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# AWARD NOMINATION FORM

Name of Person being Nominated: Thandiwe Bongani Radebe

Which Award is the Person being nominated for: SAIRAC Prize

Details of the Achievements

Mr TB Radebe is the final year student for Doctor of Engineering with specialization in Refrigeration in Tshwane University of Technology (TUT), his research project is entitled as "Nanoparticles enhanced phase change thermal storage for cold chain applications".

He published five (5) original research papers in accreditted journals and conference proceedings. (Attached)

Please give a detailed description of why you are nominating this person:

Mr TB Radebe is an educated doctoral candidate with right attitude and high level of skills and solid knowledge in refrigeration and its applications, he is a qualified researcher to solve the real world problems, generate new knowledge and innovate new technologies and products. He invented a new phase change thermal storage unit and published five original researcher papers in past year.

Name & SAIRAC number : Zhongjie Huan, 4617

Signature: [signature]

Date: 30 May, 2023

Cell: 0618581668

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Research Papers

# Investigation of low-cost eutectic salts to ensure food products during power outages

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ABSTRACT

Temperature-sensitive food products such as fruits and vegetables require refrigeration to minimise spoilage and prolong product shelf life for later consumption. To reduce food spoilage during power outages, a Phase Change Material (PCM) can be integrated into a domestic refrigerator to maintain the inside temperature constant. This study investigated three inexpensive eutectic water-salt solutions, KCl, $MgCl_2$ and NaCl with a phase change temperature of −10 °C, −19 °C and −21 °C, because of their high latent heat and relatively low price. Transmission and air infiltration loads were used to determine the amount of PCM required to maintain the inside temperature of a KIC KBF 525/1 ME Refrigerator below 4 °C during an average 2.5-hour power outage in South Africa. From the heat loads inquired, 1.5 and 5 l were required. For both 1.5 l of KCl and NaCl the temperature of the refrigerated compartment exceeded 5 °C after 2.5 h. For the 5 l of KCl, however, the temperature of the refrigerated compartment took 20 h before exceeding 5 °C. For 5 l of NaCl, it was able to pull down the temperature and maintain 0 °C in the refrigerated compartment for close to 10 h. It took 1.5 l of KCl and NaCl 1 day and 3 days to fully solidify and 5 l of KCl and NaCl 2 days and 6 days. It was noted that to increase the heat transfer inside the refrigerator, it is advisable to use a PCM with the lowest phase change temperature, however, the PCM might not fully freeze if the freezer temperature is not drastically below the phase change temperature.

## 1. Introduction

The preservation of agricultural produce is important in maintaining food's nutritional quality. Temperature-sensitive food products such as fruits and vegetables require refrigeration to minimise spoilage and prolong product shelf life for later consumption [1].

It was highlighted by Oró et al. [2] that some countries have a restriction on the daily use of electricity. This leads to electrical equipment being switched off, thus leading to food spoilage. One research area that seeks to provide a solution deals with integrating a phase change material (PCM) into a refrigeration system. A PCM stores and releases latent heat energy during the phase transition from liquid to solid and from solid to liquid. The high storage density possessed by a PCM makes it suitable for applications where energy efficiency is limited by weight. The application of PCM for low-temperature refrigeration is referred to as cold thermal energy storage (CTES) [3]. The need to offset peak load demands makes it feasible to incorporate latent heat PCM in refrigeration systems [4]. Domestic refrigerators and refrigerated warehouses have been integrated with CTES systems. The inside temperature of a domestic refrigerator can be maintained using PCMs while the refrigerator's compressor is switched off, this can evaluate the PCM's performance in scenarios where there are power failures [2].

Several studies have been conducted with PCM being placed on the condenser coils to reduce the condensing temperature while some create independent heat exchangers. Increasing the degree of sub-cooling of the refrigerant leads to enhancing the COP of the system [5–8]. While other authors place the PCM on the evaporator coil [9–12]. Marques et al. [13] conducted numerical modelling to estimate the PCM charge and discharge rate while incorporating the refrigerators on and off-cycle durations at different ambient conditions. His numerical model was validated with experiments, later Zarajabad & Ahmadi [14] confirmed using Marques et al. experimental data that increasing the quantity of PCM is directly proportional to the time that the PCM will maintain the compartment. A review on PCM in domestic refrigeration systems was done by Joybari et al. [15] and Kumar et al. [16], previous literature does not illustrate the t-history curves of the PCMs during the charging and discharge phase This is beneficial to determine the time needed to freeze and melt each PCM. This study therefore focuses more on the

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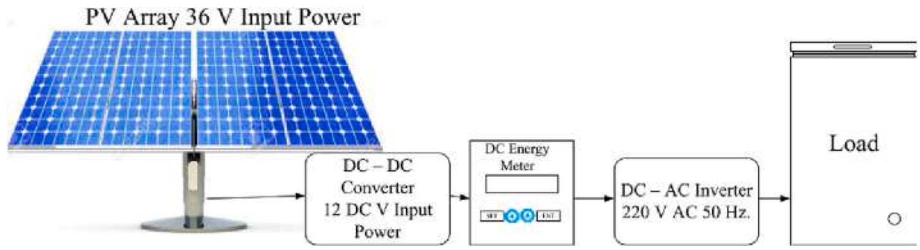


**Fig. 1.** Test rig electrical wiring block diagram [18].

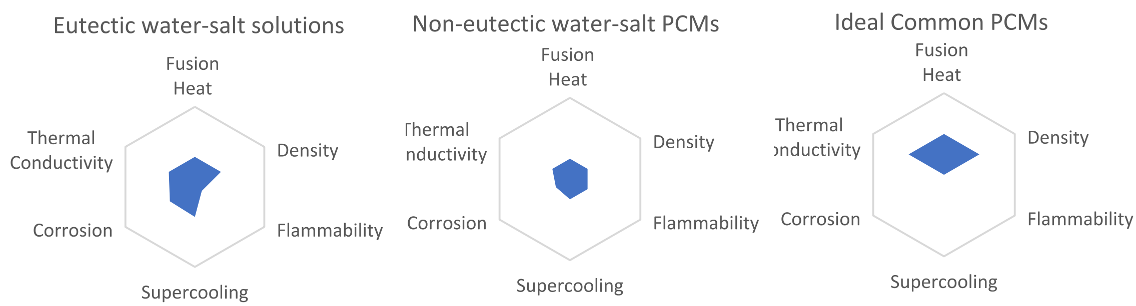


**Fig. 2.** Thermal Property comparison of common PCMs [19].

performance of the charging and discharging phase of inexpensive eutectic PCM water-salt solutions to maintain a refrigerated compartment at a constant temperature during power outages.

### *1.1. PCM in refrigerators*

Gin et al. [21] highlighted the importance of reducing temperature fluctuations to prevent or delay microbial, physiological, and chemical changes in food. In this study, Gin et al. [21] used PCM panels to improve the storage condition of frozen food. The study investigated the heat loads incurred during electrical power cuts over 2 weeks with daily power outages of 2–3 h. The authors placed two 1 l vanilla ice cream and 28 cubes (1 $cm^3$) of bovine muscle as meat samples. The study revealed that the freezer temperature escalated from −15 °C to −3 °C without PCM, and from −15 °C to −11 °C during a 3-hour power outage. The ice cream crystals size increased from 40 to 50 μm to 70–80 μm after the two weeks without PCM, while with PCM the crystal size remain unchanged. The drip loss of the meat samples after two weeks was 17 % without PCM compared to 10 % with PCM in the freezer.

In another study by Oró et al. [2] the thermal performance of the commercial 270-litre supermarket vertical freezer was improved. The vertical freezer had a fan positioned at the top of the back wall to provide air circulation. The authors used 7.84 kg of Climsel C-18 PCM solution with a phase change temperature of −18 °C. The authors mentioned that the PCM solution was corrosive. The PCM solution was separated into six 1.12 kg PCM solutions and filled in 10 mm thick stainless steel tray shelves. The PCM shelves were placed directly on the evaporator coils to increase the heat transfer rate. The study aimed to determine the thermal performance of a supermarket display vertical freezer with and without PCM during a power outage of 15, 30, 60, 120 and 180 min, with frequent door openings of 10, 30, 180, 300, and 600 s. Test packages (M-packs) were used to simulate the thermal mass of food. From the results, the freezer operating without PCM and M-packs reached the highest temperature due to the lowest thermal mass, the temperature distributions inside the compartment showed an increase in temperature at the top of −6 °C and the bottom at −11 °C. The authors noticed that the temperature increases slower when there is PCM inside with −10 °C at the top and − 16 °C at the bottom. The authors concluded the study by saying the use of PCM maintains a compartment at 4–6 °C lower after a prolonged period of power failure.

Abdolmaleki et al. [17] further developed the research work done by Oró et al. [2]. The authors aimed to optimize the parameters and find the most efficient temperature and optimum amount of PCM. The authors used a Design Expert(DX7) software together with the Central Composite Design method for two variables, with three levels and four centre points. Results showed that by increasing the amount of PCM and decreasing the phase change temperature of the solution will drastically reduce the temperature flucturations by up to 40.59 %. The study concluded that for a vertical freezer of 262 l, the optimal amount of PCM is 1.61 kg with a phase change temperature of −20 °C. This configuration resulted in a 37.67 % temperature fluctuations reduction.

Khalifa et al. [18] incorporated PCM into a 100-litre solar-powered chest freezer. The author connected the solar system to the compressor of the chest freezer without interacting batteries in between as seen in Fig. 1. Due to the high torque required by the compressor, grid electricity was used for 10 s before switching to the solar system, this enabled the compressor to run from 8 a.m. to 4 p.m. The aim was to power the chest freezer using solar energy for 8 h, then rely on the PCMs to maintain the refrigerated compartment during the night, when solar energy is unavailable. The author used 4.7 kg and 12.5 kg of KCl with a phase change temperature of −10 °C. The PCM solution was encapsulated in regular aluminium tubing after conducting a study that at specific concentrations, KCl solution has the lowest aggressiveness against aluminium. The author did not mention if the evaporator coils were embedded in the aluminium containers. The freezer compartment's temperature was maintained below −8 °C for 70 % of the holdover period. The author concluded that incorporating 12.5 kg of PCM was ideal PCM. Despite this innovative idea, the authors mentioned that the challenge is getting the solution to fully solidify within the time the compressor is on. Sun availability during cloudy days might also affect the performance of the PCM solution.

### *1.2. PCM selection*

Li et al. [19], did a comparison between Eutectic water-salt solutions, Non-eutectic water-salt PCMs, and the ideal common PCMs. Although there is no ideal common PCMs, however, six thermal properties are crucial when determining the type of PCM to be used. In Fig. 2, six thermal properties are compared on a radar chart. Three advantageous thermal properties which are thermal conductivity, fusion heat, and

**Table 1**
Comparison of organic and inorganic PCM [20].

| | Organic | Inorganic |
|---|---|---|
| Advantages | No corrosive<br>Low or no subcooling<br>Chemical stability | Greater phase change enthalpy |
| Disadvantages | Low phase change enthalpy<br>Low thermal conductivity<br>Flammability | Subcooling<br>Corrosion<br>Phase separation<br>Phase segregation, lack of thermal stability |

density are compared with three disadvantageous properties, corrosion, supercooling, and flammability. However, Li et al. [19] further elaborated that these diagrams are not according to scale but are designed to provide a general idea of the ideal common PCMs needed.

Following a study by Li et al. [19] it was indicated in a further study by Cabeza and Oró [20] that the desirable properties of LHTESS were:

- Have a high Latent Heat and specific heat per unit volume and weight
- Have a desirable melting point for the designed system
- Have a low vapour pressure below 1 bar at operational temperature
- Be chemically stable and be noncorrosive towards the material case
- Not to be hazardous, highly flammable or poisonous
- Be able to reproduce crystallization without degradation
- Have a small subcooling degree and a high rate of crystal growth
- Have a small volume variation when undergoing the solidification process
- Have a high thermal conductivity
- Be available in abundance

Table 1 and Table 2 showed that it is desirable to use inorganic PCM for a low-temperature system despite the disadvantage encountered.

*1.2.1. Phase separation and supercooling minimization*

During the phase change process from solid to liquid, the PCM can undergo a phase separation or have an incongruent melting. This will result in a loss of enthalpy of solidification occurring. This problem can be overcome by adding water with gelling in the form of a cross-linked material to the salt such as a polymer. This material will increase the viscosity of the solution. This then creates a three-dimensional network holding the solution together. Polymeric hydrogels such as a super absorbent polymer (SAP), made from acrylic acid copolymer and carboxymethyl cellulose (CMC), have been studied as cross-linked

**Table 3**
Eutectic saltwater solutions.

| | KCl | $MgCl_2$/H2O | NaCl/H2O |
|---|---|---|---|
| Salt to water (%) | 19.5/80.5 | 25/75 | 22.4/77.6 |
| Phase change temperature (°C) | −10.7 | −19.4 | −21.2 |
| Density (kg/m$^3$) | 1980 | 2320 | 2160 |
| Latent heat (kJ/kg) | 253.18 | 223.10 | 228.14 |
| Quantity used (g) | 950 | 1250 | 1120 |
| Price per 500 g (ZAR) | R168.30 | R58.36 | R100.92 |

**Table 4**
Input variables.

| | Intake |
|---|---|
| Atmospheric temperature | 30 °C |
| Compartment temperature | 4 °C |
| Freezer temperature | −19 °C |
| Polyurethane insulation | 0.028 W/mK |
| Insulation thickness | 30 mm/60 mm |
| Compartment (LxBxH) | 0.6 × 0.45 × 0.7 |
| door open-close time | 3 s |
| time door simply stands open | 1 min |

**Table 2**
Comparison of PCM types [20].

| | Organic fatty | | Inorganic metals | | |
|---|---|---|---|---|---|
| | Paraffins | Fatty acids | Salt hydrates | Metals | Eutectics |
| Formula | $C_nH_{2n+2}$ ($n = 12 - 38$) | $CH_3(CH_2) \bullet COOH$ | $AB \bullet nH_2O$ | – | – |
| Melting enthalpy | 190–260 kJ/kg | 130–250 kJ/kg | 100–200 kJ/kg | 25–90 kJ/kg | 100–230 kJ/kg |
| Cost | Expensive | 2 to 3 times more expensive than paraffin | Low cost | Costly | Costly |

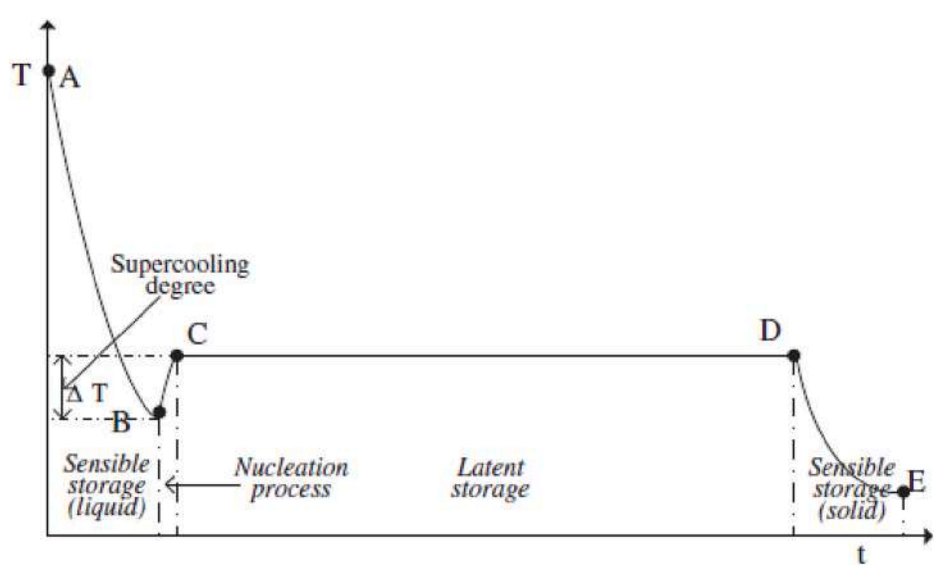


**Fig. 3.** The cooling process of a eutectic water-salt solution [19].

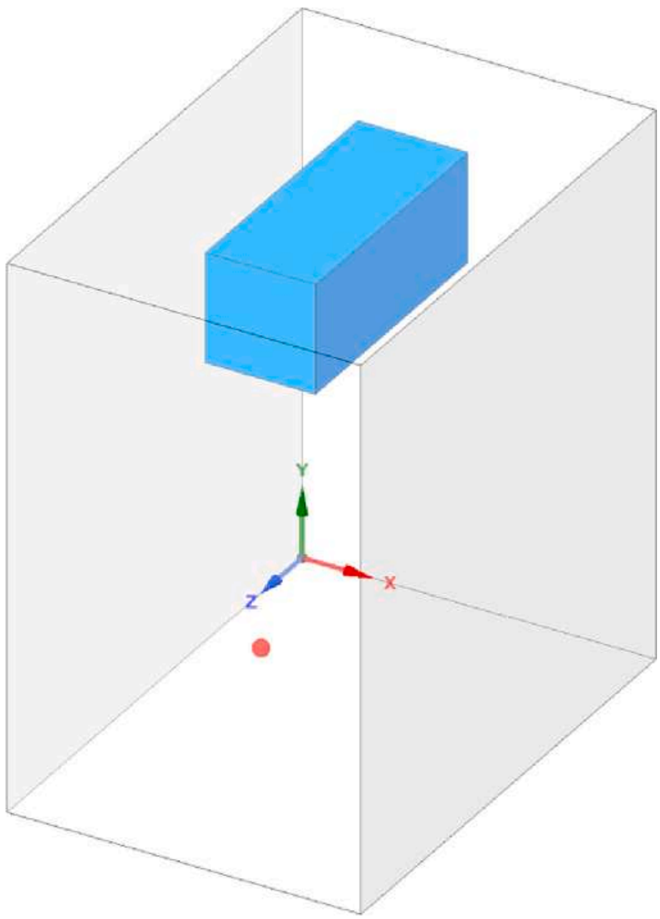


**Fig. 4.** Configuration.

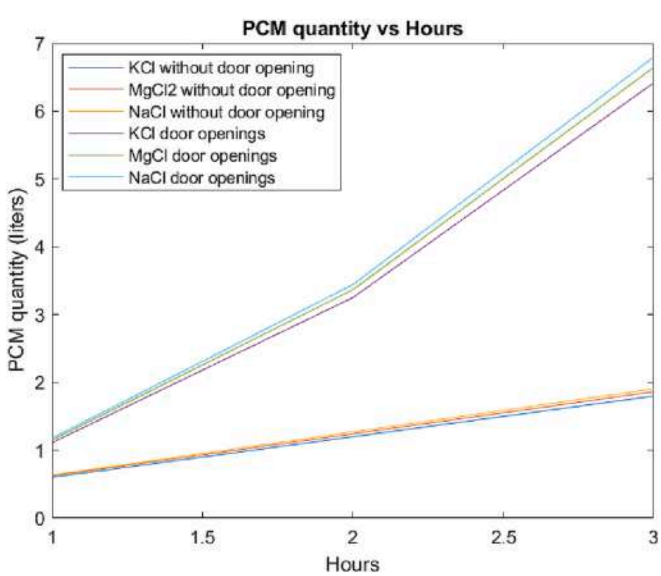


**Fig. 5.** PCM quantity for the duration of the power outage.

materials for gelling [19]. Fig. 3 illustrates the supercooling process of a PCM.

By adding nucleating agents the effects of this supercooling are reduced. Methods such as cold fingering, exerting physical fields in the form of the ultrasonic field, electromagnetic field, magnetic field, and other methods can be used effectively. Amongst other promising nucleating agents, Silver iodide was one of the methods suggested for forming nucleus ice crystals in the solution. This process closely resembles ice in its crystal structure. Ideal nucleating agents are carbon nanofibers, copper, titanium oxide, potassium sulfate, and borax [19]. The surface roughness also plays an important role, the larger the surface roughness, the better the heterogeneous nucleation [19].

### *1.2.2. Cyclic stability*

PCM has a great potential of being used repeatedly as they undergo repetitive cycles of cooling and heating. However, they tend to have poor cyclic stability. Two reasons causing this is corrosion occurring between the PCM and the casing materials and the other is due to thermal cycling [22]. Due to poor stability, the performance and life span of the PCM are greatly reduced. To avoid different kinds of salt hydrate not forming during the melting process, some researchers have opted to use the PCM as a direct contact system. However only in the case where the heat is exchanged with a fluid that will not indissoluble the water-salt solution.

## 2. Methodology

### *2.1. Eutectic saltwater solutions*

Three eutectic salt water solutions were investigated, KCl, $MgCl_2$ and NaCl. These salts were chosen because of the high latent heat and their relatively low price. To increase the heat transfer inside the refrigerator, it is advisable to use a PCM with the lowest phase change temperature, however, the PCM might not fully freeze if the freezer temperature is not drastically below the phase change temperature. The properties are displayed in Table 3.

### *2.2. Heat-load calculations*

Heat load calculations were done to determine the amount of PCM needed to maintain the compartment's temperature constant. The heat transmission loads were calculated using Eq. (1) and the input variables used are shown in Table 4.

$$Q_{trans} = \text{U A } (T_{atm} - T_{in}) \tag{1}$$

where U ($W/m^2 \bullet K$), is the overall heat transfer coefficient shown in Eq. (2). A($m^2$), is the total surface area of the compartment to be maintained. $T_{atm}$ ($^\circ C$) and $T_{in}$ ($^\circ C$) are the surrounding atmospheric temperature and the desired temperature inside the compartment. For this study, the highest atmospheric temperature was used. The desired temperature in the compartment was used as shown in Table 4.

$$U = \frac{k}{L} \tag{2}$$

where $k$ ($W/m \bullet K$), is the thermal conductivity of polyurethane insulation. $L$ ($m$), is the thickness length of the insulation. Infiltration by air exchange most commonly occurs because of the air density differences between the refrigerated compartment and the surrounding atmospheric air. For a simple model expressed in Eq. (3), the average heat gain for the load-shedding period through the doorway from air exchange was determined [23],

$$q_t = qD_tD_f(1 - E) \tag{3}$$

where, $q(W)$, is the sensible and latent refrigeration load for fully established flow expressed in Eq. (4). $D_t$, is the doorway open-time factor. $D_f$, is the doorway flow factor, which was determined as 1.0 and $E$, is the effectiveness of the doorway protective device.

$$q = 0.221A(h_i - h_r)\rho_r\left(1 - \frac{\rho_i}{\rho_r}\right)^{0.5}(gH)^{0.5}F_m \tag{4}$$

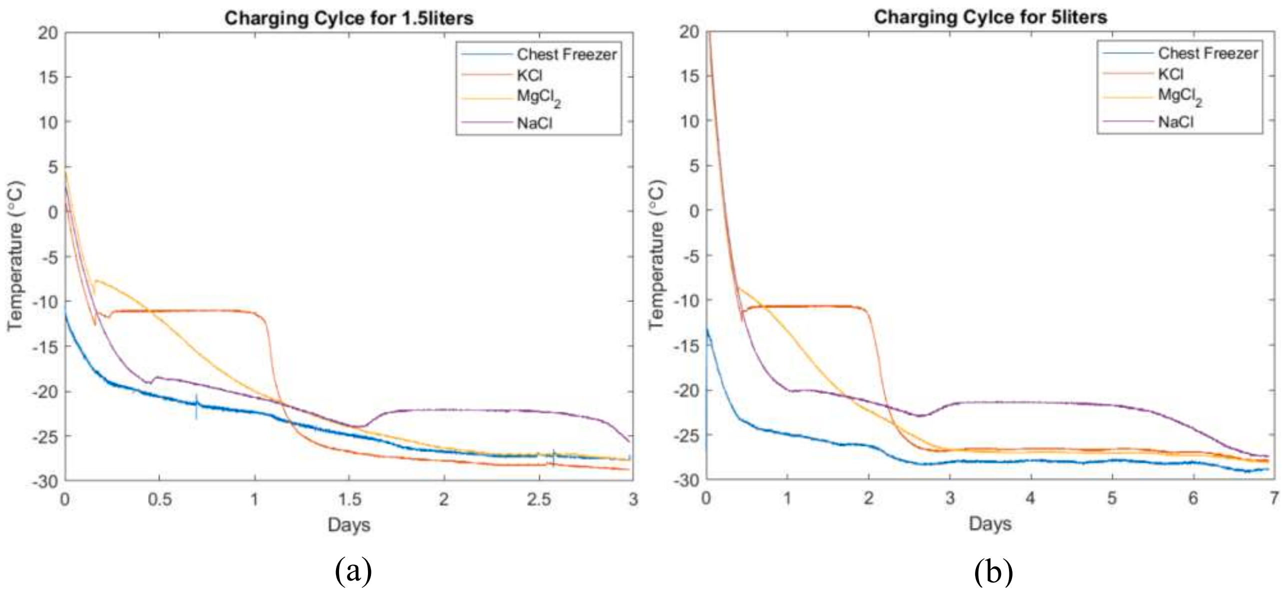


**Fig. 6.** Charging cycle of 1.5 l and 5 l PCM solutions.

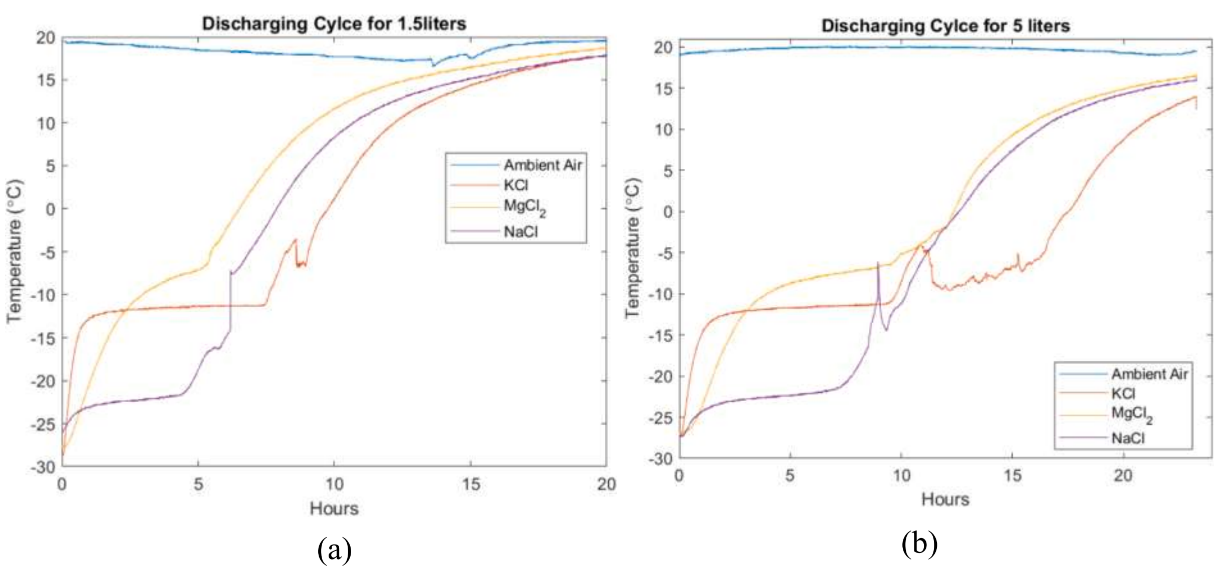


**Fig. 7.** Discharge cycle of 1.5 l and 5 l PCM solutions.

where, $h_i(kJ/kg)$, is the enthalpy of infiltration air. $h_r(kJ/kg)$, is the enthalpy of refrigerated air. $\rho_i(kg/m^3)$, is the density of infiltration air. $\rho_r(kg/m^3)$, the density of refrigerated air. $g$, is the gravitational constant $=9.81\ m/s^2$. $H(m)$, is the doorway height. $F_m$, is the density factor, expressed in Eq. (5).

$$F_m = \left[\frac{2}{1 + (\rho_r/\rho_i)^{1/3}}\right]^{1.5} \tag{5}$$

For cyclical, irregular, and constant door usage, alone or in combination, the doorway open-time factor was determined as Eq. (6)

$$D_t = \frac{(P\theta_p + 60\theta_0)}{3600\theta_d} \tag{6}$$

where, $P$, is the number of doorway passages. $\theta_p(sec)$, is the door open-close time. $\theta_0(min)$, is the time the door simply stands open. $\theta_d$, is the load-shedding period.

$$V_{PCM} = \frac{t_{off} \bullet Q}{\rho\,\lambda} \tag{7}$$

Eq. (7) determines the amount of PCM needed to maintain the compartment at a constant temperature during the load-shedding period. Where $t_{off}$ $(s)$, is the time the compressor is off, this could also be regarded as the load-shedding period. ρ $(kg/m^3)$, is the density of the PCM used. λ $(kJ/kg)$, is the latent heat of the PCM.

### 2.3. Experimentation

#### 2.3.1. PCM

The salt particles were mixed according to Table 3 salt to water ratio intending to reach the desired phase change temperature. Deionised water was used. Type K thermocouples were initially used and connected to a GL820 Graphtec data logger. After witnessing the temperature fluctuations in the container due to uneven temperature distribution. The containers were then fitted with a Pt100 temperature

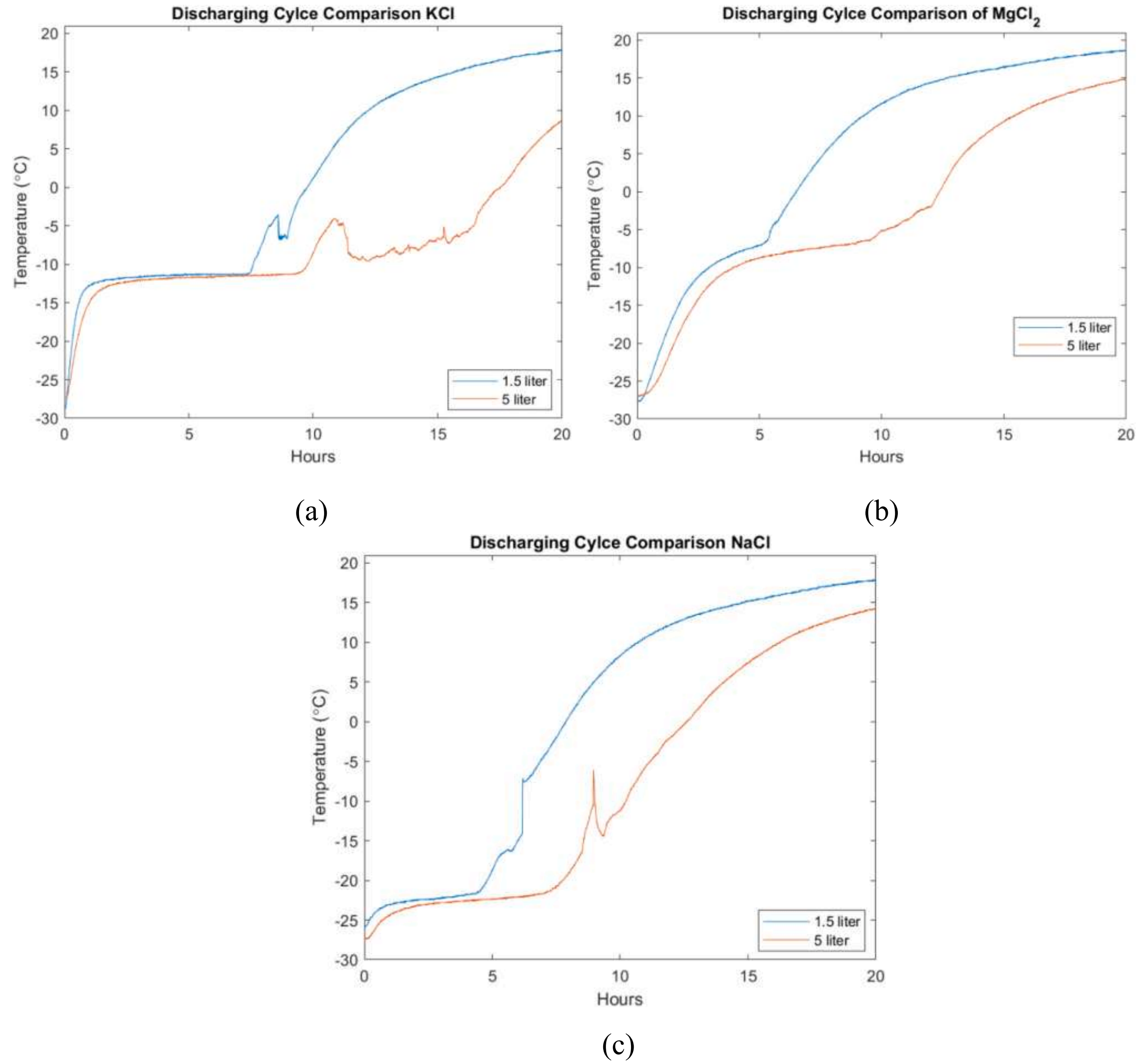


**Fig. 8.** Quantity comparison of PCM solutions during the discharge cycle.

probe to measure the uniform temperature across the container by dampening the temperature fluctuations thus increasing the accuracy of the results. The solutions were placed inside a chest freezer first to validate the phase change temperature by plotting the Temperature history diagram. This was also done to view the sub-cooling that salt-water solutions undergo. Once the solutions were fully frozen, they were exposed to the atmospheric temperature. After the discharging cycle, the solutions were shaken and mixed with the segregated salt particles in the solutions. This was more experienced in the KCl solution.

### *2.3.2. Refrigerator*

Experiments were conducted on a KIC KBF 525/1 ME Refrigerator, the configuration of the setup is displayed in Fig. 4, with the PCM container placed at the top and the thermocouple placed near the bottom. The PCM container used in this study was not optimised for maximum heat transfer rate between the PCM and the surrounding refrigerated air. Normal household 1.5 l and 5 l PVC bottle containers were used to simulate the resources available within a domestic household. The refrigerator had a gross capacity of 257 l and a net capacity of 239 l. The top compartment had inside dimensions of 700 × 450 × 650 mm with approximately 30 mm thickness insulation. With the thermostat set at maximum, the refrigerator compartments' temperature was measured to be 0.6 °C near the bottom of the compartment and 5.1 °C near the top of the compartment, while the evaporator coil measured close to −24 °C. The freezer compartments' temperature was measured to be −24.1 °C with the evaporator coil at a temperature of −31.6 °C. The atmospheric temperature surrounding the refrigerator was measured to be 22.6 °C.

## 3. Results and discussion

### *3.1. PCM quantity*

Fig. 5 displays the results from the heat load calculations. Two calculations were done, one with transmission loads only, assuming that the refrigerator compartment will not be opened during the power outage period. The second calculation combined the transmission load and the air infiltration loads, assuming that the refrigerator

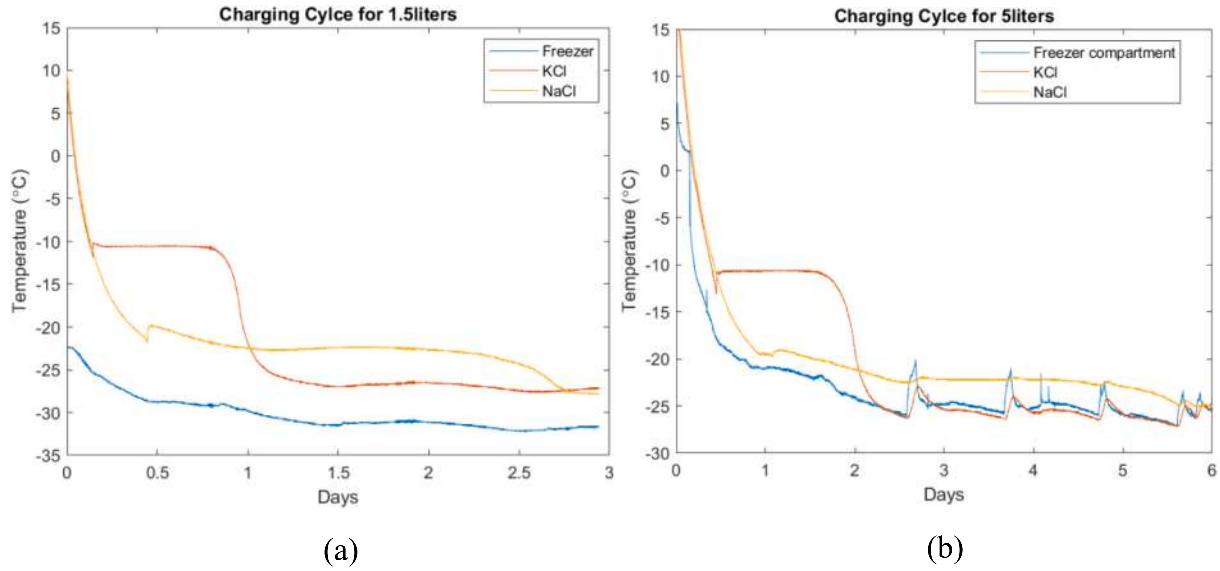


**Fig. 9.** Charging cycle of 1.5 l and 5 l PCM solution in a household refrigerator.

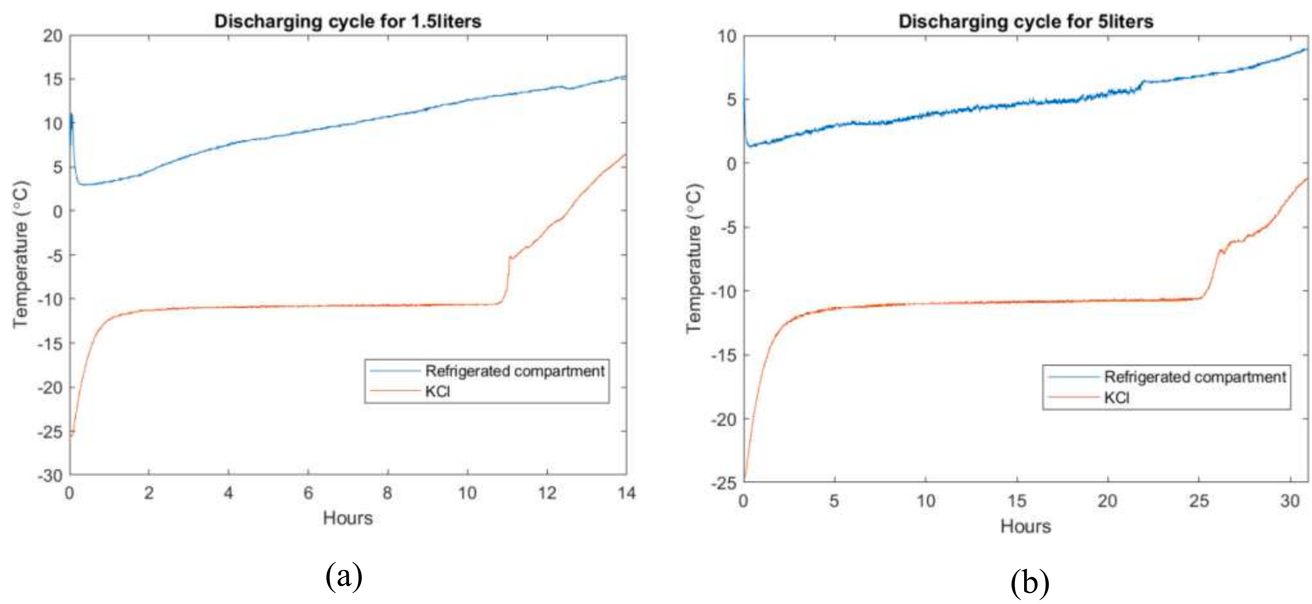


**Fig. 10.** Discharge of KCl solutions during a power outage.

compartment will be opened once during the power outage period for a full minute. From Fig. 5, the three solutions resembled a similar pattern for transmission load only. Since South Africa's load-shedding period lasts from more than two hours to three hours, 2.5 h was selected to determine the amount of PCM needed. Assuming that the refrigerator door will not be opened during this period, this resulted in 1.5 l of PCM being required. And for having both transmission loads and air infiltration loads resulted in 5 l of PCM being required.

### *3.2. Validating the phase change temperature of PCM*

To validate the Phase Change Temperature of the PCM, a Temperature vs time technique was used. Both the 1.5 l and 5 l PCM solution was placed inside a deep freezer having a potential of reaching −30 °C temperature, the results are presented in Fig. 6. From Fig. 6 (a) KCl, experienced subcooling before maintaining a constant phase change temperature of approximately −12 °C, this lasted for 24 h before the temperature entered the sensible region and dropped to the temperature of the freezer. $MgCl_2$, experienced subcooling at around −9 °C, however, it did not show a consistent latent heat region. This latent heat region ranged from −7 °C to −20 °C. The expected latent heat region was around −19 °C according to Table 3. NaCl also experienced subcooling before maintaining a constant phase change temperature at approximetly −22 °C. Although subcooling is a disadvantage to salt solutions, the effects on the subcooling time compared to the overall performance time of the solution is minimal and can be ignored. It was also observed that the KCl, NaCl solutions turned completely white after they had fully solidified, however, it was not the same for $MgCl_2$ as it was still slightly transparent. For the 1.5 l of PCM solution, the time for KCl to fully solidify was approximately a day and a half, as seen in Fig. 6 (a). For a 5 l KCl solution, two days and a half were required as seen in Fig. 6 (b). For NaCl solution, three days were required for a 1.5 l PCM while six to seven days were required for 5 l solution. For $MgCl_2$, the solution was still unpredictable as it showed no clear phase change temperature when compared to KCl and NaCl PCM solutions. The charging time of the PCM solutions was highlighted to be one of the barriers to Khalifa's et al. [18]

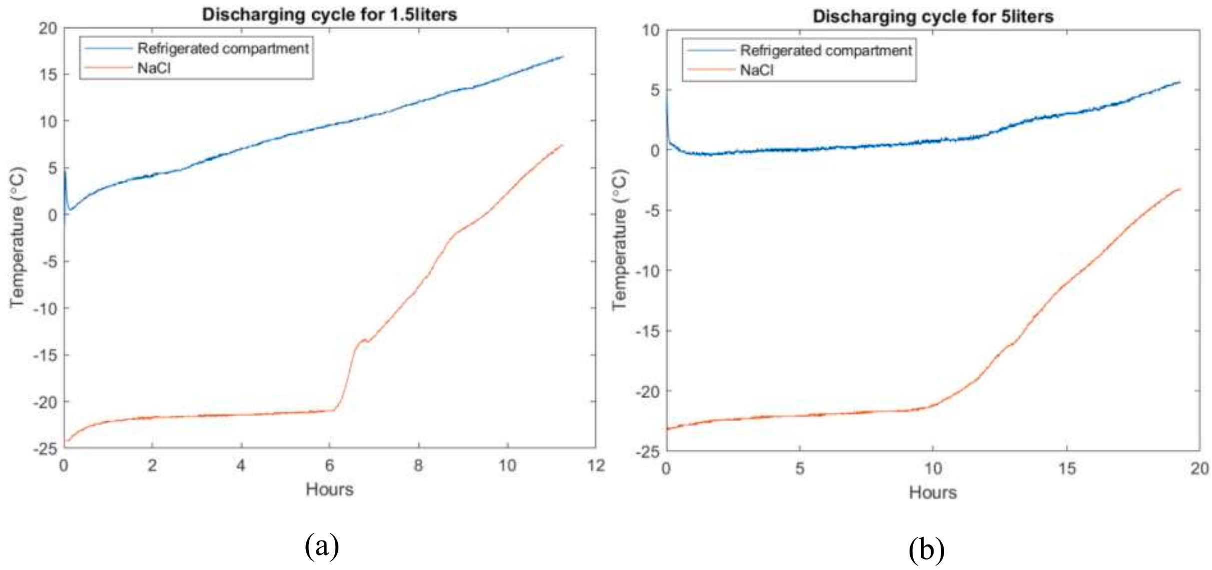


**Fig. 11.** Discharging cycle for NaCl solution in the household refrigerator during a power outage.

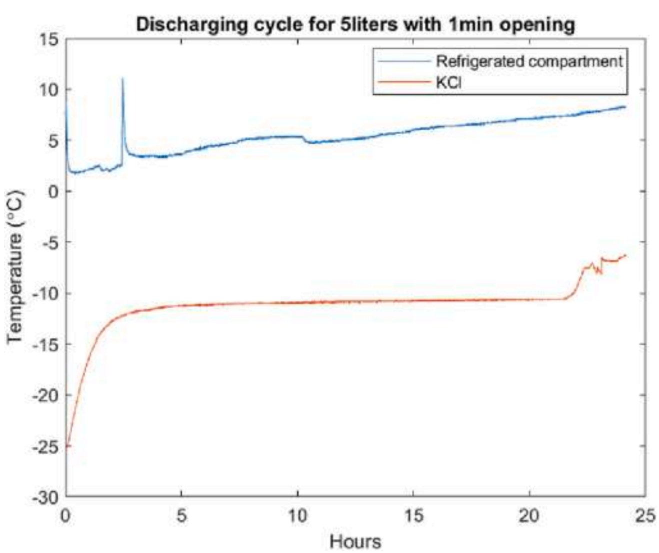


**Fig. 12.** Discharge of KCl solution during a power outage with refrigerator door opened for 1 min.

innovative idea of using solar energy to run a chest freezer since his compressor could only run 8 h a day and this is insufficient to fully freeze the PCM solutions.

The results for the Discharging cycle are presented in Fig. 7. The PCM solutions were placed in the ambient air at an average temperature of 19 °C.

### 3.3. Discharging cycles of PCM volume

From Fig. 7, it is visible that increasing the quantity of the PCM, the clearer the phase change temperature and the longer the phase change time, this was also shown in a study by Onyejekwe [24]. In this study, the phase change temperature did not vary much with an increase in the quantity of PCM as seen in Fig. 8. For KCl, the latent heat region for 1.5 l is observed to have lasted for 7 h while for 5 l it lasted for approximately 10 h as illustrated in Fig. 8 (a). A phenomenon was observed when KCl solution reached −5 °C, this could be the incongruent melting and the lack of thermal stability mentioned in Table 1 by Cabeza and Oró [20]. For both KCl and NaCl, salt particles were observed after the discharging cycle, this is also the phase separation mention by Cabeza and Oró [20]. Since this phenomenon takes place after the latent heat region, it will affect the performance of the solution over time. In a study by Khalifa et al. [18] the same phenomenon was observed and was recognised as precipitation of KCl and NaCl. The author also highlighted that due to the thermal properties changed, the energy storage capacity will be reduced. For $MgCl_2$ it was observed from Fig. 8 (b) that the phase change temperature was approximately −7 °C. The expected phase change temperature according to Table 3 was supposed to be −19 °C. it was then decided to discontinue it by the authors. This would suggest that the 25 % salt ratio might be inaccurate. A further test for the correct phase change point will be determined in a separate study.

### 3.4. Performance of PCM in a household refrigerator

From Fig. 9 the PCM solutions were placed inside the household Freezer compartment to determine the time for freezing the PCM solutions. For KCl 1.5 l, the solution completely freezes in 24 h while for 5 l, the solution takes close to 48 h. For NaCl 1.5 l solution, it took approximately 3 days and for 5-litre solution approximately 6 days. From Fig. 9 (b) the freezer compartment was opened to ensure that the NaCl had fully solidified.

From Fig. 10 1.5 l and 5 l of KCl were placed in the refrigerated compartment, and the power was turned to observe the performance of the PCM solutions. It took 1.5 l and 5 l of KCl and 1 day and 2 days to fully solidify. 1.5 l and 5 l of NaCl took 2 days and 6 days to fully solidify. From Fig. 10 (b) for both the 1.5 l and 5 l it is observed that for the first hour, the sensible region was able to maintain the refrigerated compartment temperature below 4 °C. For the 1.5 l the temperature of the refrigerated compartment exceeded 5 °C after 2.5 h as seen in. This confirmed that the calculations for determining the volume of the PCM for transmission loads were accurate. For the 5 l, however, the temperature of the refrigerated compartment took 20 h before exceeding 5 °C. It is not known why the temperature of the refrigerated compartment gradually escalates even though the PCM is in the latent heat region for both the 1.5 l and 5 l.

For NaCl the results are shown in Figs. 11, 1.5 and 5 l were also placed inside the refrigerated compartment with the power turned off. The 1.5 l of NaCl solution also validated the calculations, that the temperature of the refrigerated compartment exceeded 5 °C after 2.5 h. The temperature of the refrigerated compartment also gradually

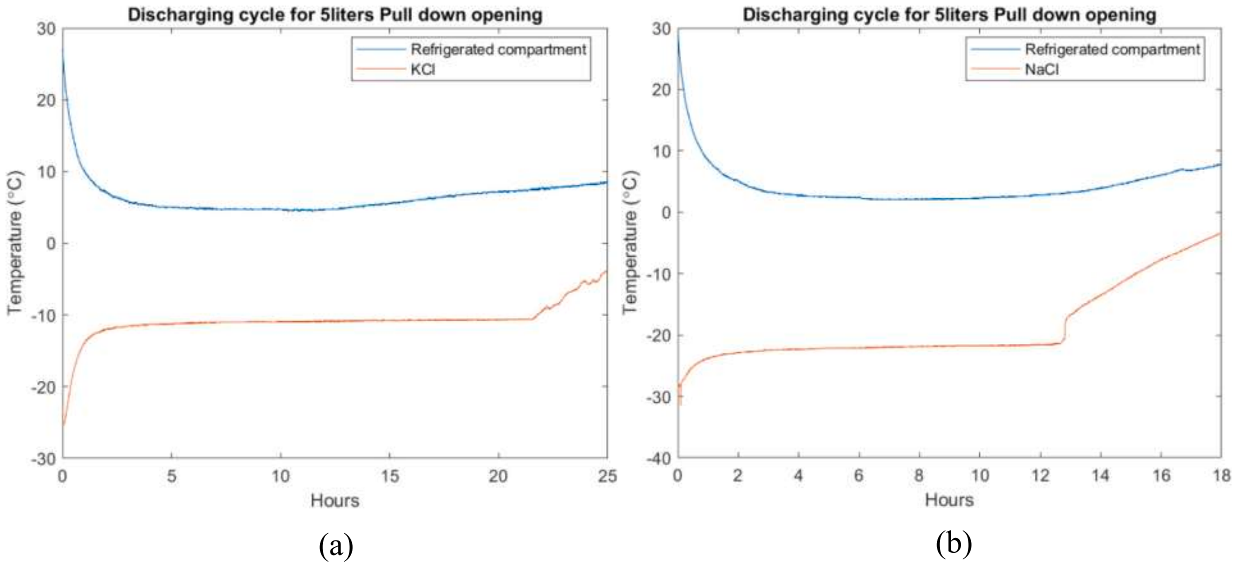


**Fig. 13.** Pull down the performance of PCM solutions in a household refrigerator.

continued to escalate even though the PCM solution was still in the latent heat region for 6 h. However a different case was observed for 5 l of NaCl, it was able to maintain the temperature at approximately 0 °C in the refrigerated compartment for close to 10 h. Despite NaCl taking longer to fully solidify, the performance is remarkable. A study should be done to shorten the solidification time.

Fig. 12 shows the result of KCl. The power of the refrigerator was turned off and KCl was allowed to maintain the compartment. After 2 h, the compartment door was opened for 1 min and then closed. The KCl solution was able to reduce the temperature to below 5 °C. A 5 l can maintain the air infiltration loads. Khalifa et al. [18] also studied the effects of the door opening. In his study, he opened the chest freezer doors every hour for approximately two minutes long 15 times. And from his results, the PCM solution was able to pull down the temperature and overcome the air infiltration loads inquired during the two-minute door opening. After analysing these results, a new experimental setup was done to determine the performance of PCM in pulling down a compartment's temperature.

### *3.5. Pull down performance*

Further experiments were carried out to determine the pull-down performance of the salt solutions. The power was turned off and the refrigerated compartment's temperature was allowed to reach 30 °C, then the PCM was inserted. Even though PCM are not good at pulling down the temperature, these two solutions proved otherwise. For KCl the temperature was pulled down from 30 °C and maintained by the latent heat region at −5 °C. For NaCl the temperature was pulled down from 30 °C to approximately 3 °C. From Fig. 13 it is noted that KCl salt solution lasts twice as NaCl.

## 4. Conclusion

The preservation of agricultural produce is important in maintaining food's nutritional quality. During power outages, while the refrigerator's compressor is switched off, the inside temperature of a domestic refrigerator can be maintained using PCMs. This study investigated three eutectic salt water solutions, KCl, $MgCl_2$ and NaCl with a phase change temperature of −10 °C, −19 °C and −21 °C. Experiments were conducted on a KIC KBF 525/1 ME Refrigerator. Heat load calculations were firstly done with transmission loads only, and with then transmission loads including the air infiltration loads combined. This resulted in 1.5 l and 5 l of PCM being required.

To validate the Phase Change Temperature of the PCM, a Temperature vs time technique was used. Both the 1.5 l and 5 l PCM solution was placed inside a deep freezer having the potential of reaching −30 °C temperature the recorded temperature for KCl was −12 °C and −22 °C. KCl, experienced subcooling before maintaining a constant phase change temperature, the latent heat region for 1.5 l is observed to last for 11 h while for 5 l it lasts for approximately 24 h. $MgCl_2$, experienced subcooling at around −9 °C, however, it did not show a consistent latent heat region, for which it was excluded from further analysis. NaCl experienced subcooling before maintaining a constant latent heat region,for 1.5 l lasting for 6 h while for 5 l lasted for approximately 10 h.

During the temperature pull down experiments for KCl, both the 1.5 l and 5 l was observed that for the first hour, the sensible region can pull down the refrigerated compartment temperature below 4 °C. for the 1.5 l the temperature of the refrigerated compartment exceeded 5 °C after 2.5 h. Despite NaCl taking longer to fully solidify, the performance is remarkable. A study should be done to shorten the solidification time of the PCM as it took 1.5 l of KCl and NaCl 1 day and 3 days to fully solidify and 5 l of KCl and NaCl 2 days and 6 days.

## Author statement

We as the authors have made the recommended changes by the reviewers. Unnecessary text to introduce the basic characteristics of PCM has been removed. This study, therefore, focuses more on the performance of the charging and discharging phase of inexpensive eutectic PCM water-salt solutions to maintain a refrigerated compartment at a constant temperature during power outages.

## Declaration of competing interest

- Experiments were conducted with permission from TUT.
- All the data belongs to the authors and it's their own work.

## Data availability

Data will be made available on request.

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ORIGINAL RESEARCH

# Investigation of energy costs for incorporating a latent heat thermal energy storage system into a South African cold room

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*Purpose:* Storing energy has been beneficial in improving our life and the environment. A Latent Heat Thermal Energy Storage System (LHTESS) has great potential to contribute to ameliorating what occurs between the supply and demand of energy. It makes systems more efficient and environmentally friendly in terms of energy consumption.

*Methodology:* This study investigated the integration of an LHTESS into a South African cold room operating at -18 °C to save both energy and operational cost while preserving goods. A heat load analysis was done to determine the number of eutectic plates needed to maintain the desired temperature, and also estimated the initial cost of the LHTESS. Eskom's tariff plans were used to capture and compare the daily operational costs of a cold room with and without an LHTESS. The tariff plans were further used to estimate the energy-saving costs from years 2021 to 2022, and project the payback period for the new system.

*Findings:* By incorporating an LHTESS operating for 16 hours, the electrical costs would amount to R2 260/year, thereby reducing the running costs by 50%. The study concluded that it is a good investment to run a full storage LHTESS as it costs R15 000 for this system and the payback period will be approximately 6 years.

*Research implications:* The study further recommends that inexpensive eutectic plates should be designed and manufactured locally for the integration to be a success.

*Originality;* However, based on the current analysis, a partial storage system is recommended to mitigate the peak demand of a cold room and preserve goods in a specified temperature range during power outages.

**Keywords:** thermal energy storage, phase change material, eutectic plate

**Ondersoek na energiekoste van die inkorporering van 'n latentehitte-termiese-energieopbergstelsel in 'n Suid-Afrikaanse koelkamer:**
*Doel:* Die opberging van energie is voordelig om ons lewens en die omgewing te verbeter. 'n Latentehitte-termiese-energieopbergstelsel (LHTEOS) het groot potensiaal om by te dra tot verbetering van dit wat tussen die vraag en aanbod van energie plaasvind. Dit maak stelsels doeltreffender en omgewingsvriendeliker wat energieverbruik betref.

*Metodologie:* Hierdie studie het die integrasie van 'n LHTEOS in 'n Suid-Afrikaanse koelkamer wat by –18 °C werk, ondersoek om beide energie- en bedryfskoste te bespaar terwyl goedere bewaar word. 'n Hitteladingsanalise is gedoen om die aantal eutektiese plate te bepaal wat nodig is om die verlangde temperatuur te handhaaf, en het ook die aanvanklike koste van die LHTEOS beraam. Eskom se tariefplanne is gebruik om die daaglikse bedryfskoste van 'n koelkamer met en sonder 'n LHTEOS op te teken en te vergelyk. Die tariefplanne is verder gebruik om die energiebesparingskoste van die jare 2021 tot 2022 te raam, en die terugbetalingstydperk vir die nuwe stelsel te projekteer.

*Bevindinge:* Deur 'n LHTEOS in te sluit wat vir 16 uur werk, sal die elektriese koste R2 260/jaar beloop, en sodoende die bedryfskoste met 50% verminder. Die studie het tot die gevolgtrekking gekom dat dit 'n goeie belegging is om 'n volopberging-LHTEOS te bedryf, aangesien hierdie stelsel R15 000 kos en die terugbetalingstydperk ongeveer 6 jaar sal wees.

*Navorsingsimplikasies:* Die studie beveel verder aan dat goedkoop eutektiese plate plaaslik ontwerp en vervaardig moet word vir die integrasie om 'n sukses te wees.

*Oorspronklikheid:* Gebaseer op die huidige ontleding word 'n gedeeltelike opbergstelsel egter aanbeveel om die spitsvraag van 'n koelkamer te verlig en goedere tydens kragonderbrekings binne 'n gespesifiseerde temperatuurbestek te bewaar.

**Sleutelwoorde:** termiese-energieopberging, faseveranderingsmateriaal, eutektiese plaat

## Introduction

Storing energy has been beneficial in improving our lives and the environment. Energy storage has come to play a significant role in supplementing intermittent energy supplies to successfully meet the rising demand. Energy storage contributes significantly towards the use of efficient and environmentally friendly energy in our societies. Two beneficial factors often result when storing energy – a reduction in energy consumption, and reduced energy costs. These benefits of efficient systems further reduce (a) the initial and maintenance costs, (b) equipment size, and (c) pollutant emissions by a reduction in the use of fossil fuels (Dincer & Rosen 2011).

Figure 1 classifies the different methods of energy storage that are available. Countries such as China are among the world's major agricultural countries and have a high demand for refrigeration equipment. Large amounts of electric energy are consumed every year due to refrigerated equipment. It was noted by Evans et al. (2015) that 60% to 70% of electrical energy in cold storage facilities is used for refrigeration. By adding latent heat cold storage to convectional refrigeration systems, the country's electrical costs have been reduced. During peak load, the latent heat thermal energy storage system (LHTESS) releases energy and during normal hours it is charged through a refrigeration system that is connected parallel to it (Yang et al. 2017).

The LHTESS generally requires a refrigerant system to freeze the eutectic phase change material (PCM). Despite its limitations, this system plays a significant role in the refrigeration industry. Its application on small vans, dedicated cargo and other applications make it a potential solution to the phasing out of harmful refrigerants from the environment. LHTESS is also ideal in developing countries, where the precision of temperature control is less relevant when compared to the overall fuel and system cost (Lambert & Roberto 2014).

This article presents an energy cost analysis of integrating an LHTESS into a South African cold room operating at a temperature of –18 °C. Eskom's tariff plans are used to estimate the energy-saving costs of a daily operational cold room and project the payback period of the new system.

### *Thermal energy storage*

Thermal energy storage (TES) is a method that has great potential to correct the mismatch between the supply and demand of energy and also has great potential to improve energy management by acting as an intermittent energy source. Liquid-solid PCMs in particular are regarded as key components for the integration of renewable energy sources. These PCMs are not limited to refrigeration systems only as they can be used in high-temperature applications such as nuclear power plants. This field alone has attracted much research as it seems to make systems more efficient and environmentally friendly in terms of energy consumption (Dincer & Rosen 2011; Gibb et al. 2018; Lazaro et al. 2020).

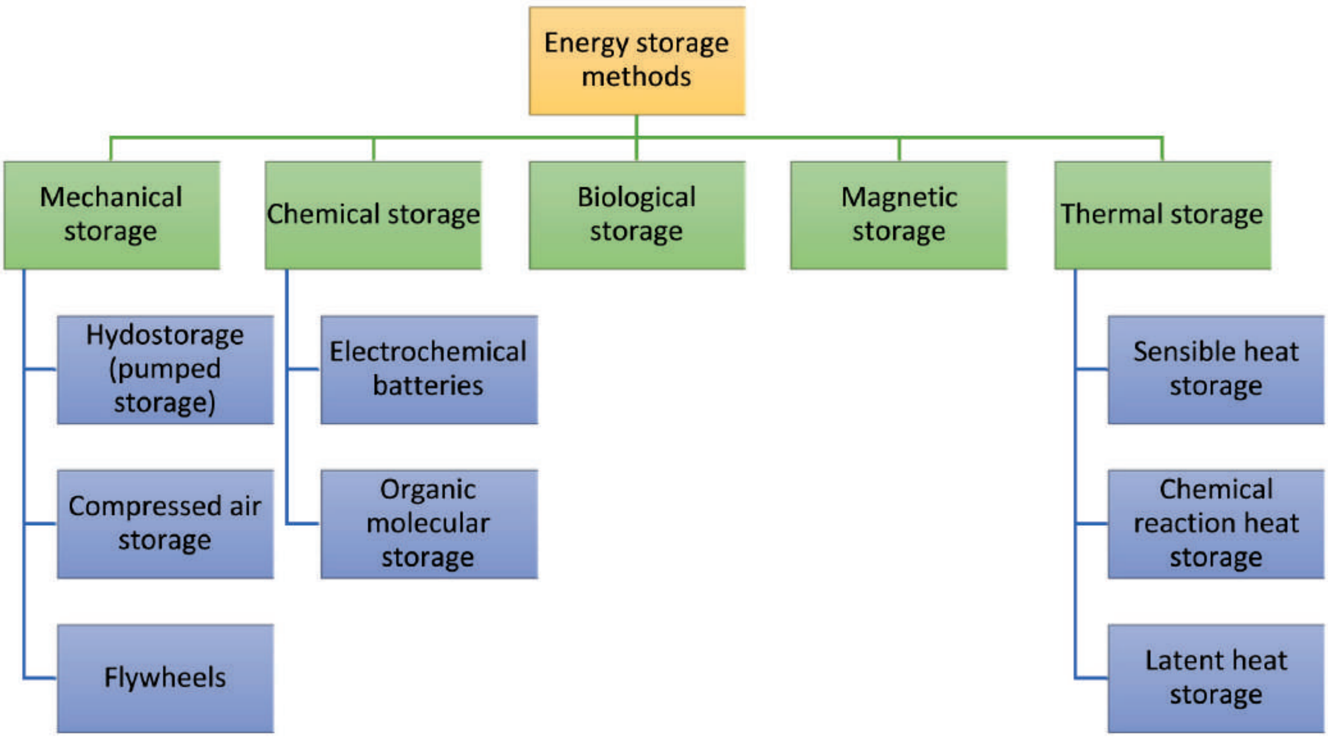


**Figure 1:** Classification of energy storage methods (Dincer & Rosen 2011; Raam Dheep & Sreekumar 2014)

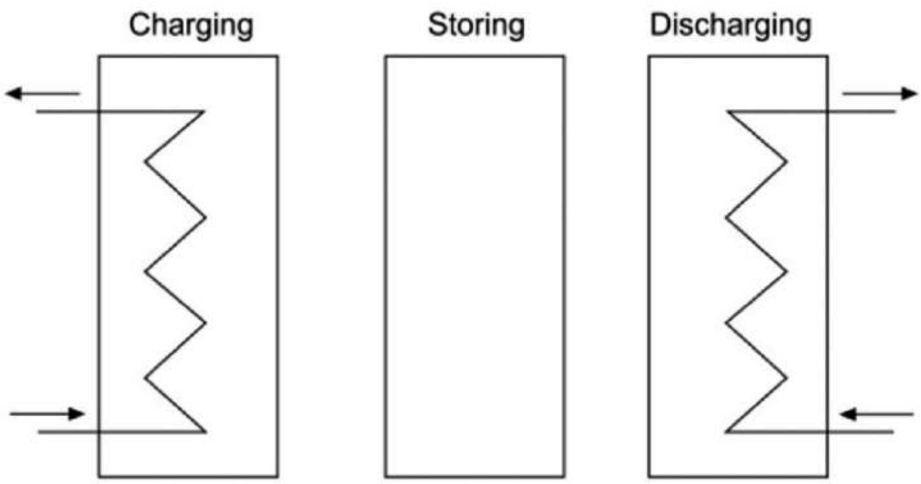


**Figure 2:** TES complete storage cycle (Cabeza et al. 2011)

TES systems work on the principle of charging and discharging. This storage cycle is clearly illustrated in Figure 2. They can store and release energy at different locations, power levels and temperatures (Cabeza et al. 2021).

*Classification of Thermal Energy Storage*

TES systems consist of three types of groups, namely Sensible Heat TES systems, Chemical Reaction Heat TES systems and Latent Heat TES systems, as displayed in Figure 3. TES systems involve three processes, namely charging, storing and discharging. Processes can occur simultaneously in a practical application, charging, storing and discharging. Each process can occur more than once in each storage cycle (Vadhera et al. 2018).

a) In Sensible Heat TES systems, the temperature of the storage medium changes to store energy based on the heat capacity of the material in the form of water, soil, rock, brine or any other storage medium. The temperature of the material changes but the material does not undergo any phase transformation during the charging or discharging cycles (Veerakumar & Sreekumar 2016).

b) Chemical Reaction Heat TES systems work by breaking and reforming molecular bonds through reversible chemical reactions. Reversible reactions, thermo-chemical pipeline energy transport and chemical heat pump storage are the three modes of storage in which the Chemical Reaction Heat TES system stores energy. This method is more advantageous compared to sensible heat and latent heat systems (Raam Dheep & Sreekumar 2014).

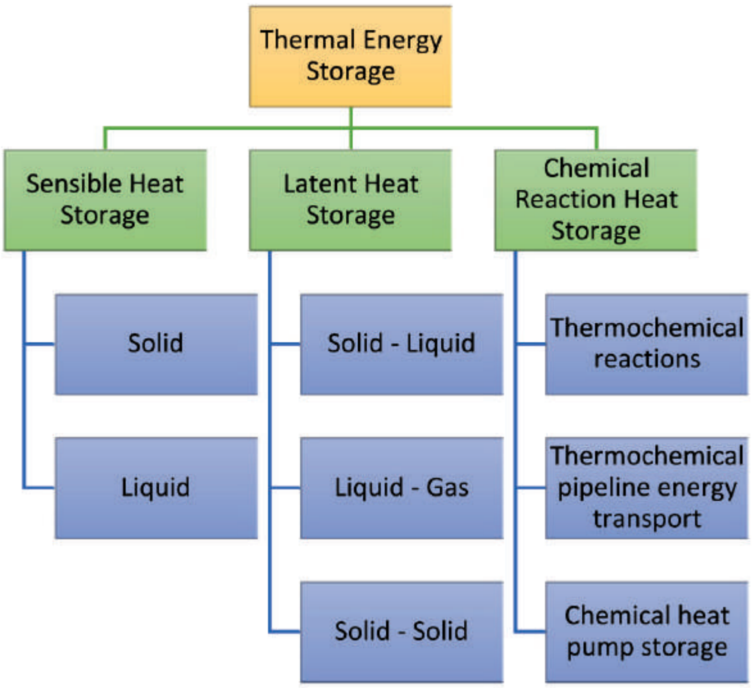


**Figure 3:** Classification of thermal energy storage (Raam Dheep & Sreekumar 2014).

c) Latent heat TES systems undergo latent heat fusion. When a storage medium undergoes a phase transformation it completes the process of storing and retrieving the thermal energy (i.e. latent heat).

Latent heat TES systems are classified into three groups, solid-solid, solid-liquid, and liquid-gas, as illustrated in Figure 3. Solid-solid is a phase transformation of a crystalline nature. Solid-liquid and liquid-to-gas make use of PCM such as cold storage water or ice, paraffin waxes or other PCM that can change from solid to liquid or liquid to gas and vice versa. While the material is undergoing a phase change, the chemical bonds in the material break up and lead to the transformation from one phase to another with less temperature swing, remaining at nearly constant temperature (Raam Dheep & Sreekumar 2014; Vadhera et al. 2018)

## Latent heat TES

Latent heat TES systems are further divided into three groups, namely inorganic, organic, and eutectic. This is shown in Figure 4.

a) Inorganic PCMs

Inorganic PCMs are highly corrosive materials and often react with the construction material of the casing. They are low-cost materials making them easily available; however, they undergo supercooling and segregation. They have good thermal conductivity, a sharp melting point, a low volume change, a low specific heat, and a high heat of fusion, which decreases after a few cycles due to the incongruent melting. These materials are made of metal and hydrated salts (Veerakumar & Sreekumar 2016), and may also consist of nitrates. Inorganic PCMs are stable for a wide range of temperatures up to 1 500 °C (Raam Dheep & Sreekumar 2014; Veerakumar & Sreekumar 2016).

b) Organic PCMs

Organic PCMs are classified into paraffin and non-paraffin. These materials are carbon-based compounds, and as the number of carbon atoms increases so does the latent heat of fusion of the material and the melting point. Organic PCMs have a high latent heat of fusion and are chemically stable, but have low thermal conductivity (Veerakumar & Sreekumar 2016).

Organic PCMs are expensive and flammable. Organic PCMs are also mildly corrosive, making them compatible with all types of containers except for plastic. When operating at high temperatures, they do not tend to supercool or segregate. Organic PCMs are stable for a wide range of temperatures below 300 °C (Raam Dheep & Sreekumar 2014). Despite the disadvantages mentioned, organic materials with eutectic mixtures have been used in the air-conditioning industry to preserve food, cool electronics and maintain building temperatures (Ndanduleni & Huan 2019; Xu et al. 2015). A study by Kaygusuz et al. (2003) showed that these materials can also be used for solar heating.

c) Eutectic PCMs

The melting point of a PCM is an important factor to take into consideration when selecting a PCM for cold storage applications. To reach the desirable melting point, Eutectic PCMs mix

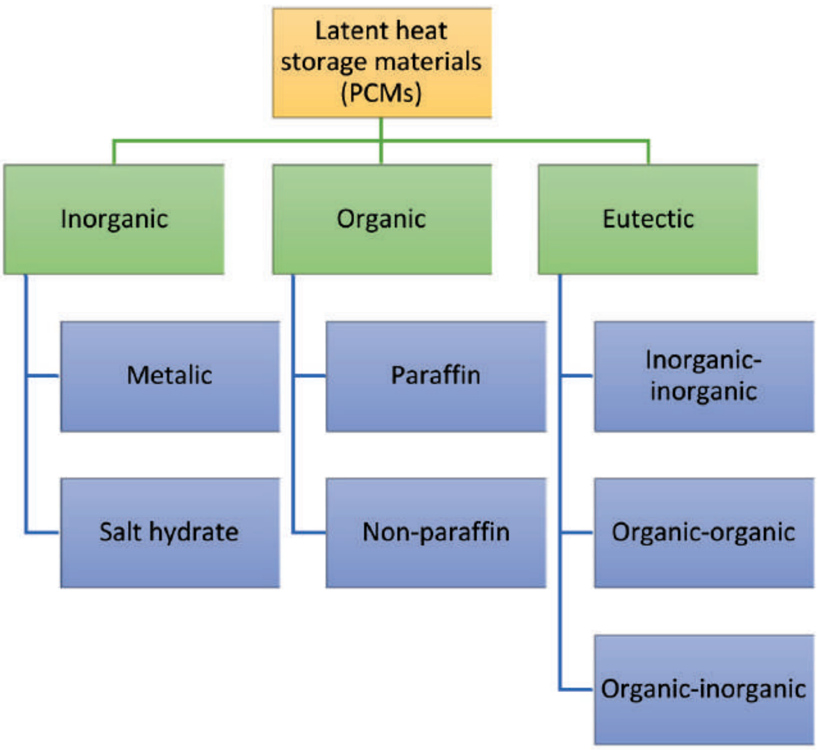


**Figure 4:** Classification of PCM for cold thermal energy storage (Raam Dheep & Sreekumar 2014; Veerakumar & Sreekumar 2016)

two or more PCMs at a particular percentage of the composition. Eutectic PCMs are categorized into organic and inorganic eutectic PCMs. This allows them to be usable in both high-temperature and low-temperature cooling systems (Veerakumar & Sreekumar 2016). Since they freeze to an intimate mixture of crystals it makes them less vulnerable to segregation (Raam Dheep & Sreekumar 2014).

### *Cold Thermal Energy Storage (CTES)*

Cold Thermal Energy Storage (CTES) is a representation of cool and cold TES. Materials such as glycol, eutectic salts and pure water can be used as cooling storage for TES systems (Dincer & Rosen 2011). These materials can be used in the cold chain for freezing products or for chilling.

Although this technology has existed for more than half a century, it has only been receiving increased attention recently due to major changes in electricity rates structures, increases in maximum power demands and utility-sponsored incentive programmes. Utility companies have higher demand charges for peak demand periods to discourage energy consumption during these peak demand periods. CTES systems can then be used to shift peak cooling loads to off-peak periods by operating on their stored capacity during the daytime peak hours and being fully recharged during the night-time off-peak hours (Dincer & Rosen 2011). This results in saving electrical energy.

#### *Operational loading of CTES*

In Figure 5, Dincer & Rosen (2011) characterised CTES into three categories, full-storage, partial-storage load levelling, and partial-storage demand limiting. These strategies are implemented to meet the cooling demand during peak hours.

a) Full-storage CTES

As illustrated in Figure 5(a), during off-peak hours the CTES system is being recharged and during peak hours the CTES system is fully operational. This shifts the entire peak cooling load to off-peak hours by decoupling the operation or cooling generating equipment from the peak cooling load. The CTES system discharges the cooling load while the generating equipment is idle, making this strategy ideal when peak demand charges are high or the peak period is short (Dincer & Rosen 2011).

Dincer & Rosen (2011) further elaborated that this strategy is economically advantageous when:

- Spikes in the peak load curve are of short duration
- Time-of-use energy rates are based on short-duration peak periods
- There are short overlaps between peak loads and peak energy periods
- Large cash incentives are offered for using TES
- High peak-demand charges apply

b) Partial storage load levelling

This strategy is designed to meet operational demand for 24 hours as illustrated in Figure 5(b). When the peak cooling load is much higher than the average load, the storage system is in use to mitigate the peak load. The chiller is sized at a smaller capacity than the design load, to allow the rest of the load to be drawn from the storage. This is also the cheapest system to run when compared with the full-storage and partial-storage demand limiting system, making it the most economic option (Dincer & Rosen 2011).

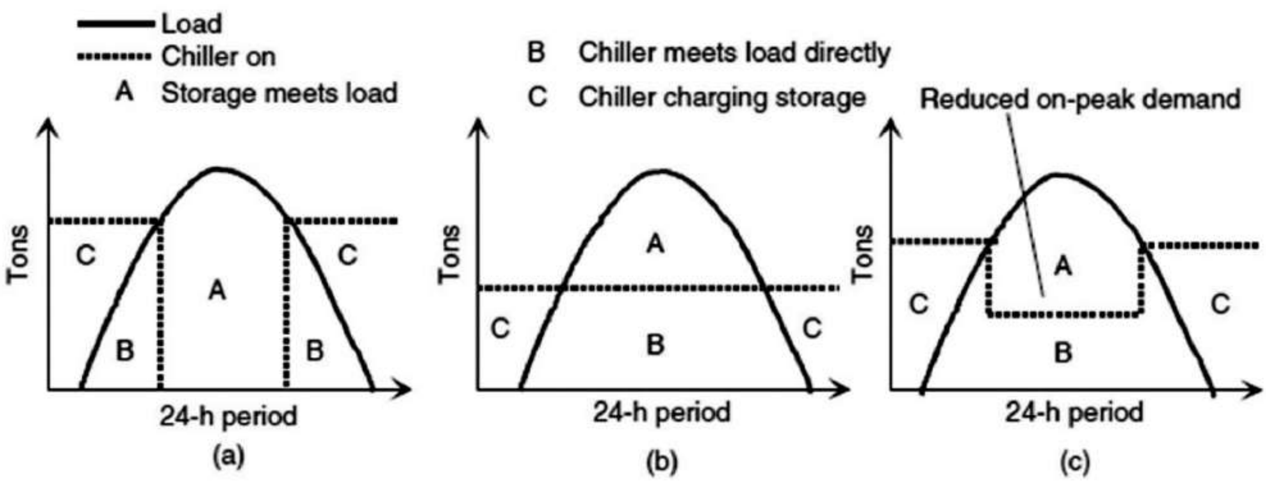


Figure 5: Operating strategies: (a) full-storage, (b) partial-storage load levelling, and (c) partial-storage demand limiting (Dincer & Rosen 2011; Selvnes et al. 2021)

c) Partial-storage demand limiting

With the partial-storage demand limiting strategy, during the peak hours when the energy demand is high, the chiller capacity is reduced, allowing the stored energy to meet the load demand. This strategy is less expensive compared with a full-storage system (Dincer & Rosen 2011).

In Figure 6, Dincer & Rosen (2011) illustrated that when designing CTES systems for full-storage and partial-storage applications, certain parameters had to be taken into consideration. Dincer & Rosen (2011) further explained that for designing part-load systems, all the components and piping must be able to maintain control of the system at different loads. However, in part-load operations, the pressure drop, velocities and flow rates of the refrigerant are decreased or reduced during the initial stages. For pull-down load systems, the components must be designed specifically to handle higher loads at initial start-up.

Selvnes et al. (2021) stated that to design and implement a successful CTES system, the peak/off-peak demand structure has to be identified. Then the system can be tailored to meet the load.

### *Energy Saving*

Figure 7 shows the concluding results of a model developed to estimate the potential impact of TES systems in Spain and Europe by Oró et al. (2014). The model was based on energy consumption and the reduction of $CO_2$ emissions. The study was carried out to determine the potential saving in different sectors by assuming full implementation of TES systems in different application scenarios. The application scenarios were existing

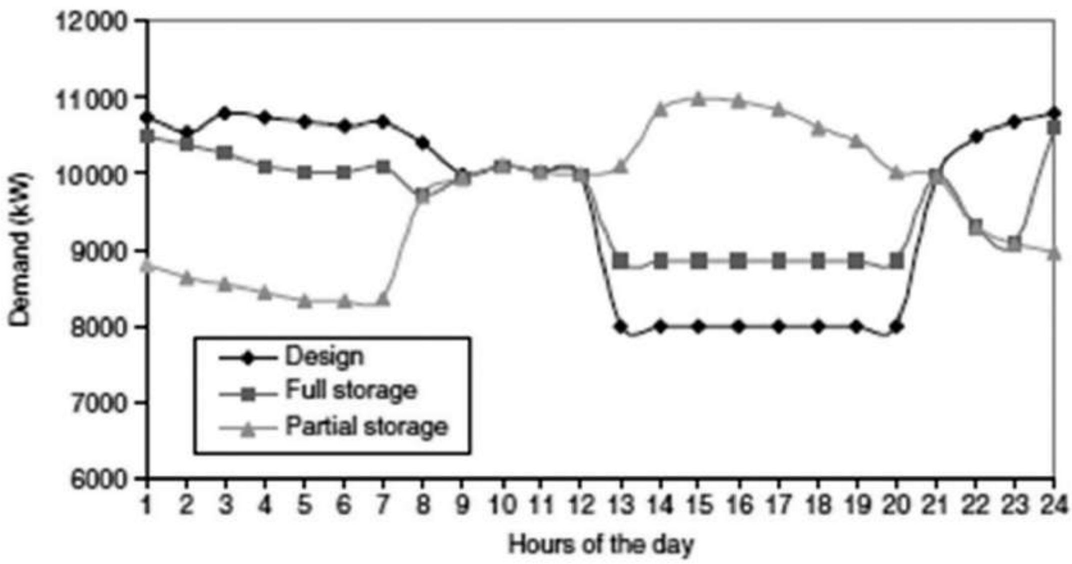


**Figure 6:** Sample demand profiles for the design, full-storage and partial-storage systems (Dincer & Rosen 2011).

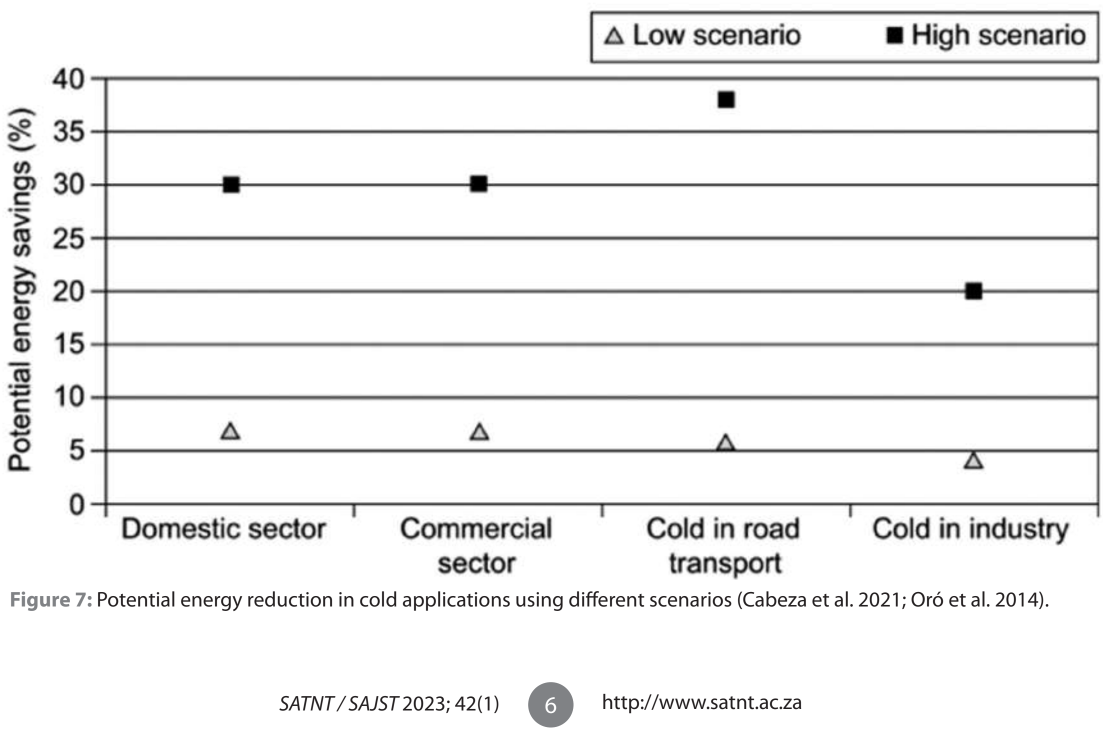


**Figure 7:** Potential energy reduction in cold applications using different scenarios (Cabeza et al. 2021; Oró et al. 2014).

published research work from other authors. Oró et al. (2014), based on the results, arranged the energy saving factors from the lowest to the highest. However, the authors indicated that these figures did not incorporate the costs of implementing TES systems in existing systems, but they still estimated the energy saving potential for each industry (Oró et al. 2014).

### *Eutectic plates*

In a previous study (Radebe et al. 2020), a detailed description of the FIC Eutectic plates was discussed. In this article, only the plates from FIC are analysed to estimate the total cost of a TESS. Eutectic plates have some advantages over other refrigeration systems that set them apart, yet some drawbacks have been encountered with these systems as well.

#### *Advantages*

Eutectic plates do not contain any moving parts while they are in operation; hence, this makes them more mechanically reliable than other refrigeration units that may be prone to mechanical failure. With eutectic plates, no noise is produced, making them ideal for use in situations requiring silence (FIC 2019).

Due to the phase change material solution inserted inside the plates, they can maintain a constant temperature inside a refrigerated compartment. This temperature is maintained even when the plates are exposed to the ambient air while goods are loaded and offloaded on the truck. Eutectic plates can be used in places where there is no electric grid, as they can be charged before use (FIC 2019).

With cold surfaces, due to the humidity in the surrounding atmosphere, frost tends to build up on these surfaces, which greatly reduces the heat transfer between the component and the atmosphere. With eutectic plates, the frost buildup does not significantly affect the heat transfer, as it does in the case of cooling gills. When considering the life span of eutectic plates, they have greater durability and lower maintenance costs compared to ventilated systems (FIC 2019).

#### *Disadvantages*

Different PCM compounds used inside eutectic plates can be very corrosive. To avoid this, the steel used for both the evaporator coils and plate should be selected according to the mixture properties of the PCM. Corrosion occurring between the PCM and the casing is one of the causes of insufficient long-term eutectic plate stability (Zalba et al. 2003).

When the PCM changes from liquid to solid as it freezes, it expands. Because of expansion during the freezing process, some of the plates may suffer leakages. To avoid this, the coils of the evaporator are designed to allow the freezing of the solution from the perimeter towards the centre of the plate. The manufacturer also rounds all the edges and eliminates any sharp areas to generate a high resistance to forces created during the expansion process (FIC 2019).

Another disadvantage of PCMs is that their working performance tend to diminish, or they tend to break down after several cycles of changing from solid to liquid, then back from liquid to solid. This instability depends on whether the type of PCM group used is organic or inorganic (Liu et al. 2012; Zalba et al. 2003).

In most studies, it has been shown that the PCM storage costs were higher than the traditional storage options (Du et al. 2018).

## South African electricity grid

- Night save urban large – this tariff plan is suitable for customers with a high load factor and with a notified maximum demand (NMD) of > 1 MVA.
- Night save urban small – this tariff plan is suitable for customers with a high load factor and with an NMD of > 25 kVA but < 1 MVA.
- Megaflex – this tariff is suitable for customers who can shift load and have an NMD of >1 MVA.

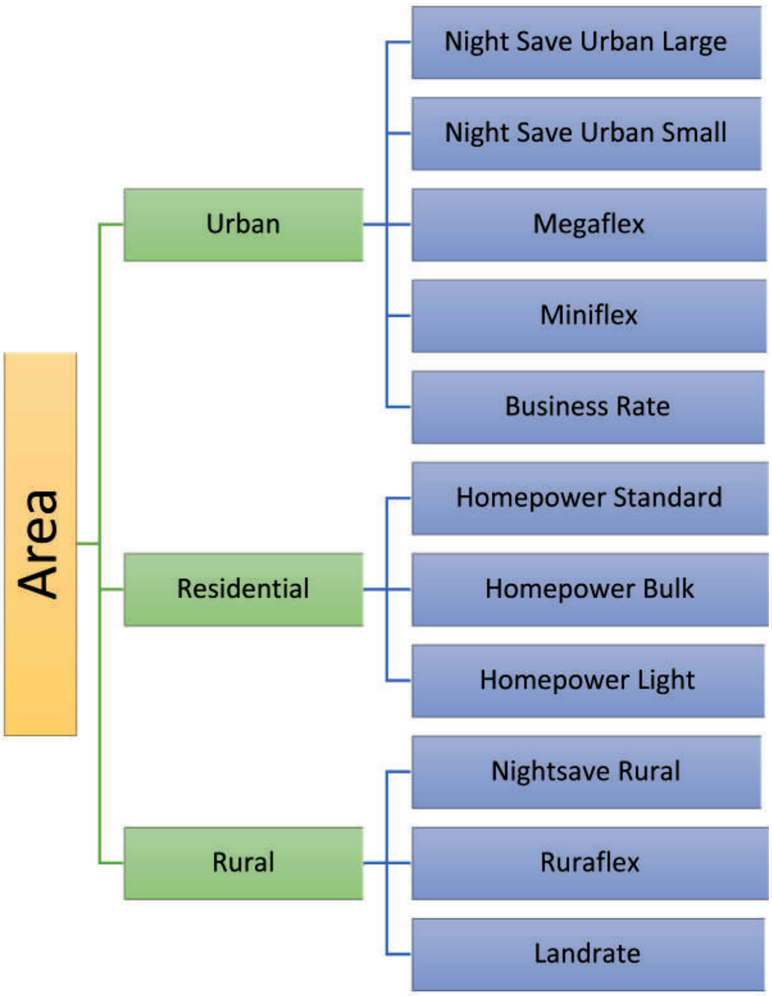


**Figure 8:** Eskom Tariff plan by Area (Eskom Ltd. 2021; National Cleaner Production Centre n.d.).

- Miniflex – this tariff plan is suitable for customers who can shift load and have an NMD of > 25 kVA but < 5 MVA.
- Business Rate – this tariff plan is suitable for customers with commercial usage and non-commercial supplies with an NMD of < 100 kVA. These are small businesses, governmental institutions, churches, schools, halls, clinics, old-age homes, public lighting, etc.
- Homepower Standard – this tariff plan is suitable for residential customers (churches, schools, halls, clinics, old-age homes) with an NMD of <100 kVA.
- Homepower Bulk – this tariff plan is suitable for sectional title developments.
- Homepower Light – this tariff plan is suitable for single-phase residential areas that are subsidized in urban areas.
- Night Save Rural – this tariff plan is suitable for rural customers with a high load factor, an NMD of > 25 kVA and a supply voltage of < 22 kV
- Ruraflex – this tariff plan is suitable for customers with dual and three-phase supplies, an NMD > 25 kVA and a supply voltage of < 22 kV.
- Landrate – this tariff plan is suitable for customers with dual and three-phase supplies and an NMD of < 100 kVA and supply voltage of < 500 V.
- Land Light – this tariff plan is suitable for single-phase residential areas that are subsidized in rural areas limited to 20 A and 60 A.

## Methodology

### *Cold-room specifications*

The cold room used in this study is illustrated in Figure 9. During the operation of the cold room with an internal temperature of -20 °C and an ambient temperature of approximately 24 °C, the measured power consumption was approximately 4,5 kW at a 3 kg refrigerant charge, at a measured mass flow rate of 0,06 kg/s. The refrigeration capacity was then calculated to be ≈10 kW, with the lowest temperature reading of -26 °C from the evaporator. The specifications are displayed in Table I.

For this study, the average cold room operation of 17 hours with a full load was used. The refrigeration system operating times were scheduled daily from 06:00 to 23:00.

### *Heat load*

Transmission load

The sensible heat gain through the walls, floor, and ceiling is calculated at a steady state as expressed in Equation 1 (Huan 2016)

$$q = UA \cdot \Delta T \qquad \text{Equation 1}$$

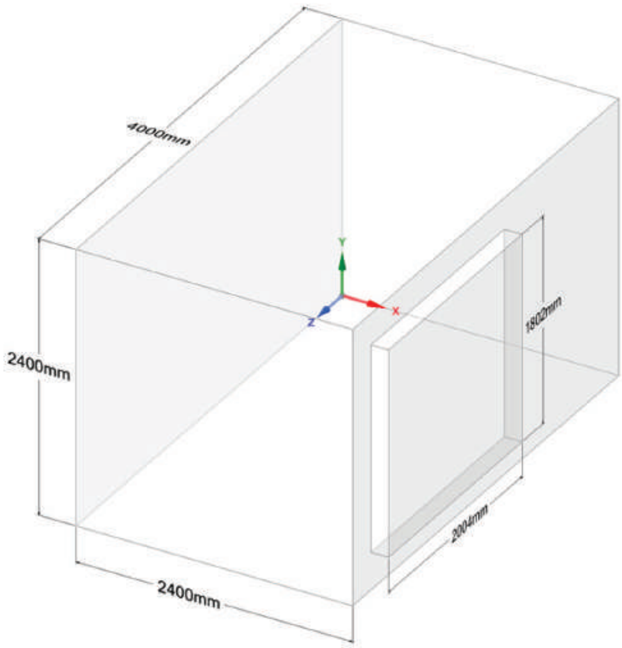


**Figure 10:** Dimensions of cold room

**Figure 9:** Cold Room

**Table I:** Tshwane University of Technology cold room specifications

| Dimensions (m) (l×b×h) | 4 x 2,4 x 2,4 with 150 mm polystyrene panels and aluminium sheets and a 2 x 1,8 door |
|---|---|
| Electric motor | 3 Phase<br>Voltage: 380 V<br>Power: 5,5 kW<br>RPM: 1 435 |
| Compressor | V: 20,3 m3/h<br>N: 1 450 r/min<br>Stroke: 325 cm3<br>Pmax = ND(LP)/HP(HP) = 19/28 bar |
| Condenser | Number of tubes in the transverse direction: 11<br>Number of rows in the longitudinal direction: 5<br>Tube length (wide) = 0,83 m staggered<br>Diameter (ID/OD) 6,25 mm |
| Evaporator | Number of tubes in the transverse direction: 11<br>Number of rows in the longitudinal direction: 5<br>Tube length (wide) = 1,07 m staggered<br>Diameter (ID/OD) = 8,75 mm |
| Expansion device | Model: electric DC 12V<br>PQM 1000 / 140 / 14 / 2<br>Diameter (ID/OD) = 3,75 mm |
| Refrigerant | HFC R404A, 3 kg charge |

Where

- U is the overall heat transfer coefficient of the wall, floor and ceiling [W/m² · K]
- A is the outside area of the section, [m²]
- ΔT is the difference between the outside air temperature and air temperature of the refrigerated space [K]

Infiltration by air exchange

The infiltration most commonly occurs because of the air density differences between rooms. The average heat gain for the 24 hours through the doorway from air exchange is determined in Equation 2 (Huan 2016)

$$q_t = qD_tD_f(1 - E) \qquad \text{Equation 2}$$

Where

- q is the sensible and latent refrigeration load for fully established flow [kW]
- $D_t$ is the doorway open-time factor
- $D_f$ is the doorway flow factor, which was determined as 1,0
- E is the effectiveness of the doorway protective device

$$q = 0.221A(h_i - h_r)\rho_r\left(1 - \frac{\rho_i}{\rho_r}\right)^{0.5}(gH)^{0.5}F_m$$

Where

- $h_i$ is the enthalpy of infiltration air [kJ/kg]
- $h_r$ is the enthalpy of refrigerated air [kJ/kg]
- $\rho_i$ is the density of infiltration air [kg/m³]
- $\rho_r$ density of refrigerated air [kg/m³]
- g is the gravitational constant = 9,81 m/s²
- H is the doorway height [m]
- $F_m$ is the density factor, expressed in Equation 3

$$F_m = \left[\frac{2}{1 + (\rho_r/\rho_i)^{1/3}}\right]^{1.5} \qquad \text{Equation 3}$$

For cyclical, irregular and constant door usage, alone or in combination, the doorway open-time factor was determined as Equation 4.

$$D_t = \frac{(P\theta_p + 60\theta_0)}{3600\theta_d} \qquad \text{Equation 4}$$

Where

- P is the number of doorway passages
- $\theta_p$ is the door open-close time, seconds per passage
- $\theta_0$ is the time the door simply stands open [min]
- $\theta_d$ is the daily period [h]

### *Eutectic plates*

In a study by Yang et al. (2017) the estimated time to charge a eutectic plate was eight hours.

### *Electricity tariffs*

The prices that were considered in this study were active energy charges only with transmission zones with distances smaller

**Table II:** Eutectic plate specifications (FIC S.p.A 2018).

| Model | | Dimensions | | | Plate surface | Evaporator | | Solution -23°C | | Solution -33°C | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | A × B × S (mm) | | | (m²) | Length (m) | Vol (dm³) | Accm. (Wh) | Weight (kg) | Accm. (Wh) | Weight (kg) |
| EFR | 1 757 | 1 740 | 690 | 53 | 2,73 | 20,7 | 4,14 | 3 510 | 83 | 3 300 | 88 |
| Price per plate excluding VAT, shipping, and installation fees | | | | | | | | ≈ R13 250 | | ≈ R14 217 | |

than 300 km, and a voltage of less than 500 V. Only seasonal, TOU and treatment of public holidays were included in the price. Business rate 1 was selected with a three-phase supply of 25 kVA and 40 A per phase. For Homepower light, the 20 A was selected as the power supply sufficient to power the cold room. The Land light tariff was excluded since it offered only a single phase. The tariff prices were grouped to simplify the price structure in Eskom Ltd. (2021). Tariff plans were calculated from 1 April 2021 to 1 April 2022. All this data is available in the Eskom Ltd. (2021) document.

## Results and Discussion

### *Cold room configuration*

The eutectic plate used in this study was the EFR 1757 plate from FIC S.p.A, the solution of which has a phase change at -23 °C and -33 °C. The manufacturer recommended a refrigeration system that operates at 10 °C below the phase change temperature to fully freeze the PCM solution. The EFR 1757 with the phase change solution of -33 °C is more suitable for meat storage cold rooms. The EFR 1757 with the phase change solution of -23 °C is suitable for preserving goods ranging from -13 °C. Using a refrigeration plant with a lower operating temperature will lower the COP of the plant, thus reducing the charging time of the eutectic plate. The technician or designer for this system should factor this into the design as the evaporator coil length of the eutectic plate is fixed.

With the current cold room scheme, the operating temperature of the evaporator is -26 °C, so the EFR 1757 with a phase change solution of -11 °C is recommended. This limits the application of the current cold room to a refrigerator application operating at a temperature below 4 °C and no longer a freezer operating at -18 °C.

Regarding the configuration setup, it was concluded in a previous study Radebe et al. (2020) that placing the eutectic plates at the top promoted high air circulation inside the compartment. This avoids the temperature build-up at the top, limiting the stacking size of the goods in the cold room. For quick temperature recovery, forced air convection is recommended. However, in this study the costs for forced air convection were not incorporated. The fans used inside the cold room not only contribute towards the heat load but also contribute to the total energy consumption of the refrigeration plant. The designer should include the fan motor heat load in the transmission loads thus contributing towards the volume increase of the eutectic plates required in the cold room. The designer should also factor in the cost of having the fans operating during the time the compressor is off.

### *Tariff prices*

It was noted that for locations with the tariff prices in local and non-local authorities, the prices are not far apart, therefore when prices are calculated for longer terms, the total cost does not differ significantly. For each tariff plan, the calculated maximum of 17 hours and the minimum of 6 hours are presented. This is the average time range per day that the refrigeration system is operational as seen in Figure 11.

With the current cold room configuration with the refrigeration plant running on average 17 hours per day, it costs nearly ZAR3 000/year for cold rooms situated in Night Save tariffs plan regions, and nearly ZAR4 000/year for Megaflex, Miniflex and Ruraflex. The cost was nearly ZAR5 000/year for Business rate, nearly ZAR5 500/year for Homepower 1, nearly ZAR9 000/year for Homepower 2, nearly ZAR4 500/year for Homepower Light, nearly ZAR7 000/year for Homepower Bulk and nearly ZAR500/year for Landrate.

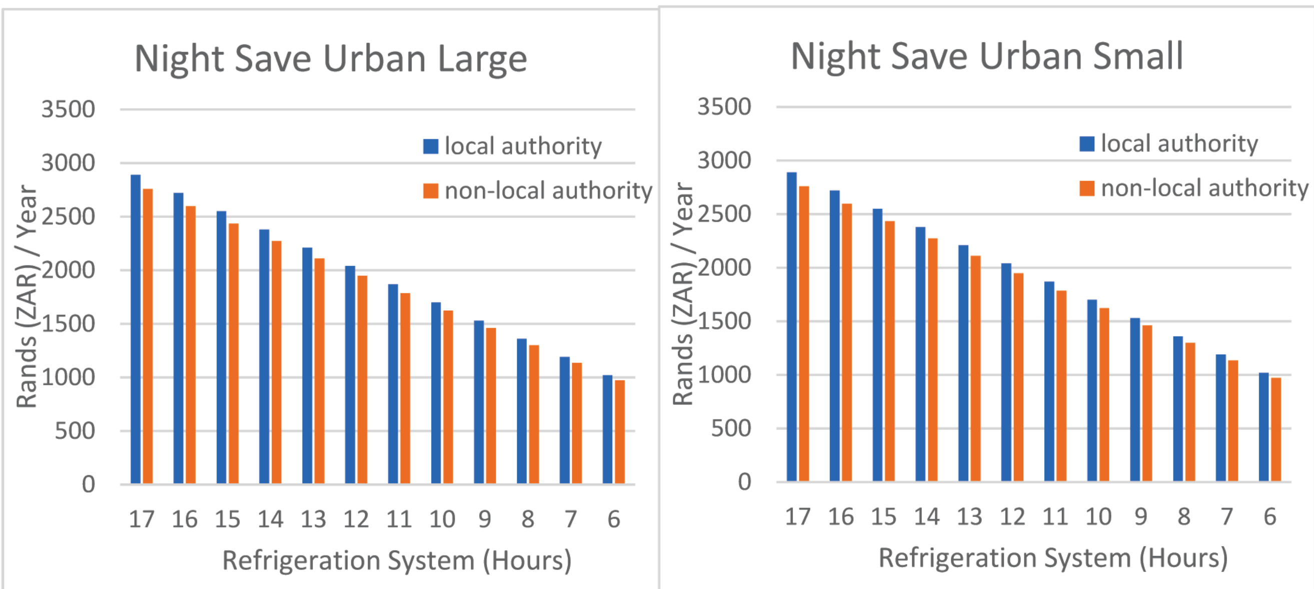


**Figure 11:** Tariff plan pricing for cold room operation/year

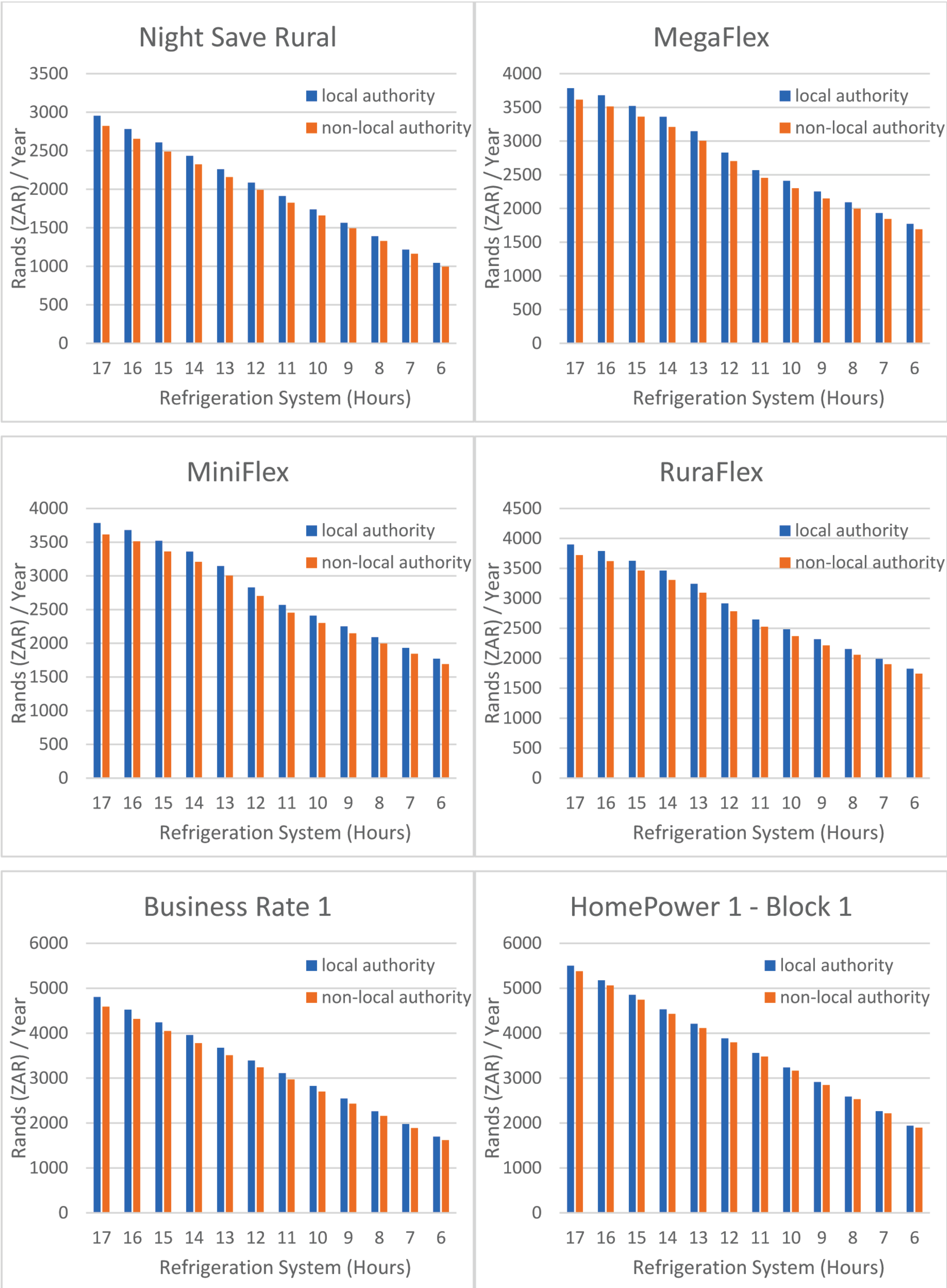


**Figure 11:** Tariff plan pricing for cold room operation/year *(continued)*

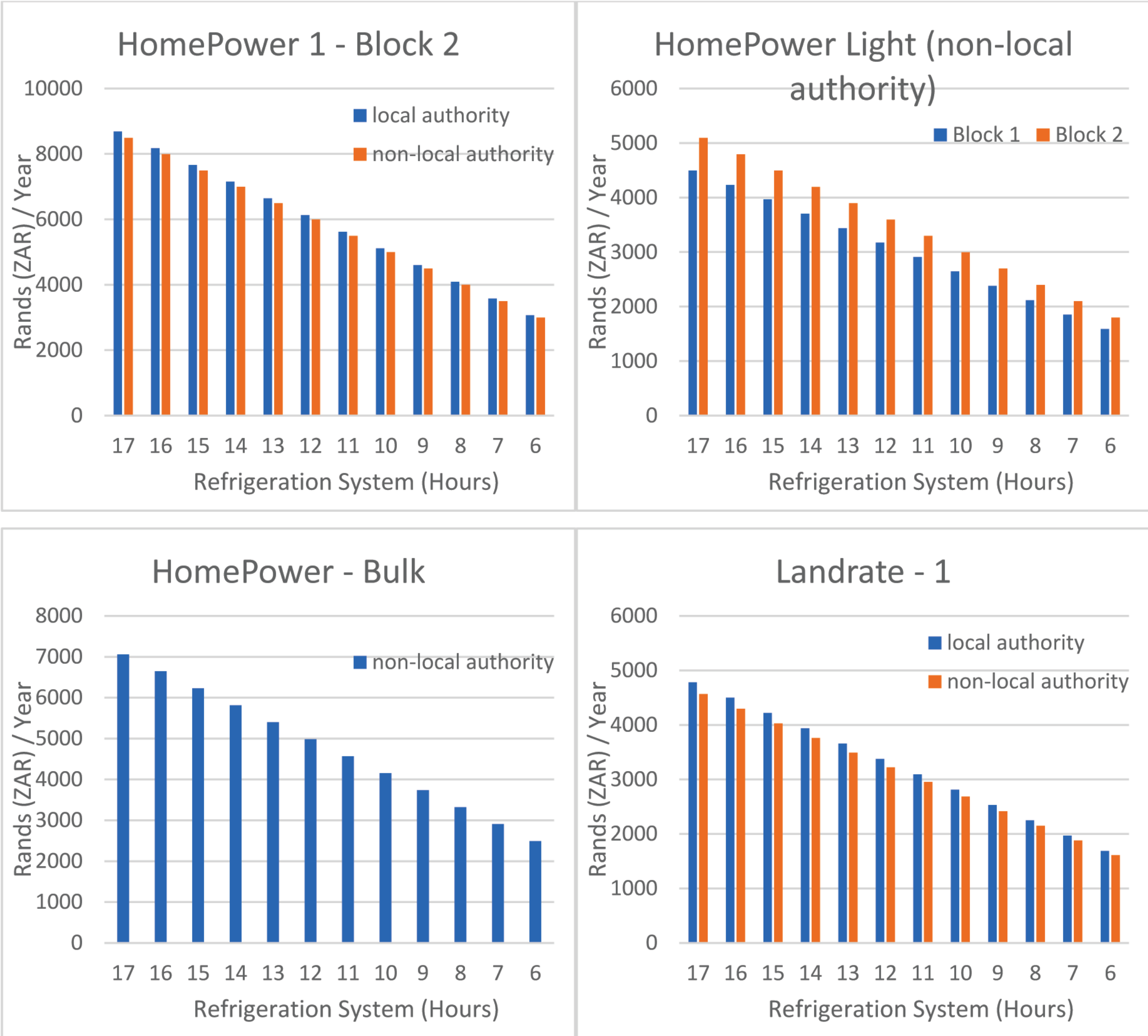


**Figure 11:** Tariff plan pricing for cold room operation/year *(continued)*

The graphs in Figure 11 depict the prices (in rands) as a function of time (for the range 17 to 6 hours) – a linear dependency. To half the price of a 17-hour operation, operating the refrigeration systems for eight hours is ideal. This would be the time to fully charge the LHTESS as illustrated by Yang et al. (2017). However, the manufacturer of the eutectic plates did not mention how long it would take to charge the plates. From known literature, having a large temperature difference between the phase change point temperature of the eutectic plates and the evaporator coil will increase the heat transfer rate, thus increasing the charging time. Factors such as the mass flow rate of the refrigerant will also play a significant role.

### *Storage system integrated into a cold room*

From Figure 12, for a cold room in which the refrigeration system operates for an average of 17 hours a day, Homelight is the most expensive tariff area for the cold room in which to be situated. By integrating an LHTESS, the refrigeration will only run for eight hours to charge the LHTESS. This reduces the cost by more than 50% of the price for a refrigeration system running for 17 hours. Should the cold room be situated in a Night Save Urban Large or Urban Small area, this would be the most cost-effective tariff for the cold room since TOU schedules are used. Hence this places these types of tariff plans at an advantage, as the cold room situated in these regions could be operated at night to charge the eutectic plate using low costs, then maintain the cold room at the desired temperature during the day, using the discharging cycle of the eutectic places as in the study of Yang et al. (2017). Unfortunately, unlike China, South Africa's power utility only supplies a fixed rate for Business.

### *Cost saving*

The Business Rate tariff was used in an analysis to determine the return on investment capital, which amounted to 16,6%/year. The calculations were based on year 1 to year 7 of the installation. A single plate amounts to ZAR 15000, shown as a constant line in Figure 13. The cost of running a cold room on a business tariff without LHTESS is double the cost of running one with LHTESS.

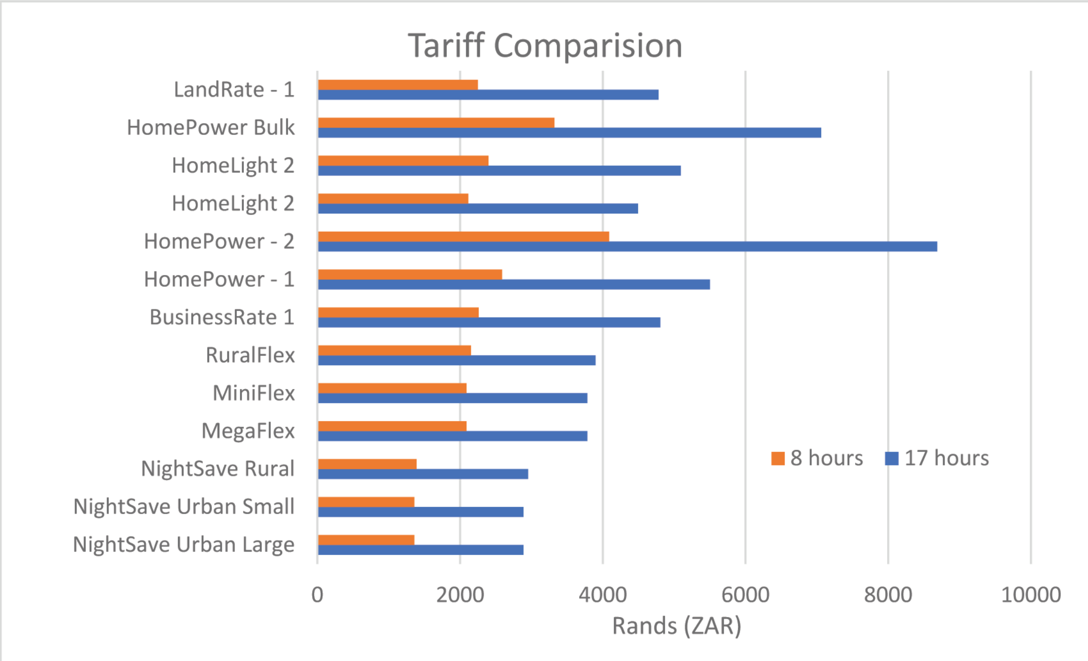


**Figure 12:** Tariff comparison after integrating LHTESS

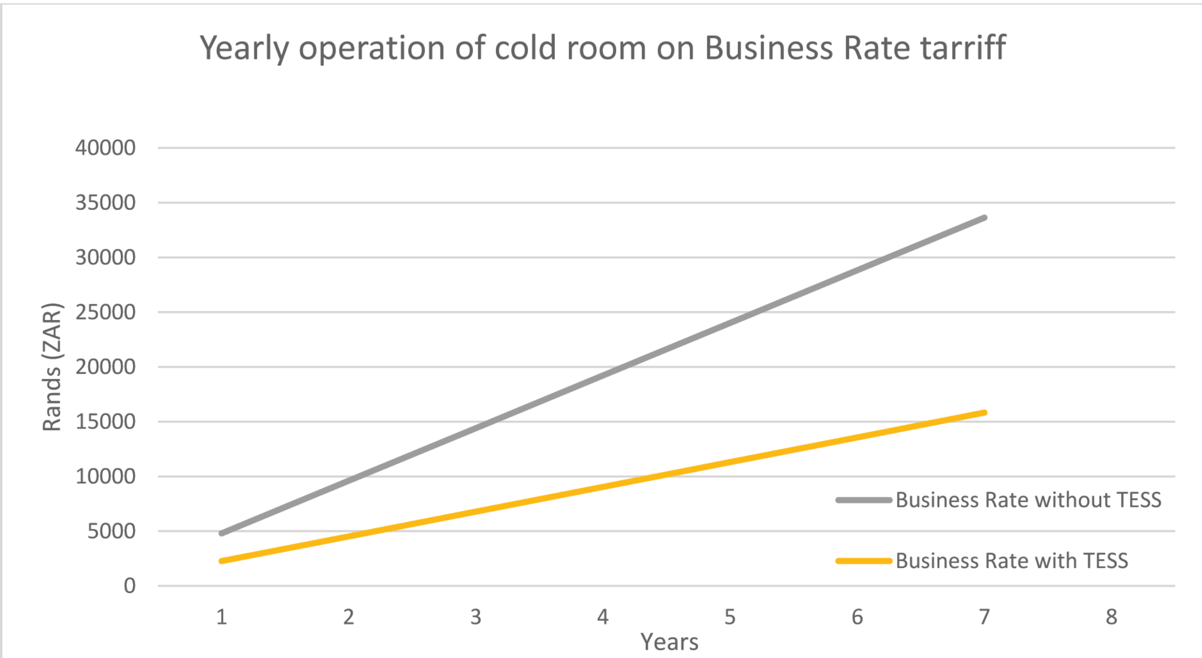


**Figure 13:** Yearly operation of cold room on Business Rate tariff

A cold room operating without an LHTESS consumes more energy and costs ZAR30 000 over six years compared to one using an LHTESS that operates for 16 hours during the day, which cost ZAR15 000.

The current pricing of the eutectic plates makes it difficult to recover the initial cost of the scheme. By deducting the electrical cost amount of a cold room operating with LHTESS from the electrical cost amount of a cold room operating without LHTESS, the cost saving could be determined. These calculated prices assume that factors such as inflation, oil prices etc. remain constant. Figure 14 shows that it will require six years for the initial cost of R15 000 to be recuperated. The cost-saving period is long, and eutectic solutions have a limited life cycle. Therefore, even though eutectic plates are reusable, this additional maintenance cost must be factored into the cost. The initial cost is recuperated in six years. It is therefore concluded that the return on the investment capital would be 16,6%/year. These costs do not include value added tax (VAT), delivery and installation. By reducing the cost of the plates, the scheme

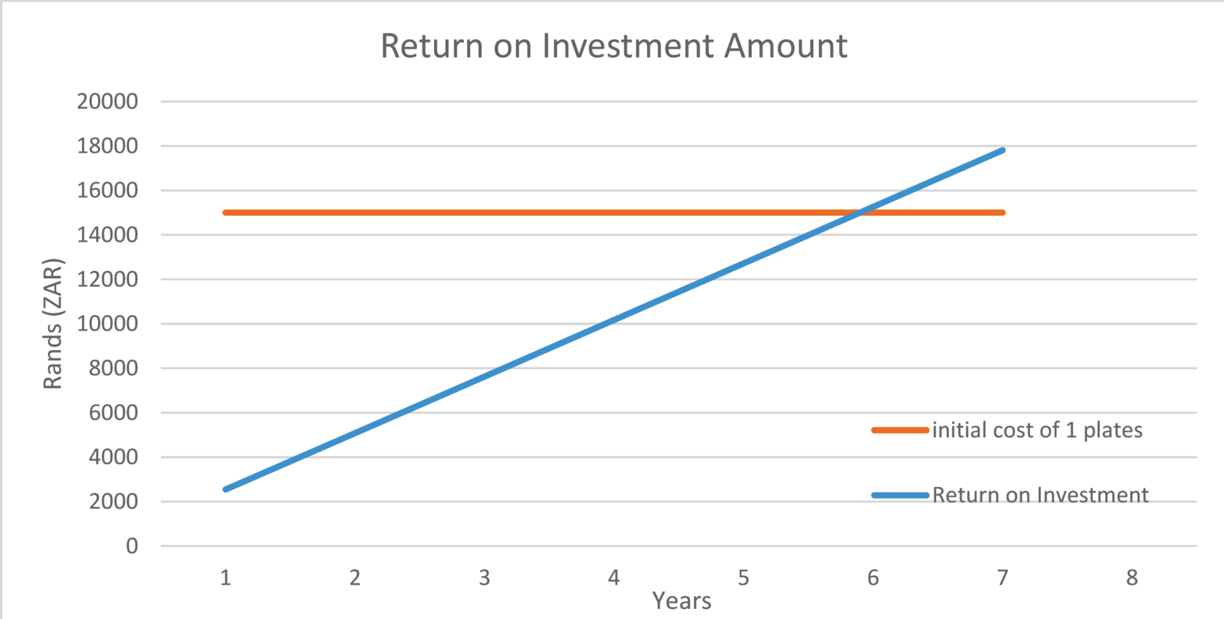


**Figure 14:** Return on investment amount

would be more attractive to customers as LHTESS reduces the potential negative impact of load shedding on refrigeration systems, and if variable tariffs are used, could also render cost savings for the user.

## Conclusion

LHTSS can contribute to reducing the potential negative impact of load shedding on refrigeration systems, storing excess energy at a time when available, to be used when an energy shortage is experienced; and if variable tariffs are utilised, cost savings can be rendered for the user. LHTESS contribute towards cold rooms' being more efficient, thus resulting in benefits for the environment. From this study, it is concluded that it is expensive to integrate an LHTESS into an existing cold room due to the high initial costs and the long payback period. If this initial cost were to be reduced, the scheme would be more attractive to customers. New methods should be used to reduce the manufacturing cost of eutectic plates so as to make the system more attractive. This study focused on overcoming the heat load required during the operation of the cold room. The focus was not on the temperature distribution within the cold room. More plates are needed to minimize the temperature fluctuations inside a cold room.

The tariffs plans of the South African power utility, Eskom, differ drastically, with Night Save Urban Large and Urban Small being the cheapest tariff plans and HomeLight being the most expensive. When integrating the LHTESS into existing cold rooms, the number of hours that the refrigeration system would be running should be estimated to reduce costs. However, a temperature difference of  between the evaporator and the PCM should be incorporated into the design, although this does restrict the purpose and application of the cold room. For new cold rooms with LHTESS, the number of plates needed to maintain the desired temperature should be calculated. This will also assist in determining the initial cost of the scheme. The designer should also take into consideration the pull-down time since this will determine if the system should be a forced-air convection or a natural convection system.

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# PROCEEDINGS OF THE 3RD ENERGY AND HUMAN HABITAT CONFERENCE

28-29 NOVEMBER 2022

CASTLE OF GOOD HOPE - CAPE TOWN

EDITOR: PROF MTE KAHN

Proceedings of the

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(28&29 November 2022)

Cape Town / Castle of Good Hope

Edited by Prof Mohamed Tariq Ekeramodien Kahn

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# 3rd Energy and Human Habitat Conference 2022

## Editor's Synopsis

This Proceedings includes the papers presented at the 2nd Energy and Human Habitat Conference which took place between 28-29 November, 2022, in Cape Town, South Africa as a face to face event at the Castle of Good Hope.

The Conference was organized by the African and International Use of Energy platform consisting of academics from the Cape Peninsula University of Technology, the University of the Western Cape, University of South Africa, and University of Stellenbosch. The organizing committee, advisory board and review board, as well as the editors are grateful to the delegates who had submitted and presented papers.

The conference papers included experimental as well as overview studies applicable to Energy and the application or enhancement of human habitat. Although the conference was open for inclusion of studies from an energy policy and energy economics perspective, almost all the papers received in this call were of a more technical nature.

The conference received papers via its online submission platform and responded by related email. Reviews were double blind with two reviewers per paper and a third editorial review for decision to include the paper in the proceedings. Several paper abstracts were received but was not of sufficient quality to meet initial review requirements and some were also outside the scope of the conference. The conference received over 48 abstracts and received 38 papers as submissions. Only 21 papers were accepted and graded for inclusion in this Proceedings after peer review and these included only highly positive reviews with minimal corrective work.. The rejection ratio of papers was 44% rejection.The highest single institution papers accepted for publication was 28%, hence meeting the South African DHET requirement.

The authors were required to avail themselves for a face to face presentation with session chairs at the conference venue.

Prof MTE Kahn

Energy Institute, Cape Peninsula University of Technology

28 November 2022

AFRICA AND INT. USE OF ENERGY
EHH
2022

**Opening Remarks**

**Dr Marco Adonis, HOD , DEECE, CPUT**

3rd Energy and Human habitat Conference

28 & 29 November 2022, Castle of Good Hope, Cape Town, South Africa

Distinguished Participants, Colleagues, Ladies and Gentlemen,

Good Morning.

I am very honoured to deliver opening remarks on behalf of the Department of Electrical Electronic and Computer Engineering of the Cape Peninsula University of Technology, at this esteemed Conference.

I would like to welcome all participants for their keen interest and enormous efforts to make this meeting possible.

At the outset, I would like to thank co-organizers of this event. My special thanks goes to Professor Mohamed Tariq Kahn, Director of the Energy Institute, and Convenor of this Conference. Prof Kahn have been at the helm of the energy conferences since 2012 and have done a first for us in organising this event at the Castle of Good Hope. A Special Thanks to the Organising Committee, and the Review Committee, the Session Chairs and the many students and staff that were involved in making this event happen here today. For two years the conference continued as a digital event, and this is the fist face to face event since 2019.

I think you, the delegates here, will be more experienced and knowledgeable than myself on the theme of Energy and Human Habitat . So my remarks will be very short. I just would like to highlight the huge potential of Energy Technology in the achievement of SDGs , which are an important international achievement for the 2030 goals and beyond.

More than 700 million people on the African continent still do not have access to modern, productive energy sources, and many of them continue to use antiquated, ineffective traditional energy sources. The difficulty is still in successfully and sustainably getting this solution to the most remote off-grid areas, even though the answers already exist.

Energy poverty is still a problem, and many homes haven't been able to connect to the electricity despite significant attempts to expand the grid to several towns, produce more megawatts, and offer various "low cost" energy products and services for the "poor". Microgrids and effective use of modern technological advances hold the key to bridge the gap with Human Habitat and electrification. Grid extension alone does not provide energy access as long as the end-use energy dilemma is not resolved.

In addition to this, since the Paris Agreement went into force in 2016, reducing greenhouse gas emissions has become another important mission for all. Our nation is embarking on the Just Transition in the Energy sector to address concerns with job losses and re-skilling that could be associated with such a change from fossil fuels to renewables. This is why Conferences like these are important. To create networks of researchers that can share their views and ideas in order to create better understanding and co-operation.

I would like to thank all the presenters, facilitators, and participants, for making the time to be here. Thank you

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# 3rd Energy and Human Habitat Conference 2022

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Energy and Society,
Smart Energy
Renewable Energy
Blockchain and smart contracts in energy
Smart Grids, Microgrids and Minigrids
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Energy Storage and Power Electronics
Energy Efficiency
Energy Economics
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The conference proceedings contain full papers which are subjected to a blind peer review process.

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The target audience for the proceedings are specialists in the field.

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The Chairman and/ or Conference Administrator informs each main author of the outcome of the evaluation timeously, inviting the successful author(s) to submit a print-ready manuscript in accordance with possible comments and the instructions and guidelines provided in the conference paper template.
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# INTEGRATION OF LATENT HEAT THERMAL ENERGY STORAGE SYSTEM IN A COMMERCIAL SOUTH AFRICAN COLD ROOM

Thandiwe Bongani Radebe*, Zhongjie Huan

***Abstract:***
*Nearly 60 to 70% of electrical energy in cold storage facilities is used for refrigeration. By infusing Latent Heat Thermal Energy Storage System (LHTESS) with convectional refrigeration systems, electrical costs are reduced. During peak load and Eskom's load shedding period, the LHTESS releases energy to maintain a compartments' temperature constant. During normal hours it is charged through a refrigeration system connected parallel to it. This study investigates the integration of an LHTESS in a South African cold room connected on Eskom's Business rate tariff. A heat load analysis was done to determine the number and initial cost of eutectic plates needed to maintain a temperature of -18°C. Eskom's tariff plans were used to capture and compare the daily operational costs of a cold room with and without an LHTESS from the year 2021 until 2022. The electrical costs of running a cold room for 17 hours on a business tariff plan is estimated to be R4800, by incorporating an LHTESS operating for 16 hours would reduce this amount to R2260/year. it initially costs R15000 for this system and takes 6 years to recuperate the initial cost. Inexpensive eutectic plates should be designed and manufactured locally for low-cost integration.*

***Keywords:***
*Thermal Energy Storage; Phase Change Material; Eutectic Plate; Business rate tarriff*

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## I. INTRODUCTION

Countries such as China are the world's major agricultural counties and have a high demand for refrigeration equipment. Large amounts of electric energy are consumed every year due to refrigeration equipment. It was noted by [1] that 60 to 70% of electrical energy in cold storage facilities is used for refrigeration. By infusing latent heat cold storage with convectional refrigeration systems, the country's electrical costs have declined. During peak load, the Latent Heat Thermal Energy Storage System (LHTESS) releases energy and during normal hours it is being charged through a refrigeration system that is connected parallel to it [2].

The LHTESS generally requires a refrigerant system to freeze the eutectic Phase Change Material (PCM). Despite its limitations, this system plays a significant role in the refrigeration industry. Its application on small vans, dedicated cargo, and other applications make it a potential solution to resolve the current situation with refrigerants and climate change. LHTESS is also ideal in developing countries, where the precision of temperature control is less relevant when being compared to the overall fuel and system cost [3].

Although this technology has existed for more than half a century, it is only receiving much attention recently due to major changes in electric rate structures, increases in maximum power demands, and utility-sponsored incentive programs. Utility companies have higher demand charges for peak demand periods to discourage energy consumption during these peak demand periods. These systems can then be used to shift peak cooling loads to off-peak periods by operating during the daytime peak hours and being fully recharged during the night-time off-peak hours [4]. This results in saving electrical energy. Furthermore, they act as a backup solution during power failure [5].

This paper presents an energy cost analysis of integrating a LHTESS into a South African cold room operating at a -18°C temperature. Eskom's tariff plans are used to estimate the energy-saving costs of a daily operational cold room and project the payback period of the new scheme.

### 1.1. Thermal Energy Storage

Thermal Energy Storage (TES) is a method that has great potential to correct the mismatch that occurs between supply and demand of energy and also has great potential to also improve energy management by acting as a coupling between different sectors. Liquid-solid PCMs in particular are regarded as key components for the integration of renewable energy sources. This field alone has attached much research as it seems to make systems more efficient and environmentally friendly in regards to using energy [4], [6], [7].

TES systems work on the principle of charging and discharging, this storage cycle is clearly illustrated in Fig. 1. They can store and release energy at different places, power, and temperature [8].

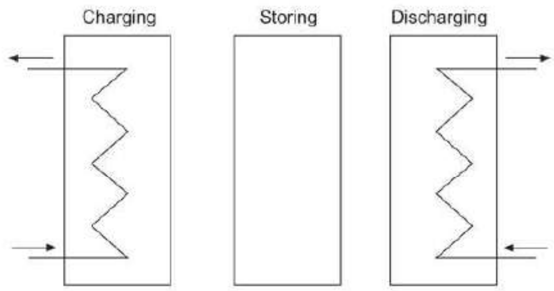


**Fig. 1 TES complete storage cycle** [9].

### 1.2. Cold Thermal Energy Storage (CTES)

Cold Thermal Energy Storage (CTES) is a representation of cool and cold TES. Materials such as glycol, eutectic salts, and pure water can be used as cooling storage for TES systems [4]. These materials can be used in the cold chain for freezing products or for chilling.

Although this technology has existed for more than half a century, it is only receiving much attention recently due to major changes in electric rate structures, increases in maximum power demands, and utility-sponsored incentive programs. Utility companies have higher demand charges for peak demand periods to discourage energy consumption during these peak demand periods. CTES systems can then be used to shift peak cooling loads to off-peak periods by operating during the daytime peak hours and being fully recharged during the night-time off-peak hours [4]. This results in saving electrical energy.

#### 1.2.1. Operational loading of CTES

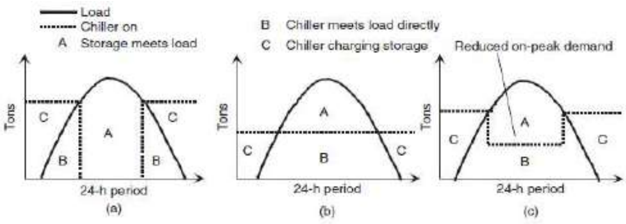


**Fig. 2 Operating strategies: (a) full-storage, (b) partial-storage load leveling, and (c) partial-storage demand limiting** [4], [5]

In Fig. 2, [4] characterized CTES into three categories, full-storage, partial-storage load levelling, and partial-storage demand limiting. These strategies are implemented to meet the cooling demand during peak hours.

a) Full-storage CTES

As illustrated in Fig. 2 (a), during off-peak hours, the CTES system is being recharged and during peak hours the CTES system is fully operational. This shifts the entire peak cooling load to off-peak hours by decoupling the operation or cooling generating equipment from the peak cooling load. The CTES system discharges the cooling load while the generating equipment is idle, making this strategy ideal when peak demand charges are high or the peak period is short [4].

[4] further elaborated that this strategy is economically advantageous when:

- Spikes in the peak load curve are of short duration
- Time-of-use energy rates are based on short-duration peak periods
- There are short overlaps between peak loads and peak energy periods
- Large cash incentives are offered for using TES
- High peak-demand charges apply.

b) Partial storage load levelling

With this strategy, it is designed to meet operations for 24 hours as illustrated in Fig. 2 (b). When the peak cooling load is much higher than the average load, the storage system is in use to mitigate the peak load. The chiller is sized at a smaller capacity than the design load, to allow the rest of the load to be drawn from the storage. This is also the cheapest system to run when compared with the full-storage and partial-storage demand limiting system, and making it the most economic option [4].

c) Partial-storage demand limiting

With the partial-storage demand limiting strategy, during the peak hours when the energy demand is high, the chiller capacity is reduced allowing the stored energy to meet the load. This strategy is less expensive when compared to a full-storage system [4].

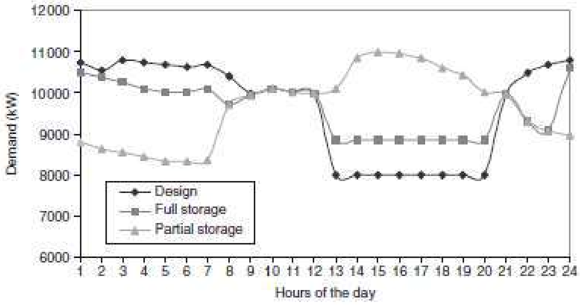


**Fig. 3 Sample demand profiles for the design, full-storage, and partial-storage systems** [4].

In Fig. 3, [4] illustrated that when designing CTES systems for full-storage and partial-storage applications, certain parameters have to be taken into consideration. [4] further explained that for designing part-load systems, all the components and piping must be able to maintain control of the system at different loads. However, in part-load operations, the pressure drop, velocities, and flow rates of the refrigerant are decreased or reduced during the initial stages. For pull-down load systems, the components must be designed specifically to handle higher loads at initial start-up.

[5] stated that to design and implement a successful CTES system, the peak/off-peak demand structure has to be identified. Then the system can be tailored to meet the load.

### 1.3. EUTECTIC PLATES

In a previous study [10], a detailed description of the FIC Eutectic plates was discussed. In this paper, only the plates from FIC are analyzed to estimate the total costs of TESS. Eutectic plates have some advantages over other refrigeration systems that set them apart and some drawbacks have been encountered with these systems as well.

#### 1.3.1. Electric tariffs

National Energy Regulatory of South Africa (NERSA) is a body that approved the electricity tariffs in South Africa. These new tariffs are then passed on to the relevant stakeholders [11]. in July 2021, a new tariff increase was introduced. The total standard tariffs were increased by 15.06 % while municipality tariffs were increased by 17.80 % and the affordability subsidy was increased by 14.75% [12].

Business rate is a tariff plan suitable for customers with commercial usage and non-commercial supplies with an NMD not exceeding 100 kVA. These are small businesses, governmental institutions, churches, schools, halls, clinics, old-age homes, public lighting, etc.,

## II. METHODOLOGY

### A. Electricity tariff

The prices that were considered in this study were active energy charges only with transmission zones of less than 300 km, and a voltage of less than 500V. Business rate 1 was selected with a three-phase supply of 25 KVA and 40 A per phase. For Home Light, the 20 A was selected as the sufficient power supply to power the cold room. The tariff prices for Business rate tariff plan are displayed in Table 1 for both local and non-local authority including VAT. Tariff plans were calculated from 1 April 2021 to 1 April 2022.

**Table 1** Business rate Tariff pricing [12]

| Term of use | Prices $(c/kWh)$ |
|---|---|
| A single $c/kWh$ active energy charge | 172.10 (local)<br>164.32 (non-local) |

### B. Eutectic plates

In a study by Yang et al. [14] the estimated time to charge a eutectic plate was 8 hours.

**Table 2:** Eutectic Plate specifications [13].

| Model | Dimensions | Plate surface | Evaporator | Solution $-23°C$ | Solution $-33°C$ |
|---|---|---|---|---|---|

| | | $A \times B \times S$ $(mm)$ | | | $(m^2)$ | Length $(m)$ | Vol $(dm^3)$ | Accm. $(Wh)$ | Weight $(kg)$ | Accm. $(Wh)$ | Weight $(kg)$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EFR | 1757 | 1740 | 690 | 53 | 2.73 | 20.7 | 4.14 | 3510 | 83 | 3300 | 88 |
| Price per plate excluding VAT, shipping, and installation fees | | | | | | | | ≈ R13 250 | | ≈ R14 217 | |

### C. . Cold-room specifications

**Fig. 4 Cold Room**

The cold room used in this study is illustrated in Fig. 4. With the operation at $-20°C$ with an ambient temperature of $\pm 24°C$. The measured power consumption was approximately $4.5\ kW$ at $3\ kg$ charge, at a measured mass flow rate of $0.06\ kg/s$. The refrigeration effect was calculated to be $\approx 10\ kW$ with the lowest temperature reading of $-26°C$. The specifications are displayed in Table 3. For this study, the average cold room operation of 17 hours with a full load was used. The refrigeration system operating times were scheduled daily from morning 06:00 to evening 23:00.

**Table 3** Tshwane University of Technology cold room specifications

| | |
|---|---|
| Dimensions (m) $(l \times b \times h)$ | 4 x 2.4 x 2.4 with 150 mm Polystyrene panels and Aluminium sheets<br>2 x 1.8 door |
| Electric motor | 3 Phase<br>Voltage: 380 V<br>Power: 5.5 kW<br>RPM: 1435 |
| Compressor | V:20.3 $m^3$/h<br>N: 1450 r/min<br>Stroke: 325 $cm^3$<br>Pmax = ND(LP)/HP(HP) = 19/28 bar |
| Condenser | Number of tubes in the transverse direction: 11<br>Number of rows in the longitudinal direction: 5<br>Tube length (wide) = 0.83 m staggered<br>Diameter (ID/OD) 5/8'' |
| Evaporator | Number of tubes in the transverse direction: 11<br>Number of rows in the longitudinal direction: 5<br>Tube length (wide) = 1.07m staggered<br>Diameter (ID/OD) = 7/8'' |
| Expansion device | Model: electric DC 12V<br>PQM 1000 / 140 / 14 / 2<br>Diameter (ID/OD) = 3/8'' |
| Refrigerant | HFC R404A, 3 kg charge |

### D. Heat load

1.1. Transmission load

The sensible heat gain through the walls, floor, and the ceiling is calculated at a steady state as expressed in Eq. 1, [15]

$$\boldsymbol{q = UA \cdot \Delta T} \qquad \textbf{Eq. 1}$$

Where, $U$, is the overall heat transfer coefficient of the wall, floor, and ceiling, $[W/m^2 \cdot K]$. $A$, is the outside area of the section, $[m^2]$. $\Delta T$, is the difference between the outside air temperature and air temperature of the refrigerated space, $[K]$.

1.2. Infiltration by air exchange

The infiltration most commonly occurs because of the air density differences between rooms. The average heat gain for the 24hour period through the doorway from air exchange determined in Eq. 2, [15],

$$\boldsymbol{q_t = qD_tD_f(1-E)} \qquad \textbf{Eq. 2}$$

Were, $q$, is the sensible and latent refrigeration load for fully established flow, $[kW]$ shown in Eq. 3. $D_t$, is the doorway open-time factor. $D_f$, is the doorway flow factor, which was determined as 1.0 $E$, is the effectiveness of the doorway protective device.

$$\boldsymbol{q = 0.221A(h_i - h_r)\rho_r\left(1-\frac{\rho_i}{\rho_r}\right)^{0.5}(gH)^{0.5}F_m} \qquad \textbf{Eq. 3}$$

Were, $h_i$, is the enthalpy of infiltration air, $[kJ/kg]$. $h_r$, is the enthalpy of refrigerated air, $[kJ/kg]$. $\rho_i$, is the density of infiltration air, $[kg/m^3]$. $\rho_r$, density of refrigerated air, $[kg/m^3]$. $g$, is the gravitational constant $= 9.81\ m/s^2$. $H$, is the doorway height, $[m]$. $F_m$, is the density factor, expressed in Eq. 4.

$$F_m = \left[\frac{2}{1+(\rho_r/\rho_i)^{1/3}}\right]^{1.5} \quad \textbf{Eq. 4}$$

For cyclical, irregular, and constant door usage, alone or in combination, the doorway open-time factor was determined as Eq. 5

$$D_t = \frac{(P\theta_p + 60\theta_0)}{3600\theta_d} \quad \textbf{Eq. 5}$$

Were, $P$, is the number of doorway passages. $\theta_p$, is the door open-close time, seconds per passage. $\theta_0$, is the time the door simply stands open, $[min]$. $\theta_d$, is the daily period, $[hr]$.

## III. Results and Discussion

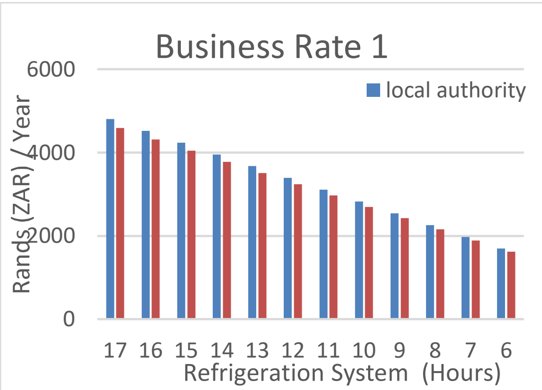


**Fig. 5 Operation of cold room**

### 1.1. cold room configuration

The eutectic plate used in this study was the EFR 1757 plate from FIC S.p.A, the solutions having a phase change at −23°C and −33°C, were selected. The manufacture recommended a refrigeration system that operates at 10°C below the phase change temperature to fully freeze the PCM solution. The EFR 1757 with the phase change solution of −33°C is more suitable for meat storage cold rooms. While the EFR 1757 with the phase change solution of −23°C is suitable for preserving goods at ranging from ±13°C. With the current scheme, the evaporator operates at −26°C, the EFR 1757 with a phase change solution of −11°C is recommended.

Regarding the configuration setup, it was concluded in a previous study [16] that placing the eutectic plates at the top promoted high air circulation inside the compartment. And this avoids the temperature build-up at the top, limiting the staking size to a certain height. For quick temperature recovery, forced air convection is recommended.

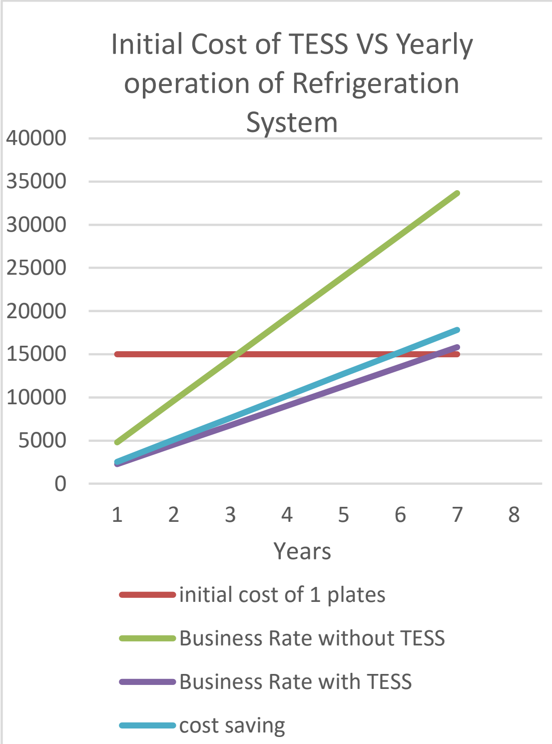


**Fig. 6 Initial cost of LHTESS against the yearly operation of the refrigeration system**

### 1.2. tariff prices

for the tariff prices between local and non-local authority prices, there is not much difference when prices are calculated in the long term. For the Business rate tariff plan, the maximum hours of 17 hours and the minimum hours of 6 hours are presented, this is the time the refrigeration system is operational. The graphs are reduced linearly. To half the price from a 17-hour operation, operating the refrigeration systems for 8 hours is ideal. This would be the time to fully charge the LHTESS as illustrated by Yang et al. [14].

### 1.3. Cost recovery

with the current pricing of the eutectic plates, it makes it difficult to recover the initial cost of the scheme. A single plate amount to $R15\,000$. These costs do not include Value Added Tax (VAT), delivery, and installation. By reducing the cost of the plates, the scheme would be more attractive to customers as LHTESS provides a solution to the energy crisis we face Fig. 6 clearly shows that a cold room operating without an LHTESS consumes more energy than one using LHTESS that operates for 16 hours during the day. However, the cost-saving period is long, the life cycle of the eutectic plate must be factored into the cost.

## IV. CONCLUSIONS

LHTESS has a great potential to correct the mismatch that occurs between the supply and demand of energy. They make cold rooms more efficient and environmentally friendly concerning using energy. Currently, it is expensive to integrate one into an existing cold room due to the initial costs and the payback period is long. If this initial cost is reduced, the scheme would be more attractive to customers. New methods should be used to minimize the manufacturing cost of eutectic plates to make the scheme more attractive. More plates are needed to minimize the temperature fluctuations inside a cold room

When integrating the LHTESS into existing cold rooms, the number of hours that the refrigeration system would be running should be estimated to cut down costs. However, a temperature difference of 10℃ between the evaporator and the PCM should be incorporated in the design. This does restrict the purpose and application of the cold room. For new cold rooms with LHTESS, the number of plates needed to maintain the desired temperature should be calculated, this will also assist in determining the initial cost of the scheme. The designer should also take into consideration the pull downtime, this will determine if the scheme should be forced air convection or a natural convection scheme.

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# PROCEEDINGS OF THE 3RD ENERGY AND HUMAN HABITAT CONFERENCE

28-29 NOVEMBER 2022
CASTLE OF GOOD HOPE - CAPE TOWN

EDITOR: PROF MTE KAHN

Proceedings of the

# 3rd Energy and Human Habitat Conference

(28&29 November 2022)

Cape Town / Castle of Good Hope

Edited by Prof Mohamed Tariq Ekeramodien Kahn

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# 3rd Energy and Human Habitat Conference 2022

## Editor's Synopsis

This Proceedings includes the papers presented at the 2nd Energy and Human Habitat Conference which took place between 28-29 November, 2022, in Cape Town, South Africa as a face to face event at the Castle of Good Hope.

The Conference was organized by the African and International Use of Energy platform consisting of academics from the Cape Peninsula University of Technology, the University of the Western Cape, University of South Africa, and University of Stellenbosch. The organizing committee, advisory board and review board, as well as the editors are grateful to the delegates who had submitted and presented papers.

The conference papers included experimental as well as overview studies applicable to Energy and the application or enhancement of human habitat. Although the conference was open for inclusion of studies from an energy policy and energy economics perspective, almost all the papers received in this call were of a more technical nature.

The conference received papers via its online submission platform and responded by related email. Reviews were double blind with two reviewers per paper and a third editorial review for decision to include the paper in the proceedings. Several paper abstracts were received but was not of sufficient quality to meet initial review requirements and some were also outside the scope of the conference. The conference received over 48 abstracts and received 38 papers as submissions. Only 21 papers were accepted and graded for inclusion in this Proceedings after peer review and these included only highly positive reviews with minimal corrective work.. The rejection ratio of papers was 44% rejection.The highest single institution papers accepted for publication was 28%, hence meeting the South African DHET requirement.

The authors were required to avail themselves for a face to face presentation with session chairs at the conference venue.

Prof MTE Kahn

Energy Institute, Cape Peninsula University of Technology

28 November 2022

## Opening Remarks

## Dr Marco Adonis, HOD , DEECE, CPUT

3rd Energy and Human habitat Conference

28 & 29 November 2022, Castle of Good Hope, Cape Town, South Africa

Distinguished Participants, Colleagues, Ladies and Gentlemen,

Good Morning.

I am very honoured to deliver opening remarks on behalf of the Department of Electrical Electronic and Computer Engineering of the Cape Peninsula University of Technology, at this esteemed Conference.

I would like to welcome all participants for their keen interest and enormous efforts to make this meeting possible.

At the outset, I would like to thank co-organizers of this event. My special thanks goes to Professor Mohamed Tariq Kahn, Director of the Energy Institute, and Convenor of this Conference. Prof Kahn have been at the helm of the energy conferences since 2012 and have done a first for us in organising this event at the Castle of Good Hope. A Special Thanks to the Organising Committee, and the Review Committee, the Session Chairs and the many students and staff that were involved in making this event happen here today. For two years the conference continued as a digital event, and this is the fist face to face event since 2019.

I think you, the delegates here, will be more experienced and knowledgeable than myself on the theme of Energy and Human Habitat . So my remarks will be very short. I just would like to highlight the huge potential of Energy Technology in the achievement of SDGs , which are an important international achievement for the 2030 goals and beyond.

More than 700 million people on the African continent still do not have access to modern, productive energy sources, and many of them continue to use antiquated, ineffective traditional energy sources. The difficulty is still in successfully and sustainably getting this solution to the most remote off-grid areas, even though the answers already exist.

Energy poverty is still a problem, and many homes haven't been able to connect to the electricity despite significant attempts to expand the grid to several towns, produce more megawatts, and offer various "low cost" energy products and services for the "poor". Microgrids and effective use of modern technological advances hold the key to bridge the gap with Human Habitat and electrification. Grid extension alone does not provide energy access as long as the end-use energy dilemma is not resolved.

In addition to this, since the Paris Agreement went into force in 2016, reducing greenhouse gas emissions has become another important mission for all. Our nation is embarking on the Just Transition in the Energy sector to address concerns with job losses and re-skilling that could be associated with such a change from fossil fuels to renewables. This is why Conferences like these are important. To create networks of researchers that can share their views and ideas in order to create better understanding and co-operation.

I would like to thank all the presenters, facilitators, and participants, for making the time to be here. Thank you

# 3rd Energy and Human Habitat Conference 2022

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# 3rd Energy and Human Habitat Conference 2022

## CONFERENCE Editorial Policy

The conference disseminates original research and new developments which are published in this conference proceedings. The conference covers the following disciplines in the field of energy:

Energy and Society,
Smart Energy
Renewable Energy
Blockchain and smart contracts in energy
Smart Grids, Microgrids and Minigrids
EV and Electric Transportation
Energy Storage and Power Electronics
Energy Efficiency
Energy Economics
Energy Development

### Publications produced for the conference

The following publications ensure that the research reports given during the conference are disseminated widely

#### Conference Proceedings

The conference proceedings contain full papers which are subjected to a blind peer review process.

The proceedings with ISBN number, will be digitally disseminated, and will be published online on our website, as well as co-published on either Elsevier SSRN and its associated e-Journals or Zenodo under the AIUE e-Journal.This is a digital library under OpenAIR and the CERN. OpenAir as the vanguard of the open access and open data movements in Europe was commissioned by the EC to support their nascent Open Data policy by providing a catch-all repository for research and is open to all search engines. This provides a high quality repository of scientific information and dissemination. A DOI number to be associated with the individual research papers.
The target audience for the proceedings are specialists in the field.

#### Editorial and the Review Process

Our review board consists of international and national experts in specialist fields covered in the conferences. They are from different academic institutions, and from industry. Authors are invited to submit an abstract prior to submission of a paper. The abstracts of proposed conference papers are sent for evaluation, and only accepted abstracts would lead to the invitation to submit a full paper which is then reviewed by no less than two reviewers. A third editorial review is done before the papers are accepted for publication in the proceedings.

The Chairman and/ or Conference Administrator informs each main author of the outcome of the evaluation timeously, inviting the successful author(s) to submit a print-ready manuscript in accordance with possible comments and the instructions and guidelines provided in the conference paper template.
The author submits his paper via the electronic paper submission and review process, indicating the original paper number.

Upon receipt of the manuscript the paper is sent for review to at least two members of the editorial panel who specialise in the disciplines covered in the paper. Reviewer members of the editorial panel, review the paper by answering specific questions, indicating if the paper meets specific set criteria. A separate section allows for comments on the quality of the paper addressed separately to the editors and to the authors. These comments often also indicate what needs to be done to improve the quality of the paper. The reviewer has the option to attach an annotated copy of the manuscript which is returned to the authors with the review reports.

Once sufficient reviews have been received, the Conference Chair and/or Administrator informs the author(s) of the outcome of the evaluation, which is either that the paper is rejected or accepted for publication in the proceedings, or the author may be invited to improve the paper in line with recommendations from the editorial panel and then resubmitted.

The papers are checked and corrected for typographical errors and adherence to the template provided, which satisfies also the requirements of the digital repository styleguide. Only papers which have been accepted by the editor(s) are published in the conference proceedings.

## Criteria used by editorial panel members when evaluating papers

Originality - Novel and interesting, warranting publication. The paper contains original research and /or new developments
Contents: Relevant to conference and socio-economic needs.
Title and abstract: Clearly describes the contents is suggested that he article
Language: Paper is clearly written without grammatical or other errors
Introduction: It clearly states the objective and the problem being investigated
Method: The author explains accurately how the data was collected and the information is suitable for answering the questions posed in the research
Result: The analysis and/or model is clearly presented, in a logical sequence and discussed sufficiently.
The paper is technically sound.
Conclusion: Claims are supported by the results and are reasonable, sound and justifiable
Reference: References are complete, adequate and appropriate
Figures and tables: All necessary and acceptable, suitable for a quality publication?
Units formulas and abbreviations conform to accepted standards

# INVESTIGATION OF SUB-ZERO PHASE CHANGE SOLUTION FOR HOUSE HOLD REFRIGERATORS

R Nokeri, ML Ramaube, TB Radebe* , AUC Ndanduleni , Zhongjie Huan.

**Abstract:**
*For a growing country such as South Africa, the energy demand outweighs the energy supply, this results in frequent power cuts. Equipment such as refrigerators are affected. To preserve food products during these power cuts Phase Change Material (PCM) material can be used. This paper presents the study of three eutectic salt water solutions investigated, $KCl$, $MgCl_2$ and $NaCl$. These salts were chosen because of the high latent heat and their relatively low price. From experiments, it was confirmed that $KCl$, $MgCl_2$ and $NaCl$ had a phase change temperature of -11°C, ± -7°C and -22°C. $KCl$ was seen as the ideal solution, however segregation will decrease performance in the long run. $NaCl$ is ideal since it offers a lower phase change temperature resulting in a greater heat transfer in the compartment. The refrigerator freezer might not be able to completely freeze the $NaCl$ solution. For $MgCl_2$, the concentration of 25% might be incorrect, the study concluded that another concentration ratio will have to be evaluated.*

**Keywords:**
*Load shedding; Phase Change Material; Refrigerator*

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## I. Introduction

Economic development and population growth have caused an increase in energy demand and consumption [1]. Population growth increases the demand for chilled fruits and vegetables, including frozen food products [2]. To satisfy this demand, refrigeration is required to preserve food's nutritional quality. Refrigeration systems account for approximately 17% of global energy consumption [3]. For a developing country like South Africa, the energy demand outweighs the energy supply. This has led to the implementation of load-shedding (electricity supply interruption). Loadshedding affects the cold chain as refrigeration systems require electricity to power the compressor. To provide continuous refrigeration during a power failure, a latent heat thermal energy storage (TES) material can be used. Phase change materials (PCM) are being incorporated in TES systems as they have high latent heat storage capacity [4]. Different PCMs were categorised by [5], and eutectic PCMs are mostly used for refrigeration [6][4]. [7] incorporated a PCM with –21.3 ºC melting temperature around an ice cream container. The ice cream container was removed from the freezer for three hours during the study, and temperature fluctuations were reduced. [6] placed PCM containers on the internal surface of a vertical freezer. The PCM effectiveness was studied considering the influence of door opening, power failure and defrosting. The results indicated a significant drop in temperature fluctuation inside the freezer. Incorporating PCM reduced energy consumption related to defrosting and door opening by 8% and 7% respectively. A similar study on a vertical freezer was done by [8] using stainless steel as PCM encapsulation. Food thermal mass was simulated using M-packs with a freezing temperature of –5ºC. During power loss, the interior temperature was maintained from –12 ºC to –14ºC for almost 3 hours. This means the PCM lowered the M-pack temperature by 2 ºC. Other potential benefits were also reported by [9][10][11].

This paper investigates the phase change process of three different PCMs, $KCl$, $MgCl_2$, and $NaCl$ with salt to water concentrations of 19.4%, 25% and 22% resulting in a phase change temperatures of -10°C, -19°C and -21°C respectively. Two different volume quantities of 1.5 and 5 liters are used to evaluate the PCM thermal response during freezing and melting process.

## II. METHODOLOGY

### A. Heat-load calculations

**Table 1** Input Variables[1]

| | **Intake** |
|---|---|
| Atmospheric temperature | 35°C |
| Compartment temperature | 4°C |
| Freezer temperature | -19°C |
| Polyurethane insulation | 0.028W/mK |
| Insulation thickness | 30mm/60mm |
| Compartment (LxBxH) | 0.6x0.45x0.7 |
| door open-close time | 3s |
| time door simply stands open | 1min |

Heat load calculations were done to determine the amount of PCM needed to maintain the compartment's temperature constant. The heat transmission loads were calculated using **Error! Reference source not found.**

$$Q_{trans} = U\,A\,(T_{atm} - T_{in})$$ Eq. 1

Where U $(W/m^2 \cdot K)$, is the overall heat transfer coefficient. A$(m^2)$, is the total surface area of the compartment to be maintained. $T_{atm}$ (°C) and $T_{in}$ (°C) are the surrounding atmospheric temperature and the desired temperature inside the compartment. For this study, the highest atmospheric temperature was used. The desired temperature in the compartment was used as shown in Table 1.

$$U = \frac{k}{L}$$ Eq. 2

Where $k$ $(W/m \cdot K)$, is the thermal conductivity of polyurethane insulation. $L$ $(m)$, is the thickness length of the insulation. Infiltration by air exchange most commonly occurs because of the air density differences between the refrigerated compartment and the surrounding atmospheric air. For a simple model expressed in **Error! Reference source not found.**, the average heat gain for the load-shedding period through the doorway from air exchange was determined as [15],

$$q_t = qD_tD_f(1 - E)$$ Eq. 3

Where, $q(W)$, is the sensible and latent refrigeration load for fully established flow expressed in Eq. 4. $D_t$, is the doorway open-time factor. $D_f$, is the doorway flow factor, which was determined as 1.0 and $E$, is the effectiveness of the doorway protective device.

$$q = 0.221A(h_i - h_r)\rho_r\left(1 - \frac{\rho_i}{\rho_r}\right)^{0.5}(gH)^{0.5}F_m$$ Eq. 4

Where, $h_i(kJ/kg)$, is the enthalpy of infiltration air. $h_r(kJ/kg)$, is the enthalpy of refrigerated air. $\rho_i(kg/m^3)$, is the density of infiltration air. $\rho_r(kg/m^3)$, the density of refrigerated air. $g$, is the gravitational constant $= 9.81\ m/s^2$. $H(m)$, is the doorway height. $F_m$, is the density factor, expressed in Eq. 5.

$$F_m = \left[\frac{2}{1 + (\rho_r/\rho_i)^{1/3}}\right]^{1.5}$$ Eq. 5

For cyclical, irregular, and constant door usage, alone or in combination, the doorway open-time factor was determined as Eq. 6

$$D_t = \frac{(P\theta_p + 60\theta_0)}{3600\theta_d}$$ Eq. 6

Where, $P$, is the number of doorway passages. $\theta_p(sec)$, is the door open-close time. $\theta_0(min)$, is the time the door simply stands open. $\theta_d$, is the load-shedding period.

$$V_{PCM} = \frac{t_{off} \cdot Q}{\rho\,\lambda}$$ Eq. 7

Eq. 7 determines the amount of PCM needed to maintain the compartment at a constant temperature during the load-shedding period. Where $t_{off}$ $(s)$, is the time the compressor is off, this could also be regarded as the load-shedding period. ρ $(kg/m^3)$, is the density of the PCM used. λ $(kJ/kg)$, is the latent heat of the PCM.

### B. Eutectic salt water solutions

Three eutectic salt water solutions were investigated, $KCl$, $MgCl_2$ and $NaCl$. These salts were chosen because of the high latent heat and their

[1] Input Variables

relatively low price. To increase the heat transfer inside the refrigerator, it is advisable to use a PCM with the lowest phase change temperature, however, the PCM might not fully freeze if the freezer temperature is not drastically below the phase change temperature. The properties are displayed in Table 2.

**Table 2** Eutectic saltwater solutions[2]

| | KCl | MgCl2/H2O | NaCl/H2O |
|---|---|---|---|
| **Salt to Water (%)** | 19.5/80.5 | 25/75 | 22.4/77.6 |
| **Phase change temperature (°C)** | -10.7 | -19.4 | -21.2 |
| **Density (kg/m3)** | 1980 | 2320 | 2160 |
| **Latent heat $(kJ/kg)$** | 253.18 | 223.10 | 228.14 |

## III. EXPERIMENTATION

### C. PCM

The salt particles were mixed according to **Table 2** salt to water ratio with the aim of reaching the desired phase change temperature. Deionised water was used. Type K thermocoupes were initially used and connected to a GL820 graphtec data logger. After witnessing the temperature flucturations in the container due to uneven temperature distribution. The containers were then fitted with Pt100 temperature probe to measure the uniform temperature across the container and increase the accuracy of the results. The solutions were placed inside a chest freezer first to validate the phase change temperature by plotting the Temperature history diagram. This was also done to view the sub-cooling that saltwater solutions undergo. Once the solutions were fully frozen, they were exposed to the atmospheric temperature. After the discharging cycle, the solutions were shacken mix together the segregated salt particles in the solutions. This was more eperientced in the $KCl$ solution

*i. Stage 1 Findings*

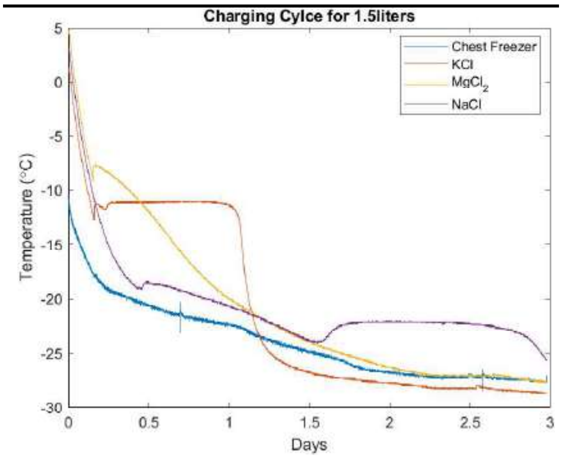


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**Fig. 1 1.5 Litre PCM Charging Cycle**

*i. Stage 2 Findings*

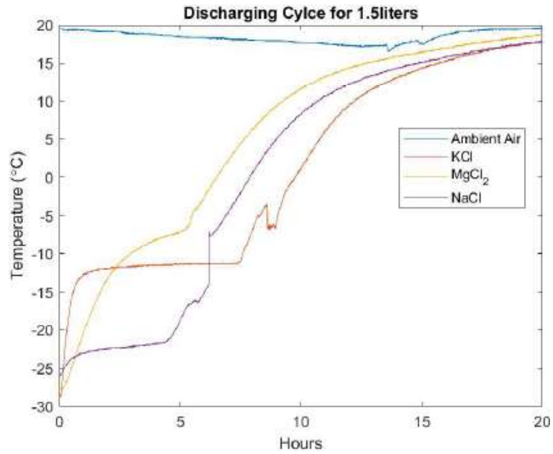


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**Fig. 2 1.5 Litre PCM Discharging Cycle**

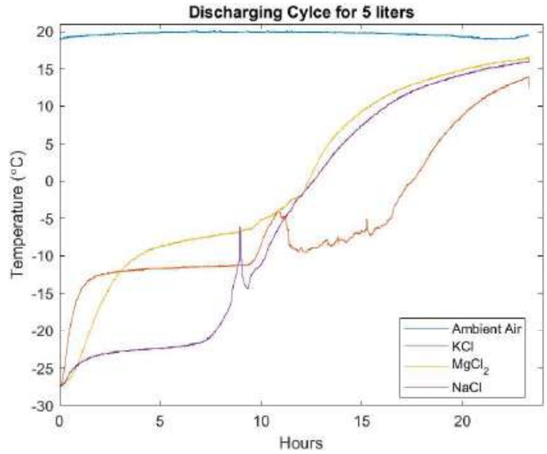


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**Fig. 3 5 Litre PCM Discharging Cycle**

[2] Eutectic saltwater solutions
[1] 1.5 Litre PCM Charging Cycle
[1] 1.5 Litre PCM Discharging Cycle

[1] 5 Litre PCM Discharging Cycle

### D. Refrigerator

Experiments were conducted on a KIC KBF 525/1 ME Refrigerator. The refrigerator had a gross capacity of 257L and a net capacity of 239L. the top compartment had inside dimensions of 700 x 450 x 650mm with approximately 30mm thickness insulation. With the thermostat set at maximum, the refrigerator compartments' temperature was measured to be 0.6°C near the bottom of the compartment and 5.1°C near the top of the compartment, while the evaporator coil measured close to -24°C. The freezer compartments' temperature was measured to be -24.1°C with the evaporator coil at a temperature of -31.6°C. The atmospheric temperature surrounding the refrigerator was measured to be 22.6°C.

*ii. Stage 1 Findings*

For $MgCl_2$ and $NaCl$, their phase change temperatures are close to the freezer compartment. This creates a delay in freezing the solutions since the temperature difference is low. This process took 3 days to comptely freeze the solutions. This places $KCl$ at an advantage above $MgCl_2$ and $NaCl$ since its able to freeze within a much shorter time. However, the heat transfer rate will be slower since the temperature different $\Delta T$ between the refrigerated compartment and the PCM is approximately 10°C.

## IV. Results and Discussion

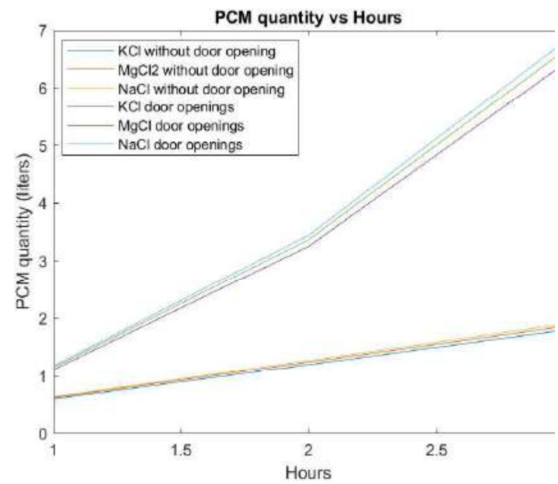


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**Fig. 4 PCM Quantity**

From determining the heat loads, Fig. 4 displays the quantity of PCM needed to maintain the desired temperature during power cuts. All three saltwater solutions display a constant gradient. When there are door openings during the powercut period, the graph clearly illustrates that more quantity of PCM is needed to overcome the air infiltration. For an average load-shedding period of 2.5 hours, close to 1.5liters of PCM is required. If the compartment door will be opened for 1 minute, close to 5liters of PCM will be required to maintain the temperature constant. From Fig. 4, it is evident that PCM is not good at pulling down the temperature, however, is good at maintaining a constant temperature inside a refrigerated compartment.

Fig. 1 illustrated the Charging cycle of the PCM. All three PCM experience a subcooling effect. $NaCl$ had the longest subcooling effect due to the low-temperature change between the freezer temperature and the PCM.

Fig. 2 showed the discharging cycle of the 1.5 Liters of PCM. From Fig. 1 and Fig. 2, during the charging and discharging cycles, the measured phase change temperature $KCl$ was -11.6 °C, this figure was close to the literature. This validated that the mixture of 19.4% was correct. It was noticed that after the discharging cycle, salt particles would accumulate at the bottom of the container, this again proved that $KCl$ tends to segregate. In the long term, this might affect the performance as the salt particles will not mix with water.

The recorded phase change temperature of $NaCl$ was -22.3 °C, which also validated the literature value. There was no segregation at the end of the cycle, however, $NaCl$ took the longest time to completely freeze between the three-phase change material. For $MgCl_2$, it is suggested that the literature value might be incorrect, as $MgCl_2$ failed to phase change at -19 °C. From Fig. 2, the gradient of $MgCl_2$ is too steep and only shows phase-changing potential at around -10°C to -5°C. In Fig. 1, the sub-cooling of $MgCl_2$ is also noted at around -10°C to -5°C.

[1] PCM Quantity

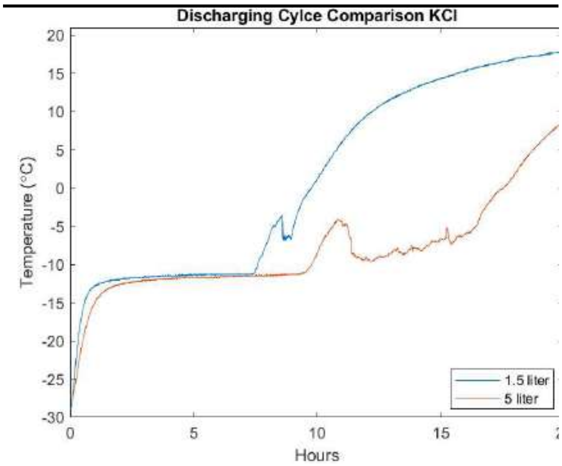


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**Fig. 5 KCl PCM Quantity comparison**

Fig. 5, Fig. 6, and Fig. 7 illustrate the comparison of the 1.5 liter and the 5 liter. It can be seen that increasing the quantity of PCM, the longer the phase change temperature. From Fig. 5 it was also noted that the temperature of $KCl$ drops around the 7th hour for 1.5 liters and around the 11th hour for the 5 liters. From Fig. 3 $KCl$ and $NaCl$ showed the quickest response time of approximately 1 hour. While $MgCl_2$ was approximately 4 hours as seen in Fig. 6. The 5 liters of $MgCl_2$ showed that the concentration of 25% result in a phase change temperature that ranges around -7 °C. Increasing the quantity of the PCM will clearly show a consistent phase change temperature.

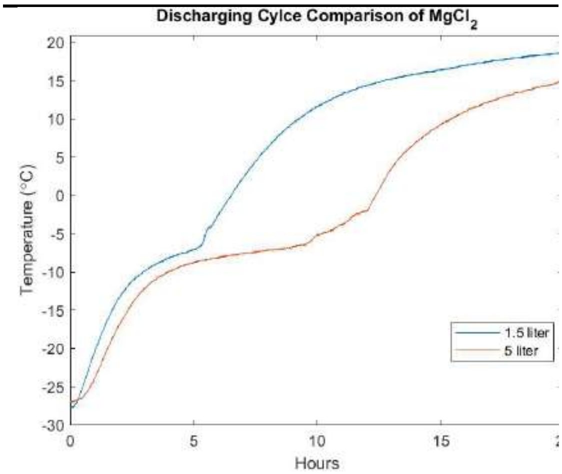


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**Fig. 6 $MgCl_2$ PCM Quantity comparison**

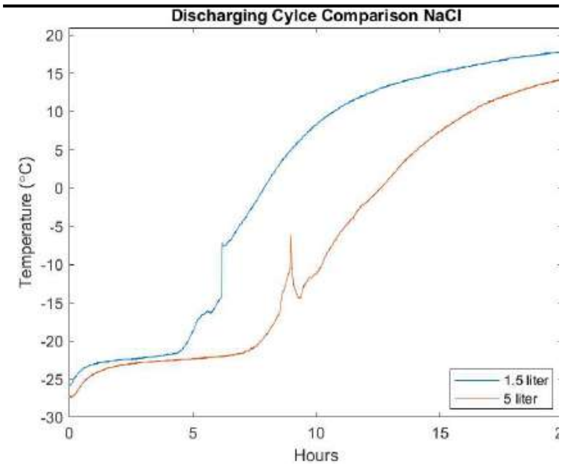


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**Fig. 7 NaCl PCM Quantity comparison**

## V. CONCLUSIONS

For a developing country like South Africa, the energy demand outweighs the energy supply. This has led to the implementation of load-shedding. Load shedding results in food quality deteriorating. The use of PCM can mitigate this phenomenon, by incorporating PCM inside a refrigerated compartment Tte results indicated a significant drop in temperature fluctuation inside the compartment. From literature, $KCl$, $MgCl_2$, and $NaCl$ with salt to water concentrations of 19.4%, 25% and 22% had phase change temperatures of -10°C, -19°C and -21°C respectively. Experimental work was done to validate these results. These temperatures were validated using 1.5 and 5 liters of PCM needed to overcome the transmission and infiltration heat loads incurred by the compartment during the load shedding period. From the experimental data -11°C, ± -7°C and -22°C were the measured values. This indicated that the salt to water concentration of 25% for $MgCl_2$ might not be correct. The response time of the salt to water solutions was approximately 1 hour. This is an added advantage since the sensible heat will also reduce the temperature in the refrigerated compartment. It is seen that increasing the quantity of the PCM will increase the phase change temperature time and maintain a compartment for longer.

[1] KCl PCM Quantity comparison

1 $MgCl_2$ PCM Quantity comparison

[1] NaCl PCM Quantity comparison

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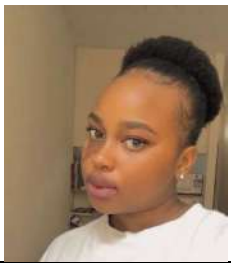

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# PROCEEDINGS OF THE 3RD ENERGY AND HUMAN HABITAT CONFERENCE

28-29 NOVEMBER 2022
CASTLE OF GOOD HOPE - CAPE TOWN

EDITOR: PROF MTE KAHN

Proceedings of the

# 3rd Energy and Human Habitat Conference

(28&29 November 2022)

Cape Town / Castle of Good Hope

Edited by Prof Mohamed Tariq Ekeramodien Kahn

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# 3rd Energy and Human Habitat Conference 2022

## Editor's Synopsis

This Proceedings includes the papers presented at the 3rd Energy and Human Habitat Conference which took place between 28-29 November, 2022, in Cape Town, South Africa as a face to face event at the Castle of Good Hope.

The Conference was organized by the African and International Use of Energy platform consisting of academics from the Cape Peninsula University of Technology, the University of the Western Cape, University of South Africa, and University of Stellenbosch. The organizing committee, advisory board and review board, as well as the editors are grateful to the delegates who had submitted and presented papers.

The conference papers included experimental as well as overview studies applicable to Energy and the application or enhancement of human habitat. Although the conference was open for inclusion of studies from an energy policy and energy economics perspective, almost all the papers received in this call were of a more technical nature.

The conference received papers via its online submission platform and responded by related email. Reviews were double blind with two reviewers per paper and a third editorial review for decision to include the paper in the proceedings. Several paper abstracts were received but was not of sufficient quality to meet initial review requirements and some were also outside the scope of the conference. The conference received over 48 abstracts and received 38 papers as submissions. Only 21 papers were accepted and graded for inclusion in this Proceedings after peer review and these included only highly positive reviews with minimal corrective work.. The rejection ratio of papers was 44% rejection.The highest single institution papers accepted for publication was 28%, hence meeting the South African DHET requirement.

The authors were required to avail themselves for a face to face presentation with session chairs at the conference venue.

Prof MTE Kahn

Energy Institute, Cape Peninsula University of Technology

28 November 2022

# Opening Remarks

## Dr Marco Adonis, HOD , DEECE, CPUT

3rd Energy and Human habitat Conference

28 & 29 November 2022, Castle of Good Hope, Cape Town, South Africa

Distinguished Participants, Colleagues, Ladies and Gentlemen,

Good Morning.

I am very honoured to deliver opening remarks on behalf of the Department of Electrical Electronic and Computer Engineering of the Cape Peninsula University of Technology, at this esteemed Conference.

I would like to welcome all participants for their keen interest and enormous efforts to make this meeting possible.

At the outset, I would like to thank co-organizers of this event. My special thanks goes to Professor Mohamed Tariq Kahn, Director of the Energy Institute, and Convenor of this Conference. Prof Kahn have been at the helm of the energy conferences since 2012 and have done a first for us in organising this event at the Castle of Good Hope. A Special Thanks to the Organising Committee, and the Review Committee, the Session Chairs and the many students and staff that were involved in making this event happen here today. For two years the conference continued as a digital event, and this is the fist face to face event since 2019.

I think you, the delegates here, will be more experienced and knowledgeable than myself on the theme of Energy and Human Habitat . So my remarks will be very short. I just would like to highlight the huge potential of Energy Technology in the achievement of SDGs , which are an important international achievement for the 2030 goals and beyond.

More than 700 million people on the African continent still do not have access to modern, productive energy sources, and many of them continue to use antiquated, ineffective traditional energy sources. The difficulty is still in successfully and sustainably getting this solution to the most remote off-grid areas, even though the answers already exist.

Energy poverty is still a problem, and many homes haven't been able to connect to the electricity despite significant attempts to expand the grid to several towns, produce more megawatts, and offer various "low cost" energy products and services for the "poor". Microgrids and effective use of modern technological advances hold the key to bridge the gap with Human Habitat and electrification. Grid extension alone does not provide energy access as long as the end-use energy dilemma is not resolved.

In addition to this, since the Paris Agreement went into force in 2016, reducing greenhouse gas emissions has become another important mission for all. Our nation is embarking on the Just Transition in the Energy sector to address concerns with job losses and re-skilling that could be associated with such a change from fossil fuels to renewables. This is why Conferences like these are important. To create networks of researchers that can share their views and ideas in order to create better understanding and co-operation.

I would like to thank all the presenters, facilitators, and participants, for making the time to be here. Thank you

# 3rd Energy and Human Habitat Conference 2022

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# 3rd Energy and Human Habitat Conference 2022

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The conference disseminates original research and new developments which are published in this conference proceedings. The conference covers the following disciplines in the field of energy:

Energy and Society,
Smart Energy
Renewable Energy
Blockchain and smart contracts in energy
Smart Grids, Microgrids and Minigrids
EV and Electric Transportation
Energy Storage and Power Electronics
Energy Efficiency
Energy Economics
Energy Development

## Publications produced for the conference

The following publications ensure that the research reports given during the conference are disseminated widely

### Conference Proceedings

The conference proceedings contain full papers which are subjected to a blind peer review process.

The proceedings with ISBN number, will be digitally disseminated, and will be published online on our website, as well as co-published on either Elsevier SSRN and its associated e-Journals or Zenodo under the AIUE e-Journal.This is a digital library under OpenAIR and the CERN. OpenAir as the vanguard of the open access and open data movements in Europe was commissioned by the EC to support their nascent Open Data policy by providing a catch-all repository for research and is open to all search engines. This provides a high quality repository of scientific information and dissemination. A DOI number to be associated with the individual research papers.
The target audience for the proceedings are specialists in the field.

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Our review board consists of international and national experts in specialist fields covered in the conferences. They are from different academic institutions, and from industry. Authors are invited to submit an abstract prior to submission of a paper. The abstracts of proposed conference papers are sent for evaluation, and only accepted abstracts would lead to the invitation to submit a full paper which is then reviewed by no less than two reviewers. A third editorial review is done before the papers are accepted for publication in the proceedings.

The Chairman and/ or Conference Administrator informs each main author of the outcome of the evaluation timeously, inviting the successful author(s) to submit a print-ready manuscript in accordance with possible comments and the instructions and guidelines provided in the conference paper template.
The author submits his paper via the electronic paper submission and review process, indicating the original paper number.

Upon receipt of the manuscript the paper is sent for review to at least two members of the editorial panel who specialise in the disciplines covered in the paper. Reviewer members of the editorial panel, review the paper by answering specific questions, indicating if the paper meets specific set criteria. A separate section allows for comments on the quality of the paper addressed separately to the editors and to the authors. These comments often also indicate what needs to be done to improve the quality of the paper. The reviewer has the option to attach an annotated copy of the manuscript which is returned to the authors with the review reports.

Once sufficient reviews have been received, the Conference Chair and/or Administrator informs the author(s) of the outcome of the evaluation, which is either that the paper is rejected or accepted for publication in the proceedings, or the author may be invited to improve the paper in line with recommendations from the editorial panel and then resubmitted.

The papers are checked and corrected for typographical errors and adherence to the template provided, which satisfies also the requirements of the digital repository styleguide. Only papers which have been accepted by the editor(s) are published in the conference proceedings.

## Criteria used by editorial panel members when evaluating papers

Originality - Novel and interesting, warranting publication. The paper contains original research and /or new developments
Contents: Relevant to conference and socio-economic needs.
Title and abstract: Clearly describes the contents is suggested that he article
Language: Paper is clearly written without grammatical or other errors
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The paper is technically sound.
Conclusion: Claims are supported by the results and are reasonable, sound and justifiable
Reference: References are complete, adequate and appropriate
Figures and tables: All necessary and acceptable, suitable for a quality publication?
Units formulas and abbreviations conform to accepted standards

# Latent Heat PCM application on a shack house

K.N Bokaba, M Ramaube, AUC Ndanduleni, T.B Radebe*, Z Huan

***Abstract:***

*According to data sourced from Statistics South Africa's 2016 Community Survey, 11.4 percent of South Africa's black population live in informal dwellings. 5.7 percent of the coloured population, 0.9 percent Indian citizens and 0.3 percent of the white population. Summer temperatures in South Africa range from 15°C to 36°C, while winter temperatures range from -2°C to 26°C. Extreme heat is a serious public health concern and one of the leading causes of weather-related mortality. This study investigated the temperature fluctuations around a metal sheet house, by experimental measurements and simulation analysis. Energy plus software was used to simulate the integration of Phase Change Material (PCM) into the shacks walls with the aim to reduce temperature fluctuations inside the shack. The results showed that by integrating a 20mm PCM layer, the temperature fluctuations ranged within ±2°C.*

***Keywords:***

*Thermal comfort, Thermal Insulation, Phase change material . Energy Plus*

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## I. INTRODUCTION

According to the Pietermaritzburg Economic Justice & Dignity group (PMBEJD), approximately 30.4 million people in South Africa live below the old upper-bound poverty line of R1,268. The group estimates that 13.8 million people live below the food poverty line. During the 2021 Socio-economic status commission, the South African Human Rights Commission (SAHRC) senior researcher on equality Channel van der Berg said, "64% of black Africans remain poor, 40% of coloured people remain poor and then on the other hand 6% of Indians and Asians are poor and only 1% of white South Africans are poor" [1].

According to data sourced from Statistics South Africa's 2016 Community Survey, 11.4 percent of South Africa's black population live in informal dwellings. 5.7 percent of the coloured population, 0.9 percent Indian citizens and 0.3 percent of the white population in the country live in informal settlements [2]. Housing and its impact on health has long been a focus of public health research. Housing influences health in a variety of ways, acting directly or indirectly at various levels. Summer temperatures in South Africa range from 15°C to 36°C, while winter temperatures range from -2°C to 26°C [3]. Extreme heat is a serious public health concern and one of the leading causes of weather-related mortality.

Due to the thermal conductivity of the material used for the settlement (shack), the temperature fluctuates according to the surrounding atmospheric temperature. People living in informal settlements to induce comfort, resort to paraffin, gas, coal, and electrical heaters as a source of maintaining a room at a warm temperature. Research has found that the people dwelling in this type of living condition are more susceptible to getting weather-related fatal health problems.

Phase change materials (PCMs) are an innovative solution that can help improve the energy performance of buildings. Incorporating PCMs into building materials is a growing technology since it enhances the ability of the building materials to store and release heat during phase transition [4]. This study experimentally investigates the temperature fluctuations experienced by a shack, and simulates the integration of the PCM layer using energy plus software, to reduce the temperature fluctuations.

### A. Thermal comfort in the building environment

People spend more than 90% of their daily activities indoors, such as in their homes, offices, and shopping malls. Thermal comfort is therefore essential not only for their health but also for their

ability to function effectively. Thermal comfort is a state of mind that expresses satisfaction with a building's thermal environment [4] .
The following are the primary factors that influence indoor air temperature: (1) outdoor environmental parameters (such as temperature, wind speed, radiation, and sky temperature); (2) thermal properties of the building envelop (such as thermal resistance and heat capacity); (3) indoor heat source and ventilation; (4) indoor auxiliary energy (such as air conditioning and heating); and so on. Indoor air temperature is closely related to building envelop material properties under the given conditions (weather, air exchange rate, room size and wall thickness, etc.) [5].

### B. Thermal load reduction

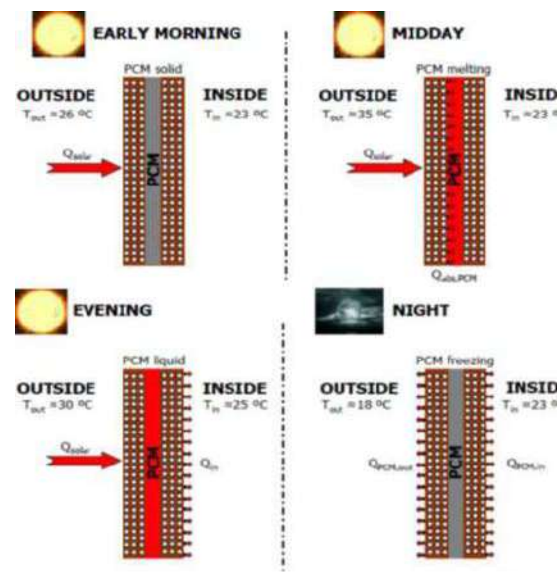
Energy is critical to the nation's economic prosperity and technological competitiveness. Rapid development has resulted in an enormous demand for energy. The expansion of resources and the expansion of energy supply have failed to meet the ever-increasing demands imposed by a growing population, rapid urbanization, and a growing economy. It is critical to develop efficient and inexpensive energy storage systems in order to conserve energy and reduce reliance on fossil fuels, as well as to reduce greenhouse gas emissions. Energy storage systems eliminate supply and demand shortages while also improving energy system performance and reliability. [6]
The building envelope is a critical solution for reducing energy consumption for heating and cooling in cold and hot climates, resulting in energy-efficient buildings. Many techniques are currently being researched to improve the thermal performance and thermal storage capacity of the building envelope. These techniques, which can be implemented passively or actively, have demonstrated advanced improvements in reducing heating and cooling loads and controlling building energy. Using such low-cost technologies, it is technically possible to reduce building energy consumption by up to 20% by 2030. [4] .

### C. Thermal Energy storage

One of the sustainable methods of regulating indoor temperature is to improve the thermal energy storage capacity of the building envelope by incorporating PCM. This research focuses on the use of PCM as a thermal energy storage building material [7].
Thermal energy storage (TES) is the process of storing available thermal energy in order to reuse it when it is scarce. The most important benefit of TES is that it can correct the mismatch between energy supply and demand. For example, using TES, solar energy during the day can be stored and used to heat the cold night, while the coolness of the night can be used to cool the warm day. Furthermore, the heat of the warm summer months can be stored for heating in the winter and the coolness of the winter for cooling in the summer. This is referred to as seasonal TES, and it can assist in meeting the energy needs caused by seasonal temperature fluctuations [8].

During summer, the sun and high temperatures generate a heat wave that penetrates the walls of buildings. PCM absorbs excess heat during the melting process, delaying and even lowering the peak temperature inside the building. The room temperature remains comfortable for the majority of the day, and the cooling system uses less energy. During the night, when temperatures are lower, the PCM releases the stored heat to both the internal and external ambient, maintaining a comfortable room temperature and closing the cycle by solidifying, this can be observed in Fig. 1. The primary distinction between PCMs and traditional thermal mass is that, whereas masonry absorbs and releases heat slowly, PCMs absorb and release heat quickly [7].

The concept of embedding PCMs in construction materials was used to reduce building heating and cooling loads in the 1980s. PCMs were considered for use in thermal energy storage systems for both large solar plants and domestic hot water systems in the 1980s. PCMs were investigated for thermal management applications for electronic cooling in the early 1990s, particularly for cooling of high-performance computational platforms and high-heat flux optoelectronic devices. Studies on PCMs have been focused on both high-temperature and low-temperature applications since the early 2000s. These studies have expanded beyond traditional topics to include waste heat energy recovery and storage, thermal management in space programs, and applications involving cooling of optoelectronic devices [9].




1

**Fig. 1 Operating principal scheme of the PCM [7].**

A PCM has the ability to store energy in the form of sensible and latent heat as it melts or solidifies. A typical PCM discharging cycle starts with the PCM in a subcooled solid state, which is then heated up to the phase transition point via sensible heating as seen in **Fig. 2** (b). As the energy input continues, the phase transformation for a portion of the PCM that is at a constant temperature is initiated.

The energy absorbed by the PCM aids in the progression of phase transformation throughout the volume of the PCM. After the phase transformation is complete, the PCM is in liquid phase, and any additional energy input causes temperature to rise, allowing sensible heat to be stored in the system [9]. In a study by [8] clearly illustrated the expected results when incorporating PCM in a insulation material for a building. The temperature fluctuations are higher without PCM. **Fig. 2** (a) illustrates the potential of PCM in reducing the temperature fluctuations and also delay the peak temperature. **Fig. 2** (b) illustrates the total heat stored between sensible heat and latent heat. By incorporating PCM in a insulation material, additional heat can be stored.

## II. METHODOLOGY

### A. PCM

The ratio of stored heat ΔQ to the temperature rise ΔT is the heat capacity C of the storage medium

$$\Delta Q = C \cdot \Delta T = m \cdot C \cdot \Delta T$$

**Eq. 1**

The heat capacity is frequently expressed in terms of the amount of material, volume, or mass. It is then denoted by c and is known as molar, volumetric, or mass specific heat capacity. Eq. 1 shows the case of mass specific heat capacity where m is the mass of the storage material.

The heat supplied upon melting is therefore called latent heat, and the process latent heat storage (LHS). Because of the small volume change, the stored heat is equal to the enthalpy difference

$$\Delta Q = \Delta H = m \cdot \Delta h$$

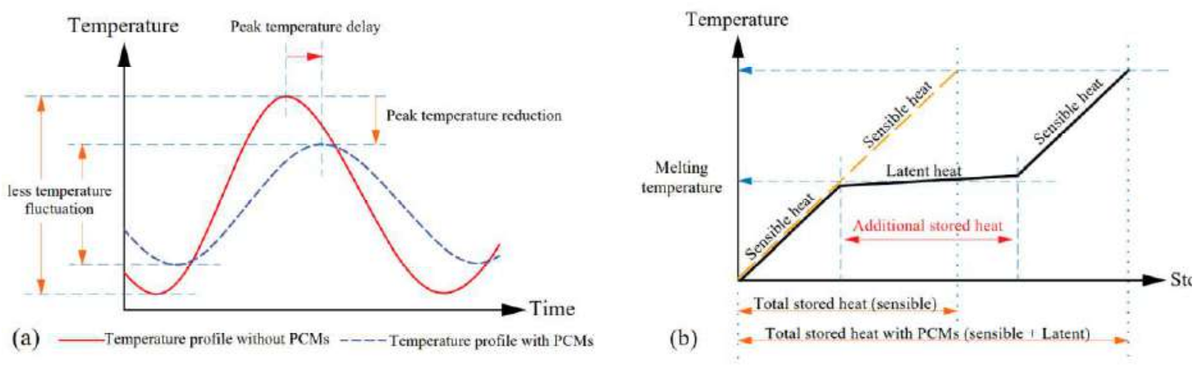
**Eq. 2**

The latent heat, that is the heat stored during the phase change process, is then calculated from the enthalpy difference ΔH between the solid and the liquid phase. It is known as solid-liquid phase change enthalpy, melting enthalpy, or heat of fusion in the case of solid-liquid phase change. Latent heat storage material, or simply phase change material, are materials with a solid-liquid phase change that are suitable for heat or cold storage (PCM) [10].

### B. Energy Plus

Shack 1 was modelled in Sketch up Pro 2022 using the Open Studio plugin as displayed in Fig. 3 and temperature simulations were done using energy plus software. The backside of the shack has little sunlight although it is exposed to wind. The left-hand side of the shack was exposed to the concrete wall of the house. The door was made up of galvanised metal sheet with plank chip board on the inside. Internal heat loads, such as lights, were not incorporated into the model since the shack was not opened for the duration of the study. Table 1 lists the construction material used in energy plus simulation.

[1] Operating principal scheme of the PCM

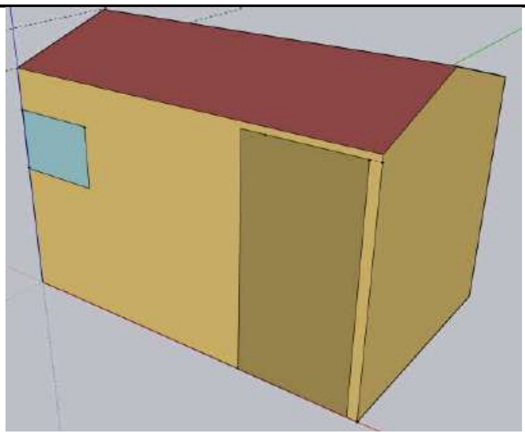



2

**Fig. 2 Role of PCMs application in regulating a building's indoor temperature (a), and the storage capacity of materials with latent heat compared to sensible heat only (b). [8]**

**Table 1 Simulation Construction Material**[3]

| **Name** | **Roughness** | **Thickness (m)** | **Conductivity (W/m K)** | **Density (kg/m^3)** | **Specific heat (J/kg K)** | **Thermal Absorptance** | **Solar Absorptance** | **Visible Absorptance** |
|---|---|---|---|---|---|---|---|---|
| **Air** | Smooth | 0.001 | 0.002514 | 1.204 | 1007 | | | |
| **Concrete** | Rough | 0.2033 | 1.7296 | 2243 | 837 | 0.9 | 0.65 | 0.65 |
| **Acoustic tile** | MediumSmooth | 0.0191 | 0.06 | 368 | 590 | 0.9 | 0.3 | 0.3 |
| **Plank chipboard** | Rough | 0.0254 | 0.15 | 608 | 1630 | 0.9 | 0.5 | 0.5 |
| **Galvanized sheet metal** | MediumRough | 0.0015 | 45.006 | 7680 | 418.4 | 0.9 | 0.6 | 0.6 |
| **Polystyrene** | VeryRough | 0,025 | 0,04 | 16 | 1200 | | | |
| **glass** | | 0,003 | 0,9 | | | | | |



4

**Fig. 3 Sketchup drawing of Shack**

**Table 2** RubiTherm Phase Change Material[5] [11]

| | **RT18HC** |
|---|---|
| **Melting area (°C)** | 17-19 |
| **Congealing area (°C)** | 19-17 |
| **Heat storage capacity ±7.5% (kJ/kg)** | 260 |
| **Specific heat capacity (kJ/kg K)** | 2 |
| **Density solid (kg/m$^3$)** | 880 |
| **Density liquid (kg/m$^3$)** | 770 |
| **Heat conductivity (both phases) (W/m K)** | 0.2 |

[1] Role of PCMs application in regulating a building's indoor temperature (a), and the storage capacity of materials with latent heat compared to sensible heat only (b).

[3] Simulation Construction Material

[1] Sketchup drawing of Shack

[5] RubiTherm Phase Change Material

## III. EXPERIMENT

### A. Shack temperature readings


6

**Fig. 4 Shack**

From Fig. 4 Shack a single-room shack situated in Pretoria, South Africa, was investigated. The shack was 3 meters long, 2 meters wide, and 2 meters high. It is mounted onto the building wall as seen in Fig. 4 Shack (b). The shack is also insulated with 25mm thick plank chipboards on three sides while the roof was insulated with a thin sheet of polyurethane as seen in Fig. 4 Shack (c). The shack was fitted with floor tiles as displayed in Fig. 4 Shack (d). The experiment was conducted at 18:00 on the 7th, until 18:00 on the 8th May 2022. Measuring the outside temperature and the inside temperature for 24 hours. 4 type k thermocouples were used to measure the atmospheric air temperature, the outside and inside temperature of the sheet metal and the inside ambient air temperature.

### i. *Findings*

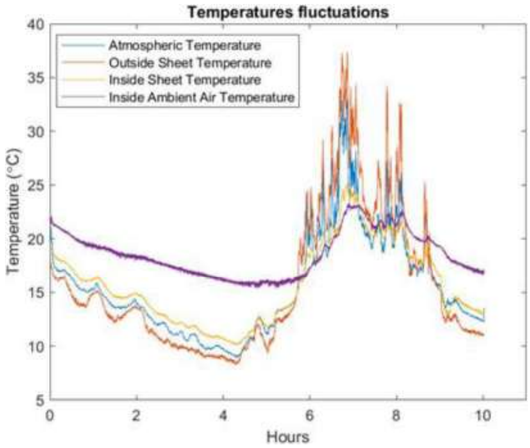



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**Fig. 5 Temperature variations over 24 hours**

## IV. RESULTS AND DISCUSSION

From Fig. 5 it is seen that the temperature difference between the temperature of outside of the sheet metal and the temperature on the inside of the sheet metal is not significant. This shows that the metal sheet is not good at resisting heat transfer through it. This results in the temperatures fluctuating together from 10°C to nearly 37°C. The temperature reading taken after the plank chip board, which is the Inside Ambient Air Temperature can be seen to have a large temperature difference when compared to the outside temperature. The plank chipboard does act as a good insulation, providing a sensible heat and its fluctuation range is only from approximately 16°C to 24°C.

From the simulations done in energy plus, Fig. 6, Johannesburg weather data was used due to the limitations on energy plus software. Although the two regions are 70km apart, it was confirmed that the Pretoria temperature are higher, this resulted in a slight temperature difference between the experimental data and simulation results. The temperature fluctuations are greatly reduced when integrating a PCM in the shack wall since they provide a sensible and latent heat. From Fig. 6 it is seen that by doubling the PCM thickness, the temperature fluctuations are drastically reduced. It was noted that to determine the suitable phase change temperature of the PCM, the mean temperature of the surrounding should be used. This greatly affects the performance of the PCM. A high

[1] 1 Shack

[1] Temperature variations over 24 hours

PCT PCM will result in the latent heat not being released, while a PCM with a low PCT will results in an early latent heat release point.

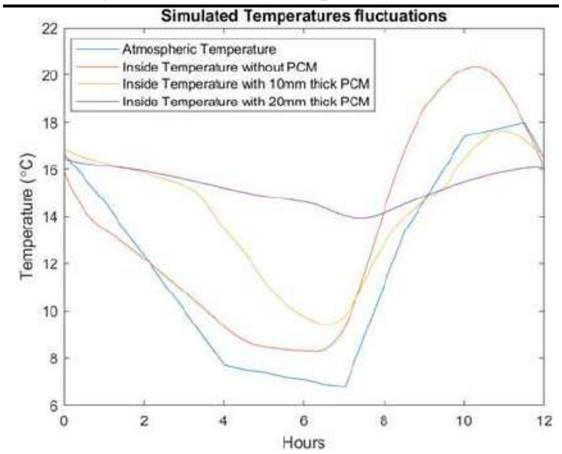


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**Fig. 6 Simulated Temperature Fluctuations**

## V. CONCLUSIONS

For many South Africans, informal housing is their home, these are made from galvanized metal sheets. These shacks are prone to temperature fluctuations due to the high thermal conductivity of the metal sheet and its low thermal resistance to heat transfer between the outside and the inside. This study experimentally investigated the temperature fluctuations around a shack fitted with plank chipboard. The temperatures fluctuating measured were between 10°C to nearly 37°C, while integrating the chipboard they dropped and ranged from 16°C to 24°C. from the simulated results, for a similar shack situated in Johannesburg, the temperature fluctuations without the PCM are from 9 °C to 20°C, however with integrated PCM layer of 20mm they fluctuate from 16°C to 18°C.

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[1] Simulated Temperature Fluctuations

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**Reduction of Temperature fluctuation in a South African Shack house using Phase Change Material insulation**


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ABSTRACT

The majority of South African informal settlements are made from corrugated profile galvanized metal sheets. These informal settlements are prone to temperature fluctuations due to high thermal conductivity of the metal sheet and its low thermal resistance to heat transfer between the exterior and the interior of the shack. Families have resorted to using fuels such as paraffin during cold days, which has resulted in fire outbreaks that ravage surrounding shacks. This study experimentally investigated the temperature fluctuations around a shack fitted with plank chipboard and one without. Energy plus 22.2.0 software was then used to simulate the temperature fluctuations effects after integrating a Phase Change Material (PCM) layer on the shack walls. From the experiments, the internal temperature fluctuations on the shack without the insulations reached close to +50°C during the day, and -5°C during the night. While the shack with insulation reached +25°C during the day and 7°C during the night. The temperature distribution inside the shack was observed to be uneven, with the top section of the shack at higher temperatures than the bottom section. The region and the location of the shack largely contributed to the temperature fluctuations. Simulations revealed that by integrating a PCM layer in the shack walls, temperature fluctuations were greatly reduced. A lower phase change temperature yielded greater results as the atmospheric air allowed the PCM to fully solidify and melt, thus releasing the latent heat energy. A phase change temperature between 17-19 °C was selected based on the average atmospheric yearly temperature range. A 30mm thick PCM reduced the temperature fluctuations to between +14°C and +16°C. However, materials with high thermal conductivity are not well supported by the Conduction Finite Difference used to simulate the performance of a phase change material in energy plus, it is proposed to remove such thin and high conductive materials in the model.



Keywords: Phase Change Material; Thermal Comfort; Insulation; Temperature fluctuation


NOMENCLATURE

| | | |
|---|---|---|
| $\dot{Q}$ | heat transfer rate | [W] |
| A | wetted area | [$m^2$] |
| $c_p$ | specific heat | [kJ/kg K] |
| h | convective heat transfer coefficient | [$W/m^2$ K] |
| H | heat storage capacity | [kJ/kg] |
| k | thermal conductivity | [W/m K] |
| L | length | [m] |
| R | thermal resistance | [K/W] |
| T | temperature | [°C] |
| x | finite difference layer thickness | [m] |

ρ density [kg/m$^3$]

*Subscripts*

∞1 internal atmospheric temperature

∞2 external atmospheric temperature

i inner surface

*i* interface node

*i*+1 adjacent node to the interior of the construction

j time step

j+1 new time step

o outer surface

wall tube wall

## 1. INTRODUCTION

Poverty is one of South Africa's major problems. The South African government works hard to reduce poverty, but it appears to be increasing as they try. As a result, South African families live in deplorable conditions. They live in informal housing or informal settlements, which can include any type of illegal housing, shelter, or settlement that is not under government control or regulation. These improvised settlements are typically made of materials such as corrugated metal sheets, wood, and/or mud. According to Statistics South Africa's 2016 Community Survey, 11.4 percent of South Africa's black population live in informal dwellings. 5.7 percent of the coloured population, 0.9 percent Indian citizens and 0.3 percent of the white population in the country live in informal settlements. A total of 2.2 million people dwell in informal settlements [1].

South Africa is extremely vulnerable to climate change and variability. South African weather can reach 36°C in summer and drop to -2°C in winter. Shacks are not environmentally controlled; hence, they always assume the outside atmospheric temperature. People that dwell in shacks are then faced with the challenge of keeping warm throughout winter. They are forced to use electrical heaters, gas heaters, paraffin lamps and candles/fire to keep warm. These people living in shacks are more susceptible to falling sick due to the poor living conditions. Poor housing conditions are linked to a variety of health problems, including respiratory infections, asthma, lead poisoning, injuries, and mental health issues.

A shack is a building structure constructed using corrugated metal sheets [2] and the sheet thickness ranges from 0.21 mm to 0.47 mm. This type of building structure is dominantly found in informal settlements with structures closely positioned to each other. A structure built from such a low-thickness material experiences high loss of thermal energy during winter. This is caused by a low thermal mass in light buildings. Wooden boards or cardboard are mostly used as insulation materials to minimise thermal loss [3]. This led to the burning of candles and paraffin stoves to warm the room air temperature [4]. Paraffin leakages or improper care of these stoves may result in a shack catching fire. Such fires rapidly spread to nearby shacks destroying property. Phase change material (PCM) as thermal energy storage (TES) can be incorporated into a shack as insulation. This will minimize the thermal loss in winter while maintaining a moderate temperature inside the shack. A PCM stores and release thermal energy at a constant temperature, during the latent heat region. This characteristic has been found to reduce the temperature of building surfaces and reduces energy demand [5]. During the day when the outside temperature increases, the PCM will melt as it absorbs heat. As the night temperature drops, the PCM will release the stored energy into the room, which will result in the PCM solidifying. Utilising PCM on such a light structure can assist in reducing indoor temperature. These experimental studies by Kong *et al.*[6] and Meng *et al.* [7]signify the potential benefits of integrating PCM into a shack.

The available literature has not integrated PCM on a corrugated sheet metal shack house. Therefore, the purpose of this paper is to study temperature fluctuations reduction through experimentation and simulation. Two shacks were investigated, shack 1 with plank chipboard insulation and shack 2 without. Experimental measurements were conducted to determine the temperature fluctuations in the shack without the PCM. Simulations were further done in energy plus version 22.2.0 to determine the thickness of the PCM and the correct Phase Change Temperature (PCT) of the PCM to be used to reduce temperature fluctuations in a South African shack.

### 1.1 Integration of PCM in Buildings

Population growth in recent years has resulted in high energy consumption, with 30% to 40% of energy being consumed by residential and commercial buildings [8]. Extreme weather conditions during winter and summer can also be attributed to this high energy usage in the building sector as indoor temperatures get moderated for human comfort. To minimise the carbon footprint related to the building's energy consumption, thermal energy storage (TES) materials such as a phase change material (PCM) can be integrated into building envelopes [9]. This integration in buildings is beneficial as PCMs have an energy storage capacity that is 18 times more than traditional building materials [10]. Such benefits include: (i) enhanced thermal inertia, (ii) regulation of indoor temperature, and (iii) acting as insulation material. In building envelopes, PCMs have been integrated into a brick wall [11], gypsum wallboards [12][13][14], flooring tiles [15], roof [16], wall surfaces [17], and ceiling [18].

Kong *et al.*[6] conducted a field test on a full-size brick room. In one room, PCM panels were placed on the inside surface, and in the second room, PCM panels were located on the outside surface. The influence of door and window opening were considered to determine the room's thermal response. A delay of 2 hours to 3 hours in peak temperatures in the rooms with PCMs was noted. It was concluded that PCM panels act as insulation when placed on the inside during the summer season. A one-year thermal performance study in an office building was done using 5mm PCM wallboards [19]. The wallboards were placed on the walls and ceiling. The PCM of 13°C melting temperature was used. The lowest and highest outdoor temperature was -2°C and 32°C in winter and summer respectively. The results indicated enhanced thermal comfort as temperature fluctuations were reduced.

Meng *et al.* [7] studied the thermal performance of a room during winter and summer by integrating two PCMs with different melting temperatures. The authors reported that during summer, a 28.8% to 67.80% reduction in indoor temperature fluctuations can be achieved by using PCM. A drop of 4.28 °C to 7.7 °C in temperature was noted on a summer day. In winter, an increase in temperature from 6.93 °C to 9.48 °C was recorded. Kośny *et al.* [20]used a PCM with a 29 °C melting point as a wall insulation material. The authors found PCM wall insulation to be more energy efficient than conventional insulation wall material. Oliver [12] ) designed and built a facility to investigate the thermal performance of different building materials. A 15 – 25 mm gypsum board was incorporated with a microencapsulated paraffin PCM , and a 15 mm gypsum board without PCM were used. . The author reported that 3 times more energy was stored in a gypsum board with 45% PCM than on a conventional gypsum board. This showed enhanced thermal inertia of the gypsum board.

Cabeza *et al*. [21] experimentally investigated a concrete wall impregnated with a 26 $^{o}$C melting point PCM for a 2 m x 2 m x 3 m cubicle. Two equal concrete cubicles were used, one with concrete mixed with PCM, and the other with traditional concrete. The authors reported high thermal inertia for the cubicle with PCM and low temperature was achieved inside the cubicle. de Gracia et al. [22] experimentally incorporated a macro-encapsulated salt hydrate PCM in a ventilated façade during winter season. Two cubicles were used, one had PCM containers installed on the façade and the other was a reference room. . A decline in indoor air temperature was observed in the cubicle with no PCM. The indoor temperature increased from 9 $^{o}$C to 18 $^{o}$C inside the cubicle with PCM installed on the wall air chamber. Vicente and Silva [11] experimentally studied the thermal response of a clay brick wall inserted with paraffin PCM under Mediterranean climatic conditions. Three scenarios were compared, namely: (i) wall with no PCM, (ii) PCM placed on the wall, and (iii) wall incorporated with PCM and insulation material. Paraffin PCM with 18 $^{o}$C melting temperature was macro-encapsulated in a steel container. The authors used the steel container as it has a high thermal conductivity which improves the heat transfer rate during the phase change process. The authors reported a thermal load reduction of 50% to 80%.

Dong *et al.*[23] performed a numerical study on the performance of residential building roofs incorporated with PCM. Four different thicknesses (100mm, 80mm, 60mm, and 40mm) of the PCM layer were evaluated. It was observed that an increase in PCM thickness reduces indoor peak temperature when compared to a room without PCM. Wang *et al.*[24] also concluded that using the highest PCM thickness and placing the PCM on the inside surface greatly reduces the heat transfer rate. Louanate *et al.*[25] simulated the energy reduction potential for a building integrated with PCMs. Different climatic conditions and a 10mm PCM thickness were considered. The results showed that placing PCMs in different positions on the interior wall influences indoor temperature fluctuation. Though PCM benefits are recorded, experimental validation is neglected by different authors [23][24] and [25].

**1.2 PCM Applications in Building**

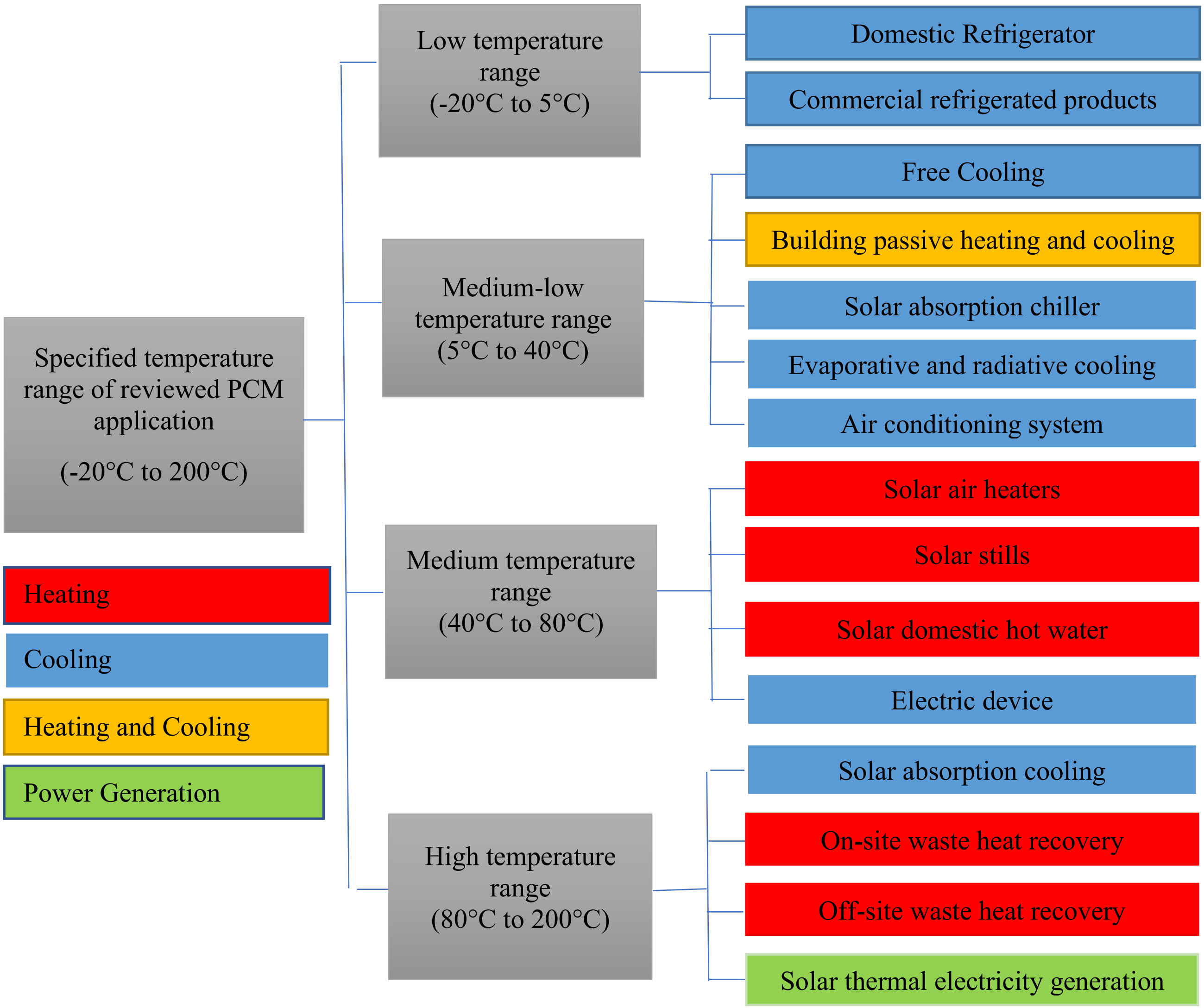



Figure 1 Classification of the reviewed applications of PCMs in defined temperature ranges [26].

Figure 1 illustrates the different applications of phase change materials across varying industries since they can be used both for heating and cooling. Figure 1 further classifies the PCM into different temperature groups and their relevant applications. This paper focuses on the Medium-low temperature range for Building passive heating and cooling.

### 1.3 Different types of PCM and their applications

A summary of different PCM is shown in Table 1. Paraffin is a common storage material of choice amongst different authors, and this is due to the thermal stability offered by the PCM.

Table 1 Summary of PCM used in building structures.

| PCM | Melting point ($^oC$) | Heat of fusion (kJ/Kg) | Results | Reference |
|---|---|---|---|---|
| RT-27 paraffin | 28 | 179 | - PCM incorporation was studied experimentally on an alveolar brick cubicle in Puigverd de Lleida (Spain) weather conditions.<br>- Two alveolar brick cubicles were used, one with PCM and the other without PCM.<br>- A 15 % reduction in energy consumption was achieved in a PCM cubicle when compared with a room operating with a domestic heat pump. | [27] |
| n-octadecane | 28 | 179 | - 10% PCM was incorporated into the gypsum wallboard to evaluate thermal performance at different locations of a North American residential wall.<br>- Placing PCM on the wallboard internal surface yielded a high reduction in peak heat flux. | [14] |
| Paraffin | 25 – 28 | 244 | - Experimentally studied temperature reduction between two rooms, one room with PCM and another without. Gypsum plasterboards were used as a building material in Weimar (Germany).<br>- A 4 $^oC$ indoor temperature reduction was achieved in a room with PCM. | [13] |
| Paraffin | 28<br>32<br>39 | 230<br>215<br>190 | - Studied thermal mass increase of a concrete roof filled with PCM for the summer season when the cooling energy demand is high. The roof had vertical cylindrical holes filled with PCM, and three different melting point PCMs were used.<br>- The authors concluded that a 12.04 – 17% heat flux reduction was attained, and the performance is dependent on the outdoor temperature. | [16] |
| Paraffin | | 107.5 | - Composite PCM wallboards were applied in an office building in Lyon (France) to study occupant thermal comfort. PCM wallboards were located on the ceiling and walls for 11 months. | [19] |

| | | | | |
|---|---|---|---|---|
| | | | - The presence of PCM resulted in a 2.2 °C lower air temperature compared to the room without PCM. | |
| Paraffin | 26 | 110 | - Experimentally studied the effects of adding awnings on top of a cubicle constructed using concrete and PCM mixture.<br>- The addition of awnings on the cubicles resulted in a 6% reduction in peak temperature. | [28] |
| Paraffin | 22 | 172 | - A gypsum board impregnated with 21 wt% PCM was applied on the internal walls, ceiling and for underfloor heating.<br>- Indoor temperatures were reduced and peak load shifting was achieved.<br>- During the day, the PCM stores solar energy through the wall and ceiling. This energy is then released at the night, thereby creating peak load shifting.<br>- A 32% energy saving was reported. | [29] |
| SP29 | 29 | 180 | - Experimentally studied PCM used for building ventilation in a hot and dry climate.<br>- The thermal performance study focused on free cooling applications in buildings.<br>- It is concluded that the hot air temperature can be reduced as PCM releases the cold energy stored during the night. | [30] |
| SP29 | 28-30 | 190 | - A thermal response study was conducted during summer and winter using two PCMs with different phase change temperatures.<br>- On a summer sunny day, an indoor temperature reduction in the range of 4.28 – 7.7 °C was recorded. A 28.8 – 67.8% reduction in indoor temperature fluctuation was achieved by using composite PCM.<br>- In winter, using PCM contributed to indoor temperature rise in the range of 6.93 – 9.48°C. | [7] |

## 2. Methodology

### 2.1 Shacks

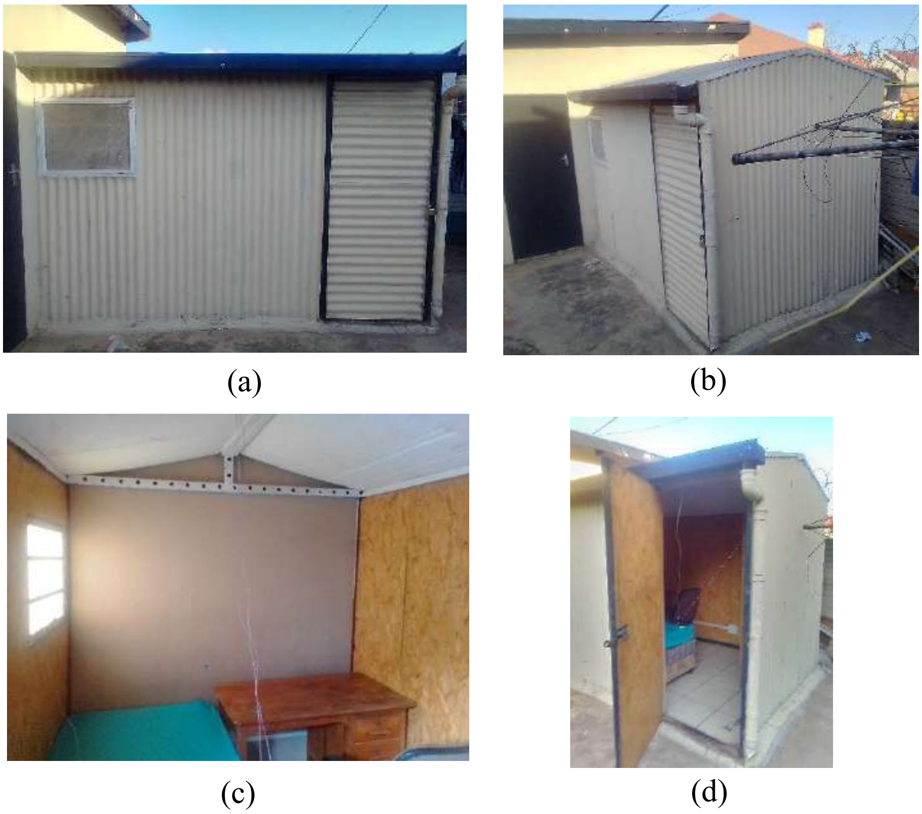



Figure 2 Shack 1 (a) front view of the exterior, (b) 2-point perspective of the shack*'s* exterior, (c) interior of the shack, (d) front door of the shack.

In this study, two shacks were investigated, Shack 1 and Shack 2.Shack 1 is situated in Pretoria West, Gauteng Province, South Africa and is displayed in Figure *2*. From Figure 2 a single-room shack was investigated. The shack is 3 meters long, 2 meters wide, and 2 meters high. It is mounted onto the building wall as seen in Figure 2 (b). It was also insulated with 25mm thick plank chipboards on three sides while the roof was insulated with a thin sheet of polyurethane as seen in Figure 2 (c). The shack was fitted with floor tiles as displayed in Figure 2 (d).The experiment was conducted on the 16$^{th}$ of June to the 24$^{th}$ of June 2022. During the study, the shack doors and windows were closed. A Graphtec midi GL820 data logger fitted with type K thermocouples (with a typical accuracy of a maximum of +/- 2.2°C or +/- 0.75%) was used to capture the data. 2 thermocouple sensors were placed outside the shack, to monitor the atmospheric temperature and the outside metal sheet temperature. 3 thermocouple sensors were placed inside the shack, 1 measuring the ambient air, 1 measuring the direct temperature on the plank chipboard, and 1 measuring the air space between the corrugated profile of the metal sheet and the plank chipboard. This was done to measure the thermal resistance impact of the chipboard on the temperature fluctuations.

(a)

(b)

(c)

(d)

Figure 3 Shack 2 (a) front view of the exterior of the shack, (b) front view of the exterior of the shack, (c) interior of the shack, (d) 2-point perspective of the exterior of the shack.

Shack 2 is situated in Harrismith, Free State Province, South Africa. It is displayed in Figure 3. From Figure 3 (b) a shack with two rooms was used for the experiments. The shack was constructed out of Galvanized Roof Sheeting Corrugated Profile of 0.25mm and Iron Equal Angle of 25mm x 25mm x 3m. The shack was 4 meters long, 3 meters wide, and approximately 2.16 meters high in the front and 1.93 meters high at the back. Shacks are constructed in this manner to avoid rainwater being stagnant on the roof.

The experiments was conducted on the 12$^{th}$ of July 2022 to the 17$^{th}$ of July 2022. In the region, these are the winter months, with less rain, colder nights, and sunny days. For the duration of the study, two people were living in the shack to resemble real conditions experienced by shack owners throughout South Africa. Two beds were fitted as seen in Figure 3 (c). During the day, the shack doors and windows were mainly closed, and during the night people slept in it.

The 3 thermocouple sensors were placed outside the shack to measure the ambient air surrounding the shack, with two sensors measuring the direct temperature of the sheet metal. 5 thermocouple sensors were placed inside, to measure the ambient temperature at the top and bottom of the shack and the direct temperature on the metal sheet.

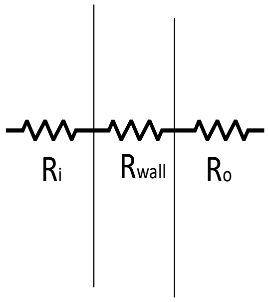



Figure 4 Thermal resistance network associated with heat transfer [31].

The thermal resistance network for this system is shown in Figure 4 and expressed in Equation 1 [31].

$$R = R_{total} = R_i + R_{wall} + R_o = \frac{1}{h_i A_i} + \frac{\mathrm{L}}{kA} + \frac{1}{h_o A_o}$$

Equation 1

When combining the thermal resistances in the path of the heat flow, results in Equation 2.

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R}$$

Equation 2

## 2.2 Simulation

The accuracy for simulating PCMs in energy plus version 22.2.0 software was validated experimentally by Velasco et al. [32]and the results were satisfactory. In this study, the operational and construction details are obtained from the study of Salihi *et al.* [33], however, Salihi *et al.* [33] analysed a house made of bricks and the positioning of the PCM layer was different to this current study. The outside temperature was used to calibrate the accuracy of the simulation. The experimental temperatures were compared to the simulated temperature, and it was found that they correlated. However, the slight difference was caused by using the Johannesburg temperature which was available in energy plus and the measured temperatures in Pretoria. The two locations are 60 km apart. it should be noted that not all the weather data for different locations within South Africa are available in energy plus.

For the EnergyPlus Input Data Files (IDF), Heat Balance Algorithm, Conduction Finite Difference, that was used during the PCM simulation, the number of timesteps per hour were set to 20. For the shack simulations without PCM, the Conduction Transfer Functions was used with 6 timesteps per hour. For both simulaitons, the ground temperature was assumed to be 18°C the default value presented by energy plus version 22.2.0. For the run period, the experimental dates were also used in energy plus version 22.2.0 for accurate weather data.

Energy plus has been gaining popularity over the years as a free software used for analysing thermal simulations in buildings. The software makes use of the fully implicit scheme based on an Adams-Moulton solution approach. The equation for this model is displayed in Equation 3.

$$C_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = \left( k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \right)$$

Equation 3

The specific heat of the material is a function of the temperature and is dependent on both the current state of the PCM and on the previous state as displayed in Equation 4.. This allows energy plus version 22.2.0 to capture the hysteresis physics present between the melting and freezing processes [34].

$$C_p = f\left(T_{i,new}, T_{i,prev}, PhaseState_{new}, PhaseState_{prev}\right)$$

Equation 4

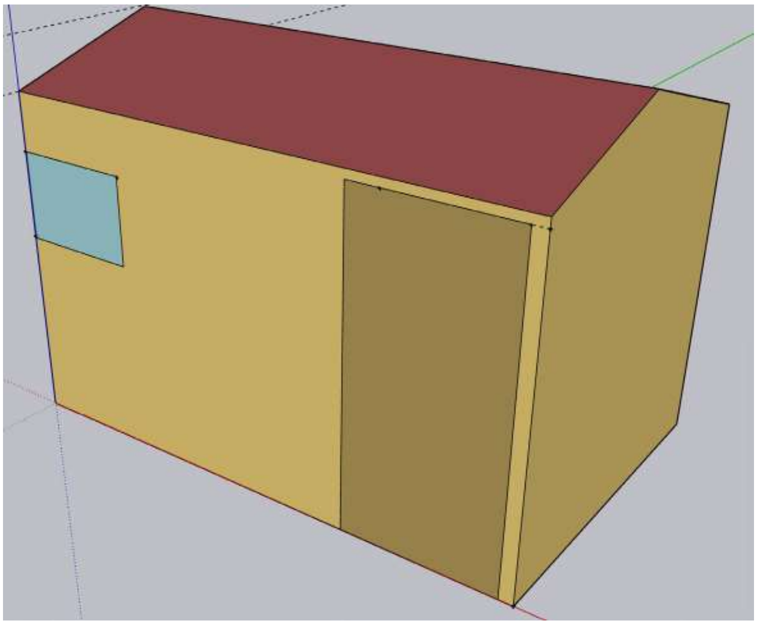


Figure 5 Shack 1.

Shack 1 was modelled in Sketch up Pro 2022 using the Open Studio plugin as displayed in Figure 5 and temperature simulations were done using energy plus version 22.2.0 software. All the exterior sides of the shack were exposed to wind and all the exterior sides excluding the back side of the shack were exposed to sunlight. The left-hand side of the shack was exposed to the concrete wall of the house. The door was made up of corrugated profile galvanised metal sheets with plank chipboard on the inside. Internal heat loads, such as lights, were not incorporated into the model since the shack doors and windows were closed for the duration of the study.

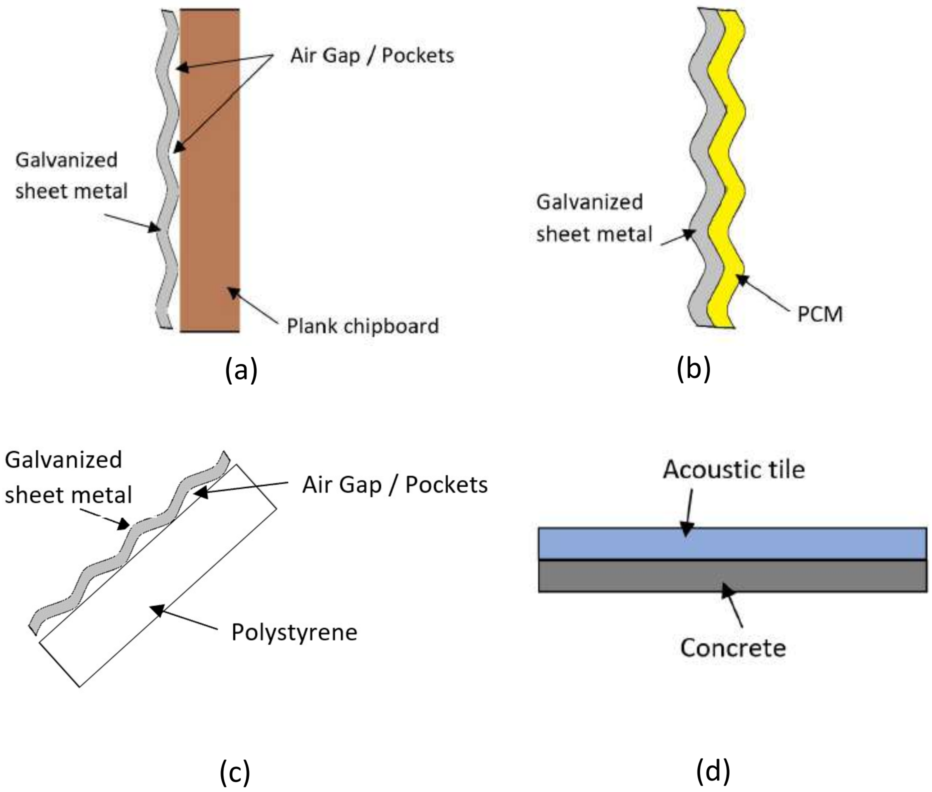



Figure 6 Construction Material Layers: (a) shack wall layer without PCM, (b) PCM incorporation into the shack wall layer, (c) roof layer and (d) inside floor.

Figure 6 illustrates the construction material layers used inside shack 1 and also how the layers were incorporated into the simulation. Figure 6 (a) illustrates the sides of the shack 1. The layer comprised of the outer material which is the galvanized sheet metal (corrugated profile), air pockets between the corrugated profile and the plank chipboard. These air gaps/pockets were incorporated into the simulation since they provide conduction resistance due to the stagnant air. Figure 6 (b) illustrates the incorporation of the PCM into the shack and how it was modelled in energy plus. The PCM layer can follow the corrugated profile of the galvanized sheet metal, hence there are no air gaps in between the sheet metal and the PCM. Figure 6 (c) illustrates the roof of the shack. It comprises of the corrugated profile galvanized sheet metal, the air gap/pockets and the polystyrene layer. Figure 6 (d) illustrates the floor of the shack which consists of the acoustic tile fitted onto a concrete floor. Table 2 lists the construction material properties used in energy plus simulation.

Table 2 Simulation Construction Material.

| Name | Roughness | Thickness (m) | Conductivity (W/m K) | Density (kg/m^3) | Specific heat (J/kg K) | Thermal Absorptance | Solar Absorptance | Visible Absorptance |
|---|---|---|---|---|---|---|---|---|
| Air | Smooth | 0.001 | 0.002514 | 1.204 | 1007 | | | |
| Concrete | Rough | 0.2033 | 1.7296 | 2243 | 837 | 0.9 | 0.65 | 0.65 |
| Acoustic tile | MediumSmooth | 0.0191 | 0.06 | 368 | 590 | 0.9 | 0.3 | 0.3 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Plank chipboard | Rough | 0.0254 | 0.15 | 608 | 1630 | 0.9 | 0.5 | 0.5 |
| Galvanized sheet metal | MediumRough | 0.0015 | 45.006 | 7680 | 418.4 | 0.9 | 0.6 | 0.6 |
| Polystyrene | VeryRough | 0,025 | 0,04 | 16 | 1200 | | | |
| glass | | 0,003 | 0,9 | | | | | |

For fire precautions and mitigation, it is advisable to use non-Paraffin PCM such as fatty acids, esters, alchohols and glycols. The ideal PCM being Soybean oil which is a waxy, non-toxic paste with small lumps of solids. Due to lack of literature on the properties of these PCM, for simulation purposed we proposed organic paraffin PCM such as RubiTherm. Which have similar features.

Rubitherm PCMs were used for simulations. Table 3 lists the PCM used in the simulation. The PCMs were selected from RUBITHERM, a company producing Versatile Organic PCM.

Table 3 RubiTherm Phase Change Material [35].

| | Melting area (°C) | Congealing area (°C) | Heat storage capacity ±7.5% (kJ/kg) | Specific heat capacity (kJ/kg K) | Density solid (kg/m$^3$) | Density liquid (kg/m$^3$) | Heat conductivity (both phases) (W/m K) |
|---|---|---|---|---|---|---|---|
| RT10HC | 9-10 | 10-9 | 200 | 2 | 880 | 770 | 0.2 |
| RT11HC | 10-12 | 12-10 | 200 | 2 | 880 | 770 | 0.2 |
| RT12 | 7-13 | 13-6 | 155 | 2 | 880 | 770 | 0.2 |
| RT15 | 10-17 | 17-10 | 155 | 2 | 880 | 770 | 0.2 |
| RT18HC | 17-19 | 19-17 | 260 | 2 | 880 | 770 | 0.2 |
| RT21 | 18-23 | 22-19 | 155 | 2 | 880 | 770 | 0.2 |
| RT24 | 21-25 | 25-21 | 160 | 2 | 880 | 770 | 0.2 |
| RT26 | 25-26 | 26-25 | 180 | 2 | 880 | 750 | 0.2 |
| RT28HC | 27-29 | 29-27 | 250 | 2 | 880 | 770 | 0.2 |

## 3. Results and Discussions

### 3.1 Shack 1 temperature fluctuations

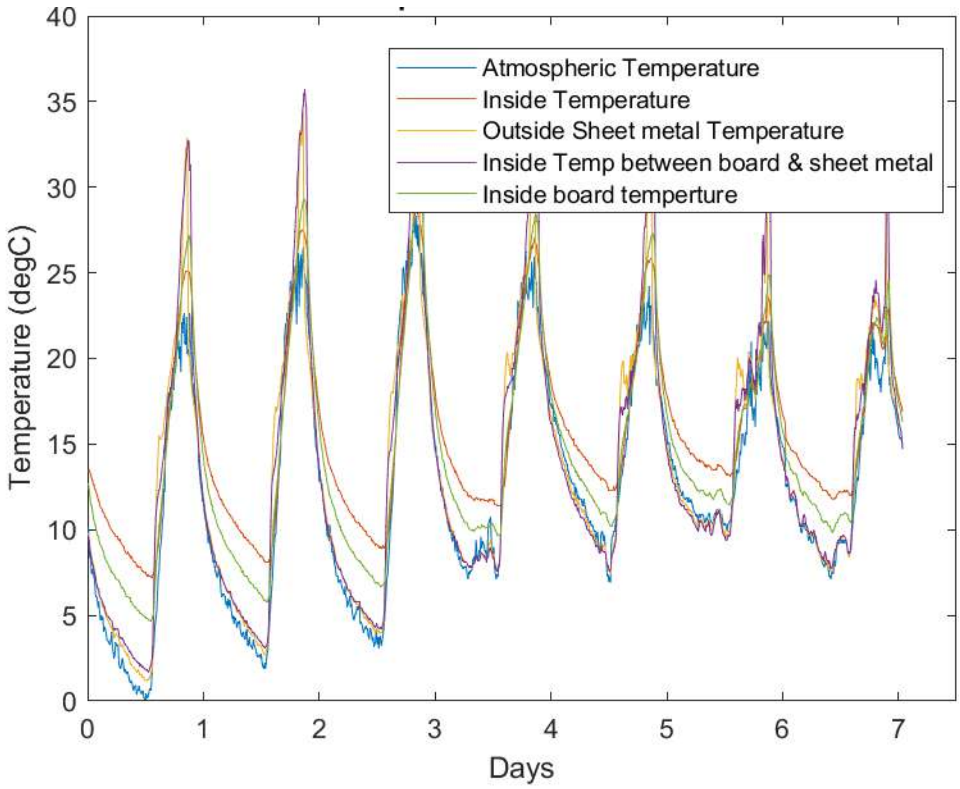



Figure 7 Shack 1 Results beginning from 16th of June to the 24th of June 2022.

From Figure 7, the atmospheric air surrounding the shack (Atmospheric Temperature), the interior temperature of the shack(Inside Temperature), the exterior temperature of the sheet metal (Outside Sheet metal Temperature), the temperature of the air pockets (Inside Temp between board & sheet metal) and the temperature on the plank chipboard (Inside board temperature) were measured. The interior temperature of the shack exceeded the atmospheric temperature by approximately 3 °C during the daytime and lagged by approximately 5 °C during the night-time. The temperature of the exterior surface temperature of the sheet metal was equal to the measured temperature of the air pockets, due to the high thermal conductivity of the metal sheet and its low thermal resistance to heat transfer between the exterior and the interior of the shack. Both these temperatures exceed the interior temperature by approximately 8 °C. It can be concluded that the plank chipboard reduces the temperature rise during the day and also reduces the temperature drop during the night, this can be seen from the measured temperature of the plank chipboard and the interior temperature. During the day, since the shack doors and windows were closed, the temperature build-up caused the temperature of the air pockets to vary drastically from the interior temperature (Inside temperature). Due to these effects, the air pockets' temperature fluctuated up to 30 °C. But the temperature after the plank chipboards fluctuated by approximately 15 °C as seen in Figure 7 (inside temperature). The process was repeated for 7 days to illustrate the daily temperature fluctuations.

**3.2 Shack 2 temperature fluctuations**

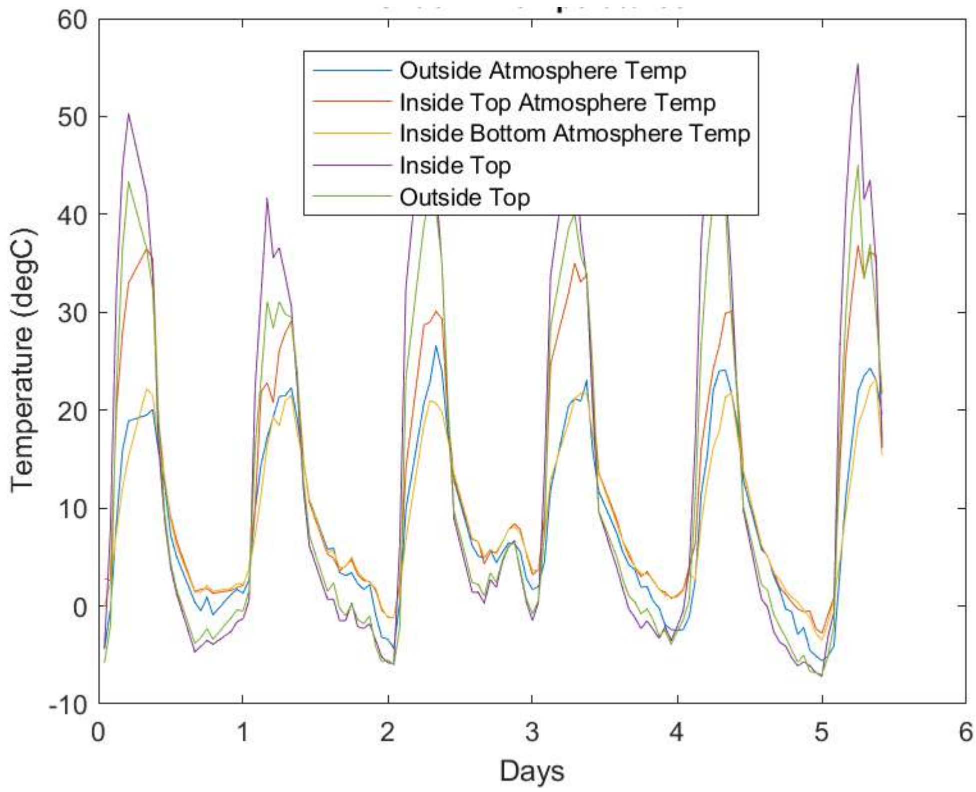



Figure 8 Shack 2 Temperatures beginning on the 12th of July 2022 to the 17th of July 2022.

The results of the experiment for shack 2 are displayed in Figure 8. Only 5 temperature readings are shown for visualization of the graph, the atmospheric air temperature surrounding the shack (Outside Atmosphere Temp), the interior air temperature near the roof of the shack (Inside Top Atmosphere Temp), the interior air temperature near the floor of the shack (Inside Bottom Atmosphere Temp), the interior surface temperature of the sheet metal at the roof of the shack (Inside Top) and the exterior surface temperature of the sheet metal on the roof of the shack. From Figure 8 it is observed that the temperature distribution inside the shack was uneven, with the interior air temperature near the roof of the shack exceeding the interior air temperature near the floor of the shack by approximately 15 °C on the first day, this was also noted for shack 1 since it had tiles on the floor. The interior surface temperature of the sheet metal at the roof of the shack (Inside top) was higher than the exterior surface temperature of the sheet metal on the roof of the shack (Outside Top), this was caused by the temperature build-up inside the since shack doors and windows were closed during the day. This was done to show that the heat transfer through the metal sheet was quick as it provides little resistance to the heat transfer. This caused the interior air temperature near the roof of the shack to fluctuate by approximately 40 °C and  the interior air temperature near the floor of the shack by 20 °C. The experiment was also repeated to illustrate the daily temperature fluctuations around a shack with no insulation. Similar behaviours were observed between shack 1 and shack 2, however, for shack 2, the temperatures were high since there was no plank chipboard to act as insulation. It should be noted that plank chipboard only provides sensible energy and does not provide the latent heat region that PCM provides. PCMs can adapt to the surrounding temperatures during their melting phase and release energy during their solidification phase.

**3.3 Shack 1 Simulation results**

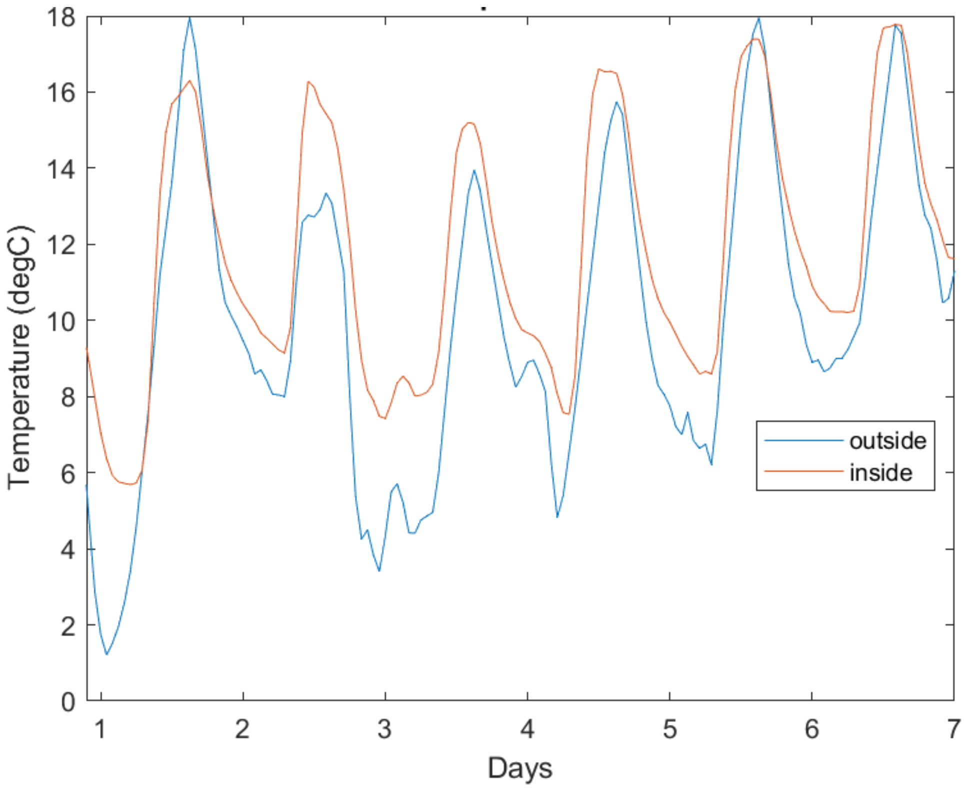
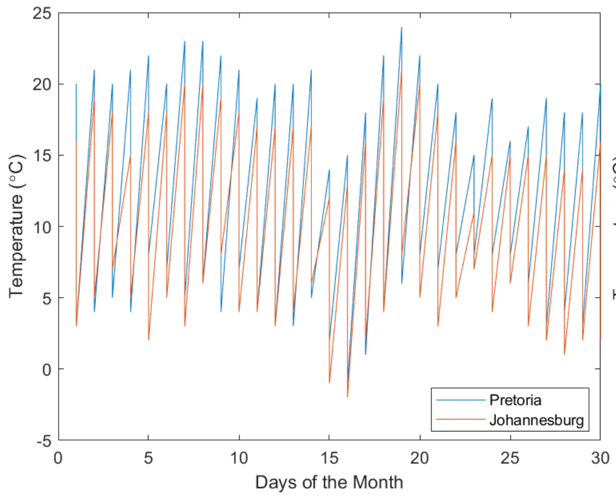


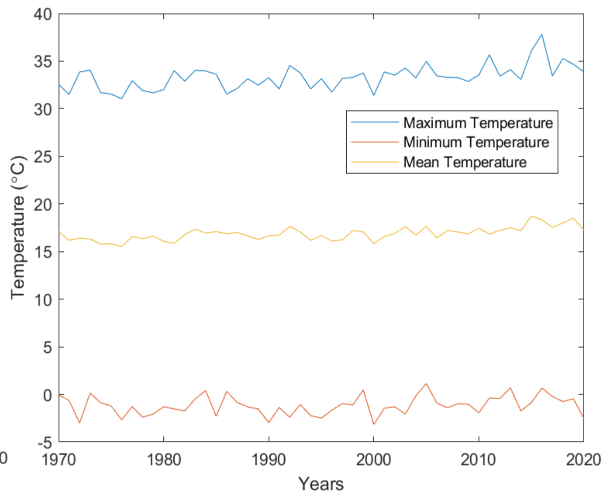

Figure 9 Simulation Results.

The results from the energy plus simulation displayed in Figure 9 showed similar results compared to Figure 7. However, there is a slight difference in the temperature range since Johannesburg weather data was used during the simulation and not in Pretoria. This greatly impacted the inside temperature of the shack. The insulation inside the shack retarded the temperature fluctuations allowing them to range at approximately 10 °C for the days.

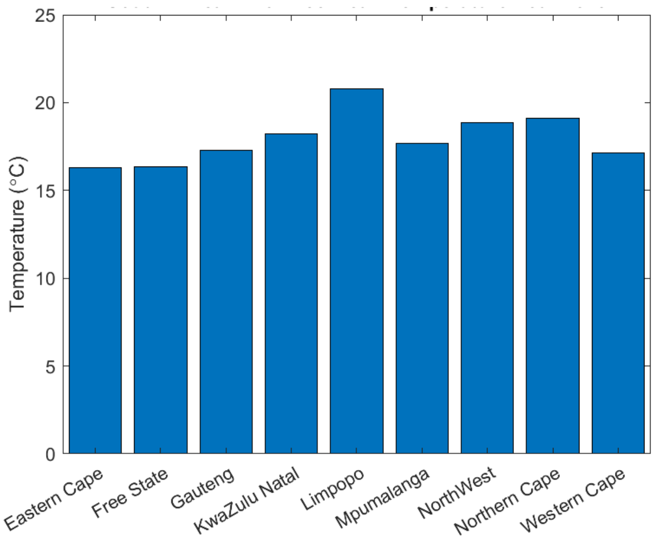
### 3.4 Weather data validations




(a)




(b)

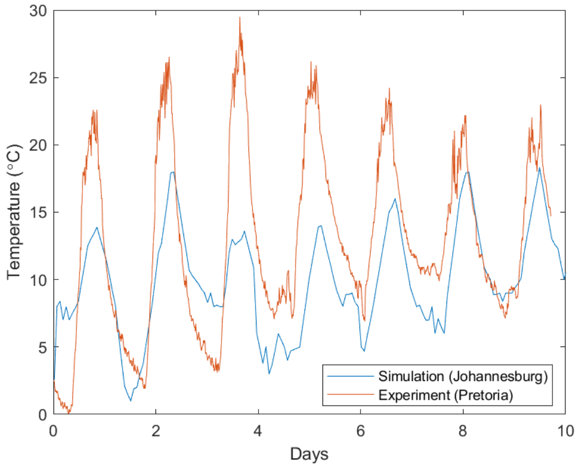



(c)

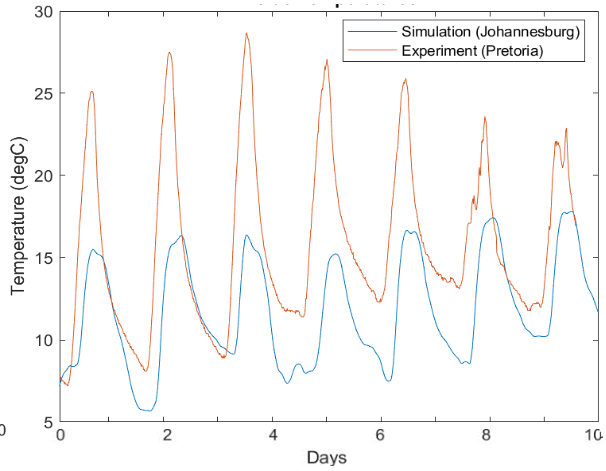
Figure 10 (a) Pretoria and Johannesburg June 2022 Weather data (b) Gauteng Province Temperature Range (c) South African Province Temperature Ranges.

Figure 10 (a) illustrates the weather data captured from the South African weather service for June. Due to the limitations of the weather data availability in energy plus software, the Johannesburg data was used for the simulation as it was the closest region to Pretoria, although they are 60km apart. From Figure 10 (a), The temperature in Pretoria is slightly higher than in Johannesburg. Figure 10 (b) illustrates the maximum, minimum and mean temperature from the year 1970 to 2020. The reason for this was to show the temperature range throughout the year. From Figure 10 (b), using the minimum and maximum values of the temperature to determine the optimal PCM phase change temperature will be inaccurate. The temperature nearest to the shack's surface does differ from the atmospheric air temperature. However, for simulation purposes, an assumption was made that the outside surface temperature of the shack was the same as the average atmospheric air temperature. The average temperature was used for simulations and to determine the PCM for the shack. It should be noted that the best or optimal thickness of PCM panels should derive from quantitative analysis with consideration of both energy efficiency and cost benefits. As a result, the optimal PCM thickness was not determined in this study. The Mean temperature range for the province of Gauteng has been ranging at about 17°C. Therefore, selecting a PCM that changes phase at this temperature would be ideal. Figure 10 (c), illustrates the annual temperature ranges of the 9 provinces, each province has a mean temperature range, however, Limpopo is seen to be the highest.

### 3.5 Weather results



(a)



(b)

Figure 11 (a) Atmospheric Temperature comparison (b) Inside Temperatures comparison.

Figure 11 (a) and Figure 11 (b) were plotted to compare the simulation weather data and the experimental data. It was shown from these two figures that Pretoria's temperature was higher than Johannesburg as seen in Figure 10 (a). By observation from both Figure 11 (a) and Figure 11 (b) the peaks and troughs of Experimental data taken in Pretoria were similar to the simulation results simulated using Johannesburg weather data in Figure 11 (a). It should also be noted that the altitude that the weather station captures the weather information is different from the altitude used to capture the experimental data, this could also lead to a slight difference between the experimental data and the simulation data as seen in Figure 11 (a). This slight difference will also affect the internal temperature as seen in Figure 11 (b). The region in which the shack is located is a major contributor to temperature fluctuations. Similar results can be obtained in all areas. For this study, the annual temperature ranges of the 9 provinces in South Africa are on the same range, however, Limpopo province is seen to be the highest. For shack establishments in different provinces throughout South Africa, different PCM will have to be selected according to the mean temperature of the area to achieve comparable results. This was also shown by [36].

### 3.6 Temperature fluctuation results

A phase change temperature between 17-19 °C was selected because the PCM needs to change phase so that the latent heat could be released, otherwise only the sensible region will be used. If a higher phase change temperature was selected, the annual average temperature would not be able to melt it. It was also noticed from the simulations that by lowering the PCT, the temperature fluctuations are also reduced further. A study by [36] showed that using a PCM with a PCT at the mean temperature was ideal.

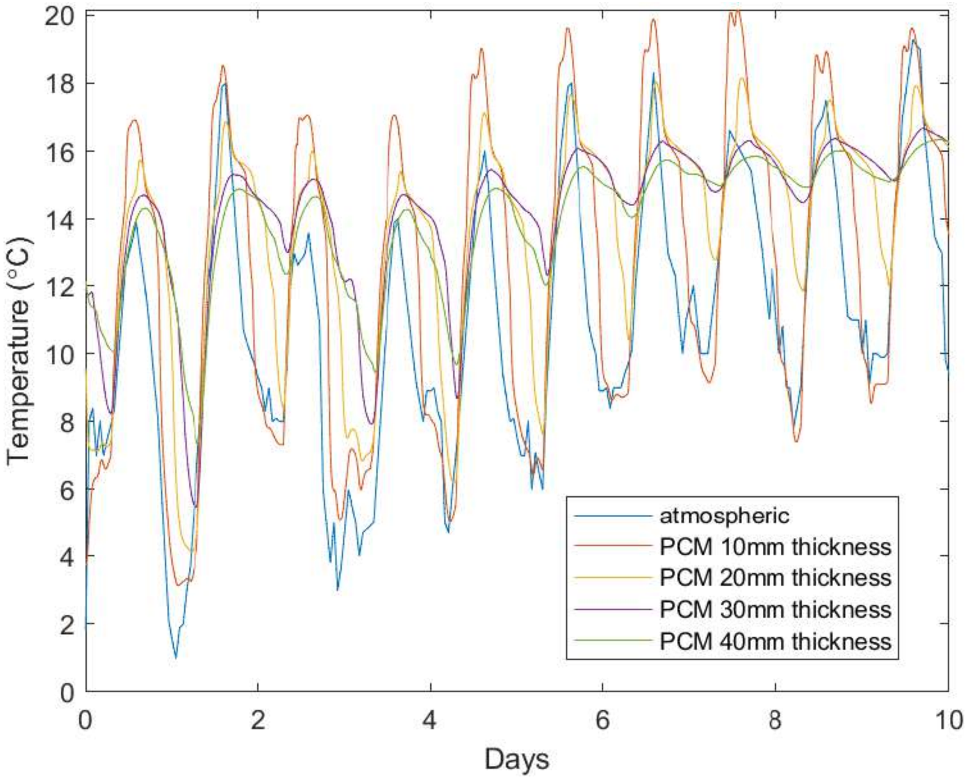



Figure 12 Temperature fluctuations.

For the simulation run in energy plus, the software found the zinc metal sheet to be too thin and have highly conductive properties. Therefore, materials with high conductivity Material layers are not well supported by the Conduction Finite Difference used to simulate the performance of a phase change material. The zinc metal sheet was then removed and replaced with a layer of RUBITHERM RT-18 PCM, the results are displayed in Figure 12. From Figure 12, the simulation showed that for a RUBITHERM RT-18 PCM with a thickness of 10mm, the interior temperature of the shack still behaves as the atmospheric air temperature outside the shack. This is a disadvantage since it shows similar behaviour patterns to a shack without a PCM just with slightly reduce temperature fluctuations of up to 10°C. Using a PCM with 30mm thickness will drastically reduce the temperature fluctuations inside the shack as compared with a shack having 20mm PCM thickness. This illustrated an ideal PCM thickness for shacks. When increasing it to 40mm thickness, the fluctuations were further reduced, however, PCM cost should also be in mind when increasing the quantity of PCM to be used. From the $6^{th}$ day to the $10^{th}$ day, for a PCM with 30mm thickness, the temperature fluctuations behaved differently. As the atmospheric temperature rises during the night, resulting in less temperature fluctuation, the PCM also maintains the inside temperature at a stable temperature between 14°C and 16°C. This configuration lead to an indoor temperature fluctuation between 14-16 °C which is lower than the ideally comfortable temperature range. It can be concluded that for more stable and constant inside temperatures, a thicker PCM will have to be used.

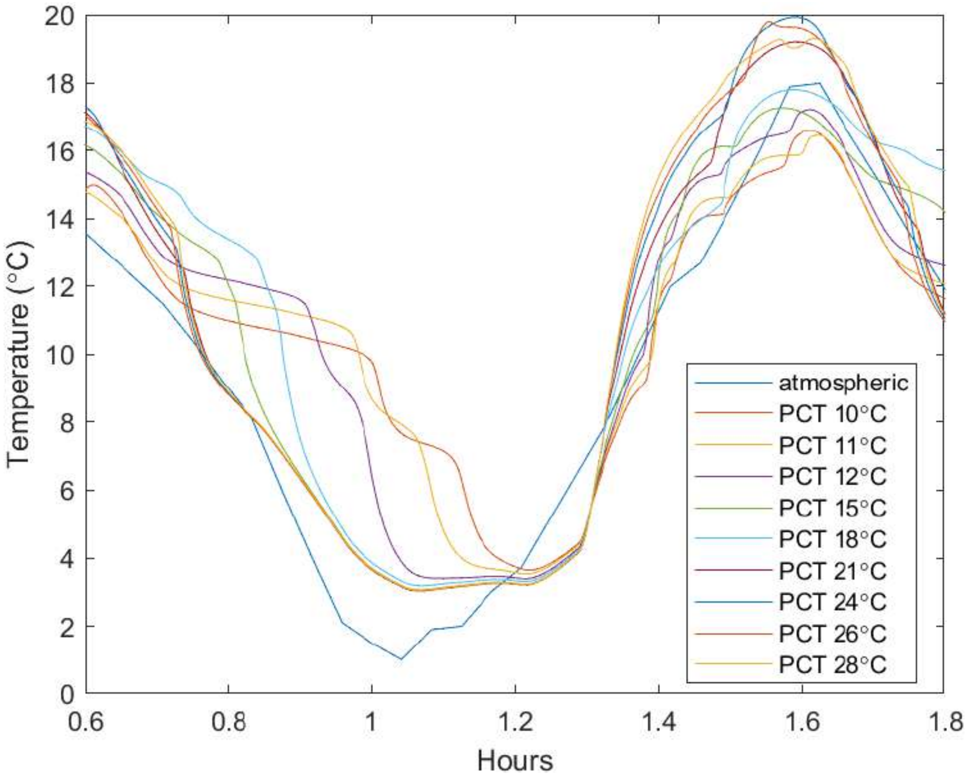



Figure 13 Different Phase Change Temperatures using 10mm thickness.

Figure 13 illustrates the different PCM and compares their phase change temperatures to temperature fluctuation as listed in Table 3. From the simulations, the PCM with the lowest phase change temperature (RT-10, RT-11 and RT-12) showed great potential as they started to phase change at a temperature ranging from 12ºC to 10 ºC during the 1 hour of simulation, they seem to reduce the temperature better than the suggested RT18 by [36]. PCM with a higher phase change temperature such as PCT 28 ºC mimic the atmospheric temperature. This shows that they have no reached the latent heat region, thus unable to reduce the temperature fluctuation in the shack. Figure 13 further emphasised that using a PCM with a PCT above the mean atmospheric temperature showed little impact, as the sensible region was being used and not the latent region. The PCMs at 1.4 hours from Figure 13 was also expected to phase change turning into a liquid with the rise in temperature for a long period but it was not so. The PCMs with a low PCT only showed this for a small amount of time.

## CONCLUSION

For many South Africans, informal housing is their home, these are made from galvanized metal sheets. These shacks are prone to temperature fluctuations due to the high thermal conductivity of the metal sheet and its low thermal resistance to heat transfer between the outside and the inside. This study experimentally investigated the temperature fluctuations around a shack fitted with plank chipboard and one without. The main conclusions were as follows:

- The inside temperature fluctuations on the shack without the insulations reached close to +50°C during the day, and -5°C during the night. While the one with insulation reached +25°C during the day and 7°C during the night.

- The inside temperature of the shack was measured to be higher than the atmospheric air due to the temperature build-up inside the shack. From the experimental data, it was also observed that the temperature distribution inside the shack is uneven, with the top part at higher temperatures than the bottom part of the shack.
- The region and the location of the shack largely contributed to the temperature fluctuations. The use of fuels such as paraffin during cold days has resulted in fire outbreaks which ravage surrounding shacks. By using a PCM layer, the temperature fluctuations are greatly reduced.
- The were challenges encountered when using energy plus version 22.2.0 software for simulating the PCM layer - the program found the zinc metal sheet to be too thin and have highly conductive properties. Therefore, materials with high conductivity Material layers are not well supported by the Conduction Finite Difference used to simulate the performance of a phase change material. The zinc metal sheet was then removed and replaced with a layer of RUBITHERM RT-18 PCM.
- An assumption had to be made that the outside surface temperature of the shack was the same as the atmospheric air temperature. Since South Africa has 9 provinces, and some of the province's mean temperature differs, the study recommends that the mean temperature of the atmosphere surrounding the shack should be used to determine the PCT of the PCM.
- A phase change temperature between 17-19 °C was selected because the PCM needs to change phase so that the latent heat could be released, otherwise only the sensible region will be used. If a higher phase change temperature was selected, the annual average temperature would not be able to melt it. It was also noticed from the simulations that by lowering the PCT, the temperature fluctuations are also reduced further.
- From the simulations, a PCM 30mm thick reduced the temperature fluctuations to between +14°C and +16°C. When increasing it to 40mm thickness, the fluctuations were further reduced. It should be noted that the best or optimal thickness of PCM panels should derive from quantitative analysis with consideration of both energy efficiency and cost benefits. As a result, the optimal PCM thickness was not determined in this study. This study only suggested the PCM thickness required to reduce the temperature fluctuations. Since a 30mm PCM thickness configuration resulted in an indoor temperature fluctuation between 14-16 °C which is lower than the ideally comfortable temperature range. A further study is recommended to analyse human behaviour in an indoor temperature fluctuating between 14-16 °C during the day and the night.
- There are economic benefits that could be realised in the South African market by incorporating PCM in building structures. Less strain on the electricity grid will minimise load-shedding as TES systems are used to condition the air space." However, this study focused only on reducing the temperature fluctuations inside a shack. No costs were inserted into the study, nor any comparison between using air-conditioning systems to minimize energy consumption. A further study is recommended to quantitatively analyse the use of PCM for shacks while considering both energy efficiency and cost benefits.

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