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Environmental Performance of a Cost-Effective Energy Renovation at the Neighbourhood Scale—The Case for Social Housing in Braga, Portugal

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Abstract: It is increasingly recognised that the energy renovation of the existing building stock will be determinant for achieving 2030 and 2050 decarbonisation targets in Europe. As operational energy is being dramatically reduced through regulatory efforts and funding from the European Union, the relevance of the environmental performance of these interventions becomes higher, namely regarding embodied energy and carbon emissions associated with the materials that compose the renovation solutions. Although some studies address these impacts in buildings, the range of studies focusing on the neighbourhood scale is limited. This article presents a methodological framework combining a life cycle cost assessment (LCC) and a life cycle assessment (LCA). The purpose is to assess the relevance of embodied energy and carbon emissions on the cost-effectiveness of building renovation solutions towards nZEB at the neighbourhood scale by comparing an operational energy approach and a whole life cycle approach in a case study of a social housing neighbourhood in Braga, Portugal. The results suggest an increase in indicators values demonstrating a negative impact on the achievable reduction of both energy and emissions when the whole life cycle approach is considered, which can constitute a critical point for policy formulation in the decarbonisation of the built environment.

Keywords: cost-effectiveness; neighbourhood scale; LCA; embodied energy; energy renovation; social housing; whole life cycle

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1. Introduction

The building sector is at the centre of the discussion for the decarbonisation objectives set for 2030 and 2050, and existing scientific knowledge points in the direction that increasing the energy performance of the already existing building stock is a cost-effective path to get there [1]. Importantly, in this regard, the Energy Performance of Buildings Directive (EPBD) from 2010 introduced determinant new concepts, namely the nearly zero-energy buildings (nZEB) [2], and is considered one of the most significant turning points in terms of legislation. Nearly zero-energy buildings are characterised by presenting high levels of energy efficiency. Moreover, according to the general concept, as defined in the EPBD, the energy required to operate such buildings should be provided to a significant extent by renewable sources produced on-site or nearby [2]. The timeline defined in the EPBD indicates that all new buildings (and major renovations) should be nZEB from December 2020. Despite its importance for achieving the objectives mentioned above, most current policies still focus too much on new buildings. According to some studies, the vast majority of the existing building stock, which is more than twenty years old, is not being properly addressed [3]. Most countries have important improvements in energy efficiency, driven by increasingly demanding regulatory requirements and available funding from the European Union. However, taking into consideration that cost-effective energy renovations can lead to significant energy savings and that the existing buildings are only being replaced by new constructions at a rate of 1–2% per year [4], it is considered that there is still immense potential for decarbonisation of the existing stock to be realised. In consequence, several strategies are being proposed and tested to accelerate the building renovation rate. In this context, implementing interventions at the district or neighbourhood scale is considered one of the avenues that would allow speeding up the process of reducing greenhouse gas emissions of the building sector. This upper scale would allow taking advantage of potential economies of scale and interactions and synergies available at this scale, including integrating and optimising renewable energy sources [5].

On the other hand, as operational energy is being dramatically reduced, the relevance of the environmental performance of these interventions becomes significantly higher [6], namely regarding the embodied energy and carbon emissions of the measures and equipment that renovations rely on. The environmental performance of an energy renovation, when evaluated according to a life cycle assessment (LCA), is directly related to the materials and energy spent in the process. Therefore, the impact of materials and equipment that are going to be added in the renovation procedure must be balanced with its effect concerning energy savings during operation. Research already identified that, as the level of ambition of an energy renovation rises, its investments costs and environmental impacts also increases, but the operation costs and impacts associated with using the buildings are less significant [7]. In this sense, it can be considered that the relevance of the embodied parcel regarding energy and carbon emissions associated with an energy renovation is directly related to the objective outlined for the intervention. Within the renovation process, reducing primary energy by minimising demand or using renewable energy sources can lead to an increase of the embodied energy associated with the added materials, both on the envelope and the technical systems. This was already identified in research, namely regarding interventions with a nearly zero target, where using renewable energy systems is considered to be crucial [8].

The use of LCA in the building sector is not new. This type of assessment has been used since the 1990s [9], including studies addressing renovation interventions (e.g., [10,11]). However, LCA studies focusing on the analysis of cost-optimal renovation solutions are limited and geographically dispersed. Nevertheless, Almeida et al. [8] compared cost-effective calculations in several national contexts across Europe with interesting results in terms of the prioritisation of measures towards the nearly zero energy level of the renovated buildings and the demonstration of a decreasing effect of the achievable energy reduction when the embodied energy and emissions are considered in the calculations. In addition, the knowledge that supports LCA and cost-effective energy renovation at the neighbourhood or district scale is still dispersed and lacks diversity, particularly considering different pre-existing situations and contexts. Examples of existing studies at this scale include research addressing environmental performance in district heating contexts, e.g., the study from Feofilvos et al. [12], where low-temperature district heating coupled with renewable sources is analysed. A very recent study from Milic et al. performed an economic and environmental performance analysis of a district heating system in Sweden and investigated the interaction between the implementation of energy efficiency measures and the operation of district heating. Results suggest that there are significant environmental benefits from implementing energy efficiency measures, but the revenue of the district heating decreases [13]. Similar results were also found by another study [14], which showed that this question can constitute a significant barrier for energy renovation implementation at this scale in northern Europe. Other studies approached the problem from the urban scale using multi-objective optimisation techniques and simplified archetypes and found out that for decarbonisation of the building stock, the use of efficient technical systems is crucial [15]. Existing studies also include exploratory approaches to building stocks whose results suggest offsetting a considerable amount (about 65%) of greenhouse gas emissions, taking into account the materials used in the renovation [16] and also that in some contexts, the trade-off between resource efficiency and environmental impacts could be necessary [17]. Following the identification of this gap, the IEA-EBC Programme launched in 2017 a project entitled "Annex 75: Cost-Effective Building Renovation at District Level Combining Energy Efficiency and Renewables" (https://annex75.iea-ebc.org/, accessed on 22 November 2021). One of its main objectives is the development of a life cycle cost (LCC) assessment methodology to analyse the cost-effectiveness of interventions that combine measures to increase energy efficiency and measures implementing on-site renewable energy sources in different national contexts. This project involves 30 institutions of 13 different countries and builds on the findings of the previous IEA EBC Annex 56 project (http://www.iea-annex56.org/ accessed on 22 November 2021) [18], upscaling the study to groups of buildings and also districts. The methodology, which is already published [5], intends to analyse and compare primary energy and the (global) costs of several renovation scenarios, taking into account a life cycle approach, following EU regulations [19]. In addition to the LCC, the work being developed also investigates the possibility of LCC/LCA integration, looking into the balance of the energy needed for the operation of the building and the embodied parcel regarding energy and emissions implied in the materials used in a renovation intervention. In that context, this paper reports a study of the integration of the cost-effectiveness calculations and LCA at the neighbourhood scale, using a case study from a social housing context located in Braga, Portugal, and comparing two different approaches: the operational energy approach and the whole life cycle approach.

Section 2 presents the methodology pursued in this study, and in Section 3, the case study is described. The results of the study are discussed in Section 4. In the final section, the conclusions are presented.

2. Methodology

The study follows a methodological framework comprising two steps: (1) a cost-optimal methodology using LCC and (2) a life cycle assessment (LCA), whose results would be integrated. The two steps are described in detail in the following subsections.

2.1. Life Cycle Cost Assessment

The methodology used in this study for the life cycle cost assessment is in line with the cost-optimal calculation procedure designed explicitly for neighbourhoods and districts in the scope of the Annex 75 project, already detailed in another publication [5]. The methodology is based on comparing several renovation scenarios. The cost-effectiveness threshold is constituted by what is normally designated as a reference case, where it is considered that there is no improvement in energy performance. The reference case is composed of "anyway renovation" measures that focus on maintaining the building and revolving around aesthetical, functional and structural issues. Using this approach, a renovation scenario will be considered cost-effective if it presents better energy performance or lower costs during the life cycle of the building than the reference case. In this study, renovation scenarios are packages of measures that can integrate building envelope improvements (e.g., increased insulation) and more efficient technical systems, which can be centralised or decentralised. The renovation scenarios can also include renewable energy sources (RES). For comparison purposes, three main indicators are computed: energy use, carbon emissions and global costs.

2.1.1. Energy Demand Calculation

Energy use was computed through numerical simulation. According to the methodology defined in the Annex 75 project, the method used in the analysis should be consistent with regulations in the national context being analysed. As such, calculations regarding energy use were performed using dynamic numerical simulations in an hourly time step by Energy Plus [20] software and an OpenStudio graphical interface for modelling purposes. Energy Plus is widely used for energy calculations in buildings, and it is considered to present the level of detail and customisable configurations for the analysis being made in this study. In particular, it allows to model several different buildings and assumptions and simulate the group of buildings as one entity. It also provides several options for graphical modelling, which was also considered a key point for the choice of the software since it facilitates the geometrical data input in a complex model. Hourly energy consumption data are not available in Portugal. As such, the calculations rely on assumptions explained in the case study section (Section 3).

Computations for renewable energy systems used SCE.ER [21] and PVGIS [22]. SCE.ER is mainly used for national regulation compliance of renewable energy systems and possess an extensive database of equipment's used in the Portuguese context. In this study, it was used for simple calculations of solar thermal systems sizing for each house. It is a simple Excel-based tool that allows obtaining verifiable and robust results. The PVGIS was used for photovoltaic calculations. It is a tool developed by the European Commission Joint Research Council that allows for calculations for sizing of PV systems with impressive accuracy due to the extensive number of solar radiation data with high spatial and temporal resolution. Both tools are widely used in the Portuguese context for renewable energy sizing calculations and are therefore considered suitable for the context of this study.

2.1.2. Global Costs Calculation

Regarding costs, the approach of this study uses the concept of "global costs", which is meant to include all costs which occur in the life cycle of the materials used in construction, as well the systems included in the renovation intervention. Therefore, the calculation of the costs includes investment costs, maintenance costs, energy costs and replacement costs. Importantly, it also includes the costs associated with materials disposal when its life cycle is considered to be over. Costs assessment was based on a market-based information tool [23]. To assure comprehensiveness, it included costs of preparation for the intervention, such as the use of scaffoldings and the cost of labour (in terms of man-hours).

The calculations generally follow the EU Delegated Regulation methodology [15] and consider 30 years as the life cycle of the building. The methodology uses the global cost method. According to this method, the present value of the costs during the life cycle of the building is discounted to the first year in the calculations (Equation (1)) [18]. In the case that the renovation measure lasts more than the period considered for the analysis, a residual value is considered and applied a linear depreciation. The application of the method implies the projection of energy costs, which were retrieved from different documentation sources (e.g., [24]). For this study, following indications from a widely used report [25] and previous research [26]), a discount rate of 3% was considered.

$$Global\ cost\quad C_g(t) = C_I + \sum_k \left[\sum_{j=1}^{t} \left(C_{a,j}(k) \times \left(\frac{1}{1+\frac{r}{100}} \right)^j \right) - V_{f,t}(k) \right] \tag{1}$$

t: Calculation period
$C_g(t)$: Global cost (referred to starting year t_0) over the calculation period
C_I: Initial investment costs for a measure or set of measures k
$C_{a,\,j\,(k)}$: Annual cost during year j for a measure or set of measures k
$V_{f,t\,(k)}$: Residual value of a measure or set of measures k at the end of the calculation period (discounted to the starting year t_0)
r: Discount rate

2.2. Life Cycle Assessment

To consider the integration of the embodied portion in the whole life cycle approach, this study investigated the integration of a life cycle assessment (LCA) approach in the cost-effectiveness calculations (using LCC) for an energy renovation at a neighbourhood scale. The LCA analysis in this study is based on the methods defined in the IEA EBC Annex 56 LCA report [7] and was used and tested in other studies in different scales of analysis (i.e., [8,27]). The LCA methodology is an established approach for quantifying the embodied parcel regarding primary energy and carbon emissions. In the LCA methodology used in this study, two types of system boundaries were defined: a temporal boundary (which defines important phases during the life cycle of the building), which was defined taking into account the EN 15978 standard [28]. It also establishes a physical boundary in order to define both materials and energy flows. Regarding the temporal boundary (Figure 1), the different life cycle phases are the following: (1) the production phase—which encompasses the processes from cradle to gate regarding the production of materials and technical systems, including extraction of raw materials to final products; (2) the construction phase—the boundary in this phase includes the processes needed for the construction and or the installation of materials and technical systems, as well as equipment such as scaffolding; (3) the operation phase—this phase is comprised by the period of time in which the building is used and operated by the occupant. It starts at the end of renovation intervention and goes until the end of the life stage. It includes processes such as maintenance and replacement of components. Importantly, it also includes the operational energy; (4) the end of life phase—it considers processes for demolition, transport and appropriate disposal of waste, which depends on the material or component. Regarding the physical boundary, this analysis is focused on measures applied in the buildings located in the neighbourhood with the purpose of improving energy efficiency. Therefore, the assessment performed in terms of LCA is restricted to measures that will affect the energy performance, such as improvements in the thermal envelope, in more efficient (including renewable-based) building-integrated technical systems (BITS).

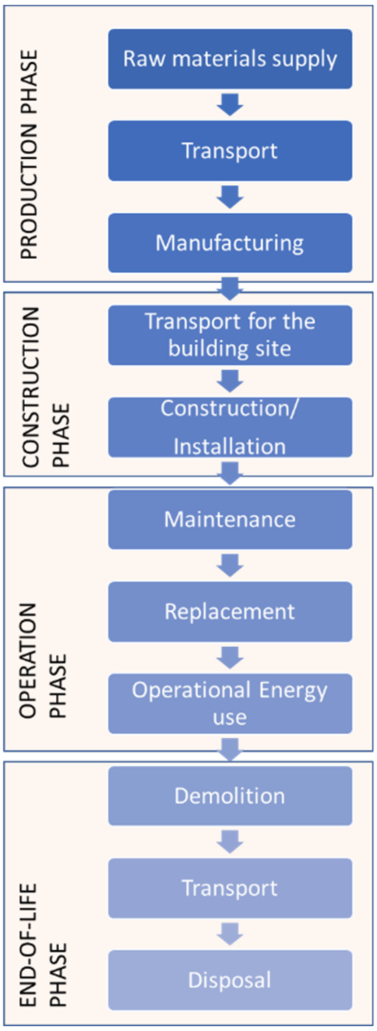

Figure 1. Life cycle main stages considered in the LCA analysis (adapted from EN 15978).

This study uses two indicators commonly used in LCA for the evaluation of environmental impacts and resource use: (1) carbon emissions, which is represented by the global warming potential (GWP), which allows for the quantification of the amount of CO_2 involved over the life cycle of a product—in this case, the materials and systems in each renovation package) and (2) non-renewable primary energy (NRPE) demand [7]. The assessment used data from the EcoInvent database [29] retrieved through SimaPro. Computation involved calculation of the materials involved in each renovation scenario and multiplication by impacts per energy carrier. Finally, the assessment results (computed as unit of surface area) are divided by the calculation period. Equation (2) exemplifies the calculation for primary energy [7], and the same rationale is used for carbon emissions.

$$PE_{building} = PE_{materials} + PE_{BITS} + PE_{op\ energy\ use} \tag{2}$$

where

$PE_{building}$ is the primary energy of the building renovation;
$PE_{materials}$ is the primary energy connected with materials used in the neighbourhood energy renovation;
PE_{BITS} is the primary energy linked with the BITS;
$PE_{op\ energy\ use}$ is the calculated primary energy for the energy spent in the operation of the building.

In order to differentiate the primary energy demand (and carbon emissions) used in the operational approach, the terms "embodied primary energy" and "embodied carbon emissions" are used in this study.

2.3. LCC/LCA Integration and Results Presentation

The methodology used in this study proposes that results from the calculations performed for LCC and LCA can be integrated and the two approaches considered in this study—Operational Energy approach and Whole Life Cycle approach—can be compared. For the operational approach, non-renewable primary energy (NRPE) and carbon emissions (represented by GWP) were calculated from the energy demand calculations detailed in Section 2.1.1 for every building in the neighbourhood, taking into account adequate distinctive assumptions such as specific constructive characteristics, occupancy and solar orientation in order to compute the total energy demand per square metre of the group of buildings. Only the energy demand that must be provided by non-renewable energy sources was considered. To obtain the primary energy and corresponding greenhouse emissions, conversion factors consistent with the national context being studied were applied. In the operational energy approach, cost-optimal calculations concerned the strict application of the LCC methodology as detailed in Section 2.1. It takes into account calculated energy required during the operation of the building for the reference case and as a result of the implementation of the renovation measures being studied and their calculated global cost (using Equation (1)) during the 30-year life cycle. On the other hand, in the whole life cycle approach, in addition to the energy spent in the operation of the buildings (and the corresponding generated emissions), the results from the LCA (detailed in Section 2.2) were integrated. This means that the embodied parcel is considered in the calculation of both the NRPE and GWP for the reference case and each of the renovation measures considered in the analysis, according to the rationale explained in Section 2.2, and in particular using Equation (2).

The results from these calculations regarding different renovation measures and scenarios can be compared by plotting the two indicators using scatter diagrams, such as the one presented in Figure 2. In the graph, the x-axis indicates the non-renewable primary energy use, and the y-axis presents the global costs. As explained in Section 2.1, results from calculating the two approaches are compared with the corresponding reference case, which also determines the cost-effectiveness threshold. Graphs in Section 4 are generated using this rationale.

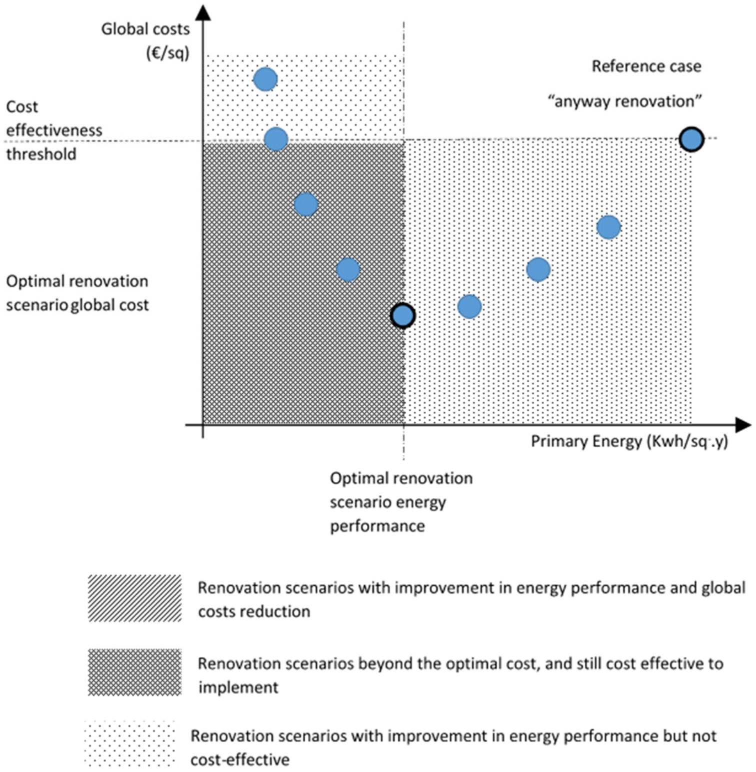

Figure 2. Generic representation of cost-effectiveness of different renovation scenarios. Source: adapted from [26].

3. Case Study

3.1. The Neighbourhood

This work focuses on the assessment of the relevance of the embodied portion of energy and carbon emissions in cost-optimal renovations at the neighbourhood scale. For this purpose, the Picoto neighbourhood in Braga (Portugal) was used as a case study to investigate the methodological framework proposed in this article. According to the Koppen and Geiger climate system, Braga is considered as Csb (Mediterranean warm/cool summer climates) [30]. The highest temperature in Braga is found in June (average of 20.3 °C) and the lowest in January (average temperature of 8.4 °C). The average annual temperature is 14.2 °C [31].

The Picoto neighbourhood was originally built in the 1990s for social housing purposes. It is currently managed by Bragahabit, which is the municipal company in charge of managing the public building stock of the city. The neighbourhood also represents the type of construction of the most prolific time in the promotion of adequate housing in low-income households in Portugal in the last century, which corresponds to the implementation of the PER (Special Resettlement Programme) in 1993. However, as in many built social infrastructures, the Picoto neighbourhood presents construction characteristics that prioritise affordability over performance. Consequently, most of the social housing stock—representing about 2% of the total national stock of buildings—presents low quality in terms of construction, with insufficient energy performance and inadequate thermal indoor conditions. In the case of the Picoto neighbourhood, there is also a noticeable lack of maintenance interventions throughout the years. The presence of informal self-constructions attached to the houses also contributed to the overall degradation of the neighbourhood. An aerial view of Picoto neighbourhood is shown in Figure 3.

Figure 3. Aerial view of Picoto neighbourhood.

The Picoto neighbourhood consists of fifty single-family houses of two stories. They are grouped into five rows of six dwellings each and two other rows of ten dwellings each. The orientations are approximately North–South and East–West. Buildings totalise 1767.10 m^2 of heated area. As stated, all buildings are similar from the constructive perspective, and the same materials are used. Each building is composed of two types of exterior walls. The designated "facade type 1"—F1—is constituted by a non-insulated wall with two plastered layers of hollow bricks (9 cm + 9 cm) and a U-value of 1.1 W/m^{2}K. On the other hand, the "facade type 2"—F2—which composes the lower part of the facade (closer to the ground) is constructed from concrete blocks (U-value of 1.9 W/m^{2}K) and the roof is covered by panels of undulating asbestos cement (U-value of 3.8 W/m^{2}K). The aluminium framed windows present only single glazing and a U-value of 5.70 W/m^{2}K. Materials were analysed in situ, whereas thermal properties were retrieved from a database used for informing national regulation [32]. Each house has a gas boiler powered by natural gas, with a performance of 80%, for domestic hot water supply. Space heating is guaranteed with individual electric heaters. These are common conditions in Portuguese households, which have no tradition of centralised approaches to heating the entire building, neighbourhood or district.

Considering these characteristics, the energy needs of the reference case were simulated using Energy Plus (Table 1). Typical user behaviour and occupancy profiles (including an average of 4 W/m^2 regarding internal gains) were considered [26]. Domestic hot water (DHW) needs were estimated according to national thermal regulations procedures, which considers a fixed value per person (40 L/person with a temperature increase of 35 °C). Temperature set points for thermal comfort were considered 18 °C in the heating season and 25 °C in the cooling season, and conversion factors for primary energy and greenhouse emissions also followed national thermal regulations requirements [33].

Table 1. Calculated energy demand for the neighbourhood.

	Heating		Cooling	DHW
Total neighbourhood load	(kWh/m^2 year) 164.31	(kWh/year) 290,335	(kWh/m^2 year) 7.33	(kWh/m^2 year) 26.16

3.2. The Renovation Scenarios

Fifteen measures were evaluated to improve the thermal performance of the envelope based on passive strategies and in accordance with the objectives and technologies proposed in the aforementioned IEA EBC Annex 75 project. In the first phase, a preliminary analysis of individual measures for improving the building envelope was performed. A comprehensive set of measures (considering different types of materials and thicknesses) were chosen to take into account common use in the Portuguese construction market and the consistency with the type of buildings found in the case study. Thermal properties for this analysis were collected from ITE50 [32]. The best results from the individual measures—according to various criteria: cost-effectiveness, best energy performance and cost—were then used for aggregating packages presented in Table 2.

Table 2. Proposed envelope renovation packages.

Renovation Packages for Improving the Buildings' Envelope				
		Facade	**Roof**	**Windows**
Renovation packages	P1	ETICS MW 80 mm (F1* and F2**)	Sandwich panel PUR 30 mm	PVC frame with double low emissivity glazing (U = 1.40 W/(m^{2}K)) with solar protection (g = 0.20)
	P2	ETICS EPS 80 mm (F1* and F2**)	Sandwich Panel MW 30 mm	Aluminium frame with double glazing (U = 3.30 W/(m^{2}K) and g = 0.76)
	P3	ETICS EPS 80 mm (F1* and F2**)	Sandwich panel PUR 30 mm	Aluminium frame with double glazing (U = 3.30 W/(m^{2}K) and g = 0.76)
	P4	ETICS EPS 80 (F1*) ETICS EPS 120 (F2**)	Sandwich Panel MW 100 mm	Aluminium frame with double glazing (U = 3.30 W/(m^{2}K) and g = 0.76)
	P5	ETICS MW 160 mm (F1*) ETICS MW 200 mm (F2**)	Sandwich Panel MW 100 mm	PVC frame with double low emissivity glazing (U = 1.40 W/(m^{2}K)) with solar protection (g = 0.20)

ETICS—external thermal insulation composite system; MW—mineral wool; EPS—expanded polystyrene; PUR—polyurethane foam; PVC—polyvinyl chloride; *F1—facade type 1; **F2—facade type 2.

The measures considered interventions in the following elements: (i) facades; (ii) sloped roofs; (iii) thermal bridges; (iv) windows. Table 2 shows the renovation packages that were prepared for dynamic simulation.

In addition, five new systems were designed to meet the need for hot water and space heating, as well as for space cooling. The first energy supply system (ESS1) is decentralised and considers individual equipment (per dwelling), which is representative of the solutions typically adopted for housing. The other four solutions represent options for centralised systems designed to meet all the neighbourhood needs, except for ESS3, the biomass boiler-based solution, which cannot meet cooling needs. This solution can be considered because the risk of having overheating in summer is low due to the specific characteristics of the building together with Braga's climate. Solutions 2, 4 and 5 are based on the use of heat pumps. In addition, the implementation of renewable energy, such as solar thermal and solar photovoltaic, was studied. Table 3 shows the proposed energy supply systems.

Table 3. Proposed energy supply systems.

	Energy Supply System (ESS)	**Heating**	**Cooling**	**DHW**	**RES**
System Solutions	1: Conventional Decentralised	Electric heater H = 1	Multi-split EER = 3	Natural gas heater h = 0.71	-
	2: Centralised heat pump	Heat pump COP/SCOP = 4.06/3.77	Heat pump EER/SEER = 3.97/8.41	Heat pump COP = 4.10	-
	3: Centralised biomass boiler	Biomass boiler H = 1.07	(zero)	Biomass boiler h = 1.07	-
	4: Centralised heat pump +ST	Heat pump COP/SCOP = 4.06/3.77	Heat pump EER/SEER = 3.97/8.41	Heat pump COP = 4.10	ST (DHW)
	5: Centralised heat pump +PV	Heat pump COP/SCOP = 4.06/3.77	Heat pump EER/SEER = 3.97/8.41	Heat pump COP = 4.10	PV (zero)

RES—renewable energy sources; ST—solar thermal; PV—photovoltaic system.

Finally, the twenty-five combinations resulting from combining each package of thermal envelope renovation measures with each proposed new energy supply system were studied and compared with the reference case with the help of a spreadsheet developed for this purpose. Results were plotted in scatter diagrams for comparison between the two indicators analysed.

4. Results

Figures 4 and 5 present the results for the cost-effectiveness calculations concerning the NRPE and GWP, respectively. The figures present the results for the two different approaches considered in this study. The operational energy approach (OE) results are represented by the outlined markers, while results from the whole life cycle approach (WLC) where embodied values are considered are represented by opaque markers. The different colours stand for the five energy supply systems, and the geometry of markers corresponds to each of the five renovation packages considered.

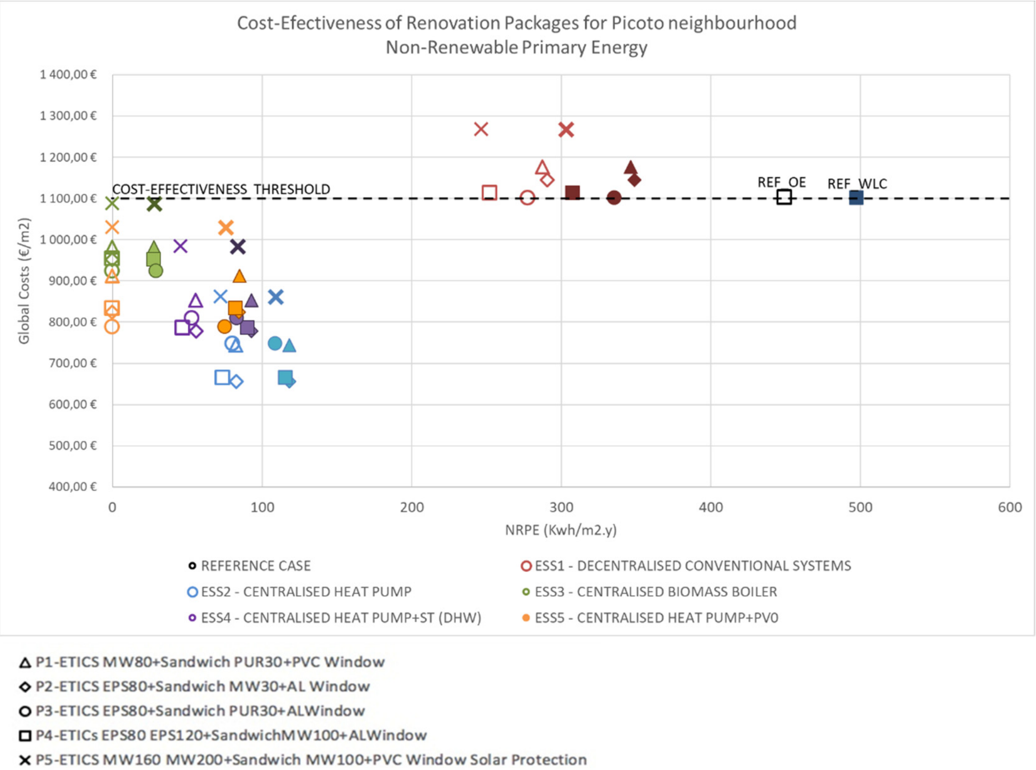

Figure 4. Cost-effectiveness non-renewable primary energy.

Except for the ESS1 (decentralised conventional systems), the results for the operational energy approach (without taking into account embodied values) indicate that the remaining four energy supply systems are cost-effective. In particular, the cost-optimal energy supply system is ESS2 (centralised heat pump), which present the lowest global costs. The global cost of the package of measures associated with this energy supply system ranges from 655.14 EUR/m^2 to 861.47 EUR/m^2, depending on the specific measures being implemented. For ESS2, the lowest value (655.14 EUR/m^2) for the global cost is associated with P2 (ETICS EPS 80 mm F1 and F2 + Sandwich Panel MW 30 mm+ AL Frame with double glazing). It should be highlighted that ESS5 (centralised heat pump + PV) and ESS3 (centralised biomass boiler) are the energy supply systems presenting the best performance by cost-effectively allowing a zero-emission neighbourhood independently of the chosen envelope renovation package. The renovation package P5 (ETICS MW160 + MW200+ Sandwich MW100 + PVC Window Solar Protection) is the one that consistently presents higher reductions both in terms of NRPE (an average of 82.21 kWh/m^2·y) and emissions (an average of 37.16 Kg CO$_{2eq}$) in all of the five energy supply systems. However, these significant reductions are also directly related to the highest cost of all renovation packages considered in this analysis.

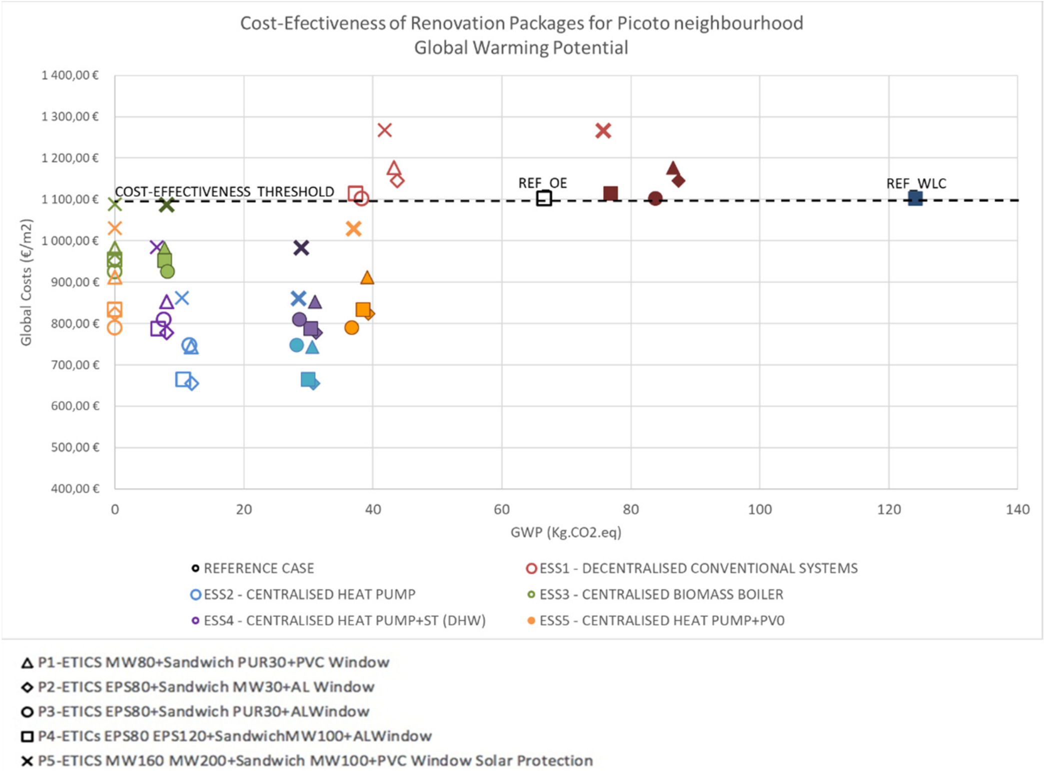

Figure 5. Cost-effectiveness global warming potential.

Results suggest that the cost-optimality of the renovation packages is related to the energy supply system that is considered in the renovation scenario. For the energy supply systems ESS1 (decentralised conventional systems), ESS3 (centralised biomass boiler) and ESS5 (centralised heat pump and PV), the cost-optimal renovation package is P3 (ETICS EPS 80 mm + Sandwich Panel PUR 30 mm + AL Frame with double glazing), which presents global costs of 1112.51 EUR/m^2, 951.08 EUR/m^2 and 832.39 EUR/m^2, respectively. For ESS2 (centralised heat pump) and ESS4 (centralised heat pump with a solar thermal system), the cost-optimal renovation package is P2 (ETICS EPS 80 mm + Sandwich Panel MW 30 mm + AL Frame with double glazing), which presents global costs of 665.14 EUR/m^2 and 777.05 EUR/m^2, respectively.

Regarding the whole life cycle approach, results from this study suggest that considering the embodied parcel both in energy and emissions does not affect the relative positioning between the analysed renovation packages and systems, although there is an expected overall increase in the value of the indicators. This increase is noticeable in the cases of the ESS3 (centralised biomass boiler) and ESS5 (centralised heat pump + PV), which led to zero energy and zero emissions. When the embodied values are considered, in terms of energy, the main differences could be found in ESS5 (centralised heat pump + PV), where the embodied values increased, on average, 80.64 kWh/m^2·y throughout all the renovation packages. ESS1 (decentralized conventional systems) also computed a relevant difference (average of 57.4 kWh/m^2·y). A particularly significant difference was found regarding the results on this energy supply system when associated with the renovation package P3 (ETICS EPS 80 mm F1 and F2, Sandwich Panel PUR 30 mm, Aluminium frame with double glazing), which presents a difference of 83.3 kWh/m^2·y. In the same direction, P4 (ETICS EPS80 EPS120, Sandwich Panel MW 100 mm, Aluminium frame with double glazing) also computed a relevant difference of 61.15 kWh/m^2·y, when compared with the operational energy approach. Not surprisingly, concerning embodied emissions, ESS1 (conventional decentralised systems) and ESS5 (centralised heat pump + PV) energy supply systems present the highest difference between the operational energy and the whole life cycle approaches. When embodied emissions are considered, ESS5 (centralised heat pump + PV) presents an average increase of 38.15 Kg CO_2 and ESS1 (decentralised conventional systems) 41.18 Kg CO_2 throughout all the renovation packages.

Concerning the carbon emissions associated with the renovation packages, the most significant difference between the two approaches was found in P3, which is composed of ETICS EPS 80 mm in both facades, Sandwich Panel PUR 30 mm in the roof and a new aluminium frame with double glazing windows. This renovation package is the one presenting higher difference when embodied emissions are considered in ESS1 (decentralised conventional systems), ESS2 (centralised heat pump), ESS3 (centralised biomass boiler) and ESS4 (centralised heat pump + ST). Results also found that P2—the package considering ETICS EPS 80 mm in both facades, a Sandwich Panel MW 30 mm in the sloping roof and new aluminium frame with double glazing windows—is the renovation package where the difference between considering embodied values and not considering these values is most notable (39.29 Kg CO_2) in ESS5 (centralised heat pump + PV).

Importantly, results highlight a negative effect on the achievable energy reduction of considering a whole life cycle approach. Results from this study suggest that, when embodied values are considered, they significantly impact the reductions promoted by the energy renovation interventions. Figure 6 shows the comparison between the two approaches in terms of average reductions achieved by the energy renovation interventions by the energy supply system. For operational energy approach, it uses the results from the energy demand calculations. Results regarding the whole life cycle approach in Figure 6 considers both the energy demand from the buildings and the embodied energy calculated by the LCA (as a result of Equation (2)). Although the decrease in the achievable reductions is relevant in all the studied energy supply systems, the effect is evident in ESS5 (centralised heat pump + PV). Here, the results indicate a reduction in the operational energy approach of 100% in terms of NRPE and carbon emissions. However, when the whole life cycle approach is analysed, it shows 84% and 69% reductions for NRPE and emissions, respectively. It should also be highlighted that in terms of individual package of measures, P3 (ETICS EPS 80 mm F1 and F2, Sandwich Panel PUR 30 mm, Aluminium frame with double glazing) is the one presenting the highest impact in terms of the difference between the two approaches. For instance, in terms of NRPE, it presents a difference in values averaging 10%. For emissions, the average difference in this package is 14%.

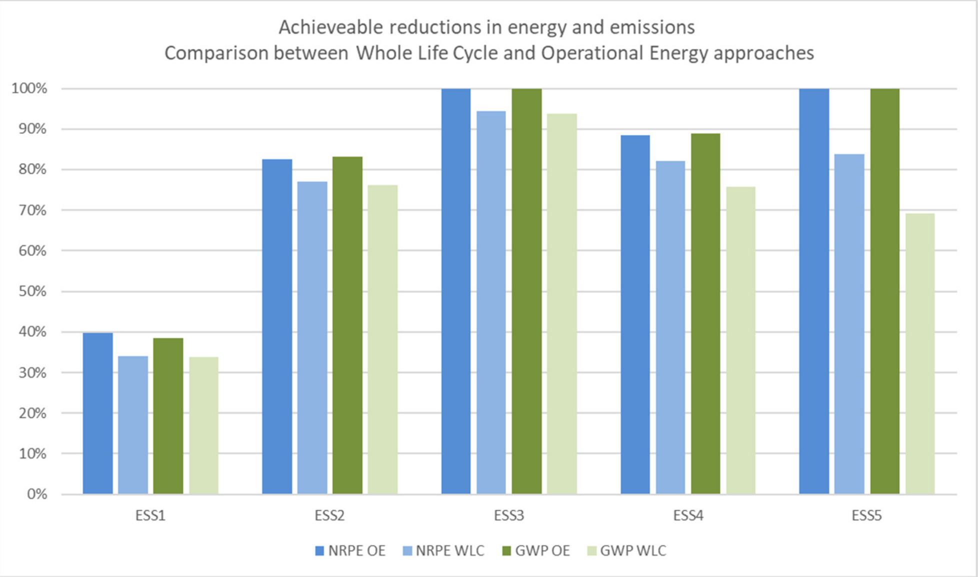

Figure 6. Comparison between achievable energy and emissions reductions. NRPE—non-renewable primary energy; GWP—global warming potential; OE—operational energy; WLC—whole life cycle.

5. Discussion

Addressing the whole life cycle of the building from an environmental assessment perspective is becoming increasingly important regarding the decarbonisation of the building stock. Buildings, both new and existing ones, are becoming progressively more energy-efficient. At the same time, the European Union is continuously pushing for more demanding regulations that would allow the necessary cuts in emissions by 2030 and 2050. As the operational energy (and corresponding carbon emissions) is being minimised, the embodied energy and embodied emissions remain mostly untreated, which is considered to be the next level on tackling "building performance levels" [6]. In this context, there is also an opportunity arising from the next revisions planned of the most important policy instruments concerning the field of energy efficiency in buildings, namely the EPBD and the Energy Efficiency Directive.

Considering life cycle emissions and energy from all phases of building materials is a complex task. It presents some significant challenges, such as the lack of available data and different boundary conditions. However, there is already evidence that embodied values can be determinant for achieving energy and emissions objectives. While some studies address the subject at the building scale level [8,27,34], research results point out that in interventions at a larger scale, such as the ones needed to achieve such ambitious results, the consideration of embodied values can offset reductions considerably [13]. However, results from this study suggest that there are some advantages in intervening at the neighbourhood scale using a centralised approach. These advantages are notable concerning, for example, the cost-effectiveness of a heat pump and the emissions in relation to decentralised systems (commonly used in Portugal). However, the results suggest that some caution is advised for interventions associated with renewable energy sources, such as solar thermal and PV panels. These interventions are beneficial when an operational energy approach is considered but can negatively impact the achieved reductions in energy and emissions when the whole life cycle of the intervention is considered. These results are in line with previous studies, such as [35,36], which also drew attention to the importance of the different energy mixes in the different contexts under analysis.

6. Conclusions

There is growing evidence that as the operational energy is being reduced in existing buildings—partially due to successful energy renovations—the relevance of the environmental performance of these interventions is becoming more significant. In this context, embodied energy and emissions are entering the realm of policy discussions, and their central place is becoming evident.

This study intends to contribute to the ongoing discussions by investigating the integration of life cycle assessment in cost-effectiveness calculations at the neighbourhood scale by comparing the operational energy approach and the whole life cycle approach and using a social housing neighbourhood located in Braga, Portugal, as a case study. For this study, the non-renewable primary energy and the global warming potential were used as main indicators.

Results suggest that the consideration of the embodied values (in the whole life cycle approach) does not affect the relative positioning of the renovation measures in cost-effectiveness analysis when compared with the operational energy approach (which does not consider the embodied values). However, there is an expected increase in the values of the indicators analysed. This is particularly visible in the results of renovation measures calculated under ESS3 (centralised biomass boiler) and ESS5 (centralised heat pump + PV) systems. When using the ESS5 system (centralised heat pump + PV), the difference in primary energy values, whether considering or not the embodied energy of the materials used in the renovation intervention, is, on average, 80.64 $\text{kWh/m}^2\cdot\text{y}$. On the other hand, the results also show that the difference between considering or not the emissions embodied in the materials used in the renovation packages simulated in the ESS5 is, on average, 38.15 Kg CO_2. Still, concerning carbon emissions associated with ESS1 (conventional decentralized systems) and the different renovation packages simulated under this system, the difference between the two approaches is, on average, 41.18 Kg CO_2.

Notably, the consideration of embodied values has a negative impact on the potential achievable reduction both in terms of energy and emissions. The decrease in the reduction achieved is noticeable in almost every renovation package and energy supply system, with particular relevance in the case of ESS5 (centralised heat pump + PV). For this energy supply system, results suggest that there is a significant negative effect in the achievable energy and emissions reduction when the whole life cycle approach is considered. The calculations concerning this energy supply system show that energy and emissions reductions are, on average, 16% and 31% lower when the embodied values are considered.

Although results are related to the Portuguese context, the study is useful for demonstrating the applicability of the approach and offering insights into the implications at the neighbourhood level. With very few adaptations, the integration between LCC and LCA as used in this study can easily be applied to different national contexts. The most critical point for the application of the methodology would be data availability and accessible inventories, namely regarding environmental impacts. This study, which aimed to test the methodology, used a very limited number of renovation packages. In terms of future studies, including a broader range of renovation measures can also provide useful information for performing cost-effectiveness calculations and informing policy decision making and formulation, such as the integration of embodied values in building energy regulations. In this regard, results from studies such as this one can be helpful to inform policy regarding the impact of considering a whole life cycle approach in decarbonisation plans of the built environment, which can constitute a critical point for policy formulation in the energy efficiency field.

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