



Multi-Functional Phase Change Materials: A Review on Integration of Thermal Energy Storage with Smart Building Applications

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Abstract: Phase Change Materials (PCM) can also be seen as a revolution in increasing thermal energy storage and making the smart building design environmentally friendly. PCMs are able to manage indoor environments, save energy, and provide comfort in occupancies by retaining and releasing latent heat during the solid and liquid phases of temperature change. This review explicitly discusses the categories, thermophysical properties and processes of PCMs including organic, inorganic and eutectic and how they are incorporated into building envelopes, walls as well as glazing systems. Interaction of PCMs with Energy Management Systems (EMS), artificial intelligence (AI) and the Internet of Things (IoT) makes it possible to adjust and optimize the energy flows. Reducing HVAC loads and saving up to 30% of energy with the use of PCMs prove to be valid and result in the case studies showing the potential of PCMs to enhance the net-zero and carbon-neutral objectives. Although these factors are problematic in terms of thermal stability, their material degradation, and economic sustainability, recent advancements in the nano-enhanced composite and AI-driven feedback systems should be more reliable and effective in their performance. The paper concludes that next generation smart, resilient and energy efficient architecture, in the overall context of sustainable urban development is made possible by multi-functional PCMs that are the; enabling factors.

Keywords: Phase Change Materials (PCMs); Thermal Energy Storage; Smart Buildings; Energy Management Systems; Nano-Enhanced Materials; Sustainable Architecture.

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1. Introduction

With the increasing population of cities and the aggravation of climate changes, energy systems are under increasing pressure, particularly in the overcrowded urban areas where temperature control requirements would rise. It is estimated that over 68 percent of the world population will have been isolated in urban centers by 2050 hence the shift towards low-carbon city infrastructures has been a significant point of sustainability agenda. In order to cope with this, recently such new technologies as Phase Change Materials (PCMs) have also proven to be the better hope in that regard as it will enable to both optimize the energy usage as well as provide the comfort inside the smart buildings.

The advantage of PCMs is that they absorb and release a lot of heat during the cycle of solidening liquid and solidifying liquid, besides having quite stable temperatures. This special feature does enable PCMs to smooth out the indoor variations of temperature by storing an additional amount of heat upon being made hot and

releasing this heat upon being made cold. This lowers the use of the traditional heating and cooling systems. Latent heat storage process is crucial to managing energy flows in buildings as it is indicated in section 3.1.

These buildings should include PCMs in their building designs to ensure compatibility with the present sustainability objectives of minimizing the quantity of carbon emissions in the buildings in addition to enhancing the comfort of the occupants. Their cooling and heating capabilities would maintain a consistent indoor climate and reduce heating and cooling costs in operation including potentially cutting cooling costs by up to 30% as mentioned in section 5.1. This renders PCMs a central component in the energy management systems (EMS) which depends upon real-time information to achieve the optimal utilization of power as clarified in section 4.2.

PCMs also favor the shift in general that aims at integrating renewable energy along with smart building technology. PCMs enhance the green qualifications of a building by saving the excess



heat collected by its building systems such as solar panels and enable the building to operate efficiently during peak hours when the demand is high so that it does not rely heavily on fossil fuels.

Nevertheless, there, PCMs have obstacles to widespread implementation. Issues regarding their thermal stability, their age-related performance, cost-effectiveness, and their ability to work in various climates must be addressed as stated in 7.1 and 7.2. The current studies are aimed at producing a high-tech PCM materials and techniques, which will help to address these issues and provide sustainable performance.

Summing it up, there are opportunities of sustainable construction when smart building technologies are introduced alongside any phase change materials. As architecture keeps adopting itself to suit so as to gain environmental accountability and the subsequent servicemen demands, PCM as an art in applying PCMs will be to the forefront in ensuring the long-term energy-saving goals in our buildings, [1] and [2].

2. Overview of Phase Change Materials (PCMs)

2.1. Definition and Characteristics of PCMs

Phase Change Materials (PCMs) and substances, which absorb and release a considerable amount of heat when stored between phase and typically between liquid and solid phases. This enables them to save the energy as latent heat which could either be utilized in heating or cooling. It changes phase at a specific temperature termed as Phase Change Temperature (PCT) and the material melts or solidifies. PCMs require the power to handle thermal loads in a manner that will not incur huge temperature variations. Such form of heating control plays a vital role to improve a building in regards to energy and comfort.

The first characteristic of the PCMs is that they will eliminate temperature fluctuation when applied to building structures like walls, roof and floors. During hot seasons they absorb the superfluous heat and when it becomes cool they emit this heat. This improves the thermal mass and inertia of a building reducing the active heating cooling systems. The energy relative savings can be very significant and the reductions usually lie in the range of 10 to 30 per cent on research.

In densely populated cities, where thermal loads may be excessive and PCM offers a cooling option with intelligent advantages of a smart passive cooling system, which is not intensive in electricity, unlike normal air conditioning. According to the section 3.1, the latent heat storage aspect also allows the permanence of constant temperature in the indoors through phase changes that provide the comfort of constant comfort all day long.

PCMs are of diverse forms depending on their chemical composition and thermal characteristics. They are usually of three types: organic mixtures, inorganic mixtures, and eutectic mixtures. Organic PCMs in many cases are based on paraffin waxes or fatty acids, and are low in toxicity, and also reasonably chemical stable, but tend to be low-thermal-conductivity compared to inorganic. Salts and salt hydrates which form a category of inorganic PCMs tend to contain a greater amount of latent heat however may experience issues such as phase segregation with time. Eutectic PCMs are mixtures of multiple materials that will fuse at one consistent temperature providing greater control over the stage

change and allowing the highest amount of energy to be held.

They all possess unique advantages and disadvantages in respect of the environmental impact, price, durability and the use in various building projects. Adding PCMs does not only sensitize the temperature, but it assists in curbing carbon emissions associated with the heating and cooling requirement. PCMs in conjunction with smart building technology enhance the prediction and control of energy consumption under different circumstances according to conditions as discussed in section 4.2 on Energy Management Systems (EMS).

Local climate is important to achieve the successful use of PCMs. It can help a great deal to deploy them in a hot and dry climate with great temperature differences. In more moderate climates where the range of daily change in temperature is smaller, however, it will need to be created to prevent the accidental addition of energy consumption.

The new development has expanded PCM applications of urban structures. Nano improvements in formulation, such as thermal conductivity and vindication with time have been addressed, and some of the main challenges of development are the breakdown of materials, which is addressed in section 7. Research is also geared towards standardization of PCM application in various settings whereby optimization of its application is best achieved according to each climate.

In short, Phase Change Materials have a significant potential as game-changers in sustainable buildings design due to their properties. They do not only enhance the comfort of occupants because they stabilize indoor climates, but also they are compatible with the rapidly developing requirements created by urban development and climatic change issues, [2], [3], [4], [5] and [6].

2.2. Classifications of PCMs

2.2.1. Organic PCMs

Importantly, organic phase change materials (PCM) are important in storage of thermal energy, when a higher level of energy efficiency during the adoption of smart buildings is required. Mostly they consist of compounds containing carbon which are paraffins and fatty acids which have high latent heat and good thermal properties.

One of the benefits of the organic PCMs is that it has lower melting points than inorganic types. This variation is due to the fact their chemical structure and molecular bonds are different. As an illustration, paraffin waxes are usually melted in temperatures that range between 20 °C to 60 °C which is not too painful as far as indoor temperature control is concerned. This gives them a very good match in the construction applications where it is the control of the indoor temperatures that counts the most. The purity of the different compounds as well has an impact on the behaviour of melting; impurities may extend the temperature span of stage change.

The organic PCM has been praised because it can be subjected to several cycles of melt-freeze. Organic substances tend to remain stable as opposed to some inorganic PCMs which tend to supercool or separate their phases with time. Studies have shown that a majority of them may require more than 10,000 cycles to wear out and with this assurance, they will be utilized in smart buildings to offer efficient control in regard to heat.

PCMs that are organic contain high volumetric heat capacity (in terms of energy storing capacity). The latter may also involve fatty acids, which, besides leading to the high latent heat storage, lower the vapor pressures as compared to other inorganic choices. This reduces the issues like leakage between the state changes.

The use of organic PCMs in the building materials has undergone creative approaches such as microencapsulation. Such an approach helps manufacturers to install these materials in the walls or the roofs without loosening the structure. It is also able to improve the velocity of heat transfer and removes the leakage in the phase shifts.

Organic PCM is also applicable in addition to the heat storage experience in order to make the occupation of the buildings comfortable by minimizing internal temperature variations, which in turn, creates a load burden on the air-cooling systems. This loss of peak heating/ cooling of up to 30 percent lowers not only the cost of energy, but also of carbon, and growing concerns of environmental footprints.

Renewable sources of energy should be used as an addition to organic PCMs that would have even more benefits. As an example, the materials can absorb the excess heat generated by the solar panels thus improving the use of power, equalizing the loads in building structures.

The thing is, though, that there are cost-issues with regards to the cost-efficacy of the extensive use. Quality PCMs might be deterred by the high initial cost as it might be reimbursed in the long run by saving on the cost of energy use.

The recent research is directed at improving performance and sustainability. There is an emergence of bio-based organic PCM which is conducive to sourcing being eco-friendly and recyclable according to the principles of a circular economy. Combinations of organic and inorganic composites that are hybrid with both good thermal conductivities also are promising, including stable phase change behavior.

To conclude, organic PCMs can be discussed as the important tools of smart buildings that should be taken into consideration to increase the level of energy saving within the building due to using the modern temperature regulators. They are stable, efficient in thermal performance, and are flexible and are therefore well placed to promote sustainable building and achieve EO targets such as net-zero energy consumption in the future, [2], [7] and [8].

2.2.2. Inorganic PCMs

One of the most popular inorganic phase change materials (iPCMs) is distinguished by good thermal performance and thus it can be used as an energy storage tool in smart buildings. The major components of these materials are salt hydrates and a little bit of metallic alloys. They provide thermal conductiveness and have the ability to store vast quantities of energy/volume and this gives them a decisive advantage over organic PCMs. Through assimilation and discharge of high heat during phase transitions, iPCMs are useful in controlling building temperatures during the day, which enhances the energy efficiency of an entire day as explained in the section above.

Using salt hydrates are some of the most common type of inorganic PCMs. They are effective in a temperature range of about 8 °C to 120 °C and exhibit very little volume change during

the melting and solidifying of the compound. They have high latent heat that ensures they are able to maintain the constant temperatures in indoor surroundings; such that imposes no excessive demand on heating or cooling operations. On the downside, they also on occasion suffer other issues like supercooling since they are kept in the liquid state below their freezing energy, and separation into phases upon repeated use. All these problems can make them less reliable, and less useful in relation to their life.

The good side of iPCMs is the fact that, it is not as expensive as the other energy storage materials are. This economic advantage fosters extensive usage of construction works that will lead to the reduction of the energy usage and the realization of sustainability policy. Furthermore, the case of iPCMs not being flammable as opposed to certain organic PCMs and not typically toxic, iPCMs also have few safety concerns with regard to daily use.

Nevertheless, challenges remain in the area of adoption. The opportunity of corrosion is also a big challenge because salt hydrates may destroy the regular building materials unless protection against contact is provided. This is the reason why the encapsulation of iPCMs is crucial, which means putting them in a solid shell or a composite structure. These measures avoid leak and enhance compatibility of walls, floors and ceilings and stability is guaranteed in the long run.

iPCMs are also vulnerable to mechanical wear caused by numerous heating and cooling cycles and thus the performance of the iPCM tends to diminish with time. A microencapsulation method is used in order to protect the material against the surroundings and minimize leakage, however, the survival is a domain in which improvement is necessary.

To take the performance to the next level researchers are looking at hybrids that combine inorganic PCMs with nanoparticles such as silica or aluminum oxide. The Nano-Enhanced Phase Change Materials (NePCMs) enhance heat transfer without reduction in the amount of energy storage. What is gained is a more efficient and faster responding system to the increase and decrease of temperature.

Designing iPCM Designing with iPCMs requires a tradeoff between such factors as melting point, thermal conductivity, lifecycle costs, and structural integration. This requires to have a close collaboration between material specialists, architects and engineers to ensure the selection of appropriate PCM to use in every smart building project.

As illustrated in history, inorganic PCM type of buildings have reduced heating and cooling requirements by up to 25 percent. These success stories represent the potential of the material under a good handling.

The current research is to address such challenges as the problem of supercooling, which are solved by the use of additives or innovative formulations that retain the structure and maximize the heat storage. There are also state of the art innovations such as AI-based systems to detect PCM performance in real-time and modify its operation according to weather and occupancy trends which perfectly fits the definition of smart buildings today.

Although this process to the ideal inorganic PCMs is in progress, the combination of their great natural merits and the innovative

methods tends to make them revolutionize the energy management of our constructed world, [2], [3], [4], [7], [9] and [10].



Figure 1: Sample of paraffin wax, [3].

2.2.3. Eutectic PCMs

The substance, which qualifies as eutectic phase change materials (PCMs), is described as a specific blend of two or more substances which condense and recondense at one temperature and has lower temperature than the numerous melting points of the actual material composition. This is the only property that allows eutectic PCMs to become the best thermal energy storage and has benefits over the simple organic and inorganic counterparts. Their evident melting point offers accurate parameters of inducing the precise temperature control of the phase changes which is most crucial in assurance of the same standards at indoors in the smart building as explains in valleys above.

Among other outstanding properties of eutectic PCMs is the fact that they are able to absorb and release high volume of heat with almost constant temperature as the liquid is being turned into a solid. This proves especially useful in a scenario where the control of temperature is required at all times like in the buildings which are designed to become more energy efficient and comfortable to occupancy. Such materials have the possibility of removing the variations in temperature which means that active heating systems and cooling can be minimized and, as a result, the total energy consumption will decrease.

An adequate choice of eutectic blend depends upon the number of the following properties demanded; desired melting temperature, thermal conductivity, latent heat storage capacity and compatibility with building material. These are sometimes a combination of organic compounds like fatty acids and inorganic salts or any other organics to optimize thermal properties to suit specific use like in wallboards or ceiling panels in smart building.

However, eutectic PCMs have issues as well. Supercooling can occur and this implies that a substance will be in liquid form below

the freezing temperature, the outcome of which is not good with regard to energy storage, which is uncontrollable with such. Furthermore, long-term thermal stability and avoidance of reaction or deterioration in case there is any combination with other elements of the building are also important attributes to the extended performance.

Recently, the latter has been taken care of by incorporating such methods as the microencapsulation and hybrid mixtures complemented with nanoparticles to increase heat transfer. Microencapsulation also means that there would be no leakages during phase transition which facilitates incorporation into the various building materials in addition to providing mechanical stability.

In addition to that, smart systems based on artificial intelligence have the capability of optimizing PCM through leakage optimization with the manipulation of occupancy and environmental factors. These energy managing systems that will be monitored by AI will dynamically adjust the thermal stores to be more appropriate to the demand in real time, and vary depending on the weather and on the day of the year as stated in the sections above.

Along with its capability to increase the comfort of the people in the building since eutectic PCMs allow to even out the levels of the enclosure, introduction of eutectic PCMs into buildings helps to sustain its purpose in the long-term perspectives that revolve around the diminishing of carbon emissions through the passive use of energy. Among such development efforts, one can distinguish the advancement of the success of the net-zero energy and the implementation of the comprehensive attitude toward the eco-friendly design of constructions.

The research is still ongoing in future to improve the durability and cost efficiency in order to make eutectic PCMs more feasible in the building on big scale. Such advances in productions and sustainable sourcing have the capability of triggering broader implementation in the urban infrastructures, as this is clearly a direction to bring with it more green building solutions to minimize the impact on the environment.

In conclusion, it can be said that the eutectic phase change materials have a great future in PCM. They consist of a combination of stability in thermal work and compatibility in diverse uses of multiple smart buildings aimed at enhancing energy efficiency and comfort to consolidate and enhance the importance of its critical function in determining sustainable urban architecture in the future, [2], [3] and [9].

3. Thermal Energy Storage (TES) with PCMs

3.1. Mechanisms of Latent Heat Storage

PCMs are substances which store a large amount of energy and release it during phase change, which is normally between solid and liquid substance. This has made them helpful with thermal storage of energy especially in intelligent buildings. The feature of a PCM is that it absorbs heat as it melts, and releases the heat as it solidifies. This loop has the possibility to make the buildings more concerning of energy and temperature control.

The central point of functioning of the PCM is the temperature at which the material passes through the state (phase change

temperature, PCT). During the melting process at a very high temperature, the PCM absorbs some heat without heating up therefore referred to as isothermal heating. The heat gained is released as latent heat and thus it cools down creating the stable indoor climate even with changes of the temperature outside.

The usefulness of PCM i.e., latent heat capacity and thermal conductivity is mainly based upon the thermophysical properties of PCM. Latent heat capacity- This is the energy that a substance can absorb / give out in a matter of unit mass with shifting phases. This is quite different like organic PCMs like paraffin tends to contain high latent heat and low thermal conduction compared to inorganic PCMs like salt hydrates or metallic mixture.

The effect of PCM to any change of temperature is determined by its thermal conductivity. Greater conductivity will mean that the material can absorb and release heat faster and this augmented the entire performance of the thermal instability in buildings. This aspect, however, does not work well with pure organic PCMs, hence, react slowly to the variation of loads, when the temperature changes.

Researchers have many ways sets of how performance has been improved. Among them, one can single out the incorporation of thermal conductive materials used in PCM like carbon nanotubes, graphene or fillers composed out of metal. These additions form networks that will enhance the transfer of heat at a faster rate without reducing the natural capability of the heat storage capacity of the PCM.

The other approach stresses on the notion of shape-stabilized PCMs in which PCMs are enclosed in a porous composite or in a matrix. Such structure eliminates leakage during melting and freezing process and enhances the mechanical strength. PCMs are also thermally quite active because of the shape-stabilized ones, which result in buildings being energy efficient in various climates.

Due to the increased temperatures in the cities and the growing need to go eco-friendlier in their design, intelligent implementation of PCM in the cities is a must. PCM installed intelligently in the walls, ceiling, or other aspect of the structure are also applied to enable the buildings to manage the climates found indoors. Nevertheless, it will only be successful with the particular attention to its choice according to the climate of the country and location in the building. Making unwise decisions is counterproductive as it makes the use of energy more intensive rather than reductionary. This is the reason why it is essential to adapt PCM solutions to particular settings and data.

The integration of the smart building technologies and PCMs provides the opportunity of achieving superior control of temperatures by reducing the utilization rates of the traditional HVAC systems, which have a direct, and, in many cases, more degrading impact on the environment. The developments in material science, in combination with real-time computational modeling, are placing PCMs as a central component in the establishment of sustainable and net-zero energy urban environment spaces.

Nevertheless, to develop the materials further, one should research this issue to remove issues related to long-term stability under dynamic conditions. This continuous study will define the extent to which PCMs can be introduced into the architectural field in the coming years in accordance with the ideas of sustainability and

resilience, [2], [3], [5] and [9].

3.2. Advantages of TES in Energy Efficiency

Phase Change Materials (PCMs) based thermal energy storage (TES) have also emerged as one of the shining lights of the quest to enhance the energy efficiency of a building. TES is most effective in balancing the energy supply and the demand, and in the cases of the varying temperatures and energy consumption. Using the latent heat storage of PCMs, buildings will be able to store the additional thermal energy when there is low demand or high solar input, and discharge it when the demand is high. This approach places the conventional heating and cooling systems with reduced pressure.

Operation costs on climate control will minimize with this type of conversion of energy. The ability of PCMs to absorb heat in the melting process and release heat in solidifying PCMs lead to their use in heating the products, as explained in the above paragraphs. This cycle helps in stabilizing the air conditioning in the house which helps calm down the activities of the occupants other than straining the HVAC machines. Studies have proved that PCM-driven structures have the potential of saving up to 30 per cent of the cooling costs, which adds to the reduced energy cost and carbon footprint in relation to energy.

PCM TES systems also give stability of the grids. During off-peak periods, they accumulate heat and release it during periods of peak demand in the energy market reducing fossil-fuel-powered plants which typically come in during peak periods. This is a move towards more environmentally friendly energy profiles and is used by utilities to postpone expensive infrastructure upgrades that are required to support peak loads.

Peculiarities of PCMs provide the opportunity to think of building designs that live in the environment and respond to it rapidly. It is possible to connect EMS (Energy Management Systems) with PCM-based TES to provide a possibility to regulate the climates indoors in order to consider occupancy, weather and use patterns of buildings. This dynamic management raises the level of energy efficiency and makes buildings move closer to the goal of net-zero emissions.

In addition, the existence of the various PCMs; organic, inorganic and eutectic, introduces flexibility in design wherein each kind applies to particular climates and situations. An example here is that the organic PCMs are more stable to temperatures and have been found to last longer than the inorganic PCMs and can therefore be used in locations where temperatures are widely differentiating.

PCM encapsulation methods are also architecture improving methods that do not decrease the style or structural correctness. The presence of PCMs in a wall or surface of the building including plaster and tiles can allow the designers to be able to create a space that is attractive yet at the same time a good thermostat area.

It is backed by case studies in life. As a case in point, research on PCM-enhanced glazing has recorded significant reduction of cooling loads and constant levels of the indoor temperature under hot residential urban heat islands. This proves that the regulated use of PCMs and judicious choice of the material can result in advancement of comfort and efficiency in buildings.

Besides direct savings and comfort, PCM structures will align with the goal of sustainability since it will decrease the consumption of the non-renewable sources of energy. They are also able to be accommodated into a circular economy thinking that helps in building of buildings that are responsive in the altering green systems.

However, problems such as preliminary capital and difficulties to materials to endure the fluctuation of the phases repetitively still remain. To make sure that these issues are addressed, the further development of advanced design and more effective durability should be conducted.

Overall, the high advantages of TES with PCMs ensure its role among the aspects of creation of a sustainable building. It not only optimizes the amount of energy consumed, but also in accordance with environmental goals, which shall characterize the future urban form in the entire world, [2] and [11].

4. Smart Building Technologies: An Emerging Paradigm

4.1. Definition and Importance of Smart Buildings

Smart buildings represent a fresh start in terms of creating spaces we occupy, and the way we utilize them. They also incorporate high technology with design in view of boosting efficiency, comfort and environmental friendliness. Their core feature is the smart buildings, whereby the intelligent systems and IoT devices are applied to keep a vigil on the activities in real time. This enables them to maximize on utilization of energy, make the occupant more comfortable, and emission of toxic substances is minimized.

Another quite noticeable trend is the emerging need of smarter energy solutions especially after urban growth and climate change that places extra pressure on available resources. As has been noted, an important share of the global energy consumption is attributed to buildings; more than 40 percent of the energy consumption is of space heating. This is why, there exists a desperate need to invent better technologies in our manufactured environment so as to ring in the objectives of sustainability needs. Smart building will help minimize the energy requirement and minimize the carbon footprint caused by the construction and operation of the building.

These structures contain Energy Management Systems (EMS) taking the roles of brains. EMS can make instantly efficient changes to improve its performance through a system of measuring sensors which measures the positions and directions of flow of energy. The deeper the explanation of the integration of EMS and AI came, the more predictive abilities it provides, aiding in the planning of the utilization of energy by structures to a more efficient way during times of peak demand. The presence of such type of vision aids in keeping the functioning systems running in an efficient way and it also takes care of the burden on grids.

Besides saving energy, the smart buildings also enhance comfort to users as there is an adjustment of lighting, temperature, and air quality based on tastes and preferences besides occupancy. Another control measure that can be adopted is the addition of the Phase Change Materials (PCMs). These materials can accumulate the heat during sunny days and emittance of the same when needed therefore maintaining the temperatures within a constant in-doors and therefore sparing the heating and cooling machines the task-load.

Green buildings must be accompanied by renewable energy. They are integrated with the application of sophisticated storage technologies like PCMs to utilize clean energy to the maximum and most of them are supplemented by solar panels or wind turbines. The objectives of the net-zero carbon emissions are supported by this plan and it is within the environmental ambitions that are discussed in this paper.

Growth in urbanization with regard to density runs up the significance of resources control. The smart buildings are sensitive and adaptable within the surrounding where the dynamic environment exists and promotes a green life. However, potential hindrances to a mass adoption that still exist are the problem with technology compatibility and cybersecurity threat. Engineers are striving to eliminate such challenges with a view to the production of designs that offer sustainability and do not interfere with safety.

In conclusion, the future of architecture in the world will be determined by the drive of smarter and more sustainable building ecosystem due to the changing nature of technology and human needs. These improvements will be able to satisfy various needs and leave the planet to the generations to come, [2], [11], [12], [13] and [14].

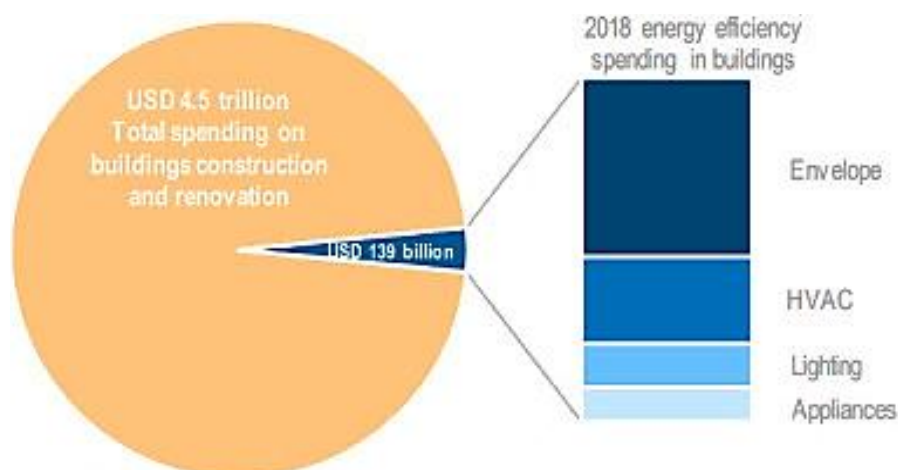


Figure 2: Global spending and investments on building energy in 2018, [12].

4.2. Role of Energy Management Systems (EMS) in Smart Buildings

The Energy Management Systems (EMS) can be discussed as the focal point of smart building operations as it is meant to provide buildings with greater energy efficiency and comfort to its inhabitants. The technologies include many ways of monitoring and controlling the use of energy in real time basis. They do not only aim at meeting the energy demands of a building, but other desired sustainability objectives.

The most significant characteristic of EMS is the fact that it can make use of data in the form of a significant number of sensors located throughout the building. The parameters that could be monitored using these sensors were the occupancy, temperature, humidity, lighting and consumption trends. As per this information, EMS adjusts such systems as heating, ventilation, air conditioning (HVAC) and lighting. An example could be given whereby the occupancy sensors can detect that occupant numbers in certain rooms are low and the system will be programmed to either turn HVAC down or lower the amount of light in order to conserve energy.

The system with Artificial Intelligence (AI) and the EMS application alters the labor cycle of the working system. AI is done on historical data to determine the trends and future rates of energy needs considering the pattern of weather and occupancy. Such vision enables the EMS to be proactive and make it more effective and minimize wastages. The machine learning models undergo continuous development, which varies with the variation of the pattern of use. This offers more responsiveness of the system that makes the operations optimized according to the existing conditions and not according to the predetermined timelines.

The EMS is also applied in the regulation of energy in a number of buildings or entire neighborhoods on the basis of complex activities like demand response programmes. EMS buildings can be turned down such that they can cut their electricity consumption or they can divert the loads of the periods of high energy demand, or when the energy is silent. This would not only lessen the load in the power grids but also be a financial incentive to the proprietors through reduced payments of utility bills or by venturing into the markets of energy.

The other element on which EMS is could be indispensable would be integration of renewable sources of energy. When it comes to the management of such variable sources of power, the management of solar panels installed into the building or wind turbines, in the case of a building, is one of the critical aspects that will enable stabilizing the energy balance. On a case-to-case basis, EMS intelligently selects to be fed either by renewable or the grid by the amount of generation and demand.

Internet of Things (IoT) is also improving the EMS capacity as it enables the remote monitoring and controlling by use of cloud infrastructure that can be accessed via a smartphone or computer. Exceptional energy consumption raises alarm to the facility managers so that they can take the necessary move in time to prevent wastage. Also, IoT improves the communications within the system of smart buildings; one such area is the lighting which will be activated itself, when HVAC sensors will register any alterations in the air quality.

There is one additional feature of the efficiency of EMS added by

the idea of integrating digital twins or synthetic models of real buildings. Managers can develop various situations and experiment with changes in the digital level and implement them in reality. This reduces turnover of the operations because it tries to streamline operations.

The application of blockchain technology should also be considered as prospective in enabling energy-oriented transactions, such as peer to peer transaction between energy-surplus buildings which have surplus renewable energy. It is also able to monitor carbon credits clearly in an event of energy saving made possible with the aid of smart technologies.

Despite such developments, EMS are faced with experience barriers, which hinder the general application. The problem of device incompatibility opens way to the problems that refer to easy integration of the platforms. Cybersecurity threats reveal the sensitive information about the operations. The use of the EMS in the already laid down infrastructure might be costly and the staff must be well trained to enable them to utilize these new high-tech tools.

As the cities continue to struggle with more sustainable and resilient development, proper Energy Management Systems will be required to make buildings future-proof. They help cities meet high climate goals and adapt to the changing weather conditions and human need. The role that EMS is smartly incorporated will be relevant in the future in creating smart and sustainable built environment in the world, [2], [13], [15], [16], [17], [18] and [19].

5. Multi-Functionality of PCMs in Smart Applications

5.1. Thermal Regulation and Comfort Enhancement

PCMs has the potential to become a step wise change solution to thermal comfort and temperature control of smart buildings. This attribute is the special property which allows them to absorb and emit heat during the solutions between solid and liquid phases. This is able to balance the temperature changes within the buildings as well as lessens the need to constantly turn on or off the heating or cooling system, which is a huge benefit in the places where the temperatures are either too cool and too hot in some parts of the day.

PCMs absorb the warmth when the air is hot and release the warmth when it becomes cold and reabsorb it when it gets hot. This is called the latent heat storage and it makes indoor spaces cooler during hot seasons and warm in the cold seasons to maintain a consistent comfortable temperature on the occupants. The reward is two-fold since it will make the place more comfortable and use less energy by becoming less dependent on the traditional HVAC systems.

In addition to comfort, PCMs can be used to reduce energy requirements through the reduction in peak cooling loads. It has been discovered that the use of PCMs will help reduce cooling energy by over 30 percent in hot climates. This translates to a significant reduction in energy expenses and reduction of the carbon foot-print since buildings would not have to excessively use the air conditioning during the heat spikes.

PCMs are flexible enough to be located in most places of the building, such as the walls and roof of a building as well as floors

and even windows. Indicatively, gypsum boards or insulation panels, combined with PCMs, increase the thermal mass of the building. They store the heat on the day and slowly discharged it at night thus passively controlling the indoor temperatures. This reduces the use of mechanical heating and cooling and increases thermal inertia of a building.

Lately, material scientists have succeeded in creating microencapsulated PCMs which can be incorporated easily in the building materials. These new forms accommodate the thermal properties stability with time and the performance of these new forms without degradation at a longer period.

On top of that, one can find smart technologies like artificial intelligence that make PCM use be taken to the next level. The problem that may be resolved are artificial intelligent systems capable of maintaining the real-time monitoring of the indoor temperature and humidity and versatile capabilities to alter the PCM functionality. PCM embedded sensors have environmental information into automated controls that then decide about the most appropriate moment in the cases of intermittent heat absorption or release. It is an ingenious system, which does not make the occupants uncomfortable and also does not decrease the energy that is wasted.

Such a PCMs and renewable energy systems are also highly promising. As an example, the solar thermal panels and PCMs can be integrated so that the buildings would be able to store more solar power produced during the day which could be utilized at the night or during the cloudy days. The positive outcome of such a mixture is the enhanced independence of power and alleviation of power grids with a balanced peak load.

That said, PCMs are yet to encounter a number of hurdles on the road to becoming a common feature of buildings. It is yet to be seen whether they will be sustainable in the long run not only in terms of longevity, but as regards their capability of producing thermal performance that is stable. Moreover, the critical observation of cost-effectiveness in different climates and the type of construction adopted would help to determine in which cases and areas PCMs would be the most logical.

Continued studies are addressing such problems as well as new PCM formulations and uses are being investigated. To develop smart buildings, scientists are interested in extending the existing high-performance building envelopes with PCMs embedded into walls or ceilings to improve the smart building thermal regulation further.

The quest to ensure that buildings are comfortable and energy-saving has become urgent with the population growth in cities and the increase in the severity of climate change. PCMs are one of the directions that promise to make the future of the house in sustainable indoor environments that would allow ensuring both convenience and saving energy, save resources, [1], [2], [5], [6], [17], [20] [21] and [22].

5.2. Integration with Renewable Energy Sources

Table 2 has shown that a massive solution to improving the energy efficiency and sustainability of smart buildings lies in the integration of renewable source of energy and Phase Change Materials (PCM). In addition to facilitating an easy operation of energy, this co-operation also aids in fighting the climate change in

the entire globe by cutting on the use of fossil fuels. PCMs can record and capture renewable energy heat like solar panels and wind turbines to allow it to overcome the issue of these energy being intermittent.

PCM will store the additional thermal energy during the brightest periods of the sun and heat sink in case the demand goes down. This alternating may reduce reliance on grid-generated electricity that is normally also of coal or gas especially when demand is high. At a sensible application, the buildings will be able to funnel their thermal loads during off peak periods that are relieving the power grids and normalizing energy supply that is definitely desirable to the above mentioned benefits of Thermal Energy storage.

The simulation tools developed are concerned with the enhancement of the cooperation between PCMs and renewable. With such models, the designers are also able to test different setups in an attempt to maximize their performance. In the case of buildings being provided with solar panels, indoor temperatures can be equalized so that with the introduction of PCM technology, smaller battery systems could be used. Since a substantial share of the energy load is spread over PCMs, the battery will not exhaust itself as quickly and the cost of maintenance is also minimized.

Simulation based methods also shedding light on the PCM integration mollify the alterations in the supply of energy which is vital to the buildings that strive to reach Net Zero Energy to initiate balance between the energy ingested by the building and the energy generated by the building. The major advantages of PCMs usage lie in that, it will assist in raising the effectiveness of the building itself and lead to the attainment of more sustainability objectives in cities.

Furthermore, PCMs make better use of the other renewable energy to prevent the possibility that the same may have been wasted. On windy cold days, as an example, the fact that it is capable of producing excessively large quantities of electricity which can later be extracted by PCMs to stored heat. The strategy helps in making the indoors to be comfortable as well as minimizing the heating expenses and carbon emission.

The growing importance of smart buildings imposes the idea of the proposal of PCMs regarding promoting advanced environmental control that does not rely on the usual heating and cooling to the fullest scope possible. This intelligent technology combined with PCMs combination enhances the level of satisfaction among occupants and also minimizes the operation carbon footprint.

The PCM integration and renewables also have the economic rationale in their favor. The initial cost of investing in advanced PCM material or microencapsulation can be high but the breakeven period comes after three to seven years depending on the climatic conditions as well as the type of building. In hot or mixed-climate regions where PCMs are combined with passive solar or photovoltaic systems it will be even clearer that the savings will be achieved.

In the near future, PCM products like modified wallboards or tile ceiling as modules offer the flexibility in the new buildings as well as retrofits both. Mass production merits and the increasing use of the products in the industry as a result of standardization will prove good in the future as the building standards looks at the performance of the thermal storage.

In addition to that, alignment of PCM application with the Internet-of-Things (IoT)-based climate control enables buildings to react to occupancy and environmental changes in a dynamic way. This minimizes the chances of oversizing HVAC systems and improves comfort of occupants.

To conclude, the combination of a Phase Change Material and a renewable system of energy is a revolutionary mechanism of smarter, greener urban architecture. This methodology is in line with the international sustainability objectives e.g. the Paris Agreement and the EU Green Deal, and it will contribute to the global decrease in the carbon footprint of the built environment, [2].

6. Integration Strategies of PCMs in Smart Buildings

6.1. Design Considerations for PCM Implementation

Inclusion of Phase Change Materials (PCMs) in smart building designs requires a lot of consideration of various reference points in the design construction to achieve sustainable and effective functionality. The local climate is one of them: it has a significant impact on the thermal load patterns and consequently on PCM effectiveness. As PCMs are based on the use of the latent heat storage, the effect of changes in ambient temperatures can radically influence their performance. It implies that the choice of the proper PCM type should be defined by the local climate to maximize the use of thermal energy management.

In areas that experience radically changing temperatures it will be important to make choices of PCMs, which is melted at suitable temperatures. As a case in point, PCMs that melt slowly ought to be installed on the roofs or the front of the buildings on the open area which are in the hot arid weather because it will absorb the heat during the day and relinquish it back at night as the weather cools down. On the other hand, a lower melting point PCM in the personalised walls facilitates in normalizing the temperature of the interior of the daytime in the warmer climates with smaller diagnostic variations, thus increasing the comfort degree of the inhabitants.

The placement of PCMs on the building envelope is also extreme. They are to be placed in good location, and they should have been secured well such that there is no leakage and resultant waste of material with time. Further encapsulation schemes include shape-stabilized PCM-microencapsulation or microencapsulation or shape-stabilized PCM to ensure stability and ensure reliability of thermal behavior of the changes in positions. Without adopting these durability concerns, not only the entire system, will be in a position to generate equal benefits.

Intervention of PCMs into the existing building systems by a combination requires so much collaboration between architects and engineers. Design must conform to the passive strategies (e.g., insulation) and active systems (e.g. HVAC). Smart integration is the key element that needs to be taken to guarantee maximum saving of energy throughout the building life. Facilitating will be via Energy Management Systems (EMS) that is a sensor to collect real time data of the interior conditions. This data assists in dynamic modification of PCM application, depending on such parameters as thermal lag, occupancy and consequently, makes the use more comfortable and makes the amount of the consumed

energy less.

BIM is a computerized application that has been very effective in the design process. BIM also possesses the functionality of being able to provide explicit visualization and simulation platform wherein architectures can experiment on how PCM will behave, as well as building elements subject to different environments. Latent heat and thermal conductivity which are introduced as the thermal physiological properties enable designers with more accuracy when it comes to forecasting interaction. This will minimize unplanned circumstances of construction and operation.

The continuous execution is achievable as a consequence of the introduction of Internet-of-Things (IoT) devices, being the components of the BIM systems. The feedback is received by the operators of the building immediately and will give information regarding the tendencies in the temperature and how the functionality of PCM has changed. This is used in the maintenance decision-making and this guarantees that the fatigue or degradation of the material is detected early before it has any negative impact on performance.

Economics also has an influence on PCM. The initial cost is used in LCA to contrast the long-time saving and environmental evaluation of the resultant saving. The recent progress on the materials of high performance including the Nano-Enhanced PCMs is expected to offer a balanced ability of power in the cost and efficiency aspects. The total embodied carbon and the monetary metrics enable the designers to have a clear-cut view of the trade-offs in this and make decisions that appeals to the budget as well as the sustainability goals.

Lastly, these certification schemes such as LEED or BREEAM into the green buildings require complete documentation to make. PCM data used in BIM is used to track the amount of energy being saved in addition to the overall impacts on human comfort in the different seasonal conditions.

In conclusion of the above, both climate-specific choice of material and a well-developed encapsulation, an intelligent location, and organizational work of the system can only be successfully implemented in cooperation with constant monitoring, correct economic and regulatory concerns and planning. Using the latest digital solutions, it is possible to be sure that the designs would be sustainable, and they would meet the requirements of the occupants, [2] and [4].

6.2. Case Studies on Successful Integration Projects

Application of building designs using phase change materials (PCMs) has been effective in some parts of the world which has proved that they can be used to improve energy efficiency, enhancement of thermal comfort as well as sustainable architecture. A good example is one that is taken in an office building located in Stuttgart, Germany. Microencapsulated PCMs were embedded on the wall systems there to ensure maximum heat storage and regulation of indoor temperatures. All these PCM-filled walls saved all the surplus heat in the daytime and emit it at night, and this drastically reduced the necessity of mechanical cooling. This solution resulted in a reduction of the energy consumption of HVAC by about 25% proving that PCM can be used to achieve energy reduction goals as well as enhance occupant comfort.

A good example of this is a high-rise residential project in Dubai. The glazing of the building facade had PCMs built into it, and the material acted as a thermal material of the same phase change temperature as the highest temperature of Dubai outdoors. This passive cooling reduced the electricity used in the cooling process and this especially during peak hours. Consequently, the project recorded the reduction of the annual energy expenses by approximately 20 percent and retained the interiors pleasant to occupants.

In Tokyo, Japan an urban development program incorporated PCMs in building roofing materials to improve thermal performance in weather changing conditions. The concept of the project was to be carbon-neutral with the use of high-tech technology, concentrating on the principles of sustainability and climate resilience. There was good thermal cycling stability with the selected PCMs, which were optimized to store high temperatures and it had high latent heat capacity during testing.

Another example is that of PCM-enhanced wallboard panels that were employed in educational buildings in Sheffield, UK. The project promised to make the classroom a more flexible learning space by stabilizing the temperatures and enhancing life in the classrooms with better indoor air quality through embedding PCM into the walls. Findings indicated that the highest drop in the indoor temperature reaches a 5 °C relative to the conventional classrooms without extensive use of the conventional heating and air-conditioning systems.

Another new practice was revealed when a commercial area in a mixed-use development was equipped with a mixture of PCMs and

renewable energy. The inclusion of solar panels and PCM storage ensured that there was successful coordination of the climatic control, shaving of peak loads which reduced operating expenses and enhanced environmental sustainability.

Residential hot water researches also pointed to the potential saving of energy by PCMs in residential hot water systems. The experiments proved the inclusion of PCMs with solar thermal units made it possible to significantly reduce the total energy consumption in heating as it points to the versatility of the materials not only when used as envelopes of buildings.

The current trend of the heterogeneous projects to the holistic designs that mix the use of PCMs in the combination of the intelligent sensors and automated controls is increasing. These systems not only make the individual components more efficient but they also are useful in long term sustainability planning in a more efficient manner.

It is worth noting that some of the barriers remain among which are total problems such as the issue of material degeneration and economic viability are realized in some of the projects. In the quest of making it more extensive, researchers have come up with more potent formulations of PCM to reduce phase segregation and improve costs and advantages of the material.

All these demonstrate that PCMs have a lot of potential in the development of the new generation smart buildings. They help the buildings to be more efficient, comfortable to the inhabitants and are driven towards the environmental sustainability objectives that are advanced by international efforts., [2] and [20].

Table 1: Energy consumption and cost savings before and after PCM integration, [2].

Building Component	Pre-PCM Energy Consumption (kWh)	Post-PCM Energy Consumption (kWh)	Energy Savings (%)	Pre-PCM Cost (USD/year)	Post-PCM Cost (USD/year)	Cost Savings (USD/year)
HVAC System	5000	3750	25	500	375	125
Lighting	2000	1800	10	200	180	20
Overall Building	7000	5550	21	700	555	145

7. Challenges in Multi-Functional PCM Deployment

7.1. Thermal Reliability and Degradation Issues

Effectiveness of smart building utilizes the use of phase change materials (PCM) that heavily rely on the thermal reliability and degradation. The latent heat storage ability within every cycle of phase change of PCMs may potentially decays with time via a number of degradation processes. The exponential decay model is one of the ways through which this loss can be explained, as it is a model with which the thermal storage capacity (Q) declines, with repeated cycles. It is a process of decay which is given on a constant (k) the greater the constant the faster the degradation process. Mathematically, the capacity at t cycles (Q_t) can be expressed in terms of the initial capacity (Q_0) as in the following way.

To a large extent also durability of PCM is subject to chemical stability. Overtime it may deteriorate chemically or phase segregate due to exposure to varying temperature which alters the heat storing properties of the system and system efficiency. A case in point is salt hydrates which are often incongruently melting, where changes of phases take place with a liquid and a solid phase decanting. It not only impairs the efficiency of the heat storing, but can lead to leakage or content of the building parts.

The skill to integrate with the encompassing materials is vital to long term performance as well. In the event that PCMs are not compatible with materials (ideally concrete or metals) such swelling and shrinking that happen during the phase transitions might cause corrosion or structural bursting. One also needs to uphold structural integrity and has to remain undamaged and has layers in composite wall structure and does not divide them asylum.

These problems have been overcome through encapsulation methods that aim at protecting PCMs that are in close touch with building materials. The structure of PCM regulated by the present microencapsulation is superior and reduces instances of chemical reactions resulting in degradation. The enclosed systems also increase safety since they decrease reactivity and also exposure to the surrounding.

However, issues of PCMs use in buildings regarding its sustainability in the repetitive cycles exist. Studies indicate that not all organic PCMs can be used in high temperatures as they develop with age. Also, most types of organic are not good thermal conductors, and this reduces the heat transfer during charging and discharging processes, reducing the efficiency of the cutting system.

All this is further complicated by thermal hysteresis that varies the melting and freezing points with temperature. It may complicate the management of the energy as well because real energy savings may not be in agreement with predictions once the PCMs are utilized either in heating or cooling.

Even economic reasons are keeping the larger use of PCNs a slowing trend. Initial expenses on high-end encapsulation and high-grade materials can tend to backfire on the long-term energy

savings unless considered alongside the long-term planning designs.

In the future, new materials that maintain the high levels of thermal stability and minimize the risks of fire outbreaks should be considered as a possible solution because, currently, fire security is one of the toughest issues in the construction industry. The other opportunity that can be pursued is to advance more on encapsulation to promote conductivity but in the process, not to render it very expensive. The study of nanostructured composite material is hopeful as it has been capable of offering apparent path through which the conduction of heat can be done more efficiently as compared to the PCMs.

On balance, it is possible to note that the hard work of overcoming these challenges through the strong testing will give the way to more trustful PCM applications. The purpose of these solutions is to make sure that optimization of the heat performance is achieved and this does not affect the structural safety and the sustainability goals. Careful integration of PCMs in everyday building could provide the environment more comfortable, eradicate energy inefficiency, and reduce carbon footprints and give back to the economic, environmental, and social wellbeing. By such holistic strategy, the buildings will be smarter and will be at peace with the planet to the advantage of all stakeholders, [2], [7], [21] and [14].

Table 2: Densities and volumetric heat capacities of various phase change materials (PCMs), [2].

Material Type	PCM Name	Density (kg/m ³)	Volumetric Heat Capacity (J/m ³ ·K)
Organic	Paraffin Wax	900	2,500,000
Organic	Fatty Acids	920	2,400,000
Inorganic	Salt Hydrate	1200	1,700,000
Inorganic	Gypsum with PCM	1100	2,200,000
Bio-based	Bio-based PCM	1000	1,800,000

7.2. Economic Viability and Cost-Benefit Analysis

To understand the real worth of the phase change materials (PCMs) in the feasibility and sustainability of a project, it is important to evaluate economic viability, and do the cost-benefits analysis of the PCMs in smart buildings. Implementing PCMs in building designs have their obvious financial benefits and at the same time have associated challenges which need to be addressed, to realize their potential.

It has a significant economic advantage; a reduction in the costs of heating and cooling. As argued above, case studies show that PCM buildings have the potential of reducing energy usage by a significant margin. An example is the Stuttgart office, which incorporated microencapsulated PCMs of its walls; overall energy consumption of the office came down by approximately 21 percent relative to its consumption in the past. These savings were then used to translate into significant cuts in day to day expenses taking the pressure off the budget.

With that said, the initial investments used in the integration of PCM tend to be more expensive because of materials and the need

to have specialized facilities. Luckily, there has been continued development of production methods in an effort to minimise such costs. As an illustration, ongoing manufacturing procedures focus on raw materials with reduced carbon content, which in addition to reducing environmental imprints reduce costs relative to outdated PCM alternatives.

Monetary financial incentives are also a significant factor in promoting PCM. Builders who use green technologies such as PCMs are often giving tax breaks or grants by their governments. Such funding decreases the impact of startup expenses and thus developers who fear making an early expenditure would find it easy to jump.

PCM can also be associated with improvement of property values. As it has been observed in previous arguments of the advantages of thermal comfort, buildings that demonstrate a strong temperature control by the use of PCMs usually command a high price in the market. Customers and tenants are more and more inclined to dwell on energy-efficient buildings and are ready to pay higher prices on them. Indications reveal that green certification involving

the use of innovative materials like PCMs as value additions are recognized as an appreciation of sustainable projects by real estate markets.

The whole lifecycle is crucial in the aspect of seeing a long-term economic picture of PCM use. Monitoring of the savings of the operations and the maintenance costs such as the routine checks of the performance decline as discussed earlier allow the owners to make predictions of returns that are more realistic. The emphasis instead of only addressing the initial costs is also placed on the durability and low maintenance cost factoring in the costs in the long-term.

The hindrances to economic feasibility do persist particularly when it comes to providing thermal consistency even when there are degradation problems. The necessity not to repeat the same item over and over again and not to become spent over the centuries demand constant work in terms of searching of more persistent materials and smart encasement. These measures aid in the minimization of risks of chemical instability or leakages in the course of alternative phases change.

Education also matters. It would be well-developed through architectures and builders on the principles of sustainable PCM to boost the acceptance of the practice in the industry. Formation of installation ideal practice, maintenance and system behavior creates trust and facilitates the adoption.

Another thing that is essential is the development of shared norms. The standardized procedures provide standardized PCM interactions and adherence to the dynamic policies of the green building, which is executed with a firmer hand throughout the world depending on the progressive anxiety levels of climate.

Finally, close management of the performance of the PCM systems through performance monitoring on a regular basis provides certification of the expected energy and cost cut in real-time. Such transparency will enhance accountability and also instill confidence to the stakeholders that investments do not fail to deliver on the promise.

All said and done, although integrating PCMs will incur initial expenses and few challenges, it will only be a good investment in the long term as it can help save a lot of energy, raise the value of property value, and create the sheath of long-term sustainability. The adoption of PCM can establish smarter, environmentally-friendly cities free of harming occupant comfort by balancing the interests of architects, engineers, contractors, financiers, and policymakers, [2] and [21].

8. Future Trends and Research Directions

8.1. AI-Driven Feedback Systems for PCM Composites

Artificial intelligence (AI) applications in the control of phase change materials (PCMs) is one of the steps that have been made to facilitate energy savings and temperature regulation in intelligent buildings. The feedback systems based on AI offer a real-time control and optimization of PCM operations, which is used to make optimal use of the energy throughout the day. Such systems are grounded on the information which is collected with the help of a network of sensors that are mounted on the very building. They log data on the streams of information about the temperature and humidity, the occupancy and other environment information

regularly. This helps the PCM systems to be adjusted literally as per the actual conditions and not under any rigid presumption.

One of the best needs of AI systems is the ability to improve predictive modeling. Even though the traditional approaches do not focus on some of the changes or variable conditions, AI algorithms can use the available information as well as the historic data to forecast the thermal reactions more closely. The use of this knowledge can be to calculate the time and quantity of heat to be stored or released with the help of PCMs in the buildings. An example would be in case of unforeseen heatwave the system can pre-activate other modes in order to achieve as much bunkling as the comfort of the indoors can take without being compromised.

Reinforcement learning in this case presents special possibilities. These models reward software agents through trial and error to develop best strategies that enable the agent to be rewarded by making good decisions when controlling them. It entails them being empowered in deciding whether HVAC should be operating or shades should be closed depending on the current state of PCMs and the future forecast of the occurrence as well. This deception is specifically favorable in urban areas where the energy demands are of most differing nature during the day because of weather variations or intrusion changes.

It also has a high degree of flexibility because the AI-based feedback will rely on the PCM life cycle. The obtained information is applicable both in the short-term management and long-term amelioration activity. The facility managers will get the chance to observe PCM behavior under various situations like being humid or daily fluctuation among other factors and to optimize the work of the systems.

These artificial intelligence devices are further boosted by incorporation of Internet of Things (IoT) technology to enable the sensors and control interfaces to communicate without difficulties. One such case is the smart thermostats that receive updates on the PCM sensors and adjust the heating or cooling plans. This feedback is the process of self-readjustment, which is an everlasting process, and is not subject to any human intervention and is controlled by predetermined comfort goals.

And as such with this perpetual stream of information buildings can become more active in reacting to new situations than merely reactive. This is essential during extreme weather conditions, where getting the comfort levels too high without excessive increase in the energy consumption when need arises is the objective of such proactive capacity.

Besides the direct control, the machine learning solutions may be applied to pass the information about the structural stability of PCMs over the time to the feedback systems. They also simplify and model more suitably the behavior of the materials under different stresses when applied thereby reducing the overall design and management methods.

Net-zero energy buildings will play significant roles in AI-controlled PCMs in their pursuit of the cities which have far-seated climate resiliency targets. These intelligent controls detected along with renewable sources of energy like solar or geothermal will reduce fossil dependency in integrated city society.

Recent trends in machine learning algorithms have high chances of improving the control of PCM interactions with the other building

components in diverse climates. Some of the models may be developed in future with more aspects on the performance of PCM which would help to narrow the predictions even in uncertain situations.

It is not only that the cooperation of AI and PCMs cannot help but also contribute to the green building and smart urban design. As cities are adopting these technologies, the scope of their uses will also be higher and these are the infrastructure of the sustainable cities in the future, [1], [2] and [10].

8.2. Innovations in PCM Materials and Technologies

The current developments in the field of phase change materials (PCM) can be attributed to the heightened demand in the direction of greater thermal efficiency, sustainability and uninterrupted supportive and effective integration with intelligent building. The most fascinating of them is the appearance of nano-enhanced PCMs (NEPCMs). These materials are far more conductive to heat as they incorporate nanoparticles in form of carbon nano-tubes and graphene. This adjustment increases the absorption and release of heat faster and NEPCMs are best suited in usage as insulation of buildings besides controlling heat like the use of battery systems. PCM can also be mixed with PM heat fillers such as the expanded graphite and metal foams to improve its operation and reach high thermal conductivity, especially, in thermal control of batteries.

The other one is the hybrid PCMs that are applied as a mixture of different materials as a means of describing the flaws of single component systems. An example is multi-PCM schemes which optimally react to seasonal variation using PCMs with optimal thermal reaction in a specific temperature subband of the year. The building is energy-saving in addition to the fact that the buildings have been made more comfortable to occupants.

The PCMs in the classical form have been long struggling with leakages prevention which is effectively handled through new ways of confined techniques. These can be the macro-, micro-, and nanoscale encapsulation of PCMs in porous substances, or as a result of fibers and nanoparticles. These boost thermophysical values and reduces the possibility of degradation in the long term.

Artificial intelligence (AI) and machine learning (ML) are also taking hold as the way of computer-programmed controller (PCM) design and optimization of functionality. The optimistic models built based on AI on a data volume sets found the best integrative approaches to introduce PCMs into the building energy system. Meanwhile, the ML algorithms can also deliver dynamic control and real time monitoring which reacts to the modifications of the surroundings and pushes the system performance to the new level.

PCM study is assuming a sustainability-based approach. Carbon footprint of the manufacturing process is helped by the utilization of locally available and environmentally-friendly raw materials. The designers who design material passports also use the principles of the circular economy that will trace the recyclability and biodegradability of PCMs once they are thrown away at the end of life.

Of concern is that the bio-based PCMs based on renewable products are increasingly becoming more popular as alternatives to the traditional paraffin or salt hydrate materials. These are more environmental friendly and they are in line with the global sustainability.

The efficiency of PCMs in varying humidity conditions and cycling constitutes the measurements taken in the current research to add certain dependability and stability to the PCMs in a diverse climate. Such work is achievable through materials scientists and engineers who collaborate, as well as sustainability experts, resulting in optimized designs that are designed to fit a given environment.

Same numerical optimization is a development of PCM optimization taking at the next level by employing an amalgamation of thermodynamic data and real-life data. The simulation of the heat moves between buildings with PCMs is done by available means of computation such as the computational fluid dynamics (CFD) to ensure the predictions are accurate.

All this in combination creates a breakthrough of the PCMs in smart buildings. They consider such materials as important stakeholders in ensuring that they become more efficient in their energy consumption in addition to developing to provide comfortable and sustainable living conditions, [2], [4], [10], [20], [25] and [26].

9. Conclusion

Introduction of PCMs in smart buildings can be described as a big jump towards designing cities in terms of energy use of the buildings. Based on the observation observed in the course of the report, the temperature within the premises was controlled using PCMs in the process of storing and releasing thermal energy during the phase changes. The given privilege not only makes the occupants more comfortable but also reduces the use of traditional HVAC systems or reduces the operation costs and reduced carbon footprints.

The latent heat capacity and the thermal conductivity are the thermophysical characteristics that are relevant to the latent heat storage process, which is explained in section 3.1. The shape-stabilized PCMs and other developments at incorporating conducting additives occur in order to enhance these properties. The above improvement will allow the buildings to be adjusted to changes in temperature better so as to attain energy conservation.

In section 4.2, it is revealed how Energy Management Systems (EMS) are important in maintaining efficiency in managing building energy. EMS utilises sensor data in real time to assist in predictive maintenance, as well as adaptive control, which offers the optimum functioning of PCMs. AI when combined with EMS will improve predictability and enable buildings to regulate energy consumption in peak demand, which will help keep the grid in check.

In addition to control over temperature, section 5.1 demonstrates the extended nature of PCMs in smart buildings. They assist in storing excess heat in solar panels during the peak generation stage to balance the load, and minimize the usage of electricity that is produced using fossil fuels during peak seasons.

Design is another considered area that is important in the effective implementation of PCMs as discussed in 6.1. Agglutative positioning of the building envelopes and highly developed encapsulation techniques guarantee the durability and performance maintenance. The cooperation between the architects, engineers, and material scientists is essential in order to develop the solutions that combine the functionality with both aesthetic and functional purposes, at the

same time increasing the level of energy efficiency.

Various challenges still exist to the adoption of PCMs despite the advantages. The issues of thermal stability and degradation of the material as mentioned in section 7.1 act as impediments to long-term reliability. Improved PCM designs should address these concerns by developing innovative, safer, and ever-cost-effective designs of PCM that would not degrade over time.

It could be projected on to the future that with interdisciplinary research that incorporates AI-driven feedback mechanism of composites with PCM (section 8.1), it is possible to have real-time monitoring of and making adjustments in smart environments. This will achieve new opportunities to sustainable architecture which will be net-zero aspirations.

PCMs do not merely add to the cities in pursuit of the infrastructure robust to climate change, but it forms the component of offering the solution needed, the future environmentally-friendly building. The capacity to qualify their emissions as well as enhance the comfort of the inside makes them central to the next-generation innovation in the field of architecture.

In conclusion, it can be said that the possibility of the application of PCMs in intelligent buildings is literally the key to the green urban design that will be tailored to the requirements of the environment of this time. The additional focus on the research and development will unify the practical application of technology and help to create the buildings that will include human needs and planet well-being.

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