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Integrated life cycle assessment and thermodynamic simulation of a public building's envelope renovation: Conventional vs. Passivhaus proposal

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Abstract

The need to improve the energy efficiency of buildings has introduced the concept of nearly zero-energy buildings into European energy policies. Moreover, a percentage of the building stock will have to be renovated annually to attain high energy performance. Conventional passive interventions in buildings are focused on increasing the insulation of the building envelope to increase its energy efficiency during the operating phase. Often, however, intervention practices imply the incorporation of embodied energy into the building materials and increase the associated environmental impacts.

This paper presents and evaluates a comparison of two different proposals for a real-world building renovation. The first proposal was a conventional project for energy renovation, while the second was a low-energy building proposal (following the Passivhaus standard). This study analysed the proposals using an integrated life cycle and thermal dynamic simulation assessment to identify the adequacy of each renovation alternative regarding the post-renovation energy performance of the building, including an evaluation of the introduction of a renewable insulation material into the low-energy building proposal, specifically a specific cork solution. The most significant conclusion was the convenience of the renovation, achieving energy savings of 60% and 80% for the conventional and Passivhaus renovations (ENERPHIT), respectively. The former supposed less embodied energy and environmental impacts but also generated less energy savings. The latter increased the embodied impacts in the building, mainly for the large amount of insulation material. The environmental implications of both proposals can be compensated for within a reasonable period of time, over 2 years in the majority of alternatives and impact categories. However, the ENERPHIT project was 30% better than the conventional proposal when the total lifespan of the building was considered. The introduction of cork did not fit the requirements for competing with the common non-renewable insulation materials because it did not imply better environmental performance in buildings, but cork insulation solutions currently present ample room for improvement.

Keywords

Zero-energy building, ENERPHIT, insulation materials, embodied energy, operating energy, cork

Nomenclature

EPBD	Energy Performance of Buildings Directive
XPS	Extruded polystyrene
EPS	Expanded polystyrene
PU	Polyurethane
SW	Stone wool
GW	Glass wool
NZEB	Nearly zero-energy building
ENERPHIT	Certification Criteria for Energy Retrofits with Passive House Components
LCA	Life cycle assessment
FU	Functional unit
EN	European norm
CML	Institute of Environmental Sciences
ADP	Abiotic depletion potential
AP	Acidification potential
EP	Eutrophication potential
GWP	Global warming potential
OLDP	Ozone layer depletion
PCOP	Photochemical oxidation
OE	Operating energy
EE	Embodied energy

Highlights

· Conventional and Passivhaus proposals for a university building’s renovation are compared.
· The energy renovation achieved high energy savings for both proposals, between 60% and 80%.
· The Passivhaus proposal is 30% better than the conventional one considering the total lifespan of the building
· The use of cork as an insulation material for envelope renovation is assessed.
· Cork does not fit the requirements for competing with common non-renewable insulation materials.

1. Introduction

1.1 Background

In Europe, 40% of energy use and the corresponding environmental impacts are concentrated in the building sector [1]. Energy use is considered the area with the greatest potential for intervention [2], playing a crucial role in the energetic transformation of the European Union [3]. The improvement of the sustainability of constructions through a more efficient and use of buildings would decrease the use of energy by 42%, greenhouse emissions by 35%, and the extraction of material by more than 50% [4]. The European Energy Performance of Buildings Directive 2002/91/EC (EPBD) [1] promotes energy efficiency and the use of renewable energy in buildings. Moreover, it presents the concept of nearly zero-energy buildings (NZEB) as a mandatory guideline for all new buildings beginning in 2021. Moreover, Directive 2012/27/EU [5], published in 2012 and effective as of 2014, requires all countries of the EU to energetically renew 3% of public administration buildings on an annual basis.

Certain efficient building practices for transforming the current building stock are active measures, while others are passive interventions. The former aim to conserve energy in building equipment and maintenance by including system controls or via the installation of renewable energy generating systems. The latter are used to reduce energy consumption in the building envelope; one of the most extended practices is to increase the insulation of the building envelope, including façades, roofs and windows [6,7]. Therefore, insulation materials play an important role because they influence the use phase of a building. For example, the installation of insulation material in envelope solutions can greatly reduce energy demand, by 64% in summer and by up to 37% in winter. With these reductions in energy demand, there is also a decrease in CO_2 emissions [8]. In most European buildings, non-renewable insulation materials are installed, including stone wool (SW), glass wool (GW), expanded polystyrene (EPS), extruded polystyrene (XPS) and the less widespread polyurethane (PU) [9,10]. Moreover, the market accounts for other alternative materials, including renewable materials. These materials are increasing in relevance because of the strategy involving the substitution of non-renewable materials in buildings. However, before such materials are implemented extensively in buildings, the environmental implications throughout their life cycle must be widely known—something that currently remains underexplored.

Focusing on passive interventions, conventional building renovations should reduce their environmental impact during the operating phase to increase indoor comfort through heating and cooling, lighting and operating appliances [11]. However, the intervention practices for energy savings imply the incorporation of embodied energy and environmental impacts from other life cycle phases into the building. Production, on-site construction, final demolition and disposal imply energy use and environmental impacts such that if all improvement strategies are focused on operational energy, the relative importance of embody energy and environmental impacts could become more relevant to the baseline situation [12–14]. For instance, the European Commission has taken the constructive methodology Passivhaus and its specific criteria for building renovation (ENERPHIT) as a reference for NZEB [15]. This standard, developed in Germany by the Passivhaus-Institut Darmstadt, is largely focused on minimising the operating energy in buildings by intensively using insulation materials and more advanced equipment but does not include the quantification of the environmental implications that this process assumes. Because the relative share of embodied energy in low-energy buildings is more relevant than that in conventional buildings [16], the selection of insulation materials must take into account solutions with low embodied energy [17]. The European Commission advises that efforts to reduce embodied energy must be further strengthened, complementing them with policies for resource efficiency. In this respect, life cycle thinking incorporates the entire product system, from the extraction of materials to their end-of-life, and aims to prevent impact trade-offs between life cycle phases [18]. There is a strong interplay among all the phases of a building life cycle, as each one can affect one or more of the others, highlighting the relevance of the life cycle approach for performing a reliable and complete building energy and environmental assessment [19].

1.2. Literature review

Life cycle assessment (LCA) methodology quantifies and identifies potential environmental implications in each of the phases of building construction [20] and evaluates the potential benefit of different renovation measures. LCA has gained wide acceptance in the building sector and is used to compare different alternatives in the design of buildings. Most studies have focused on comparisons of different alternatives for building designs regarding the selection of constructive solutions and building materials [2,21–27], while others have focused on new buildings (more specifically, residential buildings) [28–30]. Few studies have addressed the renovation of buildings, with their main goal being to achieve great energy savings, limiting their scope to the assessment of operation energy and often neglecting embodied impacts during production and assembly of materials or constructive solutions [11,31]. It is important to note that the renovation of the EU's ageing building stock was indicated by the European Commission as a key to meeting the EU's objectives to reduce greenhouse gas emissions and energy demand by 20% [32].

Among the few studies that have taken into account both the embodied energy and the operating energy of renovated buildings, different levels can be distinguished. On the one hand, at the building level, the final balance between the energy savings achieved during operation and the environmental impacts related to building material incorporation has been assessed [11,17,33]. On the other hand, at the material level, some studies have assessed the combination of different building materials in the renovation of buildings, analysing the influence on energy and environmental performance after renovation [6,31]. A notable gap has been identified in the literature because different types of building renovation have not been extensively compared; for instance, low-energy buildings have not been compared with the conventional systems that are currently utilised in European countries. In this regard, the application of the standard Passivhaus for building renovations is a reference for the European Union. Thus, the standard should be compared with conventional renovation systems beyond residential buildings [16,34,35], integrating a thermal dynamic simulation in the LCA methodology to assess post-renovation building energy consumption more realistically [31,36,37]. Moreover, it is important to note that it is necessary to analyse large buildings, in addition to housing, because doing so could reveal relevant differences in the selection of building materials during the design phase.

Additionally, insulation materials play a key role because of influence during both the use phase and the construction of the building [38–40]. Thus, their convenience, as well as that of alternatives such as renewable materials, must be assessed to enhance knowledge about their environmental implications and thermal performance [41]. As mentioned previously, the importance of renewable insulation materials has increased, and previous studies have environmentally assessed some of these, including kenaf fibre, cotton, jute, flax, hemp and cork [10,41–43]. Cork is one of the most extensively used materials in the building sector [44,45] and therefore the most studied from an environmental perspective [41,46–48]. On the on hand, cork has a very significant and varied combination of physical properties, which makes it have a wide variety of potential applications within the building sector [49]. But on the other hand, previous studies highlighted the need to introduce improvements related to the efficiency and sustainability of different stages of its manufacturing process [41]. Additionally, cork oak has great environmental importance because of its role in water retention, soil conservation, and carbon storage [50]. Regarding carbon storage, cork oaks have the capacity to fix carbon, which is transferred to cork materials and products, giving them the potential to mitigate climate change by storing carbon for long periods (until the end-of-life of cork products) [51–53].

This article presents an environmental assessment of different projects for the renovation of a Spanish university building using an integrated life cycle and thermal dynamic simulation assessment. A comprehensive analysis of different alternatives for renovation and insulation materials was performed to identify the adequacy of each renovation proposal regarding the post-renovation energy performance of the building. The alternative proposals are (a) the conventional renovation project developed by the Spanish Ministry of Defence and (b) another more efficient one developed specifically for this study using the Passivhaus criteria for the renovation of buildings, ENERPHIT. Moreover, the use of renewable insulation materials is simulated in the ENERPHIT proposal using cork instead of GW, one of the most common insulation materials in ENERPHIT.

2. Energy and environmental assessment of building renovation

2.1. Methodology

An integrated life cycle approach combining LCA and thermal dynamic simulation was implemented to assess the energy and environmental impact of the different projects for the building's renovation.

2.1.1. Environmental impact assessment of the alternative renovation proposals

The environmental impact assessment was carried out by LCA methodology [54] to evaluate different renovation proposals according to EN 15978 [55] and EN 15804:2014 [56]. For the assessment of the product stage of new building components, a cradle-to-site approach was used. This approach includes the production of building materials, their transportation to the building site and their installation. With regard to the end-of-life of the replaced building components, only end-of-life was taken into account.

The environmental implications of the materials, energy and transport involved in the system were simulated by using the software SimaPro 8.1 [57] and the ecoinvent 3.2 database [58]. According to the European standard that provides the core Product Category Rules (PCR) for all construction products and services, EN 15804:2014 [56], the following six midpoint impact categories from the CML 2 baseline 2002 [59] were included in the assessment: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (OLDP) and photochemical oxidation potential (PCOP). Additionally, as previously noted, embodied energy (EE) was included because of its increasing importance in building energy demand.

2.1.2. Functional unit and system boundaries

The functional unit (FU) selected for this study was 1 square metre of the different solutions of façades, roofs, slab-on-ground and windows that composed the envelope [22]. In this case, to renovate a given surface of the building case study according to two different renovation proposals, the FU was applied to the total area of each constructive solution. Moreover, the FU for the operating phase is the energy consumption associated with heating and cooling over a year under the same indoor thermal conditions.

The system boundaries of the study, according to the EN 15978 [55] standard related to the environmental assessment of buildings and the EN 15804:2014 [56] standard related to the environmental product declaration (EDP) of construction products, included, on the one hand, the production of the building material, transport from the factory to the site and the construction and installation processes. On the other hand, the end-of-life stage of the replaced building components also had to be taken into account. Finally, this study also included the use phase to calculate the energy savings achieved for each renovation alternative with respect to the original state of the building (Figure **1**).

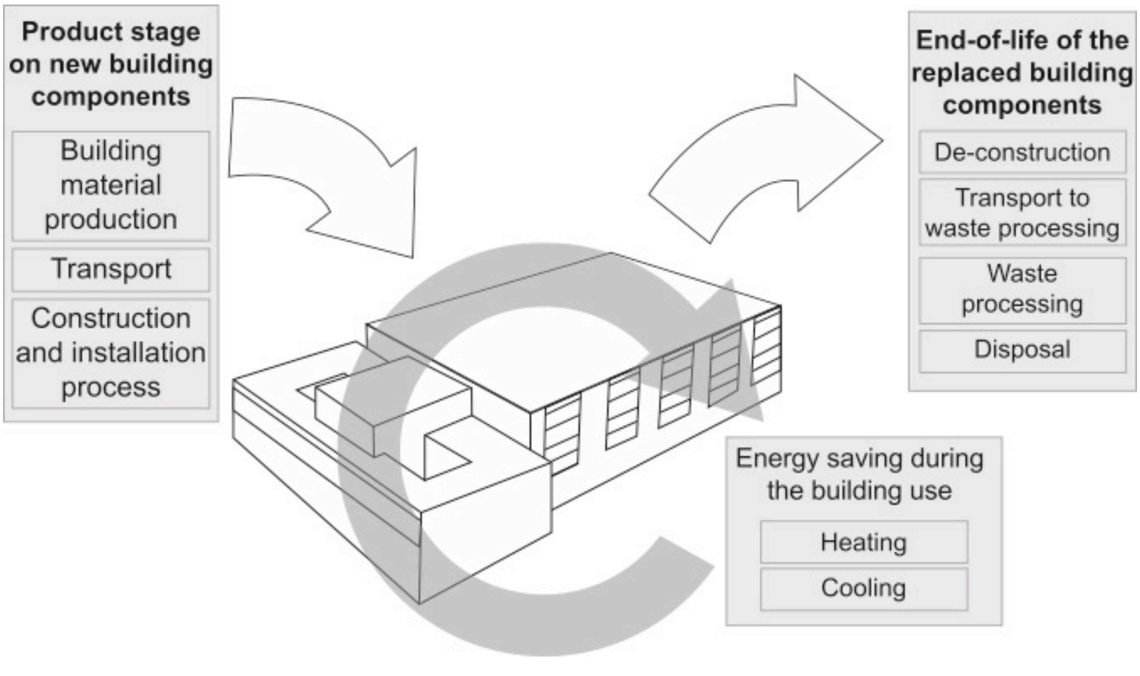

Figure 1. Information modules included in the evaluation of the evaluated building

The main assumptions made in the LCA were that the lifespan for the renovation action is 50 years, similar to that reported in other studies [17,31,34,60], and that the distance for transport from the factory to the building location is 100 km, the most representative value reported in the literature [21,61,62].

2.1.4. Measurement of the energy savings

The energy simulation was carried out with the Computational Fluid Dynamics Simulation module (CFD) of the program DesignBuilder [63]. The model includes the details of transmittances and infiltrations of the original building, and the results pertaining to energy consumption, thermal loads and temperature conditions are compared with real data obtained in the building. These data were obtained from the real thermal characterisation of the building. For this characterisation, the blower-door test was first performed, combined with the use of thermography and smoke pens to measure and observe the infiltrations of the building. The blower-door test was carried out in five enclosures, which were composed of existing construction typologies. Therefore, the average infiltration of the building for a pressure difference of 50 Pa was 46.53 air changes per hour. Most of the infiltrations were derived from the carpentry, the forged thermal bridge and the facilities. The transmittances of the different closures were then measured, and using exterior thermography, the transmittances of different thermal bridges were calculated via the differences in surface temperatures. A difference was noted between the calculated transmittance and the measured transmittance in the brick walls, curtain wall, slab on grade floor and roof. Finally, the temperatures inside the building and the energy demand for heating were measured. The energy demand was obtained by measuring the temperature of the input and output of the heated water in the secondary circuit of the heat exchanger system used for the heating system.

Once the building was thermally characterised, a mathematical model was developed with DesignBuilder. Moreover, the pattern of use was included, which helped validate the mathematical model simulated with the program, enabling different renovation projects to be simulated with the knowledge that the results obtained will be adequate. Finally, the proposals for renovation were simulated under the conditions described above, obtaining the energy consumption for heating and cooling in the climatic area where the building is located. Moreover, a pattern for the use of classrooms was included, taking into account their metabolic activity, the number of students and the operating schedule for each month of the year. From these data, the energy savings with respect to the original building could be calculated.

2.2. Case study

2.2.1.Description of the building

The assessed building is a university building located in the General Military Academy of the Spanish Army in Zaragoza in northeastern Spain. The building has a constructed surface area of 4,033 m^2, distributed over a ground floor and two upper floors. Three modules compose the building: the east module is used for classrooms and for a conference hall; the west module, with only one upper floor, is used for offices; and the central module hosts stairs. The real occupancy of the building has been included in the energy simulations by using a pattern of use. For this purpose, the sensible and latent loads produced by the real number of people occupying each space and the existing computer equipment have been introduced. The building is used only between the hours of 7:30 and 14:30. The considered months of use are October to June, with different load levels of use. Moreover, there is partial use until mid-July. Figure **2** shows a 3D rendering of the building simulated by DesignBuilder software [63], which illustrates the composition of the building. The building's floor plans and exact location are not provided for national security reasons.

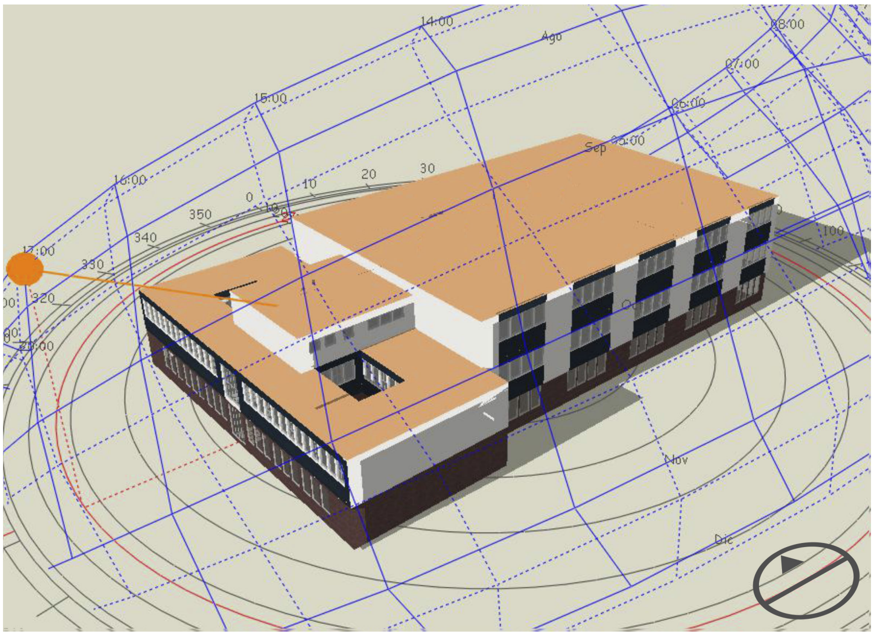

Figure 2. General view of the building simulated with DesignBuilder

The building was built in the 1970s following a similar design built in different military units. The existing building rules at that time did not require the installation of insulation material (which also true for the building's envelope). Regarding the composition of the building's envelope, the façade of the ground floor is composed of (from indoors to outdoors) plaster, an interior wall of double hollow bricks, an air chamber and another wall of double hollow bricks. For the upper floors, its composition is (from indoors to outdoors) plaster, an interior wall of double hollow bricks, an air chamber, another wall of double hollow bricks, and a metal substructure designed to hold an outer sheet of prefabricated concrete panels or a curtain wall. The slab is made of 20 cm of reinforced concrete without insulation, coated with ceramic tile. The external cladding of the curtain wall is made of tinted glass. Regarding the roof, all modules have installed reinforced concrete slabs with cement fibre cover. Windows are composed of an aluminium frame without a thermal break and 6 mm of simple glass. Table 1 presents the characteristics of the building's envelope and the transmittances (U) of each part of the envelope.

Building features		Transmittance
* Number of floors	P + 2E	
*Building floors area	3,923.21 m^2	
Ground area	1,403.59 m^2	
First floor	1,403.59 m^2	
Second floor	1,116.03 m^2	
* Building high	10.65 m	

Ground area	3.65 m	
First floor	3.50 m	
Second floor	3.50 m	
* Building exterior area	4,403.78 m^2	
Total façade	1,596.60 m^2	
· Curtain wall	268.70 m^2	U= 0.82 W/m^{2}K
· Brick wall	838.60 m^2	U= 0.76 W/m^{2}K
· Prefabricated concrete	489.30 m^2	U= 0.71 W/m^{2}K
Total roof.	1,403.59 m^2	U= 1.10 W/m^{2}K
· Inverted crossable flat	1,011.23 m^2	
· Non-crossable inclined (occupied)	287.56 m^2	
· Non-crossable inclined not occupied)*	104.80 m^2	
Slab-on-ground	1,403.59 m^2	
*Windows	358.27 m^2	
Glass	268.70 m^2	U= 6.10 W/m^{2}K
Frame	89.57 m^2	U= 5.70 W/m^{2}K

Table 1. Structural characteristics of the buildings envelope

The building is located in one climate zone denoted D3 [64], which is the largest in Spain and is the climate zone with the second most severe winter and summer seasons [65]. If we take Zaragoza as a reference city, according to the Spanish State Meteorological Agency, the annual average maximum temperature (determined on a monthly basis) is 21ºC, and the annual average minimum temperature (determined on a monthly basis) is 10ºC.

2.2.2. Description of the renovation project proposals

Two proposals were assessed for the building renovation: first, according to the conventional project of renovation of the Spanish Ministry of Defence and, second, following the Passivhaus standard for building renovation, ENERPHIT. In both cases, the energy renovation is performed inside the building for each plan, and the windows are also replaced.

Conventional renovation proposal

As previously indicated, the current building has no insulation installed in its envelope; therefore, in accordance with the EPBD, the building must be renovated to increase its energy efficiency of operation. To that end, the Spanish Ministry of Defence is currently carrying out the renovation standard for this type of building, which exists in different military units across the country. The renovation project implies the installation of insulation material on the interior side of the envelope using XPS. The installation of this material makes it necessary to demolish the existing interior brick wall and construct another. This project also involves the renovation of the tinted glass of the curtain wall façades. In the case of the roof, the existing reinforced concrete slabs with cement fibre cover are dismantled and replaced with an inverted flat roof on the classroom side and a non-crossable deck roof with thermal insulation throughout the rest of the building, using XPS and SW, respectively. In this renovation project, the slab-on-ground is not renovated.

ENERPHIT renovation proposal

In addition to the conventional renovation project, this study analysed a more efficient proposal of renovation, complying with the refurbishment standard ENERPHIT, based on the Passivhaus construction standard of nearly zero-energy buildings. The main requirements that buildings must comply with after the refurbishment of air conditioning are final demands of heating and cooling of 25 kWh/m^2 year and the infiltrations through the envelope under a pressure test of 1 h^{-1} at pressure of 50 Pa. [66]. The ENERPHIT proposal includes the same types of façades, but in the case of the curtain wall, the tinted glass is not renovated because the authors considered their current state to be good. Regarding the roof, on the classroom side, an inverted flat roof was installed, whereas in the rest of the building, a non-crossable deck roof was installed. However, in this case, a distinction was made between occupied and unoccupied spaces. In occupied areas, the deck roof included insulation materials, and in unoccupied areas (stairs), it did not. The insulation material installed in all façades and roofs was GW. Moreover, in this proposal, the slab-on-ground was insulated with EPS, following the constructive details shown in the following section.

2.2.3. Description of the constructive solutions under study

Figure **3** presents schemes of different constructive systems used in the study, either in the conventional project, the ENERPHIT project, or both. Moreover, Figure **3** explains the composition of each constructive solution and the elements incorporated into the building. The building under study had three types of façades and three types of roofs, in addition to the slab-on-ground. The façade systems included in both projects were the curtain wall façade, the brick wall façade and the prefabricated concrete façade. All of these façades were insulated from the inside, between an existing brick wall and a new double hollow brick wall. Regarding the roof systems, the study included an inverted crossable flat roof, a non-crossable deck roof and a non-crossable, non-insulated flat roof. The latter system was included only in the ENERPHIT proposal and did not include insulation because it was installed in unoccupied areas. Regarding the slab-on-ground, a new floor structure was added, as well as a thermal insulation board and a ceramic coating. This solution was only included in the ENERPHIT project.

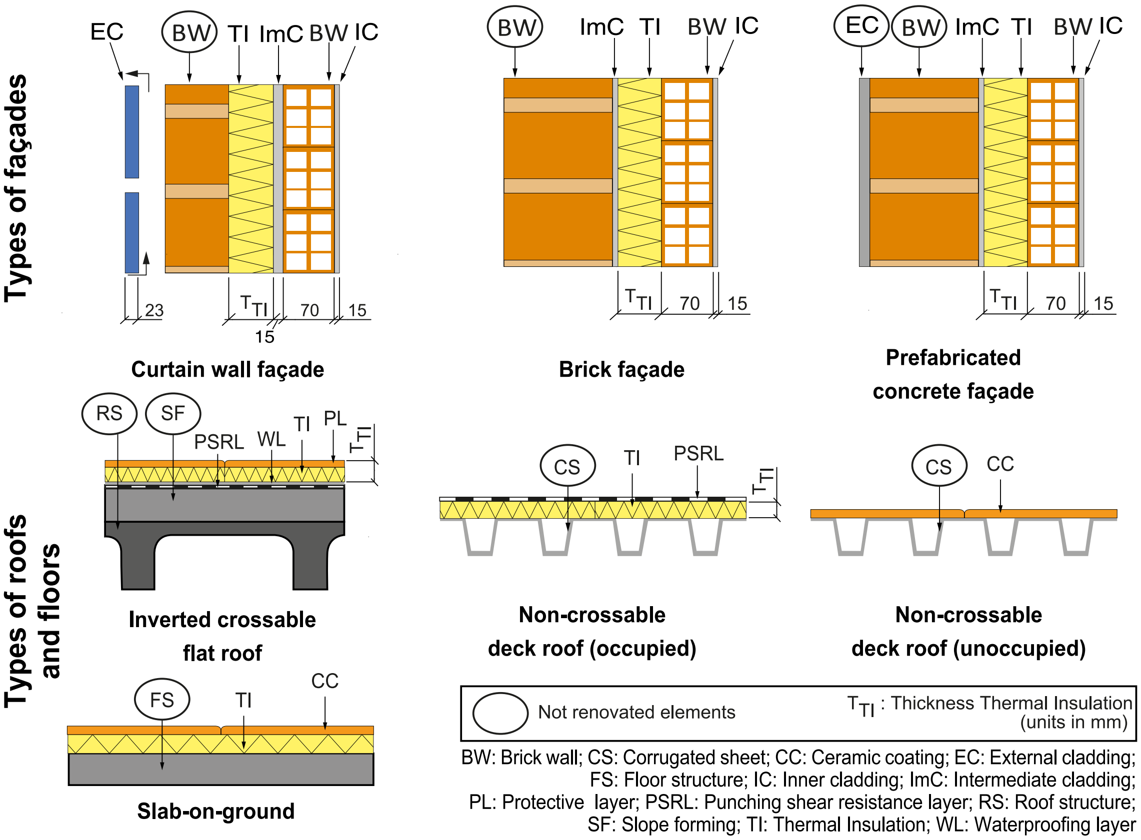

Figure 3. Constructive details of the types of façade, roofs and floors used in the renovation

2.2.4. Inventory data

The assessment of the constructive solutions required data regarding the insulation materials, quantity, and installation. According to the established FU and the building's technical considerations, Table 2 indicates the required inventory of materials for each façade, roof and slab-on-ground, in addition to the elements replaced from the building. The process used during the environmental simulation is indicated for each process. Table 2 also includes the cost of all materials used in both renovation projects [25]. For the installation phase, the materials and energy for the assembly of all of the components were considered. In the case of the windows, environmental information was collected from environmental product declarations published by the manufacturers to obtain the environmental impacts per square metre [67,68]. In the Supplementary data, a comprehensive inventory for each type of constructive system is included, in addition to the required inventory for the demolition of each part of the building can be found, as can the energy used during the building renovation. This energy is similar for different proposals. Moreover, Supplementary data provides the information related to each process and the used reference where data were collected.

		Conventional renovation				ENERPHIT renovation			
Material	**Ecoinvent 3.1 process**	**Quantity (Kg)**	**Unit cost**	**Unit**	**Cost (€)**	**Quantity (Kg)**	**Unit cost**	**Unit**	**Cost (€)**
Insulation (XPS)	Polystyrene production, extruded, CO2 blown, RER	1,873.30	6.10	m2	15,907.76	-			
Insulation (EPS)	Polystyrene production, expandable, RER	-				7,368.80	23.7	m2	33,265.08
Insulation (SW)	Rock wool production, packed, CH	2,707.30	5.46	m2	1,570.08	-			
Insulation (GW)	Glass wool mat production, CH	-				21,089.00	6.98	m2	20,209.82
Insulation (Cork)	(Sierra et al. 2016b)	-				122,188.20	23.77	m2	104,677.85
Adhesive mortar	Adhesive mortar production, CH	958	0.28	kg	447.048	2,692.20	0.28	kg	730.19
Gypsum	Gypsum quarry operation, CH	1,277.30	0.10	m2	159.66	1,277.30	0.10	m2	159.66
Base plaster	Base plaster production, CH	12,175.70	1.40	m2	2,235.24	12,156.30	1.40	m2	2,235.24
Water	tap water production, conventional treatment, Europe without Switzerland	39,595.70	0.02	m2	25.55	39,595.70	0.02	m2	25.55
Double hollow bricks	Brick production, RER	78,233.40	20.92	m2	33,400.87	105,375.60	20.92	m2	33,400.87
Cement mortar	Cement mortar production, CH	33,209.30	4.26	m2	6,801.52	33,209.30	4.26	m2	6,801.52
Tempered glass	flat glass production, coated, RER	4,030.50	236.13	m2	63,448.13	-			
Metallic fixings	Aluminium production, primary, ingot, UN-EUROPE	268.7	34.06	m2	9,151.92	-			
	Sheet rolling, aluminium/RER S	268.7				-			
Screws	Steel production, electric, low-alloyed, RER	217.6				-			
	Metal working, average for metal product manufacturing, RER	217.6				-			
Waterproofing layer	Synthetic rubber production, RER	2,807.20	5.35	m2	7,509.21	2,597.60	5.35	m2	6,948.53
Punching shear resistance layer	Polypropylene production, granulate, RER	101.1	4.2	m2	4,247.16	101.1	4.2	m2	4247.16
Ceramic tile	Cement mortar production, CH	67,246.80	4.26	m2	5,979.29	167,554.70	4.26	m2	5,979.29
Diesel (l)	Diesel, burned in building machine/GLO S	3,082.8 (l)	1	l	3,082.80	2,908.1 (l)	1	l	2,908.10
TOTAL		**245,188.20**			**153,966.24**	**393,017.60**	**SW option**		**116,911.02**
						486,748.00	**Cork option**		**168,113.96**

Table 2. Life cycle inventory

Table **3** summarises the thickness and the type of insulation material installed in each proposal. The main difference between the two proposals was the insulation material required, with more insulation required in ENERPHIT than in the current project due to the severe ENERPHIT thermal regulation. The most common insulation materials in the building market are XPS, SW, GW and EPS; but additionally, a natural alternative for the insulation material was assessed in this study for the ENERPHIT project, white agglomerated cork, and is commented on in a posterior sensitivity analysis. The environmental performance of cork has been previously analysed from different approaches [41,46,69–71]. Despite of being a natural material with high valuable thermal properties, its environmental performance is highly dependent on the process of transforming the raw cork into insulation board. All previous studies have analysed only the cork board and its manufacturing process, without analysing it in the context of use. Therefore it is necessary to know the thermal and environmental implications of thermally insulate a building with cork.

	Thickness Thermal Insulation (m)				
	Current renovation		ENERPHIT renovation		
	XPS	SW	GW	EPS	White agglomerated cork
Thermal conductivity (λ) (W/m K)	0.032	0.039	0.036	0.035	0.042
Curtain wall façade	0.05	-	0.14	-	0.15
Brick façade	0.05	-	0.13	-	0.14
Prefabricated concrete façade	0.05	-	0.14	-	0.15
Inverted flat roof	0.08	-	0.14	-	0.15
Non-crossable inclined roof (occupied)	-	0.05	0.18	-	0.20
Non-crossable inclined roof (not occupied)	*	-	-	-	-
Slab-on-ground	*	-	-	0.15	0.18

* This part of the building is not included in this renovation project

Table 3. Insulation material required for the proposal under study

The windows varied between the two projects but were from the same manufacturer. In the case of the conventional renovation project, the selected windows had double glazed insulation [68]. In the case of the ENERPHIT project, windows had triple glazed insulation [67]. In addition, in the ENERPHIT project, sealing tape was placed in every nook of the building to avoid unwanted air infiltration, particularly in windows and doors.

3. Results and discussion

3.1. Environmental implications of the building renovation

In this section, the resulting environmental impacts of each project are discussed. Moreover, the contributions of the insulation materials are analysed.

3.1.1. Environmental impact assessment of the alternative renovation proposal by a constructive solution

This section presents the results of the LCA of the construction phase for the two renovation proposals (Figure **4**). It is noted that the most intensive alternative in the use of building materials, ENERPHIT, presents the highest environmental impacts. Its environmental performance is between 40% and 230% higher than that of the conventional proposal depending on the impact category considered, particularly in EP, ADP and EE. Moreover, material use in ENERPHIT is 60% higher in terms of weight and, consequently, price. As previously indicated, the level of envelope insulation varies significantly between the two alternatives and thus has a strong influence on the final results. However, this point will be addressed in the following section.

Figure **4** shows that in both projects the most impacting constructive system is the façade, despite of having a surface similar to the roof, and in the case of the ENERPHIT project, also similar to the floor (Table **1**). For that, the intensity in the use of materials of each constructive system (façade, roof and floor) is directly related. It can be noted, especially, in the case of windows, the inverted flat roof or the slab-on-ground.

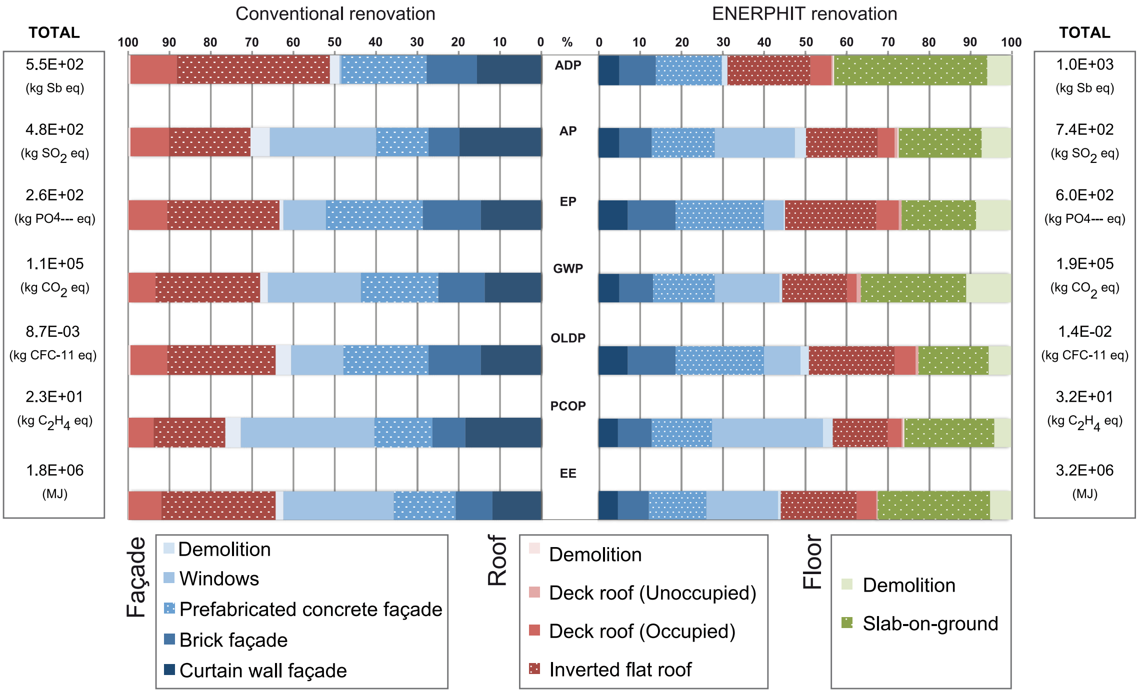

Figure 4. Environmental impacts and embodied energy of the renovation proposals assessed by constructive system

The main difference between the constructive solutions used in each proposal is the inclusion of the slab-on-ground renovation, including the demolition of the existing floor. The insulation of the slab-on-ground was included only in the ENERPHIT proposal, and its construction supposes 30% of the total amount of insulation material in the ENERPHIT renovation. In the case that the slab-on-ground will not be insulated in the ENERPHIT project, the proposal will not meet the technical requirements of the Passivhaus standard because the envelope must be completely closed. Alternatively, in the case of the curtain wall façade renovation, the conventional project has higher environmental impacts because this proposal substitutes the tempered glasses and their metallic fixing. This substitution represents 10% of the total conventional renovation. As indicated previously, the ENERPHIT project considers the current glass to be in good condition.

According to EN 15978, the environmental impacts of the decommissioning of the replaced components of the building must be included in a renovation study. The contribution of decommissioning is higher in the ENERPHIT proposal because it includes the renovation of the slab-on-ground. Moreover, the decommissioning represents between 1% and 10% of the total conventional renovation; the demolitions in the ENERPHIT renovation imply between 6% and 12% of the total environmental impacts. The façade and roof demolitions hold similar environmental implications for all impact categories.

3.1.2. The contribution of insulation materials in the renovation proposals

As previously indicated, the most common passive solution in buildings increases the relevance of insulation materials with respect to the rest of the building materials. To determine the extent of this effect, the influence of the insulation materials on the environmental behaviour of the renovation proposals has to be observed. Table **4** shows the relation between the global impacts of each building renovation proposal and the impacts of their insulation solutions. Previously, Table 2 has shown that the amount of insulation material is more than 5 times higher in the ENERPHIT proposal than in the conventional proposal. Calculations show that the contribution of the insulation material to the global impacts is between 10 and 27% in the case of the conventional renovation and between 28 and 47% in the case of the ENERPHIT renovation (Table **4**). The intensity of the insulation of the building can only be determined by knowing the energy savings. These data are presented in the following sections, and the adequacy of the ENERPHIT renovation is assessed.

	ADP	AP	EP	GWP	OLDP	PCOP	EE
Conventional renovation	**1.5E+02**	7.2E+01	3.9E+01	1.5E+04	9.0E-04	4.6E+00	3.4E+05
ENERPHIT renovation	**4.8E+02**	**2.4E+02**	**2.6E+02**	4.5E+04	**4.1E-03**	**1.1E+01**	**1.4E+06**

> 40% of the global impact	**25-40% of the global impact**	**10-20% of the global impact**

Table 4. Comparison of the contribution of the insulation material in each renovation proposal

Regarding the ENERPHIT proposal, the selected insulation material for the majority of the constructive solution is GW. Previous studies on the environmental performance of insulation materials have concluded that GW exhibits better environmental performance than XPS, EPS, PU and SW [22]. In the conventional proposal, the most frequently used insulation material is XPS, which also exhibits good environmental performance but is not as good as GW. However, all of the most extensively used insulation materials are non-renewable, and this study considers it relevant to assess the combination of a passive standard of construction and an example of a renewable insulation material, in this case, cork.

3.1.3. The environmental performance of cork as thermal insulation

As indicated previously, cork is the most commonly studied renewable material in studies on the sustainability of different intermediate and final products [45,50,72–74], and the environmental performance of an insulation cork panel produced in the largest cork insulation board manufacturing factory in Catalonia, Spain, was recently assessed [41]. This study concluded that the use of natural insulation materials does not necessarily imply a reduction of environmental impacts, as they often have higher impacts than the majority of the most commonly used insulation materials. The main reason for this finding is the low technological development of the cork board insulation manufacturing process. Thus, this study proposed improvement strategies that could be applied throughout its life cycle to create a more efficient and productive product. These strategies focused on cleaner production, in addition to the promotion of the acquisition of local raw cork to reduce the transport distance to the manufacturer because, currently, the majority of raw cork must be transported an average distance of 800 km.

The present study also simulated the use of cork as insulation material into the described ENERPHIT proposal. The environmental information was collected from the study Sierra-Pérez et al. [41]. Figure **5** presents the total results for the ENERPHIT proposal but, in this case, using cork for the thermal insulation of the building envelope in comparison to the results of ENERPHIT project using GW. It can be observed that the environmental impacts of the cork alternative are higher for the majority of the impact categories, including the embodied energy (EE). In the case of GWP, cork doubles the results of ENERPHIT with GW. Additionally, as previously indicated, the option that includes the biogenic carbon contained in the cork boards is also taken into account, decreasing the CO_2 contribution of the global building renovation by approximately 50%. Alternatively, Figure **5** also presents the results for a more environmentally friendly cork board, following the improvement scenario proposed by Sierra-Perez et al., were also simulated to assess the potential for improvement. This option is equivalent to ENERPHIT with the GW option in the majority of the impact categories; ADP and EP show better results. If biogenic carbon is included in the analysis, the global result of the building renovation, in kg of CO_2 –eq., is negative; this finding implies that the ENERPHIT project combined with improved cork boards can help to mitigate climate change. In this regard, Sierra-Pérez et al. [41] have already discussed different end-of-life scenarios for cork insulation boards, concluding that cork insulation board will store carbon dioxide indefinitely if the product is recycled for the manufacturing of another product with a lifespan of 50 years.

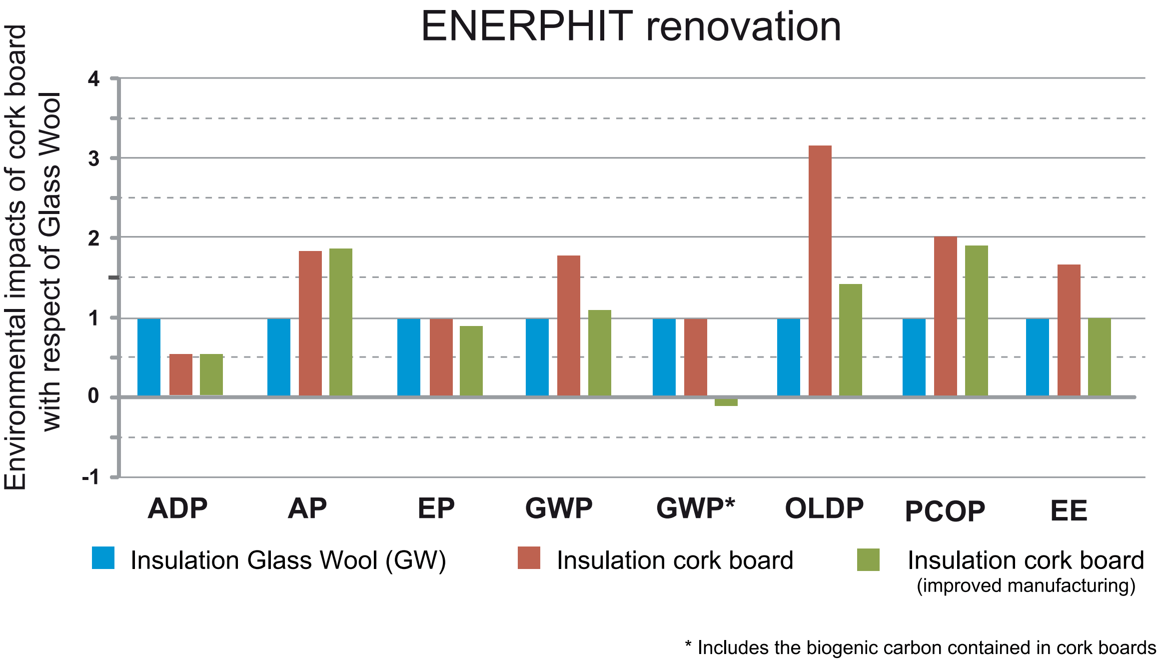

Figure 5. Environmental impacts and embodied energy of ENERPHIT proposal combined with different cork alternatives based on GW results

3.3. Energy and environmental benefits in the operational phase

This section presents the results of the operating energy of the building based on the real measurements carried out in the building for its current use and the results of the simulations for the renovation proposals, including ENERPHIT with cork (Table 5). The operating energy is expressed in terms of heating and cooling. It can be observed that the heating energy decreases drastically with respect to the current state of the building for all proposals. The convenience of renovating Spanish buildings built before 1980, when the building rules did not require insulation, can be observed. Currently, the operating energy for heating is 641,287.9 kWh/year, while the operating energies for the conventional and ENERHIT renovations are 190,864.2 and 43,429.9 kWh/year, respectively. These calculations suppose reductions of 70% and 93% for the conventional and ENERHIT renovations, respectively. In the case of cooling energy, the results for operating energy are higher for both renovation projects with respect to the current state of the building because of the reduction of the natural ventilation of the building, as its insulation and sealing have been increased. This result is obtained because a mechanical ventilation system with heat recovery is not included in the building renovation, as the associated regulations require. If the building facilities had included it, ENERPHIT would require a more efficient system of heat recovery than conventional renovations. Currently, the operating energy for cooling is 36,603.5 kWh/year, while the operating energies for the conventional and ENERPHIT renovations are 75,718.0 and 96,511.0 kWh/year, respectively. These figures represent increases of 106% and 160% for the conventional and ENERPHIT renovations, respectively. Moreover, the cork alternative for the ENERPHIT proposal is also assessed, resulting in higher energy savings than the conventional and ENERPHIT renovations with GW insulation.

In global terms, the heating months span from October to May, and the cooling months are only June and July (not including August, which is a summer holiday month). Thus, reducing the operating energy for heating is more important to energy savings. Hence, the proposed energy savings are highly significant for both renovation proposals, implying 60.7% and 79.4% decreases in operating energy for the conventional and ENERHY renovations, respectively. For the ENERPHIT renovation using cork as an insulation material, the energy savings are slightly higher than those of the ENERPHIT renovation using GW, 80.4%. In the case of heating, the two alternative ENERPHIT proposals yield similar results, and the observed differences may be due to the adjustment of the thickness of the insulation boards. Regarding cooling, the differences are greater, possibly because of the thermal inertia of cork, as the curtain wall concentrates high temperatures in summer and cork prevents its transmission into the building.

Moreover, the good thermal properties of cork, particularly its high thermal insulation and low thermal inertia, can be fully exploited in buildings with less intensive construction solutions. In the case study, two double brick walls and external claddings with an excessive overall thermal inertia composed all façades. For instance, if cork composed envelopes with a light structure, such as wood, the influence of the cork on the operating energy would be higher, which could be an important advantage of cork over other insulation materials.

	Operating energy (KWh/year)		Energy saving	
	Heating	Cooling	KWh/year	%
Current building	641,287.9	36,603.5	-	-
Conventional renovation	190,864.2	75,718.0	411,309.3	60.7%
ENERPHIT renovation (GW)	43,429.9	96,511.0	537,950.6	79.4%
ENERPHIT renovation (Cork)	45,195.4	87,487.6	545,208.5	80.4%

Table 5. Operating energy and energy saving of the renovation proposals assessed

3.4. Embodied energy and environmental impacts vs. energy savings

Energy savings also imply a reduction in environmental impacts related to energy generation. In the case of heat production, the General Military Academy, where the building is located, hosts a small thermal power plant that uses a diesel boiler for heat production. In the case of cooling, electricity is used from the Spanish electricity mix. Figure **6** shows the environmental impacts and the impacts avoided for energy savings by proposal of renovation for each impact category.

		ADP	**AP**	**EP**	**GWP**	**OLDP**	**PCOP**	**EE**
		kg Sb eq	kg SO_2 eq	kg PO4--- eq	kg CO_2 eq	kg CFC-11 eq	kg C_2H_4 eq	MJ
Conventional renovation	Embodied impacts	5.45E+02	4.76E+02	2.59E+02	1.08E+05	8.73E-03	2.26E+01	1.77E+06
	Saving impacts	8.96E+02	2.42E+02	1.25E+02	1.33E+05	2.25E-02	1.42E+01	1.47E+06
ENERPHIT renovation (GW)	Embodied impacts	1.01E+03	7.41E+02	6.01E+02	1.87E+05	1.44E-02	3.24E+01	3.23E+06
	Saving impacts	1.16E+03	2.96E+02	1.62E+02	1.73E+05	2.95E-02	1.79E+01	1.92E+06
ENERPHIT renovation (Cork)	Embodied impacts	5.47E+02	1.41E+03	6.04E+02	1.89E+05	4.31E-02	6.41E+01	5.52E+06
	Saving impacts	1.19E+03	3.23E+02	1.66E+02	1.77E+05	2.98E-02	1.89E+01	1.95E+06

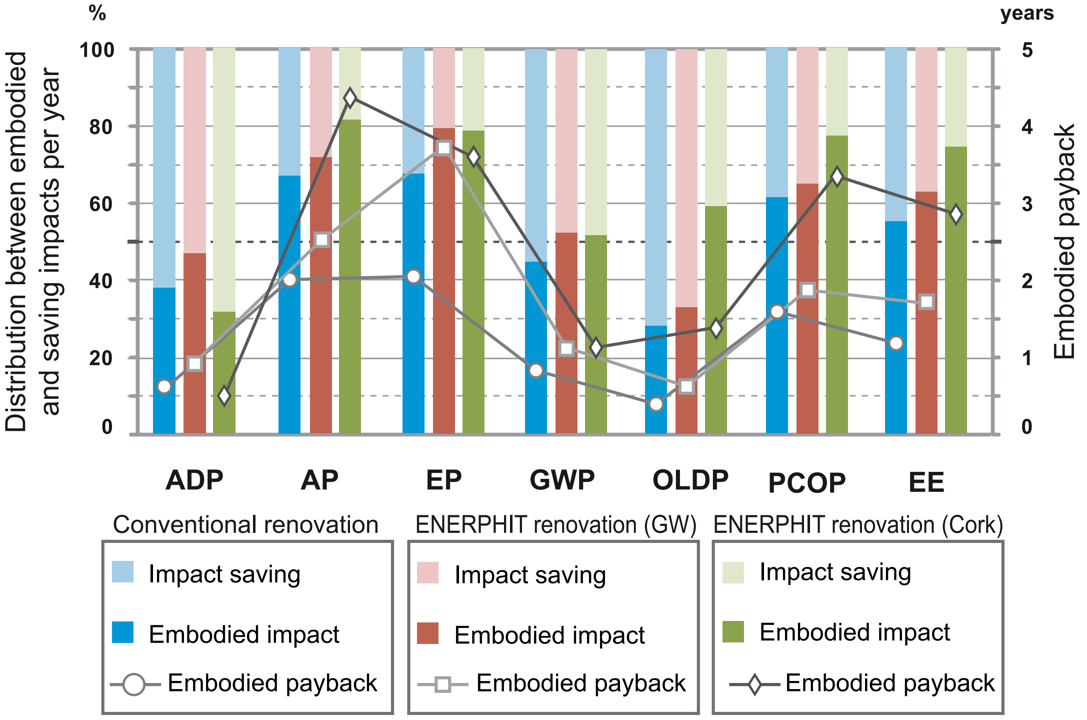

Figure 6. Comparison of embodied energy and environmental impacts with energy saving per year and renovation impacts payback for renovation proposal

The environmental impacts derived from the different renovation proposals can be balanced with the environmental benefits of the energy savings. Generally, the embodied energy and environmental impacts of a building have to be assigned to the lifespan of the building after renovation, in this case, 50 years. However, Figure **6** shows that the majority of the total impacts produced by the renovation project can be compensated for by the energy savings achieved during the operation phase in less than two and a half years, i.e., 5% of its lifespan. Some impacts have a maximum payback of 4 years and 3 months in the ENERPHIT proposal with cork. If the embodied impact is divided into 50 years, the energy savings per year will be much greater than the embodied energy each year.

Regarding the different renovation proposals, the conventional renovation has a lower environmental impact and embodied energy but also generates lower energy savings (Figure **6**). Therefore, the associated renovation impacts payback is not much lower than that of the ENERPHIT renovation proposal, with similar magnitudes for ADP, GWP, OLDP and EE. It can be noted that the lower the operation energy is, the higher the embodied energy becomes. In the case of the ENERPHIT renovation with cork, the payback is higher than that of the ENERPHIT with GW option, except for EP and GWP, which produce similar results. In the case of ADP, the payback time is shorter. The results of the final balance of energy savings for the total building lifespan are similar for both GW and cork. Given the current conditions of cork board manufacturing, cork is not a good option for actual building renovation because of its embodied impacts. In the operating phase, cork exhibits good behaviour because of its low thermal inertia, mostly in the summertime. However, cork's environmental and energy implications are also relevant and are not compensated for by its advantages in the operating phase. According to [41], because cork is a competitive insulation material in the building sector, the cork sector must implement an overall improvement strategy and a series of eco-design strategies throughout the product's life cycle and manufacturing process. If the manufacturing improvements indicated above were included, renovation using cork would produce results similar to those obtained with the GW option; thus, cork insulation products present ample room for improvement.

If the results are compared across the total building lifespan (50 years), it can be observed that the final balance of energy savings for the ENERPHIT alternative is 30% better than that of the conventional proposal (Table 6). If the energy savings are translated into monetary terms, the economic savings for ENERPHIT are greater than those for the conventional proposal by approximately €2,000,000. Comparing these economic savings with respect the initial cost of renovations, it can be noted that they are very advantageous; despite of the estimated renovation cost does not include neither labour nor machinery costs. This approach should be addressed deeply in future studies.

	Total embodied energy	**Energy saving for 50 years**	**Balance in 50 years**	**Balance in 50 years ***	**Renovation cost****
	MJ	MJ	Energy saved (MJ)	€ saved	€
Conventional renovation	2.0E+06	7.3E+07	7.1E+07	6,532,000	153,966
ENERPHIT renovation (GW)	3.2E+06	9.6E+07	9.2E+07	8,464,000	116,911
ENERPHIT renovation (Cork)	5.5E+06	9.7E+07	9.2E+07	8,371,000	168,113

* The energy price was obtained from the data of the Spanish Statistical Office for 2015 (0.092 €/kWh)
** Labour or machinery costs are not included

Table 6. Balance of the different proposals with respect to energy saving over the building lifespan

In summary, the ENERPHIT proposal with GW allows for greater energy savings despite generating a significant increase in environmental impacts and embodied energy; however, these effects are compensated for within a reasonable amount of time, and the final balance for the total lifespan of the building is better than that of the conventional proposal. It would be interesting to extend the scope of this analysis in future research to building facilities. In the case of the ENERPHIT renovation, heating and cooling systems are not required; however, a heat exchanger with a water coil support will be installed. Moreover, economic factors should also be included to complete the set of variables to consider in making decisions regarding more efficient building renovations. Indeed, the cost of more intensive renovation proposals or cork as an insulation material could influence any final decision.

4. Conclusions

A literature review revealed various gaps in the assessment of building renovations from an environmental perspective. Thus, different types of building renovations, i.e., low-energy buildings standards (ENERPHIT) and conventional projects; were compared and the LCA methodology was integrated with thermal dynamic simulation to obtain more realistic results.

The most significant conclusion is the convenience of using these two combined methodologies, because it provides a more complete view of building life cycle and the energy and environmental implications of a renovation. The use of this methodology in public buildings makes a significant contribution because the different routines of use with respect residential buildings. Regarding the case study, this study concludes the convenience of the renovation of Spanish buildings built before 1980, when the specific building rules did not require the insulation of buildings. Both renovation proposals achieved great energy savings, decreasing the operating energy by between 60% and 80%. On the one hand, the conventional renovation project supposes less embodied energy and environmental impacts but also generates less energy savings. On the other hand, the ENERPHIT renovation alternative supposes an increase in the amount of insulation material with respect to the current insulation systems and an increase in the embodied energy of the building; however, the alternative does avoid impacts associated with reduced building energy consumption, achieving an operational energy savings of approximately 80%. Moreover, the environmental implications of material placement are compensated for within a reasonable amount of time for both proposals, over 2 years in the majority of proposals and impact categories, representing 5% of the building lifespan. Over the total building lifespan, the energy savings for the ENERPHIT alternatives are 30% better than those of the conventional proposal.

In summary, the lower the operation energy is, the higher the embodied energy becomes; this relationship is closely related to the amount of insulation material used, which plays a strong role in determining the effects of building renovations. However, to adhere more closely to the aims of low-energy building standards, materials with the lowest carbon and energy contents should be selected, in this case, cork. The current products made of cork do not meet the requirements to compete with the most commonly used insulation material because they do not imply better environmental performance of buildings. However, cork insulation products present ample room for improvement, as demonstrated by simulations of the proposed strategies throughout their life cycles, and could become more efficient and productive. If the appreciated physical and thermal properties of cork could be accompanied by an efficient and sustainable environmental performance, this could equal or improve the performance of the most widespread insulation materials.

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