

A Review on the Economic Assessment of Integrating Macro-Encapsulated Phase Change Material in Building Envelopes

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ABSTRACT: The worldwide energy crisis has made energy-saving a topic of concern in almost every country. Previous research has explored the use of thermal energy storage materials (TES), such as phase change materials (PCMs), as an effective energy-saving technique. Among various immersion techniques, macro-encapsulation has proven to be efficient, safe, and convenient. However, choosing the right PCM system can be complicated due to the variety of available PCM types, encapsulation materials, and encapsulation shapes. Moreover, while macro-encapsulated PCM systems are efficient, their feasibility depends on several factors, including energy prices, economic situation, and climatic conditions. Therefore, this research aims to provide a comprehensive overview to help create a deeper understanding of the design and application of macro-encapsulated PCM systems. It explains the different types of PCM, encapsulation materials, and encapsulation shapes, guiding the selection for the most appropriate system regarding the surrounding environment. Additionally, it aims to present a guideline for conducting feasibility studies on energy-saving systems such as PCM. A total of 80 research papers covering the intersection between the thermal performance of PCM and the economic assessment have been categorized, studied, and analyzed in order to identify the most accurate method of assessing the system's feasibility. By providing a base knowledge regarding the various types of each element of the system and the factors that govern the selection of each, this research will help engineers appropriately design the system. In addition, providing a detailed guideline to the assessment of the system shall aid the decision makers in determining the system's feasibility which encourages its application. Finally, the research investigates and addresses the key issues for future studies.

Keywords: Thermal energy storage material, Phase change materials, Thermal performance, Economical assessment, Energy savings, Feasibility study.

مراجعة على التقييم الاقتصادي لدمج المواد المغلفة متغيرة الطور في اغلفة المباني

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المستخلص: في ظل أزمة الطاقة العالمية؛ تعتبر أساليب حفظ الطاقة موضع اهتمام من العالم اجمع. فقد اختبرت العديد من الأبحاث السابقة إمكانية استخدام مواد تخزين الطاقة الحرارية مثل المواد متغيرة الطور كتقنية لحفظ الطاقة. ومن بين طرق متعددة لدمج المواد متغيرة الطور في المباني، اثبتت تقنية التغليف الدقيق فعاليتها وسهولتها وملائمتها. على الرغم من ذلك، اختيار النظام الأمثل يمكن ان يكون معقد نتيجة لتعدد الأنواع المتاحة من المواد متغيرة الطور، بالإضافة الى مواد وأشكال التغليف المختلفة. وعلى صعيد اخر، فإن التقييم الاقتصادي لمثل هذه المواد يعتمد على عدة عوامل مثل أسعار الكهرباء، والوضع الاقتصادي للبلد، والظروف المناخية. وبالتالي، فإن هذا البحث يهدف الى تقديم مراجعة عامة للمساعدة في فهم تصميم وتطبيق المواد متغيرة الطور ومدى قابلية تطبيقها اقتصادياً. فيتناول البحث شرح وتقديم العوامل المختلفة المؤثرة على اختيار نوع المادة متغيرة الطور، بالإضافة الى مادة وشكل التغليف، وعلاقة كل ما سبق بالظروف المناخية. بالإضافة الى تقديم مقترح يهدف الى التقييم الاقتصادي الدقيق لدمج هذه المواد في اغلفة المباني. ولتحقيق هذا الهدف، فقد تم مراجعة وتصنيف 80 بحث علمي يغطيان كلا من الأداء الحراري للمواد متغيرة الطور والتقييم الاقتصادي لها، وذلك بهدف تحديد الطرق الأكثر دقة لتقييم الجدوى الاقتصادية من استخدام هذه المواد. وكنتيجه لهذا البحث، فقد تم تقديم قاعدة علمية توضح العناصر المختلفة بداخل نظام المواد متغيرة الطور، والعوامل المختلفة التي تؤثر على اختيار كلا منهم. وبهذا فإن هذا البحث يُمكن المهندسين المتخصصين من تصميم نظام مناسب. بالإضافة الى ذلك، فقد قدم البحث توجيهات مفصلة لتقييم النظام المستخدم اقتصادياً، مما يساعد متخذي القرار على تحديد الجدوى الاقتصادية منه وبالتالي التشجيع على استخدامه. وفي النهاية، تم تقديم مقترحات للنقاط الرئيسية التي تمثل مجالاً للأبحاث المستقبلية.

الكلمات المفتاحية: مواد تخزين الطاقة الحرارية، المواد متغيرة الطور، الأداء الحراري، التقييم الاقتصادي، حفظ الطاقة، دراسة الجدوى.

1. Introduction

The construction sector is considered the largest energy consumer worldwide. In the last few years, energy consumption has incredibly increased and is predicted to be higher in the upcoming years. A significant amount of this energy is dedicated to heating and cooling (International Energy Agency, 2019). The cooling energy consumption is predicted to increase dramatically by 300-600% in the upcoming decades (Jaradat et al., 2023). Consequently, developing more efficient thermal insulation materials was required to overcome the challenges of achieving thermal comfort inside buildings (Liu et al., 2018). Integrating thermal energy storage materials (TES) into building envelopes has been proven to have a positive impact on reducing the building's reliance on fossil fuels and aid in creating an energy-efficient environment (Soares et al., 2013). Due to their high energy storage capacity, latent heat storage materials (LHSM) such as phase change material (PCM) was found to be suitable in building applications. The aim of adopting a PCM system is limiting the amount of solar energy entering the building by absorbing it during the day and dispersing it at night, hence reducing peak cooling loads (Baetens et al., 2010). However, using PCM in the building construction industry is challenging due to some drawbacks related to its thermophysical and chemical properties such as supercooling, phase segregation, and low thermal conductivity (Bland et al., 2017).

The various kinds of PCM are usually classified based on their phase transformation temperature, latent heat of fusion, and chemical composition into three categories: organic, inorganic, and eutectic. The advantages and disadvantages of each type should be deeply investigated to select the most appropriate type for the operating conditions. However, the chosen type is recommended to possess a certain range of chemical, thermophysical, environmental, and economic characteristics (Sharma et al., 2015). These characteristics mainly govern the thermal behaviour of the PCM and should be studied thoroughly to ensure a complete phase transformation cycle (Soares et al., 2013).

Integrating PCM within building envelopes could be achieved through several methods including direct incorporation, immersion, or encapsulation. Among the various techniques, encapsulation is considered a promising solution in the construction sector (Liu et al., 2018). According to previous literature, macro-encapsulation is the most efficient integration method. It isolates the PCM from the surroundings and increases the heat transfer rate. Additionally, it enhances the thermal and mechanical stability of the PCM system (Salunkhe & Shembekar, 2012). On the other hand, selecting the material of the encapsulation shell is a major concern while designing the PCM system. The shell material should possess specific properties including physical, structural, and environmental properties (Höhlein et al., 2018). Furthermore, the shape of the shell whether it is rectangular, spherical, or cylindrical determines the efficiency of the system. The most appropriate shape should be selected based on where the application will be integrated. Moreover, the geometrical parameters such as the aspect ratio and the shell's diameter have a huge impact on the melting/ solidification process of the PCM inside the capsule (Liu et al., 2018). Furthermore, the amount of PCM inside the shell and its ratio to the shell thickness (core-to-coat ratio) highly impact the mechanical strength of the system and the energy storage capacity (Salunkhe & Shembekar, 2012). In addition, determining the system's location within the building envelope is crucial as it controls the heat transfer rate and the phase transformation cycle (Jin et al., 2013).

Despite the demonstrated efficiency of PCM, the system's economic assessment is crucial for evaluating its applicability in building envelope. It should prove huge savings to become appealing for commercial use. According to (Kneifel & Webb, 2020), the economic effectiveness of energy saving projects is usually investigated by conducting a life cycle cost analysis (LCCA). It aims to calculate all the incurred costs over the project's lifetime including any direct or indirect costs. Furthermore, for the sake of obtaining more accurate results, supplemental methods such as net savings (NS), simple payback (SPB), discounted payback (DPB), adjusted rate of return (AIRR), and savings-to-investment ratio (SIR) could be applied using the same input data used in calculating LCCA including study period, initial costs, future costs, and discount rate. However, they should yield the same results as LCCA if applied correctly.

Proving the system can provide economical savings and distinguishingly reduce the building's overall energy consumption will foster the potential of its integration into the building envelope. Furthermore, PCM systems have been proven to enhance the thermal regulation inside the buildings, which can promote not only thermal comfort, but also energy efficiency. This fosters the environment for sustainable building practices and much aligns with the three sustainability goals known as the social, environmental, and economic development dimensions (Jaradat et al., 2023; Yang et al., 2023).

Previous literature studies have shown a lack of research proposing a guideline based on which the system should be designed. Moreover, the studies investigating the economic analysis of a macro-encapsulated PCM system are not comprehensive. Most of the studies have used only the static payback period method which does not take into account the time value of the money and

consequently underestimates the actual payback period. Accordingly, this research aims to review the effect of the system’s various parameters including the type of used PCM, the material of the encapsulation shell, the form of the shell, and core to coat ratio. Moreover, it aims to present a guideline for architects and engineers to help in the process of selecting the most suitable material in the system based on factors such as climatic conditions and the system’s location within the building envelope. Furthermore, discuss the main principles of applying an LCCA along with the additional supplemental measures to ensure the reliability of the results. Finally, propose a specific guideline to help decision makers to appropriately assess the economic viability of the system and decide whether the system will gain monetary benefits.

2. Research methodology

To achieve that aim and form a deep understanding of the topic, previous research regarding PCM, its types and properties, the encapsulation process along with the methods of conducting a feasibility study for the PCM system have been investigated to form a comprehensive overview. Initial keywords regarding the topic were identified and the literature was collected accordingly. A total of 80 research articles were gathered and examined thoroughly. 34 research were eliminated due to repeated data or irrelevancy. The collected research material was divided into three groups. The first group of 20 research articles investigated the various types of PCM along with their properties. The second group consisted of 41 research articles and intended to study the process of PCM encapsulation. On the other hand, the third group, which consisted of 19 research articles, aimed to gather data regarding the economic assessment of the application of PCM systems in building envelopes while investigating several case studies. The papers were selected so they provide a deep understanding of the fundamentals of the PCM systems design including the types, properties, challenges of using the systems, and how to enhance their performance. Furthermore, research papers assessing the feasibility of the PCM in various regions have been studied and their methodologies have been analyzed. Moreover, the strategy suggested by the federal energy management program handbook for assessing energy saving projects has been investigated and applied to the PCM system. Finally, research gaps were identified to highlight the areas that need further investigation.

3. Thermal energy storage materials

Adjusting the thermal mass of the building envelope is essential for passively managing thermal comfort inside the building and controlling the energy consumption. Applying thermal energy storage materials (TES) in building envelopes has great potential to alter the indoor microclimate. Storing the solar energy in the form of thermal energy within the building envelope could be accomplished in different ways such as latent heat storage, sensible heat storage, and thermochemical heat storage (Pendyala, 2012). The main characteristics of each are stated in Table 1.

Table 1. Characteristics of thermal energy storage methods (researcher, 2024).

<p>Sensible thermal energy storage (STES) (Figure 1 – a)</p>	<p>The simplest way of heat storage. The material does not undergo phase change. The absorbed heat is used to raise its temperature without changing its phase. It depends on the mass and the specific heat</p>
<p>Latent heat energy storage (LHES) (Figure 1– b)</p>	<p>The material stores the heat by changing its phase at a constant temperature. It depends on enthalpy of fusion and specific heat.</p>
<p>Thermochemical heat energy storage (Figure 1– c)</p>	<p>A relatively new method under development. Energy is stored and released in the form of chemical reaction.</p>

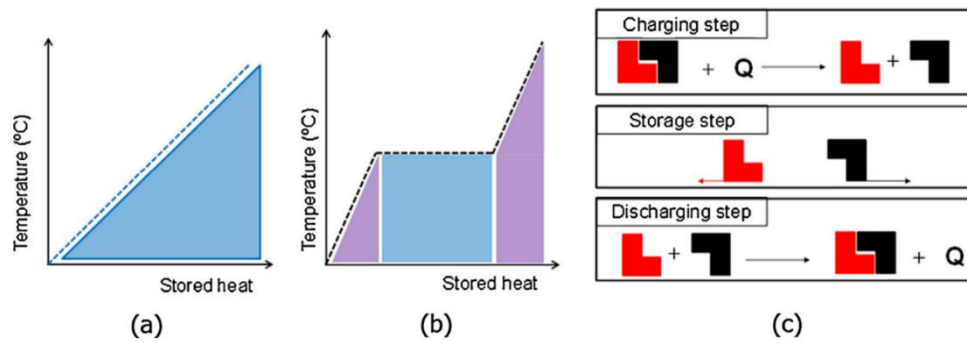


Figure 1: Thermal energy storage methods (Rathore & Shukla, 2019).

Intensive research on the different types of TES has shown that the STES has low energy density which makes it unsuitable for heat storage for long durations. Moreover, using thermochemical heat energy storage has proven efficiency due to its high energy density and low heat loss. However, it is chemically unstable, costly, and requires high charging conditions which limits its applications in building envelopes (Rathore & Shukla, 2019). On the other hand, LHES has a high energy density storage capacity within a small temperature range which increases the potential of applicability in buildings (Lizana et al., 2018).

4. Phase change material (PCM)

PCMs are latent heat materials with higher thermal energy storage densities than traditional building materials. It experiences a phase change process at a specific temperature (Sharma et al., 2015). When the ambient temperature significantly rises, the chemical bonds break, and the phase changes from solid to liquid. As the surrounding temperature decreases, the material returns to the solid state and releases the heat. Figure 2 explains the phase transition cycle. This cycle allows the PCM to exchange large amounts of heat and maintain stable thermal conditions within the building and accordingly cuts off peak cooling and heating loads.

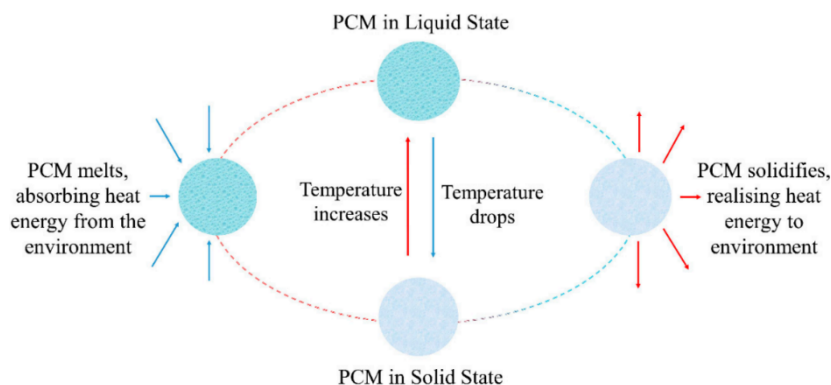


Figure 2: Phase transition cycle of PCM (Frigione et al., 2019).

4.1 Challenges of using PCM

Although PCM has proven to be more energy efficient than conventional building insulation methods, several limitations restrain its usage in the construction sector and need to be resolved to improve the system's efficacy.

- Super cooling

It is a state where the PCM starts crystallization and delays the solidification process when it reaches its solidification temperature (Mehling & Cabeza, 2008). It causes decrement in the material's efficiency and leads to system failure in the long term (Bland et al., 2017). It is more likely to occur in inorganic PCMs. However, there are several methods to overcome the effect of supercooling such as adding metal additives and nucleating agents to the PCM. Yet, these additives increase the chances of decreasing the PCM's latent heat of fusion and consequently the thermal performance of the system (Sharshir et al., 2023).

- Phase segregation

Phase segregation is one of the most critical phenomena that can cause system instability. It occurs in multi-component PCM where the components are at different phases during the phase transition cycle. Components of different densities experience

separation due to gravity which leads to a non-simultaneous melting process. Also, the incongruent melting of salt hydrate-based PCMs aids in the process of phase segregation. However, it could be managed by using nucleating and thickening agents to reduce its effect (Sharshir et al., 2023).

- Low thermal conductivity

PCMs are known to have low thermal conductivity which negatively affects the heat transfer rates during the phase change process and decreases the efficiency of the system (Sharshir et al., 2023). Previous research has investigated different methods to enhance the thermal conductivity of PCM by using additives and composites such as exfoliated graphite nanoplatelets, metal foams, and carbon fiber. However, it decreases the material’s latent heat of fusion. On the other hand, thermal conductivity could be improved through enlarging the heat exchange surface area by different kinds of encapsulation. Yet, the cost of these techniques should be considered as they can increase the overall cost of the system by four times (Bland et al., 2017).

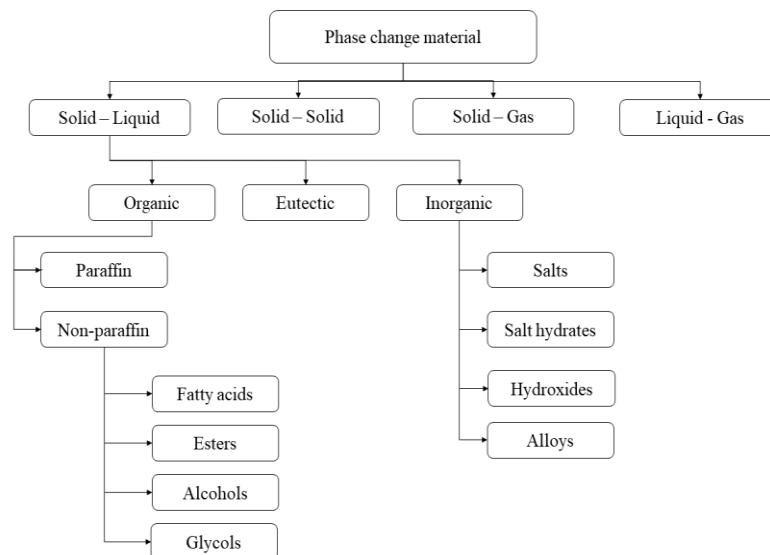
4.2 Phase change material types

The stored latent heat could be obtained through several phase transformation types such as solid-solid, solid-gas, liquid-gas, and solid-liquid. Selecting the most appropriate type to be used is dependent on the purpose of using it due to the difference in their properties. In the building construction industry, solid-liquid transformation has proved to be the most promising type that could effectively be integrated into building envelopes (Zeinelabdein et al., 2018). Table 2 indicates the advantages and disadvantages of each type.

Table 2. Advantages and disadvantages of phase transformation types (researcher, 2024).

Advantages		Disadvantages
Solid – Solid	Economically viable as they could be used without encapsulation. Have smaller volume compared to other types.	Have low latent heat.
Solid – Gas / Liquid – Gas	Have high latent heat.	Require large containers which increase complexity.
Solid – Liquid	Small volume change.	Relatively smaller latent heat.

Solid-liquid PCMs are available in various forms for several thermal energy storage applications (Rathore & Shukla, 2019). As shown in Figure 3, they could be classified into several categories based on melting/ solidification temperature, latent heat of fusion, and chemical composition (Sharma et al., 2015).



This wide range of types requires a deep investigation of each one’s characteristics to select the most suitable one to be used. Furthermore, as emphasized by (Jaradat et al., 2023), the selection of the used type PCM is highly impacted by the weather conditions, and each climatic zone should use a different PCM. Furthermore, choosing a PCM type with a phase transition temperature that does not match the surrounding environment may lead to incomplete cycles. The main advantages and disadvantages are explained in Table 3 (Soares et al., 2013).

Table 3. Advantages and disadvantages of PCM types (researcher, 2024).

	Advantages	Disadvantages
Organic PCM	<ul style="list-style-type: none"> Available in wide range of melting temperature. High latent heat of fusion. No supercooling. No phase segregation. Congruent phase change. Self-nucleation properties. 	<ul style="list-style-type: none"> Low latent heat. Low thermal conductivity. Non-compatible with plastic containers.
Inorganic PCM	<ul style="list-style-type: none"> Stable during phase change cycles. Non-Dangerous and non-reactive. Compatible with construction materials. Higher latent heat and higher heat of fusion. Higher thermal conductivity. Lower volume change. Sharp melting temperature. 	<ul style="list-style-type: none"> Experience supercooling. Incongruent melting during cycles. Experience phase segregation Slightly toxic Requires the use of nucleating and thickening agents.
Eutectic	<ul style="list-style-type: none"> Congruent phase change. No phase segregation. 	<ul style="list-style-type: none"> Have strong odour. Limited available data on the thermophysical properties.

4.3 Phase change material properties

The selection of the PCM type is mainly dependent on the climatic conditions and the material's melting temperature.

However, to ensure the effectiveness of the used type, it needs to possess a range of properties as shown in Table 4 (Sharma et al., 2015). The key determinant factor in selecting the most adequate PCM type is the phase transition temperature. According to (Abbas et al., 2021), it should be matched with the operating temperature. Meaning that the PCM solidification temperature is desired to be higher than the nighttime ambient temperature in summer months. This allows the PCM to release the stored heat even in critical summer conditions.

Table 4. Phase change material properties (researcher, 2024).

	Adequate phase change temperature that should be matched with the operating temperature. High specific heat to provide sensible heat storage. High latent heat to store large amounts of heat in small volumes of material. High thermal conductivity to minimize the required heat for melting/freezing.
Thermal properties	
Physical properties	<ul style="list-style-type: none"> High density materials: more economically viable as they require small containers. Low vapor pressure and small volume change to help in reducing the complexity of the container's geometry. No supercooling. No phase segregation.
Chemical properties	<ul style="list-style-type: none"> Chemically stable: to avoid the change in the material's chemical composition resulting from the continuous cycle of melting and freezing. Compatible with the encapsulation material: to avoid any undesirable interaction. Non-flammable and non-toxic.
Economical properties	<ul style="list-style-type: none"> Cost effective. Recycling potential. Low environmental impact and non-polluting.

Extensive research has been carried out to identify the nature of the PCM types. According to a literature study performed by (Jacob & Bruno, 2015), paraffines and salt hydrates have the potential to be a more effective mediums for thermal energy storage than the other types. This was also supported by the findings of (Khan et al., 2016) that paraffines and salt hydrates are the most efficient in storing thermal energy.

+. Paraffines are widely used in thermal energy storage applications due to their high latent heat values, wide range of phase transition temperature, chemical stability, and not going through super cooling. Furthermore, they are non-toxic, and commercially available with reasonable prices. On the other hand, salt hydrates have higher values of latent heat of fusion than paraffins. Moreover, compared to paraffins, they have higher thermal conductivity values and cheaper prices. However, salt hydrates possess poor nucleating properties and accordingly experience supercooling. In addition, they go through phase segregation which negatively affects the heat storage volume. In case of encapsulation, salt hydrates are also corrosive towards some containers' materials (Khan et al., 2016).

4.4 Phase change material enhancement

Ensuring the maximum heat transfer between the environment and the PCM system is essential to guarantee the system's efficacy. However, several types of PCM (especially organic ones) have low thermal conductivity and accordingly low heat transfer rates (Salunkhe & Shembekar, 2012). Despite the impact of encapsulation in enhancing thermal conductivity, it was proven to be insufficient. Consequently, several techniques have been developed to improve the PCM physical characteristics such as latent heat of fusion, specific heat, and thermal conductivity (Sharshir et al., 2023). These techniques involve adding high-conductivity materials to the PCM such as graphite flakes, metal particles, graphite, and carbon fibers (Figure 4).

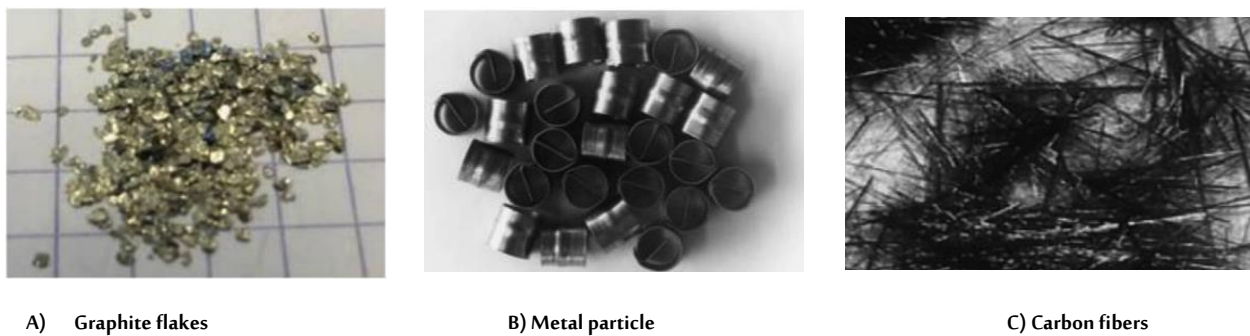


Figure 4: Types of PCM enhancement techniques (Liu et al., 2018).

Due to the impact of these additives on the heat storage capacity and the overall performance of the system, the percentage of these additives should be determined precisely to maintain the system's effectiveness. The advantages and disadvantages along with the usage of each technique are explained in Table 5 (Liu et al., 2018).

Table 5. Enhancement techniques application, advantages, and disadvantages (researcher, 2024)

Application		Advantages	Disadvantages
Graphite	Mixed with the PCM inside the shell.	High thermal conductivity and absorbability. Can enhance the thermal conductivity up to 130 times when added to paraffine.	Decrease the PCM volume and affect the heat storage capacity.
Metal particles	Nano, micron, and large metal powders made from aluminum, copper, nickel, or stainless steel	Increases the thermal conductivity especially in cylindrical shells	Their high density reduces the energy density of the system, Tend to sink to the bottom of the shell instead of dispersing uniformly.
Metal structures	Suitable for larger shells such as metal beads, metal matrix, or metal foam	Could enhance thermal conductivity up to 20 times.	Their high density reduces the energy density of the system. Tend to sink to the bottom of the shell instead of dispersing uniformly.
Carbon fibers	Promising alternative for PCM additives	Low density Compatible with PCM Reduce phase segregation for most of inorganic PCM	Decrease the PCM volume and affect the heat storage capacity.

4.5 Phase change material transformation cycle

A complete phase transformation cycle of the PCM is one of the determining factors of the system's effectiveness. The working principle could be defined as follows. In the solid state, the absorbed heat increases the temperature until it reaches the melting point, the melting process starts, the temperature remains constant, and an amount of heat is stored. When exposed to a temperature lower than its melting point, it starts solidifying by releasing the stored thermal energy. The phase transformation from solid to liquid and vice versa are known as charging and discharging processes as indicated in Figure 5 (Salunkhe & Shembekar, 2012). The behaviour of the PCM depends on several factors such as the climatic conditions, the solar radiation, the location of the PCM system within the envelope, and the façade in which the system is incorporated. Yet, the most significant factors are the type and the amount of the used material. Signifying that, the PCM melted volume depends on the amount of solar radiation and the PCM thermophysical properties especially the melting temperature, thermal conductivity, and the latent heat of fusion. The volume of the PCM during the melting process is proportional to the stored energy during the day cycle, while the volume of the solidified PCM is proportional to the released energy. Considering that, and the low thermal conductivity of the system, the volume of the used PCM is critical. If the used mass is overestimated, the required time for the melting process will exceed the sunshine period and will not be completed. Furthermore, the required time to release the heat will be longer than the discharge period and the solidification process will not be completed. Accordingly, the amount of the used PCM should be determined in a manner that all the mass will be completely melted and solidified during the daily cycle (Soares et al., 2013).

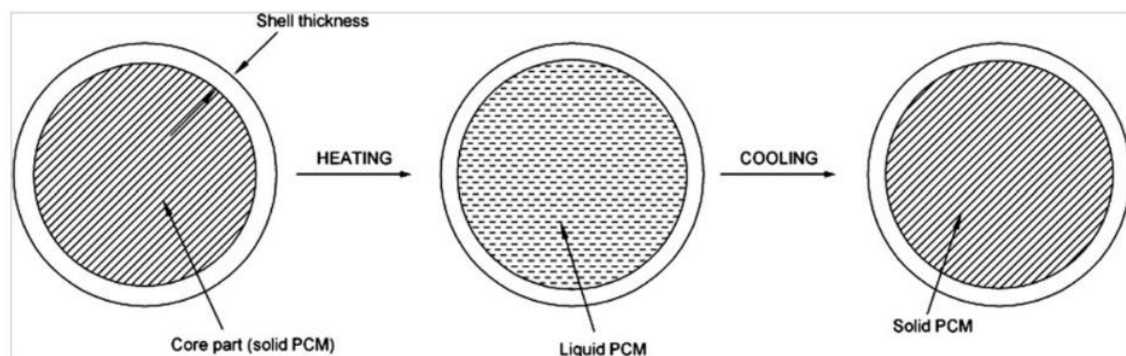


Figure 5: Phase change material transformation cycle (Salunkhe & Shembekar, 2012).

5. Phase change material encapsulation

Due to the repeated transformation cycle of PCM, holding the liquid PCM in place using the traditional immersion methods became hard. Accordingly, isolating the PCM from its surroundings is essential for protection reasons. Among the various approaches to integrating PCM within the building, encapsulation has proved to be the most effective (Konuklu et al., 2015). It could be defined as covering the PCM with a shell of an adequate material. The main purpose of this process is to hold the liquid and/or solid PCM to prevent leakage and avoid its interaction with the surrounding materials. Furthermore, encapsulation increases the heat transfer rate and enhances the PCM's mechanical stability (Salunkhe & Shembekar, 2012). In addition, it increases thermal conductivity, reduces the chance of super cooling, and controls the volume change during the phase change process (Milián et al., 2017). The encapsulated PCM is composed of a core (PCM) and a shell known as the encapsulant (Figure 6). Occasionally, additional air pockets could be added inside the core to provide room for volume change during the phase change process.

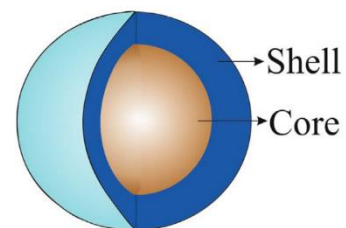


Figure 6: A representation of an encapsulated PCM shell (Milián et al., 2017).

5.1 Encapsulation types

There are several types of encapsulation classified based on the capsule's size as follows:

- Macro encapsulation (above 1 mm).
- Micro encapsulation (0–1000 mm).

- Nano encapsulation (0–1000 nm) encapsulated PCM.

Macro and micro-encapsulation are the most common types for thermal energy storage purposes. The main difference between the two types lies in the size and the shell's shape (Liu et al., 2018). The different characteristics of each one lead to various encapsulation processes and accordingly influence the selection of the shell's shape and the PCM type. Macro-encapsulation process is primarily conducted by filling the shell with the PCM. On the other hand, the process is more complicated for micro-encapsulation due to the smaller size (Salunkhe & Shembekar, 2012). Table 6 summarizes the main differences between micro and macro encapsulation.

Despite the shared merits of both types, macro-encapsulation has more potential to be used in building envelopes due to its flexibility in shape, size, simpler manufacturing process, and lower price. However, the larger shell size leads to complications such as 1) reducing the efficiency of heat transfer due to the lower surface to volume ratio, 2) inconsistent melting/ solidifying processes inside the shell, and 3) tendency to damage during building construction (Salunkhe & Shembekar, 2012). Accordingly, these factors should be considered when designing the macro-encapsulated system (Liu et al., 2018).

Table 6. Difference between macro and micro encapsulation (researcher, 2024).

	Macro-encapsulated	Micro-encapsulated
Size	In shells with a diameter above 1mm	In shells with a diameter less than 1mm
Shape	Could be encapsulated in different shell shapes	Could be only encapsulated in spherical shells
PCM types	Both organic and inorganic	Only organic PCM
Surface to area ratio	Lower ratio	Higher ratio
Heat transfer	Lower heat transfer rate	Higher heat transfer rate

5.2 Encapsulation shell material

Encapsulation material plays a significant role in determining the effectiveness of the whole system. It affects heat transfer performance, the system's mechanical strength, and stability. Also, it could be considered the main factor that determines the number of thermal cycles the system can withstand (Salunkhe & Shembekar, 2012). The selection of the encapsulation material is determined by several factors including environmental conditions, safety requirements, and material properties as stated in Table 7 (Höhlein et al., 2018).

Table 7: Characteristics of shell material (researcher, 2024).

Physical properties	Thermal conductivity. Thermal stability. Heat capacity. Mechanical strength. Compatibility with PCM type. Provide corrosion protection.
Structural characteristics	Leak proof. Water diffusion barrier.
Safety requirements	Non-toxic. Non-flammable.
Environmental conditions	Operating temperature.

The used materials for encapsulation are classified into three categories according to their chemical nature as shown in Table 8 (Jacob & Bruno, 2015). To overcome the setbacks of using organic and inorganic materials, researchers suggested combining both types to create a hybrid system. It consists of an inorganic shell to enhance rigidity, thermal stability, and conductivity with organic additives to enhance structural flexibility (Peng et al., 2020). Experiments have reported outstanding results in achieving higher thermal conductivity, mechanical durability, and chemical stability. However, the major setback of this system is the superficial attachment of the additives on the capsule as they detach from the surface due to the repeated phase change process. This approach is still under investigation, and very few studies have been found discussing the preparation and characteristics of the system (Umair et al., 2019).

Table 8. Characteristics of encapsulation materials (researcher, 2024).

	Potential materials	Advantages	Disadvantages
Organic materials	BMA–MMA copolymer, poly	-Structural flexibility resistant	-Poor chemical and thermal

	Potential materials	Advantages	Disadvantages
(plastic materials)	(urethane–urea), St–MMA, polystyrene	to volumetric change. -Less expensive.	stability. -Low thermal conductivity
Inorganic materials	Silicon dioxide, titanium dioxide, sodium silicate, calcium carbonate, silica	-Rigid materials compared to organic ones. -High thermal conductivity. -Mechanical durability. -Chemically inert.	-Inferior endurance than organic materials.
Metallic materials	Steel (stainless and carbon), nickel–chromium/carbon/ruthenium	-High mechanical strength. -High thermal stability.	-More expensive. -High potential for corrosion.

As reported by (Umair et al., 2019), The properties of the inorganic shells enhance their suitability for the application in buildings' thermal management. This was supported by the findings of (Peng et al., 2020) that the application of organic shells in encapsulation techniques is limited due to the low thermal conductivity and the flammability. Moreover, in a literature study conducted by (Khan et al., 2016), it was deduced that using organic (plastic) materials for PCM containers is not recommended when using organic PCMs. Furthermore, (Jacob & Bruno, 2015) has argued that using organic materials in the macro scale is not recommended. Instead, using metallic shell materials is more effective. The main reason is the ease of fabrication on a macro scale along with the availability. In a study executed by (Vicente & Silva, 2014), using steel (metallic shell) enhanced the PCM response to the thermal conditions due to its high thermal conductivity. Another relevant factor for the material selection was the ease of fabrication and welding processes. However, the main deterrent of the shell's material selection is the type of the encapsulated PCM (Liu et al., 2018).

5.3 Encapsulation shell form

Previous research has found that the encapsulation shell form has a fundamental influence on the heat transfer properties and the whole effectiveness of the encapsulation system. Considering the main role of the shell in regulating the melting-solidification process, a deeper understanding of the PCM behavior inside each form is required for further improvement of the system's efficiency (Liu et al., 2018). A variety of forms have been developed and used in the encapsulation process. These forms could be categorized based on the geometrical shape into rectangular, cylindrical, and spherical (Figure 7).

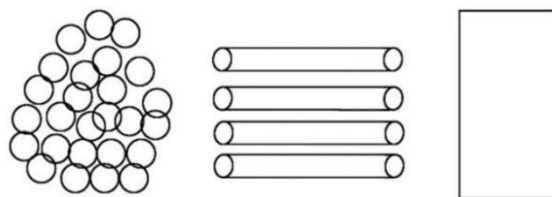


Figure 7: Different encapsulation forms (Salunkhe & Shembekar, 2012).

According to (Liu et al., 2018), rectangular forms are the most common in the construction industry due to the ease of installation and disassembly of their flat surface besides the low production cost. They have the potential to be immersed in walls, floors, or roofs. On the other hand, the application of spherical PCM capsules is limited, and there has been little discussion about their application in building envelopes. The reason behind that is the complexity of their installation process, especially in the walls. However, (Nagano et al., 2006) proved that implementing spherical beds of PCM in the floor highly reduces the energy needed for the air conditioning system. Furthermore, using cylindrical capsules has proven efficient in mitigating the daily heat transfer inside the building (Medina et al., 2008).

One deterrent factor in choosing the most suitable form is the location within the building envelope. Each type fits differently, and the installation techniques should be taken into consideration. Table 9 indicates the optimal application for each form (Liu et al., 2018).

Table 9. The application of different shell forms (researcher, 2024).

Category	Location
Rectangular shells	Wall

Category	Location
Spherical shells	Ceiling
	Windows
	Floors
Cylindrical shells	Ceiling
	walls

5.4 Melting process within different shell forms

The melting/ solidification process of PCM inside the shell is the main factor that determines the effectiveness of the whole system. It has been studied extensively in previous research to help provide a base on which the most suitable shell form could be identified. It is mainly controlled by heat conduction and heat natural mechanisms. However, the process differs in each type based on several factors.

- Rectangular shells

When heat flux is directed on one of the vertical sides of the shell, heat is transferred over two stages. The first one is conducted via conduction through direct contact with the heat. The second stage is divided into two periods, at the first one, a rapid melting happens due to the natural convection and the buoyancy-driven flow. The melting area expands during the second period. However, the isotherms appear to be almost parallel, and that thermal stratification greatly affects the natural convection process and the heat transfer rate negatively. Consequently, at the end of the melting process, a small amount of solidified PCM remains at the bottom of the container as shown in Figure 8 (Liu et al., 2018).

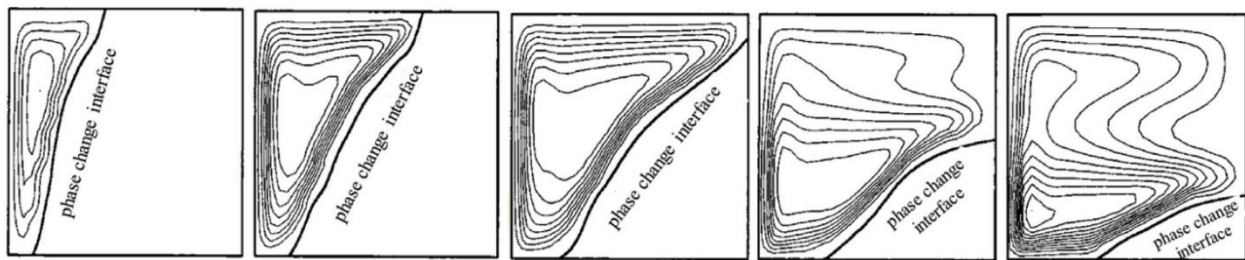


Figure 8: Streamlines during phase transformation process (Liu et al., 2018).

- Spherical shells

The melting process in spherical shells is also dominated by conduction and convection. Yet, it could be constrained or unconstrained. In constrained melting, thermocouples are inserted into the shell. They aim to constrain the solid PCM from sinking to the shell's bottom during the melting process. Consequently, natural convection is the primary mechanism driving the heat transfer process in the top and bottom regions. However, the top regions melt faster than the bottom regions due to the buoyancy effect. On the other hand, in unconstrained melting, the solid PCM tends to sink at the bottom of the shell due to the density difference between the liquid PCM and the solid PCM. When the descended PCM touches the shell surface, the heat transfers via conduction, and a thin layer of liquid PCM is formed. Meanwhile, the buoyancy-driven convection starts to be the main heat transfer mechanism to melt the top region of the shell. Figure 9- left shows a representation of constrained and unconstrained shells. Under the same conditions, the unconstrained melting has proven to occur at a faster pace than the constrained. This is due to the fact that the direct contact of the solid PCM with the shell increases the heat transfer rate via conduction as shown in Figure 9- right (Tan, 2008).

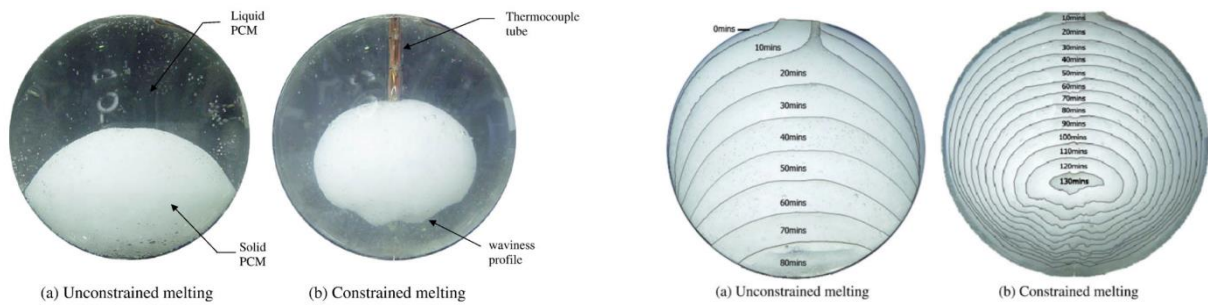


Figure 9: Melting process of constrained and unconstrained melting process (left), the rate of melting process in each (right) (Tan, 2008).

- Cylindrical shells

The melting process within the cylindrical shells was investigated and found to be mainly affected by the symmetry axis orientation. In the case of vertically oriented cylinders, the melting process is like the one in the vertical rectangular shells. As for the horizontally oriented cylinders, the melting process is similar to that in the spherical shells (Liu et al., 2018).

5.5 Effect of shell's geometric parameters

The geometrical parameters of the shell have a significant impact on both heat transfer and phase transformation process. Parameters such as aspect ratio were studied on the rectangular and the vertically oriented cylindrical shells. On the other hand, the shell's diameter was studied on the spherical and the horizontally oriented cylindrical shells. Both parameters were found to influence the PCM melting fraction (i.e., the ratio of the melted PCM to the whole PCM inside the shell). As reported in previous studies, the aspect ratio has a negligible impact when the heat is transferred via conduction. While through the natural convection process, the smaller ratio has a positive impact on the melting fraction. Moreover, the higher aspect ratio was found to extend the required time for PCM melting. Regarding the spherical and the horizontally oriented cylindrical shells, the smaller shell diameter helps in decreasing the required time for the complete melting process and results in a sharper increase in the heat flux (Liu et al., 2018).

5.6 Effect of core to coat ratio

Core-to-coat ratio (i.e., the ratio of volume of the encapsulated PCM to the capsule's volume) is a crucial factor determining the mechanical strength and the effectiveness of the system. The excessive coating increases the shell's strength yet reduces the volume of the encapsulated PCM which in return reduces the effectiveness of the system. Whereas, increasing the encapsulated volume of the PCM leads to deterioration in the system's strength and increases the chances of PCM leakage. Moreover, it results in a system failure due to its inability to sustain repeated thermal cycles (Salunkhe & Shembekar, 2012).

Several studies have investigated the effect of core-to-coat mass ratio on performance by testing the system's effectiveness under different ratios varied from 1:1 to 4:1. The results proved that a ratio of 3:1 is the most optimum in preserving the mechanical properties of the system and increasing the rate of storing, releasing thermal energy and hence enhancing the system's efficiency (Salunkhe & Shembekar, 2012). These results were supported by (Gong et al., 2009) as it proved that the ratio of 3:1 is the most optimum for sustaining the mechanical strength and increasing the thermal energy storage. Furthermore, (Borreguero et al., 2010) conducted an experiment to examine the impact of two core-to-coat mass ratios, 3:1 and 5:1. It was proved that increasing the ratio to 1:5 enhances the energy storage capacity yet increases the chances of mechanical failure.

5.7 Optimum location within building envelope

The location of the PCM system in the building envelope highly influences the heat flux reduction and the indoor temperature. Such a parameter is critical for controlling the heat transfer rate, phase change process, and determining the effectiveness of the whole system (Jin et al., 2013). Previous research has investigated the most optimum location for the PCM within the envelope. The results indicated that it is governed by several factors including the climatic conditions, wall orientation, and the thermal properties of the PCM. The orientation of the wall highly affects the optimal location due to the variation of received solar radiation. Moreover, studies have shown that increasing the thickness of the used PCM requires moving the system to the exterior surface so it can absorb more heat and complete the phase transition cycle (Liu et al., 2018). In addition, (Jin et al., 2016) has reported that the thermal properties of the PCM play a vital role in determining the optimal location. A high melting temperature and a high heat of fusion of the

PCM means the system should be closer to the surface (the heat source) to absorb a higher amount of heat to ensure a complete melting process.

On the other hand, previous studies have shown that the optimal location is determined mainly based on the purpose of using the PCM system. As shown in Figure 10, To reduce the cooling loads, the system should be located on the exterior side of the wall. To reduce the heating loads, the system should be moved towards the inner surface of the wall (Al-Yasiri & Szabó, 2021). Furthermore, (Liu et al., 2018) has argued that the location is dependent on the energy loads to be mitigated and the external weather factors. However, a study on the effect of PCM in reducing energy consumption has proven that the centrally placed system resulted in more energy savings during heating and cooling seasons than the internally and externally placed systems (Zwanzig et al., 2013). However, (Rai, 2021) recommended that in all conditions, the system should be placed on the inner side of the wall to ensure its protection from outdoor conditions. Generally, it could be concluded that the system's optimum location is circumstantial and should be investigated in each case based on the weather conditions, the used PCM type, and the purpose of the usage.

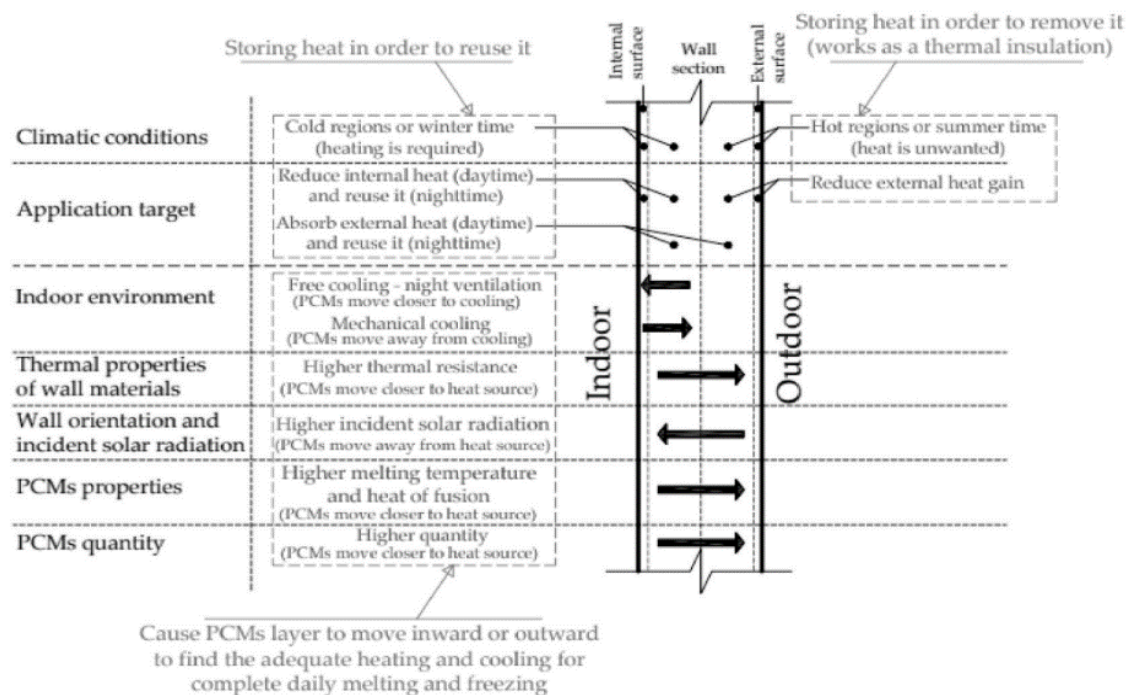


Figure 10: Optimum location of a PCM system in the building envelope based on several factors (Al-Yasiri & Szabó, 2021).

6. Economic assessment

Besides investigating the thermal performance of integrating macro-encapsulated PCM into building envelopes, economic assessment is a crucial process for evaluating the applicability of PCM capsules in building facades. Moreover, proving a system's efficiency may not always imply that the system will be applicable in real life, it must provide significant savings to become attractive for commercial use. However, literature study has shown a lack of research assessing the economic performance of PCM systems. According to (Kneifel & Webb, 2020), assessing the feasibility of a project is mainly accomplished by conducting a life cycle cost analysis (LCCA), which aims to analyze all project costs occurring over its life cycle. For more accurate results, supplemental measures such as net savings (NS), savings-to-investment ratio (SIR), adjusted internal rate of return (AIRR), and payback period whether it is simple or discounted payback could be integrated using the same input data used in LCCA (Kneifel & Webb, 2020).

6.1 Life cycle cost analysis (LCCA)

Besides being massive energy consumers, buildings are also considered as financial assets consumers during their whole life cycle. Therefore, a framework that provides an evaluation of the project cost throughout its lifetime has been integrated into the decision-making process to determine the most feasible strategy to be applied (Konstantinidou et al., 2019). According to (Gassar & Cha, 2022), LCCA is an economic evaluation method in which all costs including investment cost, operation cost, maintenance cost, or any other related costs over the estimated life cycle of the product are considered vital to the decision. This approach is mainly integrated into the early stages of the decision-making process (Kyriaki et al., 2018). According to (Mearig et al., 2018), LCCA could be

applied to any product or project regardless of its scale or use. Moreover, it is considered an effective tool for evaluating existing projects.

In energy performance enhancement projects such as a PCM system, LCCA depends on the life cycle assessment (LCA) of the energy-saving system. The assessment process aims to evaluate the environmental impact related to the applied system, quantifying the used materials, and calculating the amount of consumed energy and the waste released to the environment. Then, compare the current economic value with the energy savings. Consequently, assessing the sustainability and feasibility of the adopted system (Konstantinidou et al., 2019). However, calculating the exact life cycle cost of a PCM system is complicated due to the wide range of involved factors such as labor cost, electricity, and gas prices (Cascone et al., 2018). While calculating the feasibility of PCM, the optimum case is the one that provides the minimum life cycle cost, payback period, and the maximum energy savings. These energy savings will then be used to quantify the amount of economic savings using the energy prices in the studied region. As argued by (Souayfane et al., 2019), the economic situation of the studied area plays a significant role in determining the system's feasibility. Meaning that, in regions with lower economic level and higher energy rates, the saved energy will result in higher economic savings, while in regions with lower energy rates, the economic savings will be insignificant. Accordingly, it could be concluded that the economic situation of the studied region highly affects the viability of integrating the PCM system.

6.2 Study period

The study period in LCCA is defined as the amount of time over which all costs related to the investment lie in the interest of the stakeholders. Study periods often range between twenty to forty years depending on the project's intended life. On the other hand, while the study period could be considered an indication of the product's intended life, it is often shorter than the intended life (Mearig et al., 2018). Usually, before starting the study, the base date should be identified along with the service date, and the planning/construction period which is the time between the base date and the beginning of the service period (Kneifel & Webb, 2020).

- Base date

The base date could be defined as the first day of the study. While conducting a simple LCCA, it is more convenient to set the base date as a year only (e.g., 2023). Consequently, this assumption means that the initial costs occurred at the beginning of that year, and all the upcoming costs occurred during this year or the upcoming years. Identifying the base date is essential for conducting LCCA as it is considered as the reference date according to which all future costs will be discounted. The timing of the future costs could be either identified precisely by the day or by the year of their occurrence. They also could be discounted using the precise day or from the end of the year. However, it is advisable to discount them from the end of the year in case of simple LCCA (Kneifel & Webb, 2020).

- Service date

The service date identifies when the project will be implemented. future costs such as operation and maintenance costs (O&M) costs typically occur after. While conducting a simple LCCA, it is more convenient to assume that the initial investment costs incurred on the base date and the project will function immediately. Signifying that, both the base date and the service date are supposed to be the same, as shown in Figure 11(left). While conducting a more complicated LCCA, the service date usually occurs after the base date. In that case, that intervening period of time between the base date and the service date is referred to as the planning/construction period (P/C), as shown in Figure 11 (right) (Kneifel & Webb, 2020).

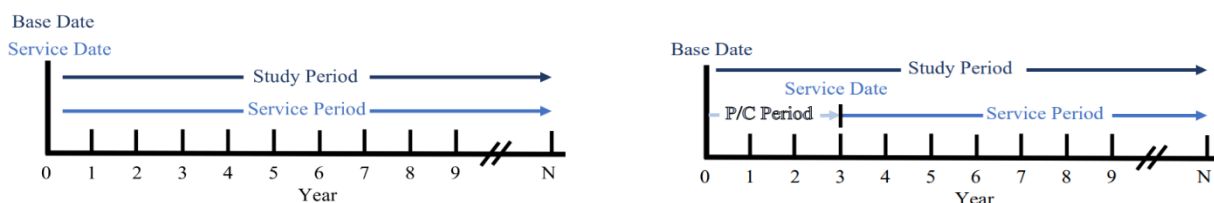


Figure 11: Study period with no P/C period (left) and study period with P/C period (right) (Kneifel & Webb, 2020).

6.3 Cost categories

The cost components of LCCA could be classified into several categories based on their role in the project, the aim of the study, and the methodology adopted. The most vital and commonly used components can vary between initial investment-related costs and future costs, and single or annual costs. Both cost categories are essential for calculating economic measures such as savings to investment ratio (SIR) or the payback period (Kneifel & Webb, 2020).

- Initial and future costs

Differentiating initial investment costs and future ones is essential when performing LCCA. The first step of conducting an LCCA is defining and calculating the initial cost of each element in the project. That includes all costs related to the planning, design, and construction costs added to any other costs that could be incurred before the usage of the product. Initial investment costs are known to be the simplest cost category to be estimated as they occur in a time frame that is close to the present time. Moreover, they can be easily obtained from the local contractors and suppliers. Although these costs should be added at their exact value, the level of detailing of all costs should be correspondent with the level of project details (Mearig et al., 2018). According to a study conducted by (Bergia Boccardo et al., 2019), in an attempt to estimate the initial investment costs of a PCM system, they calculated the price of each item and then it was multiplied by their number to obtain the total investment cost. On the other hand, estimating the accurate cost of components such as labor cost, equipment costs, and the contractor’s profit was complicated and uncertain. Accordingly, they could be deduced by investigating previous literature. Meanwhile, any expenses that can arise during the operation of the product or from maintenance, repair, usage, or occupancy are considered future costs. Moreover, the residual value at the end of the product’s lifetime or the end of the study period is also considered future costs.

- Single and annual costs

This type divides the project-related costs into two categories based on the occurrence frequency. It aids in determining the present value factor type (PVF) to be used in future cash flow discounting. Table 10 indicates the difference between the two categories (Kneifel & Webb, 2020).

Table 10. The difference between single and annual cost (researcher, 2024).

Single costs (one-time costs)	Occurs at irregular intervals during the study period. It could occur one or several times such as initial cost, replacement cost or repair costs.
Annual costs	The costs which recur on an annual basis during the study period in relatively the same amount or changes with a known rate such as energy costs or annual maintenance costs.

The annual PVF factor differs according to the type of costs. In single costs PVF, is expressed as a single present value (SPV). While in annual costs PVF is expressed as uniform present value (UPV) in case the recurring costs do not change every year and expressed as modified uniform present value (UPV*) in case the recurring costs are changing in a known rate (Kneifel & Webb, 2020).

6.4 Cash flow timing

All occurring costs during the project’s lifetime should be identified based on the time of occurrence along with the amount. However, while conducting an LCCA study, it is acceptable to use simplified models of cash flow instead of attempting to estimate the exact time of each cost. Signifying that all costs occur at different times within one year can be considered as occurring at the same time to ease the discounting operations (Kneifel & Webb, 2020).

6.5 Discounting future amounts to present value

The discount rate could be defined as the rate of interest that reflects the time value of the money. It also could be described as the rate of interest that allows the investor to determine whether it is more beneficial to receive a certain amount of payment sooner or receive a greater amount later (Mearig et al., 2018). Accordingly, all project costs that occur at different times during the project life cycle should be discounted to their present value (PV) on the base date before they can be integrated into LCCA. According to (Kneifel & Webb, 2020), the rate used to discount future cash flows to the present value (PV) is determined based on the investor’s value of the money. Consequently, the most appropriate discount rate can vary from one project to another.

Discounting methods mainly depend on the type of cost category. The discount factor is a scaler to be multiplied by the amount of the future cash flow to get its equivalent present value whether it is single present value (SPV), uniform present value (UPV), or modified uniform present value (UPV*). Table 11 indicates the formulas used to calculate each type of present factor (Kneifel & Webb, 2020).

Table 11. Present factor calculation formulas (researcher, 2023).

<p>PV formula for single amounts SPV:</p> $SPV = \frac{F_t}{(1+d)^t}$	
<p>PV formula for annually occurring amount UPV:</p> $UPV = A_0 * \frac{(1+d)^n - 1}{d * (1+d)^t}$	
<p>PV formula for annually non uniform amount UPV*:</p> $UPV^* = A_0 * \frac{(1+e)}{(d-e)} * \left[1 - \frac{(1+e)^n}{(1+d)^n} \right]$	

Where:

PV = the present value.

F_t = future amount of received cash at the end of year t.

d = discount rate.

t = number of years.

A_0 = a series of equal cash amounts.

e = constant escalation rate.

6.6 Discounting rates

The discount rate is the rate of interest that reflects the time value of a future cash flow or a future cost. Basically, it is the factor that aids in deciding whether the investor receives the payment in the present or a greater payment in the future (Mearig et al., 2018). In business activities, discount rates are dependent on market interest rates. Meaning that the nominal interest rates that reflect the expectations of general inflation could be considered as the base for nominal discount rate selection, which will be used to discount the future costs stated as current dollars. On the other side, using the real discount rate to discount constant dollars to the present value indicates the earning power of the money, not the general inflation rate (Kneifel & Webb, 2020). Simply, the main difference is that the real discount rate avoids the complexity of accounting for the rate of inflation in the present value calculations while the nominal discount rates include the rate of inflation with the calculations (Mearig et al., 2018). Usually, the discount rates are published each year by the government of each country. The following equation explains the relationship between real and nominal discount rates (Kneifel & Webb, 2020):

$$d = \frac{1+D}{1+I} - 1$$

Where:

d = real discount rate., D = nominal discount rate, I = rate of inflation

6.7 Adjusting costs for inflation

The dollar's purchasing power changes based on inflation and deflation. Expressing the future cash flow amounts could be done using current or constant dollars. Stating the future cash amounts in prices as in the year they are expected to occur follows the current dollar method, which indicates purchasing power including inflation. meaning that, the change in the dollar's power each year. On the other hand, the constant dollars method indicates the purchasing power excluding inflation, they express the cost of a product at different times over the years considering there is no change in the prices. Adjusting the costs from current to constant dollars is not the same process as discounting future costs and cash flows to the present value. Adjusting the current dollars expresses the dollar's purchase power, while the discounting process adjusts the prices based on the investor's value of the money. Determining the most

appropriate discount rate to be used is highly dependent on whether the costs are stated in current or constant dollars (Kneifel & Webb, 2020). While conducting an LCCA, future costs could be stated using two methods as follows:

- The first method: estimating all future cash amounts (savings and costs) using the constant dollar method and using the real discount rate (i.e., a discount rate that excludes the inflation rate).
- The second method: estimating all future cash amounts (savings and costs) using the current dollar method and using the nominal discount rate (i.e., a discount rate that includes the inflation rate).

Both methods will produce the exact present value results considering consistent assumptions of real and nominal discount rates provided along with the rate of inflation. However, it is recommended to conduct the LCCA in constant dollars and use the real discount rates to avoid estimating the inflation rate over the study period years (Kneifel & Webb, 2020).

6.8 Estimating future costs

LCCA is often performed in the early stages of the decision-making process when most of the cost data are not available whether the initial or the future costs. Hence, cost data is more likely to be estimated. To simplify the process of estimating costs, it is allowable to estimate future costs based on their corresponding cost at the time of analysis performance (base date). Signifying that the rate of real price escalation will be zero. Also, in constant dollar analysis, the price of a product during the study period will be the same as its price on the base date. However, if there are any documents stating that the prices will increase at any rate during the study period (e.g., maintenance cost contracts), these rates should be included in the calculations.

6.9 Estimating residual value

The residual value of a project is identified as the remaining net worth at the end of the study period. It could be based on salvage, resale value, net selling, or even disposal costs (Kneifel & Webb, 2020). Unlike other costs, it could be expressed as cost or value, negative, positive, or zero (Mearig et al., 2018). At the end of the expected life, it is more likely that the residual value is minor or neglected or even negative in case there are costs associated with the removal, or demolition of the project. In some cases, the residual value could be zero which indicates that there is no cost, or value related to the product at the end of the LCCA study period. There are multiple techniques used to calculate the residual value that might be suitable based on the project's type. According to (Kneifel & Webb, 2020), it is more convenient to consider values that can be calculated using the available data in the market. The following equation is used to calculate residual value:

$$\frac{\text{product's service life} - \text{study period}}{\text{product's service life}} * \text{initial cost} * \frac{1}{(1 + d)^t}$$

Some projects may have higher resale values based on other assets not related to the operational savings or the remaining value of the investment cost such as the projects with renewable energy generation systems. Moreover, studies have shown that green-rated buildings tend to have higher resale and rent prices. Accordingly, projecting this value in the prorated investment cost or savings costs will result in more accurate results.

In the case of a long study period, the residual value may be minor, and the discounting will diminish its weight. However, when the study period is short relative to the product's lifetime, residual value estimation will be a vital factor in assessing the effectiveness of the project and should be given proper consideration.

6.10 Estimating operating, maintenance, and repair costs

Operating, maintenance, and repair (OM&R) costs are usually more complex to estimate than other future costs. That is mainly because the operating process and maintenance schedules differ from one project typology to another. Typically, OM&R costs begin with the service date and go through the service period. Moreover, the complication in calculating OM&R costs lies in the several types of costs occurring during the project's service life, some costs recur constantly on an annual basis or change at a known annual rate. The equivalent present value for these costs could be calculated using UPV and UPV* factors.

In the field of building construction, there are several available databases to ease the process of cost estimation. Some of them derive the cost estimation relationships from historical data and produce reports such as average operational costs per square meter or building floor. A simpler method of estimating OM&R costs is to collect the required data from local vendors and suppliers. Based on the scheduled replacements and maintenance, the initial year OM&R costs could be easily obtained. For the constant dollar analysis, the future costs will remain the same each year for the rest of the service period, unless these costs are estimated to rise at a rate other than the general inflation rate. In this case, the price escalation should be included in the calculations.

6.11 Calculating life cycle cost

The calculations in LCCA could be performed manually or easily using software such as BLCC, which is ideal for energy efficiency projects. However, in a simple LCCA, the analysis could be done using spreadsheet software such as Excel. In the case of manual calculations, the present value of each incurred cost during the study period should be estimated using the discount rate. Then, the summation of all values represents the LCC. The following is the general formula for LCC present value (Kneifel & Webb, 2020).

$$LCC = \sum_{t=0}^N \frac{C_t}{(1+d)^t}$$

Where:

LCC = life cycle cost

C_t = sum of relevant costs in year (t)

N = number of years in study period

D = discount rate

6.12 Supplemental measures

Using the same assumptions data needed for implementing LCCA, including study period, initial investment costs, future costs, and discount rate, several supplementary measures could be applied to assess the project's economic performance. Measures such as net savings (NS), simple payback (SPB), discounted payback (DPB), adjusted rate of return (AIRR), and savings-to-investment ratio (SIR) if applied accurately, will yield the same results as the LCCA. Meaning that, will be consistent with the LCCA in determining whether the project is cost-effective (Kneifel & Webb, 2020).

The stated supplementary measures are used to assess economic performance. Signifying that they should be computed relative to a base case. Generally, the base case has the lowest initial cost yet the highest operational costs. However, the main reason for conducting LCCA or the supplementary measures on an alternative design is to clarify that the increased initial cost is covered by operational savings. In retrofitting projects, the base case is keeping the existing situation with no investment costs yet higher operational costs. On the other hand, for new construction projects, the base case is usually the alternative with the lowest initial investment cost (Kneifel & Webb, 2020).

6.13 Applying supplemental measures on investment projects

According to (Kneifel & Webb, 2020), the applied supplemental measures should be determined based on the project type and nature. In energy conservation projects, there are usually five types of investment decisions as follows:

1. Accept or reject a single project alternative.
2. Select the optimal efficiency level for a chosen alternative.
3. Determine the optimal system type among other alternatives.
4. Select a combination of systems.
5. Rank different alternatives to allocate a limited budget.

The aim of using assessment methods is to identify the most cost-effective alternative to the available options, excluding the technical performance and any other options that might be more feasible but not available at the required time. The common among the first four investment decisions is that they all require evaluating the available alternatives. That is, among all the alternatives, one could be selected.

In the case of assessing the feasibility of integrating macro-encapsulated PCM in building envelopes, the first investment decision should be adopted (accept or reject a single project alternative).

6.14 Accept or reject a single project alternative

This type of investment decision relates to evaluating the feasibility of a single design proposal that is being considered for purchase and has no competing proposals. Accepting or rejecting the alternative is mainly dependent on its cost-effectiveness. In this case, the evaluation of the project alternative must be against the base case, which is generally the absence of the alternative. The base case will have no initial cost, however, higher operational and maintenance costs. While the alternative is being evaluated as an accept/reject proposal, each of the following supplemental measures should be applied to determine the cost efficiency of the proposal (Kneifel & Webb, 2020):

- Net savings: should be greater than zero.
- Savings-to-investment ratio (SIR): should be greater than 1.
- Adjusted internal rate of return (AIRR): should be greater than the discount rate.
- Payback period: should be less than the selected study period.

6.15 Net savings

Net savings (NS) could be considered an alternative measure of economic performance to net benefits (NB). Generally, the NB method is used to calculate the difference between present-value costs and present-value benefits over the specified study period. It is usually applied when using the alternative is justified by positive cash flow such as (e.g., rent). On the other hand, the net savings method (NS) is used when the benefits are in the form of savings in future operational costs (eg., reducing electricity or water consumption). The NS method is based on calculating the present value of the total financial savings the alternative is expected to save over the designated study period. Moreover, other significant benefits that could be monetized should be integrated into the calculations as cost reductions (Kneifel & Webb, 2020). Calculating the NS for an alternative is expressed as:

$$NS = LCC_{base\ case} - LCC_{alternative}$$

Where: NS = net savings, LCC = life cycle cost.

The alternative is considered cost-effective in case NS is greater than zero, which is similar to acquiring that the LCC of the alternative is lower than the base case. Also, the alternative with the highest NS will be the one with the lowest LCC. Accordingly, if applied correctly, LCC and NS will yield the same results and should be consistent.

6.16 Savings to investment ratio (SIR)

SIR is a supplemental economic performance measure for a design alternative. It is mainly used to express the relationship between the increased investment cost and the savings, both expressed in present value terms. It is an alternative to the benefit cost ratio (BCR) to be used when the savings are expressed in future operation-related reductions such as energy savings. In addition, SIR is a relative measure, meaning that it should be calculated and compared to a base case with the same input data such as study period, discount rate, and base date. To consider a project to be economically viable, the savings resulting from applying the alternative should be greater than its increasing investment cost, and consequently the SIR value is greater than 1 and the NS is greater than zero. However, when evaluating multiple project alternatives, the alternative with the highest SIR is not generally the most cost-effective, instead the alternative with the lowest LCC will be the most cost-effective one. Thus, SIR should not be used in choosing among project alternatives, and it is most useful to be used to rank the project among other independent projects for funding allocation purposes. In construction industry projects, the following formula should be used:

$$SIR_{A:BC} = \frac{\Delta E + \Delta W + \Delta OMR + \Delta X}{\Delta I_0 + \Delta Repl - \Delta RV}$$

Where the amounts are calculated in present value and:

$NS_{A:BC}$ = net savings, operational savings minus alternative A investment costs relative to the base case.

$\Delta E = E_{BC} - E_A$: savings in energy costs.

$\Delta W = W_{BC} - W_A$: savings in water costs.

$\Delta OMR = OMR_{BC} - OMR_A$: savings in OM&R costs.

$\Delta X = X_{BC} - X_A$: savings in other costs.

$\Delta I_0 = I_A - I_{BC}$: alternative's initial investment cost.

$\Delta Repl = Repl_A - Repl_{BC}$: alternative replacement costs.

$\Delta RS = RS_A - RS_{BC}$: additional residual value.

6.17 Adjusted internal rate of return (AIRR)

It is a supplemental measure of the annual profit percentage from the investment over the whole study period. Similar to the other supplemental measures, AIRR is a relative measure and should be computed relative to the base case. To determine the cost-effectiveness of the project, AIRR is compared to the minimum acceptable rate of return (MARR), which is generally equals to the used discount rate. The project is considered economically effective in case AIRR is greater than MARR. On the other hand, the project is not feasible in case AIRR is less than MARR. Meanwhile, if AIRR equals the discount rate, the project is considered neutral, and the savings

are equal to the costs. AIRR could be used for the same application as SIR, including deciding whether to accept or reject a project alternative based on a base case and prioritizing the investment budget allocation among independent projects. However, this method should not be used to select among several project alternatives as the one with the highest AIRR will not necessarily be the one with the lowest LCC. AIRR can be calculated using a simple formula as follows:

$$AIRR = (1 + r) * (SIR)^{\frac{1}{N}} - 1$$

Where:

r = investment rate, N = number of years in the study period.

6.18 Discounted and simple payback

The payback period is a measure that calculates the number of required years to recoup the initial investment costs. They are stated as the number of years from the start of the service period to the point of time at which the total savings are enough to cover the initial investment costs. Two payback methods that are frequently used for the economic analysis of capital investment: discounted payback (DPB) and simple payback (SPB). Both methods are relative measures and should be computed against a base case regarding the base date, study period, and discount rate.

Discounted payback (DPB) usually results in more accurate results as the computing process requires the occurred cash flow during the study period to be discounted to the present value before it could be used as costs and savings. If the DPB period is less than the project's service period, the project is cost-effective, which is compatible with the requirement that the life cycle cost of an alternative should be less than the life cycle cost of the base case. However, in real-life applications, a payback criterion is usually used (the number of allowed years in which the payback should occur) and is typically a time period that is subjectively selected and less than the project's anticipated service period. However, if the OM&R costs or the capital replacement costs occurred after the payback period, this could negate the project's cost-effectiveness.

On the other hand, the simple payback (SPB) method does not require discounting the future cash flow to the present value in the calculations. Moreover, it tends to exclude any price variations during the payback period such as changes in energy or water prices. Similar to DPB, the acceptable payback period for the project is set to a time period typically less than the project's service period.

The SPB is more commonly used and usually shorter than the DPB as the undiscounted future cash flows are greater than the discounted ones. However, both payback methods disregard any costs or savings that occur after the payback period as well as the residual value. Furthermore, payback is not a valid measure for selecting among several project alternatives or ranking different projects for funding purposes, LCC and NS should be used instead. Generally, the payback method is more beneficial as an assessment method to choose among project alternatives that are evidently economical that a full LCCA is not sufficient. The general formula for the payback period could be stated as follows:

$$\sum_{t=1}^y \frac{S_t - \Delta I_t}{(1 + d)^t} \geq \Delta I_0$$

Where:

y = payback period.

S_t = total savings in number of years t .

ΔI_0 = initial investment cost.

ΔI_t = additional costs in number of years t .

d = discount rate.

In the previous formula, y is the SPB if the discount rate equals zero, and y is the DPB if the discount rate does not equal zero. Despite the equation resulting in an integer solution, interpolation could be used to result in a non-integer one. However, the available data does not usually support such a type of accuracy. In case of applying the study to energy or water conservation projects, a more specific formula could be used as follows:

$$\sum_{t=1}^y \frac{\Delta E_t + \Delta W_t + \Delta OMR_t + \Delta X_t - \Delta Repl_t + \Delta RV_t}{(1 + d)^t} \geq \Delta I_0$$

Where:

$\Delta E_t = (E_{BC} - E_A)_t$: savings in energy costs.

$\Delta W_t = (W_{BC} - W_A)_t$: savings in water costs.

$\Delta OMR_t = (OMR_{BC} - OMR_A)_t$: savings in OM&R costs.

$\Delta X_t = (X_{BC} - X_A)_t$: savings in other costs.

$\Delta Repl_t = (Repl_{BC} - Repl_A)_t$: alternative replacement costs.

$\Delta RS_t = (RS_{BC} - RS_A)_t$: additional residual value.

$\Delta I_0 = (I_A - I_{BC})_0$: alternative's initial investment cost.

d = discount rate.

The previous formula generates the most accurate results for both the simple and the discounted payback periods. However, it can require additional calculations in case of long payback periods, particularly when including price escalation rates. Generally, the payback method is beneficial as a guidance tool to accept or reject a project alternative and is not recommended to be used for ranking several project alternatives. Furthermore, DPB is usually preferred as it considers the time value of the money and hence yields more accountable results.

7. Findings and results

Previous research revealed that using latent heat storage materials such as PCM could be effective in reducing energy consumption. However, applying the PCM system faces several drawbacks such as phase segregation and supercooling. However, they could be mitigated using PCM enhancements such as graphite, metal particles, and structures. However, selecting the most suitable type of PCM could be complicated due to the massive number of available materials with different characteristics. Moreover, the selected type should meet the requirements of the chemical, thermal, physical, and environmental properties.

On the other hand, encapsulating PCM is a promising solution to overcome the low thermal conductivity of the PCM along with protecting the material during the phase change process. Previous research proved that macro encapsulation could be the optimal choice for building applications due to several reasons including the shape and size flexibility along with the easy manufacturing process. However, the following should be considered while designing the system.

- The shell material was recommended to be inorganic due to the ease of manufacturing on the macro scale as well as its availability and low cost. However, the used type of the PCM should be considered to be compatible with the shell material.
- The encapsulation form also plays a huge role in the melting/solidification process. The most optimal shape to be used is usually determined by the type of system's application whether it is in the walls, floors, ceilings, or windows.
- The geometric parameters of the chosen form such as aspect ratio and diameter have an impact on the heat transfer and the required time to complete the phase transformation cycle.
- The ratio of the used amount of PCM to the thickness of the shell is crucial in determining the shell's mechanical strength and the system's effectiveness. The results proved that the core-to-coat mass ratio of 3:1 is the most optimum in preserving the mechanical properties of the system and increasing the rate of storing, releasing thermal energy, and hence enhancing the system's efficiency. However, previous research proved that a ratio of 5:1 is more efficient in terms of energy storage capacity.
- While the selection of the PCM type is highly dependent on the climatic conditions, designing the elements of the encapsulation system such as the shell material, form and aspect ratio will not vary based on the climatic conditions, but rather the selected type of the used PCM.
- The location of the PCM macro-encapsulation system within the building envelope could highly affect the overall performance. However, previous literature indicated that the optimal location is circumstantial and varies from one case to another depending on the climatic conditions, wall orientation, thermal properties, and even the purpose of using PCM. Accordingly, the optimal location of the PCM should be investigated separately in each case.

Based on the previous literature, Figure 12 shows the optimal workflow to choose each factor in the system. Generally, designing a PCM macro-encapsulated system is complicated, and each factor should be studied and chosen carefully. That is due to the fact that each factor is dependent on the other and there are several available types of each. Also, several factors have not been fully investigated, and there is a lack of knowledge covering each aspect.

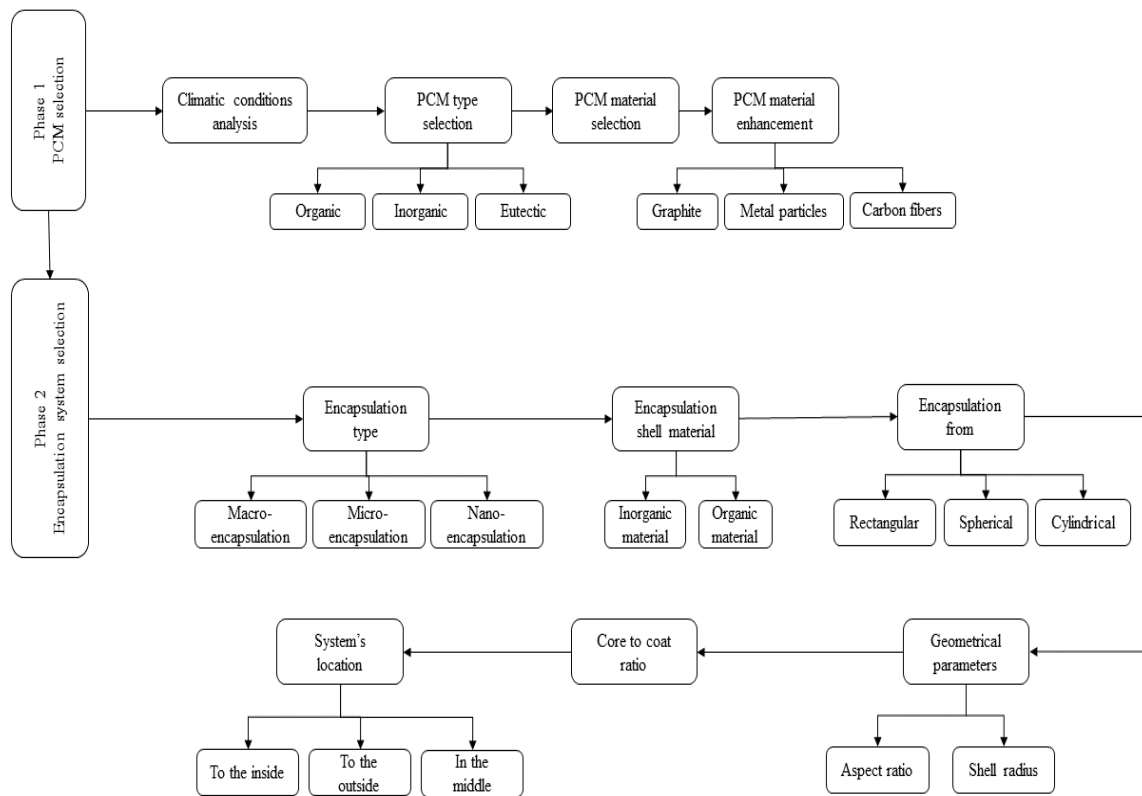


Figure 12: The process of designing a PCM encapsulated system (researcher, 2024).

On the other hand, proving the economic effectiveness of a solution, especially energy-saving ones, is crucial for ensuring its applicability. Furthermore, it will encourage the decision makers and the investors to start adopting the system in the construction industry, which will positively impact the overall performance of the building. The economic effectiveness of a project is usually proven using life cycle cost analysis (LCCA). In energy-saving projects, LCCA is mainly dependent on the LCA of the energy-saving system. In the process of assessing the feasibility of PCM, the optimum solution is the one that provides the minimum use of the PCM and the maximum energy savings. All in all, LCCA aims to calculate all the incurred costs over the project's life span.

In order to obtain more accurate results, the same data input used in LCCA such as study period, initial costs, future costs, and discount rate, several measures could be applied to ensure the cost-effectiveness of the project and clarify that the high initial cost is covered by the operational savings. However, if applied correctly, they will yield the same results as the LCCA. The used supplemental measures are determined based on the type of investment decision. In the case of applying an energy-saving solution to the building as in the PCM system case, the investment decision is accepting or rejecting a single project alternative. Measures such as net savings (NS), simple payback (SPB), discounted payback (DPB), adjusted rate of return (AIRR), and savings-to-investment ratio (SIR) should be applied relative to a base case, which generally has a lower initial cost yet higher operational ones. Generally, LCCA is sufficient in identifying the economic feasibility of a project alternative, however, applying the supplemental measures could add credibility to the cost-effectiveness of the project. Figure 13 shows the key steps of applying a feasibility study.

Furthermore, the investigated studies in the literature regarding the economic analysis of a PCM system are not comprehensive. The PCM system's feasibility in most studies was investigated using only a simple payback period or simple life cycle cost analysis, which leads to unreliable results. In addition, conducting an accurate feasibility study of an encapsulated PCM system is complicated due to the fact that the system has not been widely used, and the data regarding its application is limited.

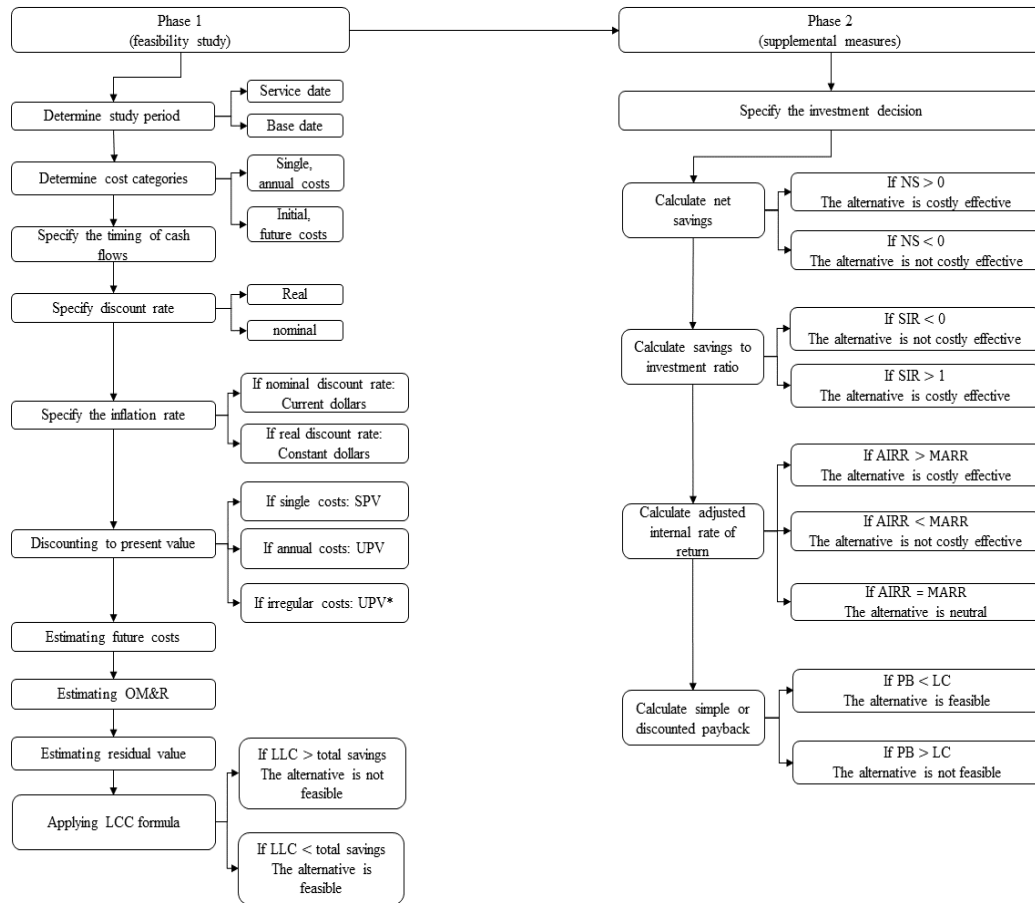


Figure 13: The process of conducting an LCCA study (researcher, 2024).

8. Conclusion and recommendations

The application of the PCM macro-encapsulation system in the construction industry has been deeply studied in recent years. Experimental studies reported huge energy savings and enhancement in thermal comfort levels. Despite the shared merits of macro and micro-encapsulation systems, macro encapsulation is considered more practical due to its flexibility in shell shape, shell material, and PCM selection. However, to ensure the system’s efficiency, the process of selecting PCM, shell shape, and material should be conducted following standard criteria and based on a deep understanding of the behavior of PCM inside each shell form. Furthermore, proving the feasibility of a PCM macro-encapsulated system is essential for assessing its applicability in building envelopes. Based on previous literature and the principles of economic assessment, the feasibility of PCM is usually assessed by conducting an LCCA in addition to supplemental measures such as NS, SIR, AIRR, and payback period. Generally, this research aimed to provide a base knowledge to aid the architects and engineers in the process of designing the PCM system and appropriately choosing the most suitable type of PCM, encapsulation type, form, and material regarding the surrounding conditions. Furthermore, it provided a detailed framework for calculating the LCCA of the PCM system along with multiple supplemental measures in order to accurately assess its economic viability, which will consequently highlight the effectiveness of the system in saving energy and encourage the practitioners in the construction industry to start adopting it. All in all, it could be concluded that the application of the PCM had gained sufficient attention theoretically, and it was proven to be efficient in several climatic regions. However, the application of the system from a practical side requires further investigation regarding several aspects. Furthermore, awareness regarding the sustainable impact of such systems should be arisen and the governments should start studying the possibilities of their integration to encourage architects and contractors to start incorporating them.

9. Future studies

Despite the promising results of applying PCM in building envelopes, some barriers need to be resolved before the system can be applied in the construction industry. The future studies that need to be addressed could be identified as follows:

- The selection of the most appropriate shell form and its related geometric parameters needs more investigation. It would be more beneficial to establish a standard selection guideline based on the melting process of each form and its location inside the building envelope whether it is inside walls or embedded in floors.
- The behavior of the PCM system in both summer and winter should be deeply investigated. Research has shown that in the case of selecting the optimum melting temperature based on winter conditions will affect the PCM performance in summer and vice versa.
- The environmental impact of the PCM plays a major role in accepting its application in the building construction industry. Its ability to be recycled and reused is an area that requires further investigation.
- Based on the previous research, most of the feasibility studies conducted on PCM systems were based only on a simple life cycle cost analysis. It does not take discounting or the time value of the money into account which might overestimate the economic efficiency of the system. A detailed LCCA study should be conducted in different regions to examine the potential of the system's application.
- Due to the limited application of the PCM system, several types of costs including some of the future costs such as OM&R and residual value are not identified. Accordingly, most of the investigated research either ignores these costs or estimates it, which leads to inaccurate results. Future research should focus on analyzing the life cycle of the buildings with installed PCM systems to gain such data. That will profoundly increase the reliability of the results.

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