Performance assessment and LCA of a PCM-based coating for residential buildings of the north-west Mediterranean region

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Abstract. The paper focuses on the thermo-economic and life cycle assessment of three different Phase-Change Materials (PCM) for use in residential buildings on the North-West Italian coast. For the purpose of this work, we considered the climatic conditions of the city of Genoa, Italy, and used publicly available weather data from year 2020. We numerically assessed three PCMs against conventional thermal insulating materials, on three different flat wall geometries, using a one-dimensional heat transfer model, implemented in MATLAB. The most relevant characteristic of PCMs is their phase transition condition. Our model is based on the assumption that PCMs transition occur in a specific temperature range, and this yields to an instantaneous increase of their specific heat. Subsequently, based on a 25-year PCM life cycle assumption, we carried out a thermo-economic analysis based on the Net Present Value (NVP) index, a life cycle assessment (LCA) and a carbon dioxide (CO2) saving estimation. Linear regression was used to predict the future economic and environmental scenarios. Simulation results showed that PCM performance is not as high as expected when benchmarked against a conventional insulating material. Specifically, PCMs do not reduce winter thermal demand and CO2 emissions over their life cycle are twice those of the classical insulator taken as a reference. We then numerically evaluated their performance in a warmer climate, corresponding to a South Mediterranean region, and under these conditions PCMs outperformed against conventional insulators, thus justifying their current higher cost.

1. Introduction

Buildings are a major source of energy consumption. They represent 40% of the share in the European Union [1] and due the rising costs of primary energy sources, improving their efficiency is a key issue in the agenda of policy makers. Most European countries have a mild climate in summer and the largest part of their energy consumption for civil use, takes place during winter months [2,3]. Even in locations on the Mediterranean coast, as is the case of the city of Genoa, the outdoor temperature is lower than 15 [°C] for 46% of the time [4], and this results in a significant energy consumption for heating civil, commercial, and industrial buildings. For this reason, governments promote policies in the forms of incentives in order to motivate citizens to improve the energy efficiency of their buildings. Such incentives oftentimes are focused on the retrofitting of old and historical heritage buildings [4,5]. The heat demand in residential buildings depends on a number of factors, including the number of dwellers, the outdoor temperature, the number of wall layers, the wall thickness, and its insulation. Catering for all these variables, and the inherent uncertainties of some of them, would require time-dependent models with increasing degree of complexity [5-9].

PCMs attracted the interest of many researchers and practitioners for their potential applications in buildings. PCMs can store heat during their phase change, due to an internal energy increase. Therefore, due to their thermal inertia, they can be used to reduce energy consumption in both winter and summer times. PCMs store heat during their melting phase and release it during the solidification phase. In winter conditions, PCMs prevent heat to be transferred outside, since they store it by melting, whereas in summer they prevent the heat to be transferred inside by storing it in.

A wide variety of research has been undertaken in recent years to investigate novel applications of PCMs. Tan et al. [10] developed a complete techno-economic analysis for a PCM-based storage within an office building in Sweden, for the daily peak shaving of the cooling load. They applied a mixed integer linear programming methodology to determine the optimal scheduling of the storage.

Technical aspects of PCM applications in buildings were analysed by Koci et al. [11]. They investigated the effect of plasters modified with PCMs on the energy consumption of buildings located in different climates and built with materials typically found EU buildings. The amount of energy saving was quantified, however authors highlighted that the economic and environmental feasibility should be more thoroughly assessed.

Similarly, Lakhdari et al. [12] studied the utilization of a dual microencapsulated PCM mixed with plaster as a coating layer on the inner wall of a building envelope and analysed numerically the performance. Their results showed a significant improvement of the energy performance of the building.

Gao et al. [13] tackled the problem of the low thermal inertia of light-weight materials used in high-rise and super high-rise buildings. These materials have a reduced weight, but also a very low thermal inertia, therefore the cooling load and the internal comfort conditions could be largely affected. The study proposed to fill the brick hollows with PCM to increase the thermal inertia. Their results were promising since the peak heat flux could be reduced by over 50%. On the other hand, the average heat flux remained unchanged.

The utilization of PCM in the walls of detached residential buildings was investigated by Vukadinovic et al. [14]. They developed a comparative analysis on building models with and without PCM within the walls. The analysis focused on the position of the PCM within the building wall to reduce energy consumption over the year, considering different cities in Serbia. The results showed that the mid-wall position is the most effective for all the analysed climatic conditions.

Sasic Kalagasidis [15] developed a numerical model of a building with PCM to obtain the energy usage for heating and cooling of buildings. The model was experimentally validated, and a normative benchmark of a whole building was also carried out. The author used the international building physics toolbox for their simulations and results showed that the annual total energy saving for heating and cooling was in the 5% to 21% range depending on the thermal comfort achieved and the PCM position inside the building.

Bland at al. [16] undertook an analysis for PCM as residential coating. In their work they pointed out several disadvantages associated with PCMs, namely super cooling, low thermal conductivity, phase segregation, fire safety, and cost. The issues caused by super cooling and phase segregation could lead to thermal cycling degradation, limiting the useful lifecycle of the material. These issues could limit their potential in building applications, where long lifespan is a design requirement. Low thermal conductivities can slow down the rate at which heat is distributed or absorbed from the building, which affects the occupant’s comfort and as well as the efficiency of the system.

An experiment with a full-scale model was performed by Kuznik and Virgone [17]. The purpose of this study was to compare the thermal performance of a wallboard made from a PCM copolymer composite, against one without PCM. The experiment was controlled using a thermal guard and a climate chamber, which allowed for the temperature to be set so that the tests could be repeated for greater accuracy of results. The key finding of their research was that the PCM filled walls greatly reduced the overheating effects of the room and led to a lower wall surface temperature. The results also showed that PCMs could be advantageously used to improve occupant’s comfort in buildings due to their energy storage capability.

Zhou et al. [18] conducted extensive research into PCMs for thermal energy storage in building applications. Their research identified many suitable materials, both commercial and non-commercial ones, exhibiting properties suitable for residential use. They also evaluated several different applications and used numerical analysis to evaluate the thermal performance of these buildings relying on thermal dynamic models. Their work, however, did not address long-term stability of PCM. It concluded that PCMs have a great potential in reducing fluctuations of indoor temperatures in buildings, as well as offering thermal storage and ventilation/cooling solutions.

The present paper contribution is an analysis pf PCM performance in North Mediterranean climatic conditions. In particular, a comparison among three PCMs, namely paraffin, OM35, HS29 and three traditional insulators, namely polyurethane foam, rock wool and cellulose fiber, is carried out. The investigation is developed numerically considering three wall configurations. A layer of 5 [cm] and of 10 [cm] are considered in each of the configurations investigated and simulations are run over a monthly period, considering two days with typical weather conditions of the month.

2. Numerical model

We developed the model of a building wall, incorporating PCMs and/or traditional insulations. We assumed that the wall is south facing, with no shading, constant internal temperature, and single-layered, as reported in [19]. The interior side of the wall is subjected by convection boundary conditions, while the external side is subjected to convection and radiation boundary conditions. PCMs are modelled by considering an effective heat capacity approach as suggested by Ogoh at al. [20].

The schematic of the problem under investigation is reported in **Figure. 1**

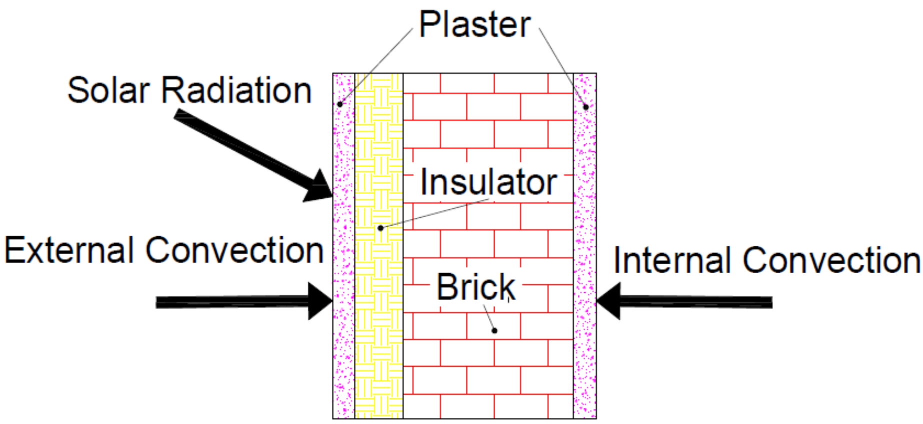

Figure 1. Schematic of the configuration under investigation

The governing equation is:

$$k\frac{\partial^2 T}{\partial x^2} = \rho C_p \frac{\partial T}{\partial \theta} \tag{1}$$

with two boundary conditions and one initial condition; on the external surface for x=0 yields

$$k\frac{\partial T}{\partial x} = [h_c(\theta) + h_r(\theta)] \cdot [T(0,\theta) - T_e(0,\vartheta)] + \sigma\varepsilon\left[T(0,\theta)^4 - T_{sky}(\theta)^4\right] - \alpha q_{sol}(\theta) \tag{2}$$

while on n the internal surface, for x=L, the condition is:

$$-k\frac{\partial T}{\partial x} = h[T(L,\theta) - T_i] \tag{3}$$

where T_i represents the internal temperature that changes in the different months (e.g. heating/cooling season), $h_c(\theta)$ (θ) and $h_r(\theta)$ the convection and the radiation coefficients, $T_e(\theta)$ is the external temperature that changes during the different hours of the day and according to the month considered, T_{sky} is the sky temperature, σ is the Stefan-Boltzmann constant and ε represents the emissivity. The internal temperature is supposed to be constant and set by a thermal control system. It has been assumed equal to 20[°C] during winter and 26[°C] during summer.

The initial condition is supposed as a linear distribution based on the values of the internal and external temperatures of the wall. In order to reduce the error of this hypothesis, two days are simulated, so the first day can be used to stabilize the evolution of the temperature profile.

In eq. (1) C_p represents an average value of the specific heat, as suggested by Ogoh at al. [20]

$$C_{p\_eff} = \frac{LH}{T_2 - T_1} + \frac{C_{p\_s} + C_{p\_l}}{2} \tag{4}$$

In this equation, LH represents the latent heat of fusion $\left[\frac{J}{kg}\right]$, T_1 and T_2 are respectively the temperature at the beginning and at the end of the melting phase, C_{p_s} and C_{p_l} are the heat capacity of the solid and liquid phases. This problem described by Eqs. (1-4) is solved in MATLAB using the finite difference method applied to a one-dimensional surface, using the Explicit Euler formula.

3. Materials and data

The candidate PCMs for the comparative simulation were initially five. Two of them were discarded after an initial performance analysis because they did not perform well, as subsequently described. The insulators chosen to have thermophysical properties of the most widespread ones in buildings.

Table 1. Properties of simulated insulating materials.

	$T_{melting}$ $[°C]$	ρ $\left[\frac{kg}{m^3}\right]$	k $\left[\frac{W}{mK}\right]$	C_{p_l} $\left[\frac{J}{kgK}\right]$	C_{p_s} $\left[\frac{J}{kgK}\right]$	LH $\left[\frac{J}{kg}\right]$	$Price$ $\left[\frac{€}{cm \cdot m^2}\right]$
Paraffin	26÷30	800	0.250	2000	2000	245000	22
HS29	26÷29	1600	1.05	2620	2620	190000	23
Paraffin Wax	38÷43	750	0.200	2600	2400	174000	/
OM35	33÷35	900	0.200	2710	2310	197000	20
Pure Temp	22÷24	870	0.250	2060	1560	170000	/
Polyurethane foam	/	30	0.028	/	1500	/	12
Rock wool	/	92	0.047	/	840	/	10
Cellulose fiber	/	65	0.038	/	2100	/	16

In Table 1, $T_{melting}$ represents the melting temperature range of the PCMs, ρ is the mass density, k is the thermal conductivity. Insulators prices are the those indicated by regulations [23], while those of PCMs were commercially available. Pure Temp and Paraffin wax are the two PCMs discarded. Pure Temp was discarded because the results for 5 [cm] and for 10 [cm] prevented heat loss only in June and July. Paraffin wax was discarded because the simulations showed that winter performance prevented heat to go out of the wall, but summer performance did not prevent heat to go inside. The comparative analysis is performed by placing the insulators in three standard stratigraphies.

Table 2. Characteristics of standard walls.

	U $\left[\frac{W}{m^2K}\right]$	k_i $\left[\frac{kJ}{m^2K}\right]$	Y_{ie} $\left[\frac{W}{m^2K}\right]$
MLP03	0.9	53.7	0.197
MCO03	1.22	60.2	0.239
MCO05	0.45	34.8	0.118

In Table 2, U represents the thermal transmittance, k_i represents the aeric heat capacity and Y_{ie} represents the periodic thermal transmittance.
MLP03 is characterised by two layers of plaster and one layer of bricks, MCO03 is characterised by two layers of plaster and one layer of concrete and MCO05 is characterised by two layers of plaster and one of cellular concrete.

4. Thermal and energetical results

Simulations were run for two different thickness: 5 [cm] and for 10 [cm] of material. Results showed that 5 [cm] of insulator for a wall in the city of Genoa did not perform well: PCMs cannot prevent heat losses during summer and winter. On the other hand, 10 [cm] of PCMs can guarantee internal comfort for the dwellers. The configuration analysis is represented by the wall with a layer of PCM/insulation having a thickness of 10 [cm]. Six cases were considered for each type of wall and a case without any layer was considered for comparison purposes.

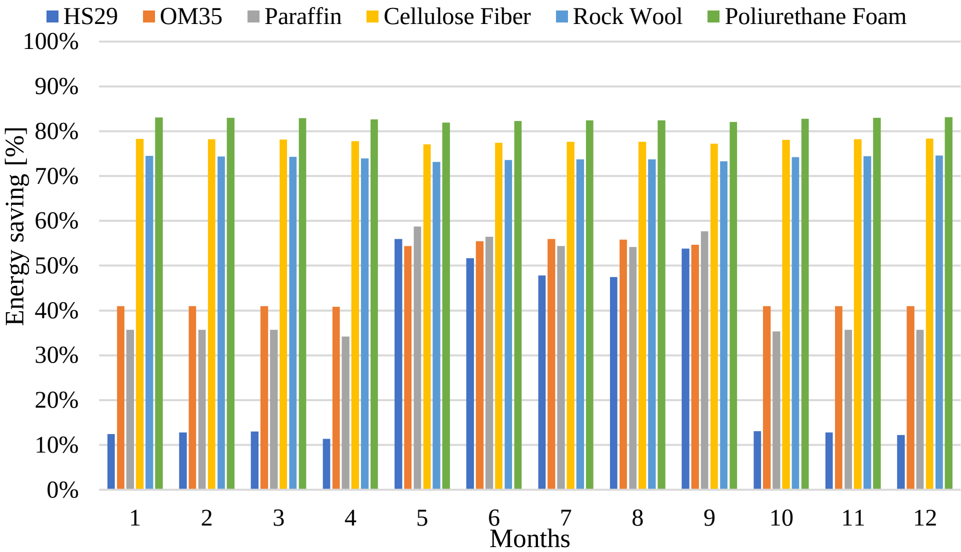

Figure 2. Energy saving for standard insulators or PCMs compared with MLP03 wall

Figure 2. shows the reduction of energy demand with respect to a case without any insulating layer for MLP03. None of the PCMs can guarantee more than a reduction of 42% of heating demand and 57% of cooling demand. Traditional insulator can provide a more consistent reduction in energy demand: a reduction of 83% of heating demand and 82% of cooling demand for polyurethane foam. HS29, in winter, cannot prevent the heat to go outside with a reduction of 12% in heating demand, while in summer it shows a reduction of 50% in cooling demand. OM35 and Paraffin perform similarly: in winter OM35 prevents a further reduction in heating demand, while in summer Paraffin prevents a further reduction in cooling demand. Traditional insulators perform better than PCMs with a reduction more than 70% in energy demand.

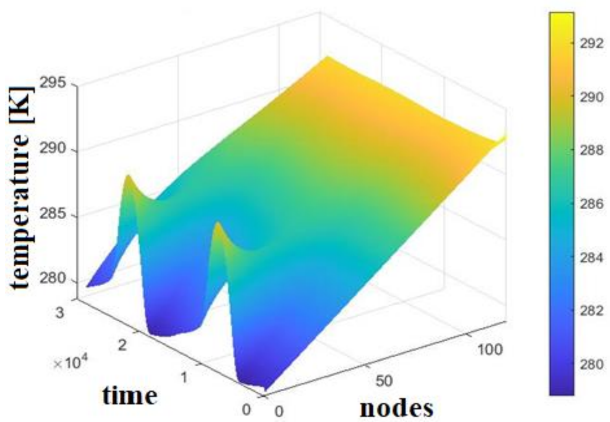

Figure 3. Thermal distribution in MLP03 with OM35 as insulator in January

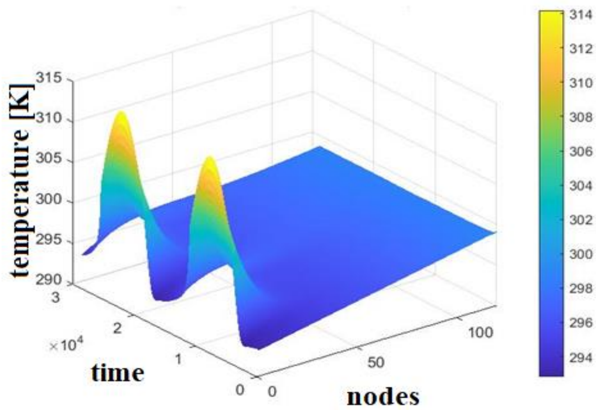

Figure 4. Thermal distribution in MLP03 with OM35 as insulator in July

Figures 3 and 4 show the thermal distribution in MLP03 in two different periods of the year: winter and summer. These results are important because we can appreciate the transition of the PCM in summer period: as wall temperature reaches 33[°C], OM35 starts the melting phase, hence it stores heat and as a consequence the internal temperature reaches its maximum value with a time delay. Because of the thermal conductivity of PCMs, the external temperature of the wall is lower than the one with traditional insulator.
By way of comparison, Figures 5 and 6 show the results, in the same period of the year for MLP03 with polyurethane foam as insulator.

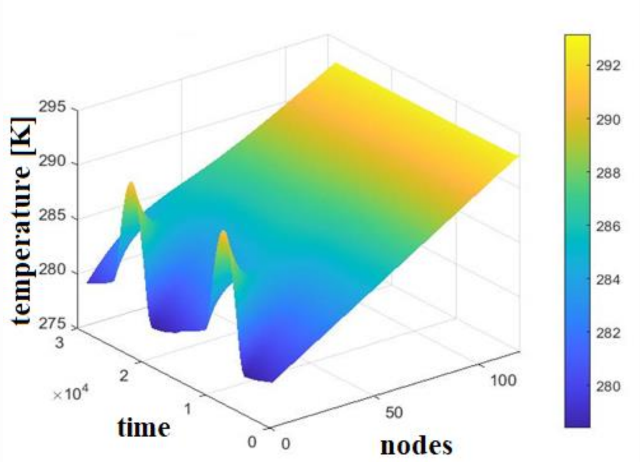

Figure 5. Thermal distribution in MLP03 with polyurethane foam as insulator in January

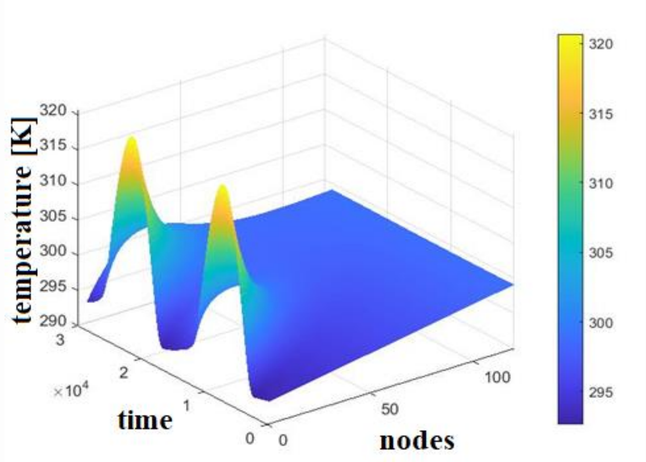

Figure 6. Thermal distribution in MLP03 with polyurethane foam as insulator in July

MCO03 shows similarly results but with a lower reduction energy demand. MCO05, because of its transmittance, can guarantee an energy reduction even without a layer of insulator.

5. Techno-economic analysis

A cost analysis is made evaluating the investment of those materials: prices of PCMs and insulators are reported in Table 1. An investment time horizon of 25 years is considered and the aim of this study is to identify the payback time of the insulators. Using linear regression, it was possible to estimate the future price of natural gas and of electricity, from 2020 to 2045, using two conditioning methods: radiators and heat pumps in a case and heat pumps only in the second one. Four coefficients were used for the linear regression: heating degree days (HDD), cooling degree days (CDD), gross domestic product (GDP) and population. We supposed that HDD and CDD will not increase over the next 25 years due to the global warming, GDP will increase byf 1.12% and POP will increase by 0.3%. Using Net Present Value (NPV) index, it was possible to estimate the investment. For this purpose, we calculated the saving energy as a difference between a non -nsulated and an insulated wall; then cash flow was calculate as follows:

$$CF = SE \cdot p \tag{5}$$

where CF represents the cash flow [€], SE represents the energy saving $[kWh]$ and p the price of the energy source $\left[\frac{€}{kWh}\right]$. Considering a discount rate of 10%, it was possible to work out the NPV as follows:

$$NPV = \left(\sum_j \frac{CF_j}{(1+R)^j}\right) - I_0 \tag{6}$$

where R is the discount rate, I_0 represents the initial investment [€] and j the time [years]. If NPV value is negative it means that the investment is not convenient, conversely if it is positive the investment is convenient. We then calculated the actualized cash flow (ACF) an index used to estimate the value of an investment today, based on projections of how much money it will generate in the future.

$$ACF = \sum_j \frac{CF_j}{(1+R)^j} \tag{7}$$

Results are shown in Figure 7 where it is reported the actualized cash flow (ACF) analysis that represents the attempt to figure out the value of an investment today, based on projections of how much money it will generate in the future. Because of their cost, PCMs are not able to reduce the consumption of natural gas or electricity to provide internal comfort to the inhabitants, and for this reason after 25 years PCMs cannot reach break-even. On the other hand, traditional insulators can guarantee a payback only for MLP03 and MCO03. Polyurethane foam is the cheapest insulator but also the one with the lower thermal conductivity and for these reasons it can be paid back in less than 10 years. Cellulose fiber, even if it has better thermal properties than rock wool, because of its cost, requires over 10 years to be paid back and only using MLP03, with radiators and heat pump, and only heat pump as conditioning system. MCO05, because of its properties as a wall without any insulator layer, cannot provide to a payback both with insulator and with PCMs. The best insulator is rock wool used in MLP03 conditioned by heat pump alone.

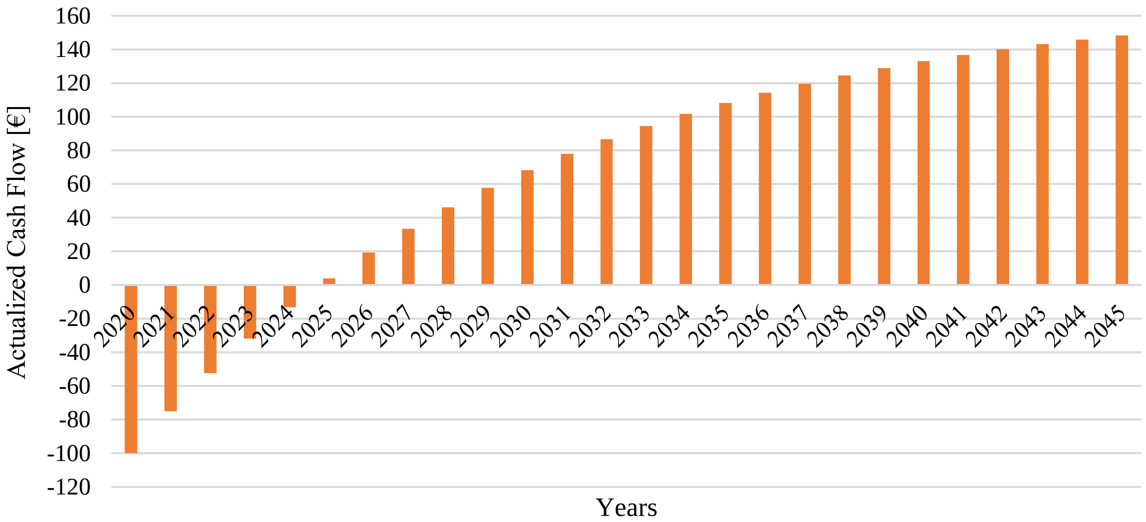

Figure 7. Actualized cash flow for rock wool, in MLP03 conditioned by heat pump alone. Payback is guaranteed in 2025

6. LCA and CO2 emissions

An LCA analysis was finally made evaluating the embodied energy of each material. The embodied energy of a material can be taken as the total primary energy consumed over its life cycle. This includes extraction, manufacturing, and transportation. One approach is setting the boundaries at the extraction of raw materials until the end of the product lifetime (from cradle to grave). Another way to evaluate the embodied energy is the from cradle to gate approach, that includes all energy used until the product leaves the factory gate. Using Inventory of Carbon and Energy (ICE) [21], it was possible to find the embodied energy of PCMs, insulators and building materials. It was considered a "cradle to gate" analysis and seven different countries were selected as exporters: India, China, Germany, United Kingdom, United States, Argentina and Colombia. Considering the CO_2 emission factors [22] reported in Table 3, and the energy mix production of these seven countries it was possible to estimate CO2 emissions for insulators and PCMs.

Table 3. Carbon emission factors for each source of energy.

	$Coefficient\ Factor$ $\left[\frac{tCO_2}{GWh}\right]$
Biofuel and waste	45
Coal	888
Geothermal, solar, wind	55
Hydro	26
Natural gas	500
Nuclear	28
Oil	735

The production of these materials is more sustainable in the United Kingdom because of the low value of CO2. The reason can be found in the energy mix of this country where only 3.4% of energy is produced from coal (Figure 8). On the other side, the less sustainable country is China where more than 60% of the energy mix is from coal (Figure 9).

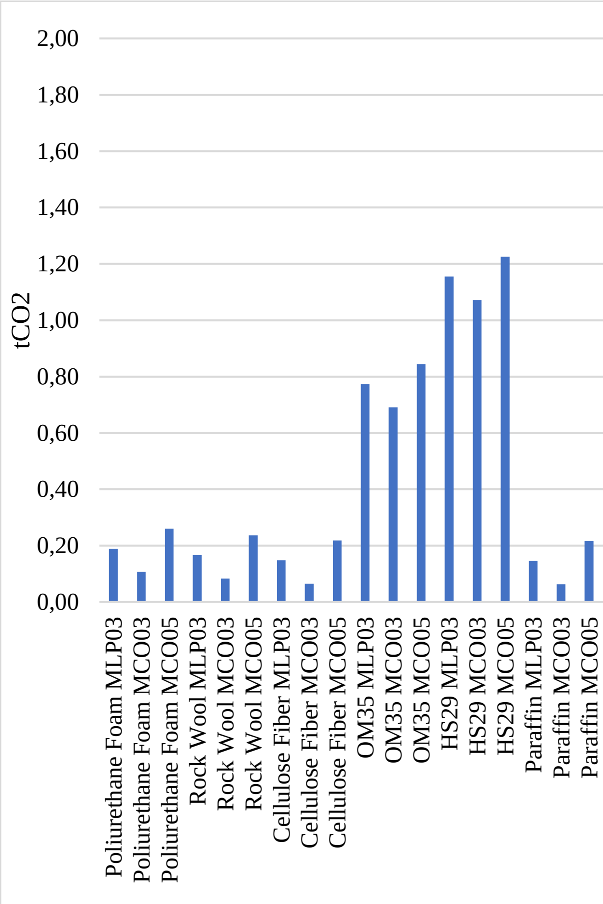

Figure 8. CO2 emission for both insulators and PCM, valuating an LCA from cradle to gate, exported from United Kingdom

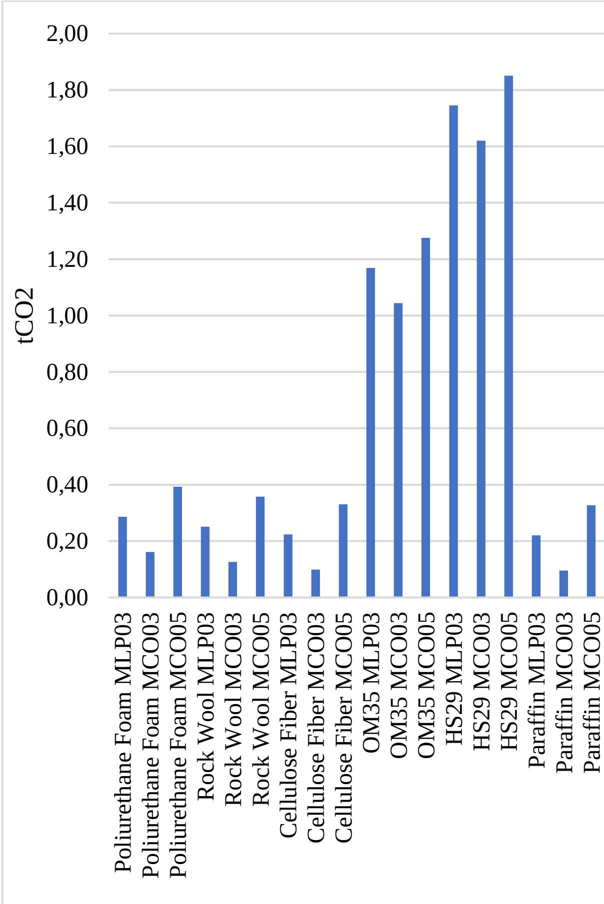

Figure 9. CO2 emission for both insulators and PCM, valuating an LCA from cradle to gate exported from China

By considering the CO_2 coefficient emission from each source of climatization, it was possible to estimate a payback of carbon emission for the three walls. The emission coefficient, in case of using only heat pump, is estimated with a linear regression because electric energy is dependent on the entire energy mix of the country. Emission coefficient of natural gas is 0.249 $\left[\frac{kgCO_2}{kWh}\right]$ as reported in EEA online database. Because of European Union environmental policies, using linear regression it was possible to estimate a reduction of 121% on CO_2 emissions: from 0.213 $\left[\frac{kgCO_2}{kWh}\right]$ in 2020 to 0.096 $\left[\frac{kgCO_2}{kWh}\right]$ in 2045.

OM35 and HS29, because of their high value of embodied energy, cannot provide a CO_2 payback in 25 years. Paraffin reaches payback for MLP03 and MCO03 in 10 years. All the traditional insulators guarantee a payback: cellulose fiber, because of its value of embodied energy provides a payback in a short period of time, from 5 to 10 years. Polyurethane foam, as rock wool, has a value of embodied energy higher than cellulose fiber but can provide to a payback in less than 15 years. MCO05, without any thermal insulators cannot provide a payback because of the high value of embodied energy of cellulose concrete. This means that is not convenient a thermal insulator for this type of wall, also because it can provide an internal comfort for the inhabitant even without insulators or PCMs. The most relevant values of payback are the ones from the United Kingdom, for MCO03 with radiators and heat pump as climatization system as shown in Figure 10.

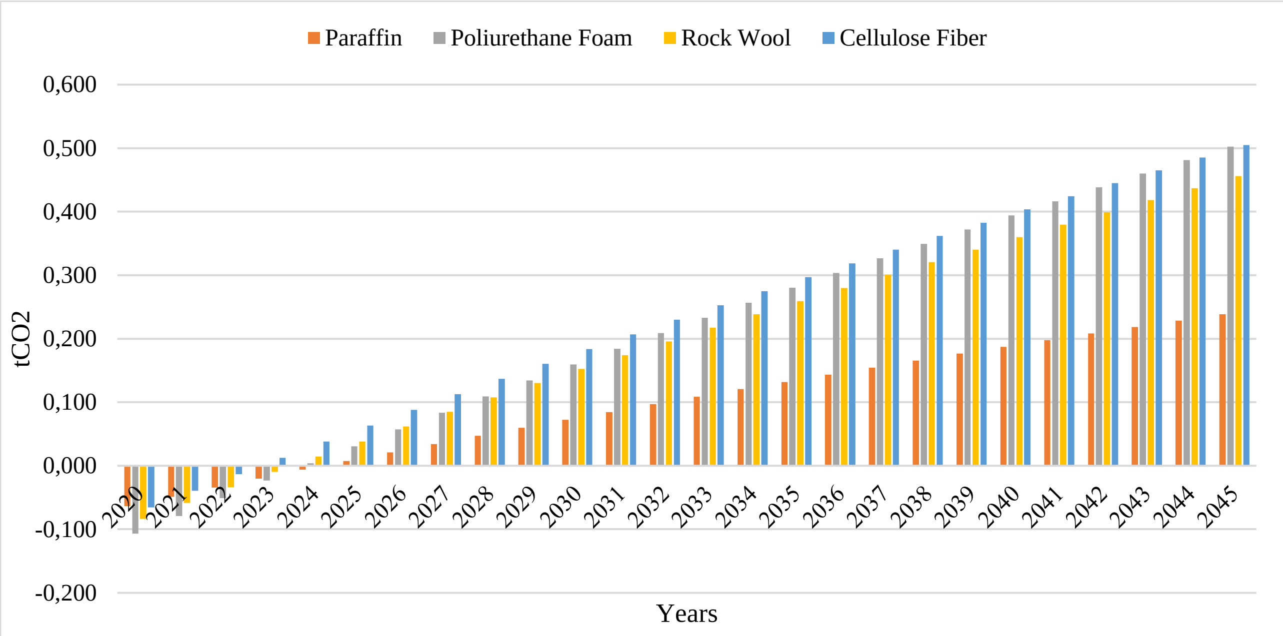

Figure 10. CO2 payback for MCO03, exported form United Kingdom, using heat pump as a climatization system

7. Conclusions

The paper was focussed on a performance assessment of three PCMs. The analysis demonstrated that the effect of the insulation layers contributes to the reduction of the energy demand but the beneficial effects of PCMs cannot be seen in a city with North-Mediterranean climate, like Genoa. The different temperatures between winter and summer dot nor allow to exploit the phase change property of PCMs. Simulations showed an improvement in a more stable and hotter climate region like North Africa with a better irradiation and similar temperatures between winter and summer. The techno-economic analysis established that PCMs are not a viable solution in Genoa. The LCA analysis showed that due to the embodied energy of paraffin and its value of CO_2 emission, PCM can be comparable with traditional insulators, but they can reach a CO_2 payback in less time than paraffin. We can conclude that PCMs are a highly promising technology to store thermal energy but the application in the residential sector is not straightforward with the climatic conditions considered in this work, because of the competition with insulator, climate variability, high prices, low demand and high values of CO_2 emission. We believe that these materials can be more effectively used in applications such as industrial thermal storage, on solar thermal panels and storage systems. PCMs have a great advantage in terms of customization, and future work, and future work will be focused on the evaluation of their performance based on a composition designed to meet the thermal requirements of the end-users.

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