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Research article

A life cycle assessment of PCM and VIP in warm Mediterranean climates and their introduction as a strategy to promote energy savings and mitigate carbon emissions

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Abstract: The building stock in southern Europe grossly lacks sufficient thermal envelope insulation, leading to high energy inputs and corresponding CO_2 emissions. Phase change materials (PCMs) and vacuum insulations panels (VIPs) could be an innovative way to curtail the high heating and cooling energy inputs to maintain comfort; however, their efficiency and environmental performance in the southern Mediterranean climate is largely unknown. To this end, two demo houses, 27 m^3 each, were constructed in the island of Crete, southern Greece. The first was constructed using conventional building materials, while in the second PCMs and VIPs were used, as a research test-bed. Actual life cycle inventory (LCI) data were collected and the life cycle assessment (LCA) methodology was employed to estimate the environmental impacts attributed both to their construction and operational phase. Compared to the conventional demo house the one covered with PCMs and VIPs appear to have a 34% higher total environmental footprint, which is attributed to the production process of PCMs and VIPs. Nonetheless, the energy savings observed during the operational phase, attributed to their higher thermal insulation, can compensate the higher environmental footprint of the construction phase within a year, depending on PCM's enthalpy. Specifically, it was identified that PCMs and VIPs largely reduced daily indoor temperature fluctuations, improving indoor thermal comfort and leading to energy savings. As such, even though their installation is associated with an initial higher environmental footprint, large energy savings, compared to conventional demo house, are achieved during its operational phase. This suggests that the introduction of PCMs and VIPs could be an efficient and environmentally friendly route to enhance energy savings and reduce the environmental footprint of building stock.

Keywords: building envelope insulation; phase change materials (PCMs); vacuum insulation panels (VIPs); life cycle assessment (LCA); environmental sustainability; environmental footprint

1. Introduction

The building industry accounts for 40% of the energy consumption and ~50% of the greenhouse gas emissions in Europe [1–4]. Therefore, the energy performance of buildings directive (EU) 2018/844 focuses on the improvement of energy efficiency in buildings targeting reduced energy consumption and wastage [5]. In the already existing building stock of southern European countries insufficient thermal envelope insulation exists, together with advanced cooling needs which increase drastically their overall energy consumption [6].

For more than 30 years, PCMs have been mixed into building materials, such as gypsum board, plaster and concrete, mainly for the purpose of thermal storage [7]. On the other hand, VIPs are innovative thin and lightweight building materials, ideal for the building industry [8]. Southern European countries could take advantage of these materials and maximize their winter energy profile by using both natural sources (sun) and energy storage components, but their behavior in the warm summer months is largely unknown. Aranda-Uson et al., 2013 [9] underlined the importance of life cycle analysis on PCM, in order to acquire a deeper understanding on their overall environmental performance, by taking into account energy savings along with the environmental impacts of PCMs.

In a recent research conducted by Song et al. in 2018, series of HVAC systems coupled with thermal energy storage were investigated and the existing gaps in literature based on the energy performance of these materials were identified. The recommendations suggested in that work, proposed researches to further conduct and evaluate life cycle assessment on economic feasibility and environmental benefits of these insulation systems [10].

In several research projects, it is found that the application of building insulation materials is associated with high energy use and CO_2 emissions, related to their manufacture and disposal phase [11–15]. Nonetheless, their application (e.g., PCMs) can lower energy consumption during the building operation phase [12]. In other researches the importance of the evaluation of the advantages and disadvantages, from the environmental perspective, derived from their application and the tradeoffs of the associated environmental impacts during the building's construction and operational phase, is being suggested [11].

Several studies have focused on the synthesis and characterization of PCM materials as well as the synthesis of some components inside VIPs. More particular in a work conducted by Jorda et al., a thermal characterization approach for PCMs based on a thermal test device (TTD) allowing temperature measurement was presented [16]. Another work compared commercially available and laboratorial microencapsulated PCM characterized using SEM, DSC, nano-indentation technique, and Gas Chromatography/Mass spectrometry [17], while in a work in 2014 by Nemanic et al., the development and optimization of melamine-formaldehyde rigid foams for vacuum thermal insulation was conducted and its synthesis procedure and characterization was presented [18]. Lastly a nanoencapsulated PCM with polystyrene as the shell and n-octadecane as the core was synthesized and characterized by TEM, FT-IR, XRD, DSC and TG. The nanocapsules were regular spherical and ranged from 100 to 123 nm in size [19].

Other studies have been conducted with the use of simulations in order to assess the effectiveness of these technologies. In a study by Fateh et al. in 2019 the researchers designed the dynamic modeling of a typical single-zone building. A set of daily temperature profiles, representative of the Mediterranean climatic condition was used. The results showed that the rate and amount of energy consumption in the building with PCM are moderately lower than the building without PCM [20]. In another research a complete dynamic model of five different cases was evaluated to study the effect of PCM on energy utilization in two different climates in Germany and USA. Results confirmed that the strong non-linearity of the PCMs' behavior and of the weather boundary condition deeply affect the thermal performance of the building [21]. Moreover in another work a dynamic model of a wall was developed considering different orientation. The results showed that utilizing PCMs could decrease the heat loads especially when the temperature variations are close to the phase change temperature, leading to energy savings up to 75% [22]. In another study, a design proposal was suggested, including advanced materials, like PCMs and VIPs, highlighting very high thermal performances appropriate for the Mediterranean climate, typical of dry, warm to hot climate [23]. In one more study with the use of energy simulation modeling, the thermal performance of VIPs and PCMs when applied to the building envelope, and their ability to improve the building thermal behaviour in the Mediterranean area was investigated. The results highlight that, in summer, thermal discomfort and remarkable increases in the energy needs for cooling may occur when the building is retrofitted with VIPs, whereas better conditions are achieved with PCMs [24]. In Greece, a research was conducted focusing on evaluating the potential impact of PCM on building comfort and energy performance, also with the use of simulations. The numerical results revealed that the use of PCMs can significantly contribute to reducing the number of discomfort hours occurring in the space, while also reducing the cooling requirements [25].

Recently, there have been a series of works that involve the real assessment of PCMs or VIPS in demonstration cases. In one research, involving real case demos, an experimental set-up was developed in order to evaluate the influence of insulation in buildings. Several cubicles were constructed and instrumented. The cubicles were built in Lleida, Spain, under a conventional Mediterranean construction system, differing only in the insulation material used. The results showed energy reductions up to 64% in summer and up to 37% in winter [26]. Another study focused on the evaluation of the effectiveness of vacuum insulation panel (VIP) for typical Mediterranean climate circumstances, in three real buildings of south Italy. Experimental and numerical results show the effectiveness of VIPs also for the Italian climate [27]. In another research in Greece, a two-storey typical family house was built in the mid-western part of Greece and its walls consisted of multiple layers of insulation materials and gypsum plasterboard panels containing PCMs for thermal energy storage purposes. It was shown that the thermal mass of the walling system was enhanced during late spring, early summer and autumn, due to the PCM implementation, resulting also in a decrease of the decrement factor by a further 30–40% [28].

The input of real performance record of such materials, and their environmental and energy performance, could accommodate the selection of the appropriate material per area/type of building. Therefore, scaling up the research, from the material and component level to the building level, can result to further refinement of the optimal material selection, by direct measurements of each materials performance [29]. For this purpose, two demo houses, 27 m^3 each, one using conventional building materials and the other covered with PCMs and VIPs, were used as case studies. The environmental performance of each demo house, both for the construction and operational phase, was estimated by means of the life cycle assessment/analysis (LCA) methodology. For the assessment of their operational phase, their year-round outdoor and indoor temperature was recorded, using a 40 s time step, and the energy inputs required to maintain thermal comfort were estimated.

2. Materials and methods

2.1. Demo house construction and data collection

In order to study the performance of PCMs and VIPs under the Greek climatic conditions, two demo houses were used. These buildings were build in the premises of both the Foundation for Research and Technology (FORTH) and the Science and Technology Park of Crete (STEP C), in Crete, Greece (35.304540, 25.073543), and have been used as research test beds for a series of materials. Their entrances are facing west and their windows face east. In order to be consistent the same dimensions were considered in both demo houses, i.e., 3 m × 3 m × 3 m or 27 m^3. The first demo house, called the red house, uses internally PCMs (PCMs-23, Maxit/SGW) and it is covered externally with VIPs (Vacupor® by Porextherm). The second demo-house, called the green house, uses solely conventional building materials, without the use of PCMs and VIPs. The VIPs used have a density of 150–300 kg/m^3, thermal conductivity at ambient pressure and at 22.5 ^{o}C < 0.019 W/mK, heat resistance between −50 to 120 ^{o}C and interior pressure <5 mbar. The PCMs have compressive strength >2 N/mm^2, thermal conductivity >0.3 W/mK and water vapor diffusion resistance μ equal to 10. The interior temperature in both demo houses was recorded using the EPO-Elements 5.3 software and a time step of 40 s. According to existing long-term temperature measurements the monthly mean temperature for the area of study is shown in Table 1. From this table it is observed that the average temperature in the area around the demo houses during the whole year is 20.4 °C. However it is seen that from April until November the temperatures are higher or equal to 18 °C, and from May to September above 23 °C. These observations led to the decision of the selected technologies (VIP and PCM-23)

Table 1. The monthly profile of the area where the demo houses are located.

Month	Measured monthly average temperature (^{o}C)
January	13.8
February	14.0
March	13.4
April	21.5
May	23.8
June	26.0
July	28.1
August	28.1
September	25.3
October	20.3
November	18.0
December	12.7

2.2. Environmental modeling and goal and scope

The environmental performance of the two demo houses was examined by means of the life cycle assessment (LCA) methodology (see Figure 1), as set in ISO 14040:2006 and ISO 14044:2006 [30,31]. For the environmental modeling the software program SimaPro was employed, using actual life cycle inventory (LCI) data as will be discussed below. The setting of this work is Greece, where the city of Heraklion in the island of Crete, was used as a case study. More specifically, the purpose of this work is to assess the environmental performance of VIPs and PCMs envelope insulation materials, when operating under southern Europe's climatic conditions, i.e., Heraklion. The recorded thermal performance of the houses was obtained through measurements, taken every 40 s, over a period of more than a year, i.e., November 2012 to December 2013. The energy consumption, required to meet thermal comfort inside each demo house was also estimated and used for the environmental modeling. An assessment of the environmental performance of these materials during building stock construction phase was conducted. Since the higher insulation efficiency of VIPs and PCMs can lead to energy savings throughout the buildings life span, the analysis was expanded also to include the total environmental footprint. According to the authors' best knowledge, this comprehensive analysis is carried out for the first time under Greek climatic conditions. Therefore, the intended audience of this work is the academic community, the industry, and the general public.

Figure 1. Graphical abstract representing the life cycle assessment methodology.

2.3. Functional unit

According to ISO 14040 and ISO 14044 the functional unit is correlated to the performance of a system [32]. Here in order to accommodate a comprehensive comparison between the two demo houses, the most well suited functional unit, that better fits the goal and scope of this work, is one cubic meter (1 m^3) of building internal volume.

2.4. System boundaries

The system boundaries define the smallest elements (i.e., unit processes) for which input and output data are quantified in the LCI and, as such, are considered in LCA study. Here, all main inputs for the construction and operation (for a timeframe of 25 years) of each demo house are included in the analysis, i.e., they are included in the LCI boundaries. Furthermore, the emissions generated from the disposal, typically as inert waste, of the non-recyclable materials of each demo house after the end of their lifespan, as well as the avoided emissions from the recycling of the recyclable materials are include in the analysis. Specifically, the production of raw materials, their packaging, transportation, application, their final recycle/disposal, other inputs (e.g., water during the construction phase) and the energy used to construct each demo house, are included in the system boundaries. This is also the case for recycling, i.e., it is inside the system boundaries, since it is a very effective way to reduce the embodied energy of a building [33]. The energy consumption during the whole lifespan of a building is one of the most important resources [5,34]. For this reason, the energy required to maintain comfort in both houses, i.e., 23 ^oC during winter period and 24 ^oC during summer, was also included in the analysis. A heating, ventilation, and air conditioning (HVAC) was assumed to be used in both houses to maintain thermal comfort. The HVAC system was not included in the analysis, since the same system was assumed to be installed in both houses and its impact, as a material, would be significantly lower compared to energy input, which is included in the analysis, i.e., inside the system boundaries.

2.5. Life cycle impact assessment method

The software SimaPro 8.0.3 was used to assess the environmental sustainability of the two demo houses. Results were via a robust multi-issue life cycle impact assessment (LCIA) method, i.e., ReCiPe. In ReCiPe, results can be expressed both at (i) midpoint level, i.e., problem oriented approach where environmental impacts are examined earlier in the cause-effect chain and as such are translated into environmental themes (e.g., climate change and human toxicity) and (ii) endpoint level, i.e., damage-oriented approach where impacts are examined at the end of the cause-effect chain, after midpoint is reached thus translating environmental impacts into issues of concern (e.g., damage to human health and to ecosystem quality). It should be mentioned that due to data gaps and assumptions stacking up along the cause-effect chain, the endpoint approach has a higher level of statistical uncertainty, nonetheless is easier to comprehend by policy- and decision makers as well as the public [35]. On the other hand the midpoint approach is more robust and informative. For these reasons both the mid- and endpoint approach were considered in this work, by means of the ReCiPe

LCIA method, which is the successor of Eco-indicator 99 (endpoint) and CML-IA (midpoint) methods.

Specifically, ReCiPe is a state of the art method that is harmonized in terms of modelling principles and choices. ReCiPe comprises 18 midpoint impact categories, i.e., climate change (CC), ozone depletion (OD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionizing radiation (IR), agricultural land occupation (ALO), urban land occupation (ULO), natural land transformation (NLT), water depletion (WD), mineral resource depletion (MRD), fossil fuel depletion (FD). At the endpoint level most of the abovementioned midpoint impact categories are further converted and aggregated into three endpoint categories, i.e., damage to human health (HH), damage to ecosystem diversity (ED) and damage to resource availability, which afterwards can also be aggregated into a single score. Results were expressed using the ReCiPe method, which uses a set of 18 midpoint and 3 endpoint environmental impact/damage categories [35,36]. The Hierarchist perspective (H), which is ReCiPe's default model, using European normalization was applied to express results both at mid- and endpoint level. The H perspective was used, according to which the environmental impacts can be avoided with proper management, while what is included/excluded in the model is based on a mean scientific consensus, fitting best the goal and scope of this study.

2.6. Life cycle inventory

All inputs that are required for the life cycle inventory (LCI) of each demo house were either obtained from existing LCI databases, or in their absence were built based on high-quality environmentally-relevant data obtained from the literature and manufacturing companies. Specifically, for the case of PCMs and VIPs LCI data were not identified in SimaPro databases and hence data from the manufacturing companies, i.e., Maxit/SG Weber and Porextherm, respectively, were used. For the masonry fine plaster, regular plaster, VIP, adhesive and wall primer were used. After these steps 21 mm of cement board, rockwool, plasterboard, wall primer, 15 mm of PCM-23, fine plaster, and paint were applied. In the reference house (green house) the above mentioned materials were used, albeit lacking VIPs and PCM-23. However, for effective comparison in the two house interiors, the exact same volume of materials was applied. Therefore, the reference demo house was treated with an inert material, i.e., base plaster instead of PCM-23. The flooring of both houses was composed of wood treated with oil, while being mounted on wooden boards and placed on a terrace of ceramic tiles. The amount of the materials used for each house is listed in Table 2. Finally, each house contained one wall window (double glazed 120 cm ×40 cm), one roof window (double glazed 90 cm × 40 cm), and one aluminum door (210 cm × 70 cm) (See Figure 2).

Table 2. LCI for the two demo-houses.

Demo houses	Red house	Green house
Fine plaster	100 kg	100 kg
Plaster	230 kg	100 kg
Wall primer	90 kg	90 kg
Cement board	477 kg	477 kg
Rockwool	115 kg	115 kg
Plasterboard	414 kg	414 kg
Paint	34 kg	44 kg
Oil for wood	4 L	4 L
Wood paint	2 L	2 L
Adhesive for VIP	90 kg	-
Anti-fire coating	3.6 kg	-
PCM-23	850 kg	-
VIPs	294 kg	-
Wood	545 kg	545 kg
Water	970 kg	970 kg
Inert PCMs (plaster)	-	680 kg
Wall window	1	1
Roof window	1	1
Aluminum door	1	1

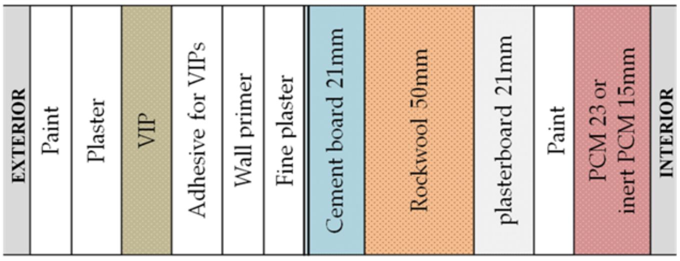

Figure 2. Layers of the building envelope from exterior to interior of each house (wall composition).

For the end of their 25 year lifespan, the recycling of the metallic parts (e.g., aluminum in doors and windows) was taken into account, while the rest of the inert material (e.g., plaster) were assumed to be disposed at a landfill. For locally acquirable material a mean transportation distance of 50 km was ascribed by means of a Euro IV emissions standard lorry. The VIPs and PCMs were assumed to be transported from the place of their production (Germany) to the place of installation (Crete, Greece) by train (Germany-Greece) and boat (Piraeus-Heraklion). During their 25 year lifecycle, each house was assumed to be repainted every five years.

Since, in this work a comparative analysis of the environmental performance of two demo houses, one with and the other without PCMs and VIPs is presented, the focus is given to the construction materials used and the indoor temperature profiles observed on a year-round basis. However, the environmental assessment was expanded to include a preliminary analysis of the operational phase of each house. This analysis was restricted to the effect of the energy required for each demo house to maintain thermal comfort under the Greek climatic conditions, i.e., to maintain an indoor temperature of 23 °C during winter and 24 °C during summer. The desired temperature for heating at 23 °C and cooling at 24 °C has been chosen according to Greece's thermal comfort needs, taking also into account the humidity levels of the island of Crete. For this reason, following Kreith and Black, in Basic Heat Transfer book published in 1980 [37] the law of heat conduction (Fourier's law) was applied, using as inputs the measured indoor and outdoor temperatures. For comparative studies, such as here, where similar conditions exist (i.e., both buildings have been constructed under the exact conditions in the same area, using the same materials and only differ in the insulation materials used) Fourier's law of heat conduction could provide useful insight. However, a dynamic analysis where a wide array of factors affecting the energy input to maintain thermal comfort in each house, such as the incident solar radiation, would provide a deeper insight. Nonetheless, this falls outside the goal of this LCA study while the Fourier's law of heat conduction suffices for the preliminary analysis required herein. In future work the effects of scaling up each system will be examined and a dynamic analysis of the energy demand of each house will be performed. It was assumed that thermal comfort was maintained in both demo houses, throughout their lifespan, by means of a typical HVAC system. As mentioned above, including the HVAC system, as a material, is outside the goal and scope of this work, however, the energy input of this system is inside the system boundaries and was taken into account for whole lifespan of both houses.

3. Results

3.1. Life cycle impact assessment (LCIA) results for the construction phase

Initially, the environmental footprint for the construction phase is estimated. To obtain a comprehensive overview, results were compared at midpoint level using ReCiPe's 18 midpoint indicators, namely: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, mineral resource depletion and fossil fuel depletion. Figure 3 shows the comparative analysis of the environmental performance of the two demo houses. Results are shown per functional unit, i.e. 1 m^3, using the Hierarchist (H) perspective with European normalization.

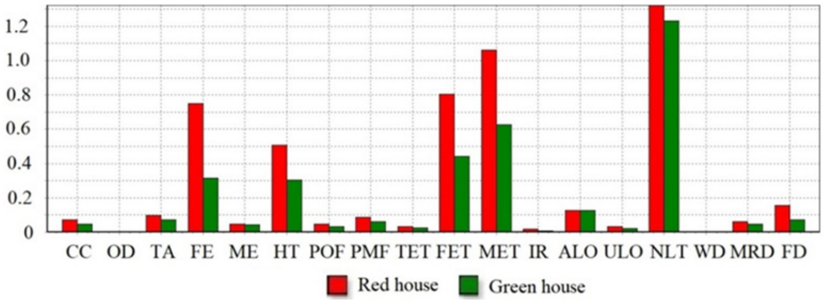

Figure 3. Normalized impact scores of the "red" (PCMs and VIPs) and "green" demo house.

The use of PCM and VIPs appears to have higher impacts on freshwater eutrophication, human toxicity, freshwater ecotoxicity and marine ecotoxicity (Figure 3). The aggregated environmental impacts using ReCiPe endpoint method (H version, European normalization and average weighting set) are presented in Figure 4. The total environmental footprint of the isolative house is ~34% higher than the reference one. In particular, when ReCiPe's three damage categories are used, it is observed that human health and resources have a higher impact with the use of PCM and VIPs whilst the ecosystems category is not affected with the use of innovative insulation materials.

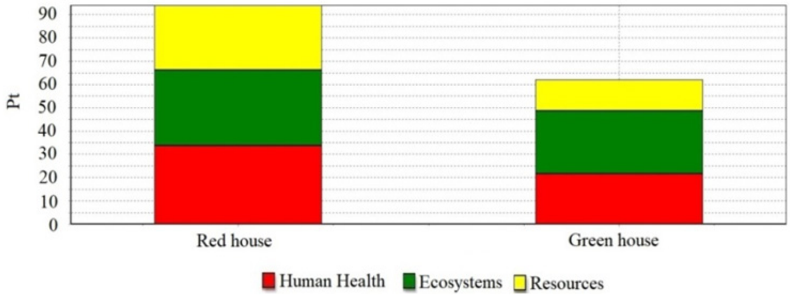

Figure 4. The results for construction phase of both demo houses at endpoint level.

Based on the construction materials that both houses have in common, the highest environmental footprints were found in the use of windows, door and cement boards. VIPs exhibit a four times higher environmental footprint (31%) compared to PCMs (7.5%).

3.2. LCIA results for the operating phase

3.2.1 Insulating performance

The profile of both indoor and outdoor temperature (T) for the period November 2012 to December 2013 is shown in Figure 5. The fully insulated red house was found to have more stable temperature than the green house (reference house), making the latter one deeply dependable on the outdoor temperatures fluctuations (Figure 5).

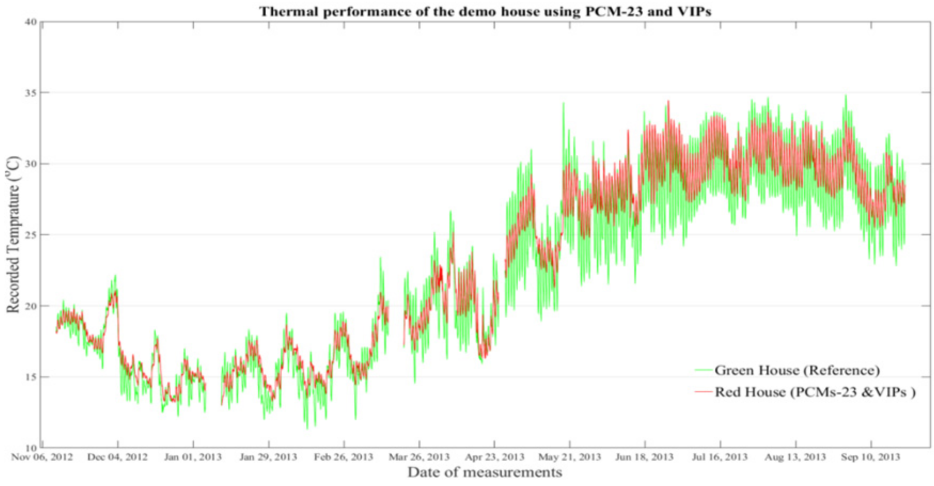

Figure 5. The temperature profile of the reference versus the "red" demo house using PCMs-23 &VIPs (reference period November 2012 to September 2013).

In the building industry, as already discussed, not only construction but also its operational phase should be taken into account. Therefore the energy consumption required to maintain indoor thermal comfort (23 °C during winter and 24 °C during summer) was estimated and used as input in the LCA modeling as shown below.

Figure 6 shows the environmental impacts of both houses, by taking into account construction and operation phase, the latter includes the energy required to maintain thermal comfort. Nonetheless the Greek energy mix is still significantly based on fossil fuels and includes 54% lignite, 11% crude oil, 17% natural gas, and 18% renewable energy, and thus contributes more to a high environmental footprint [36]. When using this energy consumption in order to reach thermal comfort input, the results are altered. The house with the use of PCM and VIPs performs better in regard to the environmental footprint, since it requires lower electricity for indoor thermal comfort. The use of lignite, resulting to airborne and waterborne emissions, which increases the impact of ecotoxicity and eutrophication is the driving factor here. An increase in electricity consumption would result in higher environmental impacts. During the entire 25 years life span the reference house accounts for 10.65 kPt/m^3, whereas the demo house using PCM and VIPs accounts to 57% lower impact, particularly 4.54 kPt/m^3.

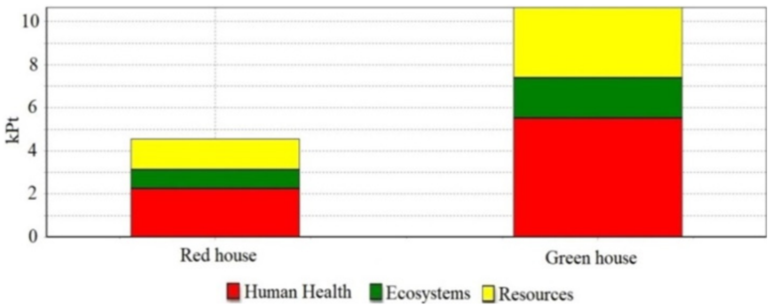

Figure 6. Results for the construction and operation phase of each demo house, after the inclusion of energy consumed to reach thermal comfort for a 25 years timeframe.

Overall, the non isolative house has a total environmental impact during construction of 6% while during its operation is at 94% The isolative house on the other hand has a construction phase environmental impact of 21% and a 79% operational impact, which is mainly due to the savings in energy aspects since the insulation has an advanced thermal behavior. The initial higher impacts during construction for the isolative materials can be compensated with 14 months.

From previous studies the focus was mainly given to the use of PCMs, where they appeared to have less energy consumption during operation; nonetheless they had higher environmental impact throughout the building's lifetime [12].

4. Discussion

Life cycle assessment results showed that during the construction phase the application of PCMs and VIPs resulted in higher impacts on freshwater eutrophication, human toxicity, freshwater ecotoxicity, and marine ecotoxicity. These impact categories are mainly affected by the VIPs and to a smaller degree to the PCMs as materials. More specifically, these high environmental footprints could be traced back to the expandable polystyrene used in VIPs and the paraffin used in PCMs. The transportation of these materials from Germany to Crete had a small contribution to the total environmental footprint. It was observed that human health and resources damage categories were mainly affected by the use of PCM and VIPs whereas the ecosystems damage category was affected to a smaller degree. Overall, VIPs exhibit a four times higher environmental footprint (31%) compared to PCMs (7.5%). Research in northern European climates has shown that the embedded materials used for building construction have a high environmental impact, while recycling could possibly minimize these impacts [38].

On the other hand, taking into consideration the thermal behavior of the demo houses, with the addition of PCMs and VIPs the demo house's thermal behaviour is more stable and less dependent on outdoor temperature fluctuations. In particular, the red house's temperature performance appears to have the most pronounced variations at T crossing the 23 °C mark. This is expected because the selected PCMs have a functional T at 23 °C. However, in temperatures beyond this level (at around 26 °C) the application of PCM-23, and VIPs, is found to have reached its limit. This indicates that for cases that temperature exceeds 25 °C, the PCMs-23 increases the internal T, creating a slightly warmer environment than would be the case without the material. This small diversification could be explained by the accumulation of heat within PCMs when overheated above a specific temperature range.

It should be noted that the PCMs-23 that were used in this work had an optimal performance during the winter, but they did not perform well during the summer. However, the T fluctuation of the demo house with the PCMs is lower than the reference demo house, providing higher thermal stability. Therefore, there is a trade-off between using PCMs with low versus high crossing T marks, since the first perform better during the cold winter months and the latter during the warmer summer months, respectively. In any case, more measurements should be performed and attention should be given to the proper selection of PCMs functional temperature range for different climates. Moreover, based on the maximum and minimum recorded T of both demo houses the red house was found to have an average T closer to human comfort necessities and therefore requiring less energy in order to reach thermal comfort.

Furthermore, the construction phase of the reference house was found to contribute 6 % while its operational phase constituted 94 % of the total environmental footprint. On the other hand the construction phase of the demo house covered with PCMs and VIPs contributed to 21%, while the operational phase 79% of its impact, which is mainly due to the energy savings compared to the reference house.

From the obtained results, it is obvious that reducing energy inputs to maintain comfort through insulation also provides a cost-effective way to mitigate carbon emissions. Furthermore, building insulation reduces energy consumption and therefore reduces Europe's dependence on foreign energy supplies [26]. VIPs and PCMs are among the materials that exhibit a high potential for the building sector since they are thinner, lighter and more energy efficient, particularly the VIPs rather than conventional insulation materials have an impact here [27]. We should also mention here that future works of our group will deal with a scale up system. Furthermore, bigger demonstration cases should be used in order to assess the actual performance of these materials, regarding the thermal behavior, since the performance of these materials is expected to be dependable on the overall volume of the building. Moreover, future studies should focus on the development of a life cycle cost (LCC) assessment in a bigger scale demonstration case, in order to further bridge a connection between research and market exploitation of these technologies for the warm Mediterranean climate.

5. Conclusions

In this work the environmental performance of PCM-23 installed along with VIPs as building insulation materials was assessed, being subjected to Greece's warm Mediterranean climate. Actual LCI data were collected for the construction phase using two demo-houses as case studies, one using the PCMs and VIPs and one without. Furthermore, the year-round indoor temperature profile of both houses was estimated using measurements collected using a very small time-step. It was observed that the application of PCMs and VIPs is associated with a ~34% higher total environmental footprint during the construction phase, compared to the conventional demo house. However, these materials substantially improve the building's insulating performance during its operational phase, thus limiting indoor daily temperature variations and offering large energy and, by extension environmental savings throughout their life span.

Specifically, PCMs and in particular VIPs were found to be the main contributor to the additional environmental impacts during the construction phase. Furthermore, the windows, the door and cement boards, have overall high contribution to the total environmental footprint in both demo houses. The result of this work also suggests that PCMs-23 perform better in the temperature range 20 to 25 °C, and as such their optimal performance is observed during the during the winter under the local climatic conditions. However, during the summer months it was observed that the PCM-23 did not operate properly. This highlights the importance of the appropriate selection of PCMs functional temperature range for different climates. Since VIPs and PCMs have the advantage of requiring lower energy inputs to maintain a thermally comfortable in-home environment, these energy savings lead to ~57% lower environmental footprint compared to the reference house, during a 25 years life span. Overall it was found that even though the application of PCMs and VIPs lead to initial increased environmental impacts, these can be compensated within just over a year, if the energy consumption to maintain comfort is considered. As such, their application will lead to improved environmental performance and energy savings in the long term.

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Conflict of interests

All authors declare no conflicts of interest in this paper.

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