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Review

Perspective on the Development of Energy Storage Technology Using Phase Change Materials in the Construction Industry: A Review

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Abstract: The construction industry is responsible for high energetic consumption, especially associated with buildings' heating and cooling needs. This issue has attracted the attention of the scientific community, governments and authorities from all over the world, especially in the European Union, motivated by recent international conflicts which forced the countries to rethink their energy policies. Over the years, energy consumption has been based on non-renewable energy sources such as natural gas, oil and coal. Nowadays, it is urgent to implement solutions that aim to minimize these high energetic consumptions and act based on clean and renewable energy sources. In recent years, phase change materials (PCM) have become an area of high interest and development, since they allow to minimize the energy consumption in buildings, based in solar energy, due to their thermal storage capacity. The main objective of this work consists of a perspective of the evolution of the development and application of thermal storage technology through the incorporation of PCM in the construction sector, focusing on the last 10 years of research, showing the most recent developments of its application in construction materials, such as mortars, concrete, incorporation in porous aggregates, naturally based materials, carbon-based materials, boards, blocks and solar thermal systems.

Keywords: energy efficiency; thermal storage technology; phase change materials

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1. Introduction

Currently, humanity faces challenges never experienced before, related to the little or no sustainable development we have witnessed, which is further aggravated by conflicts and wars that increasingly expose and leave the most fragile populations vulnerable.

The United Nations Organization has been working and establishing policies and objectives that allow combating the main problems of today, with the 2030 Agenda being a clear example of this effort [1,2]. The 2030 Agenda is a broad and ambitious program that addresses various dimensions of sustainable development, establishing 17 main goals. The seventh goal, "Ensure access to affordable, reliable, sustainable and modern energy for all" is directly related to energy consumption worldwide, indicating that it is necessary to establish universal, reliable, modern and affordable access to energy, substantially increasing the participation of renewable energies. On the other hand, it will be necessary to improve energy efficiency, increase research into energy technologies and modernize the technology for providing energy services [1]. Thus, taking into account the high energy consumption verified in the construction industry, the development of energy storage technology using phase change materials (PCM), based on solar energy in the construction industry and especially applied to construction materials, can constitute an important line of research and development to achieve these objectives and their implementation goals. It is important to note that solar energy is a clean energy source without carbon dioxide emissions and waste generation, is widely available and free [3], and also allows to contribute to carbon neutrality [4]. It should also be noted that lower energy consumption based on low-cost energy sources with no impact on the environment will lead to a decrease in the population living with difficulties in heating and cooling buildings (situation of energy poverty). On the other hand, it will also be possible to contribute to sustainable cities and communities, in order to make cities and communities more inclusive, safe, resilient and sustainable. Finally, it will be possible to move towards a more innovative, resilient, inclusive and sustainable construction industry, which aims for the development of quality and sustainable buildings, supporting economic development and human well-being. Thus, this manuscript addresses the follow United Nations Sustainable Development Goals:

- ODS 1: End energy poverty;
- ODS 7: Affordable and clean energy;
- ODS 9: Resilient, sustainable and innovative infrastructures;
- ODS 11: Sustainable cities and communities.

The aim of this work is to provide a perspective on the development of energy storage technology using phase change materials in the construction industry, addressing energy consumption in the construction sector and the development of thermal storage technologies using phase change materials, as well as a broad and current demonstration of the application of this technology to different construction materials.

Scope of the Review Paper

The methodology followed in the creation of this review was based on the premise of giving priority to articles published in the last 10 years (since 2012), using numerical and experimental approaches, with the objective of keeping the review up to date.

The review is divided into seven sections. The Introduction presents the policies and objectives defined by the European Union, namely, the objectives for sustainable development, in which the theme of this review is inserted. Section 2 presents the energy consumption in the construction industry, i.e., the final energy consumption in households by type of fuel, the purpose of the energy uses in the residential sector and also the European countries most vulnerable to energy poverty. Section 3 describes the evolution in the last years of the thermal energy storage technology, showing the number of papers published and the countries more active in researching this topic. Section 4 is dedicated to phase change materials, being subdivided into several subsections, addressing the main criteria for the correct application of PCM in buildings, its classification and existing incorporation techniques, which makes the article comprehensive in this domain. These concepts are directly related to the information presented in the next Section. Section 5, in fact, provides an in-depth approach to the use of PCM in different construction materials and building applications, presenting different subsections covering mortar, concrete, functionalized aggregates, carbon-based materials, naturally based materials, boards, bricks and solar thermal systems. Thus, the immense potential of this thermal storage technology is demonstrated, using several PCM's and several incorporation techniques. Section 6 is devoted to the cost analysis of these types of constructive solutions. Finally, Section 7 highlights detailed recommendations and conclusions, and the future prospects and challenges in thermal storage technology.

2. Energy Consumption in the Construction Industry

Nowadays, the world energy consumption is increasing, due to world population growth [5], technological development [6] and industrial intensity [7]. In the last 30 years, the total energy supply from all sources (oil, biofuels and waste, hydro, wind and solar, nuclear, natural gas and coal) and the carbon dioxide (CO_2) emissions associated with energy production increased about 60% [8]. At the present time the utilization of renewable energy sources such as hydro, wind and solar energy represents only 5.21% of the total energy supply. However, it is important to bear in mind that since 1990 there has been an increase in the use of energy from renewable sources and, according to the most recent data (2020), the verified increase has been around 300% [8].

The construction industry is a huge consumer of energy. This consumption starts from the extraction of raw materials, production of construction materials, building constructions, maintenance, demolition and finally disposal of the generated waste. Thus, the construction industry possesses several ways to contribute to the minimization of energy consumption, from reducing the extraction and use of natural raw materials [9,10], to reducing the amount of construction and demolition waste in landfills [11,12], and also reducing the energy demand of buildings during their operating cycle through the adoption of more efficient constructive solutions [13–15].

Figure 1 shows the final energy consumption by sector in 2021 in Europe: it indicates that 30% of energy is associated with the transport sector, 29% with the residential sector (households), 27% with the industry sector and 14% with commercial and public services [16]. It is important to note that Europe is dependent on non-European countries in terms of energy, with this dependence increasing slightly, since data from 2012 point to a dependence of around 55% and data from 2021 to a dependence in terms of imported energy of around 56%. Italy and Portugal are countries that have high energy import dependency rates, above the European average, being around 74% and 69% in 2021, respectively [17].

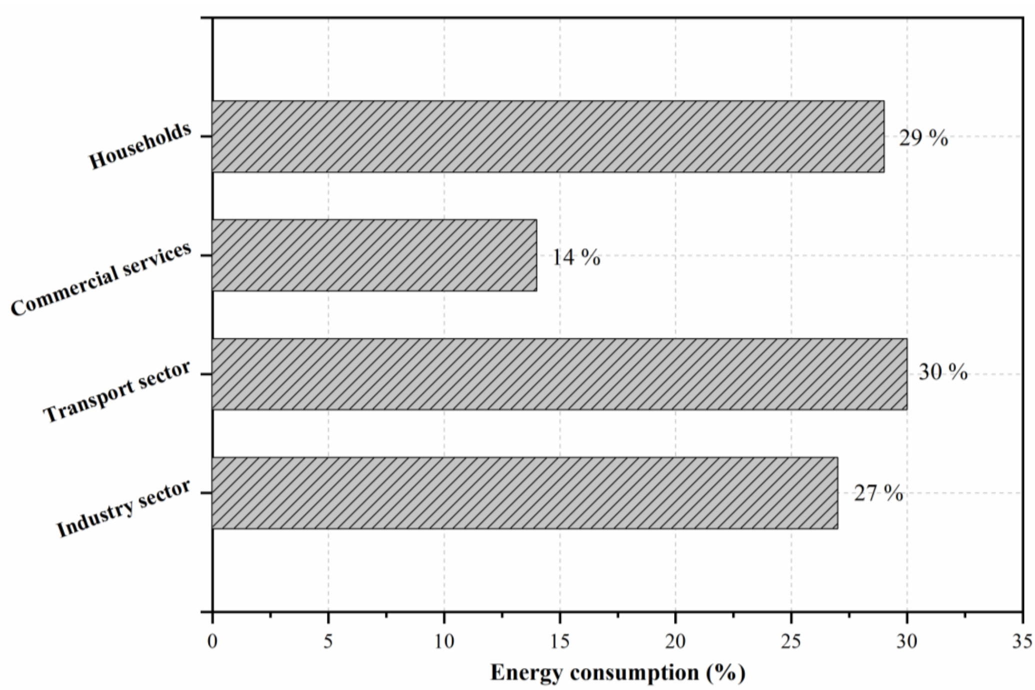


Figure 1. Final energy consumption by sector in Europe.

The energy consumption in households is based on different types of fuels (Figure 2). Natural gas, electricity and solid biofuels represent the most important fuel sources, contributing around 33%, 25% and 17% to energy consumption in the residential sector [18]. It is also important to note that in the last 10 years there has been a slight increase in the use of these energy sources and between 2012 and 2021 the consumption of natural gas, electricity and solid biofuels increased by around 3%, 4% and 2% [18]. Bearing in mind that these are non-renewable energy sources, it is important that the construction industry begins to think about and invest in constructive solutions that can be implemented in buildings which contribute to the minimization of energy consumption but are based on renewable energy sources.

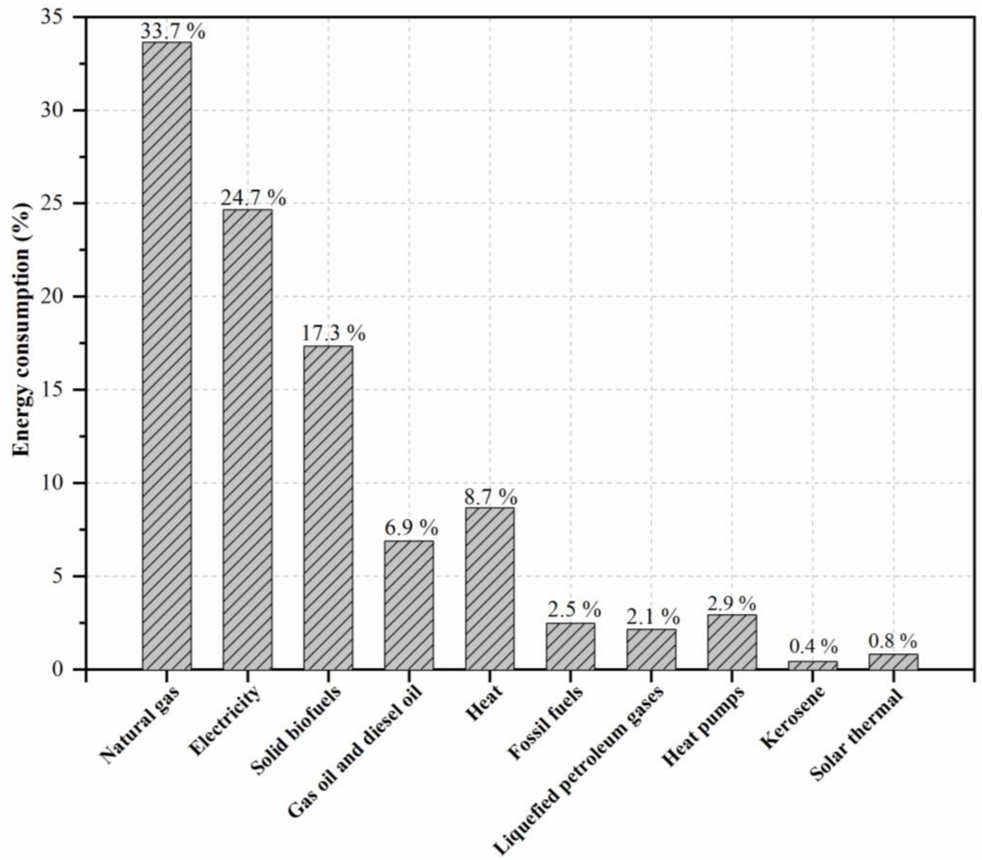


Figure 2. Final energy consumption in households by type of fuel.

The energy consumption in the residential sector is associated with different purposes such as the space heating, space cooling, water heating, cooking, lighting and other end-uses. According to Figure 3, in 2020 in the European Union, 63.2% of the consumed energy in the residential sector was associated with space climatization needs [19].

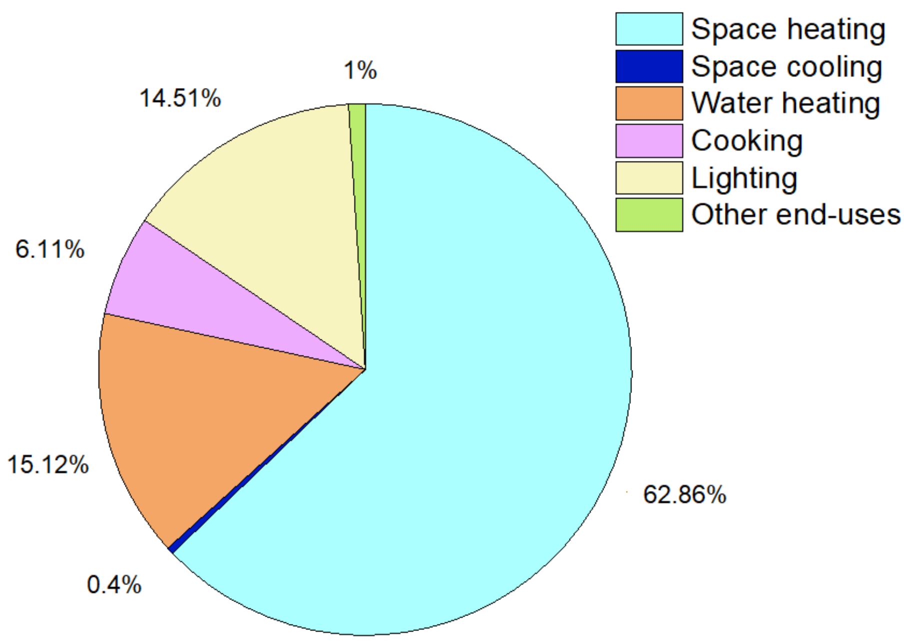


Figure 3. Final energy consumption in the residential sector by use.

Taking into account the enormous heating and cooling needs of buildings, the heating, ventilation and air conditioning (HVAC) systems have huge utilization rates, which consequently implies large energy consumption to maintain comfortable conditions inside buildings; thus, in recent years the concept of energy poverty has emerged, affecting the European Union's population, essentially the most vulnerable families. In Figure 4, it is possible to see a geographical distribution of the countries most vulnerable to energy poverty [20]. Due to the cost increase of natural gas, electricity and oil, an increase in the number of households living in energy poverty across Europe is expected. Thus, the high energy consumption in the construction industry, but especially during the buildings' utilization due to the enormous need for heating and cooling, constitutes one of the highest challenges for the sector's development, as well for the sustainable development of the planet. For this reason, it is essential that sector stakeholders start to develop and invest in constructive technologies and functional construction materials that contribute to minimizing energy poverty and increasing the energy efficiency of buildings. This can be achieved by investing in thermal storage technologies and in the incorporation of phase change materials (PCM) in construction materials.

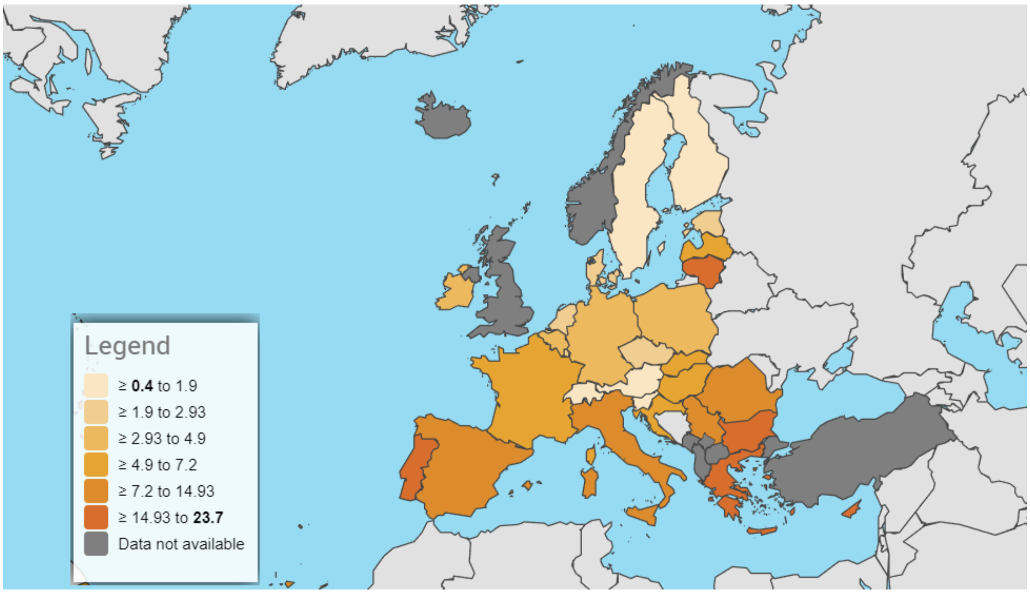
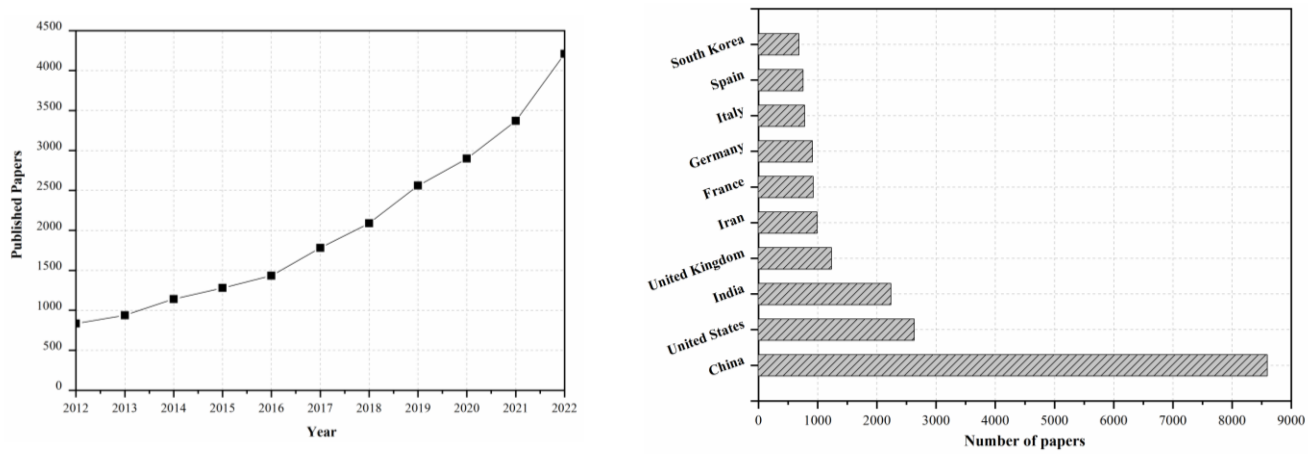


Figure 4. Geographical distribution of the population unable to keep home adequately warm by poverty status [20].

3. Evolution of Thermal Energy Storage Technology

The technology known as Thermal Energy Storage (TES) is a method that can store thermal energy, making it available when needed. This process is made possible by a medium that takes over the excess thermal energy. In general, there are three methods based on this technology: Sensible Heat Thermal Energy Storage (SH-TES), Thermo-Chemical Thermal Energy Storage (TC-TES) and Latent Heat Thermal Energy Storage (LH-TES). In the SH-TES mode, thermal energy is retained in a medium by varying (traditionally increasing) its temperature. A classic example is hot water storage (i.e., hydro-accumulation) but other materials are used, such as: rock, iron, aluminum, air, steam and hydrogen [21]. In general, it is important that the material used in this type of application has a high specific heat capacity per unit mass to store more thermal energy, high conductivity, and thermal stability as well as chemical stability and low thermal expansion. The TC-TES method is characterized by a reversible chemical reaction during which two or more reacting chemical compounds absorb and release thermal energy. Basically, during the reaction, endothermic dissociation, storage of the reaction products and, finally, an exothermic reaction of the dissociated products take place. Then, in the final stage of the reaction, the initial materials are recreated so that the process can be repeated [22]. The most used materials for this kind of application are $MgSO_4 \cdot 7H_2O$ that reacts with $MgSO_4$ using H_2O as working fluid, $Ca(OH)_2$ that reacts with CaO using H_2O as working fluid, $CaSO_4 \cdot 2H_2O$ that reacts with $CaSO_4$ using H_2O as working fluid, and $FeCO_3$ that reacts with FeO using CO_2 as working fluid [23]. In the LH-TES, a phase change material is employed as a medium to store and release thermal energy according to its physical state. In most cases, this is a solid-to-liquid transformation and vice versa (although there can be other transformations, such as solid-to-gas, solid-to-solid and liquid-to-gas). Phase change materials generally used are paraffin waxes, polymers, fatty acids, esters, eutectic salts and hydrated salts [24]. Among these three modes, recently LH-TES has attracted a considerable attention. The main reason is related to the isothermal nature of the phase exchange process, but also to its low weight per unit storage capacity and compactness. In addition, compared with the storage materials used in SH-TES and TC-TES technologies, phase change materials have better thermal properties, such as stable phase exchange temperature and high latent heat [25,26]. These reasons have strongly contributed to its affirmation and diffusion. The interest in this technology is also confirmed by the increasing number of scientific publications on this subject. Looking only at the last 10 years (2012–2022), it is possible to observe how research on "phase change materials" has progressively grown (Figure 5a) and in which country the scientific interest has been predominant (Figure 5b).

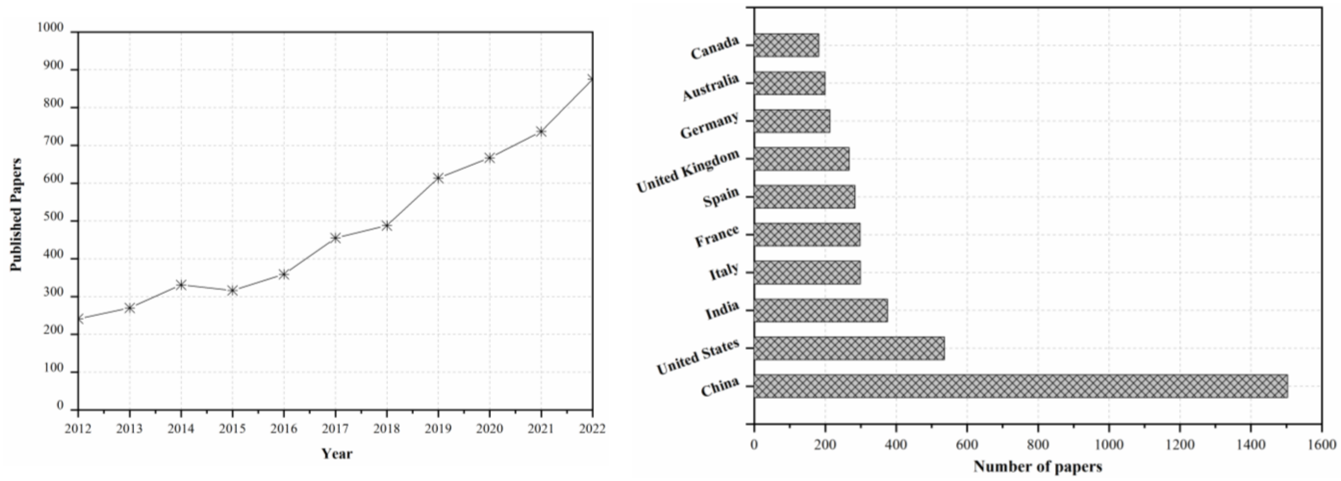


(**a**) (**b**)

Figure 5. (**a**) Number of papers published within 2012–2022 on "Phase Change Material"; (**b**) the 10 countries that have published the most on this topic. Source: Scopus Database. Searched on the day: 3 February 2023.

To date, PCMs are considered one of the most viable strategies for saving energy, and the sector in which they are most widely used is the building industry [27]. Even in this case, the growing number of publications related to the use of PCMs applied in construction has demonstrated the enormous interest in them. This can be seen with a simple bibliometric analysis considering the number of papers published in the last 10 years (2012–2022) on "Phase Change Material used in buildings" (Figure 6a) and in which state this interest was greatest (Figure 6b).

The trend of using PCMs to improve the energy efficiency in buildings is also demonstrated by the keywords that appear most often in scientific articles: thermal comfort, energy efficiency, building, thermal performance and building envelope are the top five keywords appearing most often. Figure 7 shows the network visualization among the keywords found most often in those articles that the Scopus database generated by searching the "phase change material" topic.



(**a**) (**b**)

Figure 6. (**a**) Number of papers published within 2012–2022 on "Phase Change Material used in buildings"; (**b**) the 10 countries that have published the most on this topic. Source: Scopus Database. Searched on the day: 3 February 2023.

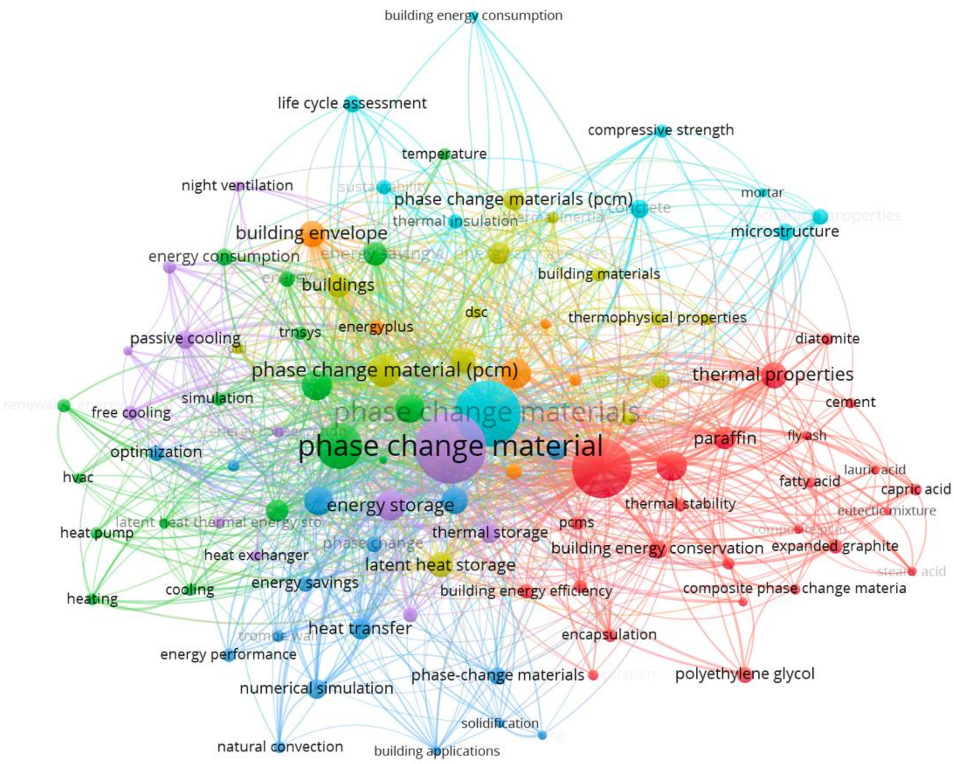


Figure 7. Network visualization of the keywords.

This knowledge will benefit future researchers in choosing keywords that will make it easier to spot previously published material on a certain topic. These keywords also highlight the increasing interest of researchers in this area because it is demonstrated that the application of a PCM brings with it several advantages from a thermal point of view and, consequently, this has important economic benefits that cannot be underestimated.

4. Phase Change Material

A Phase Change Material (PCM) is a substance that can absorb, store, and release a large amount of energy in the form of heat during a phase transition. These materials can exist in different phases, such as solid, liquid and gas, and can change their phase when heated or cooled. During this phase change, the material can either absorb heat (melting) or release heat (freezing), which allows it to be used for various applications such as thermal energy storage, temperature regulation and heat transfer [28,29]. Figure 8 shows schematically the physical operation of a PCM and how, as temperature increases or decreases, its energy content changes.

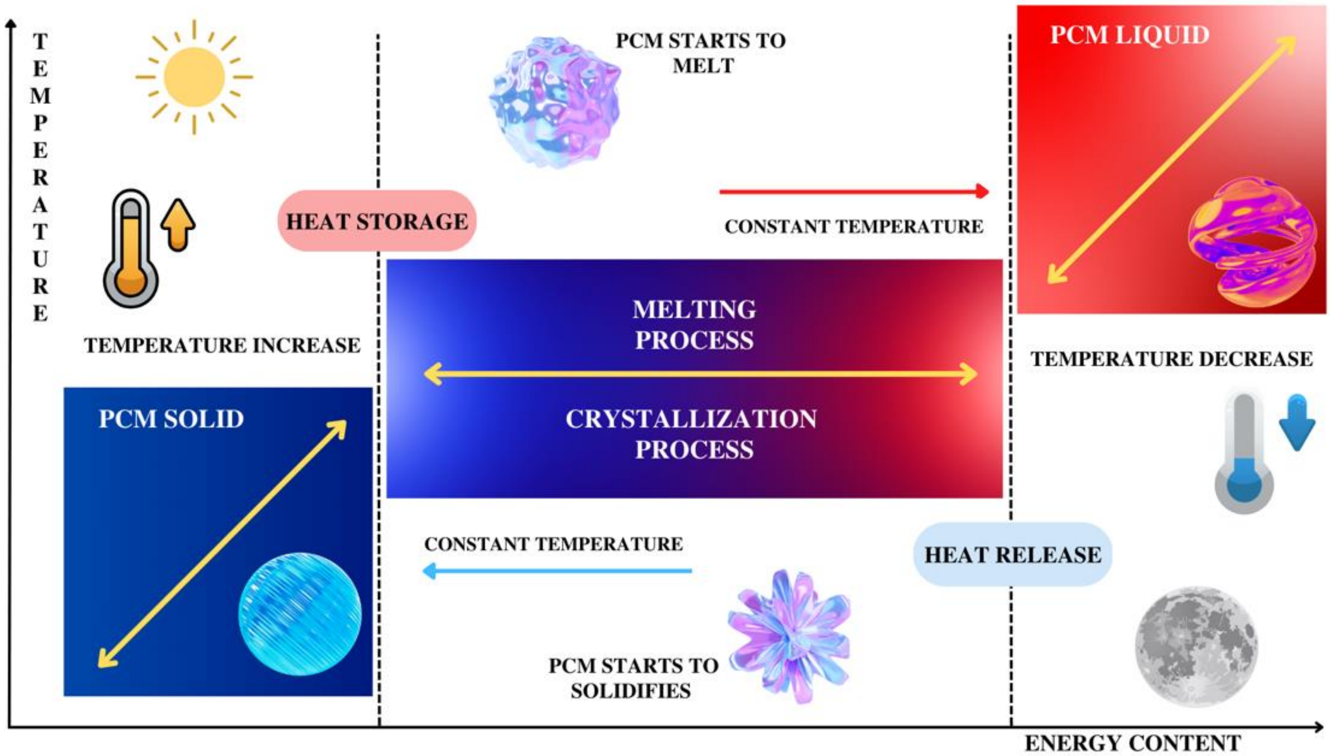


Figure 8. Phase Change Material process.

In general, PCMs have high energy storage density, meaning they can store more energy per unit mass than conventional materials such as water or concrete. This makes them useful for a range of applications, including building insulation [24], refrigeration [30] and renewable energy systems [31]. It is commonly agreed that the ability of PCMs to store and release thermal energy can help improve energy efficiency, reduce the use of fossil fuels and contribute to a more sustainable future [32]. There are several substances which are used as PCMs; each of them has a different melting and crystallization temperature, making them suitable for different temperature ranges and applications.

4.1. PCMs: A Novel Classification

PCMs can be classified based mainly on their melting temperature, which determines the range of temperatures at which they can store or release heat. Commonly, PCMs classification include organic, inorganic and eutectic PCM. However, very recently a new and interesting class of PCMs has emerged which is worth reporting, namely, bio-based PCMs [33–35]. They are briefly illustrated in Figure 9.

The difference between these PCMs, including advantages and disadvantages, can be described as follows:

- Organic PCMs are typically made from paraffin wax or non-paraffin substances, such as fatty acids, esters, alcohols and glycols, and have a melting temperature range of 0 °C to 150 °C [36]. They are commonly used in building materials and implemented into different construction materials, as will be seen later. Organic PCMs are characterized by a high energy storage capacity and a high latent heat of fusion. A very important aspect is that of supercooling. Organic PCMs do not undergo this phenomenon during solidification and have a good nucleation efficiency. They are available in a wide range of melting temperatures; this makes them suitable for use in a variety of applications. Typically, organic PCMs are considered non-corrosive, non-toxic, and environmentally friendly, making them safe for use in many applications, including food storage and transportation [34]. Nevertheless, these kinds of PCMs have some disadvantages that should be considered, such as low thermal conductivity, meaning that they may not transfer heat efficiently, and may require more material to achieve the same thermal storage capacity (even though progress has been made to remediate this issue [37]). Some of the organic PCMs are potentially flammable or combustible, which could pose a safety risk in some applications and may require additional safety measures [38]. Their limited durability is another problem: organic PCMs can degrade over time due to chemical reactions, which can reduce their effectiveness and lifespan. This may require more frequent replacement or maintenance of the PCM system. Finally, referring to their costs, organic PCMs can be more expensive than some other types of PCMs, which could be an important factor in the choice of a PCM for a given application [39].

- Inorganic PCMs are generally composed of salt hydrates or metals and have a higher melting temperature range, i.e., from 100 °C to 1000 °C. They are commonly used in industrial applications, such as metal casting or high-temperature energy storage and in solar applications [35,40]. Their temperature range makes them more durable than organic PCMs as they do not degrade quickly over time. This means that they may require less frequent replacement or maintenance, which can be cost-saving over the lifetime of a PCM system. Referring to their costs, inorganic PCMs are less costly compared to some other types of PCMs, also considering that they can be produced from readily available materials, which can help keep costs low. Furthermore, inorganic PCMs have a high thermal conductivity and they are non-flammable [41,42]. However, they have a corrosive nature and therefore can rarely (depending on applications) stand alone. In many cases, they must be contained in other materials/elements to avoid the damaging of materials with which they come in contact. In addition, but only in the case of salt hydrates, they may encounter phase segregation and the phenomenon of supercooling, which consequently decreases the energy storage capacity [43].
- Eutectic PCMs are mixtures of two or more substances that have a lower melting temperature than each of the individual components. They are commonly used in refrigeration and air conditioning systems since they are characterized by a low melting point. The latter, moreover, can be customized to meet specific requirements of a given application by adjusting the ratio of the component materials. Eutectic PCMs have a high energy-storage capability and they are chemically stable. They have a long lifespan and result in non-toxic final materials. However, their use may be limited by the availability and cost of the component materials, and they may not be suitable for all applications [44].
- Bio-based PCMs are very close to organic PCMs but they are derived from natural materials originating from animals or plants, such as oils, fats and starches, i.e., not from petroleum refining. They can have a wide range of melting temperatures and they represent an eco-friendly alternative to traditional PCMs [45,46]. They are able, in fact, to ensure biodegradability, sustainability, lack of flammability and non-toxicity. Fatty acids can be easily and cheaply produced from animal fat or oily plants; in addition, non-edible or waste materials can be employed to produce them, helping to avoid wasting food. Referring to their main characteristics as PCM materials, they have small volume changes during the phase change process, small corrosion activity, and thermal and chemical stability [47]. The melting temperature of the most common fatty acid-based PCMs is approximately in the same range as paraffins and, likewise, they have poor thermal conduction capacity. However, several research works have shown

that the addition of metal nanoparticles or other conductive materials (i.e., graphite nanoplatelets, carbon nanotubes, etc.) can overcome this problem [48].

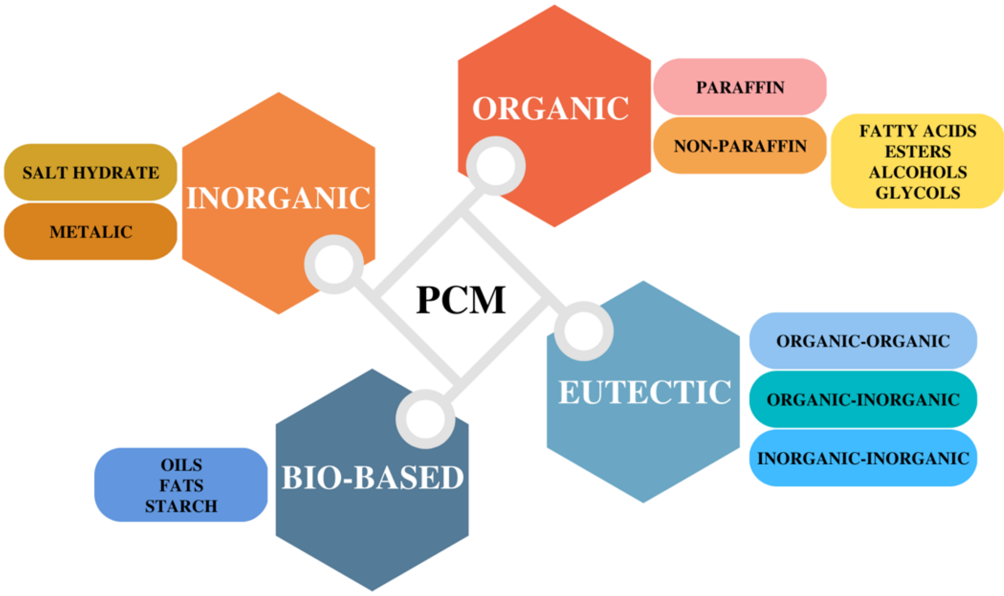


Figure 9. Classification of PCMs.

4.2. Application of PCMs in Building Materials and Associated Challenges

It is possible to incorporate PCMs into building materials in several ways [27]. The presence of many techniques makes it possible to insert PCMs into a wide variety of construction materials, as will be seen in Section 5. So far, the techniques used are direct embedding, immersion, (micro, macro and nano) encapsulation, form-stable and shape-stabilization.

Direct embedding and immersion are the simplest and least expensive methods. The former involves embedding PCM directly into the mix design of a mortar or concrete [49]; the latter, on the other hand, involves immersing a (relatively porous) building material in a PCM, which is then absorbed into its pores by capillary action. Absorption of a PCM can take place at atmospheric pressure or under vacuum [50]. These techniques showed, however, some issues such as leakage of the PCM causing alterations in the final properties of the material in which it was embedded, also leading to possible corrosion problems, incompatibility between the combined materials and increased flammability of the final material [51].

The encapsulation method is divided into three sub-methods: micro-encapsulation, macro-encapsulation and nano-encapsulation. These methods differ in the size of the capsules involved: the size of nano-capsules is less than 1 µm, of micro-capsules between 1 µm and 1 mm in diameter, and macro-capsules from 1 mm upwards. Nano-capsules are only recently becoming widespread, and for this reason their production (which is complex) has not yet been optimized on a large scale [50,52]. However, their conception and diffusion are linked to overcoming certain difficulties related to the use of micro- and macro-capsules. In fact, problems such as low thermal conductivity, supercooling and phase segregation phenomena seem to affect micro- and macro-encapsulated PCMs [53]. To create the micro-capsules, a small amount of PCM is enclosed in another material (which can be a polymer, a lipid or an inorganic compound) that acts as a barrier between the PCM and its surroundings. Then, these micro-capsules can be mixed with other materials, such as mortar or concrete, to form composite materials with enhanced thermal properties [54,55]. At the same time, macro-capsules are made by a PCM or a combination of different PCMs enclosed in a shell made of a suitable material (metals, polymers or composites) that can be integrated into plaster, concrete or gypsum board. These have been the most common techniques so far, although they are very expensive methods [56]. For this reason, and for all the issues mentioned so far, two other techniques have become widespread in the past decade and have shown considerable promise: the form-stable and shape-stabilization methods. These are based on the same idea: to create a composite material (consisting of a matrix and a PCM) that retains its shape even during phase transition. In fact, the matrix must provide structural stability and prevent dispersion of the PCM during its melting or heating [50,57]. When these two methods became popular, they differed in two respects: in the type of matrix used and in the type of methodology employed to produce the final material. The shape-stabilization method involved the use of polymer or metal matrices. Both the matrix and PCM were melted and then mixed. Once they were given the desired shape, they were brought to a solid state and then used as a composite PCM [52,58]. On the other hand, the form-stable method is characterized by porous matrices, such as silica, vermiculite, perlite, diatomite, calcium carbonate, etc. [52,57]. In this case, the final composite material can be obtained by immersion or vacuum impregnation of the active PCM phase [50,59]. As research went on, this distinction gradually narrowed, making, in fact, these two methods coincide; today, they can be considered synonymous [27]. Furthermore, in the present day, this overlap can be translated in only one way: if the term "shape-stabilized" is encountered in an experimental work, it means that it is a porous matrix impregnated (with or without a vacuum) with PCM. Over the past decade, the number of experimental research works involving the use of this technique has steadily increased, and this is due to several advantages of the method: it is very simple and low-cost, requires modest equipment, creates a stable composite PCM reducing its leakage over the melting temperature, is thermally reliable and has a high heat transfer rate [60].

Each of the techniques described so far have arisen from the need to overcome certain problems. Some of these have already been mentioned but in Table 1 they are briefly described and analyzed.

Table 1. Issues related to the incorporation of PCMs in building materials.

Problems	Description	Possible Solutions
Leakage	Leakage of PCM into building envelope causes a number of problems: the PCM loses its storage capacity, and its dispersions can cause the corrosion of the surrounding materials (especially if it is in contact with reinforcing steel). Therefore, mechanical properties start to decrease. Last but not least, leakage is also associated with possible aesthetic defects.	PCM capsules were created to contain PCM and prevent its dispersion. However, these (especially the macro-capsules) need extra attention (e.g., against nails being hung on the wall or other housework involving holes) [61]. Composite materials generated by the shape-stabilized or form-stable method seem not to incur this problem. It was observed that the matrix can contain the PCM even when it undergoes phase change, avoiding its dispersion [62].
Low thermal conductivity	The conductivity of organic PCMs is very low (around 0.2–0.3 W/m K). This has consequences for the PCM's ability to retain and release heat.	PCM capsules were designed to improve the thermal conductivity of PCM, and after them, more success was achieved by composite materials (shape-stabilized or form-stable) because additives can be used, such as: expanded graphite, graphene, metal particles, carbon-fiber, or multi-wall nanotubes [37,63].
Supercooling	This phenomenon occurs when the solidification temperature is lower than the melting temperature. For this reason, the melting temperature should coincide with the crystallization temperature; otherwise, there is a risk that the stored latent heat will not be released. However, this phenomenon occurs only in inorganic PCMs.	The following solutions have been developed to avoid this problem: the addition of nucleating agents or metal additives, or the use of nanofluid PCMs [64].

Table 1. *Cont.*

Problems	Description	Possible Solutions
Phase segregation	This phenomenon usually occurs when there are more than one PCM that have different densities and that, due to gravity, separate causing the fusion process to take place at different times. PCMs that are affected by this problem are hydrated salts or eutectic compounds.	This problem can be solved by adding additives such as a thickening agent or gelling material [27].
Flammability	This problem is mainly associated with organic PCMs that are highly flammable.	The only possible solution so far is the addition of an additive known as a flame retardant. Studies have shown how the addition of this additive reduces fire hazards at the cost of a slight change in the thermal properties of the PCM [65].
Thermal stability	The thermal stability of a PCM indicates its ability to keep its thermal characteristics intact after numerous melting/crystallization cycles. This ability is critical for not losing the thermal properties of storing/releasing latent thermal energy within a building.	Studies conducted to verify the thermal stability of a PCM have observed that composite PCMs produced through shape-stabilized or form-stable methods are able to maintain the thermal properties of PCMs embedded in the matrix intact [66,67].
Suitable PCM	In general, the PCM that is applied in a certain environment must be suitable for that specific climate. The problem arises when the application of a PCM is required in a climate characterized by temperatures (high or low) that are too extreme. In fact, the summer and winter seasons are the most challenging ones.	In the recent period, the use of combinations of PCMs (which have different characteristic temperatures) to increase the range within which the phase change takes place is spreading [68,69].

4.3. Criteria for PCM Selection to Be Applied to Buildings

After listing the problems associated with the use of PCMs in building materials, it becomes easy to understand that there is no such thing as the perfect one. However, there are certain criteria that can be used to select the most suitable PCM for the type of application for which it is intended. Each individual PCM is characterized by thermal, chemical, physical and kinetic properties. However, nowadays, properties such as environmental sustainability, availability and cost are considered extremely important as well. Figure 10 shows the main criteria that should be followed when applying PCMs in buildings, according to [50,52,70,71].

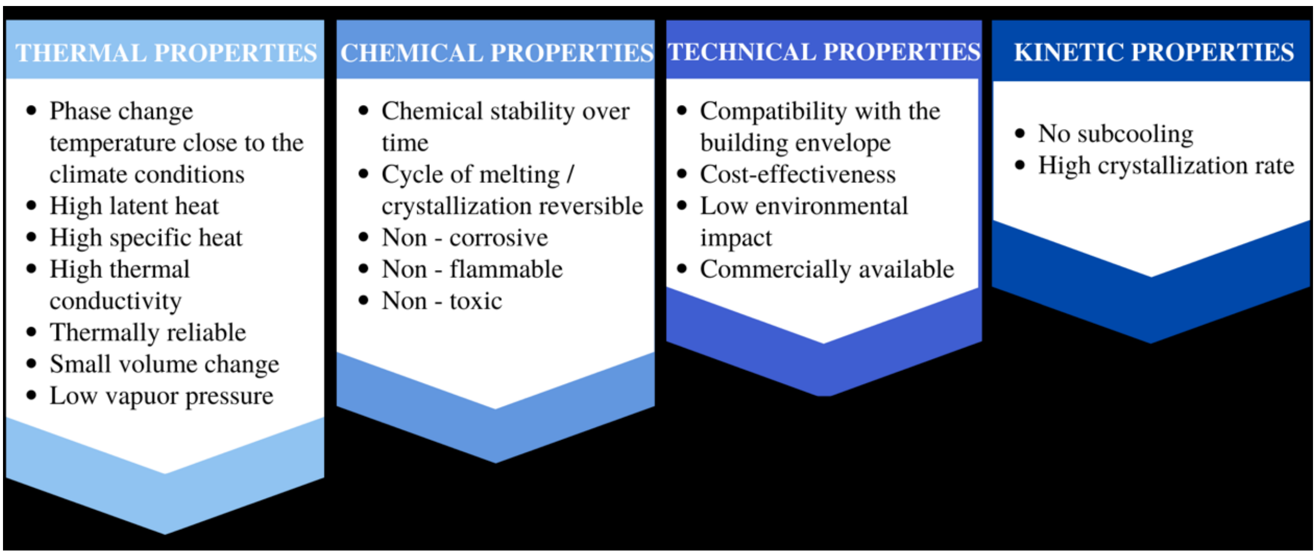


Figure 10. Criteria for selecting a suitable PCM for building materials.

In addition to the criteria given in Figure 10, some experimental calculations can also be relied upon to select a suitable PCM for the type of application. In [72], for example, a simple calculation is proposed that can determine the melting/crystallization temperature a PCM should have in a given context and also the thickness of the wall containing the PCM. A more modern tool for identifying the most appropriate PCM is algorithms. In recent years, several algorithms have been developed (e.g., Analytical Hierarchy Process (AHP), COmplex PRoportional Evaluation (COPRAS), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Technique for Order Performance by Similarity to an Ideal Solution (TOPSIS), ELimination and Choice Translating REality (ELECTRE), etc.) [73,74]. These algorithms can select a PCM from those available based on multi-criteria decision making. Therefore, this tool considers not only the target environmental conditions but also other factors concerning the properties of the PCM according to the priorities that are set at the beginning of the search.

5. Applications of Thermal Storage Technology in Buildings Using Phase Change Materials

Construction materials that employ thermal storage technology through the use of phase change materials can be applied in a wide variety of constructive solutions, whose working principle is shown in Figure 8. Thus, PCMs can be included in walls [75–79], ceilings [80–82], floors [83–85] and even in solar thermal systems [86–88]. It is also possible to choose different construction materials, such as: mortars [75,89–91], concrete [92–95], functionalized aggregates [96–100], naturally based materials [101–103], carbon-based materials [104–107], boards [108–111], bricks [77,112–114] and others, according to the specific needs of the building and the available budget for the intervention.

5.1. Mortars

The development of mortars incorporating PCM has attracted the attention of several researchers worldwide [54,75,76,89–91,115–119]. Several incorporation techniques and different types of PCM have been used. The incorporation of PCMs in mortars has also been developed, becoming one of the most used inclusion techniques [75,76,115–118]; it has, however very high raw material acquisition costs [59]. Cunha et al. [75,76,115,116] developed mortars based on gypsum, aerial lime, hydraulic lime and cement doped with different microcapsulated PCM contents: for each type of binder, a reference mortar without any PCM and mortars with 20%, 40% and 60% by weight of PCM as mortar aggregate were developed and characterized. The results of mechanical properties revealed a decrease in the mortars' flexural and compressive strengths, due to a high water/binder ratio which led to a greater porosity related to the incorporation of a higher PCM content. Regarding the thermal behavior, the same research team indicated that all PCM mortars reveal higher thermal regulation, due to the decrease in maximum temperature, increasing the minimum temperatures and lowering energy needs. Illampas et al. [91] used PCM microcapsules in cementitious repair mortars, producing a mortar without PCM microcapsules and three mortars with different PCM contents (5%, 10 and 20% by weight of the powder components). The study revealed that a higher PCM content in mortars originated an increase in the open porosity and a decrease in the flexural strength, compressive strength and elastic modulus, due to the lower strength and stiffness of the PCM microcapsules when compared to the aggregate particles. On the other hand, the thermal performance of the PCM mortars was improved due to the decrease in thermal conductivity and thermal diffusivity and increase in the specific heat capacity, which contributed to the attenuation and time shifting of temperature peaks.

Other studies present an alternative to the utilization of microencapsulated PCM, in order to decrease the PCM cost, due to the treatment that material suffers during the encapsulation. The utilization of a pure PCM, based on direct incorporation technique or immersion can be an alternative since the use of a non-encapsulated PCM causes a decrease in the production cost of the mortars [59].

Cunha et al. [54,90] developed cement mortars with pure PCM incorporation through the direct incorporation technique, demonstrating a decrease in the compressive strength with the presence of a higher PCM content, due to the delay in the cement hydration process. These studies also proved that the PCM did not move from the mortar matrix, being contained in the pores and coating the structural matrix of the mortars.

The immersion technique was approached by Lopez-Arias et al. [89], who developed three different mortars with different water/binder ratios (0.45, 0.55, 0.65) and consequently, different porosity. In this study, the PCM was added to the hardened structure of the mortars through the immersion technique and with resource to a vacuum application, during different periods of immersion (15 min, 1 h and 4 h). The test results showed that the mortars with higher porosity had a higher absorbed PCM content; on the other hand, it was observed that the PCM content increases with the higher immersion time of the samples in PCM. It was also possible to verify that a higher PCM content in the mortars resulted in a higher thermal conductivity and compressive strength. Thus, the samples with higher water/binder ratio (0.65) and 4 h of PCM vacuum immersion presented the most interesting behavior and higher PCM content.

5.2. Porous Aggregates

The necessity to prevent PCM from being dispersed in the main building material has made inclusion in porous aggregates increasingly common. This is done, as was seen in Section 4.2, through shape-stabilized or form-stable methods by direct or vacuum impregnation. Initially, expanded perlite (EP) [96,120], vermiculite [121,122], diatomite [123] and montmorillonite [124,125] were the most used porous aggregates.

Expanded perlite and vermiculite are widely used materials in building applications and are famous for their thermal insulation. Zhang et al. [126], developed a composite material based on EP and paraffin through the vacuum impregnation method. To improve the thermal conductivity of the final material, they added carbon nanotubes (CNTs), producing four different samples containing different CNTs mass fraction (0, 1.83, 3.62, 5.27 wt%). A complete characterization of these materials showed good chemical and thermal stability and a thermal conductivity significantly improved by CNTs that, consequently, enhanced the storage and release properties. In another work, Zhang et al. [97], proposed a new composite PCM made through the vacuum impregnation method as a potential PCM for building energy reserve. They used a mixture of lauric-palmic-stearic acid as PCM impregnating vermiculite as supporting matrix. The composite material demonstrated excellent chemical and thermal stability but low thermal conductivity. Adding 2 wt% of EG increased the thermal conductivity by 68%, going on to also improve the thermal and enthalpy properties of the final material. In a more recent work, Rathore et al. [66], prepared a composite PCM, with the aim to produce a PCM capable of regulating the indoor temperature of a building, using expanded vermiculite and EG and combining both with a commercial and low-cost PCM (i.e., OM37), using the vacuum impregnation. Good results of thermal and chemical stability are achieved in this work, as well as significant results achieved from the point of view of thermal performance: the realized PCM can regulate the internal temperature by lowering the temperature peaks. Costa et al. [98] prepared a form-stable based on diatomite-vermiculite and paraffin for cement mortars. Different amounts of PCM (5 to 25 wt%) were used. Again, characterization of the composite materials demonstrated improved thermal performance and the ability of the porous aggregates used to retain PCM.

In this paper [57], several porous materials used as a matrix to contain PCMs are presented. Nine porous materials are considered: kaolin, diatomite, sepiolite, montmorillonite, perlite, SiO_2, attapulgite, vermiculite and fly ash. They are all presented as suitable media to hold PCMs and then be incorporated into various applications that require temperature control. However, all these materials, before being used, require preparation to improve their absorbability, such as acid/alkali treatment, ionic exchange method, calcination or hydrothermal method, according to their physical and crystal structure. These treatments affect not only production time but also costs, and that is why some researchers have proposed new materials that are naturally porous, such as some types of stones. Frigione et al. [99,100] proposed a novel porous aggregate, called Lecce Stone (LS), a biocalcarenite composed mainly of $CaCO_3$ with a total open porosity of 30.33 $\pm$ 0.99%. Due to these porosimetric characteristics, LS was successfully impregnated with Poly-Ethylene Glycol (PEG) as PCM. The study of thermal properties showed that PEG, once incorporated into LS through vacuum impregnation, had characteristic temperatures and enthalpy suitable for incorporation into mortars for thermal control of buildings. This composite material (i.e., LS/PEG) also demonstrated excellent chemical stability and good thermal performance especially in cementitious mortars in a temperate climate, such as the Mediterranean [127]. Another virtuous aspect of this research is represented by the fact that the LS came from processing waste. In recent years, as a matter of fact, this trend of reusing waste materials as PCM carriers is growing. Uthaichotirat at al. [128] studied the thermal and sound properties of concrete containing highly porous aggregates from manufacturing waste impregnated with paraffin. They used autoclaved aerated concrete (AAC) coming from waste which are extremely interesting because they have a large content of voids (almost 80% of their volume). Therefore, they do not require any further processing to make them suitable as matrix. The presence of these porous materials impregnated with the PCM and used as aggregates in concrete shown improved compressive and flexural strength and improved thermal properties. However, as the amount of the PCM increased, the sound insulation decreased because of the porosity reduction with the presence of the PCM filling the pores.

5.3. Concrete

The utilization of PCM in concrete was also developed by several authors evaluating the properties in fresh and hardened state, with recourse to a different incorporation technique [92–94,129–132]. Different studies indicate different behaviors in mechanical terms. However, the positive influence of the PCM in the temperature control is attested by all, which influences the concrete heat of hydration or the environment in which the concrete was applied.

Most of the studies carried out focused on the incorporation of encapsulated PCM. The study of a PCM macroencapsulation solution in concrete was evaluated by several authors [92,129]. Cui et al. [92] adopted a PCM macroencapsulation solution in metallic capsules, in order to replace the aggregate in concrete reinforced with steel fibers. The effect of different contents of steel fibers and different thickness of the metallic macrocapsules (0.3 mm and 1 mm) were evaluated. The microcapsules used presented a diameter of 19 mm. The test results showed that the thermal conductivity and compressive strength of the concrete activated with the PCM macrocapsules increased with an increase in the steel fiber content and metallic macrocapsules thickness. Dong et al. [129] also developed a study in concrete with incorporation of PCM macrocapsules with 22 mm of diameter, observing that the PCM incorporation leads to a lower peak indoor air temperature and fluctuation of indoor temperature. However, a decrease in the compressive strength of the concrete doped with PCM was observed when the PCM macrocapsules content increased in the concrete mix.

The utilization of microencapsulated PCM solutions also attracted several researchers [93,130–132]. Cellat et al. [93] developed a PCM microcapsule coated with a capsule in polystyrene and a core with a eutectic mixture (capric acid and myristic acid). The PCM microcapsules were added to a different concrete mixture, allowing to observe that the PCM did not affect the hydration reaction; however, the peak temperature of fresh concrete in the first 40 h was lowered due to the absorption of heat by the PCM. A decrease in the concrete compressive strength with the PCM incorporation was also verified. Additionally, metal surfaces and concrete samples in contact with rebar were examined to determine the corrosion products, observing that the PCM incorporation did not affect the corrosive effect on metal surfaces in concrete. Jayalath et al. [130] also studied the properties of concretes with PCM microcapsule incorporation, as replacement of fine aggregate. The test results allowed to observe a decrease in the thermal conductivity and an increase in the heat capacity due to the PCM incorporation. However, a loss in the compressive strength was also observed, due to the PCM low density when compared with the fine aggregates.

D'Alessandro et al. [94] developed a concrete solution with incorporation of two types of PCM (microcapsules and macrocapsules). Several concrete compositions with different PCM microcapsules and macrocapsules contents were developed. It was possible to observe that the PCM incorporation produced a concrete with higher thermal performance. As expected, the PCM incorporation resulted in a decrease in the compressive strength, as mentioned for other studies. However, this decrease in the mechanical performance does not compromise their use as structural material.

However, the costs of acquiring and developing PCM nano, micro or macrocapsules continue to be quite high, especially when applied in concrete, taking into account the enormous consumption of raw materials. Thus, a new study has emerged in which pure PCM (non-encapsulated PCM) is incorporated into construction and demolition waste, the waste being used as a substitute for natural aggregate for the concrete production [95].

5.4. Carbon Based Materials

Thermal conductivity is a determining factor in evaluating the thermal performance of PCMs. The magnitude of thermal conductivity determines the rate of energy storage/consumption and therefore affects energy utilization efficiency. Normally, carbon materials have high thermal conductivities, so their use as a support material for PCMs is an effective way to improve the thermal conductivity of PCMs [101,133]. Carbon-based materials such as graphene, expanded graphite, carbon nanotubes, carbon nanofibers and carbon nanosheets with high thermal conductivity can effectively increase the thermal transfer rate of PCMs [133].

Porous carbon-based materials are varied and can be obtained at different costs; for example, carbon fiber and expanded graphite are cheaper compared to other porous materials such as metal foam or porous ceramics [133]. Thus, the studies developed based on carbon materials are based on different materials. However, the high cost of these materials still limits their potential application.

Some authors adopted graphite as support material to improve the thermal properties of PCM [104,134–137]. Graphite is one form of carbon, is black and soft, and is constituted by a planar and multi-layered structure. The carbon molecules in each layer are systematically arranged in the form of a honeycomb [133]. Karthik et al. [104] developed a composite consisting of paraffin wax and graphite using a low-cost and small-scale process, observing an increase in the thermal conductivity when compared to the paraffin wax. The obtained results also demonstrated a composite compressive strength higher than the graphite foam. The developed composite can also be considered as a potential material for various thermal energy storage applications in buildings, vehicles and solar thermal harvesting.

Graphene is a crystal with a unique thermal conductivity, considered the mother of all carbon materials due to its superior thermal and mechanical properties [133]. Thus, it has become an interesting candidate for phase change material applications [105,138–141]. Mehrali et al. [105] studied a composite material using a palmitic acid as a PCM impregnated by vacuum in graphene oxide as supporting material. The thermal test showed that the PCM composite material exhibits good thermal reliability and chemical stability. The PCM composite thermal conductivity increases about three times. Thus, the composite material was considered adequate for thermal energy storage applications. However, even though it has numerous advantages related to its thermal properties, graphene is not widely used due to its high cost, which can make its practical applications unsustainable.

Some works have also been developed using carbon nanotubes [106,142–145]. These materials are extremely thin and long cylindrical structures, consisting of carbon atoms. There are two main types of carbon nanotubes: single-walled and multi-walled. Single-walled nanotubes consist of just one layer of graphene (a flat sheet of carbon atoms arranged in a hexagonal lattice), while multi-walled nanotubes contain multiple layers of graphene stacked on top of each other. These materials are synthesized at high temperatures, usually between 600 °C to 1000 °C, whose properties can be affected by impurities [133]. Yang et al. [106] created a composite material composed by stearic acid as PCM and carbon nanotubes as porous material support, evaluating their thermal performance. The results allow to conclude that the phase change temperatures varied slightly while the latent heat decreased with the increased carbon nanotubes content. On the other hand, the thermal conductivity of the composites is higher than the pure PCM, which indicates the material's potential for thermal management.

Carbon nanofibers are materials composed of thin carbon fibers, with diameters ranging from 1 to 100 nanometers. These materials present high mechanical strength, excellent electrical and thermal conductivity, low density, large surface area and high chemical stability. Liu et al. [107] prepared a new composite material using steric acid as a PCM and carbon fiber as a nanoparticle. The results of this study allow to observe high latent heat and good thermal and chemical stabilities of the composite material even submitted to 200 melt/freeze cycles, which indicates a potential application for solar energy storage application such as solar heat storage tank.

5.5. Naturally Based Materials

The search for inexpensive, easily available and environmentally friendly composite materials with high enthalpy is still a great challenge; thus, the incorporation of PCM in natural materials has been attracting the interest of the academic community. Considering the high cost of carbon-based materials, some researchers carbonized natural materials in order to obtain biological porous carbon to combine with PCM [146–149]. Several solutions based on various natural materials have been developed such as the application of PCM in flower stems [101,150], potatoes and radishes [149], corn stalks [146], rice straw [103,147], watermelon rinds [148], wood [151–154] and earth construction [102].

Wen et al. [146] used stearic acid as phase change material; this is a saturated fatty acid abundant in nature, obtained from different vegetable and animal oils and fats with low acquisition cost. In this study, carbonized maize straw was used a low-cost matrix, impregnated by vacuum. Corn straw is a porous waste material of an economical nature, since corn is one of the most planted crops in the world, existing in large quantities. The test results revealed a good chemical compatibility between stearic acid and the maize straw, leading to a higher thermal conductivity. Zhang et al. [103] developed a study based on the PCM incorporation into a rice carbonized matrix, once again a very implemented culture with large quantities available. The selected PCM was a eutectic mixture based on palmitic and lauric acid, two natural compounds very abundant in nature. The developed composite material presents a potential to be used in construction industry, namely, in building envelopes, due to their high thermal energy storage and good thermal and form stability. Wang et al. [101] prepared form-stable composite PCMs for building temperature regulation based on daisy stem as support material. The selection of this raw material was justified by the high absorption capacity of daisy stems. The presented results allowed to observe that the PCM composites presented a good thermal reliability without enthalpy alteration after a high number of heating and cooling cycles. Regarding thermal efficiency, a decrease in temperature fluctuation was observed and on the recorded differential between the interior and ambient temperature of the cardboard test cells.

Even adopting low-cost and widely available natural materials, biomass-based materials require additional treatments, which normally require high energy consumption, compromising the energy gains obtained with their application. Thus, other studies have emerged based on the incorporation of PCM into natural materials without the need for prior treatment. Cunha et al. [102] developed different compressed earth blocks with direct incorporation of different content of pure and non-encapsulated PCM. The soil used was collected in the north region of Portugal and was stabilized with a lower content of Portland cement. The test results showed that the incorporation of PCM in compressed earth blocks can be carried out successfully, without danger of PCM leakage. The PCM incorporation leads to a decrease in water absorption, due to the partial or total occupation of earth blocks by the PCM; however, a decrease in the mechanical behavior (compressive strength) was also observed related to the lower water content added during the mixture procedure, which can negatively affect the cement hydration.

5.6. Boards

One of the earliest applications of PCMs in construction was involving boards (plaster board or gypsum board). The main reasons of this application were related to the wide use of these boards in buildings (due to their low cost) and for their location (in the interior side of the wall) in the building system [155]. In this work, A. Oliver [109], studied the thermal behavior of a gypsum board containing 45 wt% of a commercial micro-capsulated PCM (Micronal DS 5001X, produced by BASF, Ludwigshafen, Germany) with a phase change temperature around 26 °C and an enthalpy of about 110 J/g. It was concluded that the panel with the presence of PCM was able to store five times more energy than a thermal brick wall, nine times more energy than a standard brick wall and three times more energy than a normal gypsum board (without the PCM). This was one of many papers that highlighted the advantages of the use of PCMs in boards. Kuznik et al. [156] performed a full-scale experiment to evaluate the presence of a PCM in plasterboards. These were applied to the walls and ceiling of an office, and that room was monitored for one year. Similarly, another identical room but without the PCM was monitored for the same period. A commercial paraffin-based microencapsulated PCM was employed (ENERGAIN by the Dupont de Nemours Society). The results demonstrated an improvement in thermal comfort.

Lai et al. [110] evaluated the incorporation of micro-encapsulated PCM into gypsum board and then they studied the physical properties, heat transfer and thermal storage behavior. A commercial paraffin-based PCM (MPCM 28-D by Microtek Laboratories, Inc., Moraine, OH, USA) with a melting point around 28 °C and a melting heat of about 180–195 J/g was employed. In this work, different experimental test cells were prepared using different PCM content (23%, 30% and 40% of mass fraction), and different temperatures (hot and cold) were used to investigate the thermal performance of the gypsum boards. Numerical and experimental simulations were performed. The results showed that increasing the content of PCM does not necessarily increase its energy storage capacity. In fact, in this case, the best percentage of PCM was at 30%. In addition, it was noted that at low temperatures the phenomenon of supercooling was observed while at temperatures close to the melting temperature of PCM, an improvement in thermal properties was recorded. More recently, Mourid et al. [111], conducted a full-scale experimental work integrating a commercial micro-capsulated paraffin-based PCM (Energain man, produced by BASFufactured by DuPont™) into wallboards. This experiment was performed in Morocco, which is characterized by a Mediterranean climate, in the winter and spring seasons. The wallboards had been placed in different ways within the different rooms (walls or ceilings). The results obtained showed an interesting aspect: the boards placed on the ceiling performed better than the others on the walls. This should make it clear that the placement of a PCM in each environment must be customized, taking into account the specific thermal properties of a building (air passage, exposure to the sun, number of inhabitants, amount and height of buildings around, etc.).

5.7. Bricks

Numerical and experimental research have found that inserting PCMs into bricks increases the thermal mass and improves the thermal properties of the walls, ensuring the indoor comfort while saving energy. Gao et al. [112] found that, usually, PCMs are inserted into bricks following two techniques: macro-encapsulation and form-stable. The amount of PCMs that can be inserted using these two techniques is around 16.44% and 20.55%, respectively.

In the literature, there are several experimental works concerning the study of PCMs in bricks, and the experiments almost always involve the construction of scaled test cells placed in climatic chambers in which certain climatic conditions are simulated. Zhu et al. [113], studied the inner surface index of a brick wall with and without the PCM. This study demonstrated an attenuation of the internal surface temperature amplitude for that wall added with the PCM brick. This attenuation was 3.8–4.4 times less that of the reference brick wall; the lag time ratio of the internal surface was 8–12 times that of the reference brick wall. Vicente et al. [114] prepared three different specimens and tested them in a climatic chamber. The first specimen was the reference (M1), the second was with the PCM (M2) and the third was with the PCM and insulation material (M3). The results showed that the maximum peak of the temperature was decreased by about 50% (using the M2) and 80% (using M3) compared with the reference brick wall; the time lag of the brick walls with PCM was increased by 2 h compared with the wall without the PCM. Saxena et al. [77] incorporated two different commercial PCM (Eicosane and OM35) into hollow brick using the typical climatic conditions of Delhi during summer. They recorded a reduction of about 5–6 °C compared to the conventional brick wall and an energy saving of 8% using the Eicosane PCM and of 12% using the OM35. Abbas et al. [157] performed a test using natural conditions outdoors consisting of two identical rooms using PCM bricks. The results illustrated that the inner surface temperature of the brick wall with the PCM was reduced of about 4.7 °C, the time lag was increased by 2 h, the temperature fluctuation was reduced by 23.84 % and the damping factor was 70% compared with the reference wall. In general, the literature that has been developed on this topic reports that the application of PCMs in brick walls should be developed because it is believed to be an excellent method of incorporating PCMs into a building. Moreover, studies should be conducted based on actual climatic conditions, and more study of these full-scale applications is desired.

5.8. Solar Thermal Systems

Nowadays, photovoltaic panels for electricity generation have become a common practice all over the world due to their contribution to decreasing electrical energy consumption. Many countries in the European Union, namely, Portugal, have created funding programs in order to economically support families to be able to install this type of systems in their buildings [158]. Thus, worldwide there was an increase in the installation of photovoltaic panels of about 12% between 2018 and 2019; however, an increase of more than 10 times the currently installed photovoltaic capacity is expected by 2050. However, the lifetime of these systems can be reduced due to the high incident solar energy, which causes an increase in the panels' operating temperature. The temperature surface of the photovoltaic panel can reach temperatures of 40 °C above the environmental temperature [159]. Thus, it has been necessary to find ways to refrigerate and regulate the photovoltaic panels' temperature. PCM applications can be seen as a suitable solution [3].

The application of PCMs in photovoltaic panels requires specific characteristics quite different from those required for applications in traditional building materials. Thus, several researchers, especially in recent years, have been dedicated to studying the transition temperature, which is a dominant aspect for photovoltaic panels' thermal management to achieve high electrical and thermal power [160–162]. For an effective management, the transition temperature of the PCM must be lower than the photovoltaic panel temperature, being also limited by the summer ambient temperature during the night and by the panel temperature during the winter [163,164]. Hasan et al. [86] used two different PCMs, a eutectic mixture of capric–palmitic acid and a salt hydrate (calcium chloride hexahydrate) applied to a metallic PCM container attached to the back of the photovoltaic panel. Three different panels (reference, capric-palmitic panel and slat hydrate panel) were placed outdoors facing south in Dublin, Ireland and Vehari, Pakistan, enabling the analysis of cold and hot climatic conditions. The test results and simulations allow to observe a better performance of the salt hydrates when compared to the eutectic mixture. Salt hydrate PCM coupled to the photovoltaic panel successfully reduced panel temperature by 10 °C in Ireland and 21.5 °C in Pakistan. The two PCMs used conducted a panel's higher performance in hot and stable climatic conditions. However, applications other than the cooling panel systems have also been studied. Sharma et al. [87] evaluated the influence of the PCM's presence on the electrical efficiency of photovoltaic panels, observing that the PCM use increases the electrical efficiency of the system by 7.7%.

The low thermal conductivity of PCMs is currently still a challenge regarding exploring these materials as a solution for thermal regulation of photovoltaic panels. Thus, Abdulmunem et al. [88] studied the incorporation effects of carbon nanotube nanoparticles as additives to the PCM and copper foam matrix on the PV panel performance. The test results allow to observe that the carbon nanotubes' incorporation within the PCM and copper foam greatly improved the effective thermal properties of the material and consequently the electrical performance of the panels, when compared to the panels without passive cooling materials.

Other applications in solar thermal systems can arise, combining for example the use of PCM with solar thermal water heating systems, in order to increase the thermal storage capacity of solar energy for long periods of time [165–167], or even solar dryers for application in other industries, such as the food industry, in the drying of fruits and vegetables [168]. Huang et al. [167] performed a numerical analysis and experimental test of a solar water heating system, developed based on the use of capillary pipes placed above and below a prefabricated concrete skeleton with vacancies occupied by PCM macrocapsules. A reference model and a PCM model were simulated, indicating that the floor's energy storage capacity with PCM is greatly enhanced with the benefit of saving water tank space.

Table 2 summarizes the main information about the various works presented earlier.

Table 2. Summary of PCM incorporation in construction material studies.

Study	PCM Type	PCM Properties	PCM Incorporation Technique	Construction Material	Main Results
Lopez-Arias et al. [89]	Organic—Paraffin	Temperature transition of 70 °C; Enthalpy of 120 J/g; Density of 0.968 g/cm^3.	Immersion	Mortars	Higher PCM content leads to a higher thermal conductivity and higher compressive strength.
Cunha et al. [75,76]	Organic—Paraffin	Temperature transition of 24 °C; Enthalpy of 150 kJ/kg; Density of 880 kg/m^3.	Microencapsulation	Mortars	Higher PCM content leads to a higher water/binder ratio, lower flexural and compressive strength. However, a decrease in extreme temperatures and a decrease in heating and cooling needs was observed.
Cunha et al. [90]	Organic—Paraffin	Temperature transition of 22 °C; Enthalpy of 200 kJ/kg; Density of 760 kg/m^3.	Direct incorporation	Mortars	Higher PCM content leads to a lower water/binder ratio, a higher liquid/binder ratio, lower compressive strength and better thermal performance, due to the decrease in heating and cooling needs.
Illampas et al. [91]	Organic—Paraffin	Temperature transition of 37 °C; Enthalpy of 190 J/g.	Microencapsulation	Mortars	Higher PCM content leads to an increase in the open porosity and a decrease in the flexural strength, compressive strength and elastic modulus. The thermal performance of the PCM mortars was improved, decreasing the thermal conductivity and thermal diffusivity, increasing the specific heat capacity and attenuation of the temperature peaks.

Table 2. *Cont.*

Study	PCM Type	PCM Properties	PCM Incorporation Technique	Construction Material	Main Results
Kheradmand et al. [117]	Organic—Paraffin	Temperature transition of 26 °C; Enthalpy of 110,000 J/kg; Apparent density of 350 kg/m^3.	Microencapsulation	Mortars	Higher PCM content leads to an increase in water absorption and a decrease in the compressive strength.
Shadnia et al. [118]	Organic—Paraffin	Temperature transition of 28 °C; Enthalpy of 180–195 kJ/kg; Density of 900 kg/m^3.	Microencapsulation	Mortars	Higher PCM content leads to a decrease in the compressive strength. The PCM incorporation can effectively reduce the transport of heat through geopolymer mortar.
Aguayo et al. [119]	Organic—Paraffin	PCM-M temperature transition of 24.3 °C and enthalpy of 100 J/g. PCM-E temperature transition of 23.4 °C and enthalpy of 159 J/g.	Microencapsulation	Mortars	Higher PCM-E content leads to an increase in the compressive and flexural strengths until a certain replacement level of PCM. Higher PCM-E content leads to an decrease in the compressive and flexural strengths until a certain replacement level of PCM-M.
Rathore et al. [66]	Organic—Paraffin	Temperature transition of 38.23 °C and enthalpy of 206.32 J/g for the fusion process; Temperature transition of 29.40 °C and enthalpy of 229 J/g for the freezing process	Form-stable through vacuum impregnation	Porous aggregates	They used EV as main supporting matrix and EG to act both as a support matrix and to improve thermal conductivity. The latter was enhanced, indeed; the leakage phenomenon was avoided and the thermal performance was significantly appreciable.
Frigione et al. [99,100]	Organic—Polymer	Temperature transition of 42.8 °C and enthalpy of 129.3 J/g for the fusion process; Temperature transition of 23.6 °C and enthalpy of 129.8 J/g for the freezing process	Form-stable through vacuum impregnation	Porous aggregates	The porous matrix was a natural stone from waste production. The composite form-stable PCM was used as aggregate for mortar based on different binders. A decrease in the flexural and compressive strength was detected.
Zhang et al. [126]	Organic—Paraffin	Temperature transition of 44.32 °C and enthalpy of 177.54 J/g for the fusion process; Temperature transition of 48.30 °C and enthalpy of 181.31 J/g for the freezing process	Form-stable through vacuum impregnation	Porous aggregates	They used EP as supporting matrix and added carbon nanotubes to improve thermal conductivity. The final material showed good chemical and thermal stability.
Cui et al. [92]	Organic—Paraffin	Temperature transition of 23 °C; Enthalpy of 188 kJ/kg; Density at solid state of 833.8 kg/m^3; Density at liquid state of 786.7 kg/m^3.	Macroencapsulation	Concrete	Higher PCM content leads to an increase in water absorption, thermal conductivity and compressive strength.
Cellat et al. [93]	Eutetic Mixture (capric acid and myristic acid)	Temperature transition of 26 °C; Entalpy of 155.44 J/g.	Microencapsulation	Concrete	The PCM microcapsules' incorporation did not affect the hydration reaction in concrete; however, the peak temperature of fresh concrete decreases due to the absorption of heat by the PCM. The PCM addition leads to a decrease in compressive strength and does not affect the corrosive effect on metal surfaces in concrete.

Table 2. *Cont.*

Study	PCM Type	PCM Properties	PCM Incorporation Technique	Construction Material	Main Results
D'Alessandro et al. [94]	Organic—Paraffin	Temperature transition of 18 °C; Microcapsules particle size between 14 and 24 µm; Macrocapsules particle size between 3 and 5 mm.	Microencapsulationand macroencapsulation.	Concrete	Higher PCM content leads to an increase in the thermal performance and a decrease in the compressive strength.
Jia et al. [95]	Organic—Paraffin	Temperature transition of 22 °C; Enthalpy of 200 kJ/kg; Density of 760 kg/m^3.	Direct incorporation	Concrete	Higher PCM content leads to a decrease in the compressive strength.
Dong et al. [129]	Organic—Paraffin	Temperature transition of 29.2 °C and enthalpy of 246.4 J/g for the fusion process; Temperature transition of 22.7 °C and enthalpy of 249.7 J/g for the freezing process.	Macroencapsulation	Concrete	Higher PCM content leads to an increase in the thermal performance and a decrease in the compressive strength.
Jayalath et al. [130]	Organic—Paraffin	Temperature transition of 23 °C; Entalpy of 100 kJ/kg; Density 250–350 kg/m^3	Microencapsulation	Concrete	Higher PCM content leads to an increase in the thermal performance and a decrease in the compressive strength.
Karthik et al. [134]	Organic—Paraffin	Entalpy of 206 J/g; Density of 0.91 g/cm^3; Thermal conductivity at 25 °C of 0.24 W/mK.	Form-stabilization	Carbon materials—Graphite foam	PCM incorporation leads to an increase in the thermal conductivity and compressive strength.
Mehrali et al. [105]	Organic—Non-paraffin	Temperature transition (melting process) of 61.14 °C; Entalpy (melting process) of 202 kJ/kg; Temperature transition (freezing process) of 59.84 °C; Entalpy (freezing process) of 208.87 kJ/kg.	Form-stabilization	Carbon materials—Graphene oxide	The PCM composite material exhibits good thermal reliability, good chemical stability, and higher thermal conductivity.
Yang et al. [106]	Organic—Paraffin	Temperature transition (melting process) of 69.45 °C; Entalpy (melting process) of 210.9 kJ/kg; Temperature transition (freezing process) of 66.96 °C; Entalpy (freezing process) of 211.9 kJ/kg.	Form-stabilization	Carbon materials—Nanotubes	Higher carbon nanotube content leads a slight change in temperature transition and a decrease in enthalpy. The thermal conductivity of PCM composite is higher than the pure PCM.
Liu et al. [107]	Organic—Non-paraffin	Temperature transition of 68 °C; Enthalpy of 229.4 J/g.	Form-stabilization	Carbon materials—Nanofibers	High latent heat and good thermal and chemical stabilities of the composite material even submitted to 200 melt/freeze cycles.
Wang et al. [101]	Organic—Paraffin	Temperature transition of 40.1 °C; Entalpy of 213.6 J/g.	Form-stabilization	Natural materials—Daisy stems	Good PCM thermal reliability and higher thermal efficiency with the PCM composites' application, due to the decrease in temperature fluctuation inside the test cells.
Cunha et al. [102]	Organic—Paraffin	Temperature transition of 22 °C; Enthalpy of 200 kJ/kg; Density of 760 kg/m^3.	Direct incorporation	Natural materials—Compressed earth bricks	Higher PCM content leads to a decrease in the water absorption, compressive strength and modulus of elasticity.

Table 2. *Cont.*

Study	PCM Type	PCM Properties	PCM Incorporation Technique	Construction Material	Main Results
Zhang et al. [103]	Organic—Non-paraffin	Temperature transition (melting process) of 35.7 °C; Entalpy (melting process) of 171.8 J/g; Temperature transition (freezing process) of 28.2 °C; Entalpy (freezing process) of 160.5 J/g.	Form-stabilization	Natural materials—Carbonized rice	High thermal energy storage and good thermal and form stability.
Wen et al. [146]	Organic—Non-paraffin	Temperature transition (melting process) of 69.23 °C; Entalpy (melting process) of 208.16 J/g; Temperature transition (freezing process) of 65.78 °C; Entalpy ((melting process) of 207.44 J/g.	Form-stabilization	Natural materials—Carbonized maize straw	Good chemical compatibility between PCM and carbonized maize straw matrix and higher thermal conductivity.
Liu et al. [148]	Inorganic—Salt hydrates	Temperature transition of 63.2 °C; Enthalpy of 255.9 J/g.	Form-stabilization	Natural materials—Watermelon rind	High thermal conductance, good shape stability and excellent thermal cycle stability.
Liang et al. [151]	Organic—Non-paraffin	Temperature transition (melting process) between 45.8–63.7 °C; Entalpy (melting process) between 96.6–144.7 J/g; Temperature transition (freezing process) between 22.2–39.6 °C; Entalpy (freezing process) between 77.3–167.3 J/g.	Immersion	Natural materials—Wood flour	Good thermal reliability and chemical stability.
Oliver [109]	Organic—Paraffin	Temperature transition of 26 °C; Enthalpy of 110 J/g.	Microencapsulation	Gypsum Boards	This board with the presence of PCM was able to store five times more energy than a thermal brick wall, nine times more energy than a standard brick wall and three times more energy than a normal gypsum board (without the PCM).
Kuznik et al. [156]	Organic—Paraffin	Temperature transition of melting process 13.6 °C and enthalpy of 107.5 J/g. Temperature transition of freezing process 23.5 °C and enthalpy of 104.5 J/g.	Microencapsulation	Gypsum Boards	The gypsum board with PCM was applied into the walls and ceiling of an office. Monitoring was performed for one year and compared to another identical room without the PCM. The results demonstrated an improvement in thermal comfort.
Vicente et al. [114]	Organic—Paraffin	Temperature transition of 18 °C; Enthalpy of 134 J/g	Microencapsulation	Bricks	The bricks containing the PCM macrocapsules were able to decrease by about 50% the maximum peak of temperature and to reach a time lag of 2 h compared with the wall without the PCM.

Table 2. *Cont.*

Study	PCM Type	PCM Properties	PCM Incorporation Technique	Construction Material	Main Results
Abbas et al. [157]	-	Temperature range of 38–43 °C for the fusion process and temperature range of 43–37 °C for the freezing process; enthalpy of 174 J/g	Microencapsulation	Bricks	The thermal performance was studied in a natural outdoor environment. The results illustrated that the brick wall with the PCM reduced by about 4.7 °C the maximum peak of temperature, increased the lag time by 2 h and reduced the temperature fluctuation by 23.84% compared with the reference wall.
Hasan et al. [86]	Eutetic mixture (capric acid and palmitic acid) and a salt hydrated	Eutectic mixture: - Temperature transition of 22.5 °C; - Enthalpy of 173 kJ/kg. Salt hydrated: - Temperature transition of 29.8 °C; - Enthalpy of 191 kJ/kg.	Macroencapsulation	Solar thermal systems	The PCM decreased the photovoltaic panel temperature.
Sharma et al. [87]	Organic—Paraffin	Temperature transition of 42 °C; Enthalpy of 165 kJ/kg.	Macroencapsulation	Solar thermal systems	The PCM increased the electrical efficiency of the photovoltaic panel.
Abdulmunem et al. [88]	Organic—Paraffin	Temperature transition of 59.01 °C; Enthalpy of 154.42 J/g	Macroencapsulation	Solar thermal systems	The incorporation of carbon nanotubes nanoparticles as additives to the PCM increased the average electrical efficiency of the photovoltaic panels.
Huang et al. [167]	Organic—Non-paraffin	Temperature transition of 29.3 °C; Enthalpy of 162 kJ/kg.	Macroencapsulation	Solar thermal systems	The use of the PCM as a composite energy storage layer in a solar water floor heating system greatly enhanced heat storage capacity of the floor, saving water tank space.

6. Technology Cost Analysis

The cost analysis of this type of thermal storage technology is still an area under development, taking into account the diversity of external temperature laws and the diversity of constructive solutions with PCM integration, being able to vary the type of PCM used, its content, incorporation technique and location in the constructive solution. Thus, the number of existing studies that take an approach in terms of cost analysis is much lower than the number of studies developed in which the various additive solutions with PCM are tested in physical, mechanical and thermal terms.

Gholamibozanjani and Farid [169] constructed two identical test cells, with external dimensions of 2.7 × 2.7 × 2.7 m^3. In one test cell, an air-PCM heat storage unit was installed (active thermal storage system) and in the other, the PCM was integrated into the wallboards (passive thermal storage system). It was observed that the test cell with air-PCM heat storage unit consumed less energy, saved more costs and maintained comfortable conditions inside. However, the reduction in cost was not proportional to the decrease in energy consumption. On one of the analyzed days, a reduction of 20% in energy consumption corresponded to a reduction cost of 32%. It was also possible to verify that the active thermal storage system solution was more efficient than the passive thermal storage system solution. Cunha et al. [76] estimated the energy consumption per month and the cost related to the energy consumption of small test cell coating with different mortars based on different binders and activated with microencapsulated PCM. It was observed that the PCM use suppressed the heating and cooling needs in typical spring and autumn months in the north part of Portugal. The results allow to conclude that mortars with PCM incorporation lead to a cost decrease higher than 52% for all binders analyzed. M'hamdi et al. [170] studied the influence of using different PCM types in different types of buildings located in three different climatic areas in the north of Africa. An environmental and economic analysis was performed showing that the PCM utilization can reduce by 10% the energy cost and by 707 kg/year the carbon dioxide emissions. Panayiotou et al. [171] studied the PCM influence in the Mediterranean region. The energy savings achieved by PCM incorporation were between 21.7 and 28.6%. However, for the PCM combined with a common thermal insulation topology, the energy savings per year were 66.2%. A Life Cycle Cost analysis showed that the PCM solution presented a payback period of 14 years, while the payback period of the combined solution was reduced to 7 years.

There are only a very limited number of studies in which economic analyses are carried out [76,172–175]. Mi et al. [172] developed one of the only studies which used a dynamic payback period concept, considering concepts such as the money time value. The authors compared the obtained values for the dynamic payback period with the static payback period for different discount rate levels.

The cost-effectiveness of constructive solutions with PCM is highly sensitive to inflation and discount rates, as these solutions are more economical as the inflation rate increases and the discount rate decreases [175]. Thus, due to the wide variation in inflation rates currently being experienced in Europe, it is quite difficult to establish specific conclusions about the cost analysis of these types of solutions.

7. Conclusions

In recent years, especially in the last 10 years, research in the area of phase change materials has evolved a lot, largely due to the enormous environmental and economic challenges that the world has been going through. The political measures implemented worldwide, but especially in Europe, have also been a driving force to increasingly seek more sustainable and efficient construction solutions based on thermal storage technologies.

Currently, there are several possibilities for incorporating PCMs in construction materials, based on different incorporation techniques. However, it is important to note that a detailed study on the type of PCM to be incorporated must be carried out in advance based on the problems related to the incorporation of PCMs in building materials and the criteria for PCM selection to be applied to buildings.

So far, the form-stable method turns out to be the most versatile one because it is only necessary to have a porous material as a substrate and to impregnate it with any PCM (according to the type of application intended for). However, it would be necessary to reduce additives used to improve the properties of the PCM because the consequence is the reduction of the PCM amount.

This article discussed the possibilities of incorporating PCMs in mortars, concrete, porous aggregates, carbon-based materials, naturally based materials, boards, brick and solar thermal systems, as well as an approach to the economic analysis of the application of this type of technology. Despite the various advances in the development of thermal storage technology using phase change materials, some issues still require further investigation and others need to be investigated, namely:

- Applications of constructive solutions for the exterior of buildings;
- Development of economic analysis;
- Development of life cycle analysis of constructive solutions.

Studying the thermal behavior of a PCM in the real world contributes greatly to the understanding of these materials. Therefore, it is recommended as part of future development that more full-scale experiments be performed.

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