Research Inventy: International Journal of Engineering And Science
Vol.15, Issue 5 (May 2025), PP 35-40
Issn (e): 2278-4721, Issn (p):2319-6483, www.researchinventy.com

Numerical Study of Thermal Storage Tank Lagged with Phase Change Materials for Domestic Hot Water Application

ONIBIYO Olawale John., Abioye A. M. PhD., & Nuhu M. PhD
Department of Mechanical Engineering, ATBU, Bauchi

Abstract
This study investigates the numerical modelling (using TRNSYS software) and thermal performance of a Phase Change Material (PCM)-lagged thermal storage tank (TST) for domestic hot water systems. A computational model was developed to simulate heat retention in PCM-lagged tanks using paraffin, PEG 4000, and sodium thiosulphate as storage media. Results indicate that PCM-lagged tanks significantly outperform conventional insulated tanks, maintaining water temperatures above 52.31°C after 24 hours compared to 24.65°C in non-PCM tanks. Sodium thiosulphate emerged as the most cost-effective PCM, offering optimal thermal stability, while PEG 4000 demonstrated superior heat retention in larger volumes. Smaller tanks (0.01 m³) heated rapidly but cooled faster, whereas larger tanks (0.10–0.13 m³) exhibited prolonged heat retention, making them ideal for sustained demand. The study concludes that PCM integration enhances energy efficiency, reduces reheating frequency, and cuts operational costs, with a strong case for scalability in residential and industrial settings. Recommendations include coupling PCM-TST systems with solar thermal technologies and prioritizing smaller-volume tanks for budget-sensitive projects while adopting larger systems for long-term sustainability. This research contributes to renewable energy storage optimization, supporting global efforts toward energy conservation and reduced carbon emissions.

Keywords: *Phase Change Material, Thermal Storage Tank, Domestic Hot Water, TRNSYS*

Date of Submission: 02-05-2025 Date of Acceptance: 13-05-2025

I. Introduction

The fast growing technological and economic development in our societies has increased the demand for energy. The most consumption of energy comes from burning of fossil fuels. The side effect of burning fossil fuel to generate energy is environmental pollution and climate changes. To effectively utilize energy and reduce the greenhouse effects efforts are being shifted towards various sources of sustainable and renewable energy. In many parts of the world, direct solar radiation is one of the most prospective sources of renewable energy, however, its intermittency reduces the energy conversion efficiency and becomes the major setback (Waterson, 2017).

To address the intermittency problem, energy storage devices are developed, and they are as important as developing new sources of energy (Beaudin *et al*. 2010). Energy storage not only reduces the mismatch between supply and demand but also improves the performance and reliability of energy systems and plays an important role in conserving energy. It leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy and capital cost. Energy storage is the capture of energy produced at one time for use at later time.

Thermal energy storage (TES) is a form of energy storage with promising solution to energy conservation and has undergone rapid development. The implementation of TES enhances the overall efficient and the dispatch ability of power generation applications with renewable sources (Rathod, 2014). TES, which utilizes the change of the internal energy within the storage media, can be classified into thermochemical-, sensible, or latent heat storage. Compared to sensible heat, latent heat storage is a more efficient method and provides a much higher energy density with a smaller temperature difference between storing and releasing heat (Sarbu and Sebarchievici, 2018).

Phase change materials (PCM) are ‘‘Latent’’ heat storage materials. The thermal energy transfer occurs when a material changes from solid to liquid, or liquid to solid. This is called a change in state, or ‘‘Phase.’’ Initially, these solid–liquid PCMs perform like conventional storage materials; their temperature rises as they absorb heat. Unlike conventional (sensible) storage materials, PCM absorbs and release heat at a nearly constant temperature (figure 1) and store more heat per unit volume than sensible storage materials such as water, masonry, or rock. Many PCMs are known to melt with a heat of fusion in any required range. Moreover, economic considerations and easy availability of these materials must be kept in mind.

Currently, the application of PCM has been widely developed in different fields including, heating, and cooling of domestic buildings, solar power plants, solar drying systems, photovoltaic electricity generations, refrigerators, waste heat recovery and domestic hot water systems.

Domestic hot water systems supply water at temperature above the ambient (not more than 49 ℃ - to avoid pain and dangerous scalding injuries, especially in children and the elderly) for bathing, laundry, and cooking in the homes (Mezei and Stanwick, 2004). To produce water at this temperature every time it is needed, water at ambient temperature must be heated mostly through the burning of fossil fuel or with electric boilers (Verdier *et al*. 2014). An energy conservation approach is to store hot water in an insulated water cylinder for subsequent use. Generally, a well-insulated water cylinder can keep water hot for a considerable amount of time. As a rough estimate, water in a properly insulated cylinder can stay hot for several hours, typically ranging from 6 to 12 hours or even longer (Montet *et al*, 2021).

Most hot water cylinder manufacturers suggest that the water will lose between 1 kWh and 2.5 kWh of heat per day (Beaudin *et al*. 2010). The better insulated your tank is, the more heat it will retain. The presence of Phase Change Material (PCM) in an insulated water cylinder can significantly improve its ability to retain heat and keep the water hot for an extended period. PCM is designed to absorb and release thermal energy during phase transitions, such as solid to liquid and vice versa (Sharma and Sagara, 2005). The exact time that hot water will stay hot in an insulated water cylinder with PCM will depend on various factors, including the type of PCM used, the volume of water, the initial water temperature, and the level of insulation.

In general, water in an insulated cylinder with PCM can stay hot for a much longer duration compared to a cylinder without PCM. It can extend the heat retention time to several hours, potentially ranging from 12 to 24 hours or even more, depending on the specific circumstances and the quality of the PCM and insulation. (Esbati *et al.*, 2020*)*

The aim of the numerical study is to numerically study a thermal storage tank (TST) lagged with phase change material for domestic hot water application by

(i) Development of a model equation for the simulation of a TST for domestic hot water application.
(ii) Simulation of three TSTs lagged with three different phase change material using TRNSYS software
(iii) Comparison of thermal performance analysis of the TST lagged with PCMs and without PCM

II. Materials and Method

i. Paraffin
ii. Polyethylene Glycol 4000
iii. Sodium Thiosulphate
iv. Stainless steel tank
v. Fiberglass materials for lagging

The tool for this project is TRNSYS Software

In this study, a uniform steady flow distribution in the flow direction inside the energy storage is assumed. Therefore, only energy balance equations are considered. The energy models are calculated by the finite difference method in the implicit formulation. The PCM hot water tank model does not exist in the TRNSYS 18 simulation library and therefore needs to be developed based on theoretical equation that describes the thermal behaviour of the PCM tank as found in different studies (Weiqiang Kong et al. 2022).

Heat Stored

$$Q = \int_{T_i}^{T_f} mC_p dT = mC_{ap}(T_f - T_i) \quad \text{... (1)}$$

Latent Heat Stored

$$Q = \int_{T_i}^{T_m} mC_p dT + ma_m \Delta H_m + \int_{T_m}^{T_f} mC_p dT \quad \text{..(2)}$$

The energy differential equation in one dimension for the cylindrical water tank

$$\frac{\partial \rho c T_W}{\partial t} + \frac{\partial \rho c u T_W}{\partial x} = \frac{\partial}{\partial x}\left(k\frac{\partial T_W}{\partial x}\right) + h_{hl}A_s(T_a - T_w)/V + \Gamma A_{pw}\left(T_p - T_w\right)/V \quad \text{... (3)}$$

By finite difference method equation 3 becomes

$$mc\frac{T_i - T_i^0}{\Delta t} = kA_c\frac{T_{i-1} - T_i}{\Delta x} + kA_C\frac{T_{i+1} - T_i}{\Delta x} + \dot{m}c\left(T_{i-1} - T_i\right) + h_{hl}A_s(T_a - T_i) + \Gamma A_{pw}\left(T_{pi} - T_i\right)$$

...(4)

Sorting out the term in Eq. 4, it is further written as shown in Eq. 5

$$\left(-\frac{kA_c}{\Delta x}-\dot{m}c\right)T_{i-1}+\left(\frac{mc}{\Delta t}+\frac{2kA_c}{\Delta x}+h_{hl}A_s+\dot{m}c+\Gamma A_{pw}\right)T_i+\left(-\frac{kA_c}{\Delta x}\right)T_{i+1}=h_{hl}A_sT_a+\Gamma A_{pw}T_{pi}+\frac{mc}{\Delta t}T_i^0 \quad ...(5)$$

The boundary conditions for the nodes can be found using Eq. 6 and 7 below

$$\left(-\frac{kA_c}{\Delta x}\right)T_1+\left(\frac{mc}{\Delta t}+\frac{2kA_c}{\Delta x}+h_{hl}A_s+\dot{m}c+\Gamma A_{pw}\right)T_1+\left(-\frac{kA_c}{\Delta x}\right)T_2=h_{hl}A_sT_a+\Gamma A_{pw}T_{p1}+\frac{mc}{\Delta t}T_1^0 \quad ...(6)$$

$$\left(-\frac{kA_c}{\Delta x}\right)T_{N-1}+\left(\frac{mc}{\Delta t}+\frac{2kA_c}{\Delta x}+h_{hl}A_s+\dot{m}c+\Gamma A_{pw}\right)T_N+\left(-\frac{kA_c}{\Delta x}\right)T_N=h_{hl}A_sT_a+\Gamma A_{pw}T_{pN}+\frac{mc}{\Delta t}T_N^0 \quad ...(7)$$

Similarly, conducting an energy balance on the PCM region of the tank Eq. 8 is applicable

$$\frac{\partial \rho H_p}{\partial t}=\frac{\partial}{\partial x}\left(k\frac{\partial T_P}{\partial x}\right)+\Gamma A_{pw}(T_w-T_p)/V \quad ...(8)$$

The dynamic energy change of Eq. 8 is described by the enthalpy of PCM since its nonlinear energy-temperature relationship. This phenomenon is described and estimated from the Eq. 9 (Weiqiang et al. 2022).

$$H_p=\begin{cases} c_sT & T<T_{m1} \\ c_sT_{m1}+\frac{E_L(T-T_{m1})}{T_{m2}-T_{m1}} & T_{m1}\le T\le T_{m2} \\ c_sT_{m1}+E_L+c_i(T-T_{m2}) & T>T_{m2} \end{cases} \quad ...(9)$$

The hot water thermal hourly energy requirement will be estimated based on the volume of hot water tank using Eq. 10

$$\dot{Q}_{DHWL}=\dot{m}_LC_p(T_L-T_{mains}) \quad ...(10)$$

The quantity of thermal energy delivered by the proposed system to meet building's hot water demand is estimated as shown in Eq. 11

$$\dot{Q}_d=\dot{m}_LC_p(T_d-T_{mains}) \quad ...(11)$$

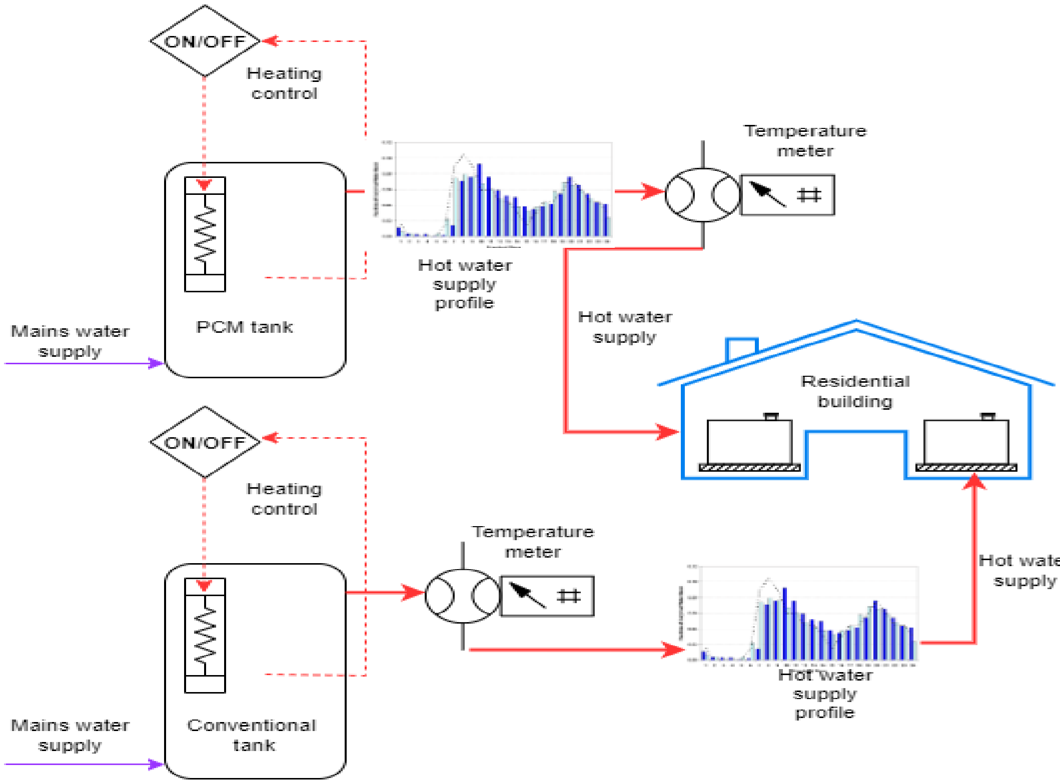
The Since the extra energy to heat water to the desired hot water temperature is only required when the water temperature in the heater tank falls below the designed temperature, the required auxiliary thermal energy is calculated as expressed in Eq. 12

$$\dot{Q}_{aux}=\max((\dot{Q}_{DHW}-\dot{Q}_d),0) \quad ...(12)$$

System Development

A family of four adults is Bauchi is estimated to use about 0.55 m^3 daily of water and 0.3 m^3 out of this 0.55m^3 is estimated to be required in hot quantity (Victor, 2017). Therefore, the system consists of a 0.3 m^3 phase change material (PCM) hot water storage tank connected to a residential building to supply hot water for domestic application in simple residential house (figure 6). The supply water into the PCM tank is conveyed through the pipe connected to the mains water supply. Inside the hot water tank is the electric heating element sized to heat 0.3m^3 of water to 80°C in less than 3 hours and the heating element is controlled to stop by means of a controller immediately the water temperature in the tank has reached 80°C. When heating of water is stopped, the hot water temperature supplied to the residential building for domestic application based on the hot water draw profile as described in the diagram is monitored and recorded for 24 hours.

Similarly, the same approach and technique is adopted to measure the performance of a conventional hot water system similar in size to the one described above. Figure 6 is the schematic of the described system in this study.



The two hot water systems are designed to be heated, then passed through the hot water supply profile and a temperature meter before been supplied to the household. This will enable data such as the quantity used and temperatures at different times to be properly taken.

3.4 System Modelling and Analysis

One of the objectives of this study is to formulate a representative model of the proposed energy system for the performance simulation and evaluation. The formulated model will used to predict the thermal behaviour of the system. It will also be the bases for the estimation of the benefit of the proposed system over the conventional system. In this study, the transient system simulation tool TRNSYS 18 is selected for the system modelling, performance simulation, and evaluation. TRNSYS 18 is a modular software package with a library of validated models that can be customized to any conceived energy solution and with great flexibility for adaptation for thermal applications. Additionally, its flexibility for users to formulate algorithms and logic that control the operation of the formulated models to adapt to specific control as desired by the user has made it suitable for studying different scenarios and control strategies (Pirmohamadi et al. 2021). Unlike other energy modelling software, its capability for transient system simulation and analysis has made it possible for system simulation for any specific length of time of interest.

Consequently, a dynamic model of the system, as depicted in the schematic as shown in figure 6 is developed as a representation of the actual system to predict the system performance and evaluate the system's annual performance using TRNSYS 18 software. This model consists of the various system components referred to as ‘Type’ found in the simulation library and connected to one another. The model components are connected in a manner that represents the actual working of the real system as illustrated in the model flow diagram in figure 7.

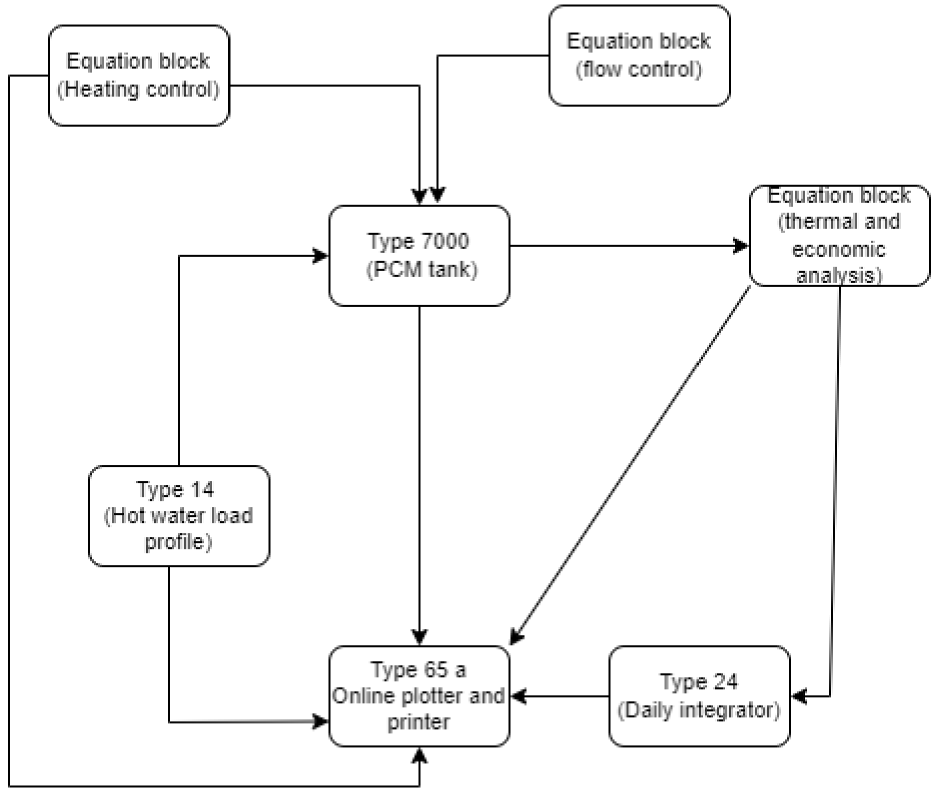


Figure 7: Flow diagram for the Model Formulation of the PCM Hot Water Heating System

III. Results and Discussions

Comparison of thermal characteristics of PCM tanks

Figure 12 show the thermal behavior of three PCM hot water tanks during heating and cooling compared to hot water tank without PCM.

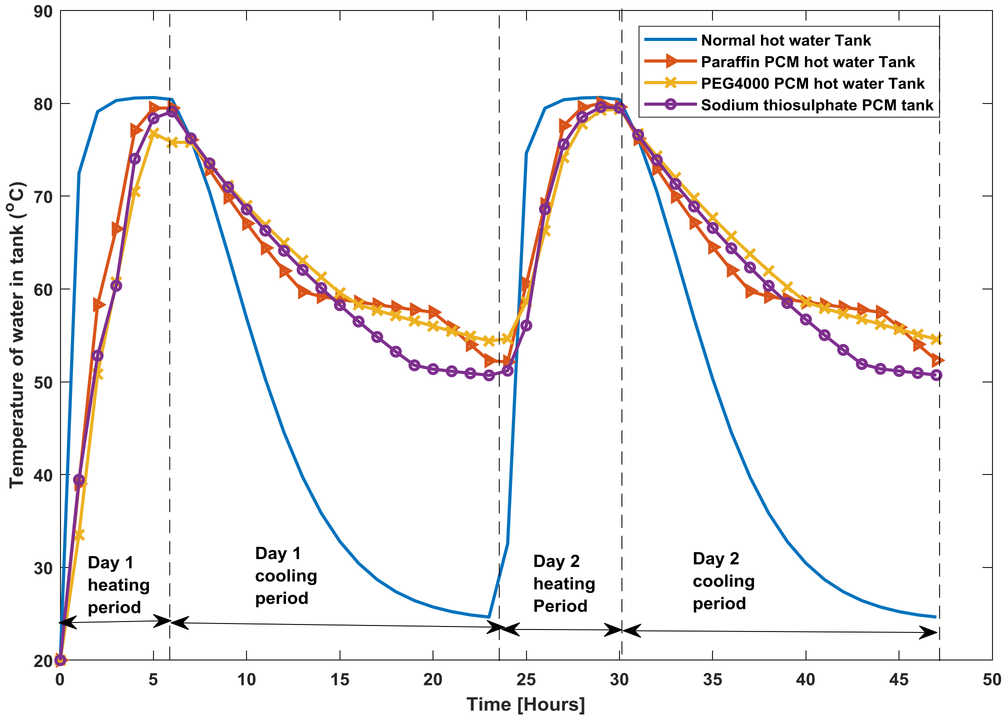


Figure 12: Thermal Characteristics of Non PCM and PCM Tanks

It is seen from Figure 12 that the thermal behaviour of the hot water in the three PCM tanks compared to the normal hot water tank reveals significant differences in temperature stability and energy efficiency. For the normal hot water tank, the temperature increases rapidly, reaching a maximum of around 80.63°C at 3 hours. This indicates that the normal tank heats up quickly. On the other hand, the temperature of paraffin and PEG 4000 PCM tanks increase slowly compared to the normal tank, reaching about 79.99°C and 79.34°C respectively in 5 hours. The slower increase of the PCM tanks is due to the heat absorption and phase change of the PCM, which acts to moderate rate of temperature rise.

It is also seen that after the heating phase, the temperature of the normal tank is observed to drop steadily, reaching about 24.65°C after the first day (24 hours) and second days (48 hours) respectively. This rapid cooling implies that the normal tank loses heat quickly once the heating source is removed. Comparing the normal tank thermal behaviour with the PCM tank, during the cooling phase, the Paraffin PCM tank maintains a relatively stable temperature for a longer period, dropping to around 52.31°C at 24hours. This can be explained by the fact that the PCM helps to slow down the rate of temperature decrease, indicating better thermal retention. PEG400 PCM tank shows very similar but better behaviour with a slower cooling rate compared to the normal tank. For the PEG4000 PCM tank, the temperature decreases to about 54.57°C in 24 hours showing a 2^oC better retention capacity compared to the Paraffin PCM tank. This slower cooling rate demonstrates that PEG 4000 PCM provides better thermal retention than the normal tank but slightly higher than Paraffin PCM tank. The Sodium thiosulphate tank has a similar cooling profile to the other PCM tanks, with the temperature falling to about 50.72°C at 48 hours.

These results implies that the normal tank will require the lowest energy input to heat the water to desired temperature compared to the PCM tanks. However, its poor heat retention can lead to higher energy consumption if maintaining temperature is required over a longer period compared to the PCM tanks. On the other hand, the slower cooling rate of the PCM tanks implies that PCM tanks retain heat for longer periods, which can result in significant energy savings.

IV. Conclusion

The study successfully developed a detailed numerical model that simulated the operation of thermal storage tank (TST) for hot water tanks. This model serves as a tool for predicting the system behaviour under varying conditions

The performance evaluation of the TSTs lagged with phase change material revealed its thermal storage efficiency and energy savings capability. The system achieved extended thermal stability and reduced heat loss, leading to potential energy savings and more consistent hot water availability. Thus, for applications requiring sustained temperature maintenance and reduced energy consumption, PCM tanks are a more efficient choice.

References

[1]. Agyenim, F., Hewitt, N., Eames, P., and Smyth, M. (2010). A review of materials, heat transfer and phase change prob-lem formulation for latent heat thermal energy storage systems (LHTESS), Renew. *Sustain. Energy Rev.*, 14, 15–28.

[2]. Avghad, S. N., Keche, A. J., and Kousal H. (2016). A thermal energy storage: A review. *J. Mech. Civ. Eng. 13,* 72–77.

[3]. Bechiri, M. and Mansouri K, (2016). Analytical study of heat generation effects on melting and solidification of nano-enhanced PCM inside a horizontal cylindrical enclosure, *Appl. Therm. Eng. 104,* 779–790.

[4]. Beaudin, M., Hamidreza, Z., Schellenberglabe, A., and William, R (2010). Energy storage for mitigating the variability of renewable electricity sources: An updated review. *Energy for Sustainable Development, 14,* 302-14.

[5]. Calvet, N., Py, X., Olivès, R., Bédécarrats, J. P., and Dumas, F., (2013). Enhanced performances of macro-encapsulated phase change materials (PCMs) by intensification of the internal effective thermal conductivity, *Energy 55,* 956–964.

[6]. Esbati, S., Mohammed, A. M., Sadeghzadeh, M., Mohammad, H., Pourfayaz, F., and Tingzhen, M (2020). Investigating the effect of using PCM in building materials for energy saving*:* case study. *Energy Sci Eng, 8*. 95-99

[7]. Mezei, R. and Stanwick, R. (2004) Hot water scalds prevention: A case for the power of public health partnerships in affecting regulatory change. *Pediatr Child Health*. 3, 153–155.

[8]. Montet, F., Lorenz, R., Alessandro, P., Hennebert, J. and Bacher, J. P. (2021). Prediction of Domestic Hot Water Temperature in a District Heating Network. *Journal of Physics: Conference Series,* 2042.

[9]. Pirmohamadi, A., Dastjerdi, S. M., Ziapour, B. M., Ahmadi, P., and Rosen, M. A. Dec (2021). Integrated solar thermal systems in smart optimized zero energy buildings: Energy, environment and economic assessments. *Researchgate, Vol. 48,* 101580.

[10]. Rathod M. (2014). Phase change material and their applications. *National Institute of Technology*. *11* 55–61

[11]. Sarbu, I. and Sebarchievici, C. (2018). A Comprehensive Review of Thermal Energy Storage *Sustainability 10,* 191.

[12]. Sharma, S. D., and Sagara K. (2005) A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies. *International Journal of Green Energy*. *2,* 19-21.

[13]. Verdier, D., Ferrière, Q., Falcoz, F., Siros, F. and Couturier, R. (2014). Experimentation of a High Temperature Thermal Energy Storage Prototype Using Phase Change Materials for the Thermal Protection of a Pressurized Air Solar Receiver. *Energy Procedia. 49,* 1044-53.

[14]. Victor Istifanus. (2017). ' Analysis of Quantity of Domestic Water Use in Bauchi Metropolis. *IOSR Journal of Environmental Science*. *11,* 01-05.

[15]. Waterson, M. (2017). The characteristics of electricity storage, renewables and markets energy policy. *Elsevier. 14,* 34-38

[16]. Weiqiang, K., Gang, W., Englmair, G., Nomonde, E., Noma N., Dragsted, J., *et al* (2022). A simplified numerical model of PCM water energy storage. *Journal of Energy Storage*. *55,* 16-18