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Enhanced Thermal Performance of Solar Heating Systems using Phase Change Materials in Stratified Water Storage Tanks

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ABSTRACT

Over the past few decades, there has been a steady increase in the use of solar water heaters in regions with abundant solar energy. However, because the sun can only provide electricity for a fraction of every 24-hour period, it is necessary to supplement solar water heaters with thermal energy storage systems. These thermal water storage tanks for solar systems use phase change materials (PCMs), which can store additional energy to provide sufficient power, for example, to compensate for potential shortcomings that can arise from limited production time, such as at night or during cloudy weather.PCMs can undergo a solid-to-liquid phase transition (i.e. melting process) when heated to a temperature suitable for the heat input used. This study explores ways to improve the thermal efficiency of thermal water storage tanks by applying a potential digital model using PCM containing paraffin wax. This research aims to find the most suitable PCMs for finite element modelling, including detecting changes in thermal conductivity and enthalpy at different temperatures.Potential factors for increasing the efficiency include the use of encapsulated PCM for spheres on the heat exchanger and varying the time required for the melting/solidification process. The study also includes an overview of the Latent Heat Energy Storage System (LHESS) and its underlying theory.

1. Introduction

Renewable energy sources such as solar, geothermal, wind, marine, biomass, and hydropower have seen increased demand due to current efforts to address the lack of access to sufficient energy, which has severe consequences for humans and the environment [1]. With advances in thermal energy management, modern lifestyles have created numerous new applications for thermal energy, further increasing its demand. Stratified water storage tanks are commonly used for energy storage.

With global pressure to reduce carbon emissions, alternative energy sources that help decrease greenhouse gas emissions are becoming increasingly popular. Among these, solar energy is

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particularly important, particularly in sunny areas. However, finding ways to store energy for future use remains a challenge. Energy storage (ES) technologies must be sufficient to meet high demands while remaining cost effective [2]. Thermal energy storage systems can help save energy from peak hours for use during low-power generation periods, thereby improving generator integration into the grid. One of the main advantages of thermal energy storage systems is the ability to store thermal energy for later use, either at the harvest source or elsewhere. However, many thermal storage materials have low thermal conductivity, which is an undesirable characteristic that results in a low thermal energy storage efficiency.

Numerous studies have explored the incorporation and effectiveness of Phase Change Materials (PCMs) in thermal energy storage systems. Chen *et al.,* [3] highlighted the advantages of using stearic acid in PCM thermal energy storage, demonstrating a 50.3% increase in efficiency by focusing on the liquid-solid interface, transition time, and heat flow stability. Zeng *et al.,* [4] reviewed the effects of thermal energy storage compared with solid-liquid phase change and tested over 150 materials to understand the heat transfer impacts in various applications. Ardahaie *et al.,* [5] examined energy conservation in construction, testing PCM's ability to store heat in floors, ceilings, and walls and identifying material-specific issues.

Chaturvedi *et al.,* [6] improved the efficiency of PCM laminate wall panels for thermal energy storage by integrating different types of PCM, enhancing heat transfer and recycling efficiency. Stephant *et al.,* [7] tested PCM behaviour in a solar pilot plant and found that adding PCM to the top of a hot water tank improved stratification. Dogkas *et al.,* [8] focused on the challenges preventing wider adoption of PCMs in solar energy storage. Madhhachi and Smaisim [9] improved the solar thermal energy storage capacity in hybrid systems during the winter months and applied digital analysis to model latent heat storage using different PCMs.

Mehmood *et al.,* [10] examined temperature control and energy storage in encapsulated plates with micro-encapsulated PCM, finding consistent thermal behavior and improved steady-state achievement. He *et al.,* [11] tested paraffin wax in traditional solar water-heating systems, showing that forced circulation has a minimal effect on performance and highlights the impact of daily usage patterns on PCM recovery. Hongbing *et al.,* [12] discussed the importance of solar water heaters for industrial and domestic use and suggested improvements in convection heat transfer and thermal efficiency through passive techniques. Wu *et al.,* [13] studied the heat storage properties of expanded graphite and paraffin as synthetic PCM, finding similar melting temperatures and latent heat values, but noting lower performance for the PCM composite's heat-storage filler. Khargotra *et al.,* [14] developed a V-trough accumulative solar water heater system with improved efficiency through forced circulation.

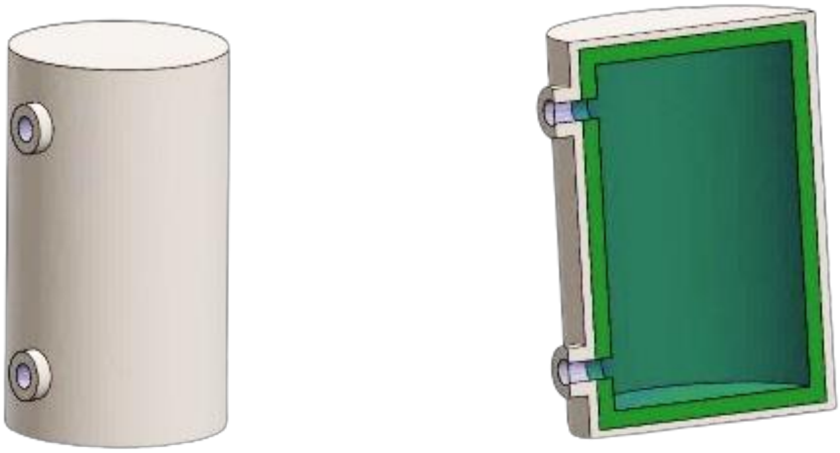
Li *et al.,* [15] investigated different PCMs for domestic hot water tanks and found that incorporating PCM improves energy storage and efficiency. Brembilla and Mardaljevic [16] examined PCM's potential of PCMs to improve thermal efficiency in residential water heaters and reduce peak electricity demand. Douvi *et al.,* [17] conducted a digital study on a solar water heater with integrated collectors, finding higher efficiency in the Latent Thermal Storage Unit during daylight and nighttime when using PCM. Majumdar and Saha [18] studied the behaviour of paraffin PCM in storage systems, focusing on the temperature stratification behind solar collectors.

This study aims to develop and design a stratified storage water tank microencapsulated with a Phase Change Material (PCM) for thermal energy storage. The objective was to simulate the thermal performance of the tank under varying hot water temperatures and to analyse the charging and discharging processes of the encapsulated PCM acting as a thermal insulator. ANSYS and SolidWorks were used to design and simulate the thermodynamics between the water and tank insulated with encapsulated PCM. The simulations considered Malaysia's maximum and minimum weather temperatures, including hot/dry and cold/rainy conditions. Additionally, this study explores the effects of varying the PCM thickness and water volume on the thermal performance of the system.

2. Methodology

2.1 Geometry of stratified Energy Storage

A model of the stratified water storage tank was created using SOLIDWORKS, as depicted in Figure 1. The tank, constructed from steel, features an insulation layer of phase-change material (paraffin wax) on its wall surface. Hot water was used as the heat transfer fluid (HTF) in this study. Table 1 lists the tank dimensions.



(a) (b)

Fig. 1. Design of Stratified storage tank (a) Full tank (b) Half-view

Table 1
Dimensions of the tank

Parameter	Value (inches)
Outer diameter	15.75
Inner diameter	14.5
Length	23
Insulation	0.5

2.2 Meshing

The Mesh generation is a critical aspect of engineering simulation. ANSYS meshing technology was used to balance the requirements and obtain an optimal mesh for each simulation. The tank meshing is illustrated in Figure 2, featuring 860,000 elements, 780 bodies, 2,500,000 nodes, and a simulation time of 72 h.

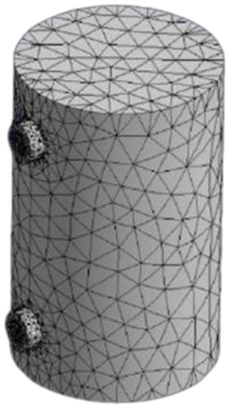


Fig. 2. Mesh generation of stratified storage tank

2.3 Governing Equation

The governing equations used in this simulation include continuity [19], momentum [20], and energy equations. These equations describe the behaviour of the fluid and the heat transfer within the system. The equations are as follows:

Continuity: $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho V) = 0$ (1)

Momentum: $\frac{\partial (\rho_H)}{\partial t} + \nabla \cdot (\rho V) = -\nabla \cdot P + \mu \nabla^2 V + \rho g + S$ (2)

Energy: $\frac{\partial}{\partial t}(\rho_H) + \nabla \cdot (\rho V H) = \nabla \cdot (k \nabla T) + S$ (3)

where V is the fluid velocity, ρ is the density, μ is the dynamic viscosity, P is the pressure, H is the enthalpy, and S is a source term.

2.4 Boundary Condition

In the simulation, the temperature of the water inside the stratified storage tank was maintained at 80°C from the initial hour of 7 am until 7 pm on the same day. The temperature distribution of the PCM during charging and discharging was simulated hourly under no-water draw-off conditions to represent a steady state in the stratified storage tank. The mass flow rate was considered to be zero because no water draw-off occurred. The average water temperature in the stratified tank was maintained at 45°C for domestic water-heating purposes.

3. Results

3.1 Charging and Discharging Process of the Encapsulated PCM Epoxy

Figure 3 illustrates the charging and discharging distribution curves of the encapsulated PCM, the PCM stratified tank temperature (water temp 1), and the stratified tank temperature (water temp 2), showing the temperature variations at each point. The PCM (phase change material) began charging when the hot water in the storage tank started losing heat to the PCM. After an hour, as the temperature of the hot water decreased, the temperature of the PCM increased, reaching a peak value of 54°C at approximately 2 pm. At this point, the PCM transitions from solid to liquid, absorbing heat from the water in the form of latent heat. Concurrently, the water temperature decreased to 38°C. Over 7 h, hot water lost more than half of its heat to the environment.

During the discharging process, the hot-water temperature fell below the melting point of the PCM, causing the PCM to solidify and release heat back into the storage tank. As the PCM solidified, heat was transferred to the water, increasing the temperature of the water. By 3 pm, the water temperature dropped to its lowest value at 33°C, whereas the PCM was at 53°C. Over the next three hours, the PCM released heat, which was absorbed by water, bringing both to an equilibrium temperature of 41°C by 6 pm. This process demonstrated how the PCM enhanced the thermal performance of the stratified storage water tank by stabilising temperature fluctuations.

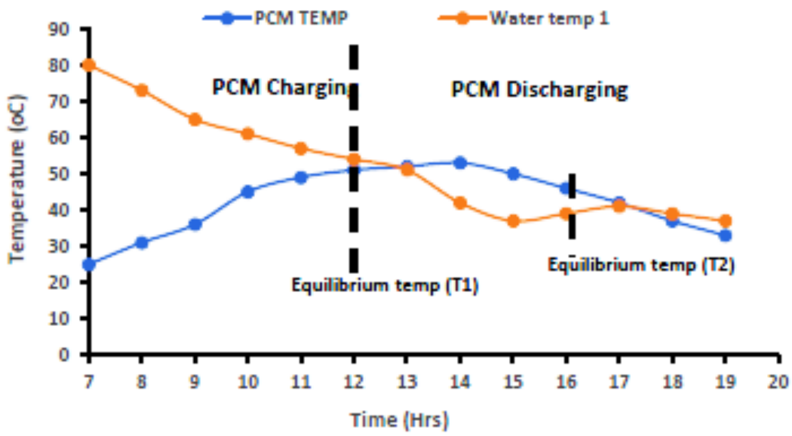
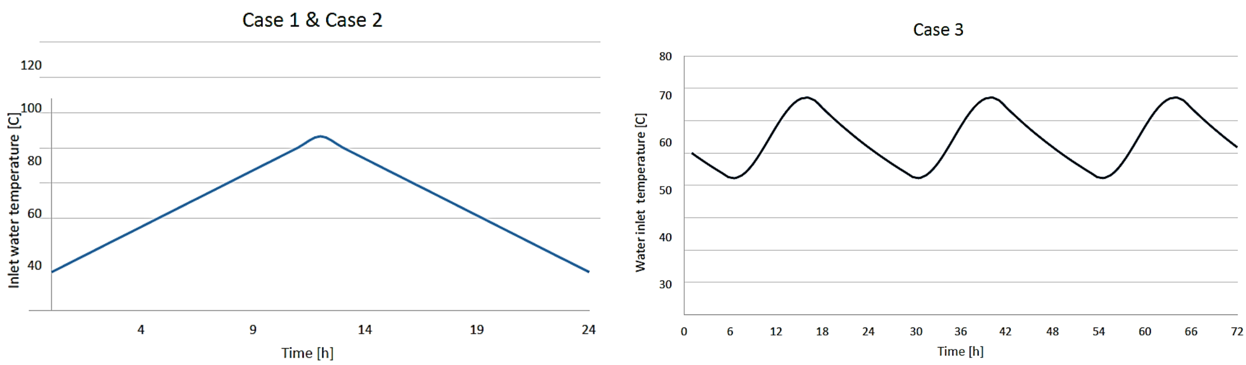


Fig. 3. Charging and discharging process of the encapsulated PCM epoxy

3.2 Inlet Water Temperature

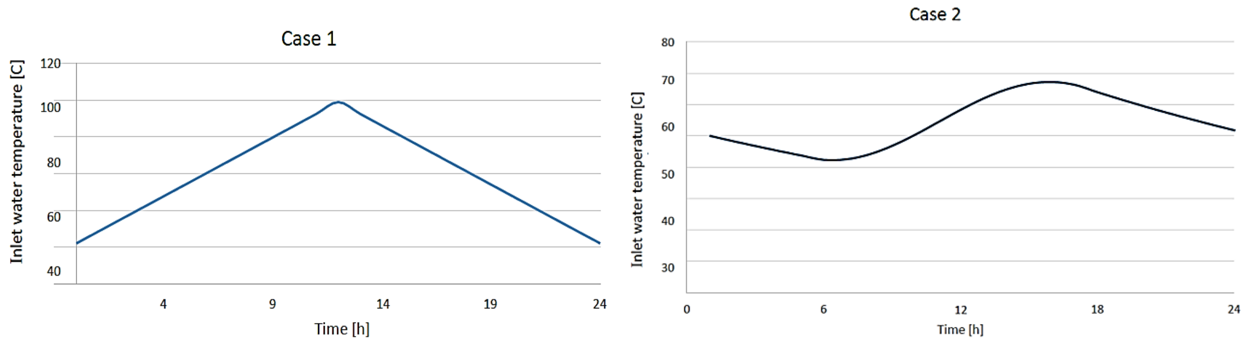
The simulation assumes perfect insulation on the outer surface of the tank. Figure 4 shows the simulation of the inlet water temperature during the day for Cases 1 and 2. There was a steady increase in temperature, reaching a peak at 12 h and steadily decreasing back to approximately 40°C. This indicates a single heating and cooling cycle within a 24-hour period, suggesting that the system likely heats the water to a maximum temperature before allowing it to cool gradually. The inlet-temperature graph for Case 3 illustrates a repeating cyclical pattern with multiple peaks and troughs over 72 h. The temperature peaked at approximately 70°C and decreased to approximately 50°C at the troughs. These cycles appeared to be repeated every 12 h, indicating a regular and consistent pattern of heating and cooling.

Figure 5 displays the graphs of the inlet water temperature variations over time for the two cases when the tank was filled with the encapsulated PCM. In Case 1, the temperature gradually increased to a peak of 100°C at 12 h and then steadily decreased after 24 h. For Case 2, the temperature dropped to approximately 50°C, rose to a peak of around 70°C at 12 h, and then gradually declined back by the end of 24 h. Case 1 showed a single significant heating and cooling cycle, whereas Case 2 demonstrated a more moderate temperature variation with a smaller peak and trough.



(a) (b)

Fig. 4. Inlet water temperature during the day (a) Case 1 and 2 (b) Case 3



(a) (b)

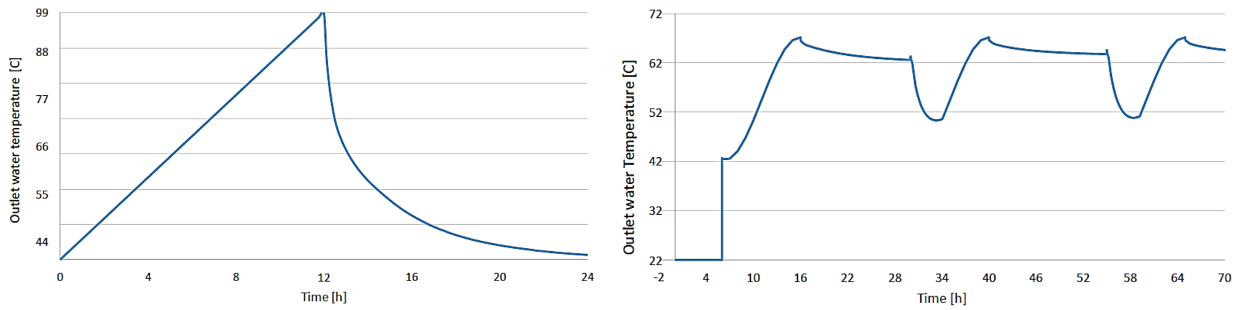
Fig. 5. Inlet water temperature when the tank was filled with encapsulated PCM (a) Case 1 (b) Case 2

3.3 Outlet Water Temperature

Figures 6 and 7 illustrate the temperature changes in both the outlet water and PCM in the two different cases over time. In Case 1, the outlet water temperature showed a steep rise, reaching a peak at approximately 12 h before gradually declining. This implies that free convection and the lack of insulation for the tank significantly affected the system, particularly affecting the temperature distribution. Similarly, the PCM temperature in Case 1 followed a comparable trend, peaking around the same time before cooling. This pattern indicates that the PCM effectively absorbed heat during the initial hours and released it as the system cooled down. The results of Case 3 show how the outlet water temperature and PCM temperature change over three days owing to variations in solar irradiance.

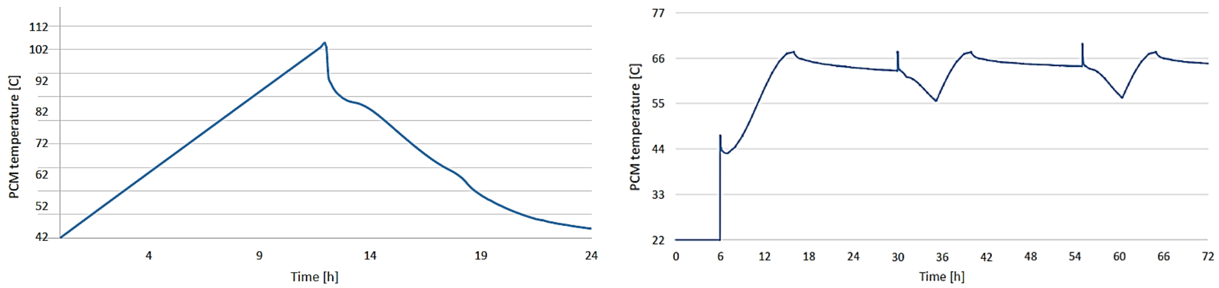
For Case 3, both the outlet water temperature and PCM temperature exhibited a more complex pattern with multiple peaks and valleys. This suggests a fluctuating thermal environment in which the PCM undergoes repeated cycles of melting and solidification, thereby continuously exchanging heat with water. The overall trend indicates that the PCM in Case 3 maintained a relatively higher average temperature compared to Case 1, highlighting its effectiveness in stabilising the water temperature over an extended period.

Figure 8 shows how the temperatures of the outlet water and PCM change when the tank is filled with encapsulated PCM. In Case 1, both temperatures rose quickly to approximately 100°C in 10 h and then stabilised. For Case 2, the temperatures increased more gradually, peaking at approximately 70°C after 20 h, with the PCM temperature slightly higher than the water temperature.



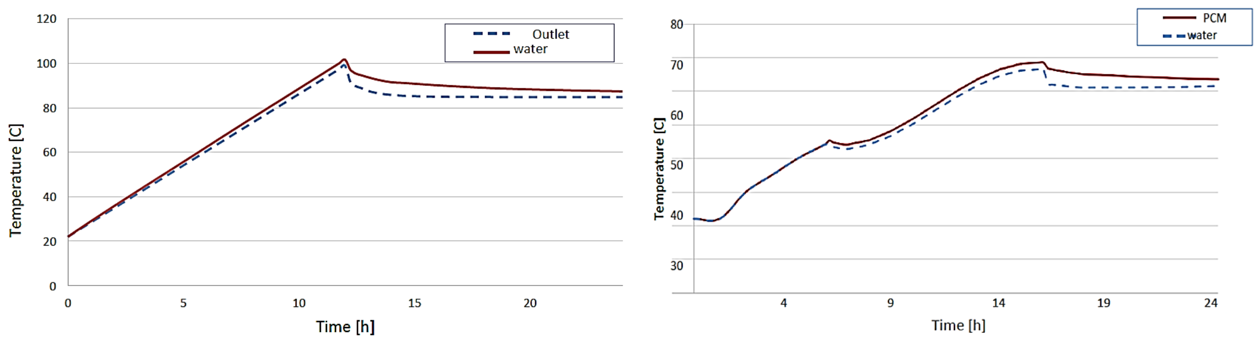
(a) (b)

Fig. 6. Outlet water temperature (a) Case 1 (b) Case 3



(a) (b)

Fig. 7. PCM temperature (a) Case 1 (b) Case 3

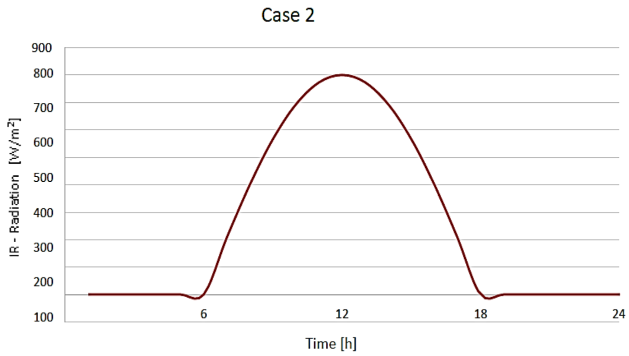


(a) (b)

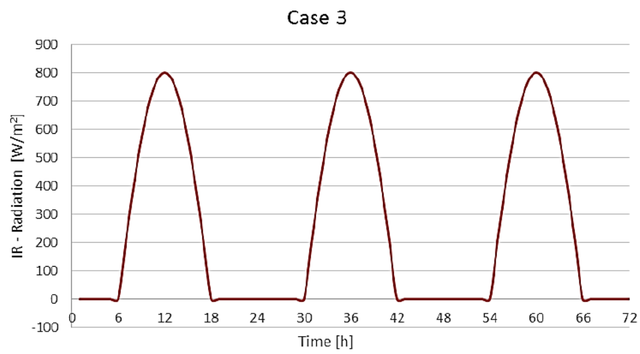
Fig. 8. Outlet water and PCM temperature when the tank was filled with encapsulated PCM (a) Case 1 (b) Case 2

3.4 Input IR-Radiation

During the simulations of three days of input with a given IR radiation, perfect insulation of the outer surface of the tank was considered. Figure 9 illustrates the changes in the IR radiation over time for Cases 2 and 3. In Case 2, the IR radiation followed a single smooth bell-shaped curve, peaking around 12 h before gradually decreasing. Conversely, Case 3 displayed a more complex pattern with three distinct peaks, each reaching a similar maximum radiation level as the single peak in Case 2.



(a)



(b)

Fig. 9. IR-radiation changes (a) Case 2 (b) Case 3

4. Conclusions

This chapter concludes the study of a stratified storage water tank encapsulated with epoxy PCM for thermal performance enhancement. The findings indicate that thermal stratification is crucial for maintaining the water temperature, and the use of PCM as a latent heat storage material effectively absorbs and releases heat, reducing heat losses to the ambient environment. The encapsulated PCM served as a thermal insulator, enhancing the thermal performance and enabling heat recovery. Specifically, the PCM-retained hot water demonstrated a temperature difference of 8°C over a 12-hour period from morning to night, demonstrating its efficacy in prolonging hot water availability.

There are several limitations to the current simulation. These include the neglect of thermal interactions between the surface of the stratified storage water tank and the epoxy PCM encapsulate and the need for improved meshing conditions to account for thermal differentials over time. Additionally, the water draw-off characteristics were not considered, and the initial tank temperature was assumed to be constant and higher than the PCM temperature. For future studies, it is recommended to extend the digital analysis to include charging and discharging with various types of phase change materials, such as inorganic PCMs, and to incorporate natural convection into the loading analysis. Furthermore, utilising more powerful computers for simulations is suggested to enhance the data accuracy and processing speed.

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References
[1] Rahman, Abidur, Omar Farrok, and Md Mejbaul Haque. "Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic." *Renewable and Sustainable Energy Reviews* 161 (2022): 112279. https://doi.org/10.1016/j.rser.2022.112279

[2] Martín-Sómer, Miguel, Jose Moreno-SanSegundo, Carmen Álvarez-Fernández, Rafael van Grieken, and Javier Marugán. "High-performance low-cost solar collectors for water treatment fabricated with recycled materials, open-source hardware and 3d-printing technologies." *Science of The Total Environment* 784 (2021): 147119. https://doi.org/10.1016/j.scitotenv.2021.147119

[3] Chen, Xiao, Hongyi Gao, Zhaodi Tang, and Ge Wang. "Metal-organic framework-based phase change materials for thermal energy storage." *Cell Reports Physical Science* 1, no. 10 (2020). https://doi.org/10.1016/j.xcrp.2020.100218

[4] Zeng, Chao, Xiaoling Cao, Fariborz Haghighat, Yanping Yuan, Lubomir Klimes, Mohamed El Mankibi, and Mohamed Dardir. "Buried water-phase change material storage for load shifting: A parametric study." *Energy and Buildings* 227 (2020): 110428. https://doi.org/10.1016/j.enbuild.2020.110428.

[5] Ardahaie, S. Saedi, M. J. Hosseini, M. Eisapour, A. H. Eisapour, and A. A. Ranjbar. "A novel porous metal hydride tank for hydrogen energy storage and consumption assisted by PCM jackets and spiral tubes." *Journal of Cleaner Production* 311 (2021): 127674. https://doi.org/10.1016/j.jclepro.2021.127674

[6] Chaturvedi, Rishabh, Anas Islam, and Kamal Sharma. "A review on the applications of PCM in thermal storage of solar energy." *Materials Today: Proceedings* 43 (2021): 293-297. https://doi.org/10.1016/j.matpr.2020.11.665

[7] Stephant, A., M. Wadhwa, R. Hervig, M. Bose, X. Zhao, T. J. Barrett, M. Anand, and I. A. Franchi. "A deuterium-poor water reservoir in the asteroid 4 Vesta and the inner solar system." *Geochimica et Cosmochimica Acta* 297 (2021): 203-219. https://doi.org/10.1016/j.gca.2021.01.004

[8] Dogkas, George, John Konstantaras, Maria K. Koukou, Michail Gr Vrachopoulos, Christos Pagkalos, Vassilis N. Stathopoulos, Pavlos K. Pandis, Kostas Lymperis, Luis Coelho, and Amandio Rebola. "Development and experimental testing of a compact thermal energy storage tank using paraffin targeting domestic hot water production needs." *Thermal Science and Engineering Progress* 19 (2020): 100573. https://doi.org/10.1016/j.tsep.2020.100573

[9] Al-Madhhachi, Hayder, and Ghassan F. Smaisim. "Experimental and numerical investigations with environmental impacts of affordable square pyramid solar still." *Solar Energy* 216 (2021): 303-314. https://doi.org/10.1016/j.solener.2020.12.051

[10] Mehmood, Aamir, Adeel Waqas, Zafar Said, Shek Mohammad Atiqure Rahman, and Muhammad Akram. "Performance evaluation of solar water heating system with heat pipe evacuated tubes provided with natural gas backup." *Energy Reports* 5 (2019): 1432-1444. https://doi.org/10.1016/j.egyr.2019.10.002

[11] He, Zhaoyu, Xiaohui Wang, Xiaoze Du, Chao Xu, and Lijun Yang. "Cyclic characteristics of water thermocline storage tank with encapsulated PCM packed bed." *International Journal of Heat and Mass Transfer* 139 (2019): 1077-1086. https://doi.org/10.1016/j.ijheatmasstransfer.2019.05.093

[12] Hongbing, Chen, Yan Xiaoli, and Chen Xilin. "Study on the performance of residential centralized solar hot water System." *Energy Procedia* 158 (2019): 223-228. https://doi.org/10.1016/j.egypro.2019.01.080.

[13] Wu, Wei, Xiaoyu Wang, Man Xia, Yiping Dou, Zhengyu Yin, Jun Wang, and Ping Lu. "A novel composite PCM for seasonal thermal energy storage of solar water heating system." *Renewable Energy* 161 (2020): 457-469. https://doi.org/10.1016/j.renene.2020.06.147

[14] Khargotra, Rohit, Raj Kumar, and Sushil Kumar. "Impact of perforated shapes in delta type hindrance promoter on thermo-hydraulic performance of solar water heating system (An experimental study)." *Case Studies in Thermal Engineering* 24 (2021): 100831. https://doi.org/10.1016/j.csite.2020.100831

[15] Li, Yantong, Nan Zhang, and Zhixiong Ding. "Investigation on the energy performance of using air-source heat pump to charge PCM storage tank." *Journal of Energy Storage* 28 (2020): 101270. https://doi.org/10.1016/j.est.2020.101270

[16] Brembilla, Eleonora, and John Mardaljevic. "Climate-Based Daylight Modelling for compliance verification: Benchmarking multiple state-of-the-art methods." *Building and Environment* 158 (2019): 151-164. https://doi.org/10.1016/j.buildenv.2019.04.051

[17] Douvi, Eleni, Christos Pagkalos, George Dogkas, Maria K. Koukou, Vassilis N. Stathopoulos, Yiannis Caouris, and Michail Gr Vrachopoulos. "Phase change materials in solar domestic hot water systems: A review." *International Journal of Thermofluids* 10 (2021): 100075. https://doi.org/10.1016/j.ijft.2021.100075

[18] Majumdar, Rudrodip, and Sandip K. Saha. "Effect of varying extent of PCM capsule filling on thermal stratification performance of a storage tank." *Energy* 178 (2019): 1-20. https://doi.org/10.1016/j.energy.2019.04.101

[19] Algabri, Yousif A., Surapong Chatpun, and Ishkrizat Taib. "An investigation of pulsatile blood flow in an angulated neck of abdominal aortic aneurysm using computational fluid dynamics." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 57, no. 2 (2019): 265-274.

[20] Soodmand, Ahmadreza Mohammadian, Siyamak Nejatbakhsh, Hadi Pourpasha, Hassan Aghdasinia, and Saeed Zeinali Heris. 2022. "Simulation of Melting and Solidification Process of Polyethylene Glycol 1500 as a PCM in Rectangular, Triangular, and Cylindrical Enclosures." *Alexandria Engineering Journal* 61 (11): 8431–56. https://doi.org/10.1016/j.aej.2022.02.011.