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Cost Optimal and Zero Energy levels in the renovation of residential buildings – Rainha Dona Leonor case study

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Abstract: *Improving energy efficiency in existing buildings is a great challenge. These buildings have their own limitations related with their design, location and function. To study the possibilities of cost-effectively improve the thermal performance of these buildings and increase the chances of reaching the nearly zero energy (nZEB) target, one building of Rainha Dona Leonor neighbourhood has been analysed. The purpose of the study was to analyse the robustness of the cost optimal methodology when renovating towards nZEB targets. With this work it was possible to understand that the most cost effective package of renovation measures to achieve cost optimal levels and to achieve the nZEB target are very similar and these results do not suffer major changes when variations on the energy prices, discount rates or photovoltaic (PV) costs are considered. However, these changes make the use of PV more cost-effective and nZEB levels become, sometimes, also cost optimal levels.*

Cost optimal, nZEB, energy efficiency, sensitivity analysis

Introduction

In Europe the buildings sector is responsible for 40% of total energy consumption and 36% of CO_2 emissions [1]. In Portugal the building sector is the third largest consumer [2], therefore it is important to improve the energy performance of buildings in order to reduce the greenhouse gas emissions (GHG) [3].

In a step further to fight against the increase of GHG, EU released a recast of the Energy Performance of Buildings Directive (EPBD) [4] introducing the nZEB concept and establishing its mandatory implementation for new buildings after the end of 2020 [1]. EPBD recast further requires that energy performance levels for buildings and building elements are cost-effective during their life cycle and established a methodology for its calculation [4].

The nZEB target in buildings usually involves high levels of insulation, very efficient windows, good levels of air tightness and controlled ventilation [1]. Regarding the energy sources, EPBD demands that most of the already very low energy needs in these buildings are to be satisfied by renewable energy sources harvested on-site [1]. Existing buildings face several barriers when it comes to refurbishment and even more when the target is nZEB, getting even more difficult when the building is part of social housing [5] where buildings are usually rented to poor people and so, the rents should be kept at reasonable levels [5].

Methodology

The present article describes the life cycle cost assessment of different renovation scenarios for a tipical social housing neighbourhood recently renovated [6]. In this work, the cost optimal levels were identified and it was analysed in what way it is possible to reach a building with zero non-renewable energy use. The cost optimal calculations were based on the cost optimal methodology proposed by the European Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 [7], [8]. Different scenarios were tested, involving improvements in the building envelope and the replacement of the building integrated technical systems for heating, cooling and DHW (BITS). A life cycle of thirty years was considered, taking into account BITS replacement after their lifetime according to EN 15459 and considering its residual value in the end of the period. A discount rate of 6% was used. The different packages of renovation measures considered are presented in Table 1.

Table 1 Summary of the different renovation measures considered in the study

BITS (Heating/cooling/DHW)	Scenario	Walls	Roof	Window	Glass
HVAC + electric heater with storage tank + Solar panels (except B)	B	EPS 6cm	XPS 5cm	wood	single
	S1	EPS 8cm	XPS 8cm	PVC	double
	S2	EPS 10cm	XPS 10cm	PVC	double
	S3	EPS 12cm	XPS 12cm	PVC	double
Gas boiler	S4	EPS 5cm	XPS 5cm	wood	single
	S5	EPS 8cm	XPS 10cm	PVC	double
	S6	EPS 12cm	XPS 12cm	PVC	double
Heat pump	S7	EPS 6cm	XPS 5cm	wood	single
	S8	EPS 8cm	XPS 8cm	PVC	double
	S9	EPS 12cm	XPS 12cm	PVC	double
	S10	EPS 8cm	XPS 8cm	PVC	double
Biomass boiler + HVAC	S11	EPS 6cm	XPS 5cm	wood	single
	S12	EPS 8cm	XPS 10cm	PVC	double
	S13	EPS 12cm	XPS 12cm	PVC	double

For each BITS there are different combinations of measures to improve the building envelope that together form different renovation scenarios (Sn). The reference renovation scenario (B) is the adopted renovation solution for the case study. The investment and maintenance costs were calculated with the Cype® software for generation of construction prices (http://www.geradordeprecos.info/). The energy needs were calculated according to the Portuguese regulation for the residential buildings thermal performance [9] in accordance with ISO – 13790 and primary energy was calculated considering conversion factors of 2.5kWh$_{PE}$ per kWh for electricity and 1kWh$_{PE}$ per kWh for gas. The indoor comfort temperatures considered were 20ºC for winter and 25º for summer. The energy costs were based on the Portuguese energy costs and it has been considered the EU scenario [8] for the estimation of the energy prices in the near future. To assess the robustness of the methodology used and the confidance on the results achieved, some sensitivity analysis were carried out regarding the evolution of energy prices, discount rates and PV prices.

Case-study

The case study is a building from the social housing Rainha Dona Leonor neighbourhood. It was built in the fifties of the twentieth century and it is located in Porto, northwest of Portugal. The building under analysis is a semi-detached house. The envelope did not have any insulation and there were wooden window frames with single glazing and external plastic shutters. The system for DHW production was an electric heater with storage tank and there were no heating and cooling systems apart from portable electric heaters or fan coils.

The renovation project aimed at increasing indoor living areas, improving thermal insulation and replacing BITS. Figure 1 shows the building before and after the renovation process. The initial heating needs of this building were 119,7kWh/m².a, the cooling needs 6,5kWh/m².a and DHW needs 37,1 kWh/m².a.

Figure 1 Building before and after renovation on Rainha Dona Leonor neighbourhood

Renovation process

The reference renovation scenario corresponds to the renovation solution really implemented in the building, including ETICS with a 6 cm thick layer of EPS on the exterior walls, XPS with 5 cm on the roof, wooden frame windows with double glazing and a new electrical water heater with storage tank combined with solar panels for DHW. For heating and cooling, a HVAC system with multi-splits was considered. Table 2 shows the energy needs, the primary energy use and carbon emissions for the initial situation of the building (before renovation) and considering the above mentioned renovation scenario (after renovation).

Table 2 Summary of the energy needs and carbon emissions before and after renovation

	Heating needs (kWh/m².a)	Cooling needs (kWh/m².a)	DHW (kWh/m².a)	Primary energy use (kWh/m².a)	Emissions (Ton eq CO_2)
Before renovation	119,7	6,5	37,1	413,7	18,9
After renovation (Scenario - B)	68,5	7,9	27,1	127,2	5,8

Taking this renovation scenario as reference and analysing the cost optimal solution for the alternative renovation scenarios from Table 1, the results are presented in figure 2.

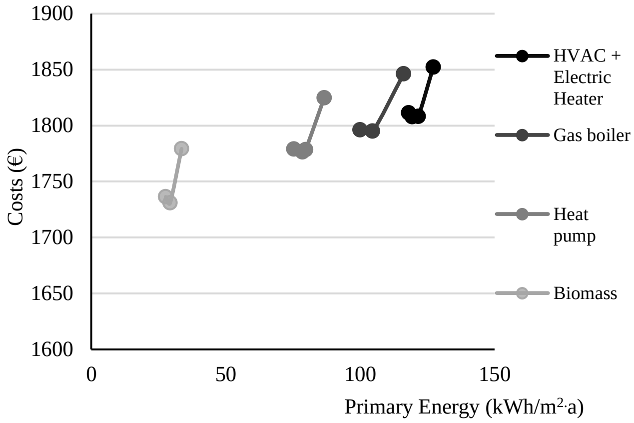

Figure 2 Global costs for each one of the alternative scenarios regarding primary energy use

This figure shows a graphical result with the primary energy for each scenario and its global cost. Each group of points corresponds to different BITS and the lower point of each group is the cost optimal solution for that equipment. The cost optimal renovation scenarios for each BITS are (according to Table 1): S2 for HVAC with electric heater and solar panels for DHW preparation; S5 for the gas boiler; S9 for the heat pump; and S12 for biomass boiler.

Among all the renovation scenarios analised, the cost optimal solution is S12 (the global lowest point in Figure 2) corresponding to the use of a biomass boiler for heating the living room and preparation of DHW and a HVAC system in the rooms. This solution leads to primary energy needs of 29.3 kWh/m².a, which corresponds to 30% of the primary energy needs of the reference scenario (B). Table 3 shows the U-values for the reference scenario, for the cost-optimal solution and the Portuguese thermal regulation reference values.

Table 3 U-values for the base solution, for the cost-optimal solution and the Portuguese thermal regulation reference values

Element	U – Value (W/m².ºC)		
	Reference scenario B	Cost optimal scenario	Thermal regulation reference values
Exterior walls	0,45/0,48*	0,37/0,39*	0,50
Roof	0,34	0,34	0,40
Windows	3,90	2,40	2,90

* The 1st value is for the first floor and the 2nd for the second floor

Renovation process towards net zero energy level

To achieve the nZEB level, beyond the cost optimal level, it is necessary to harvest renewable energy on site. In this case-study, the nZEB level was achieved considering the contribution of PV panels. Figures 3 and 4 show the results obtained, in terms of energy and global costs, with the contributions of PV panels for each one of the analysed renovation scenarios. Each figure represents the results for each one of the combinations taking into account heating, cooling and DWH preparation, with and without PV panels. Each different marker on figures represents one scenario, with and without PV panels to reach zero balance between the use of primary non-renewable energy and the on-site generation of energy from renewable sources.

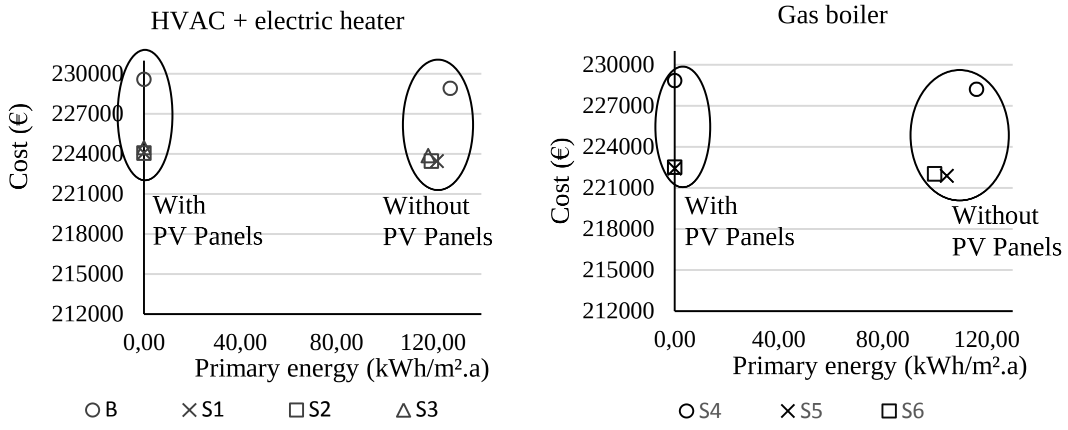

*Figure **3** Results with photovoltaic panels for HVAC + Electric heater and for the Gas boiler*

Analysing the figures it is possible to observe that most scenarios do not have significant changes with the addition of the PV panels in terms of the lowest global costs. In Figure 3, the cost optimal solution for HVAC with the electric heater for DHW preparation corresponds to the square marker (the lowest point) and it corresponds to scenario 2 (S2). For the gas boiler the cost optimal solution is the X marker and it corresponds to scenario 5 (S5).

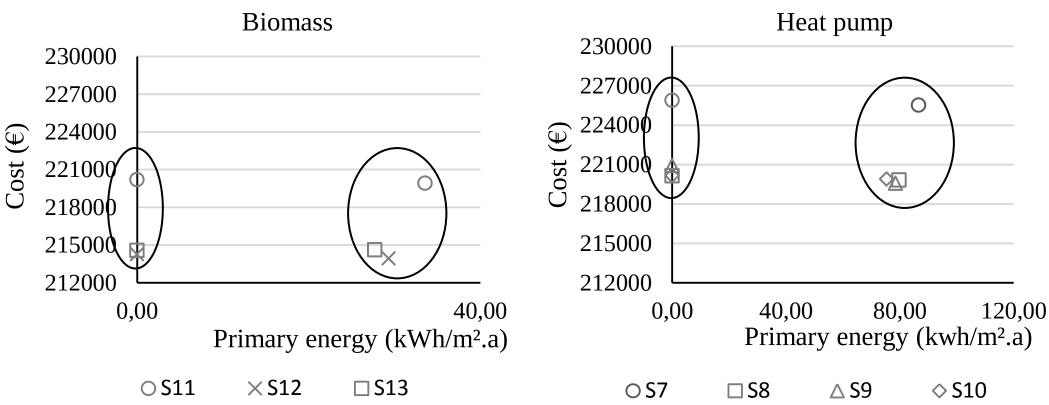

Figure 4 Results with photovoltaic panels and heat pump and biomass boiler

The inclusion of the PV panels to reach nZEB level does not change the cost optimal solution for these two BITS. It remains the S2 and the S5 solutions respectively. Figure 4 shows the same situation for the case of having a biomass boiler or a heat pump as BITS in the renovation process. The cost optimal solutions for each one of these BITS are the scenario 12 (S12) and the scenario 9 (S9) respectively. The addition of PV panels does not change also the cost optimal solutions in each case that remain the S12 and S9 scenarios.

Sensitivity analysis

To assess the robustness of the results regarding future changes in the energy prices, discount rates and PV prices, some sensitivity analyzes were performed. For the energy prices it was considered a growth of 5% per year and for the discount rates 3%. For the photovoltaic prices, instead of 3.000 €/kWp, it was used 2.500€/kWp and 3.500 €/kWp.

Regarding the changes in the energy prices, the results show that for the cases of using HVAC with the electric heater and for the case of using biomass boiler, there are no changes in the cost optimal scenarios. For the case of using gas boiler and for the case of using heat pump without the contribution of the photovoltaic panels, the cost optimal scenarios correspond to the ones with higher levels of insulation in the building envelope.

Changes in the discount rates in the cases of using gas boiler or heat pump also demand higher levels of insulation, when compared to the base solutions in order to reach the cost-optimal solutions.

Regarding the PV systems, considering a price of 2.500€/kWp, the cost optimal solutions for the analysed BITS do not change. When the price rises to 3.500€/kWp, the less efficient equipment requires a better envelope solution. Table 4 summarises these results.

Table 4 Results of the sensitive analysis showing the cost-optimal solutions for each BITS

BITS	Base	Energy evol. 5%	Discount rate 3%	PV 2500€/kWp	PV 3500€/kWp
HVAC + gas heater	S2	S2	S2	S2	S2
HVAC + gas heater + PV	S2	S2	S2	S2	S2
Gas boiler	S5	S6	S6	S5	S5
Gas boiler + PV	S5	S5	S6	S5	S6
Heat pump	S9	S10	S10	S9	S9
Heat pump + PV	S9	S9	S10	S9	S9
Biomass boiler	S12	S12	S12	S12	S12
Biomass boiler + PV	S12	S12	S12	S12	S12

Figure 5 shows the global costs for each one of the cost optimal scenarios, in each BITS with and without photovoltaic contribution, for each sensitivity analisys. Each bar is an alternative scenario in the sensitivity analisys and each group of bars corresponds to one of the BITS.

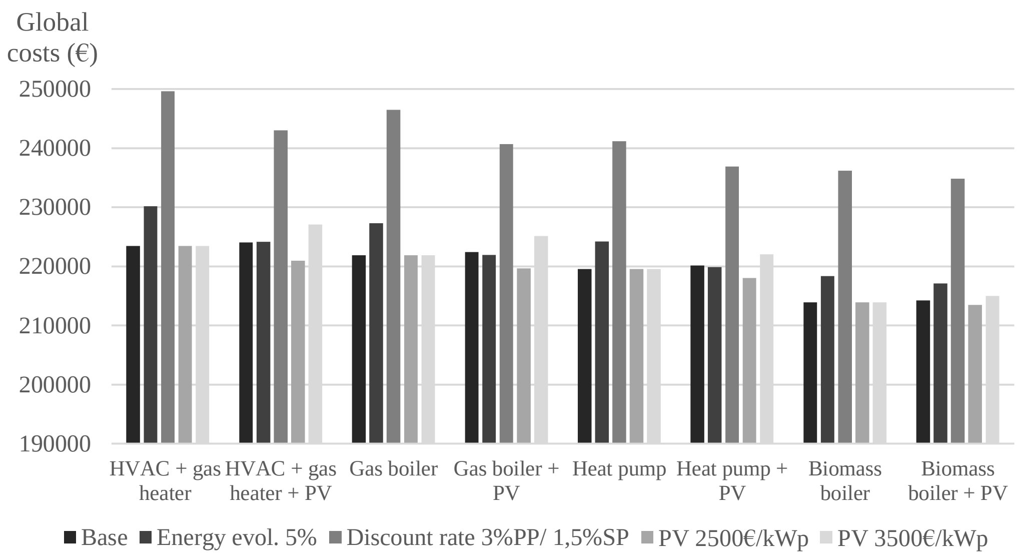

Figure 5 Global costs for the sensitive analysis in each system without and with photovoltaic panels

As shown in figure 5, for higher energy prices, lower discount rates and lower PV costs, the solutions which consider the PV systems for the energy generation are more cost-effective than the same solutions with energy supplied by the power grid.

Conclusions

In this paper, a renovation process of a residential building from a social housing neighbourhood built in the fifties in Porto was presented to evaluate how cost optimal levels relate with nZEB targets. Some clues on how the Portuguese building stock can cost-effectively move towards nZEB are pointed out.

The cost optimal calculations show that the lowest global costs are achieved with the combination of a small biomass boiler for DHW and heating and a HVAC for heating and cooling. For the building envelope, values below the current reference values of Portuguese regulation are cost-effective. The combination of a building envelope with good energy performance with simple, but efficient, BITS with low maintenance costs, proved to be a winning strategy either for the cost optimal target as well as to be combined with the use of PV panels for the zero non-renewable primary energy goal.

Sensitivity analyses on the variation of energy prices, discount rates and PV prices, allowed concluding that, for some cases, the energy performance of the building envelope has to be improved for future perspectives of higher energy prices or lower discount rates. However, this improvement in the building envelope is never very significant and doesn't happen with the use of the most efficient equipments.

The sensitive analysis further allowed concluding that lower PV costs, lower discount rates and higher energy prices, lead the solutions with photovoltaic contribution to present lower global costs than the same solutions without that contribution. This means that for these scenarios the electric energy produced by the PV panels is cheaper than the energy purchased from the grid and nZEB scenarios become cost optimal as well.

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