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Life-cycle costs and impacts on energy-related building renovation assessments

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ABSTRACT

Many regulations and initiatives to promote the reduction of energy consumption and carbon emissions have been implemented in the building sector. However, they are mostly targeted at new buildings. In order to reach the goals that are being established, while it is necessary to implement measures in new buildings, this is doubly the case for existing buildings, which correspond to the majority of the European building stock. Building renovation improves buildings' energy performance and reduces the carbon emissions related to the operation of the building, but this involves adding new materials and technical systems. The production process of these new materials uses energy (embodied energy) and releases carbon emissions. In this sense, to evaluate the relevance of the embodied energy in building renovation, the International Energy Agency Energy in Buildings and Communities (IEA EBC) project, Annex 56, developed a methodological framework to evaluate the cost-effectiveness of building renovation solutions that includes a life-cycle impact assessment (LCIA). Thus, using a particular case study, different renovation solutions are compared both with and without consideration of the embodied energy. The results show that the embodied energy does not have a major impact on the evaluation of the cost-effectiveness of the renovation solutions, but that as the renovation energy target gets closer to a zero non-renewable energy level, its relevance increases.

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Life cycle impact assessment, LCIA, LCA; building renovation; energy efficiency; carbon emissions; embodied energy

Introduction

In Europe, buildings are an important target for the reduction of energy consumption and related carbon emissions; they are responsible for 40% of the final energy consumption, which leads to 32% of the carbon emissions sent into the atmosphere each year. These values are not stabilised either, and present an increasing trend [1].

In an attempt to slow down the increase of these values, the European Commission (EC) has released and reviewed many regulations. A turning point was marked by the Energy Performance of Buildings Directive (EPBD) recast in 2010, wherein new concepts are introduced – namely the cost-optimal, nearly zero energy buildings (nZEBs) [2]. Also, to promote energy efficiency in different sectors, including the building sector, strategies like Europe 2020 and Europe 2030 are also defined [3]. Despite these efforts, the legal means are mainly targeted at new buildings, when the majority of the European building stock has more than 20 years left in its expected life cycle. Given the low rates of replacement of existing buildings by new efficient ones (1% to 2% per year), the European Union (EU) will not achieve its reduction targets unless there is a focus on the renovation of existing buildings [4].

Existing buildings have their own technical, functional and economic constraints, which may lead to expensive and complex renovation procedures – something that is rarely authorised by owners or promoters. This fact may contribute to missed opportunities in improving the energy performance of buildings [5]. However, while building renovation does improve energy performance, it also increases the investment cost and presents environmental impacts due to the new materials and building integrated technical systems (BITS) that are added to the building [6]. In an attempt to address these trade-offs and optimise the energy-related intervention in existing buildings, the International Energy Agency Energy in Buildings and Communities (IEA EBC) project was launched: Annex 56 – Cost-Effective Energy & CO_2 Emissions Optimization in Building Renovation [6].

The aim of the project is to develop a methodology for the cost-effective renovation of existing buildings which combines energy efficiency measures and the use

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of energy from on-site renewable sources. This methodology is intended to be used by private entities to help in decision-making for building renovation and also by governmental agencies for regulatory purposes. The methodology developed within Annex 56 balances the energy consumption and global costs of each renovation scenario in order to compare them. It uses a life-cycle approach instead of the payback period method, as established by the methodology for the cost-optimal analysis presented by Delegated Regulation no. 244/2012 [7]. In addition to the life-cycle costs (LCCs), the Annex 56 methodology also considers a life-cycle impact assessment (LCIA) method, balancing not only the energy necessary for the operation phase but also the embodied energy and carbon emissions related to product manufacturing [5]. In existing buildings, the environmental performance is related to the materials added to the building, while in new buildings it is related to structures that involve far bigger amounts of material, and consequently the impact is much more noticeable [5].

Concerning existing buildings, a question arises as to whether or not the embodied energy of the renovation materials and related carbon emissions have a significant impact on the final primary energy use. When the target is a building with a very high energy performance, a significant amount of material is added in order to significantly decrease its energy needs; beyond a certain level, the additional savings in energy use may be lower than the embodied energy of the materials being used. When the target is an nZEB, where besides the very high energy performance there is a significant use of energy from renewable sources, the question is even more relevant if the non-renewable energy that could potentially be saved is very low.

Within the Annex 56 methodology and concerning the LCIA, the participants in the project reached an agreement on restricting the number of indicators used in the analysis. Since the methodology consists in comparing different renovation scenarios, analysing many indicators could potentially be very time consuming and render the methodology impractical to use [5]. In this sense, only the global warming potential (GWP), the cumulative non-renewable primary energy demand (CED_{NRPE}) and the cumulative total primary energy demand (CED_{TOTAL}) were assessed. The choice is related to the fact that these indicators have a good correlation with the remaining environmental indicators considered in the LCIA method, as concluded in other studies [8].

Taking advantage of one of the several case studies of the project [9], different renovation scenarios were analysed – both with and without the embodied energy –, in order to verify its relevance to the renovation process.

Method

In this paper, the Annex 56 methodology is applied to a Portuguese case study.

The first part of the methodology involves an LCC analysis which offers an overview of the solutions that are cost-effective along with the optimal solutions in relation to cost and energy efficiency. The LCC analysis involves four main steps: calculation of the energy use of the building in a reference case scenario, the establishment of different renovation scenarios, calculation of the energy use for these alternative scenarios, and calculation of the global costs associated with each renovation scenario. The second part of the methodology involves the LCIA, which is detailed later in this section.

The LCC analysis starts with the calculation of the primary energy use in the reference scenario – a collection of renovation measures aimed at restoring the functionality of a building, mainly driven by aesthetical concerns and the need to solve the physical problems of the building without consideration of improving energy performance. This scenario is the base for the comparison of alternative renovation solutions and marks the limit of cost-effectiveness.

The primary energy was calculated using Portuguese thermal regulation [10], which follows ISO 13790 [11]. The calculations are performed using a quasi-steady method which takes into account an indoor comfort temperatures of 18 °C during the winter and 25 °C during the summer. In these first stages of the analysis, the primary energy is related to the energy necessary for heating, cooling, domestic hot water (DHW) and lighting. The energy use for lighting is based on an average value determined by [12] which considers the residential stock.

Regarding the contribution of on-site renewables, the electricity generation from the photovoltaic panels was calculated using the Photovoltaic Geographical Information System (PVGIS; http://re.jrc.ec.europa.eu/pvgis/) [13] and the solar thermal contribution was calculated using Solterm (http://www.lneg.pt/iedt/projectos/370/) [14].

After this step, it was necessary to establish different renovation scenarios, which include renovation measures for building envelopes (walls, roofs, floors and windows) and BITS, including the contributions from renewable energy sources. For each of the established renovation scenarios, the primary energy use was calculated as per the reference scenario.

Then, the global costs were calculated for each of the renovation scenarios. The global costs calculations were performed using the net present value (NPV) method or annuity values [15]. For this case study, the NPV was used and then converted into annuity values to allow a comparison of these results with those of other participating countries.

The global costs include investment, maintenance, replacement and energy. The investment, maintenance, and replacement costs were calculated using CYPE®, which generates prices for construction work in Portugal [16]. The energy costs for the first year were retrieved from the Entidade Reguladora dos Serviços de Energia (ERSE), the Portuguese entity that controls energy prices [17,18]. The future costs of the energy were estimated using EC predictions [7]. The price of the pellets is based on research on the Portuguese market with an estimated increase of 3% per year. A discount rate of 6% is assumed, in accordance with the recommendations of Delegated Regulation no. 244/2012 [7], and a lifetime period of 30 years is considered. The described methodology allows a comparison of the renovation scenarios balancing the energy during the operation phase and the related global costs.

The second part of the methodology consists of using an LCIA to calculate environmental performance. The LCIA can be complex due to the number of impacts that it is necessary to calculate, so some simplifications have been adopted – namely, only processes which make a relevant contribution to the total environmental impacts of renovated buildings and which can be put into practice with a reasonable effort are included. Only life-cycle impacts of measures that affect the energy performance of the building are considered (thermal envelope, BITS, energy use for on-site production and delivered energy). Thereby, the methodology only includes the operational and embodied energy use and related carbon emissions.

In order to proceed to the LCIA analysis, some renovation scenarios were selected – namely, the cost-optimal scenario for the building envelope and the scenario that leads to the best energy performance, once the carbon emissions are reduced.

In order to calculate the environmental impact, it is necessary to quantify the materials and BITSs that are required in each renovation scenario. This involves the quantification, in kilograms or units, of each type of material and BITS in each renovation package. It is also necessary to consider the energy used for the operation of the building. The methodology used for the environmental LCIA is based on EN 15978:2011 [19] and follows the steps of EN ISO 14044:2006 [20].

One of the most important stages of the LCIA method is the inventory analysis, which for this study entails the quantification of the flows for and from each renovation scenario. Several sources are used for the inventory data – and in this study, the background data related to the considered process units was taken from the Ecoinvent 3.1 database [21]. To facilitate the quantification of the environmental indicators, the life-cycle analysis software SimaPro 8.0.5 [22] was used to modulate the life cycle of the analysed renovation scenarios and assess the three selected life-cycle impact categories: GWP, CED_{NRPE}, and CED_{TOTAL}. The software retrieved the unitary impacts.

To obtain the total impacts it is necessary to multiply the unitary impacts by the related amounts of each renovation scenario. The impact of each renovation scenario is obtained from the sum of all the impacts related to it, including materials and energy.

The results of the LCIA make it possible to quantify the primary energy, including the embodied energy, the energy for the operation phase, the embodied carbon emissions, and the carbon emissions related to the operation phase. Thus, it is possible to compare the primary energy use of each renovation scenario with and without the embodied energy.

Case study

The case study focuses on a building constructed in the 1950s located in Porto, in the north of Portugal. Most of the buildings in this neighbourhood are exhibiting signs of degradation and appear inadequate to current living standards due to their small living areas, which is why the decision was made to renovate them. Figure 1 shows the building both before and after the renovation.

(a) (b)

Figure 1. Exterior of the building (a) before the intervention and (b) after the intervention.

The building under examination has two floors with two apartments on each floor. It had no insulation on the envelope and there were no BITSs for heating and cooling, apart from portable electric heaters and fan coils. The DHW was provided by an electric heater with a storage tank.

Concerning the construction solutions, the exterior walls consisted of single hollow brick walls with cement mortar on both sides, while the roof was composed of a lightweight concrete slab and a structure that supports the fibre cement sheets. The floor consisted of a solid ground floor and the windows were framed in wood with single glazing and external shutters. The U-values of these elements before the renovation process are presented in Table 1.

From the several renovation scenarios analysed, the implemented scenario consists of an increase in the living areas by merging the apartments on each floor into a single apartment per floor, and improving the building's envelope. In this context, insulation was added to some of the elements of the envelope, the windows were changed and new BITSs were installed. The solution implemented on the envelope includes the application of an external thermal insulation composite system (ETICS) with 6 cm of expanded polystyrene (EPS) on the external walls. For the roof, the solution consists of removing the lightweight slab and introducing a suspended ceiling, with extruded polystyrene (XPS) with a thickness of 5 cm placed between the ceiling and the fibre cement sheets. The windows were also replaced with double glazing. It was decided not to make any changes to the floor since the low ceiling height did not realistically allow for an increase in the floor's thickness. These measures represent the common building renovation scenario in Portugal.

Two different building envelope configurations were analysed, each of which involve different insulation materials. Envelope A involves insulation materials that are usually applied in renovation works (EPS and mineral wool) and Envelope B uses cork which, despite being produced in Portugal, is applied less often due to its higher price. Table 2 shows the analysed solutions for the building envelope. The analysis always includes intervention in almost all elements. Renovations that do not improve the energy performance of the building are considered as maintenance, such as painting, repairing cracks and making smaller adjustments to avoid potential future issues from occurring that would require further repair and renovation. These two envelope solutions were paired with four different combinations of BITS, and Table 3 shows the eight different envelope and BITS solutions that were analysed.

Table 1. The pre-renovation U-values.

Element	U-value
Exterior walls	1.38/1.69
Roof	2.62
Windows	5.10

Results of the life-cycle costs (LCC) analysis

The LCC analysis starts with the calculation of the energy needs and primary energy use of the building for each of the renovation scenarios considered and the calculation of the related global costs. In Figure 2 it can be seen that there are two curves, each relating to a different solution for the building's envelope. The lower curve relates to the solution with the current insulation materials and the higher curve considers the insulation cork board (ICB). Figure 2 shows

Table 2. Summary of the analysed renovation measures for the envelope.

Envelope	Wall	Roof	Floor	Windows
Reference	Maintenance	Maintenance	–	Maintenance
A	EPS 10 cm	MW 14 cm	MW 8 cm	Maintenance
B	ICB 8 cm	ICB 8 cm	ICB 8 cm	Wood U = 2,4
Chosen/ applied	EPS 6 cm	XPS 5 cm	–	Wood U = 3,9

Note: EPS = expanded polystyrene; ICB = insulation cork board; MW = mineral wool; XPS = extruded polystyrene.

Table 3. Summary of the analysed renovation solutions.

Solution	Envelope	Heating	Cooling	DHW	REN
Reference	Reference	Electric heater	Multi-split air conditioning	Electric heater with storage tank	–
1	A	Multi-split air conditioning	–	Electric heater with storage tank	Solar thermal
2	A	Gas boiler	–	Gas boiler	–
3	A	Air-source heat pump	–	Air-source heat pump	Photovoltaic
4	A	Biomass boiler	–	Biomass boiler	Biomass
5	B	Multi-split air conditioning	–	Electric heater with storage tank	Solar thermal
6	B	Gas boiler	–	Gas boiler	–
7	B	Air-source heat pump	–	Air-source heat pump	Photovoltaic
8	B	Biomass boiler	–	Biomass boiler	Biomass
Chosen/ applied	Chosen	Multi-split air conditioning	–	Electric heater with storage tank	Solar Thermal

Note: DHW = domestic hot water; REN = Renewable.

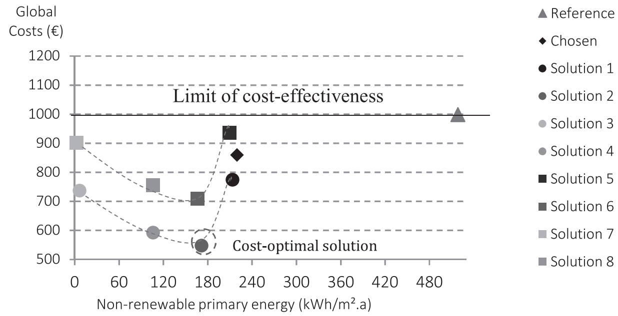

Figure 2. Results of the LCC analysis (non-renewable primary energy values without considering the embodied energy).

that the solution with lower global costs uses the current insulation materials due to the high price of ICB. In this sense, the cost-optimal solution is achieved with Envelope A for the building envelope (which consists of 10 cm of EPS for the wall, 14 cm of mineral wool for the roof and 8 cm of mineral wool for the floor) and a gas boiler for heating and DHW.

The solutions that result in a significant reduction in the primary energy use (close to zero) are the ones which use a heat pump and photovoltaic panels, followed by those which use a biomass boiler. These results do not include the embodied energy in the materials used.

Results of the LCIA analysis

After calculating the LCC for the operation phase, it is necessary to calculate the impact that each renovation scenario will have in terms of GWP, CED_{NRPE}, and CED_{TOTAL}. Table 4 presents the potential unitary environmental impacts for 1 kg of material, one complete BITS or for 1 kWh of energy, by energy carrier.

In order to obtain the full impact, the unitary values are multiplied by the total amount of material, BITSs or energy.

Figure 3 shows the results of the GWP for each renovation solution, in Solutions 1 to 4 consist of Envelope A for the building envelope and one of the four BITSs and Solutions 5 to 8 consist of Envelope B for the building envelope and one of the four BITSs. It can be seen that the Solutions 3 and 7 have the lowest GWP, which include a heat pump and photovoltaic panels, followed by Solutions 4 and 8, which include a biomass boiler. The solution that was applied is among the worst in terms of the GWP, and the cost-optimal one (Solution 2) also has a high GWP. Envelope A yields a slightly higher GWP compared to Envelope B, except in the comparison between Solutions 3 and 7.

Looking at Solutions 1 and 5 (BITS 1 combined with Envelopes A and B, respectively) and Solutions 2 and 6

Table 4. Summary of the environmental impacts.

Description		GWP, kgEP $CO_2/(m^2y)$	CED_{NRPE}, $kWh/(m^2y)$	CED_{TOTAL}, $kWh/(m^2y)$
Materials	Exterior wall painting	$7.36x10^{-4}$	$4.01x10^{-3}$	$4.31x10^{-3}$
	Repairing and painting wood window frames	$7.36x10^{-4}$	$4.01x10^{-3}$	$4.31x10^{-3}$
	Black agglomerated cork	$3.10x10^{-4}$	$1.86x10^{-3}$	$3.90x10^{-3}$
	XPS	$2.83x10^{-3}$	$7.44x10^{-3}$	$7.54x10^{-3}$
	Rockwool	$2.91x10^{-4}$	$1.42x10^{-3}$	$1.48x10^{-3}$
	EPS	$1.12x10^{-3}$	$7.87x10^{-3}$	$7.95x10^{-3}$
	ETICS (without the insulation)	$2.21x10^{-5}$	$1.16x10^{-4}$	$1.30x10^{-4}$
	PVC window	$6.99x10^{-4}$	$4.46x10^{-3}$	$4.64x10^{-3}$
	Wood window	$4.37x10^{-4}$	$2.16x10^{-3}$	$4.41x10^{-3}$
	Aluminium window	$2.54x10^{-3}$	$1.07x10^{-2}$	$1.22x10^{-2}$
	Glass (single)	$2.63x10^{-4}$	$9.31x10^{-4}$	$9.57x10^{-4}$
	Glass (double)	$3.80x10^{-4}$	$1.53x10^{-3}$	$1.60x10^{-3}$
	Windows sills (aluminium)	$2.25x10^{-3}$	$8.44x10^{-3}$	$1.02x10^{-2}$
	PVC membrane under floor cork insulation	$7.69x10^{-4}$	$6.98x10^{-3}$	$7.12x10^{-3}$
BITS	Gas boiler	$1.02x10^{-1}$	$4.74x10^{-1}$	$5.13x10^{-1}$
	Air-source heat pump	$4.26x10^{-1}$	$5.78x10^{-1}$	$6.10x10^{-1}$
	Biomass boiler	$7.87x10^{-1}$	2.45x10	2.60x10
	Solar thermal	$3.59x10^{-1}$	1.57x10	1.77x10
	Photovoltaic	$1.05x10^{-1}$	$4.79x10^{-1}$	$5.50x10^{-1}$
Energy	Electricity (PT energy mix)	$6.91x10^{-1}$	2.74x10	3.22x10
	Natural gas	$2.62x10^{-1}$	1.24x10	1.24x10
	Biomass	$4.50x10^{-2}$	$2.42x10^{-1}$	1.34Ex10

Note: BITS = building integrated technical systems; CED_{NRPE} = cumulative non-renewable primary energy demand; CED_{TOTAL} = cumulative total primary energy demand; EPS = expanded polystyrene; ETICS = external thermal insulation composite system; GWP = global warming potential; PT = Portuguese; PVC = polyvinyl chloride; XPS = extruded polystyrene.

(BITS 2 combined with Envelopes A and B, respectively), the average GWP percentage attributed to the energy for the operation of the building – including production and consumption – ranges from 95% to 96%, meaning that the weight attributed to the production of the materials ranges from 4% to 5%. For Solutions 4 and 8, which use a biomass boiler, the GWP percentage attributed to the energy produced and used for space heating, DHW and lighting decreases to 86%, meaning that 14% of the GWP is attributed to the manufacturing of the materials and the BITS.

Examining Solutions 3 and 7 however (which use a heat pump with photovoltaic panels), the GWP percentage attributed to the production of the materials and BITS is considerably higher at 63% and 84%, respectively. In these two solutions, the weight attributed to the energy for lighting, space heating, and DHW is much smaller at 37% for Solution 3 and 16% for Solution 7.

The results for the CED_{NRPE} and CED_{TOTAL} are presented in Figure 4. These indicators present the same trend as the GWP, where Solutions 3 and 7 (which include a heat pump and photovoltaic panels) are the ones with the lower CED_{NRPE} and CED_{TOTAL} values, followed by Solutions 4 and 8 (which include a biomass boiler). Both combinations use renewable energy sources.

Looking at CED_{NRPE}, in cases where the BITS uses electricity or gas for DHW and space heating, the non-renewable energy ranges from 95% to almost 100%, with the remaining residual percentage related to the production of materials and BITS. There is a decrease in the amount of non-renewable energy related to the operation of the building in Solutions 4 and 8, and the embodied energy of the materials and BITS increases to 14%.

In relation to the CED_{TOTAL}, the percentages are very similar to the CED_{NRPE} as the primary energy is mainly related to the production and use of energy for lighting, space heating, and DHW. The exceptions to this is found

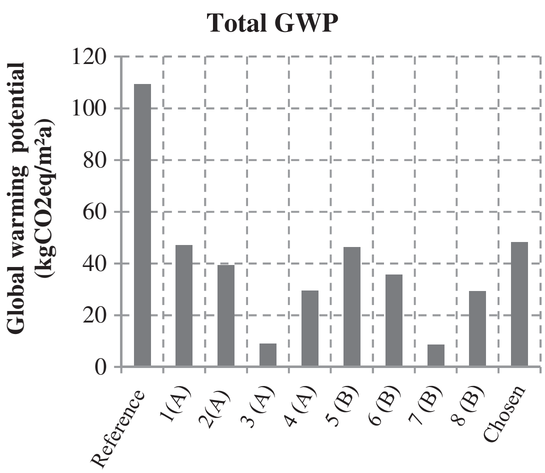

Figure 3. Results for the global warming indicator (GWP).

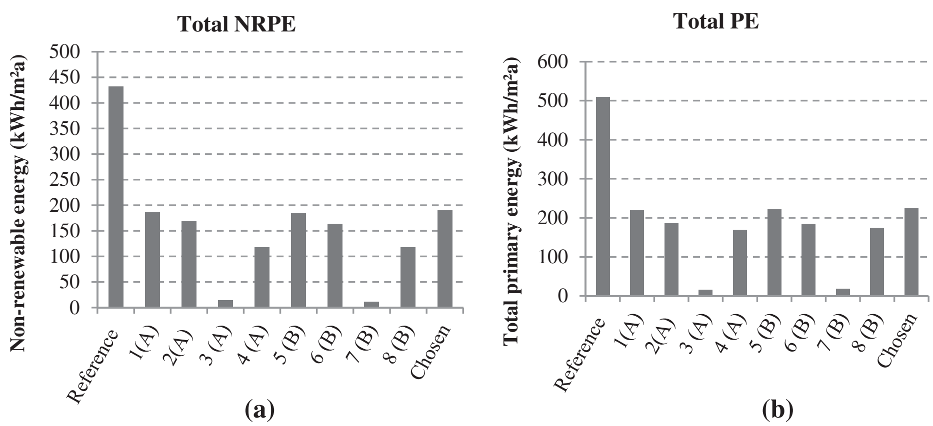

Figure 4. Results for (a) the CDE_{NRPE} indicator and (b) the CDE_{TOTAL} indicator.

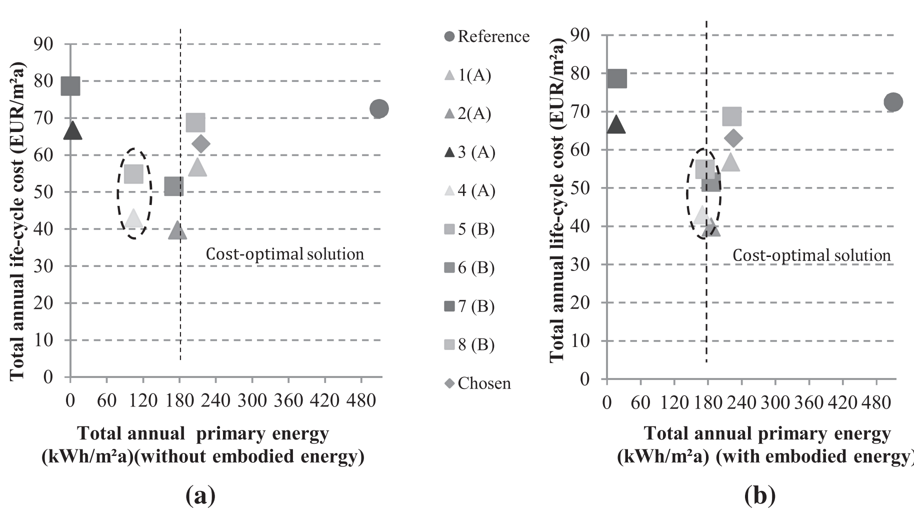

Figure 5. Results for the total primary energy (a) without embodied energy and (b) with embodied energy.

Table 5. Summary of the difference between the primary energy with and without the consideration of embodied energy.

Embodied energy	Reference	A + bits1	A + bits2	A + bits3	A + bits4	B + bits1	B + bits2	B + bits3	B + bits4	Chosen
Without	509.23	210.06	176.09	4.14	104.24	206.4	170.70	0.27	104.24	215.86
With	509.23	220.22	185.61	16.33	169.94	222.09	184.92	18.01	174.26	225.28
Difference	0.00	10.16	9.52	12.19	65.70	15.69	14.22	17.74	70.02	9.42

in Solutions 3 and 7, for which the biggest percentage of the total primary energy is related to the production of the materials and BITS, accounting for 63% for Envelope A and 88% for Envelope B. This inversion in the impacts is related to the fact that a high percentage of the energy used in the buildings is produced from renewable energy sources. Therefore, with low levels of non-renewable energy used, the embodied energy gains relevance.

A comparison of the eight renovation solutions in terms of the primary energy needed for the operation of the building and the total primary energy (which also considers the embodied energy) is presented in Figure 5. Observing Figure 5 it is possible to verify that generally there are no significant changes in the results. Solution A for the building envelope combined with a gas boiler is still the cost optimal solution. The inclusion of the embodied energy leads to a slight displacement of the points (increasing the primary energy values). This is more noticeable in solutions 3 and 7 that without the embodied energy were almost over the vertical axis and with the inclusion of the embodied energy have moved slightly away from this level. Solutions 4 and 8 are another example, that without the embodied energy were approximately halfway between the cost optimal and the nZEB solutions with a primary energy of 104 $KWh/m^2.y$. With the embodied energy, these solutions are closer to the cost optimal solution, with an increase in the primary energy of at least 65$kWh/m^2.y$. The total impact of these two solutions is mainly related to the production and use of electricity with an average weight of 60%, followed by the energy for DHW that has a weight of 25% in the total impact and the manufacturing of materials with an average weight of 12%.

When the embodied energy is not factored in, Solution 7 results in a primary energy value of 0.27 $kWh/m^2.y$ and Solution 3 results in a value of 4.14 $kWh/m^2.y$. When embodied energy is included, the total primary energy value reaches 18.01 $kWh/m^2.y$ for Solution 7 and 16.33 $kWh/m^2.y$ for Solution 3. Thus, concerning the total primary energy value, there is a switch of rank between these two solutions; when the embodied energy is factored in, Solution 3 demonstrates the superior energy performance, whereas without considering the embodied energy it is Solution 7 that is most efficient.

For Solutions 3 and 7, and given the presence of the renewable energy sources, the CDE_{TOTAL} is mostly due to the impact of the embodied energy of the insulation materials and the BITSs (especially the photovoltaic panels). The reference situation presents a high value for the CED_{TOTAL} that is mostly related to the energy used (production and consumption) for the operation of the buildings. Unlike other solutions, and when compared to the primary energy (without the embodied energy), the reference solution presents a slight reduction of total primary energy due to differences in the conversion factors used in the LCIA and the grid factor used for the LCC calculations. Table 5 presents a summary of the difference between the primary energy values with and without the embodied energy, in each renovation package.

Conclusion

This paper has investigated the relevance of embodied energy in the evaluation of rehabilitation interventions on buildings by analysing a Portuguese case study using the methodology developed by the IEA EBC Annex 56 project. The initial results obtained by the LCC method gave clues to the cost-effectiveness of the renovation scenarios and the cost-optimal one without considering the embodied energy. The LCIA approach, which followed the LCC calculations, allowed the embodied energy to be included and compared this with the LCC results.

The comparison between the LCC, which considers only the operational energy, and the LCIA, which considers both the operational and the embodied energy, shows that the inclusion of the embodied energy does not impact on which solutions are cost-effective or on which is the cost-optimal solution. On the other hand, in terms of total primary energy, the renovation scenario that leads to the lowest primary energy (approaching zero primary energy) changes due to differences in the environmental impacts of the insulation materials used in a renovation scenario with very low operational energy.

The results for this Portuguese case study are similar to those achieved in the IEA EBC Annex 56 project for another five case studies [23], located in different European countries (from North, Central and South Europe), which confirms that the results of this study can be generalised.

Embodied energy and embodied carbon emissions were not found to be very influential in the building renovation case studies when the focus is on cost-effective renovation solutions. However, when the energy performance approaches nearly-zero carbon emissions or nearly-zero energy renovation levels then the relative contribution of the embodied energy or embodied carbon emissions rises and can become significant; in some cases, the renovation solutions with the highest energy performance when considering only the energy use are not the ones with the best overall environmental performance.

These results indicate that when the target is nearly-zero carbon emissions or nearly-zero energy renovation levels, the primary energy and carbon emissions optimisation for both new and existing buildings should be carried out using a life-cycle perspective that factors in the embodied impacts.

Disclosure statement

No potential conflict of interest was reported by the authors.

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