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# A review of energy conversion technologies in evacuated tube solar collectors using phase change materials (PCMS)

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**Abstract**
This review provides a comprehensive summary of the latest advancements in energy conversion technologies for phase change material (PCM) integrated evacuated tube solar collectors (ETSCs). In the context of increasing global energy demands and environmental concerns, the application of PCMs in solar thermal systems has emerged as a viable option to improve thermal efficiency and achieve efficient thermal energy storage (TES). The article begins with an overview of PCMs' thermo physical properties and classifications, followed by detailed discussions of their applications in active and passive solar heating systems. Particular focus is placed on evacuated tube collectors, which outperform conventional flat plate collectors by better retention of heat and optical efficiency Integration techniques of PCM, such as annular filling, internal/external embedding, and fin-assisted heat transfer, are contrasted with each other in terms of the merits and demerits. A comparison study of the performance of five PCM candidates (Paraffin, Triacontane-Paraffin, RT65, RT70HC, and RT82) is conducted and found that RT82 and RT70HC are the best in terms of thermal efficiency in the operating temperature range of 319-329 K. In addition, literature-supported solutions such as cascaded PCM designs and thermal conductivity enhancement by using metallic fins or nanoparticles are proposed as primary solutions for heat transfer improvement and storage capacity. The paper concludes by recommending further research into hybrid PCM systems and their practical implementation in real solar energy systems. This review aims to close PCM knowledge gaps in selection, design, and application, with the ultimate objective of facilitating more efficient and sustainable solar thermal technologies.

**Keywords:** Phase change materials (PCMS), evacuated tube solar collectors (ETSCS), thermal energy storage (TES), solar thermal systems, heat transfer enhancement

## 1. Introduction

As a step for reducing environmental stress and increasing energy demand, renewable resource development and thermal energy storage (TES) technology have become the focus of widespread attention. TES systems could contribute significantly to greenhouse gas reduction and fossil fuel mitigation [1]. Since solar and wind power, being renewable sources of energy, are dependent on weather conditions and do not at all times arrive at fixed intervals, utilization of storage systems to supplement fluctuating levels of power generation is essential [2]. Of the two options for choice, thermal energy storage is comparatively cheaper economically than electrical energy storage and hence an economic choice [3].

Among various TES methods, the use of phase change materials (PCMs) has attracted much attention due to their large thermal energy storage capacity at constant temperature [4]. Compared with batteries, PCMs store more energy per unit volume and are considered a potential solution for electricity saving and reducing energy costs [5]. These are used for short- and long-term thermal storage, like for storage on a daily and seasonal basis. When there is an excess of energy production, heat is taken in by PCMs, which can be released during periods of energy deficits [6]. Seasonal thermal storage using PCMs requires the availability of insulated thermal mass and the process of stable super cooling [7]. PCMs with this capability can store energy for extended periods of time without loss. Such unique characteristics render PCMs highly suitable for the storage of solar thermal energy as they can store an enormous quantity of energy at a constant temperature [8]. This aspect can potentially enhance system stability for solar collectors and create possibilities to expand large clean energy systems [9].

Solar collectors are important in thermal energy harvesting as they gather solar radiation and turn it into heat. Among all types of collectors, the most common ones are flat plate collectors (FPC), evacuated tube collectors (ETC), and compound parabolic collectors (CPC). ETCs are better compared to FPCs due to their higher solar absorption efficiency and lower thermal losses [10]. These collectors come primarily in three forms: thermosyphon, heat pipe, and U-pipe. Among them, ETCs with a thermosyphon configuration are more prevalent because they possess a simpler design, are cheaper, and possess relatively better thermal performance [11].

ETCs' working relies on various parameters, including geographical location, installation angle of the tubes, tube configuration, heat transfer fluid, and tube shape [12]. ETC systems can either be a direct or indirect circulation system. Direct heating and circulation of domestic water through the collector is possible in direct circulation, while in indirect circulation, domestic water is exposed to heat via a heat exchanger [13]. A typical ETC structure consists of two concentric borosilicate glass tubes with partial vacuum between them. The outer tube is highly transparent, while the inner tube is provided with high-absorptivity selective coating. The heat transfer is carried out through internal heat pipes and aluminum fins, which provide mechanical strength to the pipe as well as enhance heat conduction [14].

Due to the intermittent nature of solar radiation, thermal storage devices or booster devices are needed to have a steady supply of hot water. In this context, phase change materials (PCMs) have shown specific interest due to their high latent heat storage density [15]. PCMs are commonly categorized as low-melting point and high-melting point PCMs. Paraffins are particularly favored for solar collector systems among low-temperature PCMs because they are chemically stable, nontoxic, fire resistant, inexpensive, and readily available [16].

Apart from their advantages, use of paraffins directly in evacuated tube collectors has some limitations. One such limitation is thermal compatibility between melting point of the PCM and the internal working temperature of the tubes under vacuum, ranging up to 180°C. As such, the choice of PCMs having appropriate melting points and high thermal stability is extremely crucial for successful and safe thermal energy storage in ETCs [17]. Keeping the above facts in mind, it is obvious that integration of phase change materials with evacuated tube solar collectors is a promising strategy towards increasing energy conversion efficiency and thermal storage capacity. Yet, despite significant research work, there remains a lack of adequate integrated information regarding selection, configuration, and utilization of the optimum PCMs in ETC systems. Therefore, the primary focus of this review is to provide a comprehensive overview of energy conversion technologies used in evacuated tube solar collectors with the assistance of phase change materials. The review should include recent developments, point out key challenges, and show promising areas for future research and development for this new area of endeavor.

## 2. Literature Review

The world's increasing demand for renewable energy and sustainable technologies has instigated large-scale research into new methods of enhancing energy storage systems. Among this list, Phase Change Materials (PCMs) have been a promising candidate due to their ability to charge and discharge high amounts of latent heat during phase transitions. PCMs are particularly interesting for application in solar thermal systems, where they can easily buffer the temperature fluctuations and extend the usability duration of collected solar energy. In this chapter, a review of the fundamentals of PCMs, their classification, thermal properties, and recent advancements in their utilization with solar thermal systems such as evacuated tube solar collectors (ETSCs) is given.

### 2.1 Phase Change Materials (PCMs)

In recent years, the application of Phase Change Materials (PCMs) has drawn greater scientific interest and prominence in the area of efficient utilization of energy. The theory, engineering, and evaluations of the use of PCMs to store latent heat have been thoroughly explored [17-20]. If the ambient temperature is above the melting point of a PCM, it undergoes a phase change from solid to liquid and emits heat from the water storage tank during daytime. If the ambient temperature falls below the melting point of the PCM, it emits heat to the environment while undergoing the phase change from liquid to solid.

PCMs have been found to be efficiently used as energy storage devices in solar engineering, heat pumps, spacecraft, and various other uses [21].

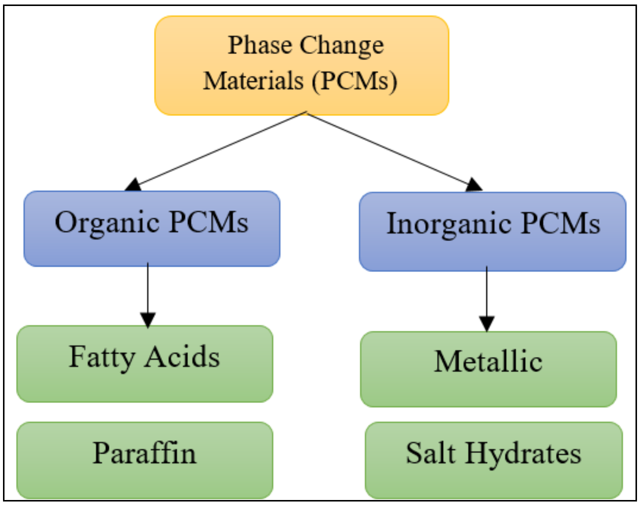


**Fig 1:** PCM classification into organic and inorganic PCMs

### 2.2 Organic Phase Change Materials

Fatty acids are often used in thermal storage systems because they are cheap and easy to obtain. Their melting points range from -5 °C to 71 °C, and their latent heats are between 45 and 210 kJ/kg. Chemically synthesized substances and eutectic mixtures of fatty acids, however, are not as preferable for direct practical applications as the commercial ones. Feldman and coauthors [22, 23] analyzed the properties of some of Henkel Canada's fatty acid compounds, but since some of the eutectics have such a pungent odor, they should not be employed for stuffing walls.

For n-alkanes, the latent heats of various compounds are quite distinct. For example, dodecane has a latent heat of 135-216 kJ/kg, tetradecane of 172-258 kJ/kg, and octadecane of 203-251 kJ/kg. Dutsenko *et al.* [24] demonstrated that n-alkanes containing an odd number of carbon atoms exhibit some phase behavior in the solid state. While dodecane is not seen to display this effect, Hong *et al.*'s [25] reported value for its specific heat needs reassessment. Due to their cost, these materials only have use in particular instances. Industrial waxes and paraffins, on the other hand, due to production in large quantities, are more cost-effective candidates for solar systems for heating. In addition, Kakowichi *et al.* [26] demonstrated suitable characteristics of erythritol as a PCM, and later, trimethylethane (TME)-based materials were investigated for the application of thermal energy storage [27].

### 2.3 Inorganic Phase Change Materials

Inorganic materials such as salt hydrates, while possessing a high level of thermal energy storage capability, have not received the same interest as organic materials. Thermal instability and supercooling tendency are one of their major issues and limitations to industrial applications. Scientists are working to devise a solution in the form of novel compounds made from salts, which is time- and research-intensive. Nagano [28] reported manganese nitrate hexahydrate as a candidate with melting temperature of 7.7-25.3 °C and latent heat of 125.9 kJ/kg. The same researchers synthesized a new material based on magnesium nitrate hexahydrate [29].

To be used on a commercial basis, the purity of PCMs must be at par with commercially available products. Hong *et al.* [25] analyzed the heat capacity and latent heat of sodium acetate trihydrate, while Inana [30] conducted the thermophysical property analysis of paraffin 53 both in solid and liquid states. These findings can be used to inform selection of suitable PCMs for energy storage systems.

### 2.4 Enhancing Heat Transfer of PCMs

A number of steps have been taken for the improvement of the heat transfer process in latent heat thermal storage (LHTS) systems. Among them, two methods are the most promising ones:

1. Integrating finned surfaces into the heat storage medium (HSM).
2. Using high thermal conductivity matrix structures in the heat storage medium.

### Use of Fin Arrangements

A number of researches [32-39] have investigated the impact of using fins in order to enhance the melting and solidification process of phase change materials (PCMs), as a way of providing higher thermal conductivity in thermal storage units. Velraj [38] analyzed the behavior of RT60 paraffin during freezing in a vertically placed aluminum tube with internal fins. The experiments showed that there is an ideal fin and wall thickness (around 1.5 mm) which improves heat transfer efficiency and more than four fins gives flexibility in height.

Nagano [39] also examined the effect of fins on the heat transfer coefficient using a slurry mixture of PCM, water, and salt hydrate. In contrast to the work by Velraj, Nagano observed that in certain instances the heat transfer coefficient nearly doubled. Nevertheless, because there was not sufficient information about research procedure, the contradiction of results is not established yet.

Ismail *et al.* [40] also conducted experimental and numerical heat transfer behavior analysis on finned tubes. Stritih [41] used steel fins with enhanced conductivity in a rectangular storage facility with RT30 paraffin. Results indicated that during melting, fins are capable of reducing thermal efficiency by way of hindered natural convection (with efficiency less than 1 for small Fourier numbers). During solidification, though, performance of the fins was thermodynamically dependent and effectiveness values ranged from 0.5 to 3 and varied with Stefan and Fourier numbers. The above works highlight that geometry and material of fins are accountable for thermal performance of PCM-based systems.

### Application of High Thermal Conductivity Structures

In 1996, Tayeb [42] conducted the initial experiments for thermal conductivity modification in cold storage media (HSM) such as paraffin by adding metal shavings. Hafner and Schwarzer [43] investigated the impact of different metal geometries on heat transfer in paraffin following that. Cabeza *et al.* [44] investigated three alternatives for heat transfer enhancement in cold storage: the use of steel tubes, copper tubes, and graphite matrix impregnated with PCM. Zätzker and Skah [45, 46] proposed the incorporation of mesophase-expanded graphite (MEG) with PCM for improving thermal performance—a process later researched by Mehling [47]. Xiao *et al.* [48] developed a form-stable composite of paraffin, SBS copolymer, and expanded graphite (EG) that showed improved thermal conductivity.

A number of research studies have explored the application of carbon fibers to improve heat transfer in thermal energy storage systems. Fukai *et al.* [49] reported that the thermal conductivity of market-purchased carbon fibers can be greater than 1000 W/m·K. In two experimental situations, the carbon fibers were either dispersed randomly within the PCM or parallel to the direction of heat transfer. Further, a new composite material was created with paraffin and compressed, expanded natural graphite (CENG) [50]. Results indicated that graphite loading increased the effective thermal conductivity of the material.

Follow-up studies by Fukai *et al.* [97, 98] were carried out on the thermal characteristics of a carbon fiber brush/PCM composite in shell-and-tube mode. In this work, n-octadecane was used as the base PCM, and it was found that at a fiber volume fraction of 0.012, the effective thermal conductivity was about three times larger compared to pure PCM. These advancements in the development of new storage materials and graphite-based composites have promising pathways to improve the thermal efficiency of latent heat storage systems—providing material-to-heat exchange surface interaction can be successfully controlled.

### 2.5 Use of Phase Change Materials in Active and Passive Solar Heating Systems

In active solar heating systems, there have been a number of studies performed on the combination of solar collectors and phase change materials (PCMs) for latent heat storage. Kaigısız [51] designed an early experimental system which consisted of a solar collector, heat exchanger, water circulation pump, an energy storage tank containing PCM, and a control system. Despite the good functioning of the collector tank and storage tank (efficiently 0.60 and 0.70, respectively), the heating demand was fulfilled by just 30-35% due to cloud coverage. Later research by Esen and Ayan [52] pointed out that maximum thermal efficiency could be obtained only if the characteristics of the PCM, tank radius, and the temperature of the fluid are known with accuracy. Later studies by Esen *et al.* [53] showed that the configuration of fluid flowing through tubes inside a PCM enclosure greatly improved thermal storage efficiency. The serial connection of the solar heat pump with the tank also resulted in greater efficiency (68%) compared to the parallel scheme (48-60%) [55, 56]. Experiments by Kanbazoglu *et al.* [57] using sodium thiosulfate pentahydrate also supported the cost-effectiveness and efficiency of these materials for solar energy storage systems.

In passive solar heating, PCMs have been incorporated into building components such as walls and concrete blocks. Rad [61] impregnated gypsum walls with coconut fatty acid and found that the incorporation of more than 25% PCM by weight caused leakage, and volatile impurities in fatty acids caused corrosion in metals such as copper and aluminum. This was avoided by evaporating the impurities prior to application. Besides, Athienitis' research [58] and Rad's tests [57] showed that PCM-embedded walls provided higher thermal comfort than the control samples; yet the flammability of organic PCMs when no fire-retardant additives are added remains a point of concern. Lee *et al.* [62] also confirmed higher thermal performance in concrete blocks impregnated with PCM. In the research of Manz *et al.* [63], dual-layer walls incorporating a transparent insulation material (TIM) and semi-transparent salt hydrates as PCMs featured efficient heat storage and radiation. However, reflection phenomena in the solid state of the PCM limited solar energy absorption and light transmission in certain instances.

### 2.6 Applications

Figure 2 illustrates the various applications of Phase Change Materials (PCMs) utilized in the field of solar energy.

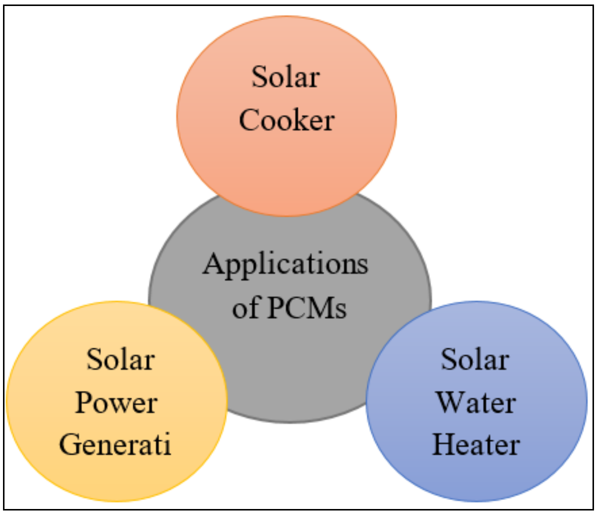


**Fig 2:** Different applications of PCMs in solar energy sector

### Solar Power Generation Using PCMs

Currently, solar energy is firmly established as the most widely utilized renewable source of energy for household electricity needs. However, high-temperature thermal energy storage (TES) technologies are still at the research and development phases and have been pilot-scaled in only a few power plants [64, 65]. Synthetic lubricants have been used in modern SEGS systems to achieve high temperatures (300-400 °C), but because they are very expensive, they limit their economic use [66]. Phase change materials (PCMs) provide an attractive solution for the reduction of the cost of electricity production; however, because of their low thermal conductivity, charging and discharging are slow. Hohnehold *et al.* [67-69] established in their research the theoretical capability of PCMs for thermal storage and proposed the use of shell-and-tube heat exchangers to enhance efficiency.

Despite such advantages, extensive use of PCMs at high temperatures in Concentrated Solar Thermal (CST) power plants has not yet been attained due to the need for improved encapsulation methods and efficient heat transfer [70]. The best temperature range of application of PCMs in these systems is estimated to be 293-393 °C, while PCMs with melting points above 600 °C are proposed to achieve improved efficiencies. One of the most promising methods in this regard is hybrid thermal storage systems on the basis of sensible heat storage in combination with PCMs (Hybrid PCM-sensible). Hybrid PCM-sensible systems are capable of offering greater energy efficiency, reduced costs, and increased storage capacity compared to traditional methods, hence being an innovative technique for future solar thermal power plants [71, 72].

### Solar Cookers with PCMs

In the majority of developing countries, cooking accounts for a significant proportion of domestic energy consumption. Modern fuels such as kerosene and liquefied petroleum gas (LPG) are normally relied upon by urban areas, whereas rural areas continue to utilize traditional fuels such as wood and crop residues. Solar cookers may offer a solution to the decrease in the utilization of fossil fuels and the release of greenhouse gases. Their sensitivity to direct sun, however, limits their use during clouded conditions or night hours [73, 74]. In a bid to counter this limitation, incorporating phase change material (PCM)-based thermal storage systems into solar cookers has been sought to introduce cooking capacity into the night hours [75].

Several experiments have been conducted to explore the design of solar cookers with latent heat storage. Budi [76] developed a solar cooker using industrial-grade stearic acid as PCM for evening cooking, while low heat transfer rates resulted in longer cooking times [77]. Sharma and others [78] utilized industrial erythritol as a solar collector together with an evacuated tube solar collector and noticed that night-time cooking using stored heat took shorter time than day-time cooking in the absence of storage. Hussain *et al.* [73] suggested an indirect solar cooker through the utilization of magnesium nitrate hexahydrate as PCM. With reflectors being added to increase solar radiation, there was 24% improvement in energy absorption. Such projects show that integrating PCMs into solar cookers can significantly improve their performance and use at daytime and nighttime.

### Solar Water Heaters Based on PCMs

Solar water heaters have grown more popular in the last few years due to their high efficiency levels, affordability, and low maintenance requirements. Solar thermal energy conversion is up to 70% more efficient than photovoltaic systems [79], and water heating is one of the most significant applications of solar energy. For continuous hot water provision even during night or even on sunless days, thermal energy is stored using phase change materials (PCMs). They typically consist of a solar collector to heat the water and a storage tank of PCM that gets heated throughout the day and gives out heat during night for maintaining water temperature.

Extensive research has been conducted to enhance these systems, and various PCMs and latent heat thermal energy storage (LHTES) units are already available in the market that can be incorporated into solar water heaters [80, 81]. Careful selection of a PCM and storage tank design significantly influence system performance [82]. In order to further enhance thermal efficiency, other heat transfer fluids can be used instead of water. In addition, the use of nanoparticle-based upgraded PCMs has been proposed as a reliable means of upgrading the thermal conductivity and enabling more precise analysis of thermal performance. Such advancements lead the way towards the design of future solar water heaters with higher reliability and efficiency.

### 2.7 Evacuated Tube Solar Collector

The evacuated tube solar collector is a next-generation thermal solar collector utilizing cylindrical glass tubes with vacuum insulation between the outer and inner walls to minimize heat loss. There is an absorber plate with selective coating at the inside of every tube that confines the solar radiation and converts it into heat. This heat is transferred by a heat pipe with a low fluid volume, which is vaporized by heat and conveys thermal energy into a header pipe. This heat is transported to a heat exchanger or storage tank using a circulating heat transfer fluid, such as antifreeze or water. The cylindrical shape allows for effective absorption of sunlight throughout the day from various directions, resulting in improved overall system efficiency [83].

These collectors have several advantages including high efficiency through low heat loss due to their vacuum-sealed condition. They are maintenance-free, corrosion, scaling, and freezing-proof. Their capability to withstand high-temperature conditions and low sun conditions renders them highly versatile to diverse climatic conditions and application. Additionally, they can be utilized in conjunction with other systems of solar energy in an attempt to enhance overall efficiency and reliability.

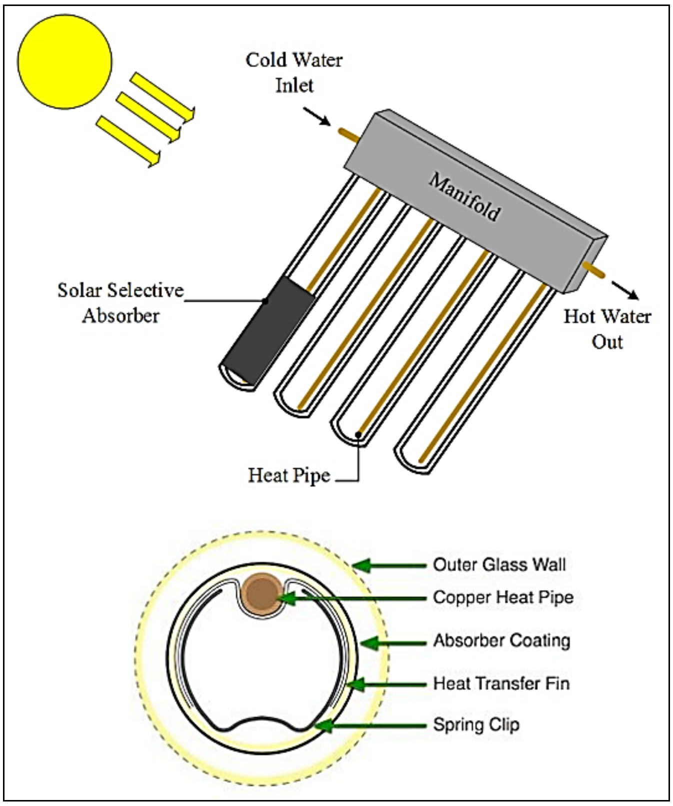


**Fig 3:** Schematic of an evacuated tube solar collector and its cross-sectional view.

Energy storage has been a subject of significant interest as an efficient and economic method to improve system performance without the inclusion of additional power plants. Phase change materials (PCMs) form a vital aspect in this area since they have the capability to absorb latent heat during change of phase and can exist at a constant temperature during the process. Heat transfer during these transitions is via conduction and convection, and the requirement is to optimize methods that enhance conduction and minimize convective losses.

To achieve optimum PCM performance, it is necessary to combine existing knowledge with developments in related technologies to provide value-added services to end users. Public awareness, increasing the efficiency of solar systems (such as solar desalination plants), and developing cheap and durable storage technologies can significantly enhance the widespread utilization of energy storage systems. Next-generation PCMs with high durability, low cost, and minimal aging effects need to be developed in the future to achieve high-efficiency outcomes and remarkable societal advantages.

### 2.8 Literature Review

In the past few years, the integration of Phase Change Materials (PCMs) into solar thermal systems, especially evacuated tube solar collectors (ETSCs), has been widely recognized and focused attention upon due to their latent heat storage release amount. The type of PCM chosen along with its thermophysical characteristics such as melting point, latent heat of fusion, thermal conductivity, and specific capacity impacts the thermal performance and efficiency of these systems. Several research studies available in the literature analyze the influence of different kinds of PCMs, system geometries, and enhancement techniques to enhance energy storage and thermal efficiency. The following studies provide some good fundamental input into understanding applications of and performance with PCMs in ETSCs.

Al-Abdali and Ammari (2022) conducted an in-depth investigation of the thermal efficiency of evacuated tube solar collectors (ETSCs) integrated with paraffin-based phase change material (PCM) [84]. The outcome confirmed that incorporation of paraffin increased thermal efficiency by approximately 7% and energy storage capacity by approximately 8.6% compared to PCM-free systems. Moreover, the study broached the economic sustainability of such integration, pointing out that PCMs like paraffin significantly enhance energy performance and cost savings of solar thermal systems. Rashid *et al.* (2022) performed an experimental test of RT70HC as a thermal energy storage phase change material [85]. Experiments confirmed that RT70HC, with its high solid phase specific heat capacity and thermal stability, delivers repeatable and efficient thermal discharging and charging performance. This means that RT70HC is a medium- to high-temperature solar thermal stable material, particularly in thermal stability and repeatable required systems.

Zhang *et al.* (2022) investigated the use of a cascaded PCM configuration with multiple materials having different melting points to enhance latent heat storage in solar systems [86]. The authors' research indicated that the use of cascaded PCMs widens the optimal range of operating temperatures and boosts system efficiency overall. The cascaded approach was especially valuable under changing heat transfer conditions, yielding smoother heat control across a wider temperature range.

Mehrali *et al.* (2015) have cast a comprehensive overview of the enhancement of thermal conductivity of PCMs by adding nanomaterials like metallic nanoparticles and thermal fins [87]. A thermal conductivity enhancement of up to 35 times has shown that heat charge and discharge cycles can be conducted much more quickly and effectively. These optimizations are particularly advantageous for PCMs with intrinsic low thermal conductivity, such as paraffin and RT82, thus making them more prospective for high-temperature thermal applications.

## 3. Material and methods

With the increasing global demand for renewable energy, solar thermal systems are now a feasible alternative. Evacuated tube collectors (ETCs), being very efficient and reducing heat loss, can be further enhanced by adding phase change materials (PCMs). This paper provides a comprehensive review of PCM choice, integration, and performance study in the application of ETCs. The selection of appropriate PCMs depends on their melting point, latent heat, thermal conductivity, and stability against many cycle phase changes.

PCMs should be compatible with the operation temperature range of ETCs and should also resist thermal degradation during repeated cycle phase change.

Several methods exist for integrating PCMs into ETCs:

Filling PCM in the annular space between tubes.

Embedding PCM in external/internal containers.

Bonding PCM to heat transfer surfaces using metallic fins.

Each method presents trade-offs between thermal efficiency, design complexity, and system cost.

**PCM Mass Calculation**

To determine the required mass of PCM for achieving a desired level of thermal energy storage, the following equation is used:

(1)

$$m_{\mathrm{PCM}} = \frac{Q}{L + C_p \cdot \Delta T}$$

**Where:**

- $m_{\mathrm{PCM}}$: Required PCM mass (kg),
- $Q$: Required heat storage (kJ),
- $L$: Latent heat of fusion (kJ/kg),
- $C_p$: Specific heat capacity of the PCM (kJ/kg · K),
- $\Delta T$: Temperature difference across the sensible heat range (K).

Two ETC configurations are analyzed: Collector A (without PCM) and Collector B (with PCM). Candidate PCMs include paraffin, triacontane, xylitol, and erythritol. Material stability is evaluated through thermal cycling, and performance is assessed under identical irradiance conditions.

**Energy Storage in PCM**

The total thermal energy stored in a PCM comprises both sensible and latent heat components:

(2)

$$Q_s = m_{\mathrm{PCM}}\left[C_{p.i}(T_m - T_i) + C_{p.s}(T_f - T_m)\right]$$

(3)

$$Q_l = m_{\mathrm{PCM}} \cdot L$$

(4)

$$Q_{\mathrm{total}} = Q_s + Q_l$$

**Where**

- $Q_s$: Sensible heat stored (kJ),
- $Q_l$: Latent heat stored (kJ),
- $Q_{\mathrm{total}}$: Total energy stored (kJ),
- $T_i$: Initial temperature (°C),
- $T_m$: Melting point of PCM (°C),
- $T_f$: Final temperature (°C),
- $C_{p,i}$, $C_{p,s}$: Specific heat capacities in solid and liquid phases (kJ/kg · K).

**Thermal Performance Modeling**

A comprehensive thermal performance model incorporates energy balance, heat gain, and loss calculations:

(5)

$$Q_u = A_c F_r(\tau\alpha) I_t - A_c F_r U_L (T_i - T_a)$$

(6)

$$D = \sqrt{\frac{1}{N}\sum_{i=1}^{N} d_i^2}$$

(7)

$$\dot{Q}_{\text{abs}} = \dot{Q}_{\text{PCM}} + \dot{Q}_{\text{loss}}$$

(8)

$$Q_{\text{abs}} = A_c I_g \eta_{\text{opt}}$$

(9)

$$Q_{\text{loss}} = Q_{\text{cond}} + Q_{\text{conv}} + Q_{\text{ref}}$$

$$Q_u = Q_{\text{abs}} - Q_{\text{loss}}$$

(10)

$$Q_{\text{total}} = A_c\left[I_g\eta_{\text{opt}} + F_r\left(S - U_L(T_i - T_a)\right)\right]$$

(11)

$$\dot{Q}_{\text{PCM}} = m_{\text{PCM}} c_{\text{PCM}} \frac{dT_{\text{PCM}}}{dt} + m_{\text{PCM}} h_f \frac{dX}{dt}$$

**Where**

- $A_c$: Collector area (m$^2$),
- $F_r$: Heat removal factor,
- $\tau\alpha$: Transmittance-absorptance product,
- $I_t, I_g$: Incident solar radiation (W/m$^2$),
- $U_L$: Overall heat loss coefficient (W/m$^2 \cdot$ K),
- $T_a$: Ambient temperature ($^\circ$C),
- $\eta_{\text{opt}}$: Optical efficiency,
- $Q_{\text{cond}}, Q_{\text{conv}}, Q_{\text{ref}}$: Conduction, convection, and reflection losses,
- $h_f$: Latent heat (kJ/kg),
- $\frac{dX}{dt}$: Phase change rate.

These equations provide a robust analytical framework for assessing the impact of PCM integration on the thermal behavior of ETC systems under varying environmental conditions.

## 4. Results

In this study, five types of Phase Change Materials (PCMs) with various thermal properties were taken into consideration to analyze the thermal performance of evacuated tube solar collectors. They include Paraffin, Triacontane Paraffin, RT65, RT70HC, and RT82, which possess varying melting temperatures, specific heat in liquid and solid states, and latent heat of fusion. For example, Paraffin with a melting temperature range 319-341 K and latent heat of 200 kJ/kg is one of the most commonly used PCMs since it possesses comparatively high specific heat capacity in the liquid phase (2000-2400 J/kg·K). On the contrary, Triacontane Paraffin with a wider melting temperature (240 to 373.15 K) and latent heat of 233 kJ/kg has been identified as a promising material for low-temperature thermal energy storage systems.

RT65, RT70HC, and RT82 also exhibit favorable thermal properties for use in solar thermal systems. RT82 possesses the highest melting temperature range (350.15-358.15 K) and latent heat (242 kJ/kg) among them and can store more thermal energy in high-temperature applications. RT70HC offers stable and reliable performance close to the melting point of around 343 K with high specific heat capacity in the solid state (2610 J/kg· K) and latent heat of 231 kJ/kg. Generally, the selection of an appropriate PCM depends on the operating temperature range of the collector system, and materials with lower melting points enhance the thermal efficiency of solar collectors.

**Table 1:** Phase Change Materials Specification

| PCM Type | Melting Temp (K) | Cp Liquid (J/kg·K) | Cp Solid (J/kg·K) | Latent Heat (kJ/kg) | PCM Mass (kg/m²) |
|---|---|---|---|---|---|
| Paraffin | 319 - 341 | 2000 - 2400 | 1900 - 2300 | 200 | 0.01 - 0.04 |
| Triacontane -Paraffin | 240 - 373.15 | 1380 | 2100 | 233 | 0.01 - 0.04 |
| RT65 | 328.15 - 339.15 | 1820 | 2400 | 191 | 0.01 - 0.04 |
| RT82 | 350.15 - 358.15 | 2010 | 2870 | 242 | 0.01 - 0.04 |
| RT70HC | 342.15 - 344.15 | 1890 | 2610 | 231 | 0.01 - 0.04 |

The provided table illustrates the thermal performance (or a similar thermal efficiency index) for five types of Phase Change Materials (PCMs) across a melting temperature range of 319 to 329 K. The results indicate a consistent improvement in thermal performance for all PCMs as the melting temperature increases. This shows a better match of the PCMs to operating temperatures at higher temperatures.

**Table 2:** Variation of Thermal Efficiency with Melting Temperature for Different PCMs

| Melting Temp (K) | Paraffin | Triacontane | RT65 | RT70HC | RT82 |
|---|---|---|---|---|---|
| 319 | 612.4 | 631.36 | 586.04 | 678.36 | 717.68 |
| 321.5 | 611.4 | 634.96 | 588.94 | 681.96 | 721.98 |
| 324 | 610.4 | 638.56 | 591.84 | 685.56 | 726.28 |
| 326.5 | 609.4 | 642.16 | 594.74 | 689.16 | 730.58 |
| 329 | 608.4 | 645.76 | 597.64 | 692.76 | 734.8 |

RT82 possesses the highest efficiency values for the entire temperature range from 717.68 at 319 K to 734.88 at 329 K. This is due to its high latent heat (242 kJ/kg) and thermal stability at high temperatures, making RT82 a strong applicant for use in solar systems in tropical or high-radiation regions.

RT70HC also exhibits strong thermal behavior, particularly near its melting point (~343 K). Its performance rises from 678.36 to 692.76 across the given temperature range. With a high specific heat capacity in the solid state (2610 J/kg·K) and structural stability, RT70HC is a recommended PCM for medium-to-high temperature thermal storage systems.

Comparatively, Paraffin and Triacontane-Paraffin exhibit lower performance values. Paraffin with lower melting range (319-341 K) and moderate latent heat (200 kJ/kg) is applicable for low-temperature applications. Triacontane-Paraffin with higher latent heat (233 kJ/kg) and larger melting range exhibits relatively higher performance. RT65 lies in between but still lower than RT70HC and RT82.

Compared with similar studies, such as Al-Abdali & Ammari (2022), it was found that using Paraffin in ETSCs can improve thermal efficiency by up to 7% and enhance energy storage by approximately 8.6% compared to systems without PCM. These findings align with other experimental results that confirm RT70HC's reliable thermal discharge and energy storage characteristics. More recent research also suggests that using cascaded PCM configurations can expand the operational temperature range of solar collectors. Finally, studies that examined the enhancement of PCM thermal conductivity using metallic nanoparticles or thermal fins demonstrated that such techniques could increase charge/discharge efficiency by up to 35 times. Given the high performance of RT82 and RT70HC, applying these techniques could further boost their efficiency. Therefore, selecting an appropriate PCM must consider the operational temperature range and the potential for thermal conductivity enhancement.

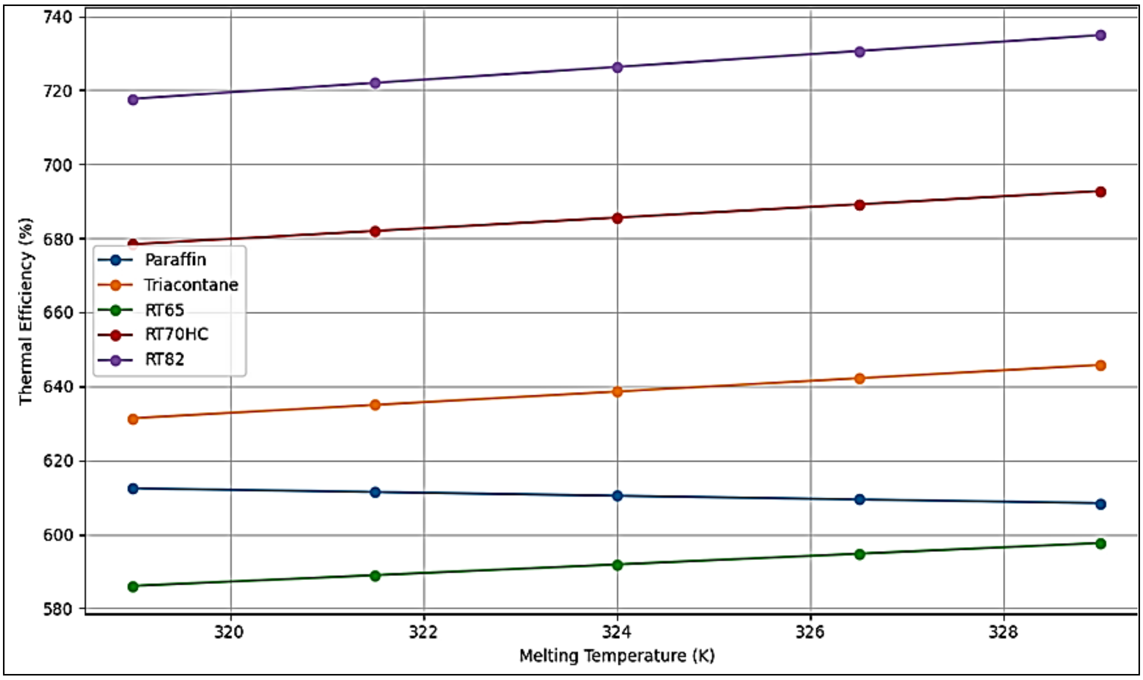


**Fig 4:** Variation of Thermal Efficiency with Melting Temperature for Different PCMs

The chart illustrates the relationship between melting temperature (K) and thermal efficiency (%) of five phase change materials (PCMs): Paraffin, Triacontane, RT65, RT70HC, and RT82. As is evident, RT82 has the highest thermal efficiency across the entire range of temperatures, increasing from approximately 717% to 735% as temperature rises from 319 K to 329 K. RT70HC follows the same rising trend with slightly lower efficiency rates. Paraffin and Triacontane, on the other hand, possess lower and relatively steady thermal performance, with Paraffin showing a slight decline in efficiency with temperature increase. RT65 is the least performant over the range but sees a marginal increasing trend. The results confirm that PCMs with high melting points and latent heat, such as RT82 and RT70HC, are more suitable for high-temperature solar thermal applications.

## 4. Discussion

The result of the present work evidently indicates that thermal performance of evacuated tube solar collectors (ETSCs) highly relies on the selection of Phase Change Materials (PCMs). Among the five PCMs examined, RT82 was the one that always exhibited superior thermal efficiency over the entire range of melting temperatures (319-329 K), which found to be an appropriate material for high-temperature applications. Its higher latent heat capacity (242 kJ/kg) and thermal stability were the explanations among many for its improved performance. RT70HC also showed good performance on these bases, owing to its large solid-state specific heat and stable charging/discharging properties. These observations agree with literature reports on the pivotal role of thermal properties—high latent heat and compatibility of melting point—towards maximizing energy storage and transmission efficiency in solar thermal systems. On the other hand, Triacontane-Paraffin and Paraffin exhibited lower to moderate efficiencies, although their ease of availability and low cost may still make them effective for cost-sensitive or low-temperature use.RT65 exhibited the poorest thermal performance but the most uniform increasing trend with increasing temperature, thus possibly it can be used as a middle-layer PCM in cascaded configurations. In general, the study stresses the importance of PCM selection based on the collector system operating range. The findings further suggest that the addition of thermal conductivity promoters (e.g., nanoparticles or metal fins) to PCMs or hybrid layering schemes of PCMs would further enhance the thermal efficiency of solar collectors, especially in changing environmental conditions.

## 5. Conclusions

This study investigated the thermal performance of five different Phase Change Materials (PCMs) integrated in evacuated tube solar collectors (ETSCs) within a melting temperature range of 319 to 329 K. The findings showed that RT82 and RT70HC provided the highest thermal efficiencies due to their favorable thermal characteristics, including high latent heat and appropriate melting points for high-temperature applications. Paraffin and Triacontane-Paraffin presented worse but stable performance and were determined to be suitable for low-temperature or economically constrained systems. The results demonstrate the critical role played by PCM choice in enhancing the efficiency of solar collectors and suggest that there is room for improvement from hybrid PCM configurations or through enhancement in thermal conductivity from advanced materials. Based on the result of this study, subsequent research is recommended to design and experiment cascaded or multi-layer PCM systems combining materials with different melting points (e.g., RT65, RT70HC, and RT82) in an attempt to increase the effective operating temperature range of solar thermal collectors. In addition, integration of thermal conductivity promoters such as metallic nanoparticles or protruding surface fins into PCM structures would be investigated to increase the heat transfer rates in charging-discharging cycles. Experimental comparison of these hybrid configurations under real solar conditions and economic viability studies would be an added boon towards further development of PCM-based energy storage in solar applications.

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