Cost Optimality and nZEB target in building renovation of Portuguese residential buildings

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Abstract

Promoting the improvement of the overall energy performance of buildings is a relevant part of the European climate action and the Roadmap for moving towards a competitive low carbon economy in 2050, with an expectation of reducing greenhouse gas (GHG) emissions by around 90% when compared to 1990 values, in the area of the built environment.

The recast of the European Energy Performance of Buildings Directive (EPBD) introduced the goal of nearly zero-energy buildings (nZEB) for all new buildings from January 1st, 2021 and plans should be drawn to stimulate the transformation of existing buildings that are refurbished into the same concept. EPBD also requires that all European Member States must ensure that the minimum energy performance requirements for buildings are set to achieve optimal levels, i.e. the energy performance levels that lead to the minimum cost during the life cycle.

Therefore, Cost Optimality and nZEB are two fundamental concepts within the current European Union policy related to the energy performance of buildings and consequently related to climate change mitigation and non-renewable resources consumption, with Cost Optimality mainly focused on costs and nZEB focused on low energy consumption levels and on site renewables harvesting.

In this context, this paper, using two characteristic buildings of the Portuguese residential building stock, aims at presenting the results that emerged from the analysis and identification of the most cost-effective packages of renovation measures needed to adapt existing buildings to zero energy balance and comparing them with those resulting from the calculation of cost-optimal levels.The investigation of the trade-offs between a renovation towards zero energy balance and a cost optimal renovation without energy use restrictions is relevant to provide clues to the development of national plans for increasing the number of nZEB and to provide appropriate financing and other instruments to catalyze this transformation.

Keywords: Nearly Zero-Energy Buildings, Building Renovation, Energy Efficiency, Cost Optimality

1. Introduction

The reduction of the greenhouse gas emissions, as predicted in the Kyoto protocol, has become an important target for the European Commission. Therefore, policies have been created to make sure that EU Member States make their best to gradually achieve the values established by the protocol [1].

The greenhouse gas emissions have different origins, such as the industry, transports, buildings, agriculture, among other, but the building sector is responsible for 40% of the energy consumption and 32% of the greenhouse gas emissions in Europe [2]. These numbers make buildings an important target in what concerns the reduction of greenhouse gas emissions [3].

In Portugal, the building sector is the third largest consumer of energy [4], therefore, the improvement of energy performance and the reduction of energy consumption in buildings is an important step to the reduction of greenhouse gas emissions that contribute to climate changes [5], [6].

In an effort to fight against this problem, the recast of Energy Performance of Buildings Directive (EPBD) [7] introduced the concept of Nearly-Zero Buildings (nZEB) implying, after the end of 2020 and for new buildings, very high energy performances and low energy needs that must be suppressed by renewable energy sources harvested on-site [8]. Despite these efforts, the European Union will only achieve its goals if also intervene in the existing buildings, once the rate of replacement of these buildings is very low [6].

The EPBD recast also requires that buildings have to be cost-effective during their life cycle and establishes a methodology for cost-optimal calculations. Improving the energy performance of buildings should take into consideration not only the improvement of users' comfort and energy performance, but also the costs associated with them throughout the life cycle of the building [2]. In this context, the limits established by the regulations for the energy needs, for the efficiency of the equipment used and for the performance of each building element, should be set with a view to achieving the cost-optimal balance between the investments and the savings achieved by implementing energy saving measures throughout the entire life cycle of the buildings [7]. These limits should be defined based on the cost optimal levels for buildings and their components, being the cost optimal level the energy performance corresponding to the lowest cost during the life cycle, considering the costs of investment, maintenance and use [3], [9]. This methodology is intended to guide member states in the process of establishing minimum energy requirements for buildings and buildings components [2], [8].

Therefore, Cost Optimality and nearly Zero Energy Buildings (nZEB) are two fundamental concepts within the current European Union policy related to the energy performance of buildings and consequently related to climate change mitigation and non-renewable resources consumption. While Cost Optimality is mainly focused on costs, nZEB are focused on low energy consumption levels and on site renewables harvesting.

If the differences between Cost Optimality and nZEB approaches result in major differences in the selection of the best package of renovation measures, the transition from the Cost Optimal concept to nZEB might result incompatible.

In this context, this paper aims at presenting the results that emerged from the analysis and identification of the most cost-effective packages of renovation measures needed to adapt existing buildings to zero energy balance and comparing them with those resulting from the calculation of cost-optimal levels. The zero energy balance means that the building only uses energy from renewable sources or, if using non-renewable energy, it also harvests on-site energy from renewable sources equivalent to the non-renewable energy used. This study uses typical single and multifamily buildings representative of the Portuguese housing stock built at the time (in the nineties for the multifamily building) or before (in the seventies for the single-family building) the entrance into force of the first thermal regulation. Investigation of the trade-offs between a renovation towards zero energy balance and a cost optimal renovation without energy use restrictions is relevant to achieve a smooth transition from Cost Optimal levels to nearly Zero Energy Buildings.

2. Methodology

The cost-optimal calculations are based on the cost-optimal methodology introduced by the European Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012, supplementing the Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings [3], [9]. The methodology basically consists in the evaluation of different renovation packages considering the calculated energy use and overall costs. The solution with the lowest overall costs indicates the cost optimal level. Graphically, as can be seen in Figure 1, this relationship between the overall costs and primary energy use of each renovation package corresponds to a point. In the analysis of several renovation packages it is possible to obtain a curve in which the lowest point corresponds to the cost optimal level, as shown in Figure 1.

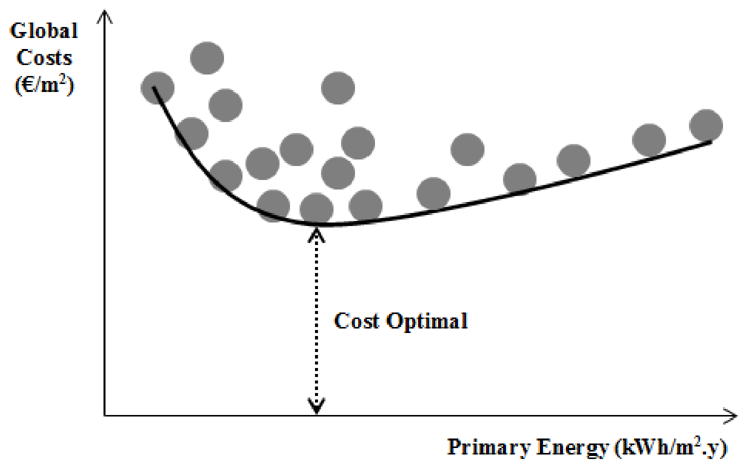

Figure 1. Cost optimal solution identification

For the application of the methodology, two representative buildings of the Portuguese housing stock were selected, and for each of these buildings measures for the improvement of the building envelope were analyzed (walls, roof, floor and glazing) and also the use of different heating, cooling, and domestic hot water preparation equipment. The calculation of the energy needs for heating, cooling and domestic hot water preparation was based on the Portuguese regulation for the thermal performance of buildings [10], in accordance with ISO-13790. The use of primary energy was calculated considering the total energy needs with conversion factors of $2{,}5kWh_{EP}/(m^2.y)$ per $kWh/(m^2.y)$ for electricity and $1kWh_{EP}/(m^2.y)$ per $kWh/(m^2.y)$ for gas. The indoor comfort temperatures considered were 20ºC for winter and 25ºC for summer.

To calculate the total cost for each of the renovation packages, the respective investment costs, maintenance costs and costs related to the calculated energy use were considered. The costs of renovation and maintenance measures were calculated based on CYPE® software (http://www.geradordeprecos.info/). The CO^2 emissions prices, as well as the evolution of energy prices were calculated based on the European Union forecasts (http://ec.europa.eu/energy/observatory/trends _2030/index_en.htm). The 2010 scenario of the International Energy Agency (http://www.worldenergyoutlook.org/publications/weo-2010/) was used to define the price of natural gas.

The contribution of the photovoltaic panels for reaching the zero energy level has been calculated using the Photovoltaic Geographical Information System (PVGIS) from European Commission (http://re.jrc.ec.europa.eu/pvgis/).

The analysis of cost effectiveness and the cost optimal level may be done under different perspectives, currently distinguishing between social or macroeconomic perspective and private or microeconomic perspective, both serving different purposes. In the social perspective, societal concerns are considered, notably those related to the effects of the consumption of fossil energy on environment health and in the elimination of non-renewable resources, while in the private perspective, only financial aspects are considered. Thus, in the social perspective, costs of CO^2 emissions are included and taxes and subsidies are excluded, while in the private perspective all fees and allowances applicable to the investment are considered and the costs of emissions are not considered [3], [9]. In the present study both perspectives are analyzed, considering, for the evaluation of the overall costs, a discount rate of 6% in the private perspective and a discount rate of 3% in the social perspective.

3. Case studies

To demonstrate the applicability of the methodology for determining the cost optimal levels, two case studies were used, whose description is presented below. The tested renovation measures are described, and the cost optimal levels, as well as the packages of renovation measures that allow obtaining a zero energy balance building with the lowest global costs, are presented and analyzed. The results of the sensitivity analysis performed regarding the changes in energy prices and discount rates throughout the life cycle of the building, are also presented.

3.1. Buildings characterization

The first case study is a single-family house that corresponds to the dominant typology of residential buildings in Portugal. It is located in the northern part of the country, in the city of Braga and was built in the 70's. This is a semi-detached building with four bedrooms, with a floor area of $157m^2$ on two floors with a ceiling height of 2.5m and with a non-heated basement. It features a reinforced concrete structure with lightweight slabs, non-heated attic under a lightweight roof slab covered with ceramic tiles, double hollow brick exterior walls with air cavity, windows with wooden frames and single glazing with exterior blinds in polyvinyl chloride (PVC) and with the box of blinds built inside the wall. The basement is partly above ground level and the facades are oriented northwest (opaque envelope with $38.18m^2$ and glazed envelope with $10.69m^2$), southeast (opaque envelope with $37.25m^2$ and glazed envelope with $8.59m^2$) and southwest (opaque envelope with $60,66m^2$ and glazed envelope with $6.70m^2$). This building has no insulation in the building envelope. The energy needs for heating, cooling and domestic hot water preparation amounts to $198kWh/(m^2.year)$.

The second case study is a multifamily building with two apartments per floor, also characteristic of the Portuguese housing stock. It is located in the north of the country, in the district of Porto and was built in the early 90's, just after the entrance into force of the first thermal regulation in Portugal. This building has five residential floors with a heated area of $673m^2$, with 2 apartments (one with two bedrooms and one with three bedrooms) per floor and a basement for garage partly above ground level. A lightweight slab covered with corrugated metallic plates composes the roof and the exterior walls are double brick walls with air gap without insulation. The windows are single glazed with aluminium frames and have PVC blinds on the outside. The three facades of the building are oriented northeast, southeast and southwest in a total area of 378m^2, of which 37.5m^2 northeast, 6.6m^2 southwest and 22.5m^2 southeast are glazed. The Portuguese thermal regulation predicts the calculation of the energy needs for each dwelling instead of the whole building. Therefore, in order to reduce the number of calculations, the energy needs used for the cost-optimal analysis were a weighted average of the energy needs of the ten apartments of this building. This way, the energy needs for heating, cooling and domestic hot water preparation considered in this study were 128kWh/(m^2.year).

3.2. Renovation measures

In both case studies, the tested renovation measures are common measures in the Portuguese market. These include improving the building envelope, with the introduction of insulation on the walls through the application of External Thermal Insulation Composite Systems (ETICS) with expanded polystyrene (EPS) and polyisocyanurate (PIR) and application of rigid extruded polystyrene foam (XPS) on the ceiling of the basement and on the roof, improving window frames and glass and replacing the heating, cooling and hot water preparation equipment. On the facades, the thicknesses of EPS considered for the ETICS system were: 30, 40, 50, 80, 100 and 120mm. The thicknesses of PIR considered were 40 and 50mm. For the roof and floor, XPS and PIR insulation were tested for the same thicknesses considered on the facade. Regarding window frames, renovation measures tested were aluminium window frames with double glazing and PVC window frames with double glazing.

The heating systems tested were electrical resistance with 100% yield, natural gas boiler with 93% yield and heat pump with a coefficient of performance (COP) of 3.33, with these last two devices also being used for domestic hot water preparation. For cooling, the systems analyzed were air conditioning with energy efficiency ratio (EER) of 3.50 and a heat pump with EER of 2.68. In addition to the equipment with dual function (heating and domestic water preparation), it was also analyzed, in the multifamily building, a gas water heater with 84% efficiency for the preparation of domestic hot water. For renewable energy harvesting, photovoltaic solar panels were tested.

3.3. Cost Optimal levels

Each analyzed package of renovation measures consists of a combination of measures related to both building envelope improvement and heating, cooling and domestic hot water preparation systems upgrading. Each combination of measures gives a building renovation variant. The cost optimal levels are expressed in Figures 2 and 3, wherein each group of variants with a different colour corresponds to one of the systems analyzed. Each figure contains two types of markers for the same variant that correspond to the private perspective and the social perspectives. The black dots represent the optimal variant for each system and each of the perspectives. In the private perspective, the variants corresponding to the optimum level imply a calculated primary energy use of about 95kWh/(m^2.year) for the single-family building and about 89kWh/(m^2.year) for the multifamily building, values that represent a reduction of about 20% and 30% of the values that the buildings had before any intervention. In the social perspective, variants that lead to cost optimal level present values of calculated primary energy use of 87 and 65kWh/(m^2.year) respectively for the single-family building and for the multifamily building.

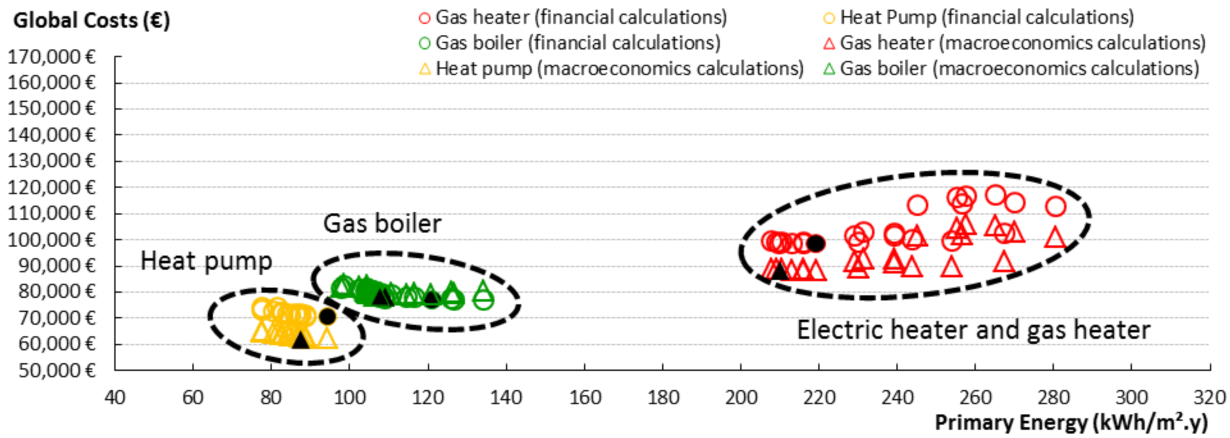

Figure 2. Cost Optimal levels for the renovation variants tested in the single-family building

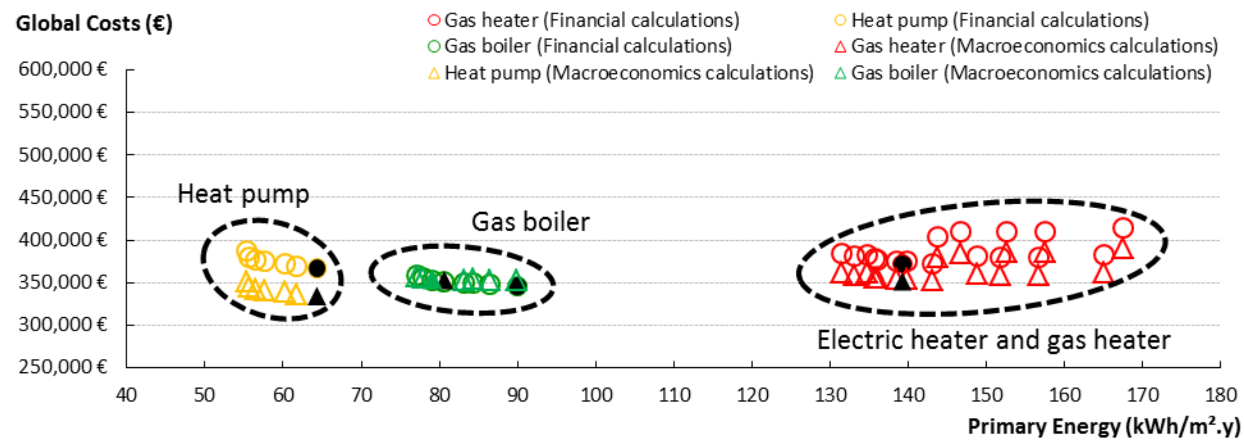

Figure 3. Cost Optimal levels for the renovation variants tested in the multifamily building

Table 1. Characteristics of the cost optimal solution for the renovation variants of the single-family building

Equipment	Perspective	Primary energy (kWh/m².y)	Heat transfer coefficients – U (W/m^2.y)			
			Facade	Roof	Floor	Window
Reference	Private and Social	469,49	1,10	2,50	1,56	3,90
Gas heater + Electric heater	Private	219,19	0,29	0,31	0,30	2,30
	Social	209,99	0,23	0,27	0,26	2,30
Natural gas boiler	Private	120,90	0,52	0,64	0,61	2,30
	Social	109,03	0,29	0,33	0,50	2,30
Heat pump	Private	94,25	0,60	0,72	0,72	2,30
	Social	87,43	0,38	0,77	0,69	2,30

Table 2. Characteristics of the cost optimal solution for the renovation variants of the multifamily building

Equipment	Perspective	Primary energy (kWh/m².y)	Heat transfer coefficients – U (W/m^2.y)			
			Facade	Roof	Floor	Window
Reference	Private and Social	277,41	1,08	1,88	2,50	4,80
Gas heater + Electric heater	Private	139,23	0,33	0,39	0,38	2,40
	Social	139,23	0,33	0,39	0,38	2,40
Natural gas boiler	Private	88,62	0,52	0,62	0,72	2,40
	Social	85,19	0,46	0,54	0,52	2,40
Heat pump	Private	64,31	0,52	0,62	0,72	2,40
	Social	64,31	0,52	0,62	0,72	2,40

Comparing the results obtained with different heating, cooling and domestic hot water preparation systems, there is a close relationship between their efficiency and energy performance of the building envelope. The optimal variants have more demanding levels of energy performance of the building envelope for the least efficient equipments, both in private and in social perspective. Tables 1 and 2 present the main characteristics of the optimal variants for each set of equipment and for both perspectives.

3.4. Sensitivity Analysis

In order to assess the robustness of the results obtained depending on possible future changes in the data used in the calculations, especially regarding the evolution of energy prices and discount rates, sensitivity analysis were performed varying these assumptions. For energy prices, instead of the European Union and IEA forecasts above described, a scenario of a continuous growth of energy prices of 5% per year has been tested. With this assumption, there are significant changes in the design of the cost curves and the optimal renovation variants, in the private perspective, also change, as can be seen when comparing Figures 2 and 4 and Figures 3 and 5. For the discount rates, instead of the values contemplated in the reference scenarios (6% for the private perspective and 3% for social perspective), discount rates of 3% for the private perspective and 1.5% for the social perspective have been tested. In these cases, there are no significant changes in the design of the cost curves and renovation variants, which indicate that the cost optimal levels are also kept in both buildings and in all equipments tested.

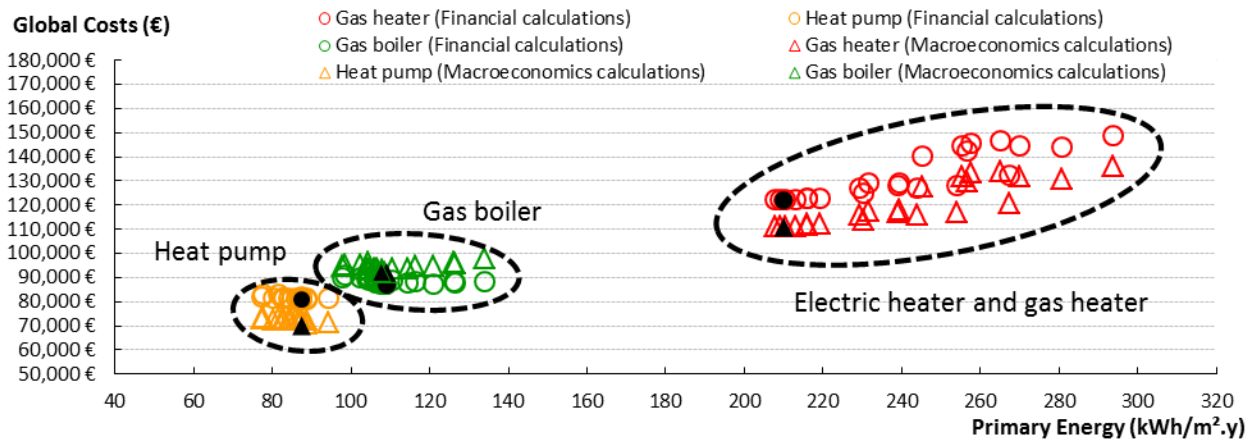

Figure 4. Cost Optimal level for the single-family building with an annual growth of energy prices of 5%

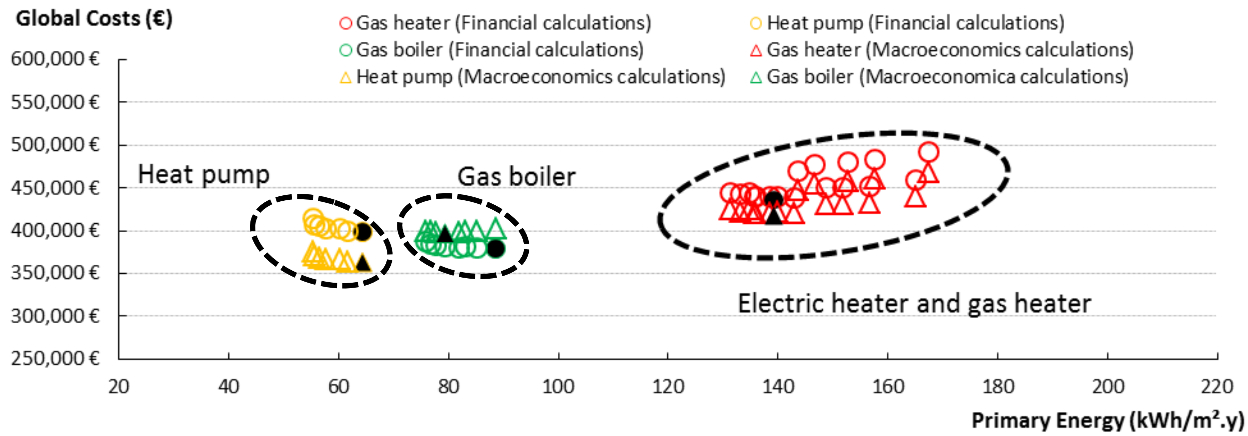

Figure 5. Cost Optimal level for the multifamily building with an annual growth of energy prices of 5%

3.5. Zero energy balance

Given the long-term expectation that greenhouse gases emissions may, by 2050, be reduced by approximately 90% when compared to 1990 levels, as advocated in the roadmap for transition to a competitive low carbon economy by 2050 [6], the use of energy from renewable sources harvested on the building site can effectively complement the energy efficiency measures. In order to analyze how these two types of measures interact, photovoltaic panels were introduced in some renovation variants in a way they would deliver the equivalent to the required non-renewable primary energy to achieve a net zero energy balance (it was assumed a free exchange of electricity between the building and the electric grid regardless the price of energy). Figures 6 and 7 illustrate the results obtained for each one of the case studies and for each one of the equipments considered, on the private perspective. Generally, there is a strong correlation between the variants with higher cost-effectiveness in all situations. Occasionally, energy efficiency measures in the building envelope with better energy performance become more cost-effective when the goal is zero energy balance, but this effect is sporadic (see Figures 6c and 7a).

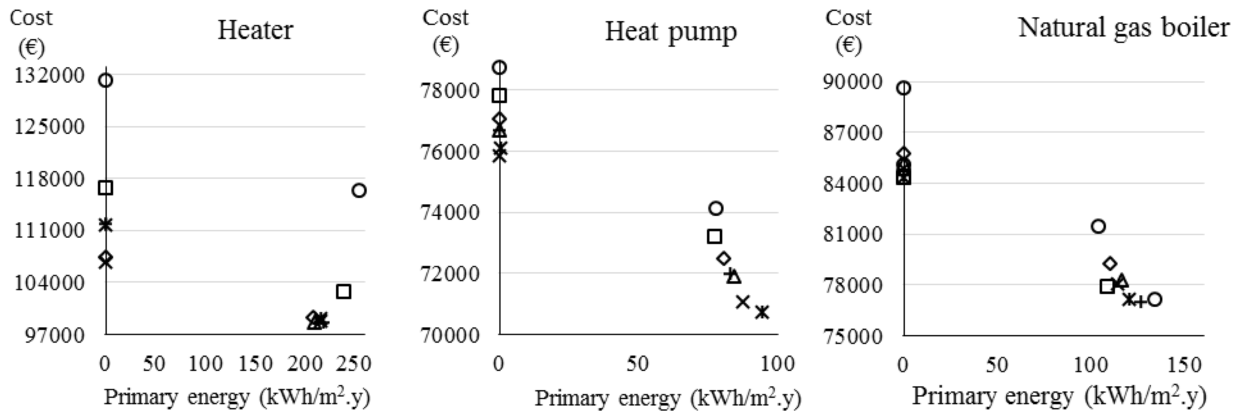

Figure 6 a), b) and c). Overall costs and calculated use of non-renewable primary energy for different variants (combinations of different measures to renovate the building envelope), in the single-family building with and without PV panels and for each type of equipment

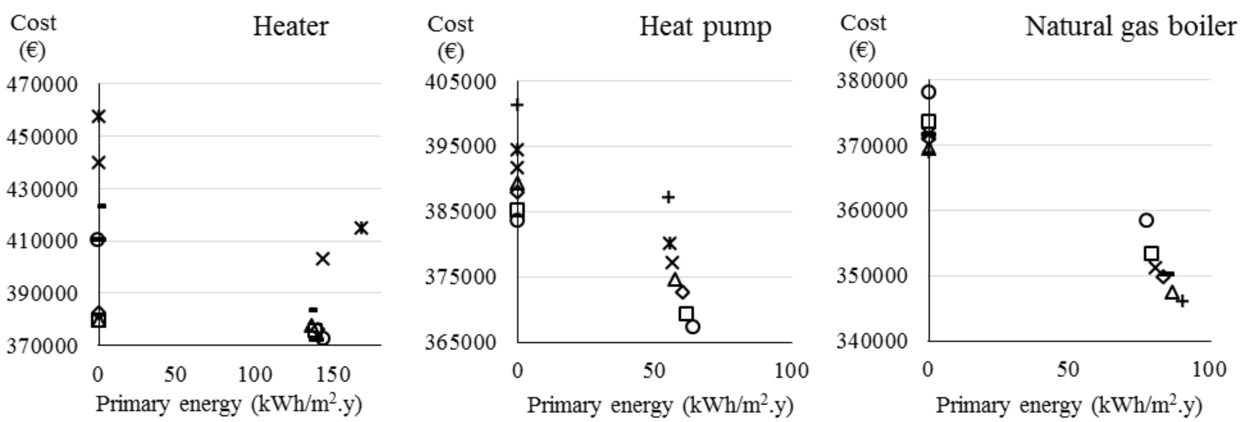

Figure 7 a), b) and c). Overall costs and calculated use of non-renewable primary energy for different variants (combinations of different measures to renovate the building envelope), in the multifamily building with and without PV panels for each type of equipment

4. Conclusions

Calculations of cost optimal levels performed for the case studies previously shown, despite the limitations resulting from dealing with only two buildings in two specific places, allow drawing some conclusions concerning the cost effectiveness of some packages of renovation measures related to the improvement of the energy performance of the building envelope, the upgrading of the building systems and the use of on-site harvested renewable energy to achieve a zero energy balance of existing residential buildings in Portugal.

The interaction between the measures for improving the building envelope and the upgrading of the building systems shows that for systems with different efficiencies and using different sources of energy, the cost optimal levels are found with different renovation measures in the building envelope. Altogether, as the efficiency of the systems increase, the necessity of improving the performance of the building envelope reduces.

Among the solutions tested, the cost optimal levels correspond to renovation variants that use a heat pump for heating, cooling and domestic hot water preparation. In the case of the single-family building, this situation occurs in both perspectives (private and social) while in the case of the multifamily building it only occurs in the social perspective. In the private perspective, the use of a natural gas boiler for heating and domestic hot water preparation, combined with air-conditioning for cooling, proved to be more cost effective.

Comparing the cost optimal levels in the two buildings studied, it can be concluded that, in general, the renovation measures are more cost effective in the case of the single family house than in the multifamily building.

The use of photovoltaic panels for meeting the energy needs towards a net zero energy balance, only occasionally causes changes in the hierarchy of the cost effectiveness of the renovation variants when compared with the situation without their contribution. When changes occur in this hierarchy, systematically the renovation variant with the lowest global cost corresponds to a higher energy performance of the building envelope in the scenario of net zero energy than in the scenario without this restriction.

The sensitivity analysis performed showed that for some of the systems tested, the cost optimal levels changed when an alternative scenario for the evolution of the energy prices was considered. These changes are particularly evident in the single-family house in the private perspective, and for all the three systems analysed. In this case, when the energy prices rise, the cost optimal renovation variant corresponds to a clearly higher energy performance of the building. These results alert for the fact that an evolution of the energy prices steeper than expected would place the identified cost optimal levels as suboptimal.

The sensitivity analyses also showed that when considering a raise in the energy prices, the optimum levels in the private perspective become similar to those obtained in social perspective. This indicates that results obtained with the social perspective might be considered more reliable once the impact of uncertainty on the future evolution of energy prices is reduced.

As a final conclusion, the results of this study show that the EC cost optimal methodology is robust in the definition of the most cost effective packages of renovation measures, leading to very similar results for a zero non-renewable primary energy goal or without this energy restriction. Nevertheless, a cost optimal range of measures instead of a cost optimal single renovation package should be considered and from this range of measures, those with a better energy performance of the building envelope should be favoured. This option decrease the impact of unpredicted strong raises of energy prices and additionally takes into account the external costs of energy (incorporated in the social perspective).

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