Solutions for Improving the Energy Efficiency of Buildings Refurbishment

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Abstract. The buildings sector contributes to 30% of annual greenhouse gas emissions and uses about 40% of energy. In this scenario and regarding the sustainable concerns, different strategies and directives have been developed. However, this consumption can be reduced by between 30% and 80% through commercially available technologies.

A critical and evolutionary way of thinking about the energy (and other resources) demand, management, and supply is necessary, because there is a clear concern about irreversible impacts to the world and a scarcity of the resources as well. Energy supplies should be mostly or entirely through renewable resources and highly efficient technologies put in place to achieve solution such as nearly Zero Energy Buildings (nZEB). The strategies and the rehabilitation benefits are more and more recognised, used and increasingly considered by the stockholders. So, the aim of this article is to: critical analyse the state-of-art regarding this matter; discuss the existing solutions, directives, and strategies; and present a case study where the energy performance and the economic viability are discussed. The case study is a Portuguese building model which represents the conventional construction between 1960 and 1990. On it, three scenarios of refurbishment were tested, and their benefits and costs are presented.

Keywords: Energy efficiency · nZEB · Building rehabilitation · Building retrofit

1 Introduction

The connection between climate change and carbon emissions is impossible to decouple, since emissions are strongly linked to energy production and use. Measures are therefore being taken to reduce energy use, promote energy efficiency and increase the use of renewable energy. Improving the energy performance of buildings is one of the most economically viable measures to achieve European climate change objectives and to stimulate sustainable growth [1]. This not only leads to environmental benefits, but also promotes important social and economic benefits by reducing energy poverty, improving thermal comfort and indoor air quality, improving health and productivity, creating jobs, and promoting finance [2].

Buildings are responsible for about 40% of the total energy use in the European Union (EU) and for 36% of total CO_2 emissions. Furthermore, it is inside buildings

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that people spend 90% of their life [3]. It is estimated that in the EU, Switzerland and Norway, there are about 25 billion square meters of constructed floor space. So, if the entire constructed area were to be concentrated, the occupied land would be equivalent to the territorial area of Belgium – 30,528 km^2 [4]. On the other hand, it is known that 75% to 90% of the existing building will still be in use by 2050. Much of it was built before 1990 (before EU legislation) and is considered energetically inefficient. So, it is necessary to increase the energy rehabilitation rate by at least 3% to achieve the objectives of the Paris Agreement and the European Energy Efficiency Directive [5].

1.1 Methodology and Objectives

This paper intends to present a critical analysis of the state of the art, discussing existing solutions, directives, and strategies with the aim of improving the energy efficiency of the existing building and presenting a case study about its economic viability. For this, a review of the most relevant literature on the subject, namely the EU directives and concepts defined by them, was carried out. Finally, five rehabilitation scenarios and their economic viability were tested in a case study of a conventional building model of a Portuguese building between the 1960s and 1990s.

2 Strategies and Directives for Improving Energy Efficiency

Considering the need to reduce energy consumption and improve its efficiency, the European Union released the Directive 2002/91/EC, known as EPBD - Energy Performance of Buildings Directive, which has since been reformulate by Directive 2010/31/EU, recognised as EPBD-recast, and amended by Directive (EU) 2018/844.

2.1 Directive of Energy Performance of Buildings

The Directive 2002/91/EC, approved in December of 2002, aimed to promote the improvement of the energy performance of buildings in the EU by means of economic feasibility, considering the climate and the local conditions of each member state (MS). The purpose was to increase the energy efficiency of building and thereby improve their quality (new buildings or renovated), reduce the external energy dependency, decrease the emission of greenhouse gas (GHG) and increase the population awareness and information. The EPBD imposed the energy certification system to demonstrate their performance level, through an integrated calculation method. This method should account for thermal characteristics of the building, heating and cooling systems, domestic hot water (DHW) preparation, ventilation, lighting, or passive solar systems, among others. The EPBD imposed also minimum requirements for the energy performance of new buildings and subject to major renovation works, and the need to regularly inspect boilers and air-conditioning systems and the heating system at each 15 years [6].

This directive implementation had some obstacles such as the MS diversity of the built environment and the low ambitions in some. The low renovation rate was also responsible for aggravating compliance with the objectives, as well as the lack of credibility of some energy certificates and the of the obligation to report the national implementation results.

In 2010, the EPBD was reformulated by the Directive 2010/31/EU (EPBD-recast). This new directive intended to: (i) reduce the CO_2 emissions to mitigate the climate change and, (ii) promote the development of sustainable and energy efficient solutions. Therefore, the following goals were established until 2020: (i) 20% reduction in energy, (ii) 20% reduction in CO_2 emissions and, (iii) 20% increase in use of renewable energy.

This requires the MS to establish minimum energy requirements considering cost-optimal levels and to revise their energy standards in building regulations, at regular intervals, which shall not be longer than five years. The EPBD-recast also established the concept of nZEB – nearly zero energy buildings – for new buildings from 2019 (public sector) and 2021 (all new buildings). The cost-optimal levels of the minimum energy performance requirements mean the energy performance level which leads to the lowest cost during the estimated economic lifecycle, see Fig. 1 [7].

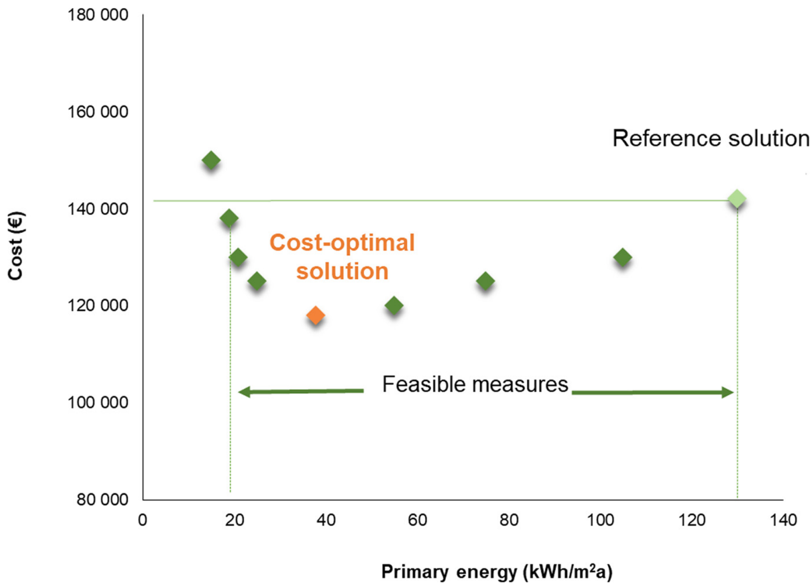

Fig. 1. Cost-optimal concept representation.

As a result of the reduction of the minimum energy requirements, the maximum allowed values, as for instance, the thermal transmission coefficient (U – W/m^2 °C), were lowered regarding the requirements imposed by Directive 2002/91/EC. In Portugal, the U-value for external walls decreased from 1.4 W/m^2 °C to 0.4 W/m^2 °C and from 0.9 W/m^2 °C to 0.35 W/m^2 °C for roofs.

All MS were compelled to implement national plans for energy efficiency or policies with alternative measures that enable reducing the final energy. The decrease of energy consumption after the implementation of EPBD and EPBD-recast can be seen in Fig. 2.

The mean annual final energy consumed which decreased 2.1 kWh/(m^2·year) until 2006, is now decreasing at higher rate of 3.8 kWh/(m^2·year).

Recently, Directive 2018/844 of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency was published. The main goal of this new directive is to increase the average renovation rate in a cost-effective manner, i.e., (i) introduce building automation and control as an alternative to physical inspections; (ii) encourage the implementation of efficient mobility infrastructures and, (iii) introduce a smart readiness indicator to measure the technologic capacity of buildings. Thus, the following amends can be highlighted [5]:

- Insertion of new definitions as “building automation and control system”;
- Implementation, until 2050, of a long-term renovation strategy to support the renovation of the building stock, into a highly energy efficient and decarbonised one;
- Convene the Commission to the implement of an optional common Union scheme for rating the smart readiness of buildings;
- Establishment of regular inspections of heating systems or of systems for combined space heating and ventilation, with an effective rated output of over 7 kW;
- Determination of the primary energy use in kWh/(m^2·year) as a numeric indicator to express the energy performance of a building for the purpose of both energy performance certification and compliance with minimum energy performance requirements.

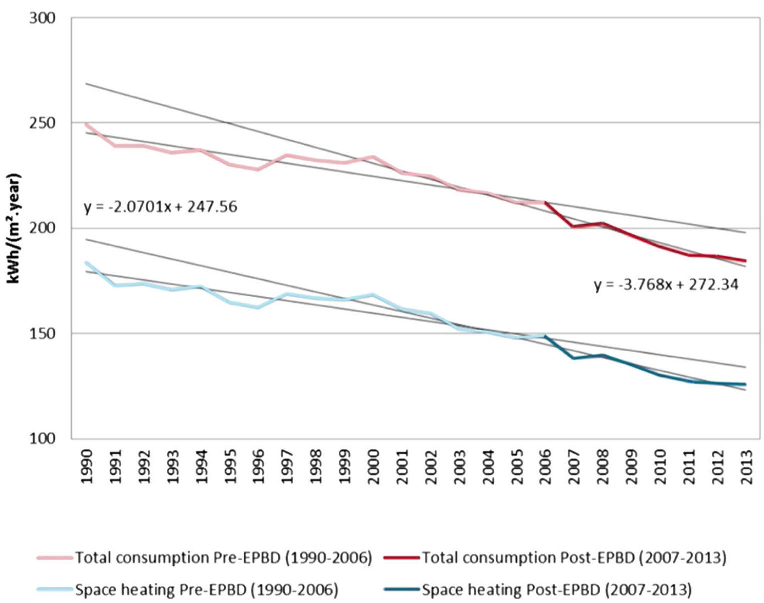

Fig. 2. Energy use evolution in the residential sector, the EU between 1990 and 2013 [8].

2.2 nZEB – nearly Zero Energy Buildings

The nZEB concept arose with the EPBD-recast. This concept refers to buildings that have a very high energy performance (Directive 2010/31/EU, 2010). According to the Directive definition the amount of energy required should be "nearly zero or very low" and "should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". Nevertheless, none precise definition was established, and each MS should draw up their definition, considering the following:

- Period – time rate used for the energy balance (annual, monthly, and weekly);
- Boundary – on-site and nearby system boundary (building, site, neighbourhood, …);
- Weighting system – which weighting factors to consider in the energy balance, dynamic or static;
- Energy flow – which use to consider (heating, cooling, lighting, DHW supply, …).

Therefore, it is of major importance to establish a holistic nZEB approach, considering not just the reduction of energy use in the building through solar passive design measures, but also satisfying the remaining needs with energy from renewable sources (Fig. 3).

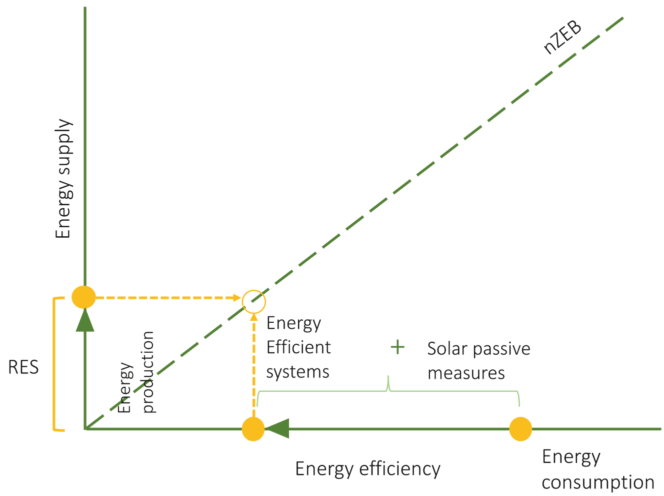

Fig. 3. nZEB holist approach.

3 Existing Buildings and Rehabilitation

It is essential to stimulate and promote the rehabilitation of the existing residential buildings, considering the European objectives already presented. Non-residential buildings, on the other hand, account for about 25% of the European built constructions, which is a more heterogeneous sector and therefore more complex than the residential sector. Additionally, according to an analysis of energy efficiency certificates in Europe, about 97.5% of the building constructions should be improved so that it could be made up of highly efficient buildings, and thus the objective of decarbonisation until 2050 will be reached [4].

3.1 Directive of Energy Performance of Buildings

The concept of rehabilitation is defined as an intervention, more or less extensive, necessary to do in a building or property, aiming to increase its useful and service life, its economic value, the quality of life of the inhabitants and the implementation of good practices of energy efficiency [9]. In this way, the thermal and energy rehabilitation of buildings is imperative as it allows correcting of other existing anomalies in buildings, as well as facilitating the compliance with the existing directives and the reduction of the energy needs, thus reducing the use of energy and emissions of GHG [10]. Therefore, rehabilitation allows implementing measures of energy efficiency and sustainability, providing the increase of thermal and acoustic comfort, and indoor air quality.

The thermal and energy rehabilitation of a building can act on several fronts, such as:

- The opaque building envelope - through the introduction of thermal insulation for correction of thermal bridges and reduction of heat losses;
- The non-opaque building envelope - by improving the type of glass used in the spans, the frame and the material that constitutes it;
- Passive solar systems - through, for example of the orientation and design of the spans, promoting natural ventilation and heat collection systems. These systems can be divided into passive direct, indirect, and isolated gain heating systems and passive cooling systems by natural ventilation, soil cooling, evaporative and radiative;
- Active systems - through, for example, solar systems such as photovoltaic panels or solar thermal collectors. These systems transform energy from renewable sources into energy for use.

4 Energy Rehabilitation of Residential Buildings

Nowadays, around 35% of the European building stock has more than 50 years [5]. An analysis to the energy certificates performed by BPIE (Buildings Performance Institute Europe) has concluded that around 97.5% of the building stock presents a label lower than class A [2]. However, the percentage of buildings being rehabilitated annually in Europe is low, ranging from 0.4 to 1.2% [2]. Thus, the rehabilitation of the building stock has a high energy saving potential. This section presents a discussion on the energy and economic performance of different energy rehabilitation scenarios, through a case study.

4.1 Methodology for Energy and Economic Performance

The energy performance of the case study building was assessed through a dynamic simulation using the *EnergyPlus* software [11], which reliability has been amply demonstrated [12]. To perform such simulations the energy balance method CTF (Conduction Transfer Functions) [11] was used. The CTF method allows to perform dynamic simulations with the necessary precision concerning current building solutions [13]. A life cycle approach of 30 years was considered both in energy and economic performance.

The economic performance was assessed using the methodology proposed by delegated regulation nº 244/2012 of January 16th [14], as presented on Eq. 1.

$$C_g(\tau) = C_I + \sum_j \left[\sum_{i=1}^{\tau} \left(C_{a,i_{(j)}} \times R_d(i) - V_{f,\tau}(j)\right)\right] \quad (1)$$

Where:
T: Calculation period
Cg (T): Global cost across calculation period
CI: Initial investment for measure j
Ca,I (j): Annual cost across year i for measure j
Rd (i): Annual cost across year i for measure i
Vf,T (j): Residual value of measure j in the end of the calculation period

A discount rate of 3% and an evolution of the energy costs were considered [7]. For the period between 2013 and 2030 the energy costs used were based on the EU predictions [15]. For the period between 2030 and 2046 the costs predicted in the Energy Roadmap 2050 [16] were considered. Finally, the investment costs were obtained through the CYPE price generator [17].

4.2 Case Study Building

A typical Portuguese single-family building model was used as case study building (Fig. 4). The building was considered to be located in Lisbon at an altitude of 71 m and have the following: (i) two bedrooms; (ii) a total built area of 110 m^2; (iii) an unventilated attic between the living area and the roof, (iv) an air conditioning through mobile heating and cooling systems (COP = 1; SREE = 3.5); (v) no mechanical ventilation system, thus being only naturally ventilated; (vi) three inhabitants being in there from 7 pm to 8 am in week days and all day during the weekends.

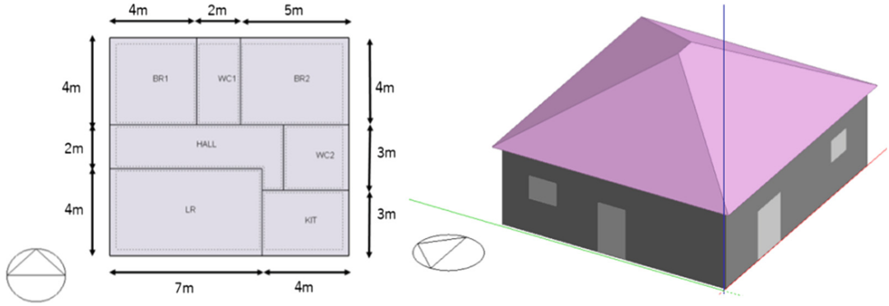

Fig. 4. Outline of the case study.

Table 1 presents the case study building solutions. These solutions were defined considering the most common building solutions used between 1960 and 1990 (period to which most of the existing buildings in the country belong) in Portugal [19].

Table 1. Case study building solutions.

Building element	Construction solutions	U (W/m^2 °C)
Walls	Single masonry wall with 22 cm with 2 cm of plaster both sides	1.8
Superior slab	Lightweight slab	2.8
Roof	Pitched roof with lightweight slab	3.0
Ground floor	Concrete slab covered with ceramic tile	1.7
Glazing	Single glazing (6 mm) and wooden frame	4.1

The thermal comfort temperatures recommended by the Portuguese thermal regulation [18] – 18 °C for the heating season and 25 °C for the cooling season – were considered for the analysis. The ventilation was assessed trough dynamic simulation using the *EnergyPlus AirFlowNetwork* module [11].

4.3 Rehabilitation Scenarios

Five rehabilitation scenarios were analysed (Table 2). In Scenario 1 only passive measures were considered. In Scenario 2, beyond the passive measures, more efficient building systems were defined. In Scenario 3 the measures from Scenario 1 were combined with a heat pump. Scenario 4 and 5 are the combination between Scenario 2 and 3 with a self-consumption photovoltaic kit.

Table 2. Case study building solutions.

Scenario	Description
Scenario 1	Application of 12 cm of thermal insulation (expanded polystyrene) on the externa walls (U = 0.24 W/m^2 °C) and on the superior slab (U = 0.27 W/m^2 °C), and substitution of the glazing systems for double glazing with aluminium frame (U = 2.8 W/m^2 °C)
Scenario 2	Passive measure of Scenario 1 and substitution of building acclimatization equipment for an air conditioning system (COP = 4.12; SREE = 8.53) for heating and cooling and of the DHW system by a gas condensing heater (COP = 0.97)
Scenario 3	Passive measure of Scenario 1 and substitution of building acclimatization equipment for a heat pump for heating, cooling and DHW preparation
Scenario 4	Measures from Scenario 2 with the addition of a self-consumption photovoltaic kit with a production of 1,500 W (Eren = 2,290 kWh·year)
Scenario 5	Measures from Scenario 3 with the addition of a self-consumption photovoltaic kit with a production of 1,500 W (Eren = 2,290 kWh·year)

4.4 Results

Figure 5 presents the energy consumptions obtained in each rehabilitation scenario.

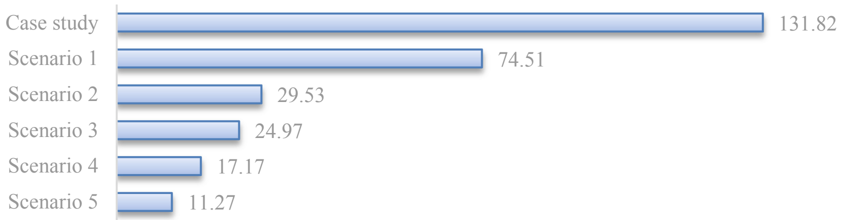

Fig. 5. Energy consumption for each rehabilitation scenario (khW/m^2·year).

It is worth to mention that the simple adoption of passive measures leads to a decrease of around 44% of the building energy consumption. These passive measures combined with more efficient but conventional building systems allow decreasing the energy consumption in 76%, approximately. The adoption of a heat pump, which is a more efficient but usually also a more expensive equipment, allows a better energy performance. However, the benefits of this system may not be sufficiently appealing to convince the user to adopt it [20]. The combination of Scenarios 2 and 3, with renewable energy production systems lead to an 87% decrease in the building energy consumption in Scenario 4 and in 91% in Scenario 5.

Table 3 presents the economic analysis regarding the implementation of the five scenarios.

Table 3. Case study building solutions.

Scenario	Initial cost (€)	Operational cost (€)	Life cycle cost (€)	Annual savings (€/year)	Payback time (years)
Ref. scenario	0	35,571.00	40,062.00	0.00	0.00
Scenario 1	9,823.00	24,692.00	36,325.00	363.00	27.00
Scenario 2	13,424.00	20,318.00	35,660.00	508.00	26.00
Scenario 3	17,171.00	24,689.00	44,415.00	363.00	47.00
Scenario 4	15,898.00	17,101.00	32,444.00	616.00	26.00
Scenario 5	19,645.00	21,472.00	41,198.00	470.00	42.00

According to the results, the payback time is too long in all five rehabilitation scenarios. Nevertheless, the scenarios with the best payback time are Scenario 2 and 4, corresponding to the adoption of passive measures, an air conditioning system, and a gas condensing heater (DHW preparation), without and with renewable energy production systems, respectively. The scenarios using a heat pump have twice the payback time than the other options. It was also noticed that regarding the payback time, the scenario based only in passive measures (Scenario 1) presents a very similar performance to the scenarios that combine such measures with more efficient energy systems (Scenario 2 and Scenario 4).

The results show that the initial cost has a very significant influence on the economic analysis of residential buildings rehabilitation measures [20]. Even in scenarios with relevant annual savings, the initial cost of the solutions makes the payback only possible in the last years of the life cycle.

5 Conclusions

Five energy rehabilitation scenarios were analysed, focusing on their energy and economic performance. This study corroborated the importance of economic analysis of rehabilitation scenarios in residential building. Here, it allowed to understand that the adoption of a heat pump may not be an interesting solution, as cheaper systems lead to a similar energy performance. However, the adoption of energy rehabilitation scenarios in residential buildings should not be seen as a way of obtaining a return of the investment. Instead, it should be a way to increase the building comfort and quality, and to decrease the building's environmental impact by using the smallest investment possible.

The energy performance of buildings in the EU is not in the overwhelming majority of cases, efficient. Its potential for improvement is significant, which can be reflected in high savings and thus, have significant contribution to a more sustainable future. In this sense, the implementation of Directive 2002/91/EC has led to a representative change in the energy dimension of buildings throughout Europe. Buildings became more energetically efficient and the population more sensitive and informed about these issues.

However, energy savings were below expectations (42%), since not all countries were able to implement the requirements entirety.

With the implementation of the EPBD-recast, in 2014, an additional 48.9 Mtoe of final energy reduction was achieved, compared to the base value of 2007, being in line with that forecast for 2020–60 to 80 Mtoe reduction of final energy [8]. Thus, with the new Directive (EU) 2018/844 reinforcements are made to the previous EPBD-recast and new targets imposed. In turn, the cost-optimal approach reveals an incentive to energy efficiency and the promotion of nZEB. However, more energy efficiency measures need to be disseminated as well as more incentive to rehabilitate.

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