

# Life Cycle Assessment of alveolar brick construction system incorporating phase change materials (PCM)

Albert Castell<sup>1</sup>, Karim Menoufi<sup>1</sup>, Alvaro de Gracia<sup>1</sup>, Lúdia Rincón<sup>1</sup>, Dieter Boer<sup>2</sup>, Luisa F. Cabeza<sup>1</sup>

<sup>1</sup>GREA Innovació concurrent, Edifici CREA, Universitat de Lleida, Pere de Cabrera s/n, 25001-Lleida (Spain), Phone: +34-973 003576, Fax: +34-973 003575, e-mail: lcabeza@diei.udl.cat

<sup>2</sup>Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Països Catalans, 26, 43007 Tarragona (Spain)

## Abstract

An evaluation of the environmental impact of construction systems that are composed of facades based on alveolar bricks and macroencapsulated phase change materials done using Life Cycle Assessment (LCA) is presented. Their energy consumption rates for both heating and cooling have been measured and registered in two experimental cubicles located in Puigverd de Lleida (Spain). This work examines if the reduction of the environmental impact that is reached due to the energy savings achieved during the operational phase of these cubicles compensates the increase of the environmental impact that is induced during the manufacturing phase. Theoretical case studies, such as assuming different climatization and weather conditions, are proposed and studied to determine the most suitable climatic conditions for using the alveolar bricks and PCM technologies. Within the context of the LCA study, it is concluded that the overall benefit of PCM is the highest when summer weather conditions throughout the whole year is theoretically assumed, where for different assumed lifetime periods of the cubicles the reduction of the overall global impact of the cubicle containing PCM ranges from 12 % to 14 % in comparison to the other cubicle without PCM.

**Key-words:** Life Cycle Assessment (LCA), phase change materials (PCM), thermal energy storage (TES), buildings, energy efficiency.

## 32 1. Introduction

33

34 The increasing consumption of natural resources during the last years is clearly represented by the high  
35 consumption rates of the building sector. For example, the energy demand for cooling and heating in  
36 buildings is increasing significantly, and thus, it is contributing largely to the total energy consumption  
37 and CO<sub>2</sub> emissions. The contribution of the corresponding energy consumption has been estimated to be  
38 around 40 % in Europe [1], demonstrating the huge potential for improving the energy efficiency of  
39 buildings. This can be done through modifying the constructive systems by using specific building  
40 technologies (such as trombe walls or double skin facades), insulating materials, and a recently applied  
41 technology, which is the incorporation of phase change materials into the building structure in order to  
42 increase the thermal energy storage capacity of envelopes and floors. The reduction of energy  
43 consumption and other natural resources during the operational, manufacturing and disposal (dismantling)  
44 phases of buildings can reduce the impact on the environment, achieving a more sustainable and  
45 environmentally friendly building sector. The criteria for analyzing the opportunities of achieving the  
46 required sustainability can be applied through adopting a Life Cycle Assessment (LCA) approach.

47

48 LCA is a tool for evaluating the environmental impact of a product through analyzing the corresponding  
49 life cycle phases from cradle to grave. In case of buildings, LCA is mainly used to evaluate the  
50 environmental impact during the manufacturing phase, the operational phase and the dismantling phase.  
51 For example, LCA has been recently used in order to analyze the energy supply and installations in  
52 Spanish buildings [2]. A state of the art regarding the use of LCA in the building sector has been carried  
53 out by Zabalza et al. [3]. This research also proposes a simplified criterion for applying LCA in order to  
54 overcome the complexity of the analysis and the difficulties related to the energy certification  
55 applications. In addition, new methodologies and calculation methods are under research and  
56 development [4] and the influence of some simplifications is being investigated [5].

57

58 Papadopoulos and Giama [6] have applied LCA in order to examine the buildings environmental  
59 performance evaluation through insulation materials selection. In this study, it has been concluded that  
60 the use of the environmental performance evaluation in the building sector can help verifying the impact  
61 of insulation on energy consumption. Another study conducted by Huberman and Pearlmutter [7] has

62 focused on evaluating the environmental impact of specific building materials showing that the impact of  
63 their embodied energy represents about 60% of the over all life cycle energy consumption. Kofoworola  
64 and Gheewala [8] have conducted an LCA approach to examine the environmental impact of a typical  
65 commercial office building in Thailand, verifying that the operational stage is the predominant one in  
66 case of commercial buildings. Moreover, twenty five commercial buildings in Hong Kong have been  
67 studied by Chau et al. [9] highlighting the most impacting building materials and building services  
68 materials as well. All these studies demonstrate the significance of using LCA in order to examine the  
69 construction solutions, and search for alternative ones that achieve the required level of sustainability.

70

71 Many constructive systems that encompass different building materials have appeared and have been  
72 considered in the recent years in order to improve the thermal behaviour of buildings; some of these  
73 solutions are trying to simplify the construction process as well [10]. For example, the use of a simpler  
74 construction system based on alveolar bricks instead of the common systems based on conventional  
75 bricks, air gap and insulating materials has been introduced in the last years with the aim of reducing the  
76 construction process time and complexity, and increasing the thermal inertia of the building walls. This  
77 solution has been further improved by embedding phase change materials (PCM) in the building envelope  
78 in order to further increase the thermal inertia of the whole system and hence reduce energy demand; this  
79 is especially important for reducing the cooling demand as it has been verified experimentally [11,12].  
80 Besides, using the alveolar brick construction system without insulation has been proved to achieve  
81 similar energy savings to those accomplished by the conventional brick construction solutions that  
82 incorporates insulation materials. This conclusion is attributed to the high thermal inertia provided by the  
83 alveolar bricks constructive system [13,14]. However, an LCA is still needed in order to determine the  
84 global benefits of such solutions including the contribution of the relevant life cycle phases and taking  
85 into consideration the possible burdens shifting from one life cycle phase to another due to the use of such  
86 emerging technologies within the construction systems.

87

88 Thus, the LCA approach in this article is applied to two experimental house-like cubicles that are made of  
89 alveolar bricks (with inner dimensions of 2.4x2.4x2.4 m) located in Puigverd de Lleida (Lleida, Spain).  
90 The location of the experimental setup represents a typical continental Mediterranean climate that is  
91 characterized by cold winters and dry hot summers. The list of the materials used in the cubicles

92 construction process will be used in evaluating the environmental impact of the manufacturing and  
93 dismantling phases. The temperature variations and the energy consumption rates of these cubicles have  
94 been monitored. The registered energy consumption values of the heating/cooling systems will be used  
95 for the operational phase impact evaluation [12]. Also, some theoretical case studies, such as different  
96 weather conditions and different heating and cooling methods, are studied in order to determine the most  
97 suitable conditions for using these technologies (alveolar bricks and phase change materials).

98

99 Finally, these results will be compared to the ones obtained in a previous work [15] for three other  
100 cubicles that are built using a typical Mediterranean constructive system based on conventional bricks, air  
101 gap and insulation. The inclusion of PCM (Paraffin RT27 with peak melting point of 28 °C, and salt  
102 hydrates SP25 A8 with peak melting point of 26 °C, both PCMs from Rubitherm) in that type of systems  
103 has been examined as well.

104

## 105 **2. Methodology**

### 106 **2.1. Construction solutions of the studied cubicles**

107

108 An LCA study is conducted to evaluate the environmental impact of two house-like cubicles located in  
109 Puigverd de Lleida (Lleida, Spain) (Figure 1), both of them with facades built with alveolar bricks; one  
110 without PCM (ALV), and the other one with the inclusion of macroencapsulated PCM. The PCM used is  
111 salt hydrates SP-25 A8 encapsulated in CSM (Compact Storage Modules) panels from Rubitherm [16]  
112 with melting temperature peak of about 28 °C (ALV+PCM). The PCM panels are installed internally on  
113 the south and west walls and the roof. The envelope of the cubicles is composed of walls of alveolar  
114 bricks with interior coat of plaster and exterior coat of cement mortar (Figure 2 and Figure 3). The roof  
115 structure is based on a concrete precast beam, 5 cm of concrete slab, interior coat of plaster, insulating  
116 material (polyurethane), exterior coat of cement mortar and a double asphalt membrane that acts as a  
117 water proofing layer.

118

119 The LCA results of the two alveolar brick cubicles presented in this work are to be compared to the  
120 results of another study that comprises three cubicles built using conventional bricks [15]. Those three  
121 cubicles are: a reference cubicle (REF - no insulation is installed on the walls), a polyurethane cubicle

122 (PU - 5 cm of sprayed polyurethane is installed on the south and west walls and the roof), and a  
123 polyurethane with PCM cubicle (PU+PCM – macroencapsulated RT-27 PCM and 5 cm of polyurethane  
124 are installed on the south and west walls and the roof). The envelope of each cubicle (described in [15]) is  
125 composed of an interior coat of plaster, perforated bricks, air gap, hollow bricks, and an exterior coat of  
126 cement mortar. The roof structure is the same as that of the alveolar brick cubicles.

127

128 The construction materials of the considered cubicles constitute the inventory list that is needed to  
129 perform the impact assessment of the manufacturing and dismantling phases.

130

## 131 **2.2. *Experimental set-up characteristics***

132

133 Inside the studied cubicles, the temperatures values and the energy consumption rates are monitored and  
134 registered. Pt-100 DIN B probes calibrated with a maximum error of  $\pm 0.3^{\circ}\text{C}$  are used for measuring the  
135 surface temperatures of the walls and the roofs. A temperature transmitter for HVAC applications  
136 (ELEKTRONIK EE21FT6AA21) with accuracy of  $\pm 2\%$  is used for measuring the internal humidity and  
137 air temperature. The energy consumption rates of the HVAC systems (heat pumps and electrical oil  
138 radiators) are measured with an electrical network analyser ARDETEM PECA 15. The energy  
139 consumption values are required to evaluate the environmental impact of the operational phase of the  
140 cubicles in order to quantify the impact induced during that phase.

141

## 142 **2.3. *Life Cycle Assessment (LCA)***

143

144 According to the ISO 14040-43 standard series [17-20] that are specified for LCA, recommended steps  
145 are suggested in order to perform an LCA study efficiently:

146 • Definition of goal and scope

147 • Inventory analysis

148 • Impact assessment

149 • Interpretation of results

150

151 The impact assessment step is the most data intensive within an LCA study; it is considered as a critical  
152 step because of the involvement of complex environmental modelling that result in transforming the

153 inventory list into impact categories that express the potential impact on the environment represented by  
154 the final indicators. Thus, several impact assessment methodologies have been developed in order to  
155 resolve this complexity, saving time and effort for the LCA practitioners and reducing the uncertainties in  
156 the data and environmental models. These methodologies are also called Life Cycle Impact Assessment  
157 (LCIA) methodologies [21,22]. The methodology used for performing the LCA study in this article is  
158 based on the impact assessment methodology Eco-Indicator 99 (EI99) [23] using the database EcoInvent  
159 2009 [24]. More information about the EI99 methodology will be detailed in the following subsections.  
160 This is the same impact assessment methodology that has been used in [15] so that the results of both  
161 articles can be compared. The LCA steps recommended by the ISO 14040-43 standard series are to be  
162 applied in the following subsections.

163

### 164 **2.3.1. Goal and scope definition**

165

166 The aim of this study is to apply the LCA concept in order to examine the environmental impact of two  
167 house-like experimental cubicles that are mainly built using alveolar bricks and include phase change  
168 materials (Salt hydrates SP-25 A8 from Rubitherm). Furthermore, the results of this assessment are to be  
169 compared to the results of a previous work [15] regarding three cubicles of the same experimental set-up.  
170 The life cycle phases considered are the manufacturing, dismantling and operational phases. Based on [5],  
171 the construction of the cubicles is not taken into account since it has little impact and can be omitted.

172

173 The general conditions assumed for applying the LCA in the two studied cubicles are as follows:

174

- 174 • The considered lifetime for a cubicle is 50 years.
- 175 • In order to simplify the analysis and to be consistent with the assumptions set for the previous  
176 study [15], the maintenance operations of the cubicles and the HVAC systems are considered  
177 equal for the ALV and PCM cubicles. Hence it does not produce any difference in the overall  
178 global impact. Notice that the cubicles structures are similar and the aim of the work is to  
179 compare between relative differences, this assumption will not significantly affect the results.
- 180 • The electricity used considers the production mix corresponding to the Spanish energy  
181 production system.
- 182 • No data is available in the EcoInvent database about the disposal of salt hydrates. Its value is  
183 estimated considering the same percentage for all the other used components to the total impact.

184 This estimation method is also used in [15] to calculate the disposal impact of PCM and does not  
185 affect significantly in the LCA study, since the disposal of both PCM (paraffins and salts  
186 hydrates) represents less than the 0.01% of the impact during the manufacturing and dismantling  
187 phase.

188 • In order to compare the results of this article with those obtained in [15], the results of the  
189 manufacturing and dismantling phases are aggregated into one phase  
190 (Manufacturing/dismantling phase).

191 • As detailed in subsection 2.2, to evaluate the operational phase impact, the measured energy  
192 consumption values from the cubicles are used (Table 2). Within this context, three different  
193 periods per year are defined:

194 – Winter period: 4 months with similar heating demand to the third week of February  
195 2009. Comfort conditions are achieved using an electrical oil radiator with a set point of  
196 24 °C [25].

197 – Summer period: 4 months with similar cooling demand to the fourth week of August  
198 2009. Comfort conditions are achieved using a heat pump with a set point of 24 °C [25].

199 – No controlled temperature: 4 months without temperature control.

200

201 LCA is accomplished for the following three theoretical case studies:

202 1. Heat pump case study: a heat pump is used instead of the electrical oil radiator during  
203 the winter period to reduce the energy consumption for heating. This reduction is  
204 evaluated by the Coefficient of Performance of the heat pump (COP considered as 3).

205 2. Summer weather conditions case study: since the selected PCM melts/solidifies around  
206 28°C, then, in Mediterranean weather conditions, it only operates during the summer  
207 season. In order to increase its cycling throughout the year summer weather conditions  
208 are assumed to be predominant during the whole year (summer period of 12 months).  
209 This scenario might be used to study the environmental impact of using PCM in the  
210 building envelopes in a location with these constant hot environmental conditions over  
211 the year.

212 3. Extension of the cubicles lifetime: some studies consider buildings lifetime to be  
213 between 50 and 100 years [\[26\]](#), [\[27\]](#). Therefore, a parametric study considering 75  
214 and 100 years lifetime for the cubicles is also presented.

215

### 216 **2.3.2. Inventory analysis**

217

218 In this step, the inventory list of all the materials used in the manufacturing/dismantling phase of the  
219 cubicles is shown. The energy consumption rates of the studied cubicles are quantified as well. The  
220 correlation between the cubicle components used in the manufacturing/dismantling phase and the  
221 EcoInvent data base is shown in Table 1. The measured energy consumption values for heating and  
222 cooling are shown in Table 2.

223

### 224 **2.3.3. Impact assessment**

225

226 According to the EI99 methodology and the requirements of this study, the environmental impact is  
227 evaluated and expressed through ten damage categories (Acidification & eutrophication, ecotoxicity, land  
228 occupation, carcinogenics, climate change, ionising radiation, ozone layer depletion, respiratory effects,  
229 fossil fuels, and mineral extraction). Those damage categories are further aggregated into three areas of  
230 protection that express the main aspects of environmental and societal concern: Human health, Eco  
231 system quality and natural resources. After extracting the inventory data needed from the data base, each  
232 damage category is evaluated according to equation (1):

233

$$234 \quad IMP_j = \sum_k d_{k,j} \cdot LCI_k \quad (1)$$

235

236 Where  $IMP_j$  is the  $j$  damage category,  $d_{kj}$  is the coefficient of damage extracted from the considered  
237 database [23] associated with the component  $k$  and damage  $j$ , and finally the  $LCI_k$  is the life cycle  
238 inventory entry (i.e. kg of polyurethane). The results of equation (1) are single score indicators  
239 representing the potential impact on the environment through different damage categories. The coefficient  
240 of damage for the natural resources damage category is expressed in MJ of surplus energy needed for  
241 future extraction. For the ecosystem quality damage category, the coefficient of damage stands for the  
242 loss of species over a certain area, during a certain time (% plant, species / m<sup>2</sup>·year). Finally, the damage  
243 to human health is expressed as the number of years life lost and the number of years lived disabled  
244 (disability adjusted life years, DALYs).

245

246 The absolute value of these points is not very relevant as the main purpose is to compare relative  
247 differences between products. Lower impact score results mean lower impact on the environment and  
248 hence mean that the product associated with the results is more environmentally sound. These single  
249 score indicators from the EI99 methodology are convenient for the case studies of this article, as the  
250 impact of the cubicles and their relevant components on the environment can be easily interpreted and  
251 demonstrated [28].

252

### 253 **3. Results and discussion**

254 In this section, the results of the impact assessment phase are interpreted and the environmental impacts  
255 caused by the studied cubicles and their components are evaluated. This is considered to be the fourth and  
256 last step within an LCA.

257

#### 258 ***3.1. Life Cycle Assessment of the real case study***

##### 259 **3.1.1. Manufacturing/dismantling phase**

260

261 A list of all the materials used in the construction of the studied cubicles and their environmental impact  
262 during the manufacturing/ dismantling phase is shown in Table 3.

263

264 The component with the highest impact is the alveolar brick, with an impact around 66 % and 61% from  
265 the total in the ALV and ALV+PCM cubicles, respectively. In the ALV+PCM cubicle, PCM and  
266 aluminium represent about 4 % and 3.7 % of the total impact, respectively.

267

268 The impact of each damage category during the manufacturing/dismantling phase is shown in row A of  
269 Table 4. The inclusion of macro-encapsulated PCM increases the environmental impact by 8% during the  
270 manufacturing/dismantling phase.

271

272

273

### 274 **3.1.2. Operational phase**

275

276 The measured energy consumption values for heating and cooling (Table 2) are used to determine the  
277 impact during the operational phase of the cubicles. The impact of each damage category during the  
278 operational phase for the real case is shown in rows B and D of Table 4.

279

280 For the winter period (row B of Table 4), no difference can be observed between the cubicles due to the  
281 addition of PCM, since in cold weather conditions, temperatures do not reach the melting point of the  
282 PCM; hence no energy savings are achieved [12].

283

284 For summer period (row D of Table 4), the addition of PCM to the alveolar cubicle reduces the  
285 operational environmental impact by about 17 %. However, as it has been proved in previous  
286 experimental results [12], the rates of electrical energy consumption during the winter period are more  
287 than ten times higher than those during the summer period for the two cubicles. Thus, the effect of PCM,  
288 which is only effective under summer weather conditions, remains small. Those findings are represented  
289 by the year-round results of the operational impact of the ALV+PCM cubicle, which is only 1.3 % lower  
290 than that of the ALV cubicle.

291

### 292 **3.1.3. Global results**

293

294 Table 5 and Figure 4 show the results of the manufacturing/dismantling phase combined together with the  
295 operational phase for the real case. As expected, the cubicle with PCM presents the highest impact during  
296 the manufacturing/dismantling phase and the lowest impact during the operational phase. The inclusion of  
297 the PCM does not affect significantly the overall global impact (reduction percentage of about 0.8 %).

298 Thus, this insignificant difference in the global impact points can be attributed to the following reasons:

299 • The impact reduced during the operational phase is balanced out with the high impact induced  
300 during the manufacturing phase of the cubicle.

301 • The energy consumption needed for heating is about ten times higher than that required for  
302 cooling.

303       • The operation period of the PCM is short, since it is active only during summer period, and  
304       hence the energy savings and the reduced impact on the environment are benefitted from during  
305       a short period.

306

307 In the considered life cycle phases, it is noticed that the damage categories that contribute significantly to  
308 the total impact points are the fossil fuels and the respiratory effects.

309

### 310 ***3.2. Life Cycle Assessment for the theoretical case studies***

#### 311 **3.2.1. First theoretical case study: heat pump**

312

313 In this case study, the electrical oil radiator is replaced by a heat pump as a heating system, reducing the  
314 operational impact of the cubicles during winter to one third due to a much higher efficiency (COP  
315 considered as 3). Row C of Table 4 and Figure 4 present the results for this case study. The important  
316 reduction of the operational impact during winter helps in highlighting the behaviour of the PCM during  
317 summer.

318

#### 319 **3.2.2. Second theoretical case study: summer weather conditions throughout the whole** 320 **year**

321

322 Previous experimental results [12] show that the use of PCM reduces the energy consumption and hence  
323 the environmental impact during summer since the PCM only works under these conditions. Therefore,  
324 the use of this technology in regions where summer weather conditions are predominant throughout the  
325 whole year is expected to achieve much better results regarding the energy savings and hence the  
326 environmental impact reduction.

327

328 Row E of Table 4 shows the operational impact results of the two studied cubicles in these conditions  
329 where 50 years of lifetime is assumed. Considering the global results for this case study, as shown in  
330 Figure 4, the addition of PCM to the ALV cubicle reduces the impact by about 12 % (ALV+PCM), which  
331 is considered the best case study regarding the impact reduction achieved as a result of using PCM.

332

333 **3.2.3. Third theoretical case study: extension of the cubicles lifetime to 75 and 100 years**  
334

335 As it has been previously discussed, the use of PCM reduces the environmental impact during the  
336 operational phase but increases it during the manufacturing phase. Therefore, a longer lifetime operation  
337 of buildings will result in a reduction of the global impact when using PCM. Depending on some studies  
338 [26,27], different lifetime periods are estimated for buildings. Here, the environmental impact of the  
339 cubicles is evaluated considering 75 and 100 years of lifetime in order to analyze the payback time of  
340 applying the suggested construction system.

341  
342 This case study is considered as a two-layer theoretical case study, where the first layer is extending the  
343 lifetime of the cubicles to 75 and 100 years, and the second layer evaluates each scenario, which are:  
344 using electrical oil radiator (as in the real case study), using a heat pump (the first theoretical case study)  
345 and assuming summer weather conditions throughout the whole year (the second theoretical case study).

346  
347 As it is expected, results show that when the lifetime of the cubicles is extended and PCM is extensively  
348 used (summer conditions), slight increments in the global impact reduction are noticed between the two  
349 cubicles. In the case of 50 years life time, the ALV+PCM cubicle impact score points is about 12% lower  
350 than that of the ALV cubicle, while in case of 75 and 100 years life time, this difference is increased to be  
351 around 14% (Only 2% more of impact reduction) (Figure 4 to Figure 6).

352

353 ***3.3. Comparison of the results of the alveolar brick cubicles with the conventional***  
354 ***brick ones***

355  
356 In a previous work, an LCA study was applied for three monitored cubicles with a construction system  
357 based on conventional bricks [15]. In that study, and specifically for the real case study (based on  
358 experimental results) of using an electrical oil radiator during winter and assuming a lifetime of 50 years  
359 for the cubicles, an impact reduction in the global impact of about 37% is recognized when PU is added  
360 to the reference cubicle. This reduction is achieved due to the decrease of the energy consumption in the  
361 operational phase for the cubicle insulated with PU, since the thermal transmittance of its walls has  
362 become much lower after adding the PU insulation. Besides, it was concluded that the addition of PCM  
363 does not lead to significant variations in the global impact results (only 0.4%) because the impact savings  
364 achieved during the operational phase are balanced out with the high impact generated during the

365 manufacturing phase. Besides, it is important to highlight that PCM is not working during winter season,  
366 which means that no energy savings are achieved during winter. Moreover, as it has been verified  
367 experimentally, the energy consumption required for heating is about ten times higher than that required  
368 for cooling. These facts have to be taken into consideration when observing the insignificant variation  
369 that may occur in the global results.

370

371 A wider comparison that includes the real case study and the theoretical case studies between both  
372 construction systems (conventional and alveolar brick) with and without the inclusion of PCM can be  
373 done. It must be considered that real construction systems are studied and therefore the different facades  
374 do not present the same thermal transmittance in steady-state. The comparisons are highlighted as  
375 follows:

376 • For the real case study, the reference cubicle presents the highest impact due to the lack of  
377 thermal insulation; this lack of insulation causes more heat flux through the cubicle envelopes  
378 and consequently leads to higher energy consumption rates for both heating and cooling  
379 demands. On the other hand, the lowest impact score is achieved by the PU and PU+CM  
380 cubicles (impact reduction of about 37% compared to the reference cubicle). However, the PU  
381 and the PU+PCM cubicle and all the other cubicles present very similar global impact results,  
382 with maximum differences of 2 % (Table 5). These results show that both insulated conventional  
383 bricks and alveolar bricks construction systems are comparable for Mediterranean continental  
384 climate conditions.

385 • Also, the reference cubicle presents the highest impact for all the different damage categories.  
386 This is due to the higher energy consumption of this cubicle during the operational phase. Since  
387 the most of the electrical energy production is mainly based on fossil fuels, it strongly affects all  
388 the damage categories, especially fossil fuels and respiratory effects. On the other hand, the  
389 energy consumption rates for the other 4 cubicles (PU, PU+PCM, ALV, and ALV+PCM) are  
390 very similar.

391 • For summer weather conditions throughout the whole year (the best case study for the PCM  
392 regarding the global impact reduction), and by excluding the reference cubicle from the  
393 comparison, it is found that the ALV cubicle represents the highest global impact points among  
394 all the cubicles. The global impact of the PU cubicle is about 13.5 % lower than that of the ALV  
395 cubicle. Only by using PCM within the alveolar construction system (ALV+PCM) the global

396 impact is reduced to a similar value to that of the PU cubicle. However, the PU+PCM cubicle  
397 further reduces the global impact (Figure 4). Therefore, in case of predominant summer weather  
398 conditions, the use of insulated conventional brick systems is much better than alveolar brick  
399 ones. Besides, the use of PCM in both construction systems presents similar reductions in the  
400 global impact (within the range of 10-12 %).

401 • For the case study of extending the lifetime of the cubicles to 75 and 100 years, the reference  
402 cubicle, as expected, presents the highest impact. In case of assuming summer weather  
403 conditions throughout all the year, the PU cubicle achieves a reduction in the global impact with  
404 respect to the ALV cubicle of about 16%. This reduction value is further increased to 26% in  
405 case of adding PCM (PU+PCM cubicle). Adding PCM to the ALV cubicle decrease the impact  
406 points to a value that is similar to that of the PU cubicle. (Figure 5 and Figure 6).

407

#### 408 **4. Conclusions and recommendations**

409

410 The environmental impact of alveolar brick construction systems with and without phase change  
411 materials (salt hydrates SP-25 A8 from Rubitherm) is analyzed using an LCA approach based on the Eco-  
412 Indicator 99 methodology (EI99). The study is applied to real monitored cubicles; other theoretical case  
413 studies as well are investigated concerning different weather and operating conditions.

414

415 The use of PCM did not significantly reduce the overall environmental impact under the experimental  
416 conditions considered. However, for some theoretical scenarios, the environmental benefits achieved by  
417 the PCM are enhanced (12-14% reduction in comparison with no PCM).

418

419

420 From this work, some recommendations about the use of PCM in buildings can be drawn:

421 - A higher storage capacity of the PCM may result in higher energy savings and therefore in a  
422 larger reduction of the environmental impact during the operational phase.

423 - Developing phase change materials with lower embodied energy can help achieving  
424 sustainability within the life cycle of buildings by reducing the impact on the environment while  
425 avoiding the possible shifting of burdens of the operational phase to the manufacturing phase.

- 426 - Locations with weather conditions (and with daily temperatures around the phase change  
427 temperature of the PCM) that ensure a much longer operation of the PCM will increase the  
428 environmental impact reduction during the operational phase.
- 429 - Long term operation of buildings will also reduce the environmental impact when using PCM, as  
430 shown in the case studies with extended lifetime for the cubicles (75 and 100 years). However  
431 the improvements were low (difference about 1-2 % compared to that of the case studies  
432 assuming 50 years lifetime).
- 433 - The use of PCM that melts/solidifies within suitable temperature range during winter periods  
434 presents a huge potential to reduce the energy consumption, since the energy demand for heating  
435 is more than ten times higher than that for cooling.
- 436 - For Mediterranean continental climate, the global impact induced by insulated conventional  
437 brick and alveolar brick construction systems is comparable. On the other hand, for summer  
438 predominant weather conditions, the use of insulated conventional brick construction system is  
439 better than the alveolar brick
- 440 - Increasing the dependency of energy supplies on renewable energy resources can reduce  
441 significantly the impact related to the fossil fuels and respiratory effects damage categories. And  
442 consequently, within the different LCIA methodologies and the associated databases,  
443 considering the environmental impact using independent on-site renewable energy resources for  
444 manufacturing of building materials will be a necessity in this case.

445

446 Moreover, new materials with lower environmental impact must be developed. This requires a new  
447 perspective when defining the desired properties and producing the materials. Nowadays only the  
448 technical specifications are considered, but in the future also the environmental ones should be included.  
449 For phase change materials, the improvement of the PCM and also its encapsulation must be considered.

450

451

## 452 **Acknowledgments**

453

454 The work was partially funded by the Spanish government (projects ENE2008-06687-C02-01/CON and  
455 DPI2008-04099) and the European Union (COST Action COST TU0802), in collaboration with the  
456 company Hypsalit and City hall of Puigverd de Lleida. The authors would like to thank the Catalan

457 Government for the quality accreditation given to their research group (2009 SGR 534). Lidia Rincón  
458 would like to thank the University of Lleida for her research fellowship.

459

## 460 **References**

461

462 [1] Ardente F, Beccale M, Cellura M, Mistretta M. Building energy performance: A LCA case study of  
463 kenaf-fibres insulation board. *Energy and Buildings* 40 (2008) 1-10.

464 [2] Rodrigo J, Cañellas N, Meneses M, Castells F, Solé C. El consumo de energía y el medio ambiente en  
465 la vivienda en España. Análisis de Ciclo de Vida (ACV) “Energy consumption and environment in  
466 spanish dwellings. Life Cycle Assessment (LCA)”. Fundación Gas Natural, Barcelona, 2008.

467 [3] Zabalza I, Aranda A, Scarpellini S. Life cycle assessment in buildings: State-of-the-art and simplified  
468 LCA methodology as a complement for building certification. *Building and Environment* 44 (2009) 2510-  
469 2520.

470 [4] Zheng G, Jing Y, Huang H, Zhang X, Gao Y. Application of Life Cycle Assessment (LCA) and  
471 extenics theory for building energy conservation assessment. *Energy* 34 (2009) 1870-1879.

472 [5] Kellenberger D, Althaus H. Relevance of simplifications in LCA of building components. *Building*  
473 *and Environment* 44 (2009) 818-825.

474 [6] Papadopoulos AM, Giama E. Environmental performance evaluation of thermal insulation materials  
475 and its impact on the building. *Building and Environment* 42 (2007) 2178–2187.

476 [7] Huberman N, Pearlmutter D. A life-cycle energy analysis of building materials in the Negev desert.  
477 *Energy and Buildings* 40 (2008) 837–848.

478 [8] Kofoworola OF, Gheewala SH. Environmental life cycle assessment of a commercial office building  
479 in Thailand. *The International Journal of Life Cycle Assessment* 13 (2008) 498–511.

480 [9] Chau CK, Yik FWH, Hui WK, Liu HC, Yu HK. Environmental impacts of building materials and  
481 building services components for commercial buildings in Hong Kong. *Journal of Cleaner Production* 15  
482 (2007) 1840-1851.

483 [10] Cabeza LF, Castell A, Medrano M, Martorell I, Pérez G, Fernández I. Experimental study on the  
484 performance of insulation materials in Mediterranean construction. *Energy and Buildings* 42 (2010) 630-  
485 636.

486 [11] Cabeza LF, Castell A, Barreneche C, de Gracia A. Materials used as PCM in thermal energy storage  
487 in buildings: A review. *Renewable and Sustainable Energy Reviews* 45 (2011) 1675-1695.

488 [12] Castell A, Martorell I, Medrano M, Pérez G, Cabeza LF. Experimental study of using PCM in brick  
489 constructive solutions for passive cooling. *Energy and Buildings* 42 (2010) 534-540.

490 [13] Menoufi K, de Gracia A, Solé C, Castell A, Cabeza LF. Thermal behaviour of Mediterranean  
491 buildings: experimental study. *Eurosun 2010 conference proceedings*, September 28th 2010, Graz,  
492 Austria.

493 [14] de Gracia A, Castell A, Medrano M, Cabeza LF. Dynamic thermal performance of alveolar brick  
494 construction system. *Energy Conversion and Management* 52 (2011) 2495–2500.

495 [15] de Gracia A, Rincón L, Castell A, Jiménez M, Boer D, Medrano M, Cabeza LF. Life Cycle  
496 Assessment of the inclusion of phase change materials (PCM) in experimental buildings. *Energy and*  
497 *Buildings* 42 (2010) 1517–1523.

498 [16] Rubitherm, [www.rubitherm.com](http://www.rubitherm.com). Consulted in June, 2011.

499 [17] ISO International Standard 14040:2006. Environmental Management – Life cycle assessment.  
500 Principles and framework. International Organisation for Standardisation (ISO).

501 [18] ISO International Standard 14041:1998. Environmental Management – Life cycle assessment. Goal  
502 and scope definition and Inventory analysis. International Organisation for Standardisation (ISO).

503 [19] ISO International Standard 14042:2000. Environmental Management – Life cycle assessment. Life  
504 cycle Impact assessment. International Organisation for Standardisation (ISO).

505 [20] ISO International Standard 14043:2000. Environmental Management – Life cycle assessment. Life  
506 cycle Interpretation. International Organisation for Standardisation (ISO).

507 [21] ILCD handbook: General guide for life cycle assessment – detailed guidance, first edition, 2010.  
508 Institute for Environment and Sustainability. Joint research centre, European Commission.

509 [22] ILCD handbook: Analysing of existing Environmental Impact Assessment methodologies for use in  
510 Life Cycle Assessment, first edition, 2010. Institute for Environment and Sustainability. Joint research  
511 centre, European Commission.

512 [23] PRé-Consultants. The Eco-indicator 99. A damage oriented method for life cycle impact assessment.  
513 Methodology report and manual for designers. Technical Report, PRé Consultants, Amersfoort. The  
514 Netherlands, 2000.

515 [24] The ecoinvent Center. A competence centre of ETH; PSI;Empa & ART; <http://www.ecoinvent.ch/>.  
516 Ecoinvent data v2.1.

517 [25] ASHRAE Handbook. Fundamentals. SI Edition; American Society of Heating, Refrigerating and  
518 Air-Conditioning Engineers; 1997.

519 [26] Mithraratne N, Vale B. Life cycle analysis model for New Zealand houses. Building and  
520 Environment 39 (2004) 483-492.

521 [76] Gustavsson L, Joellsson A. Life cycle primary energy analysis of residential buildings. Energy and  
522 Buildings 42 (2010) 210-220.

523 [28] Goedkoop M, Spriensma R. Eco-indicator 99, a damage oriented method for life cycle impact  
524 assessment, methodology report, Third edition, June 2001, Ministry of Housing, Spatial planning and the  
525 Environment, The Netherlands.

526

527

528

529 **Figure captions**

530

531 Figure 1. Experimental cubicles in Puigverd de Lleida (Lleida, Spain).

532 Figure 2. Construction system of the Alveolar brick cubicle.

533 Figure 3. Construction system of the Alveolar brick +PCM cubicle.

534

535 Figure 4. Impact results for each cubicle and studied scenario for a lifetime of 50 years.

536 Comparison between conventional (De Gracia et al. 2010) ~~0+15~~ and alveolar construction system.

537

538 Figure 5. Impact results for each cubicle and studied scenario for a lifetime of 75 years.

539 Comparison between conventional (De Gracia et al. 2010) ~~0+15~~ and alveolar construction system.

540

541 Figure 6. Impact results for each cubicle and studied scenario for a lifetime of 100 years.

542 Comparison between conventional (De Gracia et al. 2010) ~~0+15~~ and alveolar construction system.

543

544

545