Energy Reports 9 (2023) 6434–6448

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Architectural and environmental strategies towards a cost optimal deep energy retrofit for mediterranean public high schools

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ARTICLE INFO

Article history:
Received 14 November 2022
Received in revised form 24 April 2023
Accepted 30 May 2023
Available online xxxx

Keywords:
Deep renovation
Mediterranean schools
Energy certification
Cost-optimal
Multi-objective optimization
Life cycle assessment

ABSTRACT

Deep energy retrofit of the existing public stock is a crucial strategy to promote environmental targets at national and EU private levels, as required by EU Directives. The article presents a deep energy renovation strategy focused on high school buildings. The research is carried out in a sample of school buildings in Catalonia in which their possibilities of energy rehabilitation are analysed, developing a toolkit for prioritizing the buildings to intervene and the standardization of possible energy improvement measures for high school buildings. Such methodology is specifically developed to promote the replicability of deep renovation in Mediterranean schools, the model is applied to a specific case enquiry focused on the climatic zone Cfa according to Köppen (and equivalent to the Zone D3 at the Spanish level according to Spanish Technical Building Code), in accordance with a volume and constructive characteristics replicable in large schools built at the same period (70's). Despite being schools that are over 50 years old, their demolition is not considered appropriate but it is preferred to gradually improve their construction elements and facilities system throughout their lifespan. It is worth noticing current thermal discomfort and low air quality in schools, particularly during the summer months when overheating can be a significant issue, given the absence of an active cooling system.

It should be noted that the technical aspects evaluated in this first phase are those that meet the definition of an nZEB building under the cost optimal methodological framework: (1) prioritize demand reduction (minimizing heating demand with the aim of not penalizing cooling demand decisively enough to require the new implementation of refrigeration equipment to avoid overheating), (2) followed by the energy optimization of the installations' consumption in relation to their performance and, finally, (3) promoting the implementation of renewable energies.

Next, a methodology is proposed to discriminate and prioritize the intervention measures to be carried out, in a cost optimal deep energy renovation strategy, considering environmental aspects such as the life cycle of the building. This methodology is validated and its application in a representative case study is shown. Four key strategies are followed: (1) inspection and evaluation of the reference scenario, (2) establishing the strategic vectors for deep renovation according to the official definition of nZEB, (3) Considering the life cycle analysis of the interventions carried out to assess their environmental impact beyond the use phase, and (4) evaluation of the economic performance between investment and economic benefit of the energy bill with respect to the environmental benefit, in order to guarantee a cost optimal deep energy renovation.

The research aims to show that energy rehabilitation solutions, seen from an environmental impact point of view during the use phase of the building, cease to be relevant when the environmental impact of all phases of the building (LCA) is introduced. In this case we can see how the environmental impacts generated by the improvement interventions are compensated at most after 3 years of use of the building.

It can be concluded that the reduction in demand reaches values around 40%, versus the slight increase in cooling demand (less than 10%). However, the study has managed to reduce the cooling

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https://doi.org/10.1016/j.egyr.2023.05.265

demand compared to the base scenario thanks to the action on solar protection. This is the key action to minimize overheating hours and avoid the need for refrigeration equipment and guarantee indoor comfort.

It is positive to note that the ratio of payback values in the different proposals falls within a range of 10–15 years, contemplating within this value the incorporation of non-existent renewable energies in this type of building. In this case, the installation of photovoltaic panel system to complement the electrical demand of the building could be more optimal if a two-level supply system is proposed during the week to school and at the weekend to nearby urban areas.

1. Introduction

1.1. Context of climate emergency and urgency to activate the energy renewal of buildings

Deep energy retrofit of the existing public stock buildings is a crucial strategy to promote environmental targets at both national and EU private levels as required by EU Directives (Anon, 2018, 2012a, 2010, 2002). The first directive requires that 'as from 1 January 2014, 3% of the total floor area of heated or cooled buildings owned and occupied by the central government is renovated each year to meet at least the minimum energy performance requirements in 2010/31/EU' (Anon, 2018, 2012a, 2010, 2002). Within the scope of educational buildings (17% of all non-residential buildings in the EU (Economidou et al., 2011), this role of public bodies provides an effective path to an exemplary role in energy savings and environmental responsibility for all citizens, especially among future generations. As a consequence, multiple studies have focused on different aspects: the 'deep retrofit' concept (Zinzi et al., 2016), mainly deep energy retrofit (Dall'O' and Sarto, 2013; Irulegi et al., 2017; Teni et al., 2019) and payback periods (Asdrubali et al., 2019), also, the evaluation from the point of view of replicability in similar building models (Tahsildoost and Zomorodian, 2015; Erhorn-Kluttig and Erhorn, 2014; Pons-Valladares and Nikolic, 2020) . Other study models are those that focus on the assessment of a part of the building: the building skin Ali and Hashlamun (2019), the openings (Boafo et al., 2019), solar orientation (Benincá et al., 2023) or colour (Crespo Sánchez and Masip Vilà, 2022). Others take into account the existence of public funding as a strategy to provide guidelines (Brás et al., 2015) such as including energy improvement aspects within functional improvements that adjust to the new pedagogical and usage models (Hartikainen et al., 2022; Cayubit, 2022; Rusticus et al., 2022; Acaso, 2023), as well as constructive or structural ones (Österreicher, 2018).

One step beyond the impact of CO_2 emissions during the useful life of a building, are those linked to the rest of the stages of the LCA that incorporate both the previous stages of manufacturing and construction (A1-5), as well as the end-of-life stages (C1–C4), according to ISO 14040 and ISO 14044 and, specifically, UNE-EN 15804 for buildings. On the other hand, Directive 2018/844/EU article 2a: 'Long-term renovation strategy' mentions the need for 'the identification of cost-effective approaches to renovation relevant to the building type and climatic zone, considering potentially relevant trigger points, where applicable, in the life-cycle of the building' (Oregi et al., 2015). Zimmermann et al. (2020) mentions that the demolition of the existing building represents 12% of its environmental impacts. An approach resulting from studies that incorporate the impact of the LCA on the Deep Renewal is that of Antonov et al. (2021) who points to the need to carry out pre-evaluations prior to the final study in order to cross-check data between energy savings, economic investments and the lifetime impact. Other researches question the use of deep rehabilitation with current evaluation models that are more oriented to the construction of new buildings than to rehabilitation, and therefore with different and diverse aspects consider (Caruso et al., 2017) as well as the circular economy (Bull et al., 2014). There are also reflections on the suitability of investing in renovation and not in demolition, especially buildings that are close to 75 years old. More few are the studies on the impact of the new circular economy (CE) model that may involve the introduction of concepts such as the circularity of the resources used (López Ruiz et al., 2020). As it is known, the building and construction sector is one of the main consumers of raw materials in the EU with approximately 50% of consumption. (Norouzi et al., 2021). Various studies show the significant amount of non-renewable resources and materials that we use per m^2 in the construction of our living spaces according to different construction systems. Rodríguez Rodríguez et al. (2021) and, to a lesser or greater extent, any operation that considers the cyclability of these resources should be considered a priority in our actions (Anon, 2012b).

1.2. Rehabilitation approach in the Mediterranean climate considering global warming

Returning to the energy component and focusing the debate on the Mediterranean climate, it is necessary to consider strategies to alleviate the energy impact, not only of the winter regime, but to improve the conditions during the summer months (Bianco and Marmori, 2022). Precisely this question is especially important to be treated in Mediterranean buildings, where the impact of overheating in summer is increasingly pronounced in number of days and absolute values of temperature degrees (de Rosa et al., 2015), leading to an increase in demand for cooling that questions those buildings that do not have cooling installations. Few studies focus on the summer regime when deciding on a possible rehabilitation strategy, these are generally oriented to reduce the demand for heating (between 50/80%), on energy demands and behaviour in summer regime (Santamouris, 2016; Attia et al., 2017; Economidou et al., 2020; Abolhassani et al., 2023).

In schools in Catalonia, the heating demand represents 75%–85% of the total demand, and the energy improvement actions of this vector directly imply an increase in cooling demand that entails overcoming the barrier of hours and moments of discomfort for users. Currently, as a design premise, by the Department of Education of the *Generalitat de Catalunya* it is established not to have refrigeration equipment, for this reason the existing buildings only have heating systems and hot water production. Fact that would mean an increase in the demand for cooling in the building, but that in practice is detrimental to habitability under the current conditions of use. For this reason, the strategic key to the energy improvement of these buildings, deep energy renovation, must have the condition of not installing refrigeration equipment, not only for economic or technical-constructive reasons of execution and space, but also for reduce their environmental impact (CO_2 emissions), economic (€, implementation, maintenance and energy bills) and improve their health conditions (reduce concentrations of CO_2 and other air pollutants).

This consideration is key in the current context of the school buildings of Catalonia, since they can become a thermal catalyser of overheating hours over many teaching weeks, leading to their inhabitability if refrigeration equipment is not incorporated. This fact is added to the reality of new educational and social models that involve the continuous use of school buildings throughout the summer. In addition, in recent years, the introduction of air conditioning systems has been repeatedly demanded by school family associations, since the number of hours of discomfort in this type of building is increasing, in contrast to the policy of the management not to install this equipment. This social and administrative peculiarity has been key at the same time as to propose a deep energy retrofit model for high schools in Catalonia.

In fact, the incorporation of cooling devices in all existing school buildings has not only environmental and economic implications, given that there are a total of 1131 high schools and 2663 primary schools throughout Catalonia (Idescat, 2023), but also has health effects. The installation of air conditioning systems whose sole objective is to cool without renewing the air can lead to inappropriate air quality levels that can affect the health and performance of all users. Studies have pointed out the need to focus on natural ventilation strategies (Anon, 2023a; Crespo Sánchez et al., 2020; Anon, 2023j; R et al., 2013), a need that has been reinforced after the impact of COVID-19, as evidenced by projects such as the Urban Innovation Action (UIA) Climate Shelters in Schools: Adapting Schools to Climate Change through Green, Blue, and Grey Project (2019–2022) (Anon, 2023a).

This article provides an investigation (Crespo Sánchez et al., 2020) carried out for the Department of Education of the *Generalitat de Catalunya* in high schools on the potential of deep energy renovation. A prioritization methodology is provided that can be replicable in Mediterranean climates. This methodology is useful for the prioritization of cases to be renewed and the deep energy renovation measures to be carried out, considering optimal cost factors. Likewise, the results of the application of said methodology are provided in 8 schools provided by the Department of Education of the *Generalitat of Catalunya*, as well as the most detailed study of the possibilities of Energy Retrofitting in the most representative case.

1.3. International referents of deep energy renovation in schools

A determining aspect when promoting energy rehabilitation actions is the availability of economic resources. Public and private aid models, such as the European Regional Development Fund (ERDF), facilitate competitiveness and activation of deep energy rehabilitation actions of the occupied building stock, both privately and publicly. In multiple European countries we find examples that have worked on carrying out energy renovations in groups of schools, as is the case of Ireland, Germany and England; and we also find them outside the EU, as in the case of the United States.

Among these examples, we find the Schools Energy Retrofit Pathfinder project (Ireland), which has aimed to activate the massive rehabilitation of schools (41 by 2021, 9 during 2021 and a forecast of 6 in 2022) carried out in both urban and rural areas, with an expected saving of around 50% both in demand and in CO_2 emissions. This 'pathfinder is jointly funded with a €28 million budget from the Department of Education and the Department of the Environment, Climate and Communications and administered by the Sustainable Energy Authority of Ireland (SEAI) and the Planning and Building Unit in the Department of Education, with support from Limerick Clare ETB' (Anon, 2023j).

On the other hand, in the United States, we find the K-12 project for small schools in rural areas in the 1960s and the support guide on Energy Efficiency Programs in K-12 Schools (R et al., 2013; US Environmental Protection Agency (EPA), 2023), whose objective is not only to guide possible lines of action on energy efficiency but also on the evaluation of the micro and macro-economic and health impact on society. The application of deep renovation measures means a very high initial economic investment, but it has had substantial benefits over the years since a reasonable reduction in the building's energy bill has been demonstrated. Other studies also report an improvement of up to 40% in the IAQ levels (Indoor Air Quality) (Kats, 2006).

Finally, in Germany, we find the project '*Energie effiziente Schulen*' carried out by Fraunhofer Institute for Building Physics, Munich University (Hochschule München) and the Institute for Resource Efficiency and Energy Strategies (Reiss, 2014). Five existing buildings in this project are retrofitted, and two new construction buildings are executed. Out of the seven buildings, four reached the '3-litre[1]' standard (which refers to the value of the fuel used for heating with the support of innovative technologies such as phase change materials (PCM) or electrochromic grazing).

These cases are clear examples of ambitious and successful deep renovation actions, which have been carried out thanks to the interest of the public administration and the support of funding bodies and neutral research institutions.

1.4. Key economic context to establish a realistic energy action model according to catalan public administration

However, in many countries, it is hard to promote strategies of high economic investment in activating energy rehabilitation when there is a shortage of public schools, even to ensure schooling for all students, as in the case of Catalonia. Schools in temporary buildings have been counted up to 1006 (approximately 25% of the total number of primary and high schools in Catalonia) (*Departament d'Ensenyament* official source): They are considered transitional until the new and definitive building or extension is available and are built with minimum housing criteria that do not favour optimal behaviour in the hottest periods of the year. Nevertheless, some of them have remained for more than 20 years.

Given this economic context, it is important to take into account that some of the premises considered in the study have been related to budgetary constraints as well as the widespread age of the school building sector in Catalonia. Additionally, it is worth noting that the strategies to be evaluated and standardized have been based on the cost-optimal methodology (Ferreira and Baptista, 2017) developed by the International Energy Agency Annex and also regarding the benefit of having public funding ERDF available. This funding establishes the initial requirement of improving the building's energy certification by two levels, with the goal of achieving a realistic economic investment for the *Departament d'Ensenyament de la Generalitat de Catalunya*.

2. Objectives

The purpose is to obtain a replicable methodology to achieve deep nZEB retrofits in educational buildings at an optimal cost in the Mediterranean climate zone, cross-assessing the environmental impact between winter and summer retrofits, promoting low energy demand values, mainly cooling ones, and optimizing user's comfort with the minimum economic investment of implementation and maintenance, also considering its impact on the

[1] 3-litre standard means that 'The primary energy use for heating and ventilation plus the required electricity for auxiliary energy is less than 34 kW h/m^2 a — this corresponds to the energy content of 3 litres of heating oil or 3 m^3 natural gas'.

environment throughout the product, construction, use and end of life stages.

The following are defined as secondary objectives:

- Provide a methodology that allows the prioritization of which school buildings it is more efficient to intervene in by considering the actual energy behaviour.

- Propose and evaluate passive energy rehabilitation improvements that minimize heating demand as much as possible until this reduction begins to have a negative impact on the hours and periods of cooling demand, working on both thermal transmittance and facade infiltrations.

- Propose and evaluate improvements the design, maintenance and use of the current model of solar protections, since they are a critical element both for the demand for heating and cooling. All this so that with an adequate strategy of natural ventilation the comfort of the classrooms in the summer regime can be achieved without the need to incorporate mechanical refrigeration systems.

- To propose and evaluate the impact of active systems considering whether their energy comes from clean and/or renewable sources.

- Consider and evaluate the environmental impacts of the LCA under the EC indicators ($KgCO_2$-eq) and the amount of waste generated with circularity potential.

3. Methodology

The research approaches the question of how to prioritize public investment in energy retrofits in school buildings. The first question, corresponding to the first methodological phase, responds to how to prioritize the energy retrofits of schools in Mediterranean climates (Fig. 1). For them, a prioritization toolkit is developed, described in Section 4, which is applied in eight educational centres with similar architectural models and representative in the two most restrictive climate zones in Catalonia, 4 high schools located in Lleida and 4 in Girona. These chosen high schools were characterized by the high potential for replicability in terms of construction deficiencies and low energy performance, an aspect that facilitates the justification of economic investment by the Department. The prioritized in schools were those that were built in the 1970s (most common school buildings in Catalonia), the period prior to the enforcement of the first thermal regulation in Spain and in turn had carried out fewer maintenance or updating actions of envelope elements, as well as high energy bills (Crespo Sánchez et al., 2020).

Three outcomes are obtained from this first methodological phase:

-The establishment of an intervention prioritization toolkit: the creation of a novel methodology that allows prioritizing the buildings on which to carry out real deep renovation actions.

-The evaluation the possibilities of cost optimal energy deep renovation in educational centres.

-The detection of the singularity of each building to establish a replicable strategy of energy retrofit measures.

Once an energetic singularity of each building has been identified and the different stages of maintenance of the main elements that establish the energy performance of the building have been detected, it is concluded that it is feasible and necessary to establish a standardized and replicable action model for Catalan schools that is adapted to the local economic and environmental context. This is where the following question arises: how to prioritize energy improvement measures in a building? For this, a cost optimal deep renewal methodology is developed (see Section 5) and applied, as a verification, on the case of a specific high school, the *Ribera de Sió* high school in *Agramunt, Lleida*, Spain, which is located in the D3 climatic zone, according to the Spanish Technical Building Code (CTE) (Anon, 2023f) or Cfa, according to Koppen–Geiger classification (Peel et al., 2007). This building has been chosen due to the climatic particularity of Lleida, having low winter temperatures but also extreme summer peaks and for longer periods, also for being the one with the worst energy performance and for being architecturally representative of similar models built in the territory both at a geometric level as constructive and built according to previous thermal regulations: NBE-CT-79 (Anon, 2023e). The following outcomes are obtained from this phase:

- The establishment and prioritization of deep energy actions related the energy behaviour of each element of the building and its impact values on energy performance.

- Energy evaluation considering environmental conditions such as the life cycle of materials, their circularity and the volume of associated waste.

- The validation of the standardized replicable measures for a new model of energy deep retrofit in Catalan schools with a and cost-optimal evaluation.

4. Energy retrofit priorization of school buildings in catalonia

4.1. Prioritization methodology towards a deep energy retrofit strategy for high schools

Given the low level of energy performance of the school-built stock in Catalonia, the deep renovation methodology must be accompanied by a prioritization tool that makes it possible to establish in which buildings are a priority. The specific detail of development and application of this tool can be seen in a previous publication (Crespo Sánchez et al., 2020).

The prioritizing methodology regarding this tool applied on the 8 aforementioned high schools for energy deep renovation involved establishing a specific range of scores for demand, consumption (both final and primary energy), and CO_2 emissions given each axis a weight among the total:

- Energy demand: the vector that is considered the highest priority is the demand for heating (in general it represents 80% of the total demand) to which an impact of 35% has been associated with the value of the final score. A value of 5% of the final impact has been associated with the demand for refrigeration because current buildings do not have refrigeration equipment and its increase may entail a risk of discomfort for users.
- Energy consumption has been given a score of 30%. At the energy level, it is divided into 12% for primary energy, 12% for final fuel energy and 6% for final electric energy.
- CO_2 emissions have been given a score of 30%. The toolkit also aims to emphasize that the CO_2 emissions of a building are not only a consequence of its architectural design but also a result of its usage. For this reason, the last variable is incorporated: the factor of human use, which refers to the energy awareness of users (management staff/teachers/students/cleaning staff/maintenance staff), as well as the current state of the building (regarding pathologies or constructive shortcomings).

In all the selected schools, most of the factors obtain similar values, but the location, orientation and maintenance carried out make them differ from each other when it comes to addressing a deep renovation rehabilitation.

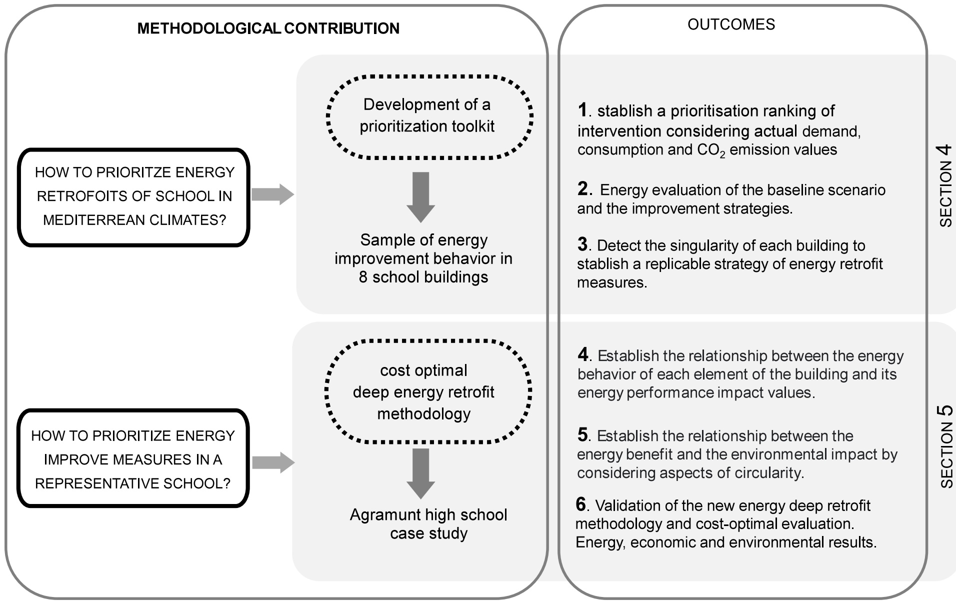

Fig. 1. General methodology and research contributions.

4.2. High school buildings sample description and energy assessment methodology

The ability to evaluate 8 buildings with the same criteria while considering their particular energy characteristics and lifespan of elements that impact energy consumption in the building allows for interesting conclusions to be drawn in the development of new deep energy retrofitting models for high schools in Catalonia.

The high schools analysed have varied surfaces and shapes, highlighting the amount of surface dedicated to classrooms. Its volumetry, both in plan and in height, varies depending on the location. On the other hand, their envelope's thermal performance, their facilities systems and use patterns present the following similarities:

- Usual building envelopes of the 70 s with high thermal transmittance values of the envelope are common, with constructive solutions of double brick sheet with no insulation and sliding windows with double glass, but without thermal break (Díaz et al., 2023). The sun protections were mobile in origin but due to lack of maintenance they have drifted into a fixed position, wasting the impact of solar radiation in winter and not optimizing its brake in summer, as well as affecting the hours of light comfort with natural lighting. In addition, the impact of thermal bridges and infiltrations that entail PVC roller blinds must be added.
- Facilities are focused on meeting the demand for heating and lighting. The heating and domestic hot water systems are conventional diesel boiler and radiators with single circuits without sectorization. There are refrigeration systems installed occasionally (split type) in some administrative rooms. The lighting is linear fluorescent, the original TL8 type lamp being replaced in many cases by a TL5 or LED, but with lighting level values above those established by UNE 12464.1.
- Absence of renewable energy systems.
- Regarding the use of the buildings and their opening hours, the occupancy values stand out (high occupancy in the classrooms and low occupancy in the circulation areas, toilets and offices for 8 h a day), use of artificial lighting, water hot sanitary and appliances.

The deep energy retrofitting strategy for achieving nearly zero energy buildings (nZEB) involves establishing technical solutions that can be replicated in future retrofitting scenarios. This includes minimizing the total energy demand by achieving a balance point where no cooling system is required to ensure comfort conditions on the hottest days of the year, promoting high energy efficiency of facilities by achieving annual comfort using exclusively a heating equipment, and considering local resources. In addition, renewable and/or clean energy sources should be added to further reduce energy consumption and improve two levels the energy rating of the building.

This methodology comprises several steps, including (1) visual data collection, (2) 3D energy building modelling using HULC (the official energy certification program by the Spanish government (Anon, 2023k), which allows to prioritize the most deficient energy elements of the building, differentiated for summer and winter regimes), (3) 3D lighting modelling using DIALUX evo (to detect excess average lighting levels that are unproductive in terms of comfort and energy efficiency, (Anon, 2023h), and (4) 3D ventilation modelling using Design Builder (to guarantee the air quality levels of the building and at the same time compute the benefits of energy demand in summer, (Anon, 2023g). Photovoltaic electrical energy production is also evaluated using PVGIS (Anon, 2023l) to determine the number of photovoltaic panels that can contribute to an improvement in primary energy and CO_2 emissions. The energy results are assessed separately by technical elements, considering the ageing and obsolescence of the building, annual and monthly energy values, and energy bills (this last is an information provided by the high school boards).

After developing the strategy for a deep energy retrofit, the next step is to consider the European cost-optimal deep retrofit scenario. This involves modelling the energy improvement of each retrofit measure and assessing its impact on energy demand, energy consumption, CO_2 emissions, and certification levels. The average return of each measure is also set based on the economic values of two databases of construction products BEDEC, iTeC-Catalan Institute of Construction Technology (Anon, 2023d) and international CYPE *Ingenieros* (CYPE Ingenieros, 2023). Furthermore, the PAREER plan (*Programa de ayudas para actuaciones de rehabilitación energética de edificios existentes*) is taken into consideration, with the minimum energy aim for the retrofit being to improve two levels of the school's energy certification.

These steps are crucial in determining the most cost-effective and efficient way to carry out a deep energy retrofit in Catalonia.

4.3. Retrofit possibilities assessment and standardization

The most noteworthy conclusion of the previous assessment is that despite the small differences between each building, there is a common thread that allows for a standardized energy approach to be established for all of them. A standardization pattern of deep energy retrofit measures can be provided as follows:

Passive level actions package.

a. Improving the thermal behaviour of the building envelope by reducing its thermal transmittance. Given that the main conclusion of the initial study is that opaque surfaces have a 49% impact on the final demand, openings have a 38% impact, and thermal bridges have a 13% impact, it is important to act at all levels. The new thermal transmittance values should be around 0.4–0.3 W/m^2 K for opaque surfaces (noteworthy aspect is that this value is half the value established by the CTE) and 1.8–2.2 W/m^2 K for openings, which provide the optimal balance between maximum heating demand reduction (around 40%–45%) and minimal cooling demand increase (5%–10%).
b. Thermal bridges (17%) and air leaks (13%). These should always be considered in three ways: carpentry (29%), structure (28% on heating demand and 9% on cooling demand), and solar protections, particularly the roller shutter boxes (34%).
c. Optimizing the relationship with the solar radiation (41%). Promoting solar gain during winter and minimizing the hours of artificial lighting demand can impact up to 60% of the lighting demand. Ensuring the minimum energy gain during summer through windows without penalizing the average level of natural lighting and avoiding the electric consumption of artificial light can contribute up to 31% of the demand.

Active level actions package.

a. Replacing the heat generator equipment (boiler) with a higher efficiency one that runs on a low CO_2 emission fuel.
b. Proposing a valve system that allows for adjusting the specific energy input to each room according to their thermal needs and minimizes the impact of having single-zone air conditioning systems. Given that it is not feasible to partition the current system, a basic option is proposed to compensate for thermal imbalances, which would minimize the presence of overheated classrooms and those with open windows.

Renewable energy sources level actions package.

a. The optimal environmental option for minimizing CO_2 emissions is to incorporate a biomass boiler. However, depending on the relationship between the exploitable areas for energy use and the geographic positioning of the buildings, the impacts on SDGs (Sustainable Development Goals) (Anon, 2023c) may not always be optimal. Therefore, based on a database of biomass production in Catalonia (Anon, 2023b, 2021), two models of action are established for schools:
   - Replace the diesel boiler with biomass.
   - Replace the diesel boiler with natural gas and incorporate photovoltaic panels as a renewable source of production. This option has an added value for schools, which is the compensation of CO_2 emissions not only thermally but also electrically (providing renewable fuel support for lighting and appliances consumption), which represents 40% of the total CO_2 emissions of this kind of buildings once the energy improvement at the envelope level is carried out.

5. Cost optimal deep energy retrofit case study with life cycle low carbon scenarios

In this section a cost optimal deep renewal methodology is presented in order to help to prioritize energy improvement measures within a building. A case study is chosen among the 8 high schools, the *Ribera de Sió* High School in *Agramunt, Lleida*, Spain, for being the one with the worst energy performance and for being architecturally representative of similar models built in the territory both in construction and geometry.

In the previous evaluation of the 8 high schools, the environmental impact of the energy improvement measures was analysed during the use phase. In the previous evaluation of the 8 high schools, the environmental impact of the energy improvement measures was analysed during the use phase. Although, as provided in this section, the environmental impacts of the interventions are shown for the entire life cycle of the building. This allows us to obtain a global vision of what the environmental repercussions of the improvements may be and, in this way, we can make optimized decisions considering the useful life of the building. For this, the environmental impacts have been calculated according to the Functional Units Declared in the Environmental Product Declaration (EPD) or BEDEC Database and, subsequently, each impact has been passed on for the useful area of the school. It is important to consider this in this way in order to incorporate and compare the results with those obtained in the use phase of the building.

The key to achieving sustainable development goals in building projects is to consider the current state of the elements with the greatest energy impact in a school building. Based on the information presented thus far, it can be stated that the final action strategies vary according to the maintenance and updates of these elements. Therefore, an expansion of the initial methodology (Section 4.1) is proposed, which allows for the measurement of environmental impact (based on specific durability and energy performance aspects) as well as the consideration of circularity options (which involves taking an inventory of the existing school stock).

5.1. Deep energy retrofit methodology

The technical aspects evaluated align with the definition of nZEB buildings, which prioritize demand reduction (to avoid the need for cooling equipment while ensuring comfort), optimize energy efficiency, and promote renewable energy implementation (Fig. 2). The study also considered LCA impacts and circular economy (CE) options to optimize not only energy consumption (kWh) and environmental impact (CO_2) during the building's lifespan but also CO_2 emissions throughout its lifecycle and waste. Zimmermann et al. (2020) noted the lack of established protocols in this area and the need for new avenues of research in this field.

For the calculation of Embodied Carbon (EC), the Environment Product Declarations of each product were used following the programs of the International EPD® System, DAPcons®, and the BEDEC (Structured Bank of Construction Elements) database from iTeC with environmental impact values calculated using "SimaPro v9.1.1 by PRé Sustainability BV" (Anon, 2023m)and "Ecoinvent v3.6 database" (Anon, 2023i) in accordance with ISO 14040, ISO 14044, and EN 15804. The environmental information used in this case is the most reliable and adjusted to the specific project

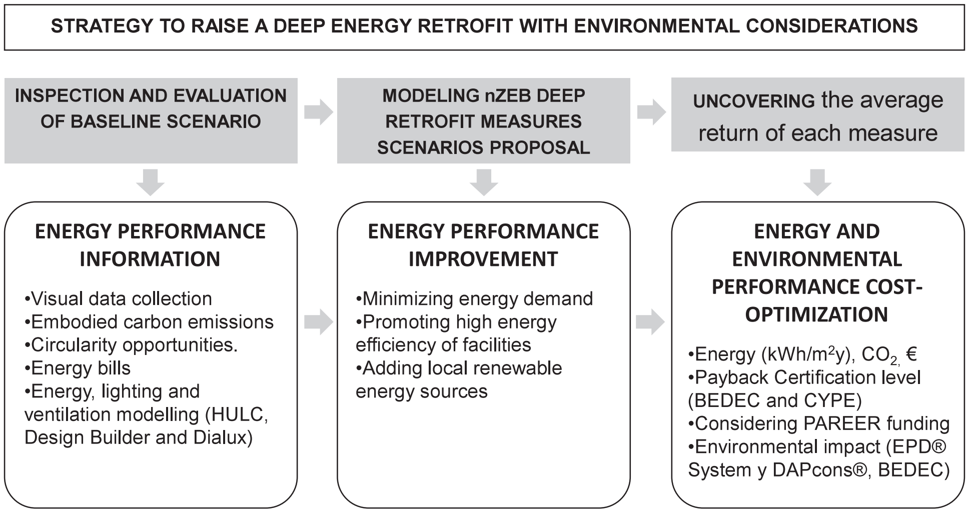

Fig. 2. Methodology to raise a deep energy retrofit with environmental considerations.

solutions and the stages considered have been A1-5 (product and construction stage) and C1-4 (end-of-life stage).

For the economic evaluation (using the BEDEC database required by the public administration and also using the CYPE database in the case of proposing a specific manufacturer model) and the cost-optimal evaluation, the subsidy from the PAREER II (Programa de ayudas para actuaciones de rehabilitación energética de edificios existentes) call for funds was considered, which allows for more profitable paybacks in the total calculation. To access this subsidy, it was necessary to ensure that the proposed actions achieved at least two levels of improvement in the Spanish energy certification scale for the current building at the CO2 level, comparing actual consumption to equivalent levels of comfort.

5.2. Case study assessment

The *Ribera de Sió* High School was built in 1970 in *Agramunt*, municipality of *Lleida*, in Catalonia. The climatic zone is D3, according to the Spanish Technical Building Code (CTE) or Cfa from the Koppen–Geiger classification. It means that the weather is severe both in the winter (cold) and summer (hot) seasons. The main orientation diverges 15° from the north and without energy impact from the neighbour's shadows. The useful floor area is 3300 m^2. The geometry of the building draws a 'U' shape on the floor, where the central courtyard is south-facing and the classrooms are distributed through a corridor facing the courtyard. The central area of the 'U' mainly contains the common use areas: school canteen, library, administration area, toilets and stairs. On the open side of the 'U', there is an isolated building that includes the gymnasium and locker room. Fig. 3 shows the floor plan geometry and distribution of activities of the complex.

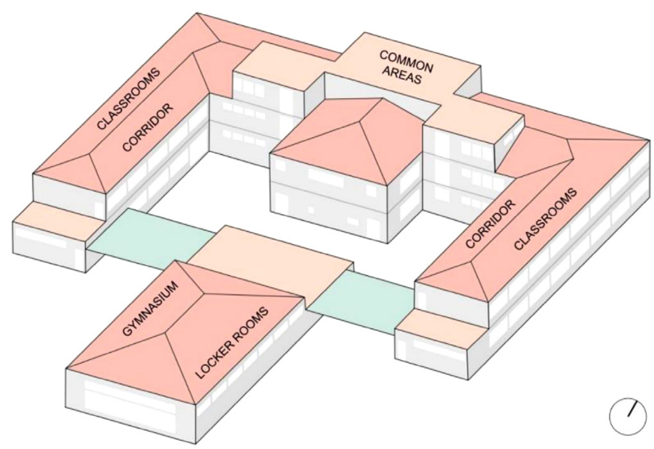

Fig. 3. The *Ribera de Sió* high school in *Agramunt, Lleida* building.

5.2.1. Passive enhancement package. Winter/summer optimal demand reduction

The actual energy performance is (here, after referred to as *baseline scenario* or *m0*) has an energy rating of 'D', the equivalent of 26.5 $kgCO_2/m^2y$, where 60.94 kWh/m^2y corresponds to the energy demand for heating (energy rating F) and 21.39 kWh/m^2y to the energy demand for cooling (energy rating B but is not satisfied). The critical areas in terms of heating demand are the rooms located under the roof as a result of the high thermal conductivity of this (the range of heating demand values is 60–75 kWh/m^2y) and the critical areas in terms of cooling demand are south, east and west-facing rooms (30–40 kWh/m^2y). The critical thermal loads, in order of greatest impact, are (1) hot season: 30% windows, 44% facades but a potential of 41% solar radiation benefit through windows and (2) cold season: 31% windows, 27% ventilation, 32% facades.

The occupancy schedule considered in this study was based on the official energy certification program in Spain, known as HULC, which follows the Building Code legislation. Specifically, Table 7 of the CTE (*Condiciones operacionales y perfil de uso para espacios de uso no residencial* (Fomento, 2019) was used to determine the operational conditions and usage profiles for non-residential spaces. For instance, the classrooms were considered to have 8 h of high occupancy and the rest of building with 8 h of low occupancy. This resulted in a latent occupancy ratio of 6.31 W/m^2 and 1.26 W/m^2, a sensible occupancy ratio of 10 W/m^2 and 6 W/m^2, and for appliances 7.5 W/m^2 and 1.5 W/m^2, as detailed in the Supporting Information.

5.2.1.1. List of actions and nomenclature. At this point, the aim is to validate the proposed method of action after conducting an energy improvement study in 8 high schools in Catalonia (4 in *Lleida* and 4 in *Girona*). The application of the first premise involves deciding on thermal insulation intervention in the opaque part. For the construction model of most schools in Catalonia, there are 2 possible courses of action: insufflating insulation into the existing air chamber (m1) or including a continuous insulation system ETICS (External Thermal Insulation Composite Systems) (m2). Once this point has been evaluated, the impact of the proposed improvement solution will be introduced to optimize the relationship with solar radiation in both winter and summer, through mobile and stationary exterior solar protection (m3).

- (m1) (m3) Insulation injected into the facades. (7 cm),
  Air cavity filled with mineral wool. Despite being the air cavity 10 cm thick, in this investigation only 7 cm insulation has been considered, including possible discontinuities due to the presence of debris.
- (m2) Addition of an ETICS in the three outer facade orientations (N/W/E), which account for 60% of the total facade area and also the 100% of the gymnasium facades.
  This solution helps minimize the thermal bridges, but its price is higher than the injected solution. For this reason, the application of thermal insulation has been considered only in the three outer facade orientations (N/W/E) in the 'U' volume and all facades in the 'gym' volume.
- (m1) (m2) (m3) Replacement of insulation on the flat roof.
  Expanded polystyrene insulation (EPS, 2 cm thick) is replaced by 8 cm extruded polystyrene (XPS). In turn, this action helps repair water leaks from the roof.
- (m1) (m2) (m3) Addition of a new window that complements the existing one in the three outer facade orientations (north, west and east, from now on call N/W/E, opposite the one facing the patio)
  One option is to keep the existing window and add a monolithic window from other school buildings that are remodelling their old windows with double-glazed ones. The technical performance of the resulting window assembly is close to that of a double-glazed window in terms of heat transmittance and infiltration values (specific values are detailed in Table 1). This solution is considered a transitional action until the current window reaches the end of its life cycle and can be replaced with a window with potentially better performance due to expected technological advancements.
- (m1) (m2) (m3) Replacement of all the windows of the 'gym'
  Replacement of all the windows of the 'gym' volume with double glazing windows with low-E layer and thermal break in the window frame.
- (m3) Addition of a sunscreen system that operates, in hot conditions in indoor facades, corresponding to
  PVC blinds are replaced by mobile exterior light grey screens. This intervention has been considered in the facades with a high incidence of solar radiation (all facades except north orientation) and apropos of the window with opaque percentage.

5.2.1.2. Summary of technical performance of envelope in relation to the improvement of the proposal's values. The most remarkable envelope characteristic is the absence of thermal insulation in the air chamber of the double brickwork facades and a gable roof covered with Arabic tile, except for the central volume of the 'U', which is covered with flat slab finished with gravel over 2 cm of EPS insulation (extruded polystyrene).

Table 1 shows the relationship between different cases of performances, the baseline scenario (m0), the injected insulation solution (m1), the ETICS solution (m2) and the injected insulation m1 case and also sunscreen system added (m3). The CTE case or m_{CTE} corresponds to the minimum technical performance values required by Spanish regulations. It should be noted that improvement injected proposal does not include the minimization of thermal loads through thermal bridges, as these are maintained. However, in the ETICS case, the thermal bridges are eliminated in the pillars and floors, with the exception of the floor in contact with the ground.

It is worth noting that the similarity in the values between m1 (7 cm of mineral wool injected into the air cavity of the facade) and m2 (ETICS 12 cm mineral wool in N/W/E facades) cases during the winter period is due to the fact that the ETICS solution is only applied to around 60% of the facades, which corresponds to the opaquest and least sunny facades. This is because applying an ETICS system to a facade with a high percentage of openings, such as the typical profile of schools in Catalonia, is currently not a viable option for technical and economic reasons. Also, from the environment impact point of view of both solutions, it is relevant the major impact form ETICS solution 24.72 $KgCO_2eq/m^2$ of mineral wool injected 3.65 $KgCO_2eq/m^2$. This fact occurs because of the incorporation of materials such as fibreglass mesh, cement-based and acrylic mortars that guarantee its durability.

Although the thermal improvement of the gable roof has been evaluated, the poor relationship between economic investment and energy reduction values reveals that this result is meaningless. The implementation of the thermal insulation panels requires hard tasks and create many thermal bridges in both options: the installation of insulation in the free spaces between the large range of internal partitions which support the coating of the gable roof and the installation of insulation between the false ceiling and the roof, which represents 8.96 $kgCO_2eq/m^2$ or 53.96 kWh/m^2 in terms of embodied energy. The use of this foamed insulating material (XPS) allows guaranteeing its durability and performance when located in humid places or inaccessible for regular maintenance operations. This latter option also involves bricklayers and electricians to remove the false ceiling and lighting systems (Table 2). In this case, the impact values are expressed in the Functional Units declared in the EPDs, but as we will see later, in order to add them to the use phase of the building, they are shown per area unit (Section 6).

The current windows description is listed below, and the sun protection is solved by conventional PVC roller blinds operated manually:

- In the 'U' volume, double glass and sliding aluminium carpentry with high air permeability were used, but these windows were replaced last year. It is proposed to implement an energy improvement action that does not involve the demolition of these windows since their lifespan cannot yet be justified environmentally. Therefore, a transitional solution is proposed, which involves adding a monolithic double glass window from the demolition of other existing buildings to the existing window. This allows obsolete monolithic windows from other schools to be valued, giving them a second life, even if only for a limited period of time. This option is considered appropriate due to the low economic investment impact (transportation and implementation) versus the benefit in terms of thermal transmittance and infiltration. It is worth mentioning that, during that period, technological regulations in force, NTE-FLC 1974 recommended designing windows according to a standard module of height and width, which now allows for their circularity. In addition, it is also common in schools from the 1970s to have the same window format. In fact, we can find schools with even the same architectural format, which was a response to the high demand for schooling at that time, partly due to immigration.
- In the 'gym' volume, the current windows have a monolithic glass with a thermal transmittance (U-value) of 5.7 W/m^2 K and a metallic frame with a U-value of 5.7 W/m^2 K. They also have an air permeability of 50 $m^3/h\ m^2$ to 100 Pa. Given the age of these windows, which is around 50 years, it is considered appropriate to replace them with new double-glazed windows with argon gas. On the other hand, in those

Table 1
Envelope characteristics improvement in each case.
Source: Self-elaboration.

Opaque building fabric		Facade				Flat roof			
		Insulation	Thickness (cm)	U (W/m^2 K)	$KgCO_2eq/m^2$ (EPD unit declaration)	Insulation	Thickness (cm)	U (W/m^2 K)	$KgCO_2eq/m^2$ (EPD unit declaration)
m0	Baseline scenario	MW	0	1.16	–	EPS	2	0.76	–
m1	Injected case	MW	7	0.37	3,62	XPS	8	0.32	8,96
m2	ETICS case	MW	12	0.26	24,72	XPS	8	0.32	8,96
m3	Injected case (m1) + Solar Protection	MW	7	0.37	3,62	XPS	8	0.32	8,96
m_{CTE}	CTE case			0.66	–			0.38	

Table 2
Summary of window performance improvement in each case.
Source: Self-elaboration.

Glazed building fabric		Classroom building						Gym building					
		Solar factor Fs	g-value	U (W/m^2K)		$KgCO_2eq/m^2$ (EPD unit declaration)	Air permeability (m^3/hm^2 at 100 Pa)	Solar factor Fs	g-value	U (W/m^2K)		Air permeability (m^3/hm^2 at 100 Pa)	$KgCO_2eq/m^2$ (EPD unit declaration)
				glass	frame					glass	frame		
m0	Baseline scenario	0.5	0.73	3	5.7	–	50	0.5	0.8	5.7	5.7	50	–
m1	Injected case	0.5	0.53[a]	1.82[a]	2.33[a]	2,30	27	0.5	0.6	1.1	2.33	27	80,36
m2	ETICS case	0.5	0.53[a]	1.82[a]	2.33[a]	2,30	27	0.5	0.6	1.1	2.33	27	80,36
m3	Injected case (m1) + sunscreen system	0.2	0.53[a]	1.82[a]	2.33[a]	2,30	27	0.2	0.6	1.1	2.33	27	80,36
m_{CTE}	CTE case	0.35		1.9 (N) 3 (SE/SW)			27	0.35		1.9 (N) 3 (SE/SW)		27	

[a]New window performance.
Where,
Ug: glass transmittance.
Uf: frame transmittance.
g-value: solar glass value.
Fs: Solar factor.

parts of a school building with monolithic windows, the direct option is to replace them with new double-glazed windows with argon gas and an aluminium frame with a thermal break. Although they are sliding windows, their air infiltration value is much lower than usual due to safety requirements in the classrooms, which is also a prescription from the Department of Education.

5.2.1.3. Ventilation system consideration. Halfway between passive and active strategies is mechanical ventilation, which affects energy demand but also consumption as a result of fan operation. The HULC program considers 0,29 renovations per hour as a default value of controlled ventilation. This ratio has a plausible impact on the final energy demand of the building, which is unfavourable for most of the winter period but becomes beneficial during the summer regime. In the same dynamic analysis, it was detected that the presence of thermal overheating in classrooms occurs even in winter, due to the internal loads of the students as well as the incident solar radiation through the windows, which occupy up to 60%–70% of the facade of a classroom. For this reason, we can say that the energy impact of the presence of a mechanical ventilation system to favour free cooling guarantees thermal comfort and demand not only in the summer regime but also in some winter days. The calculation made using Design Builder estimates that ventilation can contribute to reducing the cooling thermal load by around 25%and, on the other hand, the environmental impact between a mechanical ventilation system with heat recovery and a refrigeration system is 747 kWh compared to 13,717 kWh, which represents an impact of almost 20 times more. This value can displace the borderline so that the installation of an active refrigeration appliance is not indispensable to achieving comfort levels.

Focusing now on passive strategies, it can be concluded that the most suitable cost-optimal action to guarantee comfort throughout the year without needing the incorporation of a cooling system is m3 (injected thermal insulation with solar protection).

5.2.2. Active enhancement package. Optimal consumption reduction

The heating and hot water installation in schools located outside of high-density municipalities is typically composed of a gas oil boiler and single zone radiators. Implementing an energy-efficient improvement to this system through sectorization is challenging not only due to economic reasons, but also due to construction constraints. The proposed solution in this study is a more moderate approach that incorporates sectorization through individual valve adjustments for each radiator, slightly adapting the working surface temperature of each classroom according to its thermal demand. However, the main investment focuses on updating the current heat production system, which is an 11-year-old diesel oil boiler with 85% performance. In this package, the optimal solution (m3) from the passive improvement package is combined with the replacement of the existing diesel oil boiler by a 500 kW natural gas condensing boiler (m4) with 102% performance, and a 500 kW wood chip biomass boiler (m5) with 75% efficiency. The impact of these replacements on energy efficiency and the environment is evaluated.

The impact of artificial lighting on the final energy demand and consumption of the building was taken into consideration. This was done by analysing the electricity bills of the building, which revealed that the electricity consumption remained constant throughout the year, regardless of the daylight hours during different seasons. These measures can significantly reduce the electricity consumption associated with lighting while maintaining adequate lighting levels for students and staff. This intervention implies an environmental impact of 15kWh/m^2, on the other hand, it is a value that can be quickly compensated with the energy benefit of its use during the useful life of the building, being paid back in less than 3 years. It is important to note that these measures should be implemented in conjunction with energy efficiency measures for other systems, such as the heating and cooling system, to achieve significant energy savings and reduce the overall carbon footprint of the building.

The building has a linear lighting system with two fluorescent TLD 36 W, with twelve lamps for each classroom, and an installed power of 15.96 W/m^2 per space and a Regarding the consumption linked to this artificial lighting system (during the school's hours of occupation in those spaces without natural light), it is worth highlighting the need to update it for two reasons: firstly, to improve the performance of lamps and, secondly, to balance the level of lighting at comfort values avoiding over lighting of spaces. Replacement of the lighting system has been proposed based on cross-assessment of lighting performance at energy and light level (calculation made using Design Builder): comparing the current situation with TDL lamps and one with LED lamps in the classrooms. This alternative would have an installed power of 4.6 W/m^2 and a VEEI of 1.5 W/m^2 for 100lx. The position of the lamps would be redesigned in order to achieve an average illumination level of 300lx, instead of the 700-800lx reached in some areas of the classrooms. The financial investment of this measure would be 14,400€, an affordable value that can be assumed with the school's own resources (certain classrooms have already been updated due to the results of this research). Moreover, it has an impact not only on the electrical consumption of the building but also on the health and productivity of users (Mogas-Recalde and Palau, 2021; Yıldız et al., 2018; Monteoliva et al., 2016).

5.2.3. Renewable enhancement packages

This package offers two evaluations, which include considering the m3 case (passive deep retrofit) and adding a 40 kWp photovoltaic system directly, or considering the m4 case (passive and active deep retrofit) and an 11 kWp photovoltaic system. In both cases, the photovoltaic system is a self-consumption facility, which considers that 33% of the production coincides with non-school days such as weekends, holidays, and summer break. The performance of the polycrystalline surface cells considered is 360 Wp per cell located on the roof of the building with the guaranties that no shadows are cast. The electric consumption of the building would be 7.18 kWh/m^2y. Table 3 shows a comparison of the values obtained in each case.

6. Discussion

Deep retrofit presented in this article shows two facts: firstly, it is not only significant to minimize the total demand for a building in a Mediterranean climate, but also that it is more decisive to transversally evaluate the benefit or not throughout the year. Secondly, considering its impact not only on energy but also on the environment during its useful life. This issue is mainly associated with the refrigeration devices currently not present in schools linked to the Department of Education of the *Generalitat de Catalunya*, which expressly does not allow the installation of cooling systems in new construction buildings (and much less in existing buildings). Therefore, the research does not focus on solving global annual energy shortcomings but on minimizing the thermal discomfort, especially from mid-spring to mid-autumn and even some winter days, under the methodology framework for calculating cost-optimal levels of minimum energy performance requirements for buildings and building elements (Anon, 2012c). The analysis also includes life cycle assessment (LCA) evaluations considering stages A1-5 (product and construction stage), B1 use (use stage) and C1-4 (end-of-life stage) allowing to have a cradle to grave analysis and circular economy (EC) actions for interventions with higher economic costs in order to enhance their environmental suitability.

Furthermore, the analysis framework of this research is linked to the PAREER II program, which requires a two-letter improvement in the level of Spanish energy certification to qualify for economic incentives and ensure financial viability. Therefore, the interventions are not only justified from an absolute environmental impact perspective, but also from an economic perspective to obtain the necessary certification level.

6.1. Thermal loads and energy demand summary. Energy, economic and environmental comparison

The first energy benefit of applying the envelope improvement measures is that the thermal loads are considerably reduced. The fact of having fewer thermal loads makes it possible to opt for lower power equipment and therefore less environmental and space impact. As a result, the emitting elements (radiators) can work at lower surface temperatures, which favours the annual seasonal performance and the reduction of CO_2 emissions.

The implementation of passive measures to improve the thermal performance of the building envelope, including the reduction of thermal transmittance, elimination of thermal bridges, and control of infiltration related to windows and solar protection, results in significant energy benefits by reducing heating thermal loads. This can lead to a 30%–40% reduction in heating energy consumption during colder months (winter) and a 50%–60% reduction in intermediate months (spring and autumn) (Fig. 4). This reduction in energy consumption can also indirectly contribute to the extended lifespan of the facilities and reduce the impact of equipment obsolescence. In m3 case, the total energy demand value achieved was 53.61 kWh/m^2y, which is lower than the value required by CTE for new constructions (57.73 kWh/m^2y) and 35% lower than the original building's value (82.33 kWh/m^2y).

In all cases of passive energy improvements (m1, m2, and m3), the improvement of the thermal performance of the openings is considered. Strengthening existing windows with double windows in the U-shaped building results in an energy benefit of 5%, with an economic impact of less than €5000. Additionally, incorporating reused windows allows for direct circular economy strategies, resulting in an embodied carbon saving of 80.36 $KgCO_2$-eq/m^2 of window or 2.60 $KgCO_2$-eq/m^2 of impact per school's useful area. In absolute values, window reuse represents a saving of 41,936 $KgCO_2$-eq and a saving of 7965 kg in waste terms.

It is worth noting that m2 case (ETICS insulation) generates an energy benefit of 4% more in winter than m1 case (injected insulation), despite being implemented in only 60% of the total facade area of the U-shaped building and 100% in the gymnasium.

Table 3
Top summary of renewable energy source. Bottom summary of renewable enhancement packages.
Source: Self-elaboration.

m0. No renewable energy sources				m6 m3 + 40 kWp PV				m7 m4 + 11 kWp PV				
0 panels				Photovoltaic system 111 panels of polycrystalline surface 40 kWp installed 60,200 kWhy produced/generated 40,000 kWhy 66% self-consumption				Photovoltaic system 31 panels of polycrystalline surface 11 kWp installed 16,666 kWhy produced/generated 11,000 kWhy 66% self-consumption				
Months	01	02	03	04	05	06	07	08	09	10	11	12
Bill active energy (kW/h)	4,855	5,725	4,715	4,329	4,052	3,271	2,454	1,424	4,193	5,193	6,321	4,721
11 kWp Photovoltaic production (kW/h)	932	1,217.9	1,551	1,513	1,657	1,642	1,741	1,687	1,499	1,309	1,014	852

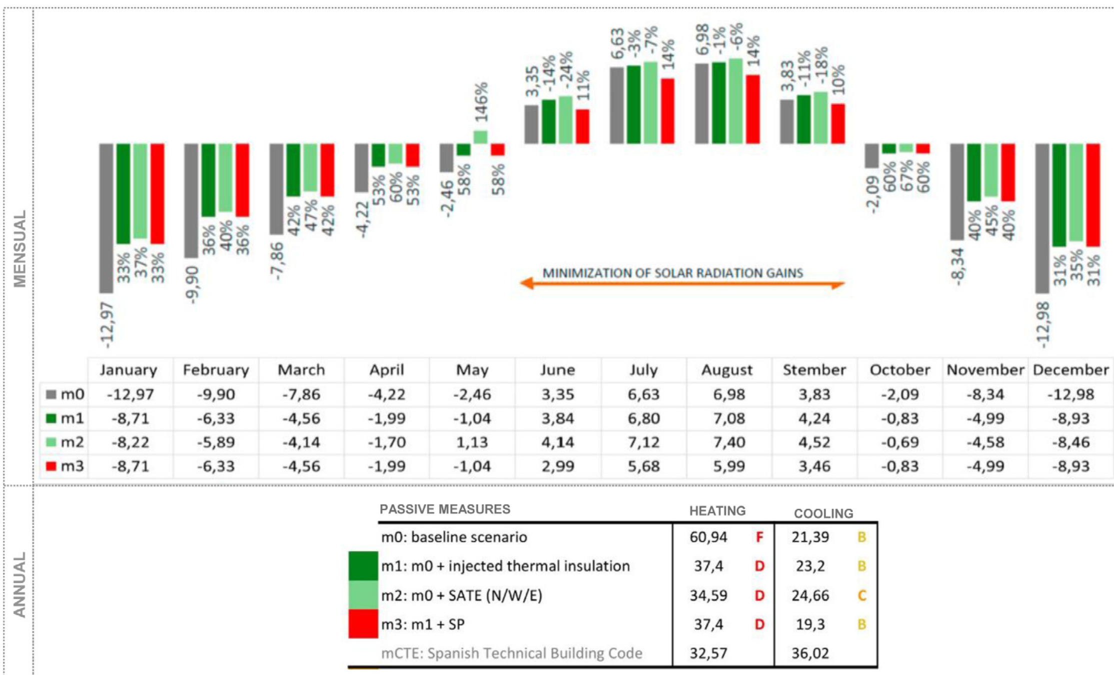

Fig. 4. Comparison of heating and cooling demands (kWh/m2y).

Another aspect to consider in the final energy demand result is that in the case of m2, the improvement of the building's energy classification is only one level, while for m1 it is two levels. This could lead to a worsening of the classification, making it impossible to access the subsidy from the PAREER II program. In terms of economic investment versus improvement actions at the envelope level, m2 case (ETICS) has the longest payback period due to the high investment needed. While it provides similar energy performance to m1 case, the economic investment is 77% higher and the payback period is five years longer.

The energy change that represents m3 action providing a 15% reduction of the cooling demand and also the new solar protection solution involves eliminating the current sunscreen model for another one that allows light capture but not solar radiation impact and at the same time contributes to minimizing the linear meters of thermal bridges linked to the blind box and the 9% of the energy impact linked to them. This new solar protection has a really low environmental impact compared to other measures and it represents a value of 0.48 $kgCO_2eq/m^2$ useful area.

From an economic perspective, the initial investment required for the renovation of sunscreens (m3 case) is considerable, accounting for almost 20% of the total investment cost of deep renovation, amounting to 391,213€ compared to 457,144€ for the entire renovation project. However, it has been deemed appropriate to include this solution as part of the improvement actions, given that it results in a payback period of only 2 years and contributes to a 15% reduction in cooling demand, allowing the building to avoid overheating. Regarding the idea of environmental amortization over the years, the impacts are incorporated throughout the life cycle, considering the annual emissions of m0 base scenario of 26.50 $KgCO_2/m^2$ year, and adding the impacts of phases (A1-5) and (C1-C4) for the different interventions (Fig. 5).

The calculation of the CO2.eq emissions associated with each of the materials of the Passive Enhancement Packages allows us to observe that despite the small variations between the m1, m3, m4, and m7 scenarios, they remain with very equivalent values. In the m2 scenario (ETICS) we see a significant increase in the environmental impact of the intervention of the order of 4 times, despite intervening in 13% or 640 m^2 less façade (1.91 $kgCO_2eq/m^2$ useful area of insufflating insulation vs 8.07 $kgCO_2eq/m^2$ useful area of ETICS)

It is worth noting that m3 scenario amortizes the impact during the first year of use of the building, while m2 scenario (ETICS) requires three years to offset the emissions produced during

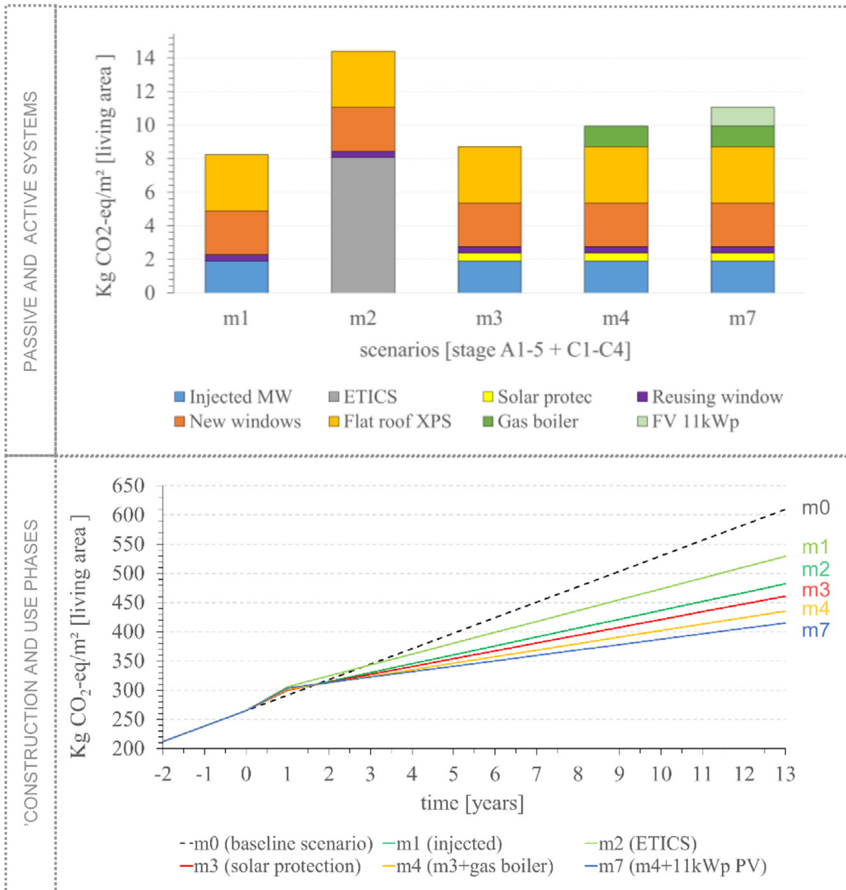

Fig. 5. Building life cycle carbon emissions.

phases (A1-5) and (C1-C4). The benefits of this solution can be observed in the electricity bill, which does not show a reduction in consumption throughout the year as it is mainly linked to lighting. It is important to note that PVC roll blinds not only block solar radiation, but also the visible spectrum and visuals, making the building dependent on artificial lighting systems.

If we add environmental impacts to these energy impacts, the decision to consider m1 as optimal versus m2 is even more reinforced. The environmental impact of the life cycle of materials in phases (A1-5) and (C1-C4) for m1 global intervention is 8.24 $KgCO_2/m^2$ useful area, compared to 14.40 $KgCO_2/m^2$ useful area for m2 intervention (ETICS system).

Sun protection measures considered in the research are mobile exterior sunscreens. HULC program does not allow for the establishment of a template for the use of sun protection measures on isolated days throughout the year. Therefore, it is not possible to observe the impact of avoiding overheating during certain hours of the day on intermediate months or very sunny winter days. For this study, we have only included the months between June and September, where the demand for heating is not influenced

The value of energy improvement has not been added to the benefit that will be provided by the schools' renovation of the artificial lighting system, which is estimated to be around 20%–25%. This is a necessary complement to minimize overheating hours even in summer months and avoid the need for a cooling system to compensate for excessive loads.

6.2. Energy consumption and CO_2 emissions. Annual summary

As other studies cited above show (Zinzi et al., 2016; Tahsildoost and Zomorodian, 2015), to achieve a deep energy retrofit scenario, it is not enough to work solely on the building envelope or facility systems, but passive and active measures must be implemented along with the incorporation of renewable energy sources.

The achievement of a total primary energy non-renewable value by simply implementing passive measures on the building envelope is positive, resulting in a 24% reduction. The reduction in heating primary energy non-renewable is even greater at 39%.

Considering the different scenarios for energy active actions (Table 4), the renewal of heating production system, the conclusions obtained concerning the value of non-renewable primary energy (PE non-RES) are:

- In m4 case, the implementation of a high-efficiency energy condensation boiler by natural gas reduces a 55% of the PE no-RES associated with heating energy consumption and 34% at the total consumption. However, this 15% of CO_2 emissions reduction is insufficient to improve energy certification by two levels regarding CO_2 emissions. Introducing a renewable energy source is required to achieve this improvement, as detailed in the following section. In terms of environmental impact, the implementation of a high-efficiency energy condensation boiler would represent 4231 $KgCO_2$ (EC).
- In m5 case, the implementation of a biomass boiler, despite its low energy efficiency, reduces the total consumption of PE no-RES almost to 60% and heating consumption at 98% as it works with renewable energy sources. This fact implies that energy certification improvement in more than two levels and also allows one to reach an A level. Also in this case, we should consider an environmental impact of 13,961 $kgCO_2$ (EC).

Table 4
Comparison of energy consumption and CO_2 emissions rating achieved in each case.

	Demand (kWh/m^2y)		PE $_{noRES}$ (kWh/m^2y)		CO_2 Emissions ($kgCO_2/m^2y$)		Energy qualify (letter)
	Heating	Cooling	Heating	Total	Heating	Total	
m0–baseline scenario	60.94 **F**	21.39 **B**	86.68	142.08	18.30	26.50	**D**
m3–injected + SP + diesel boiler	37.40 **D**	19.20 **B**	52.70	108.10	11.10	19.30	**C**
m4–m3+ gas boiler	37.40 **D**	19.17 **B**	38.78	94.18	8.20	16.40	**C**
m5–m3+ biomass	37.40 **D**	19.20 **B**	1.60	57.00	0.80	9.00	**A**

After this evaluation, there would be no doubt that the most optimal solution, environmentally speaking, is the implementation of biomass equipment. However, in the case of this particular school, this option has been dismissed due to the lack of nearby sustainable biomass exploitation, according the *Dept. de la Presidència, Dept. d'Economia i Coneixement, Dept. de Territori i Sostenibilitat, Dept. d'Agricultura, Ramaderia, Pesca, Alimentació i Medi Natural, Dept. d'Empresa i Ocupació* (Anon, 2023b). This would result in an increase in CO_2 emissions from transportation. Moreover, the school complex does not have sufficient space to install a biomass boiler and the required storage space.

To address the environmental impact, the results of phases (A1-5) and (C1-C4) in m1 and m3 scenarios m1 show very similar impact values, ranging from 8.24 $KgCO_2$-eq/m^2 (m1) to 8.72 $KgCO_2$-eq/m^2 (m3), in contrast to the added energy benefit that comes with the proposed renovation of sun protections scenario m3. On the other hand, m4 and m7 scenarios significantly increase their impact to 9.94 $KgCO_2$-eq/m^2 and 12.28 $KgCO_2$-eq/m^2, respectively, due to the incorporation of a natural gas boiler (m4) and a photovoltaic system (m7) (Fig. 5).

Based on the final energy improvement values for m1 case, it is obtained that for m4 solution heating energy saving is 10%, meaning a return of 11.5 years. For m5 solution, there is an energy increase of 4%, as it has been considered a lower biomass energy performance than the existing diesel boiler. However, the return is achieved in 14 years, since the price of fuel (splinter) is four times lower than that of diesel. This finding suggests that, for schools that have the potential to incorporate biomass, despite the initial cost, it is feasible to consider introducing a biomass system if the building allows for the necessary space. In the case of the deep energy retrofit study of the sample of the 8 high schools, the difficulty of adapting a space inside or near the building to incorporate a machine room with the technical and volumetric characteristics required by the biomass system was found.

6.3. Renewable energy production. CO2 emissions and letter of the energy certification

Discarding the use of biomass as energy production equipment makes it necessary to evaluate alternative systems that allow the new building to be provided with renewable energy and reduce CO_2 emissions to achieve a two-level improvement in energy certification, necessary to access PAREER financing. For educational centres in Catalonia, a reasonable option would be to consider a photovoltaic installation since electricity consumption is 45% of the total building consumption, and there is little demand for hot water due to the absence of showers and handwashing and cooling needs are not currently satisfied.

M6 scenario, which starts with m3 scenario (injected + solar protection) and includes a 40 kWp facility with 66% self-consumption (40,000 kWh/y) (Monteoliva et al., 2016), reduces lighting consumption by 58% and total CO_2 emissions by 21% (final value 13.3$KgCO_2/m^2$), which means for the LCA an increase of 141.247 kWh in terms of embodied energy (EE). However, the payback period is 27.5 years, a high value due to the continued impact of having a low-efficiency diesel boiler.

In m7 scenario, which starts with m4 (m3 + natural gas boiler) and includes an 11 kWp self-consumption facility with 66% total production, CO_2 emissions are reduced by 7%, and energy savings amount to 16% for lighting consumption and 9% for fuel consumption. The reduction of the solar collector surface significantly improves its environmental behaviour with a lower embodied energy, 38.843 kWh (EE). The payback period is more favourable in this case (13 years) as the cost of natural gas is 1.5 times less than that of diesel. In environmental terms, the 11 kWp photovoltaic installation is also amortized after a first year.

7. Conclusions

This study has allowed us to establish a pattern for deep energy rehabilitation, despite the singularity of architectural, construction, and maintenance characteristics of each building. Specifically, by applying this model to the *Ribera de Sió* high school, we were able to obtain specific data on the energy, environmental, and economic impacts of different technical options that could be considered for improving thermal transmittance. The following section details the most significant values resulting from this study.

At the passive improvement package level, the improvement of the thermal conductivity of the proposed façades hardly implies an energy differentiation between a thermal insulation solution in the air chamber of the entire building (m1) and a solution with external insulation in all facades except in the south (m2). The reduction in demand achieved is around 40% of the heating level. On the contrary, the performance of the building in summer is penalized by the increase in cooling demand of around 10% (8% in the injected system and 15% in the ETICS system). At the energy certification level, it represents a 40% reduction in CO_2 emissions and an improvement of one level. Finally, the profitability in both cases exceeds 20 years, somewhat lower than the profitability of the injected solution.

If we also consider the environmental impacts in phases A1-5 and C1-4, the proposed m2 solution (ETICS) does not provide sufficient performance to offset the impacts derived from its execution, while the m1 solution provides greater performance and 40% less impact. It is remarkable that no ambitious option may be the most optimal when it comes to existing school buildings in the Mediterranean area.

At the level of the active improvement package, the strategies to improve the energy efficiency of the facilities have focused on improving the heating system since there is no refrigeration equipment, there is no demand for domestic hot water and the lighting equipment is progressively improved by the school board out of the annual budgets. As only half of the CO_2 emissions produced are linked to the heating system, 26% reduction achieved by replacing the diesel boiler with a gas condensation boiler is not enough to reach another level in the total energy certification compared to the one obtained by improving the envelope conductivity. By contrast, replacing the boiler with biomass equipment improves the energy certification by reaching directly an A level, but it carries an environmental impact four times higher than the diesel boiler with a gas condensation boiler.

In both cases, the return periods are similar, slightly higher in the biomass solution (14 years) than in the natural gas condensation boiler (11.5 years). Once the energy improvement evaluation methodology (developed specifically to promote the replicability of deep renovation in Mediterranean schools) has been verified, the results can be applied to buildings of a similar size, volume, and construction characteristics for a Cfa climate zone according to Köppen–Geiger.

At renewable enhancement package level, if we want to improve two levels of the energy certification of CO_2 emissions, without incorporating biomass equipment, the use of renewable energies will need to be reinforced. In the case of Catalan high schools, where there is no real consumption of sanitary hot water, the most reasonable option is to introduce a photovoltaic system that provides electricity, not only for energy reasons but also in terms of environmental balance. We see how the incorporation of photovoltaic systems, despite seeing the initial impact increase, quickly the impacts generated in phases A1-5 and C1-4 are quickly compensated in the phases of use, resulting in environmental terms the proposal of best overall behaviour throughout its life In this sense, it has been observed that the energy certification of the building can be improved by two levels considering a 40.000 kWh/y self-consumption without replacing the existing boiler or considering only an 11.000 kWh/y self-consumption and replacing the existing boiler. This latter option fits better to the nZEB definition as a cost-optimal solution that balances a reduction in energy certification and also a reduction in terms of primary non-renewable energy source, being amortized in 13 years.

Finally, it is worth mentioning that the intervention in the solar protection systems in schools is a fundamental topic for compensating for the increased demand for cooling resulting from minimizing the demand for heating. This ensures that the hours of overheating in the building do not become problematic for its use without active cooling systems and the environmental impact generated by these simple measures is significantly low.

CRediT authorship contribution statement

Eva Crespo Sánchez: Term, Conceptualization, Methodology, Validation, Review, Editing, Supervision, Formal analysis, Investigation, Data curation, Software, Writing. **Còssima Cornadó Bardón:** Term, Conceptualization, Methodology, Validation, Review, Editing, Supervision, Formal analysis, Investigation, Data curation, Software, Writing. **Oriol Paris Viviana:** Formal analysis, Investigation, Data curation, Software, Writing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eva Crespo Sanchez reports financial support was provided by Generalitat of Catalonia Department of Education.

Data availability

Data will be made available on request.

Acknowledgements

Authors wishing to acknowledge the Departament d'Ensenyament of the Generalitat de Catalunya for their collaboration and encouragement to promote case studies in the field of the new energy models for school buildings, as a consequence of the established link in the European project ZEMedS–Promoting renovation of schools in a Mediterranean climate up to nearly zero-energy buildings (IEE/12/711/SI2.644.745).

Funding

Funded by Departament d'Ensenyament de la Generalitat de Catalunya.

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