school buildings and potential energy conservation measures [11,12,14–16]. Extensive literature has provided basic guidelines for the application of an integrated assessment of the energy performances of the building-plant system in schools, taking into account indoor climate, indoor air quality, well-being, health, and development of student cognitive and comprehension activities, based on in situ measurements, monitoring campaigns, energy audit and cost analysis, and transient simulations [16–31]. Generally, these methodologies involve architectural features and plant system analysis; experimental field measurements; collected data processing on user/student perception; dynamic simulation of building-plant system for thermo-physical and energy performance and energy consumption evaluation; thermal comfort assessment by transient simulation; assessment of the energy saving, efficacy/efficiency and cost due to retrofit and refurbishment solutions for school energy improvement and indoor quality and comfort achievement [18–20].

Some authors have also highlighted that there is a considerable non-calculated potential for energy savings and improvement of indoor conditions in school buildings, promoting student and teacher productivity, and wellbeing [12,13]. In particular, in [21], the authors showed that, for high temperature cities (i.e., those located in hot regions such as Saudi Arabia and characterized by extreme changes in microclimatic conditions) school building architectural design could include natural ventilation techniques with the highest efficacy if cross-ventilation typology is realized for specific classrooms: the consequent benefits should lead to indoor air quality improvement, operation cost reduction, and satisfactory indoor thermal comfort. References [21,30] are particularly important studies presenting an integrated design approach to systematically evaluate and optimize school design parameters at different design stages for summer outdoor thermal comfort and building cooling demand. A three-dimensional microclimate model was used to measure outdoor temperatures and the suggested physiological equivalent temperature (PET) index as a measure of the outdoor thermal comfort condition. The outdoor temperature values and PET results were assumed as thermal boundary conditions for energy simulation performed by the well-known Design-Builder software. Dynamic simulation results have proved that the integrated design approach can be effective for mitigating school heat stress and energy saving [30].

In Italy, Ministerial Decree (MD) 26/06/2015 [32], provides minimum energy performance requirements for new buildings and buildings subject to renovation. These requirements are

differentiated in function of the extent of the building retrofit. In particular, all the retrofit action affecting more than 50% of the building envelope and considering heating system upgrading, should meet stricter requirements, that concern building energy performance and technical building systems efficiency evaluated by the national reference building approach [33,34].

In addition, in Italy the EPBD was adopted by MD 26/06/2015 [32] but can hardly be applied to historical buildings, especially if they belong to the cultural heritage.

Buildings of the Italian cultural heritage vary greatly and have many different architectural constraints. This is the reason why today there are no single/univocal refurbishment and retrofitting solutions for building-plant system. Most of the historical buildings have undergone changes in their use over time. Then plant system installation can be very difficult both for strictly architectural issues (e.g., final part of the plant placement, such as fan-coils, heaters, air inlet and outlet diffusers) and for technical issues (e.g., air/water ducts crossing inside walls and cavities not always of sufficient dimensions). Sometimes, plants (e.g., heating terminals like radiators) have historical value and cannot be modified and/or replaced [8,9,35,36]. Most of the literature on energy efficiency of cultural heritage buildings has suggested operations complying with current standards concerning building envelope and plant systems [8,9,15,19,26,31,35,36].

In Italy, there are about 52000 historical buildings used as schools (80% dating back more than 30 years and almost 20% to 70 years) characterized by high inertia and thermal capacity [18,19,26,31,35–38]. Public building represents an important possibility for energy saving of the whole community, as required by UE Directives [1–3]. This can be effectively realized in the school building sector: the buildings are characterized by high energy consumption without indoor air quality and ventilation control [8,9,35,37,38]. Any building envelope refurbishment and improvement of thermo-physical performances for historical buildings cannot be easily realized and generalized because of their historical value and limits imposed for protection and preventive conservation. Similarly, plant refurbishment and/or retrofitting are difficult to implement. On the other hand, energy consumption, due to compliance with the requirements for thermo-hygrometric comfort conditions, indoor air quality, ventilation, and lighting are appreciably high, considering time profiles of use, number of occupants, hygiene, and health and safety requirements [29,31,35,36,38,39].

In particular, a crucial recent work has provided fundamental guidelines for the achievement of energy efficiency of the cultural heritage [37]. The author highlighted the fact that the suggested guidelines, addressing design engineers and the National Heritage Protection Offices (Sovrintendenza), including current Italian standards and legislation, are not always uniquely and strictly applicable to all types of existing historical buildings and plants [38]. Other in-depth research has highlighted how it is also possible to achieve very low and/or nearly zero energy standards for historical buildings of the cultural heritage [39,40]. In particular, it has been proved that the most effective and energy sustainable operations, are what the authors define as “active design strategies”, i.e., plant system retrofitting and refurbishment (e.g., lighting, air conditioning system, building-plant management, and control system), because they have a shorter payback time and are more easily achievable for historical buildings of the Cultural Heritage also taking into account the fact that for “passive design strategies”, i.e., building refurbishment (e.g., green walls and green roof, solar chimneys, solar thermal panels, and high performance windows) energy and cost effectiveness can be obtained by considering the proper scales of application [39].

Our present study aims to evaluate energy efficiency, effectiveness, and sustainability of possible refurbishment solutions of building-plant system belonging to historical buildings used as schools. We propose a methodological approach based on dynamic simulation aimed at defining an optimal regulation and control system since it is minimally invasive; reversible and dynamic; and oriented towards energy efficiency, quality of the indoor environment, as well as comfort and health of the occupants. A historical building used as a high school (with an important music department) located in Florence (Italy) is the case study. Dynamic simulations were validated by means of annual energy consumption monitoring data for the heating season. The effects of the proposed operation on the

plant system regulation and control and on energy consumption were assessed and then the mix between this solution and building envelope improved insulation was analyzed and discussed.

## 2. Materials and Methods

This study aims at identifying and evaluating the possibility of carrying out energy sustainable design proposals on building envelope and plant system. Dynamic simulation of the building-plant system was carried out to define the environmental and thermo-hygrometric conditions at present, taking into account the variation of external climatic stresses and internal thermal loads due to occupants and equipment. Implementation of transient simulation, slowly introduced over time, continuously controlled microclimatic dynamic conditions leading to their stability. Simulation results allowed the identification of critical issues and the priority of some interventions. System modelling results were validated by comparison against real building energy consumption. The next phase of analysis required new building-plant modelling for transient simulations devoted to a proposed control and regulation system of the heating plant and then, consequently, this first plant intervention combined with fundamental building envelope improvements (i.e., strong roof insulation, total window replacement, and ground floor insulation). As a consequence, all the related simulated operations should be efficient and effective, in compliance with required indoor thermo-hygrometric conditions, ventilation, air quality, and user wellbeing.

The methodological approach used was therefore based on field-practical research, necessary for useful data and information collection. In Italy, there are no databases or computerized and interfacing databases on buildings and plant system technical data, especially if they are historical and/or cultural heritage school buildings. In particular, in Italy, schools are frequently located in historical buildings, often of very important historic, architectural, and artistic value and often places of worship (e.g., churches and monasteries). Although the Council of Europe has issued precise directives on the historic and architectural heritage, in the form of the “Convention for the Protection of the Architectural Heritage of Europe” [41], it does not provide limits and parameters and/or energy regulation measures for historical building energy performance, and, as a consequence, energy retrofit is not compulsory [40]. Therefore, in this context, our proposed methodological approach can be a useful tool for the evaluation of the real applicability, in depth assessment and comparison of the efficacy, energy sustainability, environmental quality (low impact) and user comfort provided by different retrofitting and refurbishment interventions on historical building-plant systems, in compliance with the current standards for protection and preventive conservation. A scheme of the logical process of the proposed method application, that is extensible (with modifications and adaptations due to specific individual conditions) to all similar cases of existing building-plant systems, belonging to the cultural heritage, but also recent construction design, is provided by the flowchart in Figure 1.

### 2.1. Data Collection and Identification of Architectural and Geometrical Features of the School Building

The following steps were performed to develop a three-dimensional model of the building with which all the dimensional, volumetric, functional, constructive, and thermo-physical characteristics could be associated:

- direct architectural and geometric measurements with a laser meter;
- photographic surveys both inside the building and outside for the framing of the architectural, urban, and landscape context and surroundings;
- direct inspections for determination of the type and number of heaters in each classroom, structure and artificial lighting system, type of windows and shielding elements (if any);
- interviews with technicians and experts on this area for defining type of activities, number of occupants and hours of use of the various classrooms, type, characteristics and schedule for on/off switching of the heating system;

- data/information collection provided by the Metropolitan City of Florence (public authority for school buildings management and administration) such as architectural drawings, technical reports, adjustment interventions for fire regulations and any functional information;
- data collection concerning the monitoring of the annual energy consumption for heating and the connected costs;
- in-depth study by means of a comparative analysis of the information derived from comparison of historical and scientific sources to identify the constructive and thermo-physical characteristics.

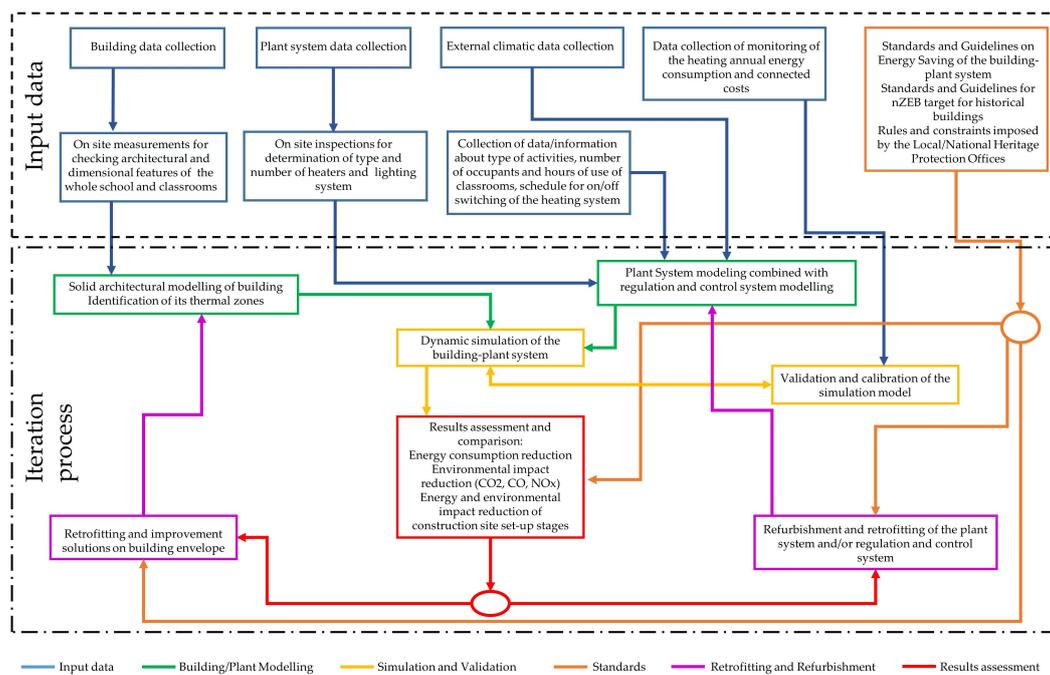


Figure 1. Flowchart of the methodological approach proposed.

## 2.2. Transient Simulation

Building-plant dynamic simulations were carried out with commercial software TRNSYS [42]. This is a complete and extensible simulation environment for transient simulation of systems, including multi-zone buildings [42].

The simulation model implementation required the 3D solid-architectural modelling of the building, plant model, and definition of the boundary conditions, time step calculation for solution convergence.

The thermal zones definition, all the geometric and thermo-physical data of opaque and transparent components, schedules of different activities, and occupation time of different classrooms and environments were fixed as boundary conditions used for simulation modelling.

The plant system modelling was based on the definition of its components and related parameters at the present state and also for the proposed efficient regulation and control system with application of thermostatic valves and zonal thermostats. The software uses the transfer functions method (TFM) for solving the governing equations of heat and mass transfer [38]: this method is based on the Z-transform (ZT) set equations; the TFM, recommended by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), is one of the most widely available tools for solving heat transfer problems in building-plant systems (i.e., building envelopes, internal environments, and heating-cooling plants). TFM utilizes Z-transforms to solve the equation system that describes heat and mass transfer in a multi-layered wall.

### 2.3. Boundary Conditions

In this section, boundary conditions assumed for dynamic simulation are shown. Hourly climatic data for the typical standard year of Florence taking into account that the city belongs to the climatic zone of medium-low latitudes labelled as D with 1821 degree days [43] with a heating period from 1 November to 15 April, were used. In particular, the Florence Reference Year with hourly climatic data provided by EnergyPlus was selected [44]. This weather file is suitable for energy analysis in compliance with the Italian Building Regulation [45]. Thermal solar gains are the main cause of overheating risk during summer and, because the historical architectural features and identity of the building must be preserved, a dedicated assessment of the solar radiation distribution on building facades was developed: hourly simulation results of shadows on the school building studied, as a function of the solar path due to surrounding buildings and landscape, were carried out.

### 2.4. Case Study Analysis

The above-mentioned school in Florence, built in 1876 and used as a school since 1921 is the case study. The building is not totally subjected to the constraints imposed by the National Heritage Protection Offices (Sovrintendenza), although it is historical and therefore protected. It consists of three floors above ground and a basement together with a large attic that is not occupied or air-conditioned. It is exposed to all four cardinal points and rotated with respect to the North by 18 degrees counter-clockwise (Figure 2).



Figure 2. “Dante Alighieri” high school building.

The collected data on thermo-physical characteristics of the building envelope components are given in Table 1. In particular, a gym is present with two areas used as changing rooms. The use of this zone ends at 10:00 p.m.

The present heating plant consists of a heat generator (condensing boiler) with modulating burner powered by methane gas with a nominal power of 756 kW and maximum fluid flow rate of 31,926 l/h.

The generator supplies two detached hydronic circuits, one for the school and the other for the gym, equipped with single-stage hydronic circulators of different sizes.

The heating system terminals consist of cast iron radiators with an important thermal inertia, without thermostatic valves and placed in a central position with respect to the building, as the original system was characterized by a natural circulation of fluid in the ducts.

The building used for the gym is supplied by a fan-coil with 100 kW maximum power and a three-speed fan; cast iron radiators supply the changing rooms.

The system control is manual. The plant modelling at the present state was carried out by setting the water supply at 80 °C to the hydronic circuit with the sole limit of its maximum power. The switching times for the heating plant were defined as follows: 6:00 a.m.–12:00 a.m. and 2:00 p.m.–7:00 p.m. for midweek days; 6 a.m.–12 a.m. for Saturday; and on Sunday, the plant was considered off.

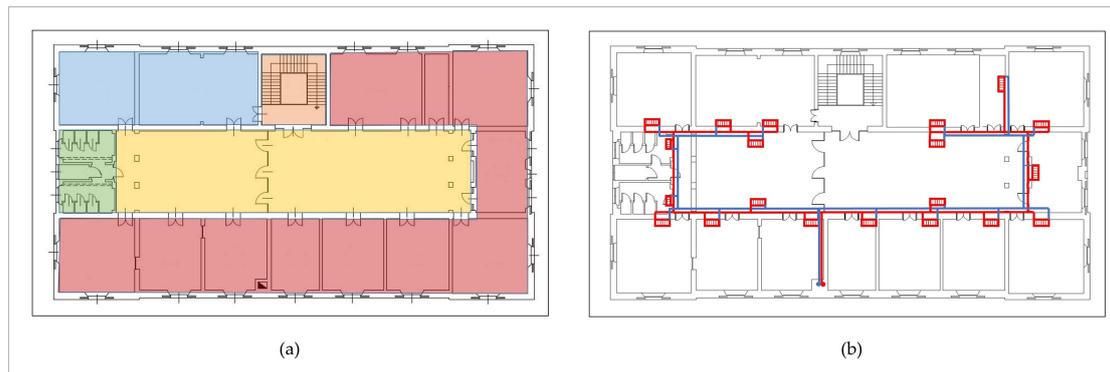
**Table 1.** Thermo-physical properties of building components.

Partition/Component	Material (From Indoor To Outdoor)	Thickness [m]	Conductivity [kJ/hmK]	Capacity [kJ/KgK]	Density [Kg/m <sup>3</sup> ]	Resistance [hm <sup>2</sup> K/kJ]	Total Trasmittance [W/m <sup>2</sup> K]
Perimetral Walls	Gypsum Plaster	0.02	1.26	1.00	1200	-	1.910
	Masonry	0.65	6.84	0.84	1600	-	
Perimetral Walls (first floor)	Gypsum Plaster	0.02	1.26	1.00	1200	-	1.903
	Masonry	0.65	6.84	0.84	1600	-	
Internal Walls	Gypsum Plaster	0.02	1.26	1.00	1200	-	2.391
	Masonry	0.45	6.84	0.84	1600	-	
	Gypsum Plaster	0.02	1.26	1.00	1200	-	
Roof	Wood	0.04	0.72	2.00	800	-	2.102
	Gypsum_Mortar	0.06	2.52	1.00	1400	-	
	Roof Tiles	0.02	3.60	1.00	2000	-	
Slab-under roof room	Wood	0.04	0.72	2.00	800	-	0.477
	Gypsum_Mortar	0.10	2.52	1.00	1400	-	
Slab (wattle)	Insulation	-	-	-	-	0.44	1.628
	Wood	0.04	0.72	2.00	800	-	
	Gypsum_Mortar	0.10	2.52	1.00	1400	-	
	Cement Mortar	0.10	5.04	1.00	2000	-	
Windows	Single Glass/Wooden Frame	0.03	3.60	1.00	2000	-	5.680
		-	-	-	-	-	

## 2.5. Solid Building Modelling

The building modelling, performed by TRNbuild software [42], required the definition of opaque and transparent building partitions and components (i.e., their geometric features and thermo-physical properties; Table 2), the schedules related to endogenous loads and air flow rates due to natural ventilation calculated in accordance with [43,45] and then equal to 1 vol/h for each thermal zone and constant during the day with the exception of the entrance area to the classrooms, that is not connected to the external environment. The national calculation method provided by [45] was used to define 24 thermal zones, including circulation, administrative offices, classrooms, laboratories, attic, toilets, gym, and changing rooms (Figure 3a).

These are the present conditions that take into account: occupation time profiles, indoor set-point, activities performed and different uses, endogenous thermal loads (sensible and latent heat), and plant terminals (Figure 3b).



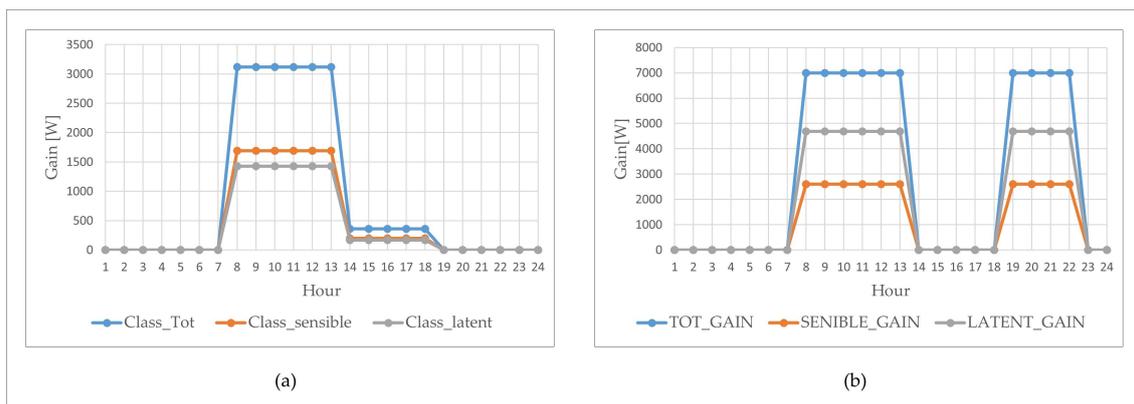
**Figure 3.** (a) Thermal zone identification, second floor; (b) hydronic network scheme, second floor.

**Table 2.** Characteristics and dimensions of the different thermal zones.

Zone	Net Floor Area (m <sup>2</sup> )	Walls Area <sub>jinguw</sub> (m <sup>2</sup> )	Windows Area <sub>jinguw</sub> (m <sup>2</sup> )	Net Volume <sub>jinguw</sub> (m <sup>3</sup> )
Basement	843.9	418.0	78.2	4218.5
Ground floor	843.9	559.9	89.0	4471.7
First floor	843.9	561.3	87.6	4471.7
Second floor	843.9	561.3	87.6	4471.7
Under roof room	843.9	190.2	0	1190.8
Roof	-	970.5	0	-
Gym	387.8	868.1	59.0	3239.8
Total	4607.3	4129.3	402	22063.7

Thermal loads due to the occupants' activity were assumed to be in agreement with [45]. In particular, for the classrooms, laboratories and offices "seated, very light writing" (i.e., 120 W per occupant, of which 60 W sensible heat and 40 W latent heat), "bowling" activity (280 W per occupant of which 100 W sensible heat and 180 W latent heat). Occasional occupation was considered for bathroom areas, locker rooms, corridors and the stairwell–elevator shaft.

Profiles over time of classroom occupation were defined by assuming precautionary conditions with maximum utilization and disregarding time for lunch because it is not included in the school timetable. Then, student numbers for each zone and occupation time were assumed to be as follows: for the classrooms (Figure 4a) 26 students in the morning (from 08:00 a.m. to 2:00 p.m.) and three occupants in the afternoon (from 2:00 p.m. to 7:00 p.m.); for the laboratories, in the basement classrooms, no student in the morning and three students in the afternoon; for the gym 25 students with the occupation times were taken into account as provided in Figure 4b. On Saturday, all the thermal loads were considered for morning hours. Thermal load due to the lighting system was assumed to be 5 W/m<sup>2</sup>: there are eight fluorescent lamps with 28 W absorbed power in each classroom (35 m<sup>2</sup> surface). The lighting turn-on time and the connected thermal load were fixed from 8:00 a.m. to 7:00 p.m. The soil temperature was assumed to be equal to 15 °C.



**Figure 4.** (a) Occupation thermal loads for classrooms, midweek days; (b) occupation thermal loads for gym, midweek days.

The indoor set-point values were set in compliance with [46], at 20 °C for all the thermal zones and 18 °C for the gym.

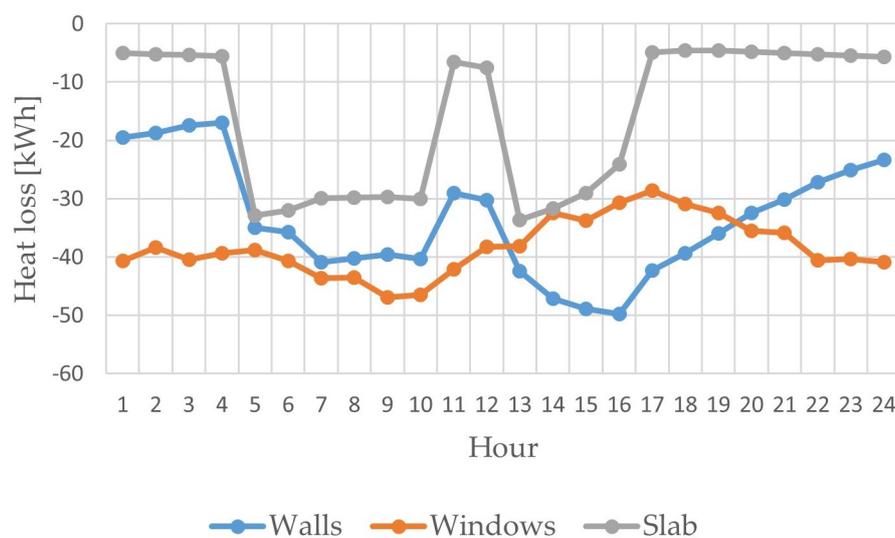
### 3. Results and Discussion: Building-Plant System at the Present

From the transient simulation results analysis, obtained with the previously described model, from now on “Present state”, it can be deduced that:

- the heat generator is consistently dimensioned;
- the dry bulb air temperatures in the classrooms are different and oscillating, with positive and negative values around the set-point, because there is no control system; radiator numbers in the different classrooms are not always sufficiently dimensioned.

As a consequence the set-point conditions cannot always be guaranteed.

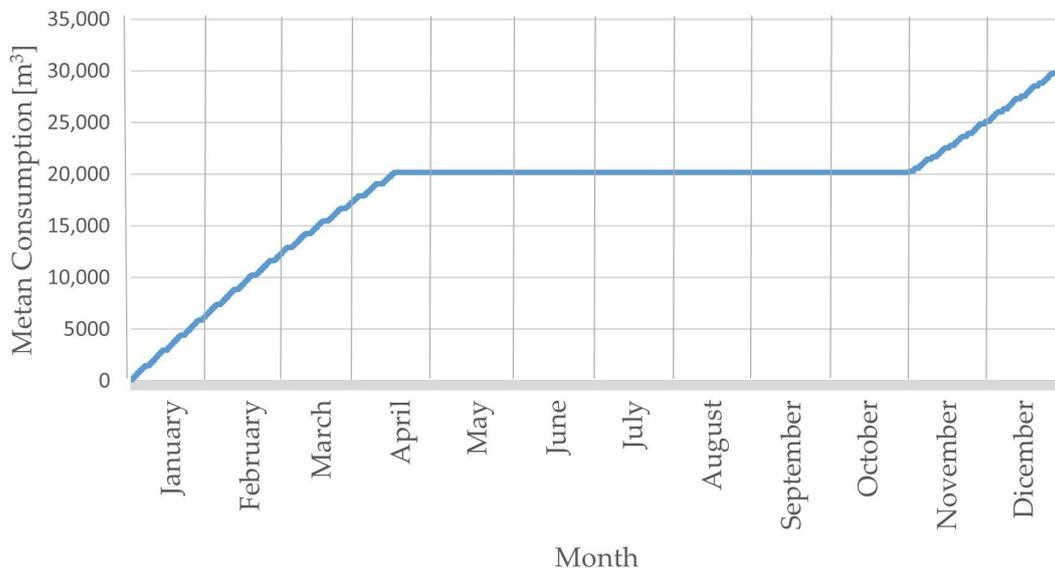
Figure 5 shows the hourly trend of heat losses for the coldest day of the year (10 January) referring to the perimeter walls, windows and the slab separating heated and non-heated volumes. The coldest day of the year was defined on the basis of climatic data used for transient simulations.



**Figure 5.** Hourly trend of heat loss through the envelop for the coldest day of the heating period, present state.

Total heat loss for the coldest day of the heating period and for the whole building is 2373 kW. This means that heat loss for all the windows is 42%, for perimetral walls 37%, for the separation slab between the environment heated and not heated 21%.

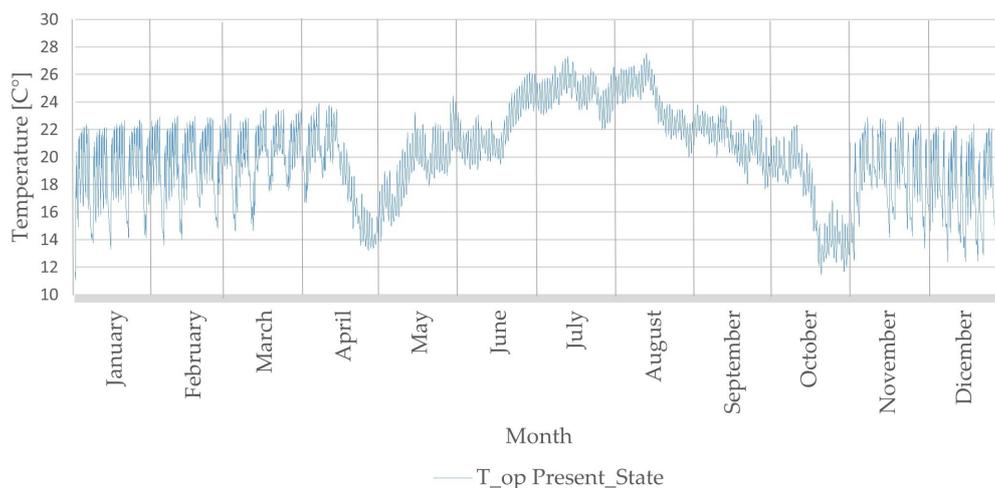
Figure 6 shows the annual consumption of methane obtained by simulation results and expressed in  $\text{m}^3$ .



**Figure 6.** Annual trend of methane consumption, present state.

Figure 7 shows, by way of example, the trend (on an hourly basis and extended to the whole year) of the operating temperature ( $T_{op}$ ) for a single thermal zone.

The thermal zone, chosen as an example, oriented to the south and east, is located on the ground floor, and consists of two classrooms that respectively have a total number of radiators that are sufficiently sized.



**Figure 7.** Monthly operative temperature trend for the considered thermal zone, present state.

Indoor thermal comfort was assessed for the heating period, in compliance with [46,47] through the PPD index (predicted percentage of dissatisfied) evaluation. The cloth thermal resistance index ( $I_{clo}$ ) was assumed to be equal to 1 and the air velocity 0.06 m/s.

Figure 8 provides the PPD index evaluated for the heating period and with hourly time steps for the thermal zone considered.

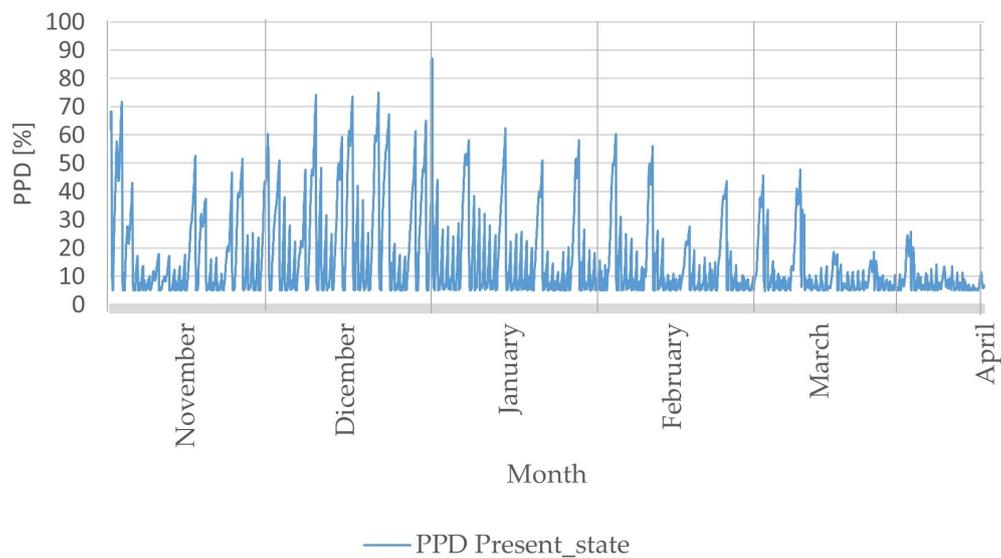


Figure 8. PPD index trend, present state.

Referring to [32], for the period of the year complementary to the heating season, the range of acceptable indoor air temperature values in the real condition of the studied school without mechanical ventilation and control systems (i.e., as defined [32] Buildings category III) was calculated in relation to the operating temperature value variations. The analysis (see Figure 9) shows that for most of the considered period (from 15 April to the 1 November), taking into account only the occupation hours, that stand for 19% of the above mentioned period, the  $T_{op}$  values are between the two limits, respectively 'upper limit' and 'lower limit'.

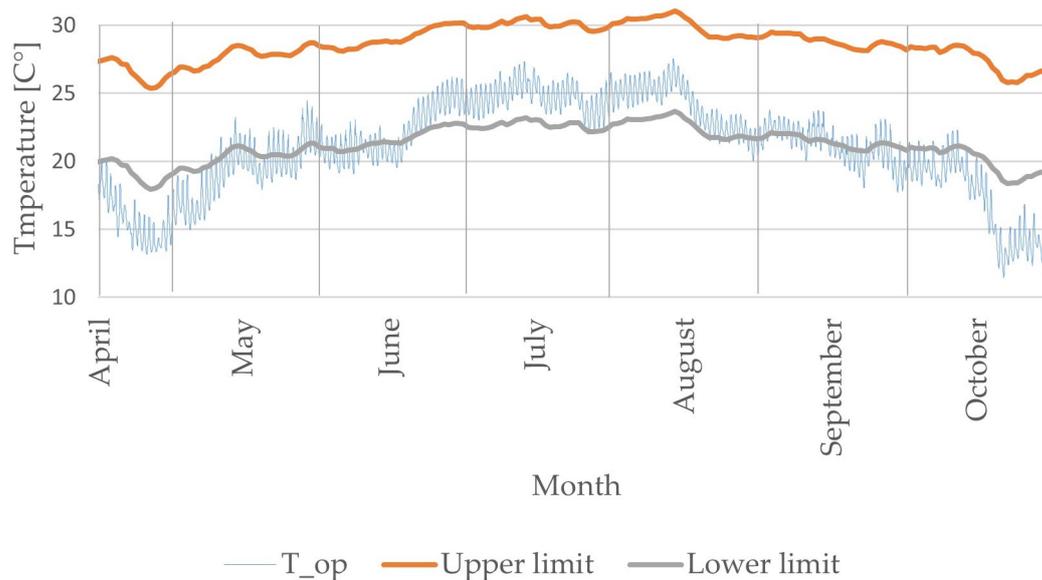


Figure 9. Monthly trend of the indoor operative temperature, present state.

Results comparison highlights the following fundamental critical questions:

- Lack of thermal zone regulation does not allow achievement of an average constant and uniform air temperature value during occupation hours, especially in those classes (or thermal zones) for which the climatic stresses are more incident and important.
- All the heat losses through transparent surfaces and separation wall between heated and non-heated volume appreciably affect the total energy balance of the building.
- The PPD index value calculated for the whole heating period with [47], assessed and compared referring to the occupation hours is between 5% and 10%; this means that thermal comfort conditions, human wellbeing, and health are guaranteed.
- The methane consumption evaluated for the heating period of 30,260 m<sup>3</sup>, stresses the important need for energy saving measures and refurbishment/retrofitting solutions that can be all the more reversible and sustainable because they are designed for a historical building. With reference to current Italian regulations concerning energy building qualification/certification, the above consumption corresponds to 73.9 kW/m<sup>2</sup> year. This result is in compliance with literature results on this subject for similar, comparable cases, both for climatic external conditions, internal environment utilization, and historical school building refurbishment proposals [9,15,19,31].

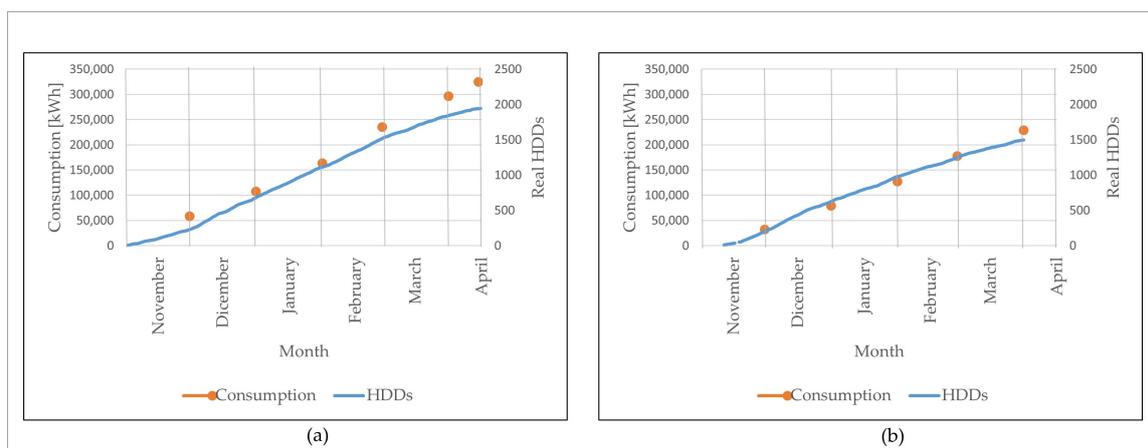
### 3.1. Simulation Model Validation

The real energy consumption for building heating demand was performed by the annual billing invoice data of two years (2012/2013–2013/2014) that were provided for us. This real consumption only refers to the methane consumption for school heating during the winter period and not to hot water use, because there is no dedicated hydraulic system.

Since the real energy consumption is strongly influenced by the external climatic conditions, it was normalized to the heating degree days (*HDDs*).

The real *HDDs* of the two years, were calculated using the corresponding real external climatic parameters. These data were provided on an hourly basis by LaMMA (Laboratory for Meteorology and Environmental Modelling) referring to the nearest meteorological station at nearby Sesto Fiorentino (Latitude 43.82°; Longitude 11.20°).

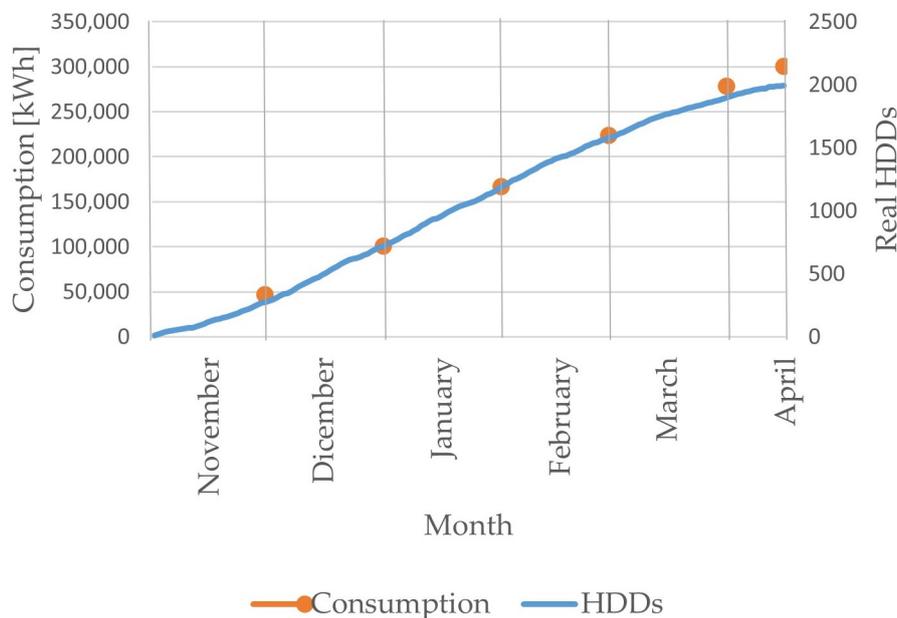
In the following Figure 10, the *HDDs* trend related with monthly consumption, expressed in kWh is shown. For methane cost we referred to data from the Ministry of Economic Development [48]. The comparison between real and calculated energy consumption provided a further validation of the transient simulation model used.



**Figure 10.** (a) Comparison between the *HDDs* trend and heating plant energy consumption, for the 2012/2013 year; (b) Comparison between the *HDDs* trend and heating plant energy consumption, for the 2013/2014 year.

Then, the calculated *HDDs* were obtained from the hourly climatic data of the standard year of Florence, used as boundary conditions for transient simulation.

The real *HDDs* were correlated with the heating energy consumption based on the *HDDs* computed using the standard year data (Figure 11).



**Figure 11.** Comparison between the real *HDDs* and the heating energy consumption, obtained by the *HDDs* computed with the standard year data.

From results comparison (Figures 10 and 11) it is possible to deduce that heating energy consumption computed by the real *HDDs* is very similar and comparable to the calculated/simulated one.

The global index defined as normalized primary energy consumption (*NPEC*) was provided for a direct comparison between real and simulated data. It is expressed by the equation

$$NPEC = \frac{TotalConsumption}{HDD}. \quad (1)$$

The *NPEC* value obtained using the real energy consumption (bill invoice) for the 2012/2013 year and the real *HDDs* (these last calculated by the corresponding climatic data) is 167 kWh/HDD.

The *NPEC* value obtained using the real energy consumption (bill invoice) for the 2013/2014 year and the real *HDDs* (these last calculated by the corresponding climatic data) is 152 kWh/HDD.

The *NPEC* obtained with the energy consumption of the heating plant, calculated by TRNSYS dynamic simulation, and the *HDDs* calculated with the climatic data of the standard year of Florence, is 152 kWh/HDD.

From *NPEC* values comparison the reliability and validity of the numerical model can be deduced because the difference between the *NPEC* simulated and that calculated, using the real *HDD* and energy consumption for the year 2012/2013 and those for the year 2013/2014, are respectively 9% and 0%.

#### 4. Proposals for Energy Efficiency and Sustainability

Starting from current conservation approaches that highlight how the preservation and restoration of the cultural heritage should be a condition as closed as possible to the state in which the building is handed over, using construction methods and techniques that approach the historical ones, any energy and comfort optimization intervention becomes a complex issue. The proposed solutions, based

on building envelope retrofitting and regulation control systems of the heating plant, were selected and then investigated because they are low-cost, reversible, minimally invasive, highly replicable, and allow enhancement of user comfort while reducing energy consumption.

#### 4.1. Heating Plant Regulation and Control System Design

The first proposed intervention concerned heating plant regulation. This involved:

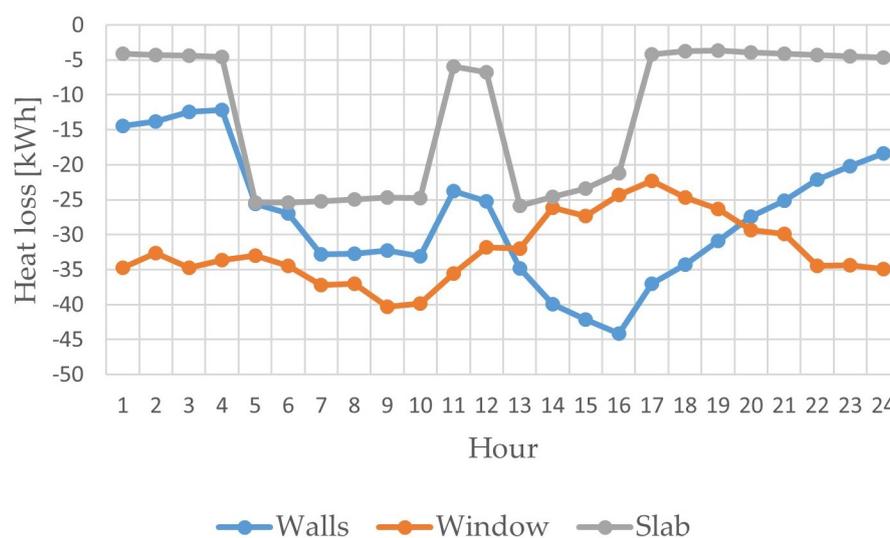
- Insertion of automatic thermostatic valves to regulate the hot fluid flow rate inside the radiators according to the ambient temperature variation to reduce the fluid flow to be heated. This regulation is obtained by a proportional regulator that works in a temperature range between 14 °C (fluid flow 100%) and 18 °C (fluid flow 0%). The lower value of 14 °C was assumed in order to obtain an effective dimming of the thermostatic valves. The upper value of 18 °C is defined as lower than the set point to take into account the high inertia of the heating system;
- Insertion of a climate probe sensitive to changes in the external dry bulb air temperature. With the climatic compensation curve connected to the probe it is therefore possible to vary the set-point temperature of the circulating fluid in the hydronic system as a function of the external temperature with the following equation:

$$T^{\circ}_{fluid} = \max\{40; \min[80; (-2 * T^{\circ}_{ext} + 80)]\} \quad (2)$$

where  $T^{\circ}_{fluid}$  is the fluid outlet temperature from the boiler and  $T^{\circ}_{ext}$  is the external dry bulb air temperature.

Transient simulation results obtained for the above described numerical model, from now on Proposal 1, are shown below.

Figure 12 provides the hourly heat losses for the coldest day of the year referring to the perimeter wall, windows, and the slab separating heated and non-heated volumes. The calculated annual methane consumption is shown in Figure 13. Figures 14 and 15 show the operative temperature and PPD index calculated for Proposal 1.



**Figure 12.** Hourly trend of heat loss through the envelope for the coldest day of the heating period, Proposal 1.

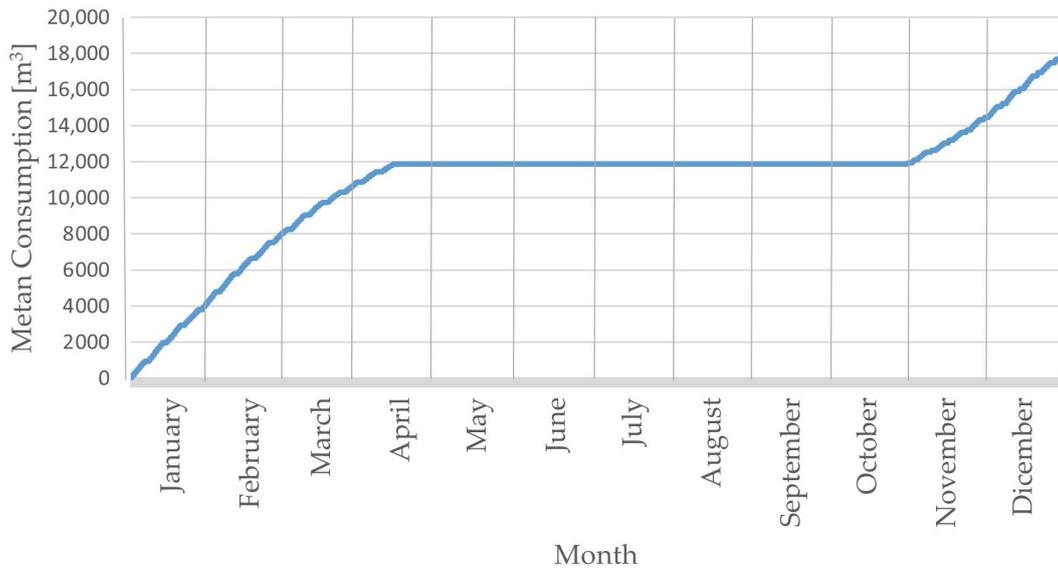


Figure 13. Annual trend of methane consumption, Proposal 1.

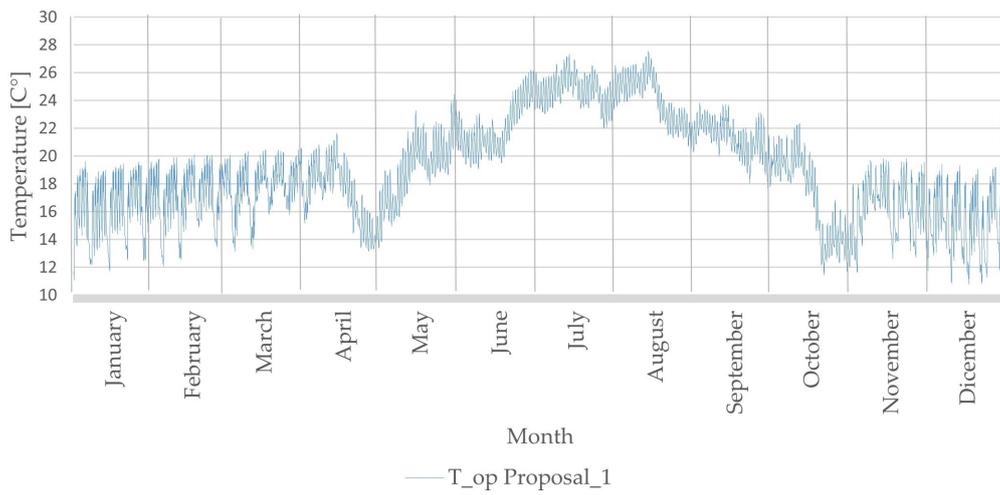


Figure 14. Monthly operative temperature trend for the considered thermal zone, Proposal 1.

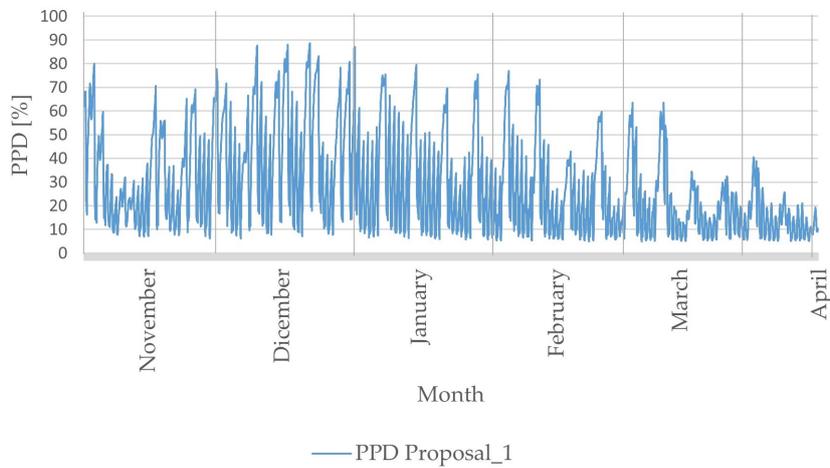


Figure 15. PPD index monthly trend, Proposal 1.

Comparison of transient simulation results points out that:

- Total heat loss for the coldest day of heating period is 2032 kW. In particular, the heat losses due to the different building components and expressed as a percentage are as follows: 41% windows, 38% perimetral walls, 21% separation slab between the heated and non-heated volumes.
- Total heated fluid flow rate is lower depending on demand.
- PPD index, evaluated for the occupation hours, is included between 10% and 5%.
- The calculated annual methane consumption is 17,860 m<sup>3</sup>. Referring to current Italian regulations concerning energy building qualification/certification the above consumption corresponds to 43.6 kW/m<sup>2</sup> year; this result is in accordance with [9,15,19,31].

#### 4.2. Building Envelope and Heating Plant Control System Improvement

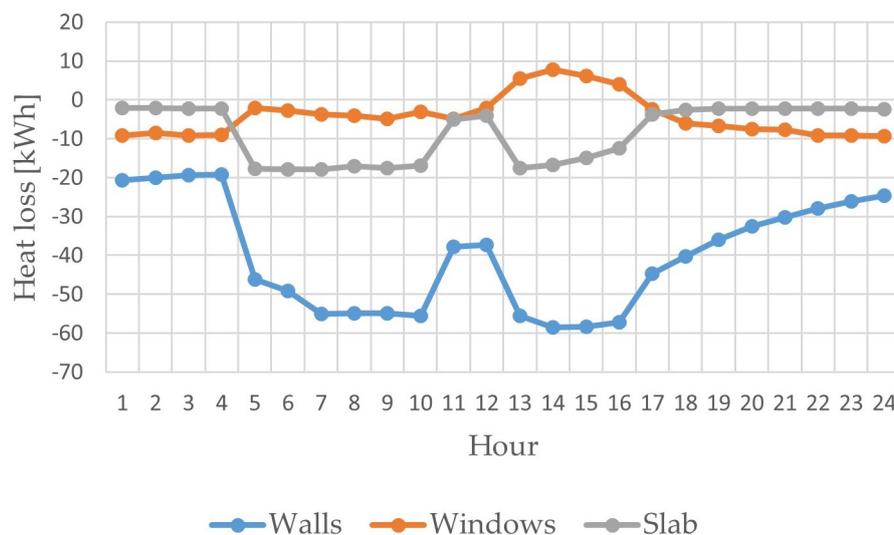
In this section a building refurbishment and plant system retrofitting solution is presented and discussed. Comparison between results obtained for the present state and Proposal 1, suggested a new design solution, from now on 'Proposal 2'. The choice of improving building envelope performances was due both to thermal loss reduction and the achievement of the mean radiant temperature value close to that of the air ambient (decreasing radiant asymmetries due to the cold window surfaces) with the effect of the improvement of global and local thermal comfort.

The improvement of thermophysical performance of building envelope concerns replacement of old single glass wooden window frame, with low air resistance, with double glass wooden window frames, highest thermal insulation for: ground slab, slab separating heated and non-heated volumes, cover roof. All the total transmittance values of components/partition subject of refurbishment was defined in agreement with [43,45].

No intervention on the perimeter walls was proposed because of the historical value of the building and the architectural constraints imposed by National Heritage Protection Offices (Sovrintendenza).

Heat plant and regulation/control system were modelled in the same way and by the same method used for Proposal 1.

In Figures 16–20 transient simulation results of Proposal 2 are given.



**Figure 16.** Hourly trend of heat loss through the envelope for the coldest day of the heating period, Proposal 2.

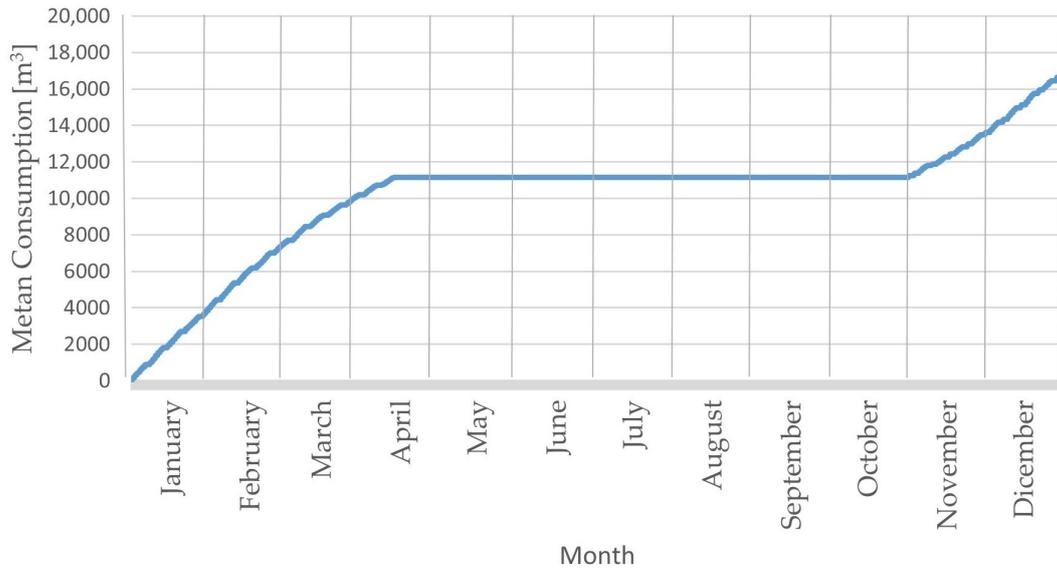


Figure 17. Annual trend of the calculated methane consumption, Proposal 2.

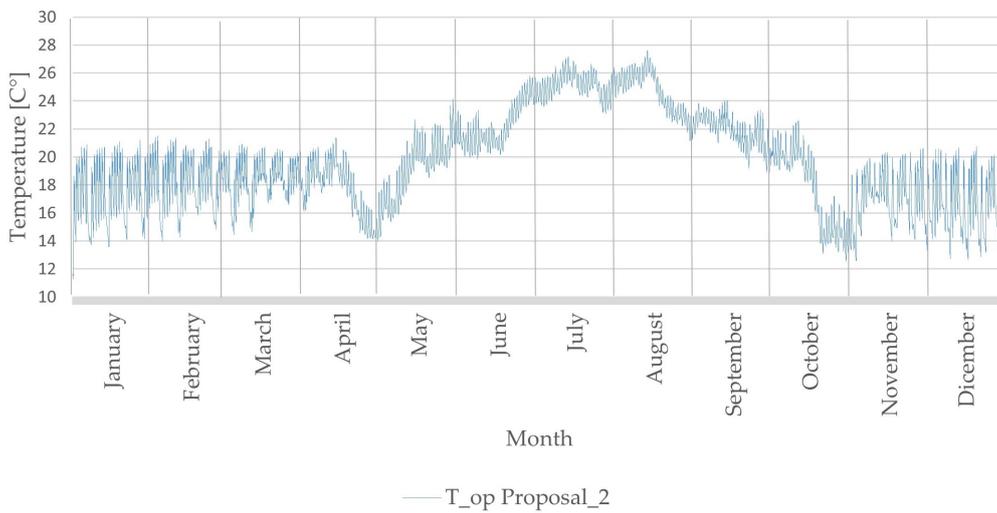


Figure 18. Monthly operative temperature trend for the considered thermal zone, Proposal 2.

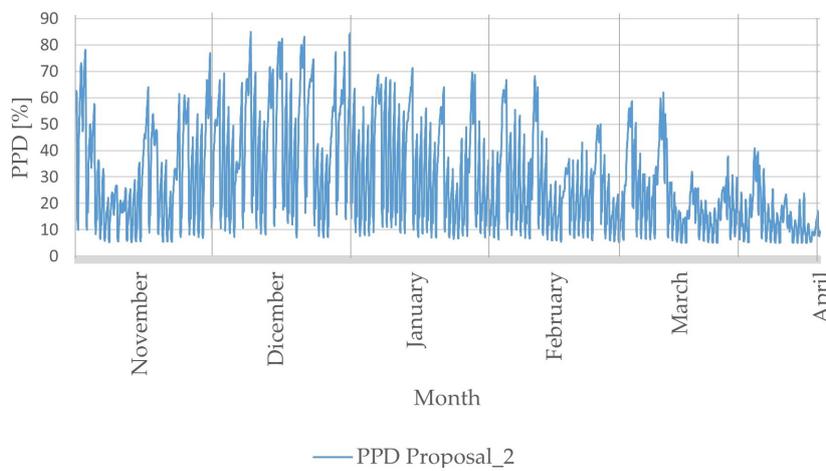
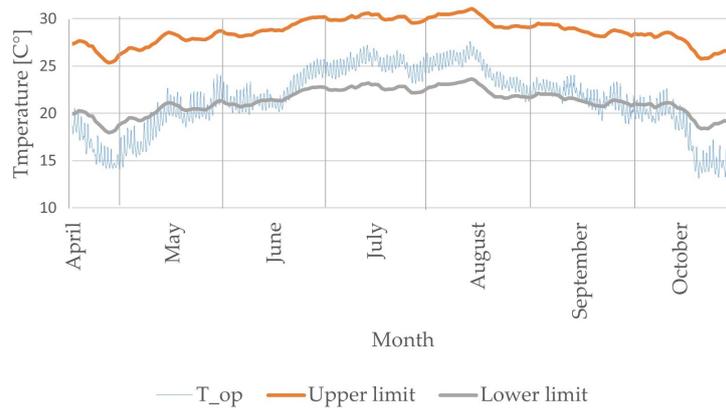


Figure 19. PPD index trend, Proposal 2.



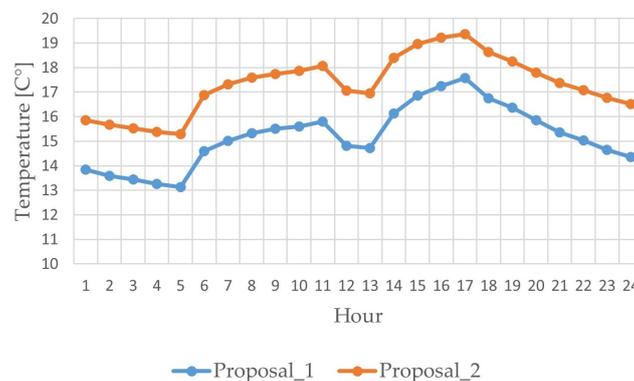
**Figure 20.** Monthly trend of the indoor operative temperature, Proposal 2.

Figure 16 shows the heat losses hourly trend for the coldest day of the year referring to the perimeter wall, windows, and the slab separating heated and non-heated volumes; Figure 17 provides the estimated annual methane consumption. In Figures 18 and 19 the operative temperature and the PPD index trend is shown. Figure 20 gives the operative temperature trend, evaluated for the non-heating period and related to the range of acceptable indoor air temperature values for buildings without mechanical ventilation and a control system.

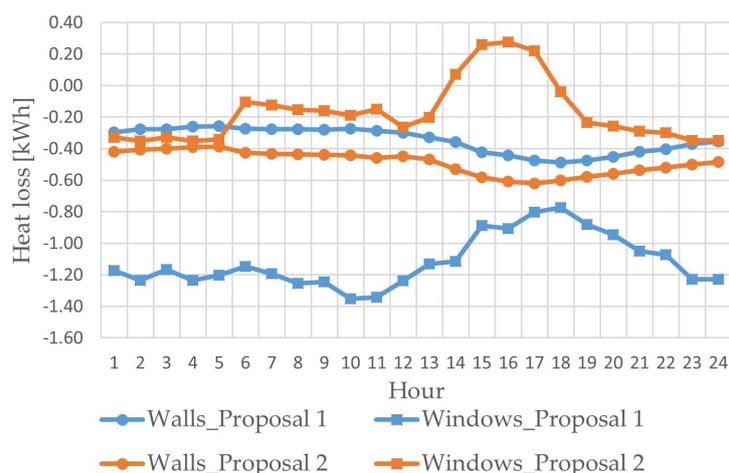
Result assessment and comparison highlights that:

- Total heat loss through the envelope is 1414 kW. Heat losses due to the different building components and expressed as a percentage are as follows: 8% for all the windows, 78% for perimetral walls, 14% for the separation slab between the heated and non-heated volumes.
- PPD index, evaluated in the occupation hours is included between 10% and 5%.
- The calculated annual methane consumption is 16,800 m<sup>3</sup>. This consumption value corresponds to 41.0 kW/m<sup>2</sup> year, referring to current Italian regulations concerning energy building qualification/certification in compliance with [9,15,19,31].

In particular, result comparison highlighted the fact that design strategies for building refurbishment are not so effective for energy consumption reduction and often not easily achievable for historical building plant systems in comparison with design solutions for plant and regulation/control system improvement. This finding is confirmed by the fundamental research in [39]. Figures 21 and 22 show as an example, the comparison between the trends of indoor air temperatures and thermal loss through the building envelope obtained with Proposal 1 and Proposal 2. The effectiveness and importance of different interventions on the building envelope for the improvement of thermo-physical and energy performance are not appreciable for both proposed solutions.



**Figure 21.** Indoor dry bulb air temperature trend, typical zone.



**Figure 22.** Comparison between Proposal 1 and Proposal 2 of hourly trend of heat loss through the building envelope for the coldest day of the heating period, typical zone.

The effectiveness of plant and control/regulation system interventions, is provided by Proposal 1 and Proposal 2 results comparison and in particular by the analysis of a particular critical zone of the school. A typical zone where thermal comfort is not guaranteed due to radiator downsizing is located on the first floor, west-oriented, and used as toilets. The external walls of this zone are differently composed: 68% opaque surface and 32% transparent surface. Figure 21 shows the comparison between the trends of indoor air temperatures due to Proposal 1 and Proposal 2 for the typical zone. Figure 22 shows the comparison of thermal loss through the envelope due to changes from Proposal 1 and Proposal 2. It can be noted that the indoor air temperature trend is comparable in the cases of Proposal 1 and Proposal 2, but with high  $\Delta$  (temperature difference) of about 2 °C which allows a close approach to the fixed set-point. Considering the hourly trend of heat loss, it can be deduced that the heat transfer trend of the walls is comparable with that of both two proposals. On the other hand, the heat transfer trend of the windows is very different in the case of the two proposals, due to the strong difference in thermal transmittance. This allows good solar thermal gains even for the coldest day of the year during the hours of direct solar irradiation.

## 5. Results and Discussion

In the present section transient simulation results obtained for the present state, Proposal 1, and Proposal 2 are compared and discussed.

The comparison between the annual methane consumption of the present state and Proposal 1 (Figures 8 and 16), shows the efficacy of the heat plant regulation system for energy consumption reduction: the obtained fuel energy saving obtained is 40%. The energy savings obtained must be read both from an economic and environmental point of view (i.e., CO, NO<sub>x</sub>, and greenhouse gas (CO<sub>2</sub>) emissions reduction).

Referring to heat generator technical data, the CO and NO<sub>x</sub> emission for the present state and Proposal 1 were evaluated. The CO<sub>2</sub> emission reduction was estimated in compliance with [49]. The emissions saved due to Proposal 1 are as follows: 9.5 kg/year of CO, 8.5 kg/year of NO<sub>x</sub> and 25,884 kg/year of CO<sub>2</sub>. Since the percentages of gas emissions are proportional to the percentage of fuel consumption the above results are in agreement with the UE Directive 2030 [50].

The PPD index value calculated for the present state and the two proposals is similar (Figures 18, 20 and 22). A cooling plant is not necessary both for high building thermal inertia, reduced occupation time in the summer period and the obtained operative temperature value (Figures 9 and 20) related to the range of acceptable indoor temperature for the design of buildings without mechanical cooling systems that is always included between the two limit values suggested by the standards.

Considering the fuel consumption due to Proposal 1 and Proposal 2 and then respectively compared with that due to the present state, the corresponding calculated difference of fuel consumption is 40% (Proposal 1) and 45% (Proposal 2). Although this difference is not important, as well as concerning harmful gas emissions, Proposal 2 provides a better indoor thermal condition for human well-being by guaranteeing air temperature values closer to fixed set-point, thanks to envelope improvement. In particular, this difference is only 5%, because improvement of thermophysical performance of the envelope does not contribute to appreciable plant energy consumption reduction although it can reduce global heat loss. This result can be directly compared with evidence in the literature [39]. Particularly, replacement with windows with high thermal resistance, has led to a significant reduction of heat loss and at the same time an appreciable direct solar gain in the hours of the highest incident solar radiation values, guaranteeing indoor thermal comfort for users. The optimal mix between retrofitting and refurbishment measures on building envelope, plant and regulation system (i.e., Proposal 1) can guarantee energy sustainability due to lower energy consumption and environmental impact connected to energy improvement of the strategy design and construction site set-up stage and management, but also to the crucial goal of user health and wellbeing.

Results comparison shown in Table 3 of the proposed plant refurbishment interventions, show that among the retrofitting solutions studied, the operations on the heating plant and in particular on the regulation/control and technological systems can satisfy energy requirements of current standards, conservation and preventive protection of the historical school building and also economic feasibility with low environmental impact. As a matter of fact, Proposal 1 is optimal as it involves lower energy consumption and environmental impact.

The extensive and comprehensive literature on this subject have pointed out that all the refurbishment interventions focused on building envelope rather than heating system renovation are very expensive and with a longer pay back time [7–9,13,15,17,19,29,31,40]. In particular, in [9] the authors have demonstrated that among the possible refurbishment solutions on a historical school building the lowest payback period is due to thermostatic valve installation (0.7 years), heat pump installation (2 years), and gas boiler replacement (4.5 years).

**Table 3.** Results comparison

	Present state	Proposal 1	Proposal 2
Fuel consumption [m <sup>3</sup> /year]	30260	17860	16800
Energy building consumption [kW/m <sup>2</sup> year]	73.9	43.6	41.0
Total emission CO <sub>2</sub> [Kg/year]	63165	37281	35068
Total heat loss (coldest day) [kW]	2373	2032	1414
Average PPD value (Occupation hours) [%]	5-10	5-10	5-10
Average temperature of considered thermal zone in coldest day (occupation hours) [C°]	17.6	17.2	18.1
Average temperature of critical thermal zone in coldest day (occupation hours) [C°]	17.3	16.0	18.1

This finding has been proved and experimentally demonstrated by [39]: the authors show that all the ‘active design strategies’, i.e., plant system retrofitting and refurbishment (e.g., lighting, air conditioning system, building-plant management, and control system), have a shorter payback time and are more easily achievable, especially in the case of historical buildings. It is then necessary to consider the environmental impact of the two kinds of operation in addition to the assessment closely linked to fuel saving.

As a matter of fact, Proposal 2 is less easily reproducible and extensible to similar cases because any retrofitting intervention on historical buildings implies comparison with the architectural and conservation/protection constraints imposed by standards and National Heritage Protection Offices (Sovraintendenza), both because it could only be realized in the context of very effective programming of spatial and temporal work. In particular, in addition to the costs to be incurred for refurbishment related to the type of building operation, those of new materials and components must be counted,

but especially energy and environmental costs related to construction site set-up phases. For this kind of intervention, the possible changes can be a temporary suspension and/or transfer (to another building/school) of the activities carried out in the school, that have strong environmental and social repercussions (energy costs/impacts) [39,51].

## 6. Conclusions

The present study proposes a methodological approach to evaluate the feasibility of retrofitting and refurbishment solutions in the case of historical buildings used as schools with the fundamental aim of energy consumption reduction and energy and environmental sustainability with due regard to requirements and constraints suggested by current standards on energy consumption and preventive conservation of buildings of the cultural heritage.

Dynamic simulations calibrated and validated with real data of yearly heating consumption demonstrated that active operations for plant system improvements can be more effective for possible retrofitting and refurbishment projects with minor impact on the historical value of the school building, but also non-invasive with lower costs and pay-back time.

The methodological approach proposed, demonstrates that refurbishment and retrofitting solutions, with an efficient energy use and low environmental impact can be defined, and that in-depth assessment of the building physics and plant performance towards energy efficacy and sustainability can contribute to finding out the balance between energy saving, climate change mitigation, and energy security due to rational use of energy and quality of life especially for historical school buildings. Our research showed that, because of school building characteristics and thermo-physical properties, occupation patterns, and climatic indoor and outdoor features, the most energy and environmentally effective refurbishment option was a properly controlled regulated heating system. This is particularly evident if one considers that the Italian school building heritage belongs to existing and for the most part historical buildings, so that any intervention on the building envelope, using advanced retrofit technologies and new innovative materials, can reduce heating and/or cooling demand and total energy consumption in compliance with the minimum energy and environmental requirements for buildings (including existing and/or historical buildings) as shown in [32,33] and the historical, architectural, and cultural constraints of the National Heritage Protection Offices, but as demonstrated in [39,51] it can often require higher energy and time use due to site labor, construction site set-up phases, and construction/realization processes. Thus, the most efficient and effective solution can be the joint operation, as provided by Proposal 2, combining optimal envelope refurbishment with plant system retrofitting. This is also clearly reflected in a crucial recent study on this matter [51].

The outcomes of this study can be a useful basis for a better understanding of energy performance of particular buildings like the one studied. The results included in this study suggest consistent improvement in air ventilation, building components (transparent and opaque) and NPEC index.

Further development and application of the analysis on the effectiveness of the proposed retrofit and refurbishment measures, to other similar case studies, can contribute to operation programming on the entire historical school building heritage, guaranteeing appreciable reductions in energy consumption and CO<sub>2</sub> emissions. The proposed methodology can be a valid instrument easily replicable on a large scale, because results obtained suggest replicable guidelines that can be a useful tool for state administration in planning energy retrofit interventions on the school building heritage.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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