

Strategic framework for sustainable energy renovation policies in educational buildings: a priority-based approach

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ARTICLE INFO

Keywords:

Urban modelling
Building renovation
Prioritization criteria
Multi-criteria decision-making
School buildings

ABSTRACT

To enhance the sustainability of the construction sector, public and private entities should increase their efforts to define the priority interventions to improve the performance of their properties, including educational buildings. In Italy, most of the schools were built before 1976 without considering energy-saving measures, thus they are in urgent need of renovation. Due to the limited nature of resources, facility managers are increasingly asked to prioritize interventions across the owned building stock, to ensure optimal resource allocation. This work presents an energy performance-based prioritization framework to address educational building stock renovation scenarios, based on three key steps: data collection, energy simulation and priority assignment. It was applied to an educational building stock of 103 buildings in northern Italy. Detailed information was gathered through archival research and on-site inspections, thus returning a full taxonomy of the building stock. Energy simulations were carried out both for the existing and renovated scenarios using an urban building energy modeling tool; results were calibrated with real consumption data, thus providing a realistic energy saving potential for the building stock investigated. The final step consists in analysing three approaches to set renovation priorities reflecting different stakeholders' goals and perspective: this allowed the development of a replicable methodology for organizing and ranking refurbishment actions by priority, while optimizing resources, minimizing costs, and maximizing effectiveness. Further research will include the integration of non-energy-related factors that might influence the renovation priority assessment, such as structural and social aspects. This comprehensive approach aims to address the multiple needs of educational building stocks.

1. Introduction

The recent reports of the United Nations and IPCC confirmed the pivotal role of the built environment in climate change issues and the related impact on the human society [1,2]. In response to the great number of out-of-date existing buildings in national building stocks and the increasing rate of earthquakes, new directives and regulations were developed accordingly, to address the challenges related to seismic risk and energy efficiency [3–6].

Across Europe, approximately 51 % of the residential sector's floor area and 40 % of the service sector's floor area were constructed before 1970 [7]. In Italy, these figures are 31 % and 44 %, respectively [8]. Considering that the first Italian law addressing building energy

efficiency dates back to 1976 [9], despite some renovation actions over the years energy efficiency issues persist due to incomplete updates on heating, ventilation, and air conditioning systems or lack of envelope insulation. A great effort was made from that period concerning energy renovation and energy efficiency, leading to several directive and standards, recently resumed in the [10] regarding the "Minimum Requirements" for the energy efficiency of buildings. Similarly, regulations on seismic risk prevention were developed due to the numerous earthquakes and the related damages. It is in 1974 that the Italian territory was firstly divided into seismic zones [11] and, until 2003, specific regulatory indications for seismic risk prevention were contained in [12]. From that year on, new strategies targeting the risk assessment were proposed [13], reaching their maximum development in the most

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<https://doi.org/10.1016/j.enbuild.2025.115702>

Received 13 November 2024; Received in revised form 25 February 2025; Accepted 2 April 2025

Available online 6 April 2025

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recent structural codes [14,15].

Refurbishment strategies for existing buildings often focus on addressing just one of these specific issues, whether it be structural stability, energy efficiency, or architectural improvement. However, a holistic approach that addresses safety and energy goals is necessary. To reduce greenhouse gas emissions by 55 % with respect to 1990, it is expected to decrease the energy use for space heating by 60 % and by 18 % for space cooling. While reducing energy consumption, other benefits of combined interventions over separate strategies include mitigating social risks associated with seismic hazards, lowering overall intervention costs, and extending the lifespan of buildings [16–19]. In Italy, a similar approach has been adopted also for national directives and incentives: the so-called “Conto Termico” [20,21] and the [22] promote retrofit strategies that address both seismic risk mitigation and energy efficiency improvements.

The present work is part of a wider project involving the Municipality of Padova [23–25], aimed at enhancing the sustainability of the educational building stock owned by the Administration. This general goal can be intended as an improvement in terms of seismic and energy performance of less safe and efficient buildings. Due to the limited nature of resources that can be allocated by the administration, priorities should be assigned, based on the aforementioned performance. Previous studies [23–25] investigated the seismic vulnerability of the stock, thus highlighting priority buildings from the perspective of structural safety. In turn, this study aims to assess the energy performance of such buildings, in order to identify the less efficient on the energy perspective. This objective is pursued by proposing an innovative and multifaceted methodology that set energy renovation priorities among the investigated schools. As a future perspective, the study also aims to set the basis for a combined priority assessment of the school buildings, including both seismic safety and energy efficiency.

With respect to a combined energy and seismic analysis, studies in literature investigate the integration approach from different point of view. Penazzato et al. [26] provided an in-depth analysis of the key challenges and opportunities in adopting integrated retrofitting methods and sustainable materials, focusing on their benefits. This work focuses on the best solutions for combined renovations, rather than priority interventions or methodologies. Meglio et al. [27] studied the application of a new method for seismic failure prevention on a school building, which can be considered an integrated seismic-energy action because it reduced the thermal losses of the opaque envelope. However, it mainly addresses only the seismic risk. Valluzzi et al. [19] proposed a similar study for integrated energy-seismic renovation applying the “Nested Buildings” approach. It preserves the existing external structure while introducing a new internal structural system using cross laminated timber that enhances both the energy efficiency and structural performance of the building. Menna et al. [18] reviewed available tools, international sustainability protocols, and methods that have been developed for integrated energy and seismic renovations. The methods were divided in two groups, separating energy performance and seismic safety first and later integrating them, to assess qualitative criteria for optimal integration, including multidisciplinary approaches, life-cycle considerations, and other relevant indicators.

Despite these examples, to the authors’ knowledge only three other studies have addressed an integrated approach more directly. Gkatzogiannis et al. [28] adopted exposure methods and deterministic contexts to address seismic risk to residential and commercial buildings, energy performance of residential buildings, and socioeconomic indicators. However, the goal was to define priority regions across the EU-27 rather than specific interventions within a limited building stock. Mucedero et al. [29] provided different prioritisation patterns and refinement scales applying an integrated framework, which has been calibrated and demonstrated for the Italian residential building stock. Furthermore, the prioritization work presented aimed to support regulatory changes to tax deduction measures and planning the allocation of regional/national funds. Caruso et al. [30] also applied two multi-criteria approaches to an

existing school building, although with a different goal: the methods incorporated economic, environmental, and social factors relevant to decision-makers planning retrofitting activities. The authors analysed twelve integrated retrofitting options to identify the optimal seismic and energy retrofitting solution. The proposed interventions were selected based on the installation time required, ease of implementation, and, most importantly, their effectiveness in reducing energy consumption. This work is interesting as it focuses on a sensible end-use, i.e. schools, but it is limited by the analyses of only one case study building.

Concerning educational buildings, they represent the 12–13 % of the covered floor area both in Europe and in Italy [7]. As shown in Fig. 1, approximately 54 % of Italy’s school buildings were constructed before 1976 [31], with only 8 % of the stock unclassified. Given the limited renovation rates, most of these buildings are nearing the end of their service life, suffering from significant structural and energy inefficiencies, low architectural quality, and poor aesthetics.

With a focus on this building type, Dall’O’ et al. [32] estimated the benefits achievable applying combined strategies to a limited number of school buildings in Lombardy; combining heavy requalification of the building envelope and plants, the energy consumption was almost halved (from 144 to 75 kWh/(m² y)). Citterio and Fasano [33] extended a similar approach to a fraction of the national building stock, estimating baseline energy consumptions based on typical buildings; they obtained energy and cost savings up to 23 %. Desideri and Proietti [34] and Corgnati et al. [35] both highlighted the lack of information regarding the energy consumption of public and school buildings and in particular the urgent need to find a replicable methodology to identify optimal energy-saving measures. Some authors have focused before on the energy assessment of grouped school buildings. They used to address the problem of choosing the best retrofit intervention. Kafatygiotou and Serghides [36] analysed the energy consumption of school buildings in Cyprus and correlated the building features to the energy use. Archetype buildings were, hence, modelled, thus enabling the assessment of energy reduction in post-retrofit conditions. Stocker et al. [37] carried out a building-by-building analysis of eight primary schools located in the Austrian Alps. The net present value (NPV) of different renovation strategies was assessed, thus allowing the Public Administration to easily understand the investment convenience. Several research carried out within the PrioritEE project [38–42] aimed at simplify the development of urban energy renovation plans. The energy use and optimal retrofit strategies were assessed for different cities located in European countries by extrapolating information from prebuilt databases.

However, none of these studies propose systematic prioritization methods, potentially based on different performance indicators. Thus, such studies do not provide specific information on how to establish an order of relative importance among the entire stock. Moreover, the use of archetypes for evaluating energy use is highly convenient in terms of computational time and cost. Nevertheless, this assessment approach does not account for the specific characteristics of each school, which could be crucial to tackle the problem of prioritisation. As for instance, schools of similar configuration and age of construction might differ in terms of energy use, depending on the maintenance conditions. Also, decisions made on archetypes might lead to misplaced priorities.

1.1. Aim of the research and novelty

The presented literature review points out the need to increase the knowledge and awareness in creating effective, efficient and replicable multi-objective energy stock renovation plans, especially in socially important building stocks as schools. To tackle this challenge, the present work describes the key findings coming from the analysis of a case study consisting of 103 schools’ buildings in Padova, northern Italy, ranging from nursery to lower secondary school. This work focuses mainly on energy consumption driven prioritization, and it is part of a broader project that aims at combining multicriteria seismic and energy prioritization.

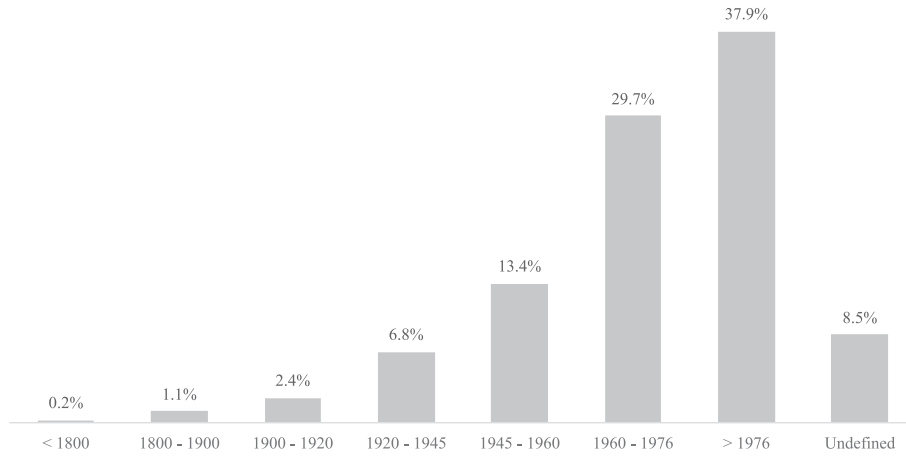


Fig. 1. Italian educational building stock, classified by age of construction [31].

The activity consists in three phases: a data collection and check (common to the energy and seismic activities), the building energy simulation of the case study, and the application of multiple prioritization approaches. The former was carried out by means of in site inspections and archival documents analysis. Given the high computational effort required for the energy assessment of multiple buildings [43], simulations have been carried out with the tool for urban building energy modelling (UBEM) developed by part of the authors, [44]. Baseline results, calibrated against real energy consumption data from the schools, were then used to simulate multiple renovation scenarios and integrate various energy criteria to define a priority list of intervention. This approach minimized dependence on assumptions, enabling the development of more precise and practical scenarios that can be applied to similar building stocks.

The key contribution and novelty of this paper is summarized as the following key points:

- an in-depth data collection and analysis has been carried out for more than a hundred educational buildings, ranging from pre-World War architecture to most recent buildings;
- the presented methodology aims to be as much general as possible, aiming to be applied similarly to different case study cities or different building types;
- the prioritization framework targets several possible stakeholders, that might be interested in minimizing/maximizing different indicators (CO₂ emission, fuel consumption, payback time);

The paper is structured with a methodology section that describes in detail the three phases mentioned before. The case study is presented in Section 3, using a taxonomy-based approach. Results of the simulation and prioritization are presented in Section 4, with a final comment in the discussion section.

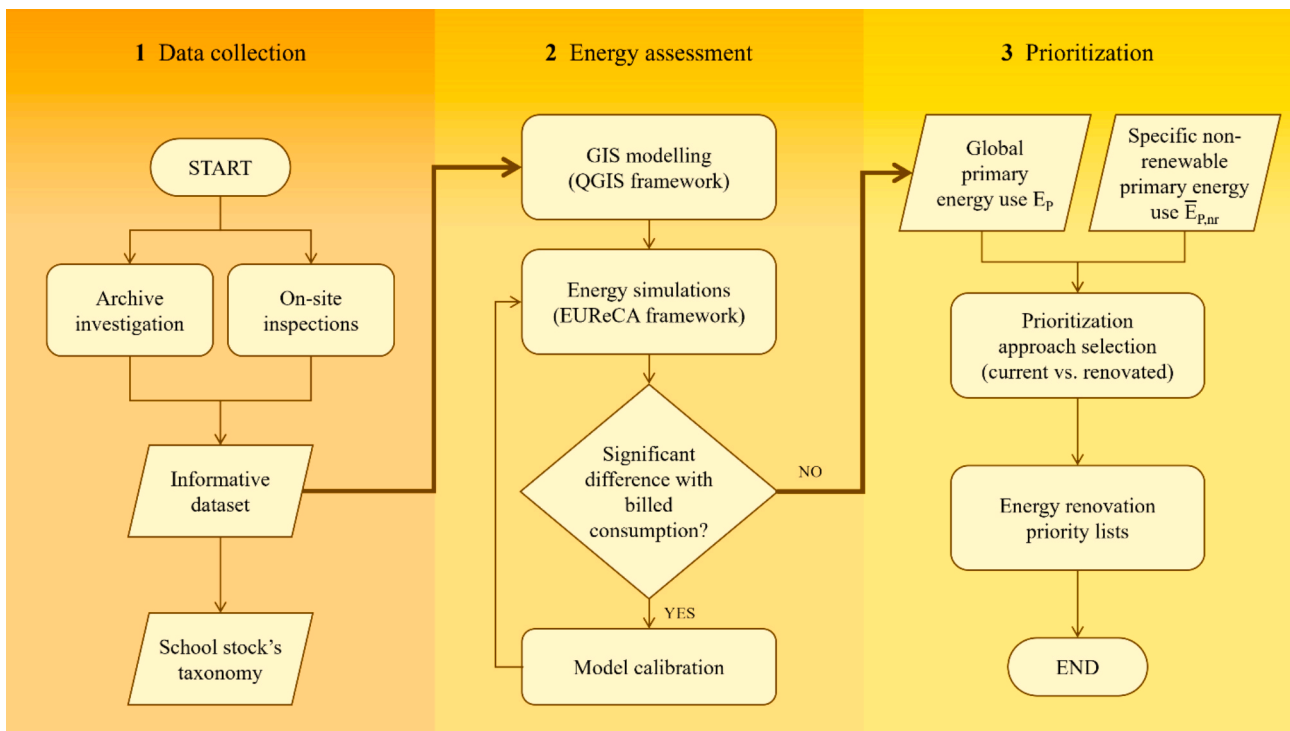


Fig. 2. Step-by-step algorithm of the adopted methodology.

2. Methodology

To address the limitations identified in the literature review, the prioritisation methodology proposed in this paper aims to be general, comprehensive and reliable. In order to achieve the goal of assigning renovation priorities to each school included in the building stock based on the specific features of each, a three-steps methodology was developed: it consists of data collection, energy assessment and prioritization. A step-by-step algorithm of the adopted methodological path is shown in Fig. 2.

Initially, an archive investigation was carried out: the available buildings' documentation was collected and analysed, thus setting the basis for the subsequent on-site inspections. The informative dataset obtained was processed, thus returning the building stock taxonomy. Afterward, a GIS model of the building stock was developed, hence processed for the energy simulation. The model was analysed by means of an Urban Building Energy Modeling tool to simulate the energy demand and consumption. As an output, this step returned calibrated values of natural gas, electric energy and primary energy use (global and specific) for each school both in current and renovated conditions. Finally, the renovation priority of each school building was assessed following three different approaches intended to represent the concerns of different virtual stakeholders. The benefits and drawbacks found thus supported the final issue on which building must be renovated with higher priority. Hence, it was possible to sort the set of school buildings and compile comprehensive renovation priority lists.

2.1. Data collection

In this first phase, the original dataset was created, thus setting the basis for the energy simulations. Two main primary sources of data were considered, consisting in the original records, documents, drawings (paper-based and digital) and direct site inspections.

Firstly, all the available documentation stored in the public archive, including architectural and structural blueprints, technical and calculation reports, bills of quantities and original photos of the construction site, was collected and processed. From the technical reports, information was gathered concerning the stratigraphy of the internal and external walls, as well as the ground, intermediate and roof floors. In some cases, it was possible to gather knowledge on HVAC systems, lighting system and windows typology from the same documents. From the graphical blueprints, the thickness of the layers composing the stratigraphy was obtained, together with the location of the aforementioned systems. Among the digital information, CAD drawings of the most recent schools and spreadsheets collecting gas and electrical energy billed consumption were made available, as well. The monthly accounts of billed energy use were provided by the municipal administration concerning the period from October 2021 to December 2022 for gas consumption and from January 2020 to December 2022 for the electrical energy consumption.

On-site inspections were conducted to fill the gaps of available information and observe the current state of the main systems (generation,

emission, lighting, domestic hot water production, air handling units). The schools' staff was interviewed during the inspections, to get the value of occupants in ordinary conditions and the use of the school's spaces. Furthermore, possible relevant energy uses were considered, including PC and server rooms, canteen, kitchen and laundry rooms. The information available from the original documentation resulted to be incomplete in some cases: when exact information was missing, the execution of site investigations allowed to integrate and update the data on currently installed systems and their operation. When it was not possible to fill the missing information through documents and inspections, hypotheses were made on the stratigraphy based on the elements' thickness, the construction age and the presence of insulating material in other parts of the building.

An inspection form was designed to summarise all the relevant information related to each school. The utility of such a tool lies in its ability to facilitate more direct access to the energy information concerning the building stock, thus supporting the activities of potential decision-makers. The form is divided into ten sections, including geometrical features (geometry and units), occupancy schedule, relevant photos, energy features (envelope and systems), energy consumption (billed, simulated and gym, where applicable) and annotations. A complete list of the sections is reported in Table 1.

2.2. Energy assessment

After the data collection phase, the building stock's natural gas and electrical energy consumption was simulated by means of an urban building energy modelling (UBEM) tool called EURECA [44]. Conceptually, the georeferenced polygons contained in a GeoJSON file are extruded, based on the building's height and the number of floors, assigned before as attributes of the input file. Envelope and scheduling databases are used to associate to each building materials and operating conditions, as opening, occupancy, HVAC systems working hours, thus allowing the creation of a Building Energy Model (BEM) of each school. The underlined BEM is a physics-based dynamic calculation based on the simple dynamic method described in [45]. The reader can find further information regarding the tool in [44].

In detail, a different polygon was modelled in the GIS environment [46] for every portion of each school, previously referred to as "energy units", thus keeping into account variations in terms of geometry, age of construction, use and HVAC systems. Specific envelope and end-use datasets were created, allowing a precise definition for each of school unit. The selected final use determined the internal loads profile, which depended, in turn, on the occupancy schedule, the room lighting and the HVAC operation time. Finally, the specified typology of heating and cooling system defined the model to be used for calculation.

Variable efficiencies of heating systems were assumed based on the age and technical specifications of the energy systems, as established by the Italian regulation [47], following the well-known subsystems method – emission η_{em} , control η_{con} , distribution η_{dist} and generation η_{gen} . Simulations were carried out using the climatic data (temperature, humidity, solar radiation) that were collected at the Venice-Tessera

Table 1
School buildings' energy characterisation form: division into sections.

Section	Description
Energy units	School subdivision into zones served by the same energy systems
Geometry	Geometrical features of the energy units (year, material, use, floors, area)
Photos	Collection of relevant photos of the energy systems and windows
Envelope	Stratigraphy and thermal properties of the envelope (walls, floors, windows)
Energy systems	Energy systems' typology, technical specifications and conservation state
Billed consumption	Gas and electrical energy billed consumption (referred to an ordinary year)
Simulated consumption	As built and renovated primary energy consumption of the main building
Gym consumption	As built primary energy consumption of the gym building (where applicable)
Occupancy	Weekly timings of the educational activities
Annotations	Relevant features that cannot be framed in the previous categories

airport [48], which is the closest place with similar climatic conditions. As a first hypothesis, the heating system working schedule was assumed from Monday to Friday, turned on at 8 a.m. and off at 4 p.m. (main building) or 11 p.m. (gym building). A set point of 20 °C was assigned to the model, assuming the air infiltration to be of 0.2 Vol/h. Additionally, mechanical ventilation was considered, where present, to be operating with a flow rate of 3.5 L/(s·m²) [49]. Domestic Hot Water (DHW) was considered only for nursery and kindergarten schools, with a starting value of 200 L/(m²·y).

The gas and electrical energy consumptions for heating, C_{GAS} and $C_{EL,H}$ respectively, were calculated as expressed in Eq. (1). Also, a Lower Heating Value (LHV) of the gas equal to 9.97 kWh/Nm³ was applied to the C_{GAS} expression, to report this value in volumetric terms. For electric resistance boiler generation efficiency is set to 1, while the coefficient of performance (COP) was considered in case heat pumps serving the heating systems and/or DHW system.

$$\begin{aligned} \text{a) } C_{GAS} &= \frac{E_{DHW} + E_{HEAT}}{9.97 \cdot \eta_{em} \eta_{con} \eta_{dist} \eta_{gen}} [Nm^3/y] \\ \text{b) } C_{EL,H} &= \frac{E_{DHW} + E_{HEAT}}{\eta_{em} \eta_{con} \eta_{dist} \cdot COP} [kWh/y] \end{aligned} \quad (1)$$

Additionally, a first assumption on the electrical energy consumption $C_{EL,L}$ related to lighting, devices and appliances was estimated, based on the typical values given by [50]. These values were modulated, to keep into account the billed consumption, provided by the administration, as reported in Table 2. The annual consumption was evaluated on a base of 200 opening days, considering a daily operating time of 4.5 h. The electrical energy produced by means of the photovoltaic system E_{PV} , where present, was cautiously neglected in this phase, since no information was available regarding the on-site use. Nevertheless, the photovoltaic energy share was included in the annual demand of non-renewable energy, for the purpose of assessing the energy class. Finally, the total amount of electrical energy consumption C_{EL} was computed by summing the estimated $C_{EL,H}$ and $C_{EL,L}$.

2.2.1. Calibration

After the first simulation, natural gas and electric consumption for 2022 were used to calibrate the model of each school. Considered the large amount of data available for each unit and the great heterogeneity emerged from the analyses of the dataset, a manual calibration was carried out. Indeed, the sources of error in heating and electric consumption are many and comes from different causes case by case, forcing a manual check of the results of each school after the first simulation. The following list details the adjustments that were considered in the calibration step depending on the deviation that was detected:

- **Geometry:**

Despite the attention paid during the georeferenced dataset creation, the first simulation provided in few cases, i.e. 5 units, a great overestimation of natural gas consumption. When such an error could not be related to other factors as the heating system scheduling, this overestimation was associated to the possible presence of large unheated spaces in the building. This is the case in areas where classrooms are not used, for instance. In such cases, the geometry was modified to exclude the detected areas. Moreover, in case of

schools located inside the historic city centre, adiabatic surfaces with surrounding buildings were also excluded when heat consumption overestimation was detected. The estimated design capacity of the boiler was also compared to the installed one to check the correct calculation of losses.

- **Heating system scheduling:**

In cases of significant deviations in natural gas consumption, the heating system scheduling was also analysed and adjusted in those cases where a different scheduling was most likely applied. This correction involved mostly building units not classified as classrooms, as corridors, gyms, technical rooms. A similar check was applied to mechanical ventilation systems, when present.

- **Efficiency of heating system:**

In case of minor deviations of heating consumption, a modification of the efficiency of the heating system was applied, due to the possible errors in defining the technical details or to account for the wear and tear of the whole system (in the case of old buildings), which is not considered by the current model.

- **Loads for electric appliances:**

Concerning electric consumption, additional electric loads were included in the simulation in case of large consumption underestimation. In particular, when present, non-standard electric appliances were added, including electric food heaters, other canteen appliances, electric DHW heater.

- **Nominal consumption of lights and other appliances:**

In case of smaller deviations of electric energy consumption, the nominal consumption for lights and appliances was individually modified, considering different use of lights, rooms not used, different efficiencies of the lighting system.

- **Photovoltaic:**

As already mentioned, photovoltaic production was not considered, since electric bills do not give clear information about produced energy accounting. Despite this aspect, a further check was applied to the schools where a PV system is installed, in order to verify that the calculated consumption was realistic considering bills and PV production.

The presented list shows the most common sources of uncertainty in the schools (or similar end uses) building stock. Concerning this aspect and despite the large case study, the well-structured methodology developed in the data collection phase strongly helped this further step.

2.3. Prioritization

Aiming at assigning renovation priorities among the buildings stock, three energy indicators were used. Based on the gas and electrical consumption returned by the model, the corresponding primary energy E_p was computed in the as built and renovated conditions, according to Eq. (2). The conversion factor considered for the gas consumption equals 1.05, while that of the electrical energy was assumed to be of 2.42, of which 0.47 renewable and 1.95 non-renewable. These values were assumed according to the Italian decree on “Minimum requirements” [10]. The corresponding specific non-renewable primary energy use $\bar{E}_{p,nr}$ was computed, by normalizing the value to the building floor area A_F . For this indicator, to favour buildings already provided with a PV array, the photovoltaic energy E_{PV} was in considered and subtracted, as formulated in Eq. (3). As a third indicator, the renovation potential ΔE_p was calculated as the difference between the as built and renovated primary energy consumption.

$$E_p = 1.05 C_{GAS} + 2.42 C_{EL} [kWh/y] \quad (2)$$

$$\bar{E}_{p,nr} = \frac{1.05 C_{GAS} + 1.95 C_{EL} - 2.42 E_{PV}}{A_F} [kWh/(m^2y)] \quad (3)$$

Three different approaches were proposed to assign renovation priorities to the school buildings, each of them representing a different

Table 2
Estimated electrical consumption for educational buildings.

Energy source	Specific power [W/m ²]	Specific consumption [kWh/(m ² ·y)]
Lighting – LED	3.00	2.70
Lighting – other	10.00	9.00
Devices	4.00	3.60
Appliances	15.00	13.50

perspective. Initially, the priority was set solely depending on the total and specific primary energy consumption, namely E_p and $E_{p,nr}^-$. This approach is useful if the decision-maker aims at targeting those buildings with greater absolute energy consumption or the most inefficient ones. Nevertheless, two issues may arise when adopting this approach. On one hand, if priority were set depending on the sole E_p , more recent but bigger buildings might be prioritized, despite their reduced specific consumption. On the other hand, if priority were set depending on the sole $E_{p,nr}^-$, smaller buildings might be prioritized, thus not inducing a significant reduction in the stock overall energy use.

To overcome these limitations, a second approach was proposed, based on both total and specific primary energy use. This approach is useful if the decision-maker aims at renovating primarily those schools being less efficient and having greater consumption at the same time. Firstly, the specific consumption $E_{p,nr}^-$ is considered, in order to give each school a qualitative priority level. In particular, a “low” level was assigned to those schools whose annual $E_{p,nr}^-$ was lower than 50 kWh/m², a “medium” level to the ones whose annual $E_{p,nr}^-$ ranged between 50 and 90 kWh/m², and a “high” level to those whose annual $E_{p,nr}^-$ was greater than 90 kWh/m². Then, the total consumption E_p was accounted, to prioritize those buildings with greater primary energy use. However, such an approach does not account for the expected energy reduction, that strongly depends on the implemented renovation solution.

Thus, a third approach was proposed based on the renovation potential of each school ΔE_p . According to this approach, a renovation solution is identified, based on the building stock characteristics, and applied to the whole schools set. Higher priorities were then assigned to buildings that maximise ΔE_p , since those are the targets which would contribute more to reduce the overall building energy use. This approach is useful if the decision-maker aims at reducing the total amount of consumed energy, as for instance to support the building stock decarbonization process.

2.3.1. Predictive model of primary energy consumption

In order to develop a predictive model of primary energy consumption, a linear regression procedure was applied to the outcomes derived from the energy assessment. The two parameters of slope m and intercept b were computed for each construction age class and educational level, which were treated as a parameter. In particular, a correlation was established between the schools' gas and overall energy ($E_{p,GAS}$ and E_p , respectively) and the buildings' volume and age of construction. No significant correlation was observed against the educational level. Similarly, the electrical energy ($E_{p,EL}$) was analysed in relation to the building's overall floor area and educational level, showing no significant correlation with the age class. A bilinear model was assumed to be representative of the aforementioned correlations, as consumption is expected to be zero for null volumes and areas, but the linear regression produced non-zero intercepts. The breakpoints of 3'000 m³ and 1'000 m² were identified to align with this assumption.

In order to include the variability of the observed data compared to the linear tendency in the consumption assessment model, an additional statistic processing was carried out for the total energy E_p , based on the concept of probability density. Although a probabilistic approach is not commonly adopted to tackle energy systems' design problems, it can be remarkably useful for public administrations to make reliable predictions on the energy use of the owned building stocks.

Assuming that the linear model represents the median value (50 % probability) of primary energy $E_{p,0}$ that would be consumed by a school of volume V_0 , a probability density function (PDF) can be defined, according to the volume and age of construction of the school. The distribution of E_p was assumed to be lognormal about $E_{p,0}$. In particular, the characteristic value μ equals to the natural logarithm of $E_{p,0}$, and β can be reasonably useful for public administrations to make reliable predictions on the energy use of the owned building stocks.

entire dataset as well as to five subsets, each corresponding to one of the volume classes. Finally, a T-test [52] was performed on volume classes V1–V4 to validate the coherence of the proposed probabilistic model with the available data. Three volume ranges were identified in each volume class. For each range, the distribution of observed energy uses was compared to that of 1000 random values distributed according to a lognormal function, whose median equals to $E_{p,0}$ calculated at the middle point of the range V_0 . Due to insufficient data, it was not possible to perform the same test on volumes greater than 12'000 m³.

3. Case study

3.1. Presentation of the school building stock

The methodology previously presented was applied to the case study of the school building stock belonging to the Municipality of Padua in northern Italy [23–25]. The set was composed of 103 items, including educational and gym buildings. In this regard, it is useful to clarify the meaning attributed by the authors to the term “school” in the context of this assessment: it generally refers to a school complex that may consist of one or more units energetically dependent on the same point of energy delivery (POD), sharing common features in terms of envelope and energy systems. In some cases, the gym buildings were constructed separately from the main school building, and were, hence, considered as independent, being detached from the latter and autonomous in terms of energy supply.

The age of construction varied between 1706 and 2018, with different frequencies among the ages (Fig. 3). The age intervals were defined from I to V, according to some of the limits proposed by the Italian Ministry of Education [53]. The 17 % of the buildings were constructed before 1945 (age class I), and 15 % were built between 1945 and 1960 (age class II), when the Italian industrial development began. A vast majority of the schools, corresponding to 47 %, arose from 1960 to 1976 (age class III), when the industrial period was fully initiated. It is still in 1976 that an important regulation on energy reduction [9] was released. Finally, 11 % and 12 % of the school buildings were built before and after 1996 (age class IV and V), respectively, corresponding to the publication of the Italian technical regulation on buildings' structural design [12]. The volume range spanned from 1'392 to 19'141 m³. One quarter of the schools had a volume which is lower than 3'000 m³, approximately corresponding to a one-floor building with a floor area of 800 m². The volume of 34 % of the schools ranged between 3'000 and 6'000 m³, representing the most numerous volume category. Lower shares were observed for volume ranges greater than 6'000 (17 %), 9'000 (15 %) and 12'000 m³ (10 %).

Based on the educational level, the schools were divided into nurseries (0–3 years), preschools (3–6 years), primary (6–10 years) and lower secondary schools (10–13 years). Considering the number of buildings, 14 % of them belonged to the first category, 19 % to the second, 40 % to the third and 27 % to the fourth. A higher presence of primary and lower secondary schools is due to the fact that larger spaces are needed for the activities that are carried out in such spaces. This difference is amplified when the volumes are considered: only 7 % (43'992 m³) and 10 % (66'389 m³) of the school spaces host nurseries and preschools, respectively. Approximately the same amount of space is allocated for primary and lower secondary schools' activities, corresponding to 41 % (261'139 m³) and 42 % (264'957 m³), respectively. Finally, a difference in the distribution of educational levels was observed over the ages. Among the most aged buildings, belonging to classes I and II, are primary schools, which account for 71 % in the first case and 60 % in the other one. Lower secondary schools were the most numerous (55 %) in age class IV, probably as a consequence of the decrease in the school dropout rate starting from the mid-20th century [54]. Nursery and preschools experienced a constant increase, becoming prevalent (58 %) in age V. As for class III, no educational level is predominant over the others in this age class.

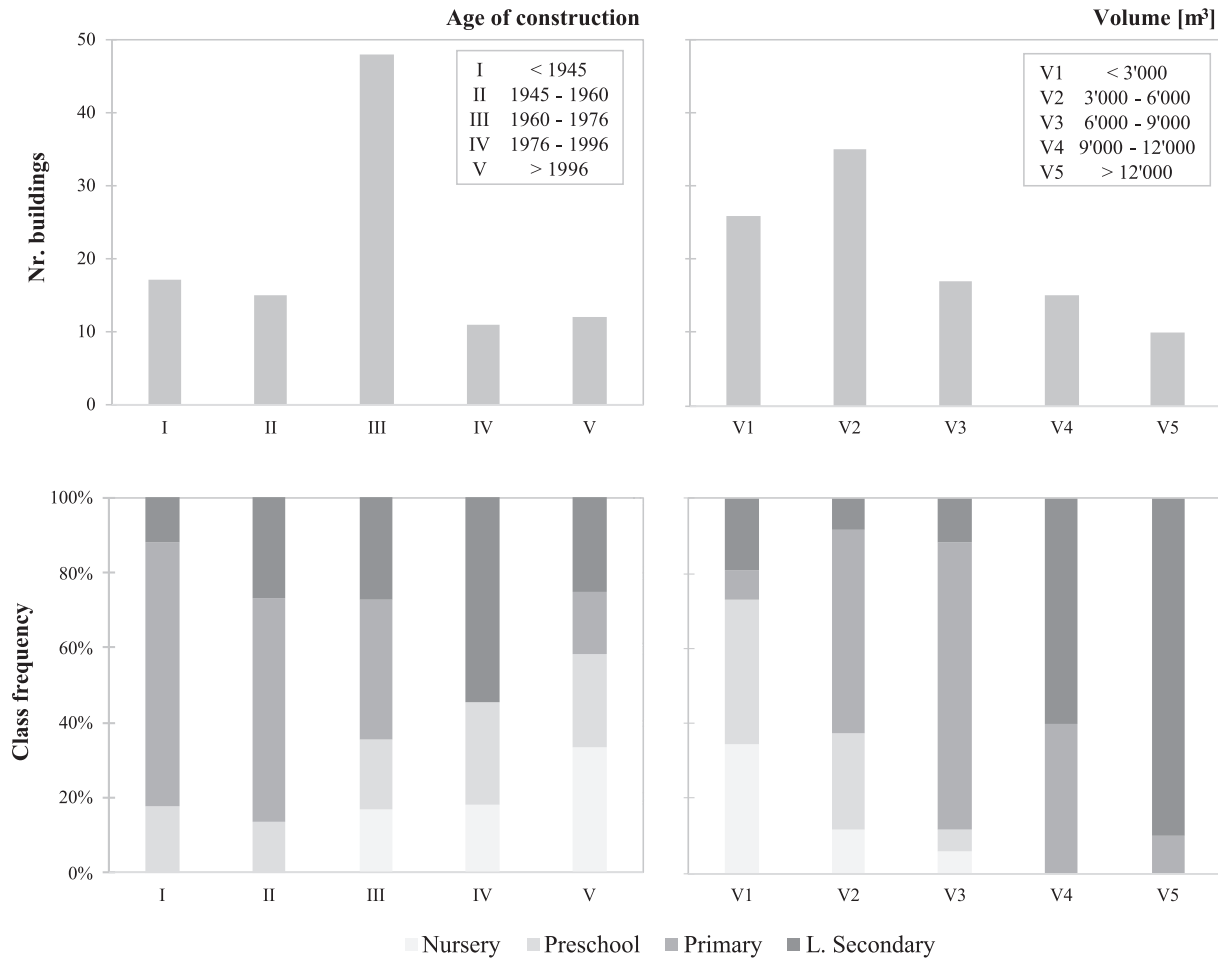


Fig. 3. Number of buildings by age of construction and volume (above) and class frequencies according to the educational level (below).

3.2. Energy features taxonomy

The energy features of the school buildings were processed, in order to return a stock taxonomy, thus giving a general overview of the schools as a whole. This step may help guide the selection of the energy renovation solution to apply, enabling the calculation of the schools'

renovation potential. Some relevant photos of heat generators, DHW storages and windows typologies that were collected during the on-site inspections are reported in Figs. 4–6, respectively.

About 58 % of the analysed schools presented non-insulated walls and roofs (WN.RN), whereas only in 15 % of cases they were fully insulated (WP.RP). A partial insulation was observed in the remaining



Fig. 4. Heat generators (from left: traditional boiler, condensation boiler and heat pump).



Fig. 5. DHW production (from left: gas boiler, electric boiler and solar panels storage).



Fig. 6. Windows (from left: single-glazed wood frame, single-glazed aluminium frame, double-glazed aluminium frame, double-glazed PVC frame).

buildings: 16 % solely presented roof insulation (WN.RP), and sole walls insulation was observed in 2 % of cases (WP.RN). Furthermore, air-cavity walls were built in 9 % of buildings (WA.RN): these structures not only provide mild insulation but could also allow alternative and less impactful insulation strategies, for example through material insufflation. Six typologies of glazed surfaces were identified. Double-glazed windows with thermal-break metallic frames (DG.ML) were predominant among the schools, being present in 34 % of the cases. Similar window typologies, consisting in double-glazed (DG.MH) and single-glazed (SG.MH) windows with thermal-bridge metallic frame (DG.MH) were present in 30 % and 13 % of cases, respectively. Wood frames were coupled with single (SG.WD) and double (DG.WD) glazes in 6 % of schools, each. Finally, double-glazed windows with plastic frame (DG.PL) occurred in 11 % of cases.

From the analysis of the current state of energy systems, it emerged

Table 3
Power intervals of the installed heating systems, divided by educational level.

Educational level	$P_{H,min}$ [kW]	$P_{H,mean}$ [kW]	$P_{H,max}$ [kW]
Nursery	75.0	117.8	264.6
Preschool	33.4	176.2	430.0
Primary	76.2	274.8	895.0
L. Secondary	185.0	450.0	1150.0

that 61 % of schools were heated by means of traditional methane boilers (TB), with variable power depending on the educational level and the building size. The 36 % of cases had condensing boilers (CB), being more recently installed and having higher efficiency compared to the previous ones. Hybrid systems (HP), combining condensing boilers and heat pumps, were present in the remaining 3 % of buildings. A range of installed thermal power P_H was defined, according to the values reported in Table 3, for each educational level. Increasing mean values of power can be observed proportional to the levels, coherently with the distribution of school typologies among the volume classes (buildings having greater volumes hosted more advanced educational level, as reported in Fig. 3). Such distribution of generation systems is justified, as well, by the strong presence of high temperature emission systems: radiators (RAD) are the main emission devices in 85 % of schools, while only reduced quantities of other system typologies were registered, consisting of fan coils (FAN, 5 %), radiant floor (RFL, 7 %), air handler units (AHU, 2 %) and hybrid versions of the previous (HYB, 1 %).

Typically, the production of domestic hot water is delegated to a separate system: 67 % of schools are provided with electrical boilers (EB), and 24 % of them meet their needs by means of additional gas boilers (GB) of lower thermal power compared to the main boilers, due to their reduced and discontinuous use during the school activity time. Solar-thermal panels (ST) were present in 2 % of schools, connected to

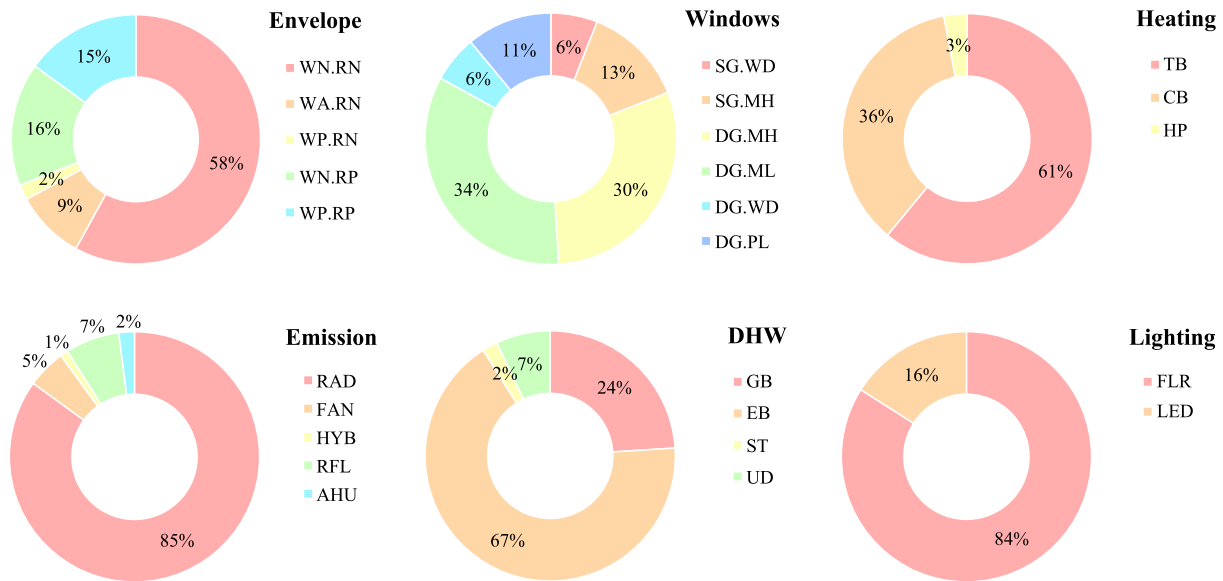


Fig. 7. Distributions of envelope, windows and systems typologies.

reservoirs placed in the boiler room. In 7 % of cases, it was not possible to determine the hot water system, which remained undefined (UD). Concerning the lighting system, some energy improvement interventions were detected, verifying the substitution of older fluorescent lamps with newer LED in 16 % of buildings. To ensure sufficient completeness, it is appropriate to report here that only four schools presented cooling systems with split air conditioners, which used to be placed in the administration rooms. Furthermore, only 12 % of schools used mechanical ventilation systems to supply gym and canteen's spaces. Finally, 44 % of buildings is equipped with photovoltaic systems. The distributions of envelope, windows and energy systems (generation, emission, domestic hot water production and lighting) are briefly described below and are reported in Fig. 7.

3.3. Proposed renovation strategies

Based on the obtained taxonomy, three energy improvement strategies were proposed, to estimate the schools' renovation potential.

The first solution "ENV" consisted in renovating the buildings' envelope, by replacing the existing windows and installing an insulating coat, thus reducing the heat dispersion. As a common factor, it was assumed that, after the intervention, the external envelope had U-values coherent with those established by the "Minimum Requirement" Italian decree [10]. Specifically, the new windows must have a U-value less than or equal to 1.40 W/(m²K), and the external coat is required to reduce the U-value of walls and roof to a maximum of 0.28 and 0.24 W/(m²K), respectively, for a climate zone E. Despite the great intrusiveness and cost, this renovation can be applied in combination with seismic intervention on the envelope, as demonstrated in [43], reducing side costs as scaffoldings.

A second solution "BLR" consisted in replacing traditional boilers, where present, with newer condensing boiler, in order to increase the generation systems' efficiency. Indeed, inspections and consumption analyses pointed out the schools with an old and inefficient system, for which this substitution might be particularly beneficial.

Finally, the third suggested strategy, "LED," focused on enhancing the efficiency of the lighting system, by replacing fluorescent lamps for LED alternatives. In particular, a specific power of 3.00 W/m² was considered for the new system, corresponding to a specific annual consumption of 2.70 kWh/(m²y). Such renovation is typically fast and with short payback times, even if on the absolute primary energy consumption of the stock it has the lowest impact. Nonetheless, the proposed

stock wide analysis gives the possibility to compare also with the other renovation strategies.

4. Results

4.1. As built consumptions

The annual as built consumption of each school was calculated in terms of gas, electrical and primary energy. Also, a differentiation was made in terms of renewable and non-renewable shares of primary energy. Separated outcomes were, hence, aggregated to get measures at the stock level. Furthermore, possible correlations between absolute and specific consumption, age and building's volume were investigated.

The overall gas consumption of the building stock S_{GAS} amounted to 13.9 GWh, and the electrical energy consumption S_{EL} equalled 2.3 GWh, respectively corresponding to 72 % and 28 % of the building stock's total primary energy consumption S_P , which was estimated to be of 20.3 GWh. The previous were converted into primary energy by means of the Italian conversion factors 1.05 and 2.42, respectively. The renewable energy $S_{P,r}$ included in the total amount was assessed considering a share produced by the photovoltaic panels installed on the roofs of schools and gyms, in addition to that already present in the energy mix. The former was estimated to equal 2.4 GWh and the latter to be of 1.1 GWh, corresponding to 12 % and 5 % respectively, compared to the S_P . Accordingly, the non-renewable amount of primary energy $S_{P,nr}$ was estimated to be of 16.8 GWh, corresponding to the remaining 83 % of S_P .

The bilinear models elaborated for gas and overall primary energy consumptions are reported in Fig. 8. As can be seen from the plots, gas consumption $E_{P,GAS}$ increased proportional to the building's volume, being greater for more dated schools and lower for more recent schools. The considerable difference among the ages in terms of gas consumption depended on improvements in the efficiency of buildings' envelope and energy systems over the decades, as well as on reduced degradation levels in less dated buildings, especially in glazed elements. A similar correlation was detected in terms of primary energy E_P , whose values are greater for larger volumes and older buildings. Nevertheless, the difference between age classes I, II and III is negligible. A more relevant difference was noted on buildings belonging to age class IV and V, built after the enactment of the first Italian law on energy consumption containment [9].

The predictive model of electrical energy consumption $E_{P,EL}$ is reported in Fig. 9. No significant correlation was observed against the age

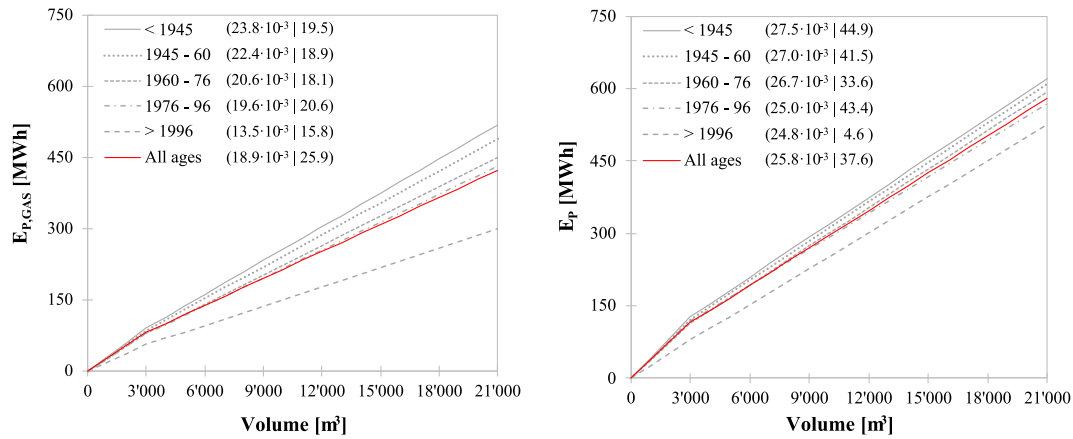


Fig. 8. As built heating energy consumption $E_{p,GAS}$ and total primary energy E_p as a function of heated volume and age of construction. Into brackets: slope and intercept (m|b).

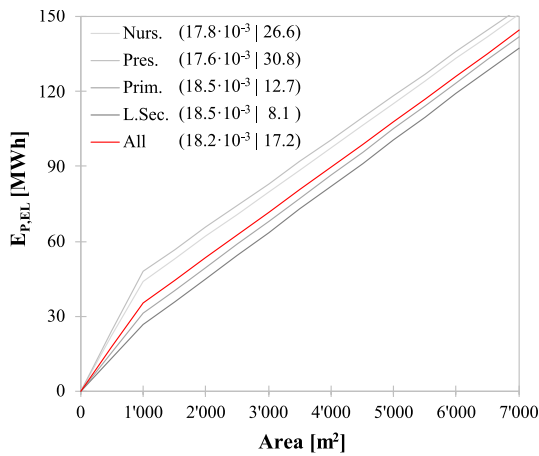


Fig. 9. As built electrical energy consumption $E_{p,EL}$ as a function of floor area and educational level. Into brackets: slope and intercept (m|b).

class, but rather the educational level influenced the energy use. Despite being smaller on average, nurseries and preschools showed greater specific electrical consumption compared to that of primary and lower secondary schools. This difference is due to the discrepancy between electrical devices and appliances installed: in nurseries and preschools, laundries and kitchens were commonly present, having dryers and washing machines continuously working, as well as refrigerators for food storage; in primary and lower secondary schools, the main sources of electrical consumption in addition to lighting consisted in interactive whiteboards, video-projectors and computers.

It is appropriate to highlight that, in 11 % of the cases (12 schools out of 103), the school's heating systems features were not considered to be representative of the age class they belonged to. In particular, for 7 buildings belonging to age class *I* and *II* gas consumptions were lower than average, due to the presence of condensing boilers, possibly replacing older traditional ones. Also, for 5 buildings belonging to age class *III* and *IV* simulated gas consumptions were higher than average; in cases where heating was provided by means of AHUs or some spaces like the gym building, bathrooms and locker rooms were more heated than usual. Regarding the electric system, 10 % of the cases (10 schools out of 103) had peculiar features, compared to schools of the same educational level. Specifically, the electrical consumption of 2 preschools was lower than average, due to the large presence of unused spaces, and 8 among primary and lower secondary schools had kitchens or were heated by means of AHUs. Thus, these exceptional values were excluded from the computation of the regression lines' slope m and intercept b .

Subsequently, the predictive model of E_p was furtherly developed as described in Section 2.3.1, to get estimations of consumption intervals instead of single values for each volume. An example of shifting from the linear model to the corresponding PDF is reported in Fig. 10 a,b. The Shapiro-Wilk test [51] (Fig. 10c) revealed that the null hypothesis is refused for V1 (p -value < 5 %): nevertheless, the T-test performed on volume subsets ranging between 1'000 and 3'000 m³ returned appropriate p -values (> 5 %). This means that, in such range, it is acceptable to approximate the consumption interval with a lognormal distribution.

The T-test [52] performed on volume classes V1–V4 allowed to validate the coherence of the proposed probabilistic model with the available data (Table 4). All the p -values from the tests exceeded the threshold of 5 %. Hence, there was no evidence to refuse the hypothesis of similarity between the observed data and the proposed model.

Finally, it was observed that the specific primary energy $\bar{E}_p$ decreased as the building volume increased, as can be noted in Fig. 11. This behaviour is due to two major reasons: first, smaller school buildings, usually corresponding to single-storey preschool or gym buildings, had higher ceilings, thus greater volumes per unit of floor area; second, smaller building are typically nursery and primary schools, with higher electricity specific energy consumption for additional appliances.

4.2. Renovation potential

After the proposed renovation strategies were implemented in the model, the difference between the primary energy consumption in current and renovated conditions, namely the renovation potential ΔE_p , was assessed for each school building. On a stock level, an energy reduction ΔS_p of 5.9 GWh would be expected, if solution “ENV” were applied concurrently to the whole building stock, corresponding to a 29 % reduction compared to the initial amount of consumed primary energy S_p . Lower values of saved energy were estimated in the cases of “BLR” and “LED” solutions, amounting to 2.2 GWh (11 %) and 0.7 GWh (3 %), respectively. Choosing among the previous alternatives, if that one which maximizes savings for each school were applied, a reduction of 6.0 GWh (30 %) would be achieved. As a last option, if the three solutions were applied in a single instance to every school, 8.8 GWh (43 %) of primary energy would be saved. Even though the aforementioned savings are only theoretical, since the concurrent renovation of all the school buildings is unlikely due to limited resources, these values provide an insight into the stock's renovation potential.

Comparing the values obtained by applying one of the first three solutions, it emerges that in terms of primary energy reduction the most efficient strategy would be to renovate the envelope. Furthermore, a significant reduction can be achieved by replacing the lighting systems with LED ones, whereas changing traditional boilers with condensing

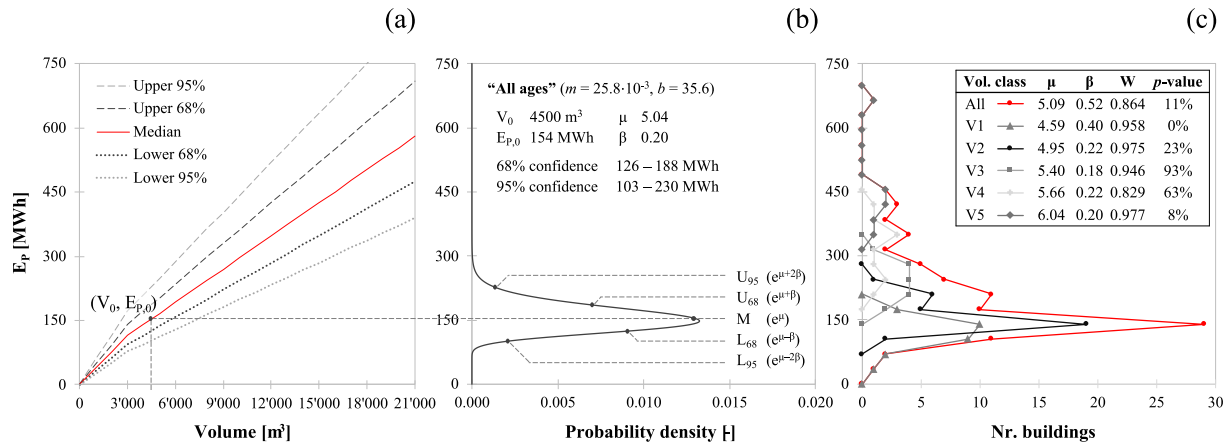


Fig. 10. Proposed probabilistic model: starting from the regression linear model (a), a consumption interval can be defined for each volume V_0 (4'500 m³ in this example) according to a lognormal distribution (b), being similar to that of the observed volume ranges (c).

Table 4

T-test results for different volume ranges (all ages).

Vol. class	Vol. range [m³]	Buildings (observed)	V_0 [m³]	$E_{p,0}$ [MWh]	T stat. [-]	p-value [%]
V1	0 – 1'000	0	500	19	N/A	N/A
	1'000 – 2'000	5	1'500	58	1.86	6.3
	2'000 – 3'000	20	2'500	96	0.30	76.3
V2	3'000 – 4'000	13	3'500	128	1.33	18.4
	4'000 – 5'000	15	4'500	154	0.49	62.6
	5'000 – 6'000	5	5'500	180	0.36	72.2
V3	6'000 – 7'000	5	6'500	206	0.29	76.8
	7'000 – 8'000	6	7'500	231	0.75	45.2
	8'000 – 9'000	4	8'500	257	0.90	36.6
V4	9'000 – 10'000	4	9'500	283	1.48	14.0
	10'000 – 11'000	5	10'500	309	0.31	75.7
	11'000 – 12'000	1	11'500	335	N/A	N/A

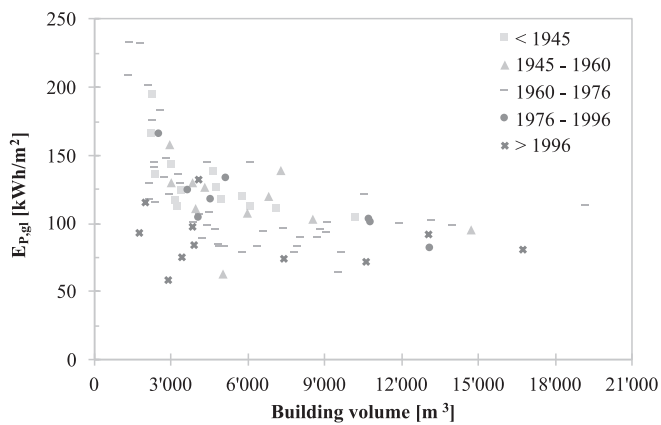


Fig. 11. Specific primary energy consumption $E_{p,sp}$ as a function of heated volume.

ones would return limited savings. The last two combined strategies set an upper limit in terms of energy savings that can be achieved in cases where the previous solutions are applied either alternately or simultaneously.

The correlation between the renovation potential, the school size and the age of construction or educational level was investigated for the

different intervention strategies. A bilinear model was adopted to express this correlation, with a breakpoint set at 3'000 or 1'000 m², depending on the intervention typology. A linear regression model was adopted to calculate the characteristic values of slope m and intercept b of the line branch that interpolates the data obtained from the analyses,

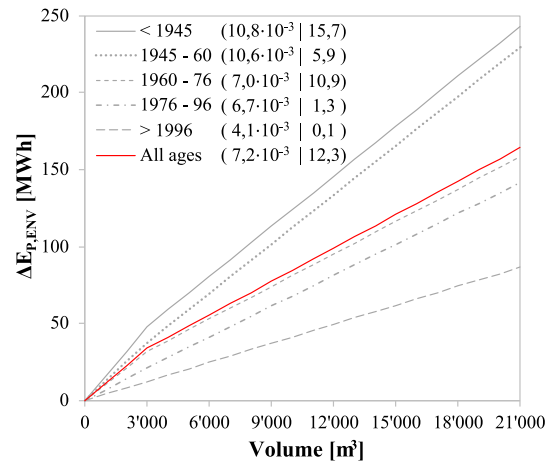


Fig. 12. Renovation potential $\Delta E_{p,ENV}$ as a function of building's size and age of construction. Into brackets: slope and intercept ($m|b$).

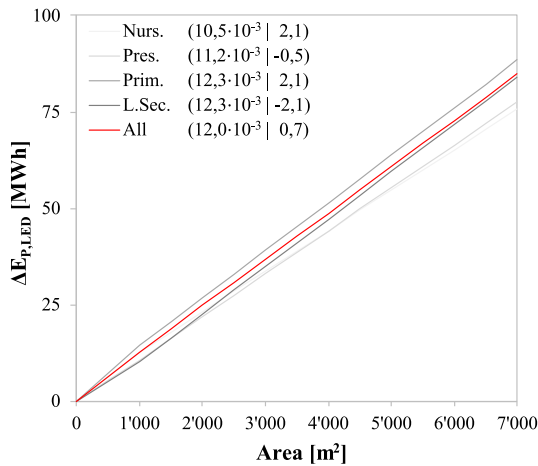


Fig. 13. Renovation potential $\Delta E_{P,LED}$ as a function of building's size and educational level. Into brackets: slope and intercept (m|b).

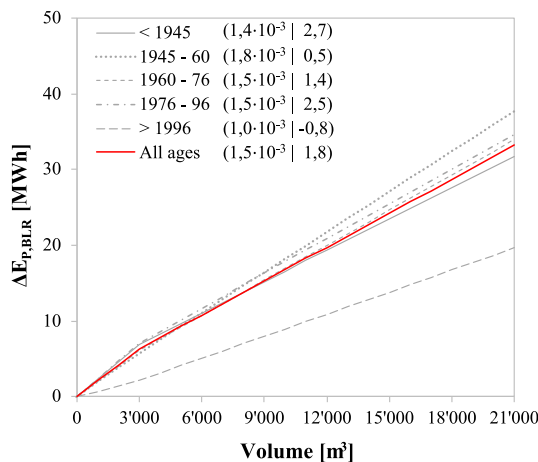


Fig. 14. Renovation potential $\Delta E_{P,BLR}$ as a function of building's size and age of construction. Into brackets: slope and intercept (m|b).

as reported in Fig. 12, Fig. 13 and Fig. 14. E_p reduction values coming from alternatives “ENV” and “BLR” were expressed as a function of the building's volume. Differently, those coming from alternative “LED” was expressed as a function of the building's area, since lighting consumption is not influenced by the floor height.

The mean value of primary energy savings $\Delta E_{P,ENV}$ induced by the “ENV” renovation alternative equals 7.2 kWh/m^3 , varying significantly in accordance with the construction age (Fig. 12). In particular, higher specific savings were observed on more dated buildings, whose specific savings amounted to 10.8 and 10.6 kWh/m^3 for age classes I and II, respectively. Lower values of the same quantity were observed on more recent buildings, whose specific savings amounted to 6.7 and 4.1 kWh/m^3 for age classes IV and V, respectively. Such results are supported by the fact that the envelope's U-values were higher for older buildings and lower for newer ones, reflecting an improvement in building technology throughout the XX century.

When the “LED” alternative was implemented, the energy model returned a mean value of energy savings $\Delta E_{P,LED}$ equal to 12.0 kWh/m^2 (Fig. 13). The correlation between this value and the age of construction is not significant. This behaviour can be explained by taking two factors into account: on one hand, lighting efficiency depends more on the installed technology rather than the age of the building itself, as lights are more often substituted; on the other hand, the share of buildings illuminated by LED lamps does not necessarily belong to most recent age

classes, since older buildings were involved in lighting system interventions during the last decades. For consistency, the results have been reported as a function of the educational level: nevertheless, only negligible deviations were observed from the mean values for different categories. This can be justified by the fact that the proposed alternative mainly depends on the renovated area, regardless of the educational level or the age of construction.

Finally, the mean renovation potential $\Delta E_{P,BLR}$ of the “BLR” solution (Fig. 14) amounted to 1.5 kWh/m^3 , with no substantial variations among the ages, exception made for age class V, whose specific reduction equalled 1.0 kWh/m^3 . This result mainly depends on the fact that the energy model does not account for systems' degradation over the years, so that traditional boilers' efficiency of more dated schools is considered to equal the factory value.

4.3. Priority rankings

After performing the energy simulation in the as built and renovated conditions, renovation priorities were assigned to each school, based on the approaches described in Section 2.3, thus returning sorted priority lists for each of them. Due to the large number of buildings investigated and the related outcomes, the results reported concern only the first ten school buildings in the rankings (Table 5), being representative of the effects that the various prioritization approaches produced on the same priority lists.

According to the first approach, priority was assigned based on either E_p or $E_{P,nr}$. In the first case, the renovation priority was assigned to the schools having greater built volumes and sometimes conditioned by means of air handling units (schools 54 and 55). Nevertheless, some of the most recent schools (62 and 82) were prioritized due to their larger size, despite the reduced specific consumption. In the second case, priority was set on those buildings having smaller volumes but greater ceiling height, such as gyms (71B and 96B), nurseries (4 and 3) and preschools (7, 16 and 34). A drawback of this approach lies in the fact that, although the efficiency of these buildings is quite low, their impact on the whole stock in terms of total primary energy is not particularly significant compared to that of other buildings.

To address these issues, the second approach was proposed, based on both E_p and $E_{P,nr}$. The so obtained renovation ranking prioritized those schools having greater overall consumption due to their volume (again 54 and 55) and being less efficient due to their age (91, 76 and 50). As can be noted, no recent buildings were prioritized, and the impact of the identified schools is significant compared to the building stock's overall consumption. However, the fact that current consumption is higher for some schools does not necessarily imply that the renovation potential of these buildings is also optimal.

Maximising the difference between current and renovated consumption can be fundamental in some cases, hence the third approach, based on the renovation potential ΔE_p assessed according to the different renovation strategies. The “ENV” solution prioritized more dated buildings, having considerable volumes and scarce efficiency (75, 79 and 38). This result depended on the fact that older buildings used to be affected by greater heat losses, due to poor performance of their envelope. In the case of “LED” renovation strategy, priority was set on those buildings having greater volumes (hence, floor area) and sources of electrical consumption different from lighting. The latter included food warmers and water heaters (62 and 43), air handling units (54 and 55) and continuously refrigerated server rooms (101). Finally, when the “BLR” strategy was modelled, priorities were assigned to those schools having greater volumes (54 and 63) and being more dated (75 and 38). This result can be explained by the fact that the effects of improving the boiler efficiency are more pronounced when the heated volume is larger and heat losses are greater.

Table 5

Priority ranking of the first 10 schools, sorted according to the proposed approaches (school ID, age class and volume class are reported for each of them).

Rank	Prioritization approach					
	1 st (E _P)	1 st ($\bar{E}_{P,nr}$)	2 nd (both)	3 rd (ENV)	3 rd (LED)	3 rd (BLR)
1	54 III V5	71B III V1	54 III V5	75 II V5	62 V V5	54 III V5
2	55 IV V5	96B III V1	55 IV V5	79 III V5	54 III V5	63 III V5
3	79 III V5	4 III V1	79 III V5	38 I V4	55 IV V5	75 II V5
4	75 II V5	7 III V1	75 II V5	41 I V4	43 I V5	55 IV V5
5	63 III V5	16 I V1	103 III V4	70 III V5	82 V V5	95 III V4
6	62 V V5	34 III V1	101 IV V2	52 III V4	101 IV V2	69 IV V5
7	70 III V5	3 III V1	38 I V4	43 I V5	103 III V4	38 I V4
8	103 III V4	101 IV V2	91 II V3	69 IV V5	91 II V3	101 IV V2
9	43 I V5	24 I V1	76 III V3	53 II V3	47 IV V4	43 I V5
10	82 V V5	11 IV V1	50 II V3	63 III V5	77 V V4	72 I V3

5. Discussion

Results of this activity pointed out three major key points for discussion in building stock analysis: 1) importance of archival data and inspections, 2) need to properly calibrate, 3) relevance of the target goals. Concerning the former, a typical procedure in urban and building stock analyses is the usage of archetypical dataset, to simplify data assignment. Despite the creation of comprehensive and extended datasets is the aim of various projects worldwide because large scale building energy models can support key decisions related to energy policy and climate change solutions, this work points out how they could be ineffective when energy conservation measures prioritization is involved. The use of GIS tools for implementing building geometries, as demonstrated by EURECA through the implementation of the shapefile, overcomes the limitations of previous approaches that relied on fixed geometries [36,55]. Indeed, while being useful during preliminary urban planning phases, an archetypical-based modelling would lead to errors in renovation prioritization, as it wouldn't capture any specific difference between similar buildings. This work points out how, even between schools having similar envelopes and belonging to the same order, several differences can occur, like electric loads or heating system operation, strongly affecting consumption. In this perspective, when prioritizing renovation actions in a building stock, engineers, architects, and planners cannot exclude an in-depth knowledge of the stock, carried out either by on-site or paperwork inspection.

Consumption calibration is also involved in the former concept, since the quality of input data is fundamental to achieve reliable outcomes [56]. Indeed, the user behaviour and the related final energy consumption of the building may impact the calibration of the model results, which in turns may affect prioritization results. For instance, the presence or absence of cooking facilities in schools can strongly change the fraction between lighting consumption and additional loads, changing the results of energy conservation measure as light bulbs substitution. In this perspective, Section 2.2.1 provides a guideline of the uncertainties which were found for this specific case study, useful to be applied in additional stock analyses.

Overall, the energy simulation results are coherent with the real energy consumption collected: on average, gas consumption was underestimated by 5.6 %, while electricity consumption was overestimated by 2.6 %. This result is comparable to the outcomes achieved

by Schwartz et al. [57] who simulated the school building stock in England, and compared the discrepancies with equivalent modelling approaches applied to residential case studies [58–61], since literature is limited or absent on large scale simulation of educational buildings.

Concerning the prioritization goals, despite the limitations discussed in the results, all the proposed approaches remain useful, according to the objectives targeted by a potential decision-maker. While Shim et al. [62] assessed the need for retrofitting or behavioral improvements by comparing actual monthly heating energy use with the optimal consumption based on a building's physical performance, Medal et al. [63] and Randelović et al. [64] carried out parametric studies to evaluate the impact of various interventions on energy consumption. Their selection criteria for prioritizing retrofit strategies included CO₂ emission reduction, the most profitable return on investment, payback period, life-cycle cost, and available funding mechanisms. However, looking at the proposed KPIs is more effective for identifying buildings with a significant impact on the stock, regardless of their construction period or financial considerations. This is because the Municipality may be interested in combining other interventions (e.g., seismic upgrades) or taking advantage of specific financial incentives. For instance, specific primary energy allows to find buildings characterized by specific inefficiencies, regardless of whether their total consumption is limited or relevant. The total primary energy consumption is effective in detecting buildings that combine low energy efficiency and high impact on the stock, neglecting whether they are among the least efficient or the most impactful in absolute terms. The third approach is suitable for identifying buildings with a high renovation potential, thereby maximizing the energy savings. The outcomes showed that priority rankings depended heavily on the chosen intervention strategy, as well as the building's volume and construction age. For instance, older and larger buildings were prioritized for envelope renovations due to significant U-value improvements. A fourth approach, foreseeable for future analyses, could benefit from an economic assessment of the renovation investment. This aspect was not considered in this work as investment returns, especially on the building envelope, would benefit from a combined seismic and energy renovation, aspect to be analysed in a further activity.

6. Conclusions

This work presented and analysed a classification and prioritization

framework for optimizing retrofit actions within a building stock of 103 schools located in Padua, Italy. Comprehensive data were gathered throughout documental investigations and on-site inspections, resulting in a detailed characterization and taxonomy for energy simulations, which are carried out after calibration with respect of real consumption. Results pointed out the great potential that a renovation plan represents on this stock. Schools built before 1960 result in the largest energy saving potential in case of envelope insulation, as they can achieve primary energy saving of more than 10 kWh/m³. Lighting retrofit effectiveness is instead almost independent from the grade or age of building, reaching a saving potential around 12 kWh/m² (primary energy).

In addition to numerical results, the major goal of this paper lies in the development of a general and replicable methodology tailored for the organization, management and prioritization of the refurbishment actions in the building stock. Such methodology aims at giving insights and guidelines during the energy auditing process, focusing on the main issues emerged during the data gathering and cleaning, calibration and validation of the model, and optimization of priorities. As shown in the discussion, the innovative aspect compared to recent literature, lies in the ability to rank interventions based on their priority for the specific case study. This allows for an optimized allocation of resources, reducing intervention time, minimizing costs, and maximizing overall effectiveness. By offering a structured framework for decision-making, this contribution ensures replicability of the actions involved and helps stakeholders, such as policymakers and municipalities, to identify the most impactful renovation actions facilitating the progress towards decarbonization goals and greater sustainability in public buildings.

Although the proposed prioritization framework is able to provide valuable and reliable analyses, the major drawback relies on the focus on solely energy-related criteria for prioritization. Indeed, this work is a first step of a larger research activity dealing with the combining of energy and seismic renovation prioritization. Exploiting multicriteria intervention rankings, in addition to an assessment of the social aspects related to the area where the building is located, would provide a more reliable priority assessment. Moreover, this new contribution would allow different prioritization targets as a reliable economic assessment of the renovation strategies. Expanding the framework to include such fields, would offer decision-maker a more comprehensive perspective of the problem, enhancing the effectiveness and the sustainability of renovation planning. The extension of this approach on a broader scale, with the inclusion of other building typologies, is a future perspective for this work, as it would represent a baseline to study integrated renovation strategies across public buildings.

CRediT authorship contribution statement

Giacomo Piredda: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Enrico Pratavia:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Laura Carnieletto:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Michele De Carli:** Writing – review & editing, Writing – original draft, Supervision. **Francesca da Porto:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Giacomo Piredda reports financial support was provided by Italian inter-university PhD organization – IUSS Pavia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Acknowledgements

This paper and related research have been conducted during and with the support of the Italian inter-university PhD course in Sustainable Development and Climate Change, coordinated by IUSS Pavia and hosted by the University of Padova. The activities were carried out in the context of an agreement between the University of Padua and the Municipality of Padua (Italy). This research was partly supported by the Italian Department of Civil Protection (DPC) in the framework of the ReLUISS-DPC Project 2024-2026 – Work Package 5: Integrated and sustainable interventions for existing buildings – Tasks 1 and 2. Special thanks are due to Elisa Saler, PhD, for supporting the activity of data collection and for discussions on priority assessment.

Data availability

The data that has been used is confidential.

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