

Article

Effect of Embodied Energy on Cost-Effectiveness of a Prefabricated Modular Solution on Renovation Scenarios in Social Housing in Porto, Portugal

Manuela Almeida , Ricardo Barbosa  *  and Raphaele Malheiro

Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal;
malmeida@civil.uminho.pt (M.A.); raphaelmalheiro@gmail.com (R.M.)

* Correspondence: ricardobarbosa@civil.uminho.pt; Tel.: +351-253-510-200

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Abstract: A large-scale energy renovation intervention in existing buildings has been consistently presented as the most significant opportunity to contribute to achieving the European targets for 2030 and 2050. One of the key points for such achievement is the cost-effectiveness of the interventions proposed, which is also closely related to decent housing affordability. Prefabricated modular solutions have been pointed out as a pathway, but there are knowledge gaps regarding both its cost-effectiveness and its environmental performance. Considering a social housing multi-family building in Porto, Portugal, as a case study, this research employs energy simulations, a cost-optimal methodology and a life cycle analysis approach to assess the influence of considering embodied energy and emissions in cost-effectiveness calculations. In general terms, the hierarchical relation between calculated renovation scenarios remain identical, as well as the choice of the cost-optimal combination, which can reduce primary energy needs by 226 kWh/(y.m²). However, embodied carbon emissions and embodied energy of the materials used in the calculations, which are indicative of the sustainability of such interventions, increase the energy and carbon emissions associated to each renovation package by an average of 43 kWh/(y.m²) and 9.3 kgCO_{2eq}/(y.m²), respectively.

Keywords: modular; prefabricated; renovation panel; energy renovation; cost-effectiveness; embodied energy; social housing

1. Introduction

Cities hold significant responsibility in terms of energy and resources consumption. Urban areas, which accommodate more than half of the global population, consume up to 80% of global material and energy supplies and produce around 75% of the carbon emissions worldwide [1]. The countries belonging to the Organization for Economic Cooperation and Development (OCDE), for example, emitted 9.6 tons of CO₂ per capita on average in 2013, solely from fossil fuel combustion. The latest data from OCDE also indicated that emissions per capita ranged from 4 to 18 tons per person in 2015 and that in Portugal these emissions were close to 4 tons per person in that year [2]. Buildings are accountable for a determinant share on carbon emissions, in particular, related with energy consumption [3], and there is strong evidence that improving the energy efficiency of the existing built environment is one of the most effective ways to achieve the ambitious goals that European Union (EU) established for 2050 [4].

The EU has set environmental and energy targets to be achieved by 2030 and by 2050 to reach a more competitive, safe and low carbon economy [4,5]. Regarding the building sector and within the regulatory initiatives elaborated in this context, the Energy Performance of Buildings Directive (EPBD), and in particular, its recast in 2010, can be considered a turning point where new game-changing

concepts were introduced, such as the nearly Zero-Energy Buildings (nZEB) [6], which are characterized by a high energy performance. The nearly zero or very low amount of energy required in these buildings must be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby [6]. Notably, according to this directive, Member States should ensure that from 31 December 2020, all new buildings are built as nZEB [6]. Although this timeline is considered to be determinant for the achievement of the EU targets, many of the current policies still have their main focus on new buildings, which some studies indicate as not being sufficient. The majority of the European building stock has more than twenty years old and present low energy performance [7]. Considering the significant energy reductions that can be achieved by cost-effective energy renovations and that the replacement rate of existing buildings by new buildings is only around 1% to 2% per year [8], there is significant potential for decarbonization of the building stock.

To unlock this potential, it is necessary to promote a large-scale energy renovation throughout Europe. There are, however, significant and well-known barriers to overcome [9]. One of the most mentioned barriers concerns the cost of interventions, which is closely linked to the concept of housing affordability [10]. Cities of today are under different kind of constant pressures, such as gentrification and speculation in the housing prices, and some authors argue for the urgent need to guarantee affordable housing [11]. The question of affordability is also determinant for reasons of energy poverty alleviation, in particular, when sensitive contexts are in place, such as in the case of renovation of social housing buildings [12].

In this context, there is a growing trend concerning the exploration of new solutions that can provide economic advantages in comparison with the conventional renovation solutions, which are already well implemented in the construction sector. One of the directions pointed out by a significant number of research studies is the use and implementation of modular prefabrication construction technology and techniques, which presents significant potential in economic, environmental, energy and material terms. Solutions produced in industrial assembly lines are potentially more accessible because the process is easily replicable, and the procurement of raw materials is higher, resulting in lower costs and greater economies of scale. The simplification of the assembly process of prefabricated solutions substantially reduces the time of application in the building and the construction waste. Furthermore, the prefabrication of renovation solutions guarantees greater quality control [13].

Although the modular prefabricated solutions for building renovation have been approached from distinctive perspectives in previous research studies (e.g., Reference [14]), in particular, in Northern Europe countries, there is a limited number of studies concerning implementation in southern Europe, where this kind of solutions are usually directed for new construction of industrial and office buildings. In addition, there is an important gap in knowledge about the environmental performance of this type of solution, but there is evidence in the literature that points out positive environmental outcomes [15]. The environmental performance of the existing buildings is directly related to the materials that are added to the building and with the energy that is spent in the process. Thus, although the impact of a building renovation would be smaller when compared to the construction of new buildings where larger amounts of materials are involved [16], the type of solution adopted is determinant for its environmental performance. In this sense, this paper investigates the influence of the embodied energy and embodied carbon emissions on the cost-effectiveness of several renovation scenarios in a southern European context, compiling different solutions, including a modular prefabricated panel developed in the University of Minho in a framework of a European research project designated as MORE-CONNECT.

Using a social housing multi-family building located in Porto, Portugal, as a case study, the methodology employs energy simulations and intends to balance the primary energy demand and the global costs of each renovation scenario, to compare them using a life cycle approach, which differs from the common approach that focus only on energy during the operation phase [17]. The methodology used in this study is presented in Section 2. Section 3 describes the case study building.

Results from the analysis are presented and discussed in Section 4. Finally, conclusions are presented in Section 5.

2. Methodology

With the objective of comparing the effects of embodied energy and the carbon emissions on the cost-effectiveness of renovation scenarios, the methodologic framework used in this study comprises a two-step approach: A cost optimal methodology and a life cycle assessment, both described in the next two sub-sections.

2.1. Cost-Optimal Methodology

The procedure used in this study is in line with the cost-optimal calculations methodology indicated by the EU Delegated Regulation No. 244/2012 [18] as a complement to the recast of the Energy Performance of Buildings Directive (EPBD-recast) [6]. The first step of the methodological framework is the cost-optimal methodology, which is based on the comparison of several renovation scenarios with a reference case, composed of what has been designated as “anyway renovation” measures. The “anyway renovation” measures constitute a renovation intervention where the energy performance of the building is not improved, just dealing with aesthetical, functional and structural issues. This reference case is also useful to establish the threshold for the cost-effectiveness of renovation scenarios. If a renovation scenario presents a lower energy demand and lower costs than the reference case, it is considered cost-effective. The renovation scenarios consist of packages of renovation measures that include improvements in the building envelope and in the Building Integrated Technical Systems (BITS), such as an air-conditioning system or a gas boiler, together with the inclusion of renewable energy sources. The comparison between the renovation scenarios requires the calculation of the energy use related to each of them, as well as the calculation of the related carbon emissions and global costs.

According to this methodology, the method for energy calculation should be chosen in accordance with local thermal regulations, given the existing diversity of climate conditions and construction characteristics. In this study, building energy performance calculations were based on the quasi-steady-state method officially prescribed in the Portuguese legislation [19]. This method is widely used in Portugal and results can be used as a benchmark for comparison with other studies in the same context. Detailed data regarding real energy consumptions for heating and cooling is not available at this scale. For calculations regarding renewable energy supply sources, SCE.ER [20], and PVGIS [21] were used. The global costs calculation used was based on the current market reference prices [22], and includes all costs, namely, investment costs, maintenance costs, energy costs, replacement and disposal at the end of the calculation period. The costs assessment considered not only the materials and systems involved in the interventions, but also preparatory works (such as scaffolding) and man-hour costs. Although the focus of the study is on the methodological approach, the use of established methods for assessing energy and costs was considered important to increase the level of confidence in the results. The calculations considered a life cycle of 30 years, in line with the previously cited EU Delegated Regulation methodology. In order to take into account future costs, the methodology follows the annuity method. The annuity method is favorable in the case of parametric cost assessments of various packages of renovation measures. By using the annuity method described in another study [23], it is not necessary to determine residual values at the end of a present assessment period for measures, which have a longer life than the assumed time horizon of the cost assessment. This way, it allows obtaining average yearly values for measures with different service lives.

The results of the comparison of the different renovation packages can be illustrated with the help of graphs, where the *x*-axis presents the primary energy use and the *y*-axis presents the global costs (Figure 1).

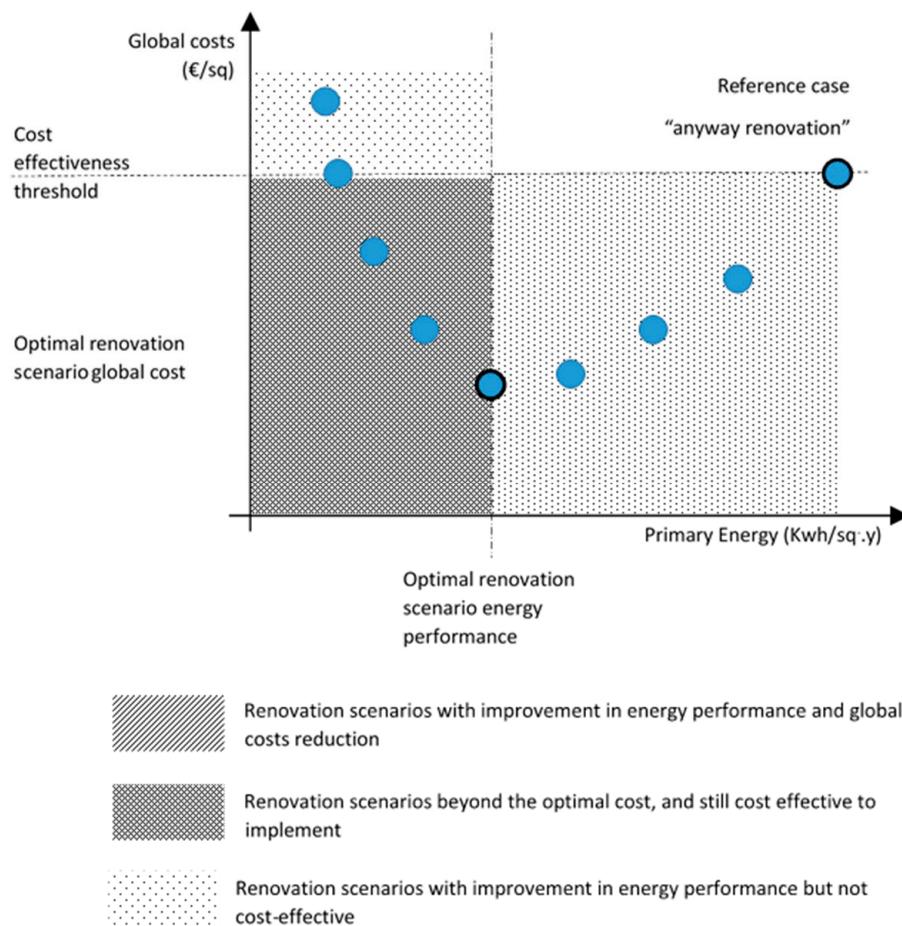


Figure 1. Cost-effectiveness threshold and identification of the cost-optimal renovation scenario. Source: Adapted from Reference [24].

2.2. Life Cycle Assessment

In this study, a Life Cycle Analysis (LCA) approach was used to expand the cost-optimal methodology. The methods used in this study concerning the LCA analysis are detailed in the Annex 56 report – Life Cycle Assessment methodology for energy-related building renovation [16].

The LCA methodology is used to quantify the embodied primary energy and embodied carbon emissions concerning the manufacturing, replacement and end-of-life of construction materials and BITEs added during a building renovation [16]. Many indicators have been developed in LCA, describing environmental impacts, resource use or additional environmental information. However, from a practical point of view, the number of indicators in this study has been limited to three: Carbon emissions represented by the global warming potential (quantifying the amount of CO₂ involved in each renovation package), cumulative Non-Renewable Primary Energy (NRPE) demand and cumulative total primary energy demand [16].

To perform a LCA analysis, it is fundamental to define two types of system boundaries: The temporal boundary (defining elementary stages, occurring during the life of the building), which was defined according to EN 15978 standard [25], and the physical boundary (where materials and energy flows are defined). The focus of the analysis is on energy-related measures applied in buildings, and therefore, the LCA assessment only took into account measures that affect their energy performance (thermal envelope, building integrated technical systems and energy use for on-site production and delivered energy). To assess the impact of the renovation scenarios analyzed in this study, the number of materials involved was calculated for each measure and was multiplied by the related impacts in

terms of embodied energy and carbon emissions (by energy carrier). Results are expressed per unit of surface area per year after dividing the LCA results for the reference study of the building (30 years). The LCA for building renovation, taking into account materials and BITS, as well as the operational primary energy use, was calculated according to Equation (1) [16].

$$\text{PE}_{\text{building}} = \text{PE}_{\text{materials}} + \text{PE}_{\text{BITS}} + \text{PE}_{\text{op energy use}} \quad (1)$$

where $\text{PE}_{\text{building}}$ is the primary energy associated to the building renovation, $\text{PE}_{\text{materials}}$ is the primary energy associated to all materials which were used in the building renovation, PE_{BITS} is the primary energy associated to the BITS, and $\text{PE}_{\text{op energy use}}$ is the calculated primary energy for the operational energy use. The same logic applied to Equation (1) is used for the carbon emissions calculations. Furthermore, for the purpose of differentiating the primary energy demand (and carbon emissions), which consider the different stages in the building life cycle, the terms “embodied primary energy” and “embodied carbon emissions” were applied. The assessment used an LCA database developed for the Portuguese context [26].

3. Case Study Building and Renovation Scenarios

3.1. Definition of the Case Study Building

The case study used in this research is a social housing building, built in 1997 (Figure 2). It is managed by the municipal company GAIURB, and it is considered to be representative of the type of construction of the national building stock of multi-family buildings built between 1991 and 2012. This type of construction represents around 40% of the multi-family buildings in Portugal [27].



Figure 2. Main (a) and back (b) façades of the pilot building in Vila Nova de Gaia, Portugal.

The building is situated in, Porto Metropolitan Area, in the north region of Portugal. The location of the building is classified as Csb (Mediterranean warm/cool summer climates) in the Köppen and Geiger climate system. The average annual temperature is 14.4 °C with the hottest month being August (average of 19.6 °C) and January being the coldest with an average of 9.1 °C [28].

The building has a predominant west–east orientation. It has three separate entrances, each giving access to three floors and corresponding to six apartments (a two-bedroom apartment and a three-bedroom apartment per floor). In total, the building has eighteen apartments. Aluminum frame windows with double-glazing, pitched roof with ceramic tiles (3 cm of insulation) and double pane masonry walls without thermal insulation constitute the building envelope. The domestic hot water is provided through a gas heater available in each apartment, and there is no central heating or cooling system installed in the building.

Table 1 characterizes the main building areas, and Table 2 presents the most important energy parameters of the pilot building. Calculated energy needs and primary energy for the existing situation clearly indicate a low energy efficiency and the need for intervention. The energy needs correspond to the energy needed to achieve a certain level of comfort temperatures, and the primary energy is the energy as found in nature, and unlike the energy needs, take into consideration equipment efficiency and conversion factors from the energy sources used.

Table 1. Main building areas of the case study in Porto, Portugal.

Building Footprint	GHFA *	Average GHFA * Per Person	Wall Area (Excl. Windows)	Roof Area	North Windows	East Windows	South Windows	West Windows
582 m ²	1265 m ²	20 m ²	2712 m ²	622 m ²	0 m ²	22 m ²	0 m ²	11 m ²

* GHFA—gross heated floor area.

Table 2. Building energy parameters of the case study in Porto, Portugal.

Energy Parameters	Unit	Data
Typical indoor temperature (Heating/Cooling Season)	°C	15/25 *
U-value wall	W/(m ² .K)	0.96
U-value attic floor	W/(m ² .K)	0.91
U-value windows	W/(m ² .K)	3.60
g-value windows	Factor	0.78
Energy needs for cooling	kWh/(y.m ²)	2.20 **
Energy needs for heating	kWh/(y.m ²)	53.36 **
Energy needs for hot water	kWh/(y.m ²)	29.60 **
Primary energy needed for cooling, heating and hot water	kWh/ (y.m ²)	177 **
Airflow rate	ac/h	1.73 *

* Average value obtained from a one year measurement campaign (2017); ** Simulated values.

The building envelope presents signs of deterioration, indicating a need for an immediate repair intervention. The common areas of the building (stairs, halls and walls) show evident signs of humidity and mold. Inside the apartments, thermal discomfort is common, and mold is clearly visible in the corners of the walls and near the windows. Extensive mold areas can also be found in some of the rooms and bathrooms ceilings. Some of the apartments have portable electrical heaters ($\eta = 100\%$) although the majority does not have any heating system installed. In general, identified current renovation needs can be related to the correction of thermal bridges, the need to an increase of the insulation level and the installation of a heating system. Despite the importance of its representativeness, the building was chosen as a case study also because, within the scope of the More-Connect research project, there was the opportunity to assist in decision making in choosing the best renovation solution to implement.

3.2. Renovation Scenarios Definition

3.2.1. The More-Connect Renovation Solution

The EU H2020 More-Connect research project (<https://www.more-connect.eu/the-project/>) aimed at developing cost-optimal solutions for deep renovations towards nZEB buildings. The project focused on the improvement of the energy performance of the building, through the development of prefabricated solutions for façades and roofs that can contribute to achieving the nZEB level. In the context of this research project, the University of Minho developed a prefabricated modular panel to improve the insulation level of the exterior walls of the existing building. The renovation solution comprises a wood frame, an internal/external cladding made of Coretech®sheets and a filling material of polyurethane foam (Figure 3).

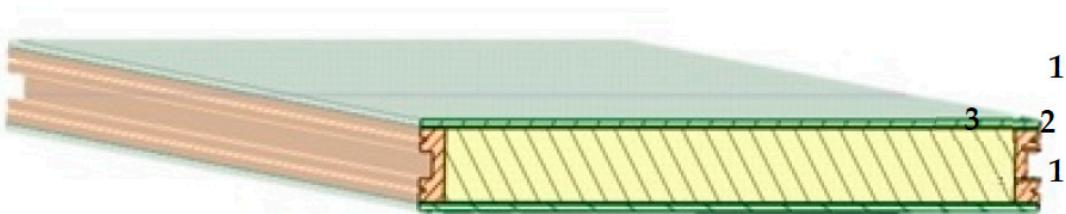


Figure 3. Prefabricated element for façade renovation: (1) Coretech® sheets, (2) Wood frame and (3) Polyurethane foam.

During its development process, aspects such as reuse and recycling were considered to support the decision in selecting the most appropriate materials for each prefabricated panel element. Regarding the frame structure, wood was chosen for its high thermal performance, allowing reducing thermal bridges, particularly in the connection between modules. Also, at the end of the service life, wood can be easily reused for secondary materials or used in processes of energy recovery. In the external/internal cladding of the façade modules, it was decided to use Coretech® that is a material manufactured with recycling by-products from the automotive industry, contributing, this way, to reduce the exploitation of raw materials and the amount of waste. In addition, it presents attractive characteristics, such as high durability, water and fire resistance, as well as a low U-value [29]. Several alternatives for the insulation material, including bio-based materials, were assessed against a set of criteria that included the ability to reuse and recycle the material, but also the cost, thickness/efficiency ratio, weight and material availability in the Portuguese context. For the insulation of the cavity of the panel, injected polyurethane foam was selected. This choice is strongly related to its recognized high thermal performance and high durability together with considerable low weight.

In this project, the developed panel is to be applied in the existing building with the dimensions of 10.00 m high and 2.40 m width. The panel, with a total thickness of 12 cm and a density of 19.70 kg/m³, consists of two 1 cm thick layers of Coretech®, a 10 cm thick wood frame and a 10 cm thick layer of polyurethane foam. The assembly between the modules is made of a male-female connection in the wood frame. For a correct and effective application of the panel, it was necessary to create an interface between the existing building wall and the prefabricated element to absorb the irregularities of the contacting surfaces and ensure continuous insulation. For this interface, it was used as a layer of mineral wool (MW) with a density of 25 kg/m³. A prototype of the module with 2.55 m × 1.00 m was built and tested at the University of Minho facilities. Thermal chamber tests indicated a thermal transmittance of 0.7 W/m².K. The system was designed to be built offsite, using an industrial assembly line, in opposition to the layered manual traditional construction techniques usually applied in Portugal. The system will be produced in different size modules to adapt to the different dimensional needs of buildings.

3.2.2. Selection of Renovation Scenarios to be Analyzed

To achieve the objectives of the study, various energy renovation scenarios (envelope renovation package plus systems solutions) were considered. The renovation scenarios considered in the analysis have an emphasis on the prefabricated modular approach, but include additional measures to improve the building envelope and systems solutions, providing heating, cooling and renewable energy. In addition to the prefabricated modular solution, combinations of building envelope measures (improvement of the roof, cellar ceiling and windows) with building systems, take into account the common use and applicability in the national context (Table 3). In the Portuguese context, the replacement of windows is a very common renovation measure, not only for its recognized benefits regarding improved thermal insulation and thermal comfort, but also because of its contribution to achieving a better acoustic environment and an increased airtightness in dwellings. Although detailed

considerations regarding airtightness are out of the scope of this study, it is worth mentioning that the replacement of the windows did not lead to a significant decrease of the airflow rates, which is consistent with the results found in other studies (e.g., [30]). In addition, it should also be highlighted that the airtightness resulting from the renovation measures considered in this study complies with the minimum requirements determined by the Portuguese legislation in what concerns the indoor air quality in both winter and summer periods.

Table 3. Proposed envelope renovation packages for the pilot building.

Renovation Package	Description
Reference	The walls are repaired and painted, and the pitched roof is refurbished (with new tiles). These measures do not improve the energy performance of the building
M1	The walls are insulated with ETICS—8 cm EPS ¹
M2	The walls are insulated with a prefabricated element (12 cm) and 6 cm MW ² layer
M3	The walls are insulated with a prefabricated element (12 cm) and 10 cm MW layer
M4	M3 plus the refurbishment of the roof (including membrane), roof battens, shuttering, gutter and a 6 cm MW layer
M5	M3 plus the refurbishment of the roof (including membrane), roof battens, shuttering, gutter and a 12 cm MW layer
M6	M3 plus the refurbishment of the roof (including membrane), roof battens, shuttering, gutter and a 14 cm MW layer
M7	M6 plus the cellar ceiling is insulated with 6 cm MW layer
M8	M7 plus the new windows (aluminum frame and a U-value of 2.70 W/m ² °C)
M9	M7 plus the new windows (aluminum frame and a U-value of 2.40 W/m ² °C)
M10	M9 plus a solar thermal system is installed
M11	M3 plus the refurbishment of roof with 6 cm of polyurethane (including membrane) roof battens, shuttering, and gutter. The cellar ceiling refurbished—6 cm XPS ³
M12	M11 with optimized costs for the production of the prefabricated element

¹ EPS—expanded polystyrene; ² MW—mineral wool; ³ XPS—extruded polystyrene.

The first renovation package (Reference) comprises the reference situation from which the cost-effectiveness is going to be evaluated, as explained in Reference [24], and shown in Figure 1. The renovation package M1 comprises the application of an 8 cm thick layer of expanded polystyrene (EPS) in an external thermal insulation composite system (ETICS). This solution is the most common solution used in building energy renovation in Portugal, and it has already been identified in another study [30] as being the cost-optimal solution for the envelope of this kind of buildings. The subsequent renovation packages (from M2 to M11) explore different insulation thicknesses and progressively test new levels of intervention for the building renovation. The last renovation package (M12) intends to explore the effect of future optimization of the prefabricated panel production costs. Currently, the developed modular prefabricated panel has very high investment costs because it does not yet have an optimized assembly line designed for mass production. According to calculations led by the manufacturing company participating in the More-Connect project, while taking into account the Portuguese industrial context, improvements in the production process, as well as economies of scale derived from mass production, would originate a reduction of 70% in the production costs.

In terms of systems, Table 4 shows the different systems solutions considered in this study in terms of heating, cooling, Domestic Hot Water (DHW) and Renewable Energy Sources (RES).

The systems shown in Table 4 are in line with the multitude of implemented options found in the Portuguese context and include innovative solutions regarding the use of renewable energy sources, with high potential for energy and emissions reduction. The conventional system solution (electric heater for heating, multisplit system for cooling and gas heater for DHW) is the default solution to be considered in the existing building before the intervention as mentioned by the Portuguese legislation [19].

In system solution D, the photovoltaic contribution consists of an installation with a peak power capacity of 7.50 kWp. The sizing of this contribution was calculated to compensate for theoretical heating needs. In system solution F, the photovoltaic contribution consists of an installation with the necessary capacity to compensate the energy needs fully. Similarly, in system solution G, the size of the photovoltaic system is adequate to compensate the heating and cooling needs, whereas,

domestic hot water (DHW) is supported by a solar thermal installation, sized according to the minimum requirements of the Portuguese legislation.

Table 4. Proposed systems solutions for the building.

System Solution	Heating	Cooling	DHW	RES
Conventional	Electric heater $\eta = 1$	Multisplit EER = 3	Gas heater $\eta = 0.71$	
A	Multisplit COP = 4.1	Multisplit EER = 3.5	Gas heater $\eta = 0.71$	
B	Gas boiler $\eta = 0.93$	Multisplit EER = 3.5	Gas boiler $\eta = 0.93$	
C	Biomass boiler $\eta = 0.92$	Multisplit EER = 3.5	Biomass boiler $\eta = 0.92$	
D	Heat Pump COP = 3.33	Heat pump EER = 2.68	Heat Pump COP = 3.33	PV ¹ (7.5 kWp)
E	Heat Pump COP = 3.33	Heat pump EER = 2.68	Heat Pump COP = 3.33	
F	Heat Pump COP = 3.33	Heat pump EER = 2.68	Heat Pump COP = 3.33	PV (Zero) ²
G	Multisplit COP = 4.1	Multisplit EER = 3.5	Electric Boiler COP 1.5	PV (Zero) ST ³ for DHW

¹ PV—Photovoltaic; ² PV (Zero)—Photovoltaic contribution consists of an installation with the necessary capacity to fully compensate the energy needs for heating and cooling; ³ Solar Thermal (ST)—Solar Thermal contribution consists of an installation, sized according to the minimum requirements of the Portuguese legislation.

After an overall analysis, due to budget constraints and material availability, the building owner selected the renovation package M11 and system solution C as the measures to be implemented in the renovated building. To assess the performance of this very specific option, the Selected System Combination (SSC), shown in Table 5, was calculated, and the results are shown in the next section.

The system solution in this combination (Table 5) is identical to system solution C without the system to deal with the cooling needs. The Portuguese thermal regulation [19] allows this simplification whenever the overheating risk in summer is minimum, which is quite common in a substantial part of the Portuguese territory. There is an expeditious method to evaluate the risks of overheating, which is to calculate the heat gains utilization factor that depends on the thermal mass and on balance between heat gains and heat losses throughout the building envelope. When this factor is higher than the reference value (which is true in the building under analysis), the overheating risk is non-existent, and the cooling needs are not accounted for in the calculated energy needs. This is a very common situation in existing Portuguese buildings, due not only to specific climate conditions, but also to significant heat losses and medium to high thermal mass that characterizes a significant number of residential buildings in Portugal.

In accordance with the national thermal regulations, the analysis performed in this study only calculated the non-renewable primary energy (NRPE) share of the total primary energy and the respective emissions.

Table 5. Renovation package and system solution for the Selected System Combination to be implemented in the renovated building.

Renovation Package	System Solution		
	Heating	Cooling	DHW
M11 (M12 ¹)	Biomass boiler $\eta = 0.92$	—	Biomass boiler $\eta = 0.92$

¹ M12 corresponds to M11 with optimized production costs of the prefabricated panel.

4. Results and Discussion

4.1. Cost-effectiveness of Renovation Packages

Figure 4 shows the results in terms of global costs ($\text{€}/\text{m}^2$) and NRPE—Non-Renewable Primary Energy ($\text{kW.hEP}/(\text{y.m}^2)$) of the combinations considered in the calculations between the twelve renovation packages (Table 3), the eight systems solutions (Table 4) and the selected system combination (Table 5). In Figure 4, the results are presented, not considering the embodied energy of the materials used in the renovation.

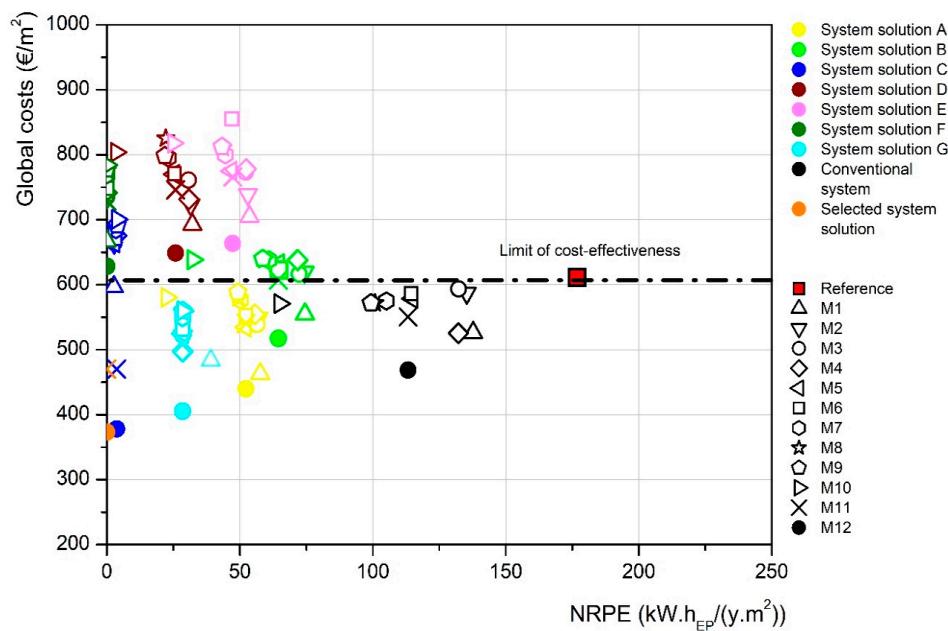


Figure 4. Cost-optimal results for the analyzed renovation packages without considering the embodied energy of the materials used in the renovation.

4.2. Cost-effectiveness of Renovation Packages Per System Solution

To compare the effect of embodied energy and carbon emissions in the cost-effectiveness of renovation scenarios, Figures 5–12 present the calculation results for renovation packages per system solution with and without considering the embodied energy of the materials in terms of global warming potential represented by carbon emissions ($\text{kg.CO}_2\text{eq}/(\text{y.m}^2)$) and cumulative primary energy ($\text{kW.h}/(\text{y.m}^2)$) per year. In the graphs, maximum difference (in red) and minimum difference (in green) in indicators considering results with and without the embodied energy and emissions parcel are highlighted in color and by indicating the measure number. The results are presented, taking into consideration annualized costs ($\text{€}/(\text{y.m}^2)$).

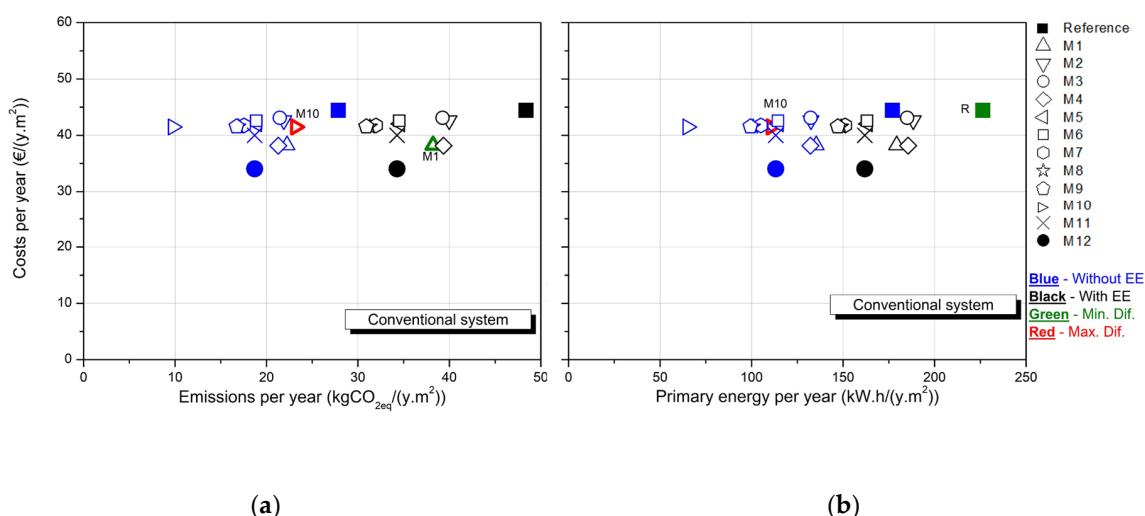


Figure 5. System solution—Conventional: (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

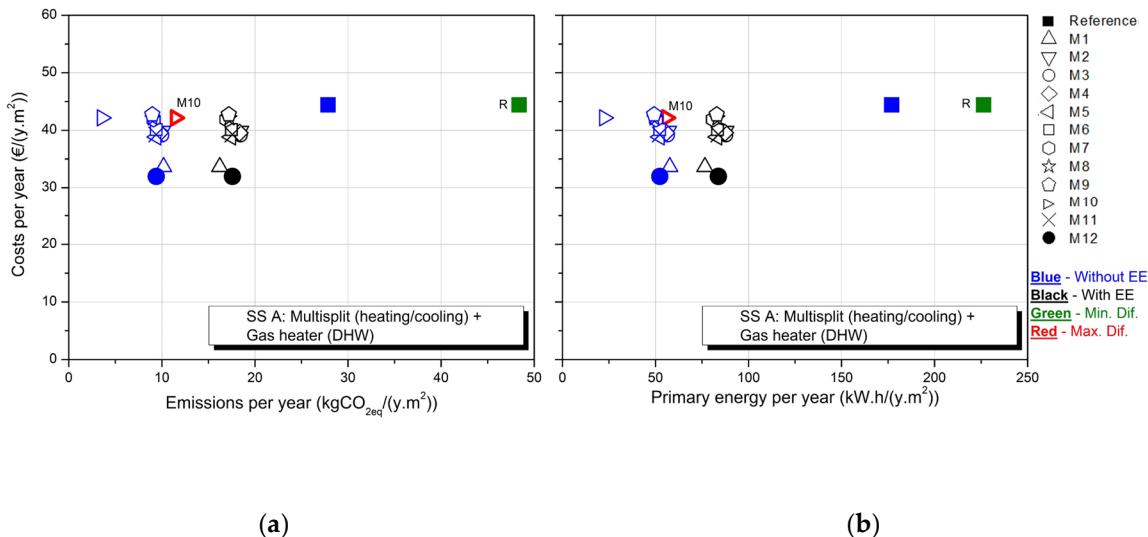


Figure 6. System solution A—Multisplit (heating/cooling) + Gas heater (DHW): (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

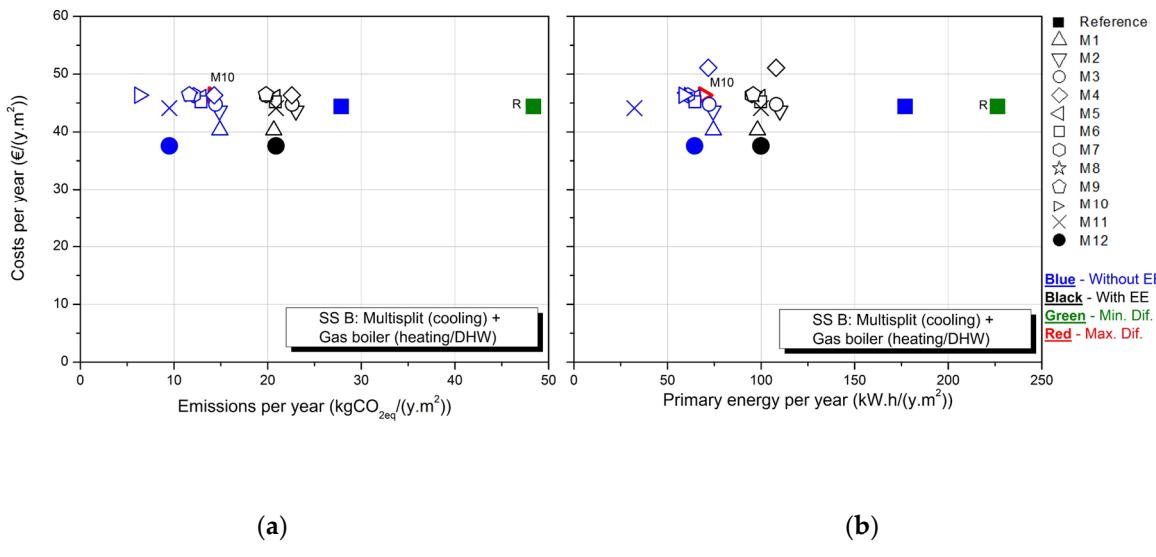


Figure 7. System solution B—Multisplit (cooling) + Gas boiler (heating/DHW): (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

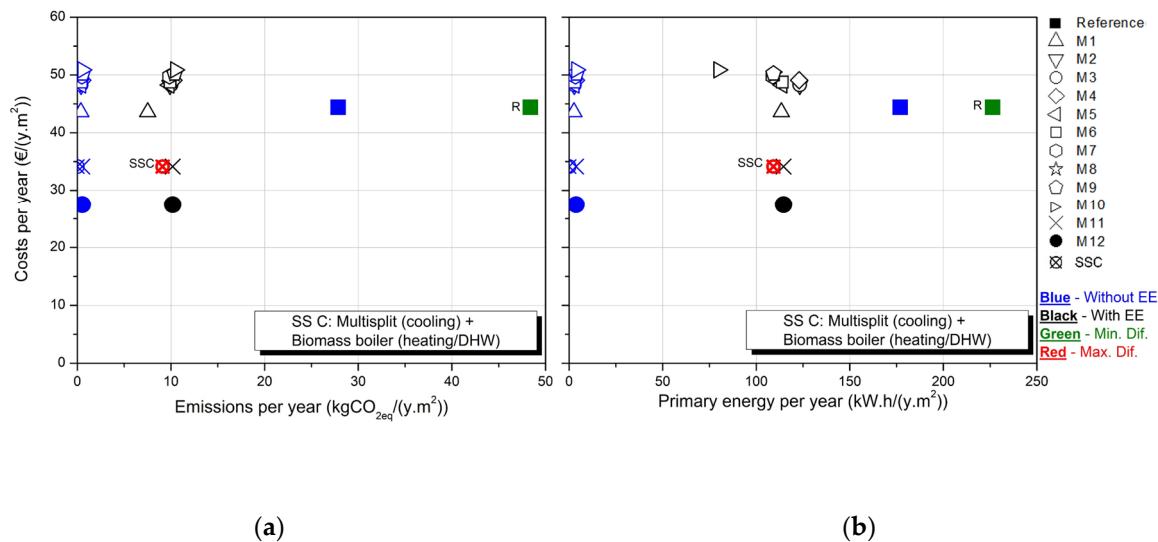


Figure 8. System solution C—Multisplit (cooling) + Biomass boiler (heating/DHW): (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization, SSC: Selected System Combination.

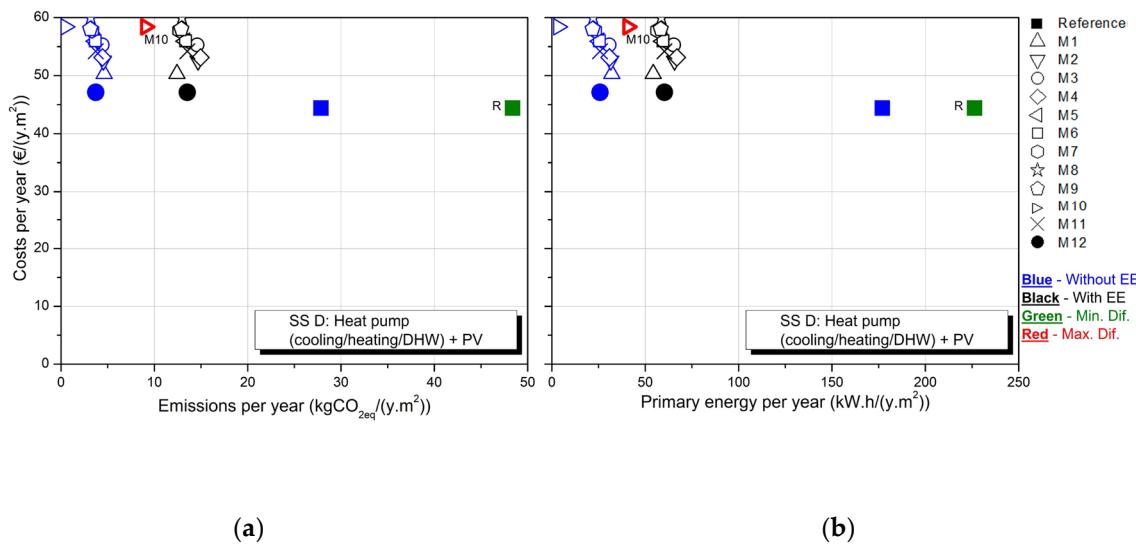


Figure 9. System solution D—Heat Pump + PV system: (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

Overall, in terms of non-renewable primary energy and CO₂ emissions (Figures 5–12), the renovation package M10 leads to the lowest energy consumption (in average 22.6 kWh/(y.m²)), as well as to the lowest CO₂ emissions (in average 3.6 kgCO₂eq/(y.m²)). The renovation package M10 (M9 + solar thermal) includes the modular prefabricated panel together with a 10 cm layer of mineral wool applied in the interface between the panel and the existing wall, a 14 cm layer of mineral wool on the roof and a 6 cm layer of extruded polystyrene in the cellar ceiling. For the windows, the solution for package M10 includes the replacement of the windows by others with an aluminum frame and a U-value of 2.40 W/m² °C.

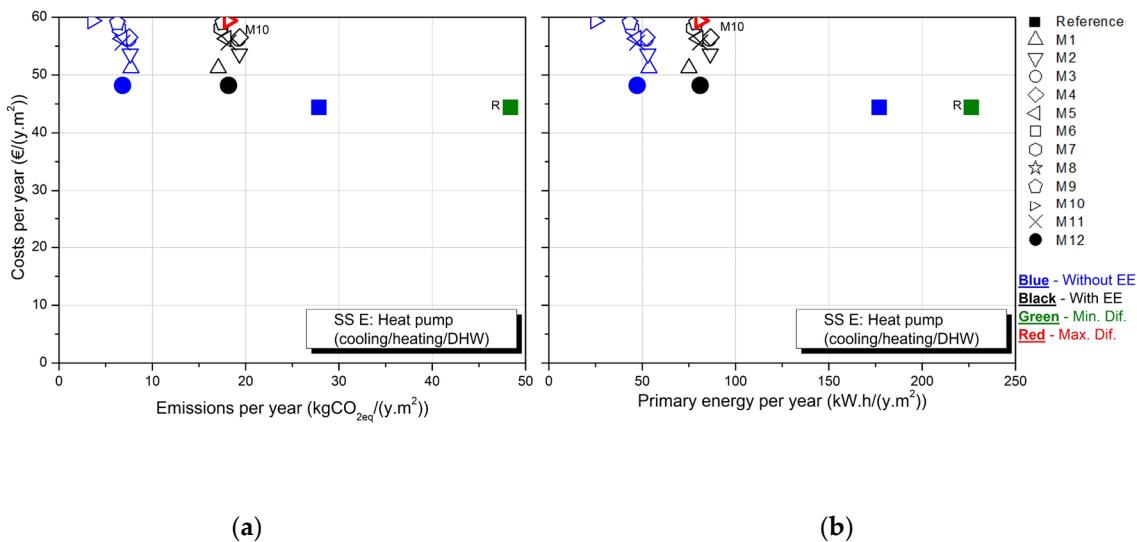


Figure 10. System solution E—Heat Pump: (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

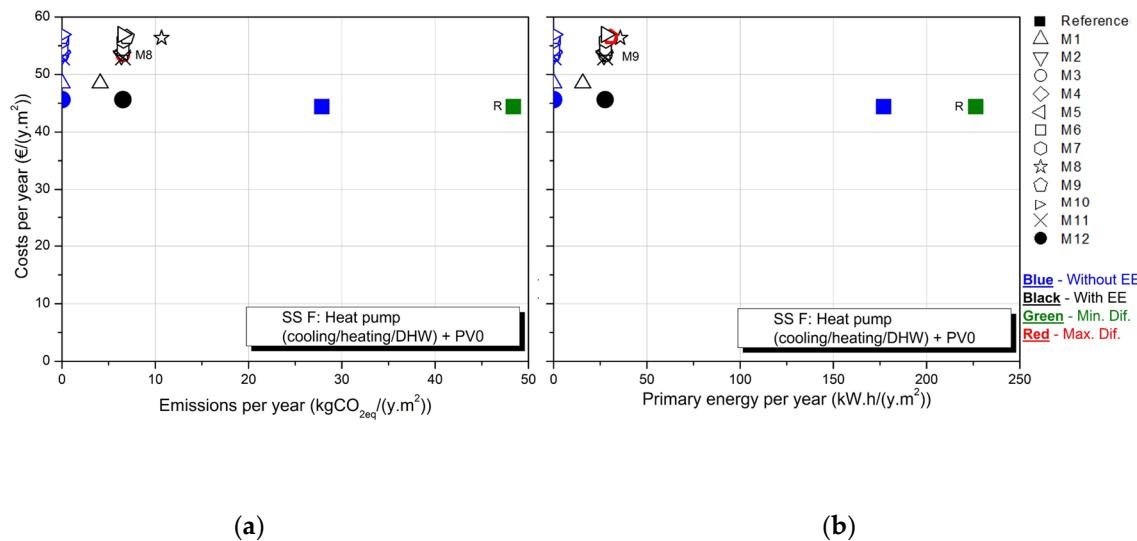


Figure 11. System solution F—heat pump + PV system towards zero: (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

The results of the calculations indicate that the solutions considering heat pump systems (systems solutions D, E and F) lead to significant reductions in the two analyzed indicators. System solution F is a clear example, where a 90% reduction in NPPE can be achieved when compared with the reference case. However, achieving these reductions with such systems are still above the limit of cost-effectiveness. In relation to global costs, the more evident increase is in the system solution E (Figure 10) where the global costs are 39.9% (M6) higher than the costs related to the reference case. This system is composed of a heat pump for heating, cooling and DHW.

Results suggest that under system solution G (Figure 12), every renovation package is cost-effective. With this system, there is an NRPE reduction of around 83.5% when compared with the reference case, while the global costs range from being 8% (M10) to 33.7% (M12) smaller than the ones related to the

reference case. This system includes a multisplit equipment for heating and cooling, an electric boiler for DHW, in addition to photovoltaic and solar thermal panels.

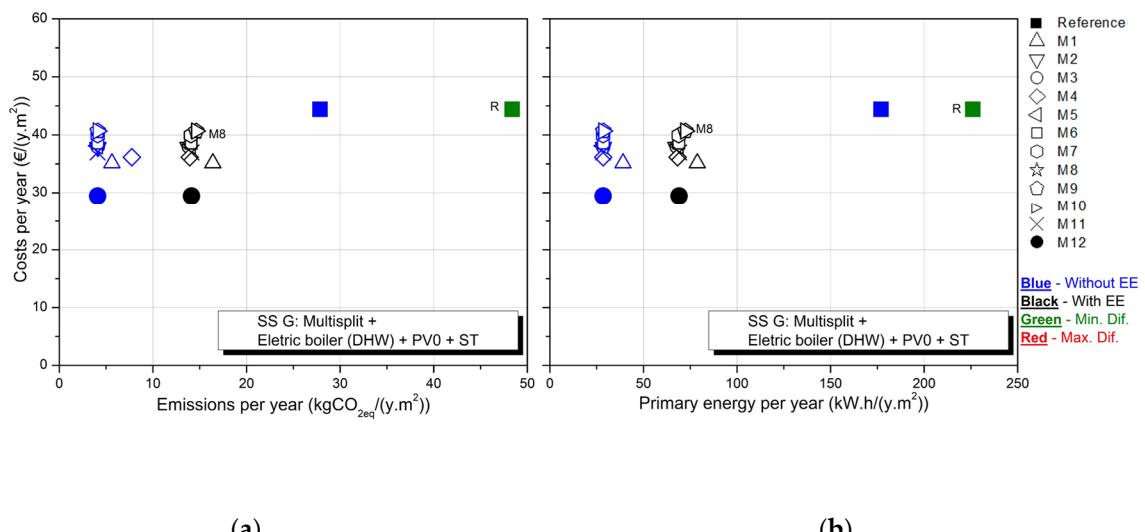


Figure 12. System solution G—Multisplit + Electric Boiler (DHW) + PV system towards zero + ST: (a) Emissions (b) Primary energy. Where: M1: ETICS 8 cm, M2: MC panel 12 cm + 6 cm, M3: MC panel + 10 cm, M4: M3 + Roof 6 cm, M5: M3 + Roof 12 cm, M6: M3 + Roof 14 cm, M7: M6 + Cellar 6 cm, M8: M7 + Windows 2.7, M9: M7 + Windows 2.4, M10: M9 + ST, M11: M3 + Roof 6 cm + Cellar 6 cm, M12: M11 + cost optimization.

In terms of renovation packages, and taking into account the calculated annualized costs (Figures 5–12), the renovation package M12 is the one that leads to the lowest global costs regardless of the system solution considered. This renovation package considers cost optimization of the prefabricated modular panel, combined with roof and cellar insulation. When the optimization of the panel is not considered, the renovation package M1 leads to the lowest global costs in all system solutions, except in system solution C, where M11 leads to the lowest global costs.

The Selected System Combination (SSC) is the cost-optimal solution (Figures 4 and 8). Although not initially considered in the renovation solutions analyzed in this study, it is the solution that the building owner will be able to implement, due to technical, financial and material availability reasons, and was therefore, calculated as a separate combination. The SSC includes the (cost optimized) prefabricated modular panel (M12) together with a biomass boiler. This renovation solution leads to a reduction of 226 kWh/(y.m²) when compared with the reference case, at a global cost of 34 €/(y.m²). This combination uses only a renewable energy source (wood) for both acclimatization and DHW.

Influence of Embodied Energy and Embodied Carbon Emissions

When the embodied carbon emissions and embodied energy of the materials used are considered in the calculations, there is a noticeable increase in the cumulative primary energy and in the global warming potential in terms of carbons emissions per year of each renovation package, regardless of the system solution used. Generically, carbon emissions increase in average by 9.3 kgCO₂eq/(y.m²) and primary energy by 43 kWh/(y.m²).

The cost-optimal solution for the envelope is the renovation package M12 (M11 with optimization of the panel cost production) considering or not the embodied energy in the materials. However, with this renovation package, when embodied energy and emissions are considered, there is an average increase of 45.3 kWh/(y.m²) in primary energy and 10.3 kgCO₂eq/(y.m²) in emissions per year. The renovation package that leads to the lowest increase in carbon emissions and primary energy (4.1 kgCO₂eq/(y.m²) and 15.6 kWh/(y.m²)) is M1 (ETICS EPS 8 cm), when system solution F is considered.

The highest increase in primary energy ($120.5 \text{ kWh}/(\text{y.m}^2)$) is found when renovation package M2 (Modular Panel+6 cm insulation) is considered together with system solution C (biomass boiler + Multisplit). Regarding carbon emissions, the highest increase ($18.1 \text{ kgCO}_{2\text{eq}}/(\text{y.m}^2)$) is found with the application of the same measure, but when the conventional system (electric heater + multisplit+ gas heater) is used in calculations. In fact, concerning systems solutions, the consideration in the calculations of the embodied energy and embodied carbon emissions of the materials lead to some changes and a significant increase in the values of primary energy and carbon emissions associated to the renovation scenarios, particularly in scenarios that include renewable energy sources. The most notable changes were observed in the combination of system solution C (multisplit + biomass boiler) with the different renovation packages. For this system solution, and regarding carbon emissions and primary energy, the values increase by an average of $9.4 \text{ kgCO}_{2\text{eq}}/(\text{y.m}^2)$ and $109 \text{ kWh}/(\text{y.m}^2)$, respectively. System solution F (heat pump + PV) also leads to significantly higher values of carbon emissions ($6.7 \text{ kgCO}_{2\text{eq}}/(\text{y.m}^2)$ in average) and primary energy ($27.5 \text{ kWh}/(\text{y.m}^2)$ in average), which is clearly associated to the size of the photovoltaic system.

Finally, it is important to refer that, despite the observed increase of these values, in general terms, the hierarchical relationship between combinations of system solutions and renovation packages remain identical, as well as the comparative position of the renovation packages in relation to the reference situation. In this case, not only the cost-optimal solution remains the same when the embodied energy is considered, but also the cost-effectiveness of the measures remains mostly unchanged.

5. Conclusions

Based on the assessment carried out it is possible to conclude that for the building envelope, the renovation package that consistently allows for the highest reduction of the energy needs in all renovation scenarios (86% in average) is M10 (M9 + solar thermal). This solution leads to a significant reduction of the energy needs and CO₂ emissions, but it is not very attractive in terms of costs. The cost-optimal renovation package is M12, which includes the modular panel, as well as roof and cellar insulation. This package assumes that the production costs of the panel are already optimized, and a production cost reduction of 70% was achieved.

Regarding the systems, the one allowing for a more significant reduction (up to $226 \text{ kWh}/(\text{y.m}^2)$) is the Selected System Combination, which considers a biomass boiler and no cooling equipment. Calculations results considering the System Solution C, which also uses a biomass boiler combined with a multisplit, show relevant results in terms of primary energy and carbon emissions reduction. In addition, system solution F allows reducing the primary energy and carbon emissions above 80%, but at a higher cost.

The consideration in the calculations of the embodied carbon emissions and the embodied energy of the materials used increases the energy and carbon emissions of each renovation package by an average of $43 \text{ kWh}/(\text{y.m}^2)$ and $9.3 \text{ kgCO}_{2\text{eq}}/(\text{y.m}^2)$, respectively in all renovation scenarios. However, in general terms, the relationship between combinations of system solutions and renovation packages remain identical. When LCA results are integrated into the cost-optimal calculations, renovation package M12 is still the cost-optimal solution. Although it is not leading to the most significant primary energy reduction, renovation package M1, with system solution F, is the one leading to the lowest increase in embodied carbon emissions and primary energy.

Results suggest that prefabricated modular systems present advantages regarding primary energy and carbon emissions reductions, but caution should be exercised in the choice of materials to reduce associated embodied energy and carbon emissions. In this case, results show that the choice of polyurethane foam harmed the overall performance regarding the environmental impact of the prefabricated modular panel. In that way, another type of materials should also be considered in future analysis. In this context, and since the module is composed of different elements with distinctive life cycles, another topic to be considered in future works concerns the assessment of circularity of the components of the prefabricated modular panel.

In addition, the results also show that, while renewable energy supply systems may be beneficial in terms of reductions in non-renewable primary energy use, embodied energy and life cycle implicit emissions associated to the materials and processes used in the renovation process can hinder the sustainability of these measures. In this sense, future research will have to include the further development of both prefabricated modular renovation solutions and renewable energy sources with reduced embodied energy and carbon emissions to improve the sustainability of the cost-effective and affordable building renovation interventions.

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