

1 **Integrated life cycle assessment and thermodynamic simulation of a public 2 building's envelope renovation: Conventional vs. Passivhaus proposal**

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13 **Abstract**

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

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

41 **Keywords**

42 Zero-energy building, ENERPHIT, insulation materials, embodied energy, operating
43 energy, cork, circular economy, industrial ecology, life cycle thinking

44 **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

45

46 **Highlights**

47

- 48 · Conventional and Passivhaus proposals for a university building's renovation are
49 compared.
50 · The energy renovation achieved high energy savings for both proposals, between
51 60% and 80%.
52 · The Passivhaus proposal is 30% better than the conventional one considering the
53 total lifespan of the building
54 · The use of cork as an insulation material for envelope renovation is assessed.
55 · Cork does not fit the requirements for competing with common non-renewable
56 insulation materials.

57 **1. Introduction**

58 **1.1 Background**

59 In Europe, 40% of energy use and the corresponding environmental impacts are
60 concentrated in the building sector [1]. Energy use is considered the area with the
61 greatest potential for intervention [2], playing a crucial role in the energetic
62 transformation of the European Union [3]. The improvement of the sustainability of
63 constructions through a more efficient and use of buildings would decrease the use of
64 energy by 42%, greenhouse emissions by 35%, and the extraction of material by more
65 than 50% [4]. The European Energy Performance of Buildings Directive 2002/91/EC
66 (EPBD) [1] promotes energy efficiency and the use of renewable energy in buildings.
67 Moreover, it presents the concept of nearly zero-energy buildings (NZEB) as a
68 mandatory guideline for all new buildings beginning in 2021. Moreover, Directive
69 2012/27/EU [5], published in 2012 and effective as of 2014, requires all countries of the
70 EU to energetically renew 3% of public administration buildings on an annual basis.

71 Certain efficient building practices for transforming the current building stock are active
72 measures, while others are passive interventions. The former aim to conserve energy
73 in building equipment and maintenance by including system controls or via the
74 installation of renewable energy generating systems. The latter are used to reduce
75 energy consumption in the building envelope; one of the most extended practices is to
76 increase the insulation of the building envelope, including façades, roofs and windows
77 [6,7]. Therefore, insulation materials play an important role because they influence the
78 use phase of a building. For example, the installation of insulation material in envelope
79 solutions can greatly reduce energy demand, by 64% in summer and by up to 37% in
80 winter. With these reductions in energy demand, there is also a decrease in CO₂
81 emissions [8]. In most European buildings, non-renewable insulation materials are
82 installed, including stone wool (SW), glass wool (GW), expanded polystyrene (EPS),
83 extruded polystyrene (XPS) and the less widespread polyurethane (PU) [9,10].
84 Moreover, the market accounts for other alternative materials, including renewable
85 materials. These materials are increasing in relevance because of the strategy
86 involving the substitution of non-renewable materials in buildings. However, before
87 such materials are implemented extensively in buildings, the environmental
88 implications throughout their life cycle must be widely known—something that currently
89 remains underexplored.

90 Focusing on passive interventions, conventional building renovations should reduce
91 their environmental impact during the operating phase to increase indoor comfort
92 through heating and cooling, lighting and operating appliances [11]. However, the
93 intervention practices for energy savings imply the incorporation of embodied energy
94 and environmental impacts from other life cycle phases into the building. Production,
95 on-site construction, final demolition and disposal imply energy use and environmental
96 impacts such that if all improvement strategies are focused on operational energy, the
97 relative importance of embodied energy and environmental impacts could become more
98 relevant to the baseline situation [12–14]. For instance, the European Commission has
99 taken the constructive methodology Passivhaus and its specific criteria for building
100 renovation (ENERPHIT) as a reference for NZEB [15]. This standard, developed in
101 Germany by the Passivhaus-Institut Darmstadt, is largely focused on minimising the

102 operating energy in buildings by intensively using insulation materials and more
103 advanced equipment but does not include the quantification of the environmental
104 implications that this process assumes. Because the relative share of embodied energy
105 in low-energy buildings is more relevant than that in conventional buildings [16], the
106 selection of insulation materials must take into account solutions with low embodied
107 energy [17]. The European Commission advises that efforts to reduce embodied
108 energy must be further strengthened, complementing them with policies for resource
109 efficiency. In this respect, life cycle thinking incorporates the entire product system,
110 from the extraction of materials to their end-of-life, and aims to prevent impact trade-
111 offs between life cycle phases [18]. There is a strong interplay among all the phases of
112 a building life cycle, as each one can affect one or more of the others, highlighting the
113 relevance of the life cycle approach for performing a reliable and complete building
114 energy and environmental assessment [19].

115 1.2. Literature review

116 Life cycle assessment (LCA) methodology quantifies and identifies potential
117 environmental implications in each of the phases of building construction [20] and
118 evaluates the potential benefit of different renovation measures. LCA has gained wide
119 acceptance in the building sector and is used to compare different alternatives in the
120 design of buildings. Most studies have focused on comparisons of different alternatives
121 for building designs regarding the selection of constructive solutions and building
122 materials [2,21–25], while others have focused on new buildings (more specifically,
123 residential buildings) [26–28]. Few studies have addressed the renovation of buildings,
124 with their main goal being to achieve great energy savings, limiting their scope to the
125 assessment of operation energy and often neglecting embodied impacts during
126 production and assembly of materials or constructive solutions [11,29]. It is important to
127 note that the renovation of the EU's ageing building stock was indicated by the
128 European Commission as a key to meeting the EU's objectives to reduce greenhouse
129 gas emissions and energy demand by 20% [30].

130 Among the few studies that have taken into account both the embodied energy and the
131 operating energy of renovated buildings, different levels can be distinguished. On the
132 one hand, at the building level, the final balance between the energy savings achieved
133 during operation and the environmental impacts related to building material
134 incorporation has been assessed [11,17,31]. On the other hand, at the material level,
135 some studies have assessed the combination of different building materials in the
136 renovation of buildings, analysing the influence on energy and environmental
137 performance after renovation [6,29]. A notable gap has been identified in the literature
138 because different types of building renovation have not been extensively compared; for
139 instance, low-energy buildings have not been compared with the conventional systems
140 that are currently utilised in European countries. In this regard, the application of the
141 standard Passivhaus for building renovations is a reference for the European Union.
142 Thus, the standard should be compared with conventional renovation systems beyond
143 residential buildings [16,32,33], integrating a thermal dynamic simulation in the LCA
144 methodology to assess post-renovation building energy consumption more realistically
145 [29,34,35]. Moreover, it is important to note that it is necessary to analyse large
146 buildings, in addition to housing, because doing so could reveal relevant differences in
147 the selection of building materials during the design phase.

148 Additionally, insulation materials play a key role because of influence during both the
149 use phase and the construction of the building [36–38]. Thus, their convenience, as
150 well as that of alternatives such as renewable materials, must be assessed to enhance
151 knowledge about their environmental implications and thermal performance [39]. As
152 mentioned previously, the importance of renewable insulation materials has increased,
153 and previous studies have environmentally assessed some of these, including kenaf
154 fibre, cotton, jute, flax, hemp and cork [10,39–41]. Cork is one of the most extensively
155 used materials in the building sector [42,43] and therefore the most studied from an
156 environmental perspective [39,44–46]. On the one hand, cork has a very significant and
157 varied combination of physical properties, which makes it have a wide variety of
158 potential applications within the building sector [47]. But on the other hand, previous
159 studies highlighted the need to introduce improvements related to the efficiency and
160 sustainability of different stages of its manufacturing process [39]. Additionally, cork
161 oak has great environmental importance because of its role in water retention, soil
162 conservation, and carbon storage [48]. Regarding carbon storage, cork oaks have the
163 capacity to fix carbon, which is transferred to cork materials and products, giving them
164 the potential to mitigate climate change by storing carbon for long periods (until the
165 end-of-life of cork products) [49–51].

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

177 **2. Energy and environmental assessment of building renovation**

178 **2.1. Methodology**

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

182 **2.1.1. Environmental impact assessment of the alternative renovation proposals**

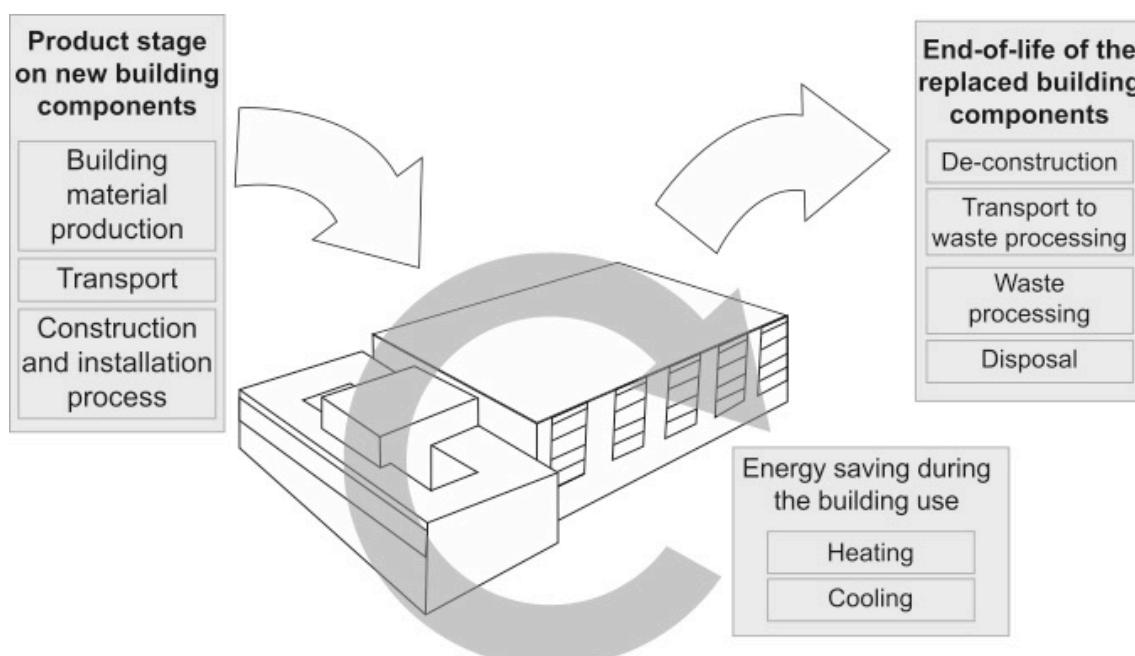
183 The environmental impact assessment was carried out by LCA methodology [52] to
184 evaluate different renovation proposals according to EN 15978 [53] and EN
185 15804:2014 [54]. For the assessment of the product stage of new building
186 components, a cradle-to-site approach was used. This approach includes the
187 production of building materials, their transportation to the building site and their
188 installation. With regard to the end-of-life of the replaced building components, only
189 end-of-life was taken into account.

190 The environmental implications of the materials, energy and transport involved in the
191 system were simulated by using the software SimaPro 8.1 [55] and the ecoinvent 3.2
192 database [56]. According to the European standard that provides the core Product
193 Category Rules (PCR) for all construction products and services, EN 15804:2014 [54],
194 the following six midpoint impact categories from the CML 2 baseline 2002 [57] were
195 included in the assessment: abiotic depletion potential (ADP), acidification potential
196 (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer
197 depletion potential (OLDP) and photochemical oxidation potential (PCOP). Additionally,
198 as previously noted, embodied energy (EE) was included because of its increasing
199 importance in building energy demand.

200 2.1.2. Functional unit and system boundaries

201 The functional unit (FU) selected for this study was 1 square metre of the different
202 solutions of façades, roofs, slab-on-ground and windows that composed the envelope
203 [22]. In this case, to renovate a given surface of the building case study according to
204 two different renovation proposals, the FU was applied to the total area of each
205 constructive solution. Moreover, the FU for the operating phase is the energy
206 consumption associated with heating and cooling over a year under the same indoor
207 thermal conditions.

208 The system boundaries of the study, according to the EN 15978 [53] standard related
209 to the environmental assessment of buildings and the EN 15804:2014 [54] standard
210 related to the environmental product declaration (EDP) of construction products,
211 included, on the one hand, the production of the building material, transport from the
212 factory to the site and the construction and installation processes. On the other hand,
213 the end-of-life stage of the replaced building components also had to be taken into
214 account. Finally, this study also included the use phase to calculate the energy savings
215 achieved for each renovation alternative with respect to the original state of the building
216 (**Figure 1**).



217

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

219 The main assumptions made in the LCA were that the lifespan for the renovation action
220 is 50 years, similar to that reported in other studies [17,29,32,58], and that the distance
221 for transport from the factory to the building location is 100 km, the most representative
222 value reported in the literature [21,59,60].

223 2.1.4. Measurement of the energy savings

224 The energy simulation was carried out with the Computational Fluid Dynamics
225 Simulation module (CFD) of the program DesignBuilder [61]. The model includes the
226 details of transmittances and infiltrations of the original building, and the results
227 pertaining to energy consumption, thermal loads and temperature conditions are
228 compared with real data obtained in the building. These data were obtained from the
229 real thermal characterisation of the building. For this characterisation, the blower-door
230 test was first performed, combined with the use of thermography and smoke pens to
231 measure and observe the infiltrations of the building. The blower-door test was carried
232 out in five enclosures, which were composed of existing construction typologies.
233 Therefore, the average infiltration of the building for a pressure difference of 50 Pa was
234 46.53 air changes per hour. Most of the infiltrations were derived from the carpentry,
235 the forged thermal bridge and the facilities. The transmittances of the different closures
236 were then measured, and using exterior thermography, the transmittances of different
237 thermal bridges were calculated via the differences in surface temperatures. A
238 difference was noted between the calculated transmittance and the measured
239 transmittance in the brick walls, curtain wall, slab on grade floor and roof. Finally, the
240 temperatures inside the building and the energy demand for heating were measured.
241 The energy demand was obtained by measuring the temperature of the input and
242 output of the heated water in the secondary circuit of the heat exchanger system used
243 for the heating system.

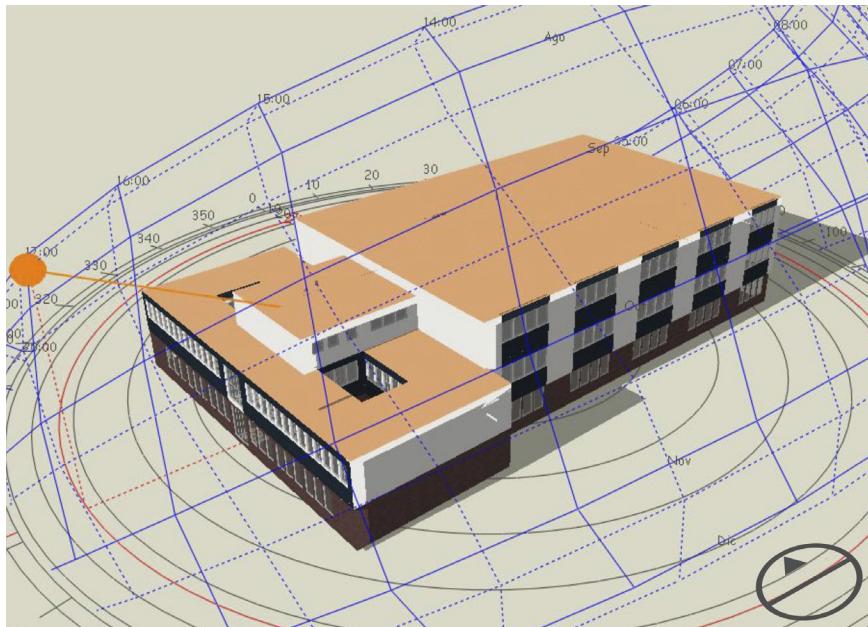
244 Once the building was thermally characterised, a mathematical model was developed
245 with DesignBuilder. Moreover, the pattern of use was included, which helped validate
246 the mathematical model simulated with the program, enabling different renovation
247 projects to be simulated with the knowledge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

254 2.2. Case study

255 2.2.1. Description of the building

256 The assessed building is a university building located in the General Military Academy
257 of the Spanish Army in Zaragoza in northeastern Spain. The building has a constructed
258 surface area of 4,033 m², distributed over a ground floor and two upper floors. Three
259 modules compose the building: the east module is used for classrooms and for a
260 conference hall; the west module, with only one upper floor, is used for offices; and the
261 central module hosts stairs. The real occupancy of the building has been included in
262 the energy simulations by using a pattern of use. For this purpose, the sensible and

263 latent loads produced by the real number of people occupying each space and the
 264 existing computer equipment have been introduced. The building is used only between
 265 the hours of 7:30 and 14:30. The considered months of use are October to June, with
 266 different load levels of use. Moreover, there is partial use until mid-July. **Figure 2**
 267 shows a 3D rendering of the building simulated by DesignBuilder software [61], which
 268 illustrates the composition of the building. The building's floor plans and exact location
 269 are not provided for national security reasons.



270

271 Figure 2. General view of the building simulated with DesignBuilder

272 The building was built in the 1970s following a similar design built in different military
 273 units. The existing building rules at that time did not require the installation of insulation
 274 material (which is also true for the building's envelope). Regarding the composition of the
 275 building's envelope, the façade of the ground floor is composed of (from indoors to
 276 outdoors) plaster, an interior wall of double hollow bricks, an air chamber and another
 277 wall of double hollow bricks. For the upper floors, its composition is (from indoors to
 278 outdoors) plaster, an interior wall of double hollow bricks, an air chamber, another wall
 279 of double hollow bricks, and a metal substructure designed to hold an outer sheet of
 280 prefabricated concrete panels or a curtain wall. The slab is made of 20 cm of reinforced
 281 concrete without insulation, coated with ceramic tile. The external cladding of the
 282 curtain wall is made of tinted glass. Regarding the roof, all modules have installed
 283 reinforced concrete slabs with cement fibre cover. Windows are composed of an
 284 aluminium frame without a thermal break and 6 mm of simple glass. Table 1 presents
 285 the characteristics of the building's envelope and the transmittances (U) of each part of
 286 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

287

Table 1. Structural characteristics of the buildings envelope

288 The building is located in one climate zone denoted D3 [62], which is the largest in
 289 Spain and is the climate zone with the second most severe winter and summer
 290 seasons [63]. If we take Zaragoza as a reference city, according to the Spanish State
 291 Meteorological Agency, the annual average maximum temperature (determined on a
 292 monthly basis) is 21°C, and the annual average minimum temperature (determined on
 293 a monthly basis) is 10°C.

294 2.2.2. Description of the renovation project proposals

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

300 Conventional renovation proposal

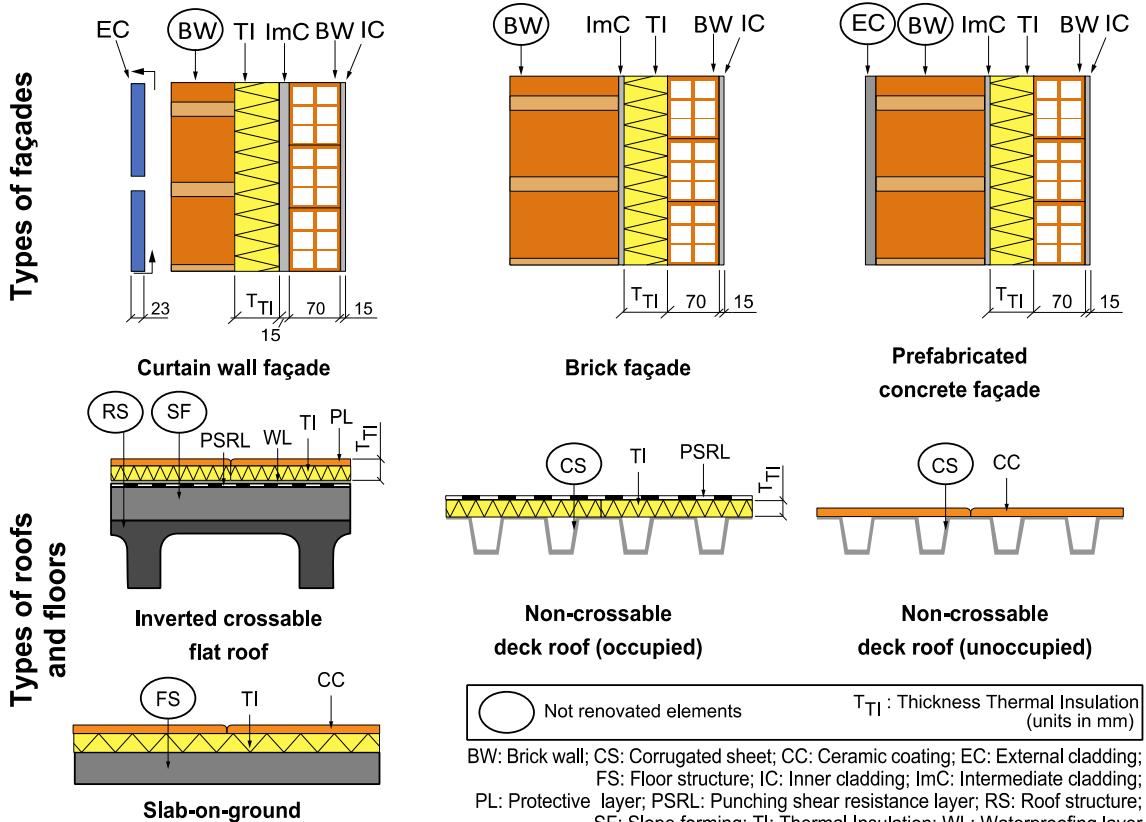
301 As previously indicated, the current building has no insulation installed in its envelope;
 302 therefore, in accordance with the EPBD, the building must be renovated to increase its
 303 energy efficiency of operation. To that end, the Spanish Ministry of Defence is currently
 304 carrying out the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

314 ENERPHIT renovation proposal

315 In addition to the conventional renovation project, this study analysed a more efficient
316 proposal of renovation, complying with the refurbishment standard ENERPHIT, based
317 on the Passivhaus construction standard of nearly zero-energy buildings. The main
318 requirements that buildings must comply with after the refurbishment of air conditioning
319 are final demands of heating and cooling of 25 kWh/m² year and the infiltrations
320 through the envelope under a pressure test of 1 h⁻¹ at pressure of 50 Pa. [64]. The
321 ENERPHIT proposal includes the same types of façades, but in the case of the curtain
322 wall, the tinted glass is not renovated because the authors considered their current
323 state to be good. Regarding the roof, on the classroom side, an inverted flat roof was
324 installed, whereas in the rest of the building, a non-crossable deck roof was installed.
325 However, in this case, a distinction was made between occupied and unoccupied
326 spaces. In occupied areas, the deck roof included insulation materials, and in
327 unoccupied areas (stairs), it did not. The insulation material installed in all façades and
328 roofs was GW. Moreover, in this proposal, the slab-on-ground was insulated with EPS,
329 following the constructive details shown in the following section.

330 2.2.3. Description of the constructive solutions under study

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



345

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

347 2.2.4. Inventory data

348 The assessment of the constructive solutions required data regarding the insulation
 349 materials, quantity, and installation. According to the established FU and the building's
 350 technical considerations, **Table 2** indicates the required inventory of materials and
 351 energy content for each façade, roof and slab-on-ground, in addition to the elements
 352 replaced from the building. The process used during the environmental simulation is
 353 indicated for each process. **Table 2** also includes the cost of all materials used in both
 354 renovation projects [25]. For the installation phase, the materials and energy for the
 355 assembly of all of the components were considered. In the case of the windows,
 356 environmental information was collected from environmental product declarations
 357 published by the manufacturers to obtain the environmental impacts per square metre
 358 [65,66]. In the **Supplementary data**, a comprehensive inventory for each type of
 359 constructive system is included, in addition to the required inventory for the demolition
 360 of each part of the building can be found, as can the energy used during the building
 361 renovation. This energy is similar for different proposals. Moreover, in the
 362 **Supplementary data** it can consult the information related to each process and the
 363 used reference where data were collected.

364

Material	Ecoinvent 3.1 process	Conventional renovation				ENERPHIT renovation			
		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				-			
	Sheet rolling, aluminium/RER	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	4247.166	101.1	4.2	m2	4247.166
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					153,966.24			SW option	116,911.02
								Cork option	168,113.96

Table 2. Life cycle inventory

367 On the other hand, **Table 3** summarises the thickness and the type of insulation
368 material installed in each proposal. The main difference between the two proposals
369 was the insulation material required, with more insulation required in ENERPHIT than
370 in the current project due to the severe ENERPHIT thermal regulation. The most
371 common insulation materials in the building market are XPS, SW, GW and EPS; but
372 additionally, a natural alternative for the insulation material was assessed in this study

373 for the ENERPHIT project, white agglomerated cork, and is commented on in a
 374 posterior sensitivity analysis. The environmental performance of cork has been
 375 previously analysed from different approaches [39,44,67–69]. Despite of being a
 376 natural material with high valuable thermal properties, its environmental performance is
 377 highly dependent on the process of transforming the raw cork into insulation board. All
 378 previous studies have analysed only the cork board and its manufacturing process,
 379 without analysing it in the context of use. Therefore it is necessary to know the thermal
 380 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
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)	*	-	0	-	0.00
Slab-on-ground	*	-	-	0.15	0.18

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

381 Table 3. Insulation material required for the proposal under study

382 The windows varied between the two projects but were from the same manufacturer. In
 383 the case of the conventional renovation project, the selected windows had double
 384 glazed insulation [66]. In the case of the ENERPHIT project, windows had triple glazed
 385 insulation [65]. In addition, in the ENERPHIT project, sealing tape was placed in every
 386 nook of the building to avoid unwanted air infiltration, particularly in windows and doors.

387 3. Results and discussion

388 3.1. Environmental implications of the building renovation

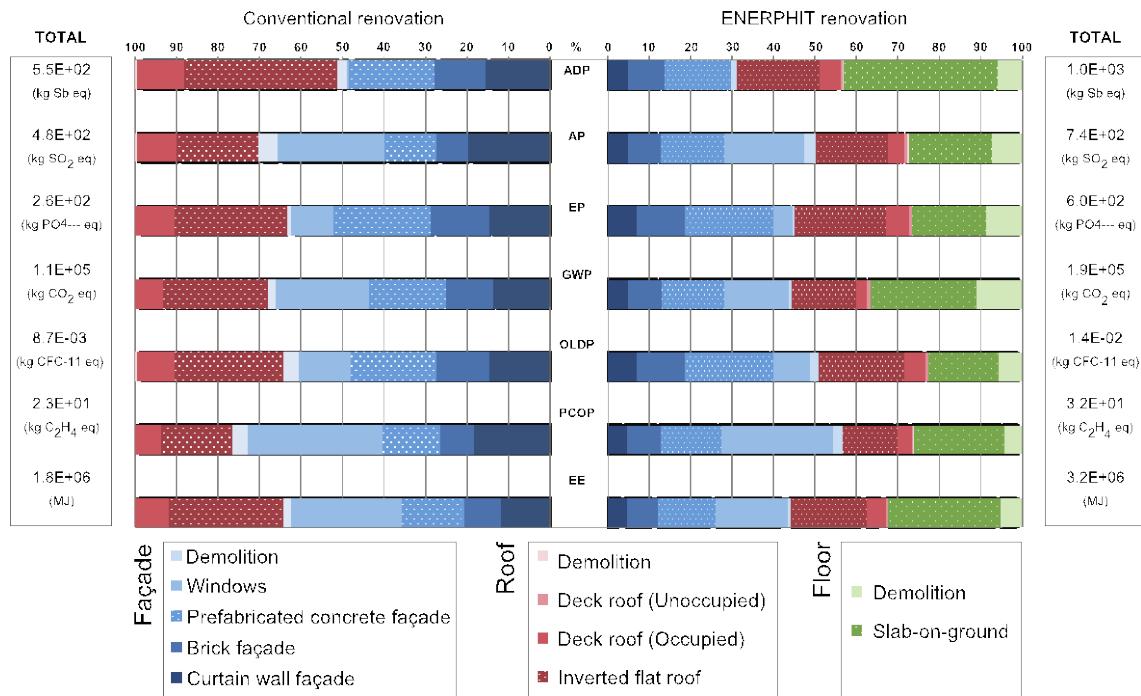
389 In this section, the resulting environmental impacts of each renovation are discussed.
 390 Moreover, the contributions of the insulation materials are analysed.

391 3.1.1. Environmental impact assessment of the alternative renovation proposal by a 392 constructive solution

393 This section presents the results of the LCA of the incorporation of new materials into
 394 the building and the demolition and end-of-life of the replaced components for the two
 395 renovation proposals (**Figure 4**). It is noted that the most intensive alternative in the
 396 use of building materials, ENERPHIT, presents the highest environmental impacts. Its
 397 environmental performance is between 40% and 230% higher than that of the
 398 conventional proposal depending on the impact category considered, particularly in EP,
 399 ADP and EE. Moreover, material use in ENERPHIT is 60% higher in terms of weight
 400 and, consequently, price. As previously indicated, the level of envelope insulation
 401 varies significantly between the two alternatives and thus has a strong influence on the
 402 final results. However, this point will be addressed in the following section.

403 **Figure 4** shows that in both projects the most impacting constructive system is the
 404 façade, despite of having a surface similar to the roof, and in the case of the

405 ENERPHIT project, also similar to the floor (**Table 1**). For that, the intensity in the use
 406 of materials of each constructive system (façade, roof and floor) is directly related. It
 407 can be noted, especially, in the case of windows, the inverted flat roof or the slab-on-
 408 ground.



409

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

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

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

432

433 3.1.2. The contribution of insulation materials in the renovation proposals

434 As previously indicated, the most common passive solution in buildings increases the
 435 relevance of insulation materials with respect to the rest of the building materials. To
 436 determine the extent of this effect, the influence of the insulation materials on the
 437 environmental behaviour of the renovation proposals has to be observed. **Table 4**
 438 shows the relation between the global impacts of each building renovation proposal
 439 and the impacts of their insulation solutions. Previously, **Table 2** shows that the
 440 amount of insulation material is more than 5 times higher in the ENERPHIT proposal
 441 than in the conventional proposal. Calculations show that the contribution of the
 442 insulation material to the global impacts is between 10 and 27% in the case of the
 443 conventional renovation and between 28 and 47% in the case of the ENERPHIT
 444 renovation (**Table 4**). The intensity of the insulation of the building can only be
 445 determined by knowing the energy savings. These data are presented in the following
 446 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
----------------------------	-----------------------------	-----------------------------

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

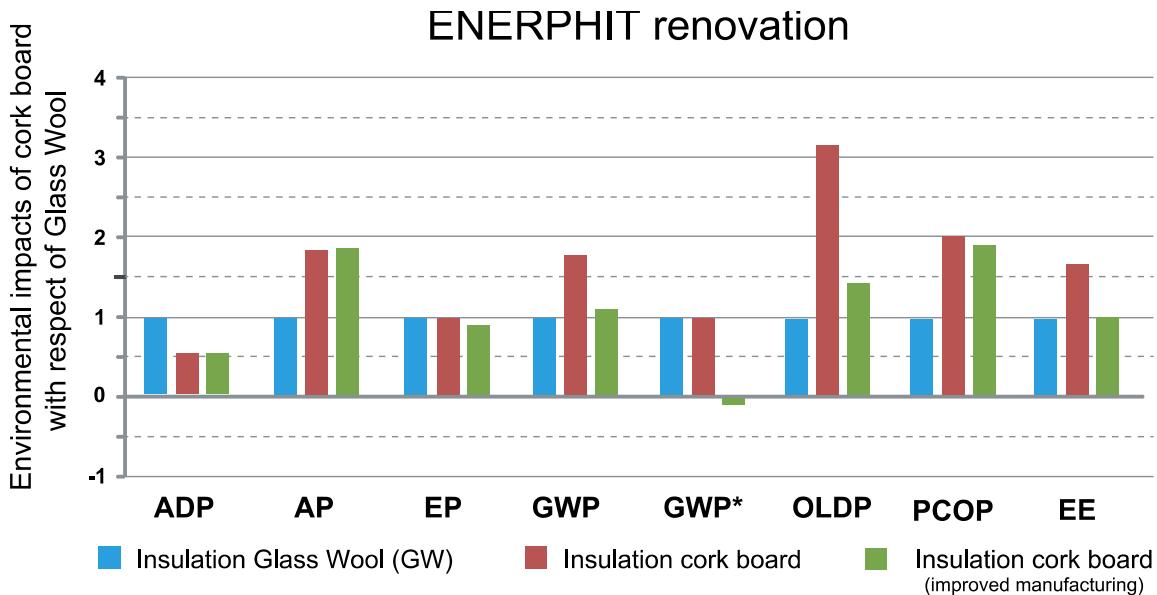
448 Regarding the ENERPHIT proposal, the selected insulation material for the majority of
 449 the constructive solution is GW. Previous studies on the environmental performance of
 450 insulation materials have concluded that GW exhibits better environmental
 451 performance than XPS, EPS, PU and SW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

457 3.1.3. The environmental performance of cork as thermal insulation

458 As indicated previously, cork is the most commonly studied renewable material in
 459 studies on the sustainability of different intermediate and final products [43,48,70–72],
 460 and the environmental performance of an insulation cork panel produced in the largest
 461 cork insulation board manufacturing factory in Catalonia, Spain, was recently assessed
 462 [39]. This study concluded that the use of natural insulation materials does not
 463 necessarily imply a reduction of environmental impacts, as they often have higher
 464 impacts than the majority of the most commonly used insulation materials. The main
 465 reason for this finding is the low technological development of the cork board insulation
 466 manufacturing process. Thus, this study proposed improvement strategies that could
 467 be applied throughout its life cycle to create a more efficient and productive product.
 468 These strategies focused on cleaner production, in addition to the promotion of the
 469 acquisition of local raw cork to reduce the transport distance to the manufacturer

470 because, currently, the majority of raw cork must be transported an average distance
471 of 800 km.

472 The present study also simulated the use of cork as insulation material into the
473 described ENERPHIT proposal. The environmental information was collected from the
474 study Sierra-Pérez et al. [39]. **Figure 5** presents the total results for the ENERPHIT
475 proposal but, in this case, using cork for the thermal insulation of the building envelope
476 in comparison to the results of ENERPHIT project using GW. It can be observed that
477 the environmental impacts of the cork alternative are higher for the majority of the
478 impact categories, including the embodied energy (EE). In the case of GWP, cork
479 doubles the results of ENERPHIT with GW. Additionally, as previously indicated, the
480 option that includes the biogenic carbon contained in the cork boards is also taken into
481 account, decreasing the CO₂ contribution of the global building renovation by
482 approximately 50%. Alternatively, **Figure 5** also presents the results for a more
483 environmentally friendly cork board, following the improvement scenario proposed by
484 Sierra-Pérez et al., were also simulated to assess the potential for improvement. This
485 option is equivalent to ENERPHIT with the GW option in the majority of the impact
486 categories; ADP and EP show better results. If biogenic carbon is included in the
487 analysis, the global result of the building renovation, in kg of CO₂ –eq., is negative; this
488 finding implies that the ENERPHIT project combined with improved cork boards can
489 help to mitigate climate change. In this regard, Sierra-Pérez et al. [39] have already
490 discussed different end-of-life scenarios for cork insulation boards, concluding that cork
491 insulation board will store carbon dioxide indefinitely if the product is recycled for the
492 manufacturing of another product with a lifespan of 50 years.



493 * Includes the biogenic carbon contained in cork boards

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

496 3.3. Energy and environmental benefits in the operational phase

497 This section presents the results of the operating energy of the building based on the
498 real measurements carried out in the building for its current use and the results of the

499 simulations for the renovation proposals, including ENERPHIT with cork (**Table 5**). The
500 operating energy is expressed in terms of heating and cooling. It can be observed that
501 the heating energy decreases drastically with respect to the current state of the
502 building for all proposals. The convenience of renovating Spanish buildings built before
503 1980, when the building rules did not require insulation, can be observed. Currently,
504 the operating energy for heating is 641,287.9 kWh/year, while the operating energies
505 for the conventional and ENERHY renovations are 190,864.2 and 43,429.9 kWh/year,
506 respectively. These calculations suppose reductions of 70% and 93% for the
507 conventional and ENERHY renovations, respectively. In the case of cooling energy, the
508 results for operating energy are higher for both renovation projects with respect to the
509 current state of the building because of the reduction of the natural ventilation of the
510 building, as its insulation and sealing have been increased. This result is obtained
511 because a mechanical ventilation system with heat recovery is not included in the
512 building renovation, as the associated regulations require. If the building facilities had
513 included it, ENERPHIT would require a more efficient system of heat recovery than
514 conventional renovations. Currently, the operating energy for cooling is 36,603.5
515 kWh/year, while the operating energies for the conventional and ENERPHIT
516 renovations are 75,718.0 and 96,511.0 kWh/year, respectively. These figures represent
517 increases of 106% and 160% for the conventional and ENERPHIT renovations,
518 respectively. Moreover, the cork alternative for the ENERPHIT proposal is also
519 assessed, resulting in higher energy savings than the conventional and ENERPHIT
520 renovations with GW insulation.

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

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

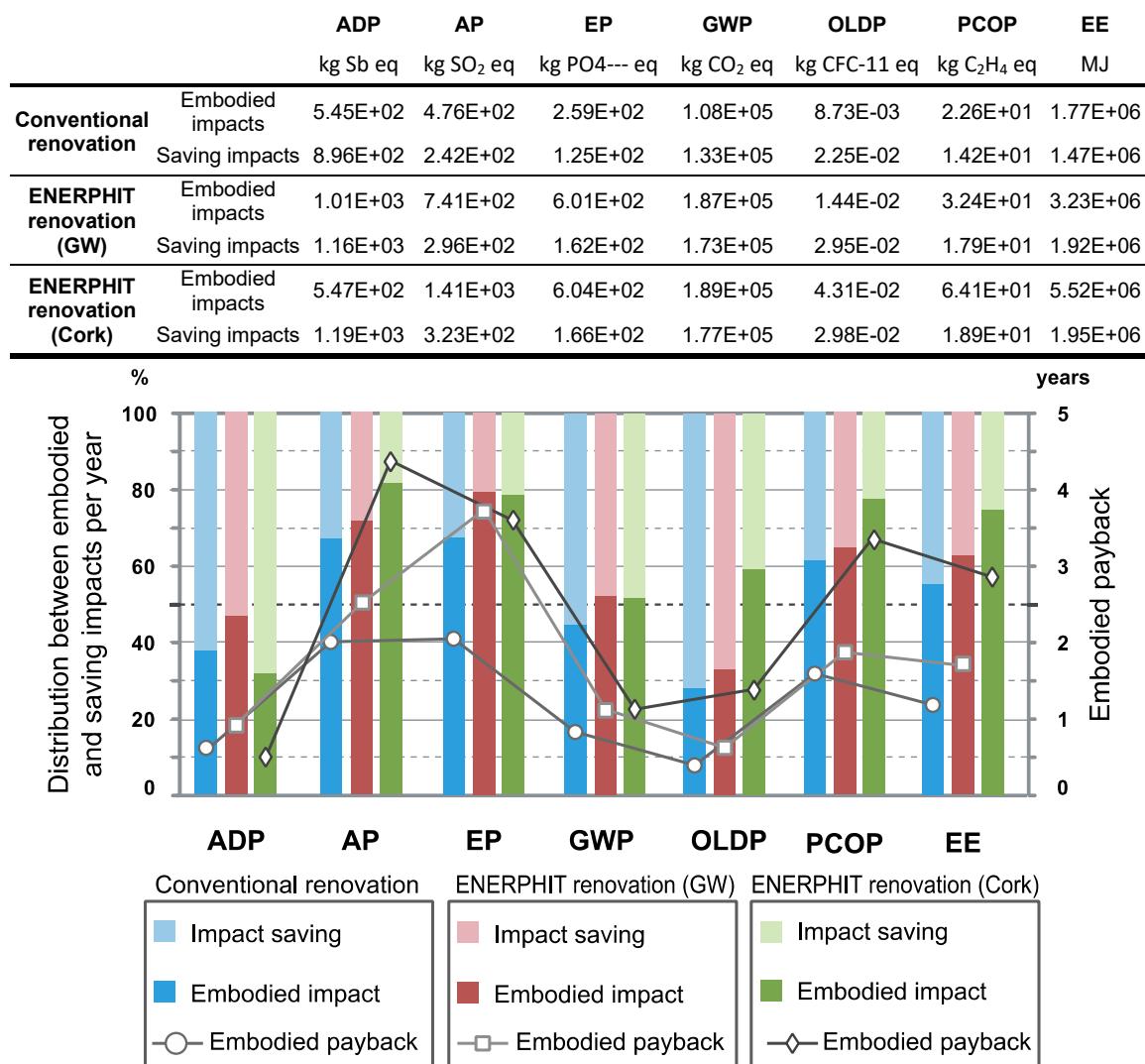
541

	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%

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

544 3.4. Embodied energy and environmental impacts vs. energy savings

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

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

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

563 Regarding the different renovation proposals, the conventional renovation has a lower
564 environmental impact and embodied energy but also generates lower energy savings
565 (**Figure 6**). Therefore, the associated renovation impacts payback is not much lower
566 than that of the ENERPHIT renovation proposal, with similar magnitudes for ADP,
567 GWP, OLDP and EE. It can be noted that the lower the operation energy is, the higher
568 the embodied energy becomes. In the case of the ENERPHIT renovation with cork, the
569 payback is higher than that of the ENERPHIT with GW option, except for EP and GWP,
570 which produce similar results. In the case of ADP, the payback time is shorter. The
571 results of the final balance of energy savings for the total building lifespan are similar
572 for both GW and cork. Given the current conditions of cork board manufacturing, cork
573 is not a good option for actual building renovation because of its embodied impacts. In
574 the operating phase, cork exhibits good behaviour because of its low thermal inertia,
575 mostly in the summertime. However, cork's environmental and energy implications are
576 also relevant and are not compensated for by its advantages in the operating phase.
577 According to [39], because cork is a competitive insulation material in the building
578 sector, the cork sector must implement an overall improvement strategy and a series of
579 eco-design strategies throughout the product's life cycle and manufacturing process. If
580 the manufacturing improvements indicated above were included, renovation using cork
581 would produce results similar to those obtained with the GW option; thus, cork
582 insulation products present ample room for improvement.

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

592

	Total embodied energy	Energy saving for 50 years	Balance in 50 years	Balance in 50 years *	Renovation cost**
	MJ	MJ	MJ	€	€
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

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

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

606 4. Conclusions

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

612 The most significant conclusion is the convenience of using these two combined
 613 methodologies, because it provides a more complete view of building life cycle and the
 614 energy and environmental implications of a renovation. The use of this methodology in
 615 public buildings makes a significant contribution because the different routines of use
 616 with respect residential buildings. Regarding the case study, this study concludes the
 617 convenience of the renovation of Spanish buildings built before 1980, when the specific
 618 building rules did not require the insulation of buildings. Both renovation proposals
 619 achieved great energy savings, decreasing the operating energy by between 60% and
 620 80%. On the one hand, the conventional renovation project supposes less embodied
 621 energy and environmental impacts but also generates less energy savings. On the
 622 other hand, the ENERPHIT renovation alternative supposes an increase in the amount
 623 of insulation material with respect to the current insulation systems and an increase in
 624 the embodied energy of the building; however, the alternative does avoid impacts
 625 associated with reduced building energy consumption, achieving an operational energy
 626 savings of approximately 80%. Moreover, the environmental implications of material
 627 placement are compensated for within a reasonable amount of time for both proposals,
 628 over 2 years in the majority of proposals and impact categories, representing 5% of the

629 building lifespan. Over the total building lifespan, the energy savings for the ENERPHIT
630 alternatives are 30% better than those of the conventional proposal.

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

644

645 **References**

- 646 [1] European Commission. Energy Performance of Buildings Directive 2010/31/EU (EPBD).
647 Brussels: 2010.
- 648 [2] Proietti S, Desideri U, Sdringola P, Zepparelli F. Carbon footprint of a reflective foil and
649 comparison with other solutions for thermal insulation in building envelope. *Appl Energy*
650 2013;112:843–55. doi:10.1016/j.apenergy.2013.01.086.
- 651 [3] European Commission. Energy Roadmap 2050. COM 885/2. Brussels: 2011.
- 652 [4] European Commission. COM 571 Road map to a resource efficient Europe. Brussels:
653 2011.
- 654 [5] European Comission. Energy Efficiency Directive 2012/27/EU 2012.
- 655 [6] Nicolae B, George-Vlad B. Life cycle analysis in refurbishment of the buildings as
656 intervention practices in energy saving. *Energy Build* 2015;86:74–85.
657 doi:10.1016/j.enbuild.2014.10.021.
- 658 [7] Aste N, Adhikari RS, Buzzetti M. Beyond the EPBD: The low energy residential
659 settlement Borgo Solare. *Appl Energy* 2010;87:629–42.
660 doi:10.1016/j.apenergy.2009.05.029.
- 661 [8] Cabeza LF, Castell A, Medrano M, Martorell I, Pérez G, Fernández I. Experimental study
662 on the performance of insulation materials in Mediterranean construction. *Energy Build*
663 2010;42:630–6. doi:10.1016/j.enbuild.2009.10.033.
- 664 [9] Papadopoulos AM. State of the art in thermal insulation materials and aims for future
665 developments. *Energy Build* 2005;37:77–86. doi:10.1016/j.enbuild.2004.05.006.
- 666 [10] Ardente F, Beccali M, Cellura M, Mistretta M. Building energy performance: A LCA case
667 study of kenaf-fibres insulation board. *Energy Build* 2008;40:1–10.
668 doi:10.1016/j.enbuild.2006.12.009.
- 669 [11] Ardente F, Beccali M, Cellura M, Mistretta M. Energy and environmental benefits in
670 public buildings as a result of retrofit actions. *Renew Sustain Energy Rev* 2011;15:460–
671 70. doi:10.1016/j.rser.2010.09.022.
- 672 [12] Thormark C. A low energy building in a life cycle — its embodied energy , energy need
673 for operation and recycling potential. *Build Environ* 2002;37:429–35.
- 674 [13] Pacheco-Torgal F, Faria J, Jalali S. Embodied Energy versus Operational Energy.
675 Showing the Shortcomings of the Energy Performance Building Directive (EPBD). *Mater*
676 *Sci Forum* 2012. doi:10.4028/www.scientific.net/MSF.730-732.587.
- 677 [14] Pacheco-Torgal F. Eco-efficient construction and building materials research under the
678 EU Framework Programme Horizon 2020. *Constr Build Mater* 2014;51:151–62.
679 doi:10.1016/j.conbuildmat.2013.10.058.
- 680 [15] BPIE. Principles for nearly zero- energy buildings. Paving the way for effective
681 implementation of policy requirements. Brussels, Belgium: 2011.
- 682 [16] Stephan A, Crawford RH, de Myttenaere K. A comprehensive assessment of the life
683 cycle energy demand of passive houses. *Appl Energy* 2013;112:23–34.
684 doi:10.1016/j.apenergy.2013.05.076.
- 685 [17] Beccali M, Cellura M, Fontana M, Longo S, Mistretta M. Energy retrofit of a single-family
686 house: Life cycle net energy saving and environmental benefits. *Renew Sustain Energy*
687 *Rev* 2013;27:283–93. doi:10.1016/j.rser.2013.05.040.
- 688 [18] Finkbeiner M, Schau EM, Lehmann A, Traverso M. Towards life cycle sustainability
689 assessment. *Sustainability* 2010;2:3309–22. doi:10.3390/su2103309.
- 690 [19] Sartori I, Hestnes AG. Energy use in the life cycle of conventional and low-energy
691 buildings: A review article. *Energy Build* 2007;39:249–57.
692 doi:10.1016/j.enbuild.2006.07.001.

- 693 [20] ISO/EN 14040. Environmental management - life cycle assessment - principles and
694 framework (ISO 14040:2006). 2006.
- 695 [21] Zabalza Bribián I, Valero Capilla A, Aranda Usón A. Life cycle assessment of building
696 materials: Comparative analysis of energy and environmental impacts and evaluation of
697 the eco-efficiency improvement potential. *Build Environ* 2011;46:1133–40.
698 doi:10.1016/j.buildenv.2010.12.002.
- 699 [22] Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Environmental assessment of
700 façade-building systems and thermal insulation materials for different climatic conditions.
701 *J Clean Prod* 2016;113:102–13. doi:10.1016/j.jclepro.2015.11.090.
- 702 [23] Monteiro H, Freire F. Life-cycle assessment of a house with alternative exterior walls:
703 Comparison of three impact assessment methods. *Energy Build* 2012;47:572–83.
704 doi:10.1016/j.enbuild.2011.12.032.
- 705 [24] Islam H, Jollands M, Setunge S, Ahmed I, Haque N. Life cycle assessment and life cycle
706 cost implications of wall assemblages designs. *Energy Build* 2014;84:33–45.
707 doi:10.1016/j.enbuild.2014.07.041.
- 708 [25] Itec M. Online IteC Database: Prices, Technical Details, Companies, Certificates,
709 Product Pictures and Environmental Data. 2010. <http://www.itec.cat/metabase>.
- 710 [26] Sharma A, Saxena A, Sethi M, Shree V. Life cycle assessment of buildings: A review.
711 *Renew Sustain Energy Rev* 2011;15:871–5. doi:10.1016/j.rser.2010.09.008.
- 712 [27] Cabeza LF, Rincón L, Vilariño V, Pérez G, Castell A. Life cycle assessment (LCA) and
713 life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renew
714 Sustain Energy Rev* 2014;29:394–416. doi:10.1016/j.rser.2013.08.037.
- 715 [28] Ramesh T, Prakash R, Shukla KK. Life cycle energy analysis of a residential building
716 with different envelopes and climates in Indian context. *Appl Energy* 2012;89:193–202.
717 doi:10.1016/j.apenergy.2011.05.054.
- 718 [29] Rodrigues C, Freire F. Integrated life-cycle assessment and thermal dynamic simulation
719 of alternative scenarios for the roof retrofit of a house. *Build Environ* 2014;81:204–15.
720 doi:10.1016/j.buildenv.2014.07.001.
- 721 [30] European Commission. COM 2012/433 final. Communication from the Commission to
722 the European Parliament and the Council - Strategy for the sustainable competitiveness
723 of the construction sector and its enterprises. *Off J Eur Union* 2012.
- 724 [31] Chau CK, Leung TM, Ng WY. A review on Life Cycle Assessment, Life Cycle Energy
725 Assessment and Life Cycle Carbon Emissions Assessment on buildings. *Appl Energy*
726 2015;143:395–413. doi:10.1016/j.apenergy.2015.01.023.
- 727 [32] Pombo O, Allacker K, Rivela B, Neila J. Sustainability assessment of energy saving
728 measures: a multi-criteria approach for residential buildings retrofitting—A case study of
729 the Spanish housing stock. *Energy Build* 2016;116:384–94.
730 doi:10.1016/j.enbuild.2016.01.019.
- 731 [33] Dodoo A, Gustavsson L. Life cycle primary energy use and carbon footprint of wood-
732 frame conventional and passive houses with biomass-based energy supply. *Appl Energy*
733 2013;112:834–42. doi:10.1016/j.apenergy.2013.04.008.
- 734 [34] Chantrelle FP, Lahmidi H, Keilholz W, Mankibi M El, Michel P. Development of a
735 multicriteria tool for optimizing the renovation of buildings. *Appl Energy* 2011;88:1386–
736 94. doi:10.1016/j.apenergy.2010.10.002.
- 737 [35] Gustafsson M, Gustafsson MS, Myhren JA, Bales C, Holmberg S. Techno-economic
738 analysis of energy renovation measures for a district heated multi-family house. *Appl
739 Energy* 2016;177:108–16. doi:10.1016/j.apenergy.2016.05.104.
- 740 [36] Su X, Luo Z, Li Y, Huang C. Life cycle inventory comparison of different building
741 insulation materials and uncertainty analysis. *J Clean Prod* 2015;112:275–81.
742 doi:10.1016/j.jclepro.2015.08.113.

- 743 [37] Tettey UYA, Dodoo A, Gustavsson L. Effects of different insulation materials on primary
744 energy and CO₂ emission of a multi-storey residential building. *Energy Build*
745 2014;82:369–77. doi:10.1016/j.enbuild.2014.07.009.
- 746 [38] Biswas K, Shrestha SS, Bhandari MS, Desjarlais AO. Insulation materials for
747 commercial buildings in North America: An assessment of lifetime energy and
748 environmental impacts. *Energy Build* 2015;112:256–69.
749 doi:10.1016/j.enbuild.2015.12.013.
- 750 [39] Sierra-Pérez J, Boschmonart-Rives J, Dias AC, Gabarrell X. Environmental implications
751 of the use of agglomerated cork as thermal insulation in buildings. *J Clean Prod*
752 2016;126:97–107. doi:10.1016/j.jclepro.2016.02.146.
- 753 [40] Zampori L, Dotelli G, Vernelli V. Life cycle assessment of hemp cultivation and use of
754 hemp-based thermal insulator materials in buildings. *Environ Sci Technol* 2013;47:7413–
755 20. doi:10.1021/es401326a.
- 756 [41] Korjenic A, Petránek V, Zach J, Hroudová J. Development and performance evaluation
757 of natural thermal-insulation materials composed of renewable resources. *Energy Build*
758 2011;43:2518–23. doi:10.1016/j.enbuild.2011.06.012.
- 759 [42] Gil L. Cork. *Mater. Constr. Civ. Eng.*, 2015, p. 585–627. doi:10.1007/978-3-319-08236-
760 3_13.
- 761 [43] Sierra-Pérez J, Boschmonart-Rives J, Gabarrell X. Production and trade analysis in the
762 Iberian cork sector: Economic characterization of a forest industry. *Resour Conserv
763 Recycl* 2015;98:55–66. doi:10.1016/j.resconrec.2015.02.011.
- 764 [44] Pargana N, Pinheiro MD, Silvestre JD, de Brito J. Comparative environmental life cycle
765 assessment of thermal insulation materials of buildings. *Energy Build* 2014;82:466–81.
766 doi:10.1016/j.enbuild.2014.05.057.
- 767 [45] Demertzis M, Garrido A, Dias AC, Arroja L. Environmental performance of a cork floating
768 floor. *Mater Des* 2015. doi:10.1016/j.matdes.2014.12.055.
- 769 [46] Rives J, Fernandez-Rodriguez I, Rieradevall J, Gabarrell X. Environmental analysis of
770 the production of natural cork stoppers in southern Europe (Catalonia – Spain). *J Clean
771 Prod* 2011;19:259–71. doi:10.1016/j.jclepro.2010.10.001.
- 772 [47] Sierra-Pérez J, López-Forniés I, Boschmonart-Rives J, Gabarrell X. Introducing eco-
773 ideation and creativity techniques to increase and diversify the applications of eco-
774 materials: The case of cork in the building sector. *J Clean Prod* 2016;137:606–16.
775 doi:10.1016/j.jclepro.2016.07.121.
- 776 [48] Rives J, Fernandez-Rodriguez I, Rieradevall J, Gabarrell X. Integrated environmental
777 analysis of the main cork products in southern Europe (Catalonia – Spain). *J Clean Prod*
778 2013;51:289–98. doi:10.1016/j.jclepro.2013.01.015.
- 779 [49] Dias AC, Arroja L. A model for estimating carbon accumulation in cork products. *For
780 Syst* 2014;23:236–46. doi:10.5424/fs/2014232-04100.
- 781 [50] European Committee for Standardization. UNE-EN 16449. Wood and wood-based
782 products. Calculation of the biogenic carbon content of wood and conversion to carbon
783 dioxide. 2014.
- 784 [51] Gil L, Pereira C. A fórmula da cortiça. *Tecnol E Vida* 2007;November:1–4.
- 785 [52] ISO. ISO 14040: Life Cycle Assessment — Principles and Framework. *Environ Manage*
786 2006;3:28. doi:10.1002/jtr.
- 787 [53] European Committee for Standardization. UNE-EN 15978:2011 Sustainability of
788 construction works - Assessment of environmental performance of buildings -
789 Calculation method. *Int Stand* 2011.
- 790 [54] European Committee for Standardization. EN 15804:2012+A1, 2013. Sustainability of
791 construction works - Environmental product declarations – Core rules for the product
792 category of construction products. 2014.

- 793 [55] PRé Consultants. Simapro 7.3.0. Amersfoort (Netherlands): 2010.
- 794 [56] ecoinvent. ecoinvent database 3.1. Swiss Cent Life Cycle Invent 2009.
795 <http://www.ecoinvent.ch/>.
- 796 [57] Guinée J., Gorrée M, Heijungs R, Huppes G, Kleijn R, Koning A de, et al. Handbook on
797 life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa:
798 Guide. IIb: Operational annex. III: Scientific background. Dordrecht: Kluwer Academic
799 Publishers; 2002.
- 800 [58] Pombo O, Rivela B, Neila J. The challenge of sustainable building renovation:
801 assessment of current criteria and future outlook. *J Clean Prod* 2016;123:88–100.
802 doi:10.1016/j.jclepro.2015.06.137.
- 803 [59] Sanjuan-Delmás D, Petit-Boix A, Gasol CM, Villalba G, Suárez-Ojeda ME, Gabarrell X,
804 et al. Environmental assessment of different pipelines for drinking water transport and
805 distribution network in small to medium cities: a case from Betanzos, Spain. *J Clean*
806 *Prod* 2014;66:588–98. doi:10.1016/j.jclepro.2013.10.055.
- 807 [60] Oliver-Solà J, Josa A, Rieradevall J, Gabarrell X. Environmental optimization of concrete
808 sidewalks in urban areas. *Int J Life Cycle Assess* 2009;14:302–12. doi:10.1007/s11367-
809 009-0083-7.
- 810 [61] DesignBuilder Software Ltd. DesignBuilder v3. Stroud, (United Kingdom): 2009.
- 811 [62] Código Técnico de la Edificación (CTE). Documento Básico de Ahorro de Energía (DB-
812 HE) 2006.
- 813 [63] Rodríguez-Soria B, Domínguez-Hernández J, Pérez-Bella JM, Del Coz-Díaz JJ. Review
814 of international regulations governing the thermal insulation requirements of residential
815 buildings and the harmonization of envelope energy loss. *Renew Sustain Energy Rev*
816 2014;34:78–90. doi:10.1016/j.rser.2014.03.009.
- 817 [64] Feist W. EnerPHit and EnerPHit+i. Certification Criteria for Energy Retrofits with Passive
818 House Components. 2013.
- 819 [65] IBU. Environmental Product Declaration QKE e.V. – PVC-U window with insulated triple-
820 glazing. Berlin: 2014.
- 821 [66] IBU. Environmental Product Declaration QKE e.V. – PVC-U window (1.23 x 1.48m) with
822 insulated double-glazing. Berlin: 2014.
- 823 [67] de Brito J, Silvestre J, Pinheiro MD. Life-cycle assessment of thermal insulation
824 materials used in building's external walls. Int. student chapter Conf., Budapest,
825 Hungary: 2010.
- 826 [68] Demertzis M, Sierra-Pérez J, Paulo JA, Arroja L, Dias AC. Environmental performance of
827 expanded cork slab and granules through life cycle assessment. *J Clean Prod* 2017.
828 doi:10.1016/j.jclepro.2017.01.071.
- 829 [69] Silvestre J, Pargana N, de Brito J, Pinheiro M, Durão V. Insulation Cork Boards—
830 Environmental Life Cycle Assessment of an Organic Construction Material. *Materials*
831 (Basel) 2016;9:394. doi:10.3390/ma9050394.
- 832 [70] Rives J, Fernandez-Rodriguez I, Gabarrell X, Rieradevall J. Environmental analysis of
833 cork granulate production in Catalonia – Northern Spain. *Resour Conserv Recycl*
834 2012;58:132–42. doi:10.1016/j.resconrec.2011.11.007.
- 835 [71] Rives J, Fernandez-Rodriguez I, Rieradevall J, Gabarrell X. Environmental analysis of
836 raw cork extraction in cork oak forests in southern Europe (Catalonia--Spain). *J Environ*
837 *Manage* 2012;110:236–45. doi:10.1016/j.jenvman.2012.06.024.
- 838 [72] Rives J, Fernández-Rodríguez I, Rieradevall J, Gabarrell X. Environmental analysis of
839 the production of champagne cork stoppers. *J Clean Prod* 2012;25:1–13.
840 doi:10.1016/j.jclepro.2011.12.001.

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