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ScienceDirect

Energy Procedia 78 (2015) 2403 – 2408

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Cost-effective energy and carbon emission optimization in building renovation – A case-study in a low income neighbourhood

Manuela Almeida[a], Alessandro Bencresciuto[b] *, Marco Ferreira[a], Ana Rodrigues[a]

[a]*University of Minho, Civil Engineering Department, Campus de Azurém,Guimarães 4800-058, Portugal*
[b]*Polytechnic of Turin, Corso Duca degli Abruzzi 24, Torino 10129, Italy*

Abstract

Construction sector is one of the major responsible for energy consumption and carbon emissions and renovation of existing buildings plays an important role in the actions to mitigate climate changes. Present work is based on the methodology developed in IEA Annex 56, allowing identifying cost optimal and cost effective renovation scenarios improving the energy performance. The analysed case study is a residential neighbourhood of the municipality of Gaia in Portugal. The analysis compares a reference renovation scenario (without improving the energy performance of the building) with a series of alternative renovation scenarios, including the one that is being implemented.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: building renovation; energy efficiency; renewable energy sources; life cycle cost; life cycle impact.

1. Introduction

The world population has been facing a problem that plagues the Earth: the climate change. Since the 1970s, mankind has been in ecological overshoot with annual demand on resources exceeding what the planet can regenerate each year. Nowadays, this problem is taking alarming proportions and consequence can be seen by all. Prevision made by the Global Footprint Network says that, starting from 2050, the world population will need 2,8 planets to satisfy its needs [1]. In this context, the building sector is one of the major responsible for resources waste,

* Corresponding author. Tel.: +39 338 170 9280.
E-mail address: a.bencresciuto@gmail.com

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.203

energy consumption and greenhouse gases emissions. New buildings have an important role to improve current trends of energy consumption, but the existing buildings represent the largest source where it is possible to save energy and to reduce emissions. In fact, while the first can be constructed with high performance levels, the second, representing the vast majority of European building stock, have predominantly low energy performance and subsequently they need renovation works [2].

Through the methodology developed in IEA EBC Annex 56 [3], this work focused on the cost-effective energy and carbon emission optimization in a residential building energy related renovation. The building examined is located in a residential neighbourhood of the municipality of Vila Nova de Gaia (outskirts of Porto, Portugal). The neighbourhood is in a degraded condition and, since 2009, has been subjected to renovation works. The present work examines the current energy needs of the building and compares them with a series of alternative renovation scenarios including both envelope renovation and replacement of building integrated technical systems (BITS).

The objective is to analyze alternative renovation scenarios that are more energy efficient compared with the one currently adopted, and, at the same time, more convenient from the economic point of view. In order to evaluate the impact of energy and CO_2 emissions throughout the entire life cycle of the building, a life cycle impact assessment (LCIA) was performed.

2. Description of case study

The urban complex, built between 1976 and 1982, is the gateway to the city for those coming from the south. The district is designated for low-income households and it consists of 18 blocks, each with several buildings. The analyzed building has 9 floors: the ground floor used for commercial activities and 8 other floors with 3 apartments per floor. In total there are 22 apartments, 3 per floor from the first to the seventh and one apartment on the top floor. All apartments consist of two bedrooms, living room, kitchen, bathroom and balcony. The average heated area per apartment is 60,45 m^2 for a total of 1330 m^2 on the whole building. As part of neighbourhood, the building has been undergoing renovations that improve the aesthetics, eliminate building pathologies and improves energy performance.

2.1. Building renovation variants

Table 1 shows different options of BITS for heating and domestic hot water (DHW). Cooling systems are not necessary because the cooling needs are very low and they can be neglected. In the case study, 22 renovation packages of measures listed in Table 2 were also considered, leading to improvements on the opaque and transparent building envelope. The reference package (REF) refers to the basic maintenance that the building requires, not improving its energy performance, including the renovation of the façade with the repair of the cracks, the painting of the walls and the replacement of windows that are at the end of their life cycle. The chosen solution (CHO) is the package of measures adopted in the ongoing renovation works. For both of these two packages, the windows were replaced with others with similar performance. The reason of that is the low impact of the windows on the total energy needs: the glazed surface is small compared to the opaque envelope; due to this fact, for the two solutions mentioned above, it was considered not necessary to invest money on high efficiency windows.

In all other alternatives, from M1 package to M9, were considered progressive improvements on the various parts of the building envelope with different insulation thicknesses and different materials (synthetic, mineral, natural).
The solutions proposed in Table 1 and Table 2 were combined in order to create multiple combinations and to increase the accuracy of the cost optimal and cost effective calculations.

Table 1. List of the building integrated technical systems for heating and domestic hot water.

CODE	Heating	DHW	Ren. energy	CODE	Heating	DHW	Ren. energy
BITS 1	Electric heaters	Electric heaters	-	BITS 4	Heat pump	Heat pump	Photovoltaic
BITS 2	Gas boiler	Gas boiler	-	BITS 5	Biomass boiler	Biomass boiler	Pellets
BITS 3	Heat pump	Heat pump	-	BITS 6	Electric heaters	Electric heaters	Solar thermal

Table 2. List of alternative renovation measures.

Code of measure	Wall	Roof	Floor	Windows (U=[W/m^{2}K])
Reference measure (REF)	No insulation	No insulation	No insulation	Frame aluminium – Single glazing U = 4,8
Chosen solution (CHO)	EPS 50 mm	XPS 80 mm	No insulation	Frame aluminium – Single glazing U = 4,8
M1	No insulation	Rockwool 80 mm	No insulation	Frame PVC – Double glazing U = 2,4
M1a	No insulation	Black cork 40 mm	No insulation	Frame PVC – Double glazing U = 2,4
M2	No insulation	Rockwool 140 mm	No insulation	Frame PVC – Double glazing U = 2,4
M2a	No insulation	Black cork 80 mm	No insulation	Frame PVC – Double glazing U = 2,4
M3	No insulation	Rockwool 140 mm	Rockwool 40 mm	Frame PVC – Double glazing U = 2,4
M3a	No insulation	Black cork 80 mm	Black cork 80 mm	Frame PVC – Double glazing U = 2,4
M4	No insulation	Rockwool 140 mm	Rockwool 80 mm	Frame PVC – Double glazing U = 2,4
M4a	No insulation	Black cork 80 mm	Black cork 80 mm	Frame PVC – Double glazing U = 2,4
M5	EPS 40 mm	Rockwool 140 mm	Rockwool 80 mm	Frame PVC – Double glazing U = 2,4
M5a	Black cork 40 mm	Black cork 80 mm	Black cork 80 mm	Frame PVC – Double glazing U = 2,4
M6	EPS 100 mm	Rockwool 140 mm	Rockwool 80 mm	Frame PVC – Double glazing U = 2,4
M6a	Black cork 80 mm	Black cork 80 mm	Black cork 80 mm	Frame PVC – Double glazing U = 2,4
M7	EPS 100 mm	Rockwool 140 mm	Rockwool 80 mm	Frame PVC – Double glazing U = 2,1
M7a	EPS 100 mm	Rockwool 140 mm	Rockwool 80 mm	Frame wood – Double glazing U = 2,4
M8	EPS 100 mm	Rockwool 140 mm	Rockwool 80 mm	Frame PVC – Double glazing U = 2,0
M8a	EPS 100 mm	Rockwool 140 mm	Rockwool 80 mm	Frame wood – Double glazing U = 2,0
M9	EPS 160 mm	XPS 160 mm	XPS 160 mm	Frame wood – Double glazing U = 2,4
M10	EPS 80 mm	XPS 100 mm	XPS 100 mm	Frame PVC – Double glazing U = 2,4
M11	EPS 100 mm	XPS 120 mm	XPS 120 mm	Frame PVC – Double glazing U = 2,4
M12	EPS 120 mm	XPS 140 mm	XPS 140 mm	Frame PVC – Double glazing U = 2,4

3. Life cycle costs

The calculation of the energy consumption is obtained using as input data the average energy needs of all of the dwellings of the building. The energy needs for cooling and the portion of electricity for lighting are excluded because the first are very low and for the second, the renovation measures do not consider any changes in the lighting equipment or lighting needs. The energy from photovoltaic panels was calculated using Photovoltaic Geographical Information System (PVGIS) (http://re.jrc.ec.europa.eu/pvgis/). The energy coming from the solar panels was calculated from the software SOLTERM (http://www.lneg.pt/iedt/projectos/370/). Concerning the increase of energy costs, the values published by the European Union for electricity [4] and from International Energy Agency [5] for natural gas were assumed. Finally, the previsions of prices of pellets were calculated with a future increase of 3% per year of the current price.

Figure 1 shows the global cost in function of the non-renewable primary energy (for heating and DHW) associated to each renovation package, for the private and social perspective, in accordance with the requirements of the EPBD methodology for the cost optimal assessment. Analysing the different measures and the different BITS, the cost optimal and cost-effective packages have been identified. In the graphs, each marker represents a different renovation scenario with the same markers referring to the BITS. All points of the renovation packages that are below the point of the existing building (reference measure) are cost-effective. Only the point with the lowest cost is cost-optimal [6]. Both in private and in the social perspective the group of measures with the lowest global cost is associated to the gas boiler. The worst group, both in terms of cost and primary energy, is represented by the one with electric heaters, namely the one currently applied to the building and for which, for ongoing works, it was considered the simple replacement without any improvement. BITS 3 and BITS 6 are almost at the same level of cost, but with significant difference in terms of non-renewable primary energy use. When the heat pump system is integrated with renewable energy by photovoltaic, a considerable improvement is achieved: the non-renewable primary energy is greatly reduced and global costs decrease slightly. The case of the biomass boiler shows 0 as impact in terms of non-renewable primary energy but higher costs compared to that of the gas boiler solution, linked to the high initial costs. Comparing the graphs in the two different perspectives a major difference can be seen at BITS 4: the contribution of renewable photovoltaic panels will greatly reduce the global costs in the social perspective, due to reduced energy needs and cost of CO_2. More important is the reduction of gap between the solutions with very low non-renewable primary energy and the cost optimal solution. This trend is greatly evident especially for the orange markers (heat pump plus photovoltaic), in which the gap decreases from 56,94 €/m^2 of private perspective to 12,66 €/m^2 in social perspective. Considering the whole scenario, the M5 alternative associated to the gas boiler is the cost optimal solution in both perspectives.

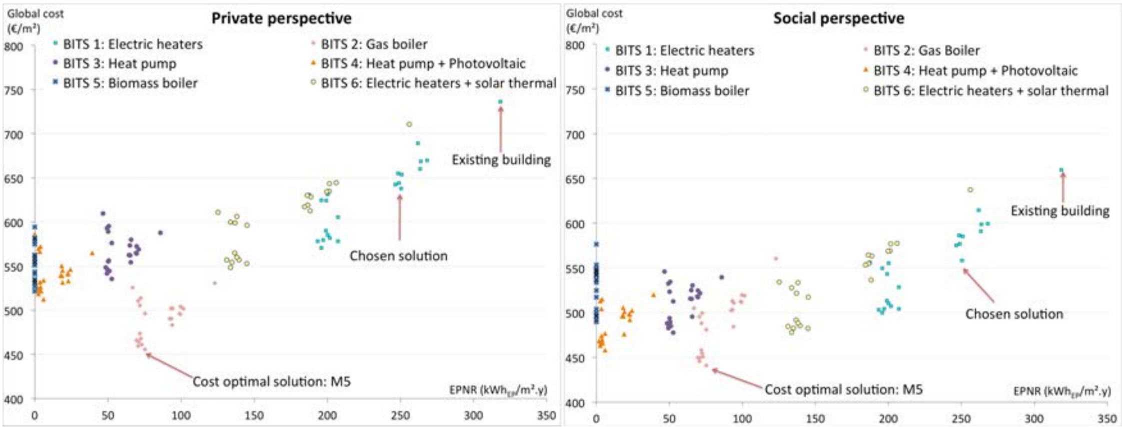

Fig. 1. Life cycle costs evaluation graphs in private and social perspective.

3.1. Sensitivity analysis

To test the robustness of the data obtained from the calculations, sensitivity analysis were performed. For the specific case changes were applied to the evolution of electricity prices and natural gas, to the value of the discount rate and to the evolution of CO_2 emissions prices. Regarding the price of energy, instead the previously considered, an evolution of the current price of 3% per year was tested. About the changes in the discount rates, first it was applied 8% and 4% respectively for the private and social perspective, and then 4% and 2%. For the cost of CO_2 emissions, a study conducted by the US Government was adopted; in which four different price scenarios for emissions are proposed [7].

After analysing separately all of these changes, substantial difference was found only for the fourth scenario of prices of carbon emissions, for which the study assumes very high costs for CO_2 emissions. In fact, for this case, the heat pump and photovoltaic solution appears to be the best in terms of global cost for social perspective. In general, all the systems with greater energy needs are shifted upwards. The cases of biomass boiler, heat pump and heat pump plus photovoltaic remain about at same level as in the first analysis.

In conclusion, excluding the last case, the sensitivity analysis confirms the robustness of the analysis conducted in the majority of cases.

4. Life cycle impact assessment (LCIA)

The LCIA estimates the impact due to the materials and to the building energy demand. The calculation was based on the Ecoinvent LCI database ver. 2.2.

Unlike results obtained from the life cycle cost approach, in this case the results (see Figure 2) show that the best technical system is BITS 4, that is heat pump associated with the PV. From the point of view of envelope renovation scenarios, the best is the M7A; in the previous analysis was the M5. However, even in this case, the worst solutions are those with electric heaters (BITS 1 and BITS 6), as technical systems, and REF and CHO as renovation scenarios. It should be underlined that the solution derived from the GWP has higher initial cost than those resulting from the cost-optimal methodology, but have less impact during the life cycle. In the following "Optimization" analysis, they are directly compared.

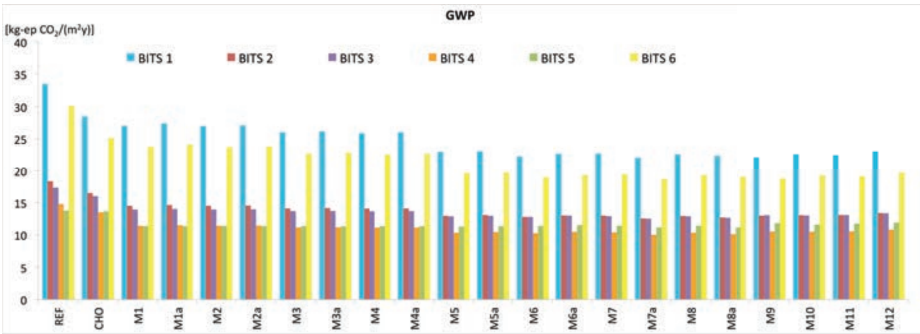

Fig. 2. Total Global Worming Potential and Total Cumulative Energy Demand by BITS and by measures.

5. Integration of Co-benefits

In this section the co-benefits coming from the building renovation are analysed. The method was to assign a unit for each plus and minus reported in the matrix suggested by IEA EBC Annex 56, obtaining numbers used in a graph in order to compare the co-benefits of various solutions. On the base of this assumption, the bar chart in Figure 3 was found. The solutions from the M5 onwards, being those with insulation on the external wall, are those in which most of the entries improve under different points of view.

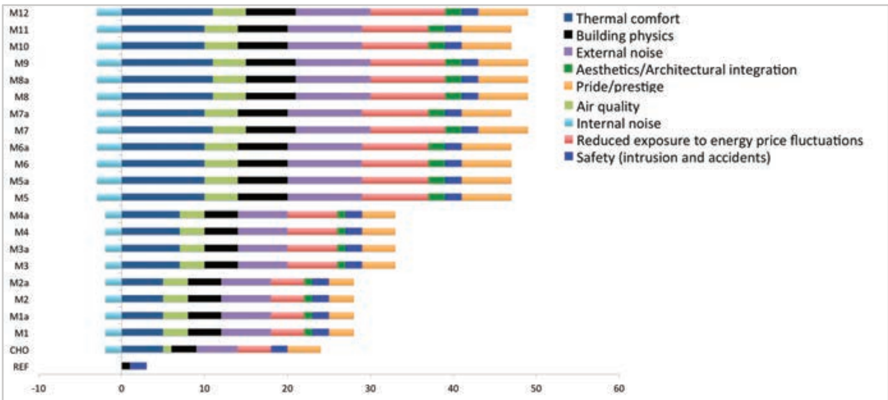

Fig. 3. Co-benefits linked to the envelope renovation.

In general, therefore, it can be said that, progressively improving the quality and efficiency of the envelope, also the co-benefits improve. The best solutions are the M7, M8, M8A, M9 and M12, in which more efficient windows are introduced, with the additional co-benefit of reducing external noise.

6. Optimization and conclusions

The assessment analysed the convenience of building renovation from different points of view, showing positive and negative sides. However, what is the best solution? To answer the question it is necessary put together the results obtained from the various analyses through an optimization process.

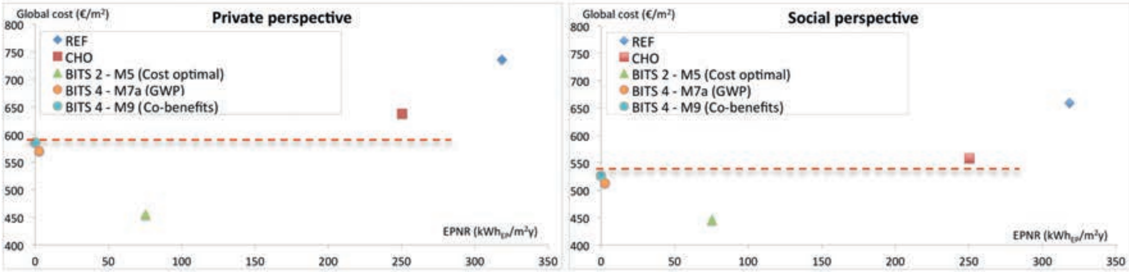

Fig. 4. Life cycle costs evaluation graphs for the best solutions of each assessment carried out.

First of all, the graphs of Figure 4 show that all alternatives are cost-effective; in fact each of them presents lower global costs not only compared to the existing building, but also to the chosen renovation. Accordingly, the solution currently adopted is not the cheapest one in the long run and it is not good regarding non-renewable primary energy use an environmental impact. In both perspectives the solution M5 and BITS 2 (gas boiler) corresponds to the cost optimal solution but BITS 4 is the best equipment from the LCIA assessment. From the point of view of the global cost the solution with best results from LCIA assessment is not convenient; it is important to underline that in the social perspective the gap in costs between solutions with BITS 4 and the cost-optimal alternative is smaller than in private perspective. Therefore, for the social perspective, the policy makers need to determine whether the gain in social terms worth the economic effort. If the policy makers consider better the most expensive solution, they might need to introduce financial incentives in order to guide the choice of private stakeholders towards that direction. It should also be noted that the M9 is the best solution when considering the co-benefits associated to the renovation process. This aspect could also affect the private decision. The choice becomes subjective: the investor could be willing to pay more money in order to get more comfort and benefits, or to sell at higher prices due to the added value resulting from those co-benefits. The private sector may be interested in investing a larger sum of money if the policy makers, coming then to a mutual agreement, also encourage it.

In conclusion, from all points of view, the solution currently used in the renovation process needs to be abandoned. If one focus only on the economic aspect, the most convenient solution turn out to be unique; if more different approaches are carried out, the results are more and different as in this case study; therefore the solutions need to be compared, in order to find the best from private and social perspective. Moreover, the final choice must be also analysed and agreed with investors for renovation to evaluate also their preferences in terms of co-benefits.

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