Suid-Afrikaanse Tydskrif vir Natuurwetenskap en Tegnologie 2023; 42(1):1-15
South African Journal for Science and Technology 2023; 42(1):1-15
https://doi.org/10.36303/SATNT.2023.42.1.926E

SATNT / SAJST
ISSN: 2222-4173 EISSN: 0254-3486

ORIGINAL RESEARCH

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

BT Radebe, Z Huan

Tshwane University of Technology, South Africa
Corresponding author: *BT Radebe* ***E-mail:*** *radebetb@tut.ac.za*

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).

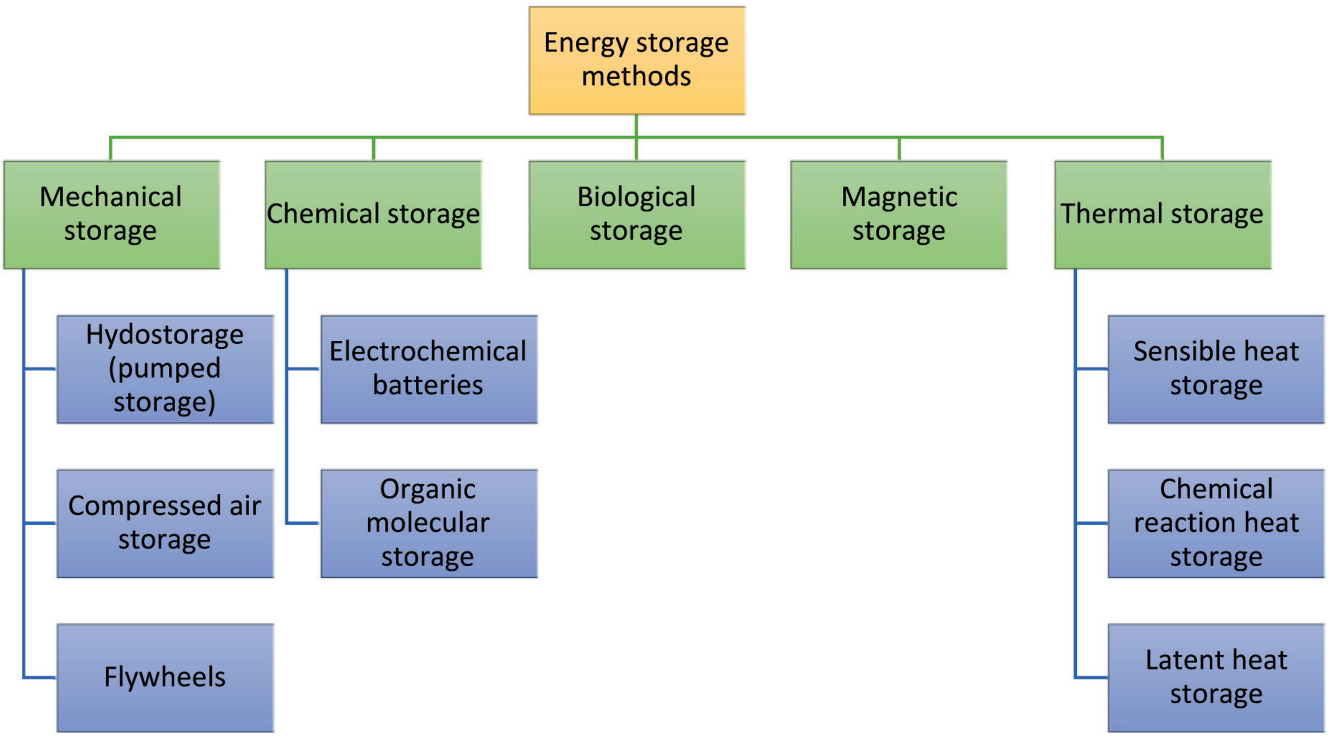

Figure 1: Classification of energy storage methods (Dincer & Rosen 2011; Raam Dheep & Sreekumar 2014)

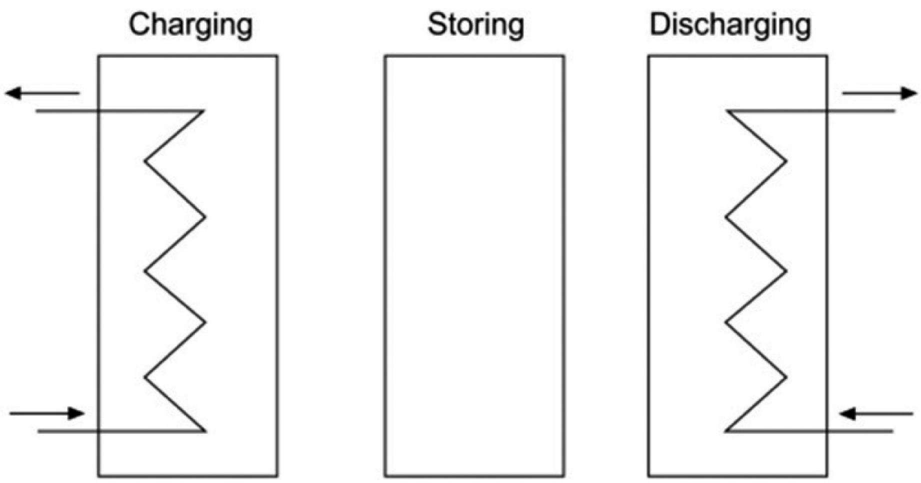

Figure 2: TES complete storage cycle (Cabeza et al. 2011)

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).

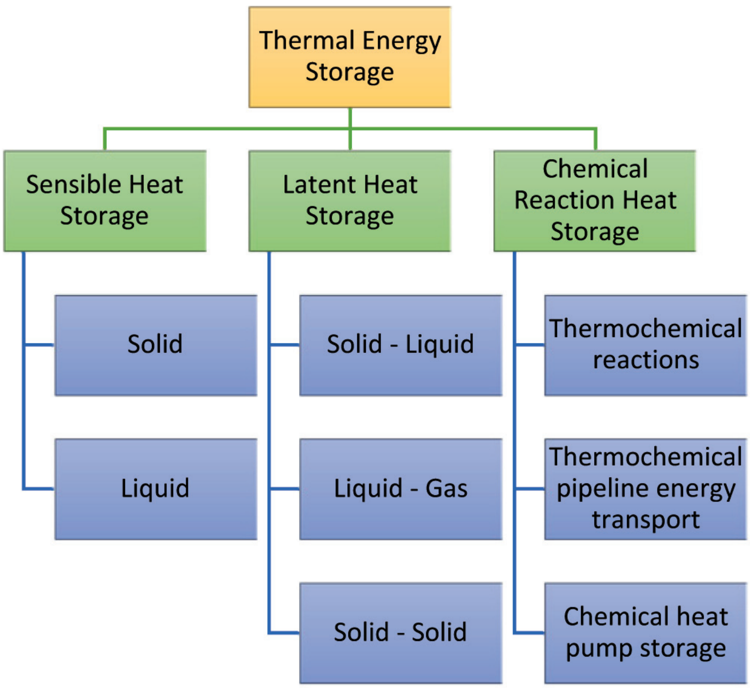

Figure 3: Classification of thermal energy storage (Raam Dheep & Sreekumar 2014).

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

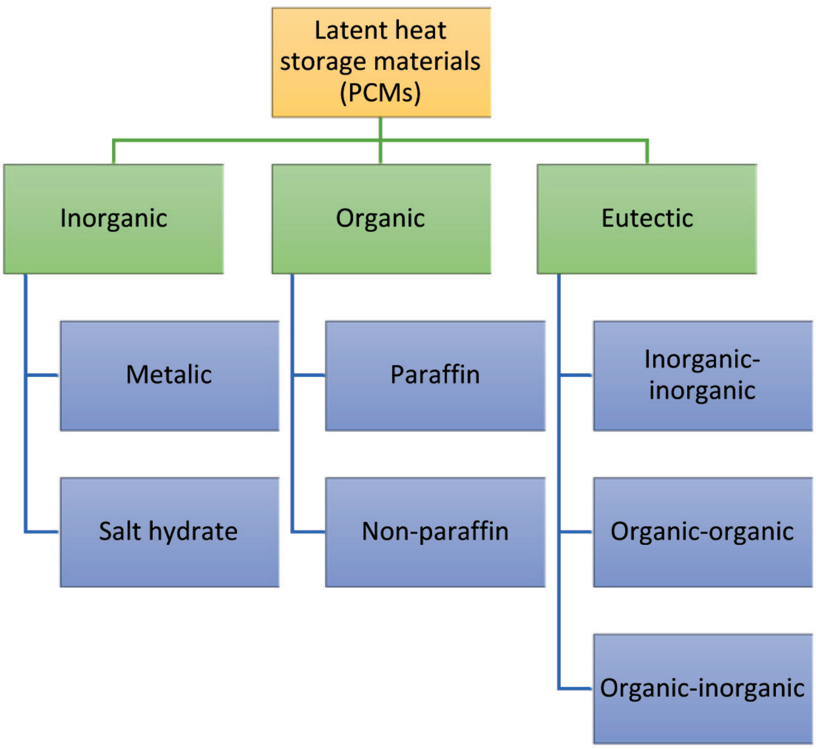

Figure 4: Classification of PCM for cold thermal energy storage (Raam Dheep & Sreekumar 2014; Veerakumar & Sreekumar 2016)

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).

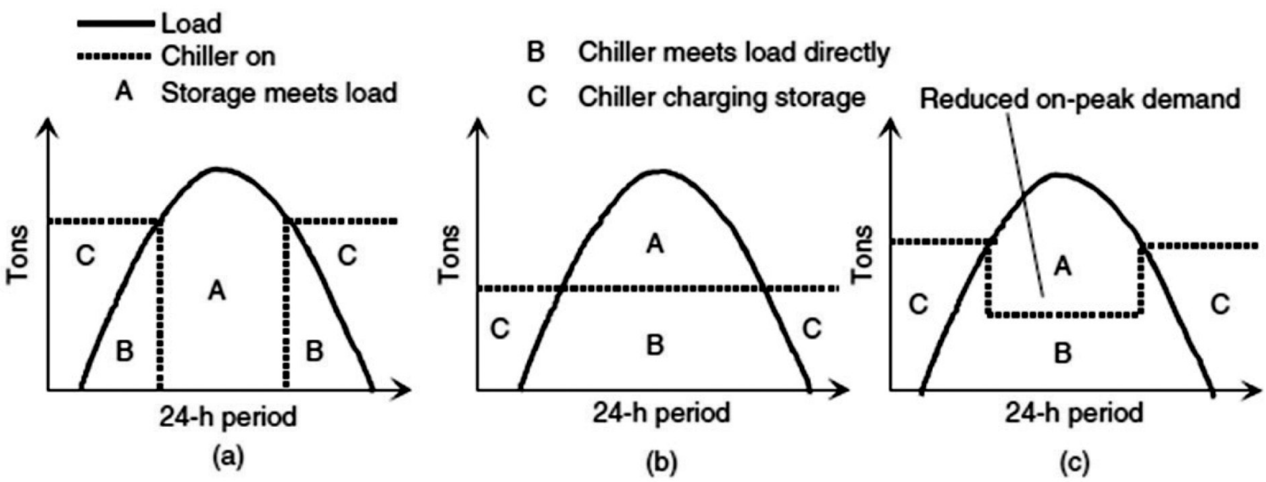

Figure 5: Operating strategies: (a) full-storage, (b) partial-storage load levelling, and (c) partial-storage demand limiting (Dincer & Rosen 2011; Selvnes et al. 2021)

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

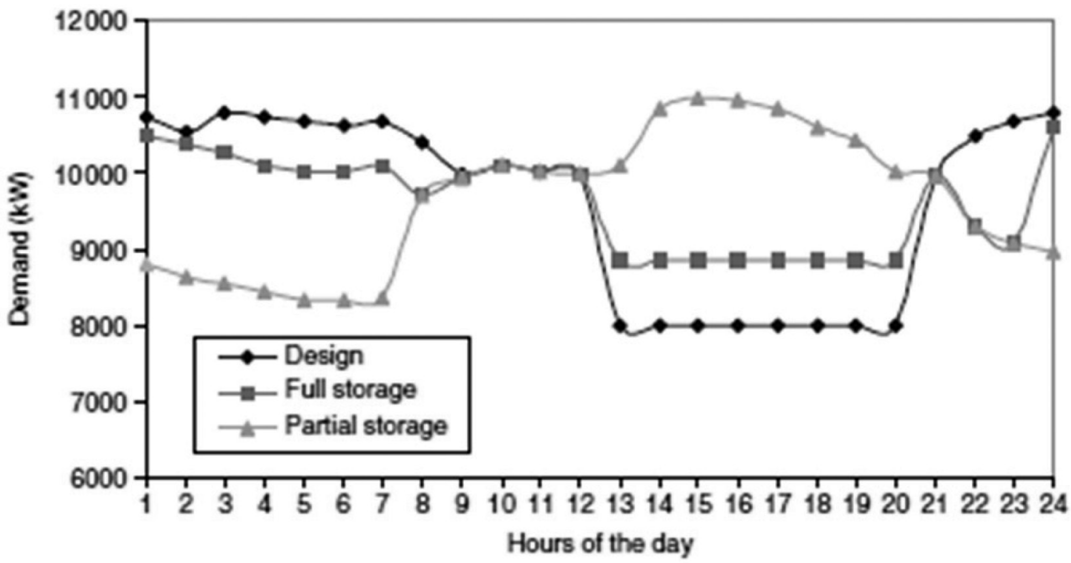

Figure 6: Sample demand profiles for the design, full-storage and partial-storage systems (Dincer & Rosen 2011).

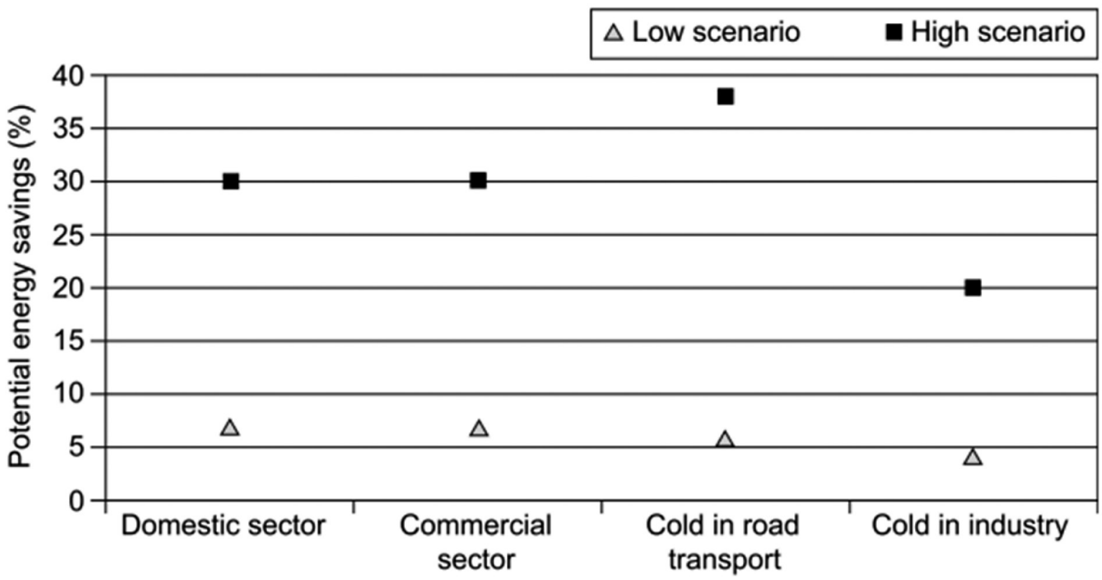

Figure 7: Potential energy reduction in cold applications using different scenarios (Cabeza et al. 2021; Oró et al. 2014).

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.

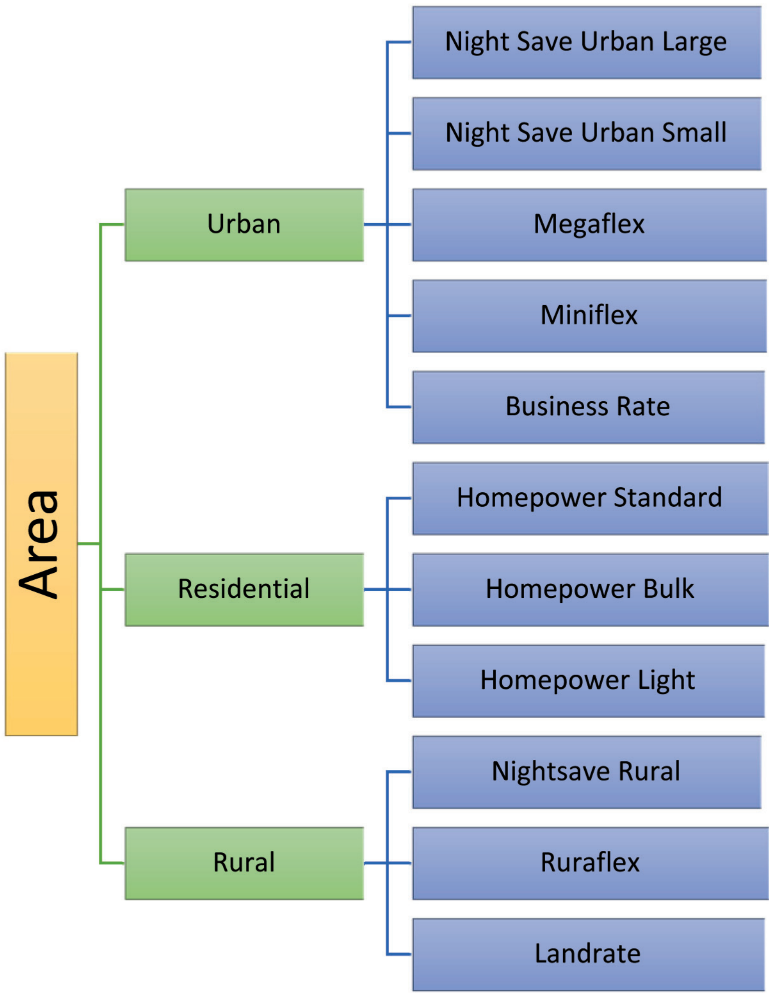

Figure 8: Eskom Tariff plan by Area (Eskom Ltd. 2021; National Cleaner Production Centre n.d.).

- 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)

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

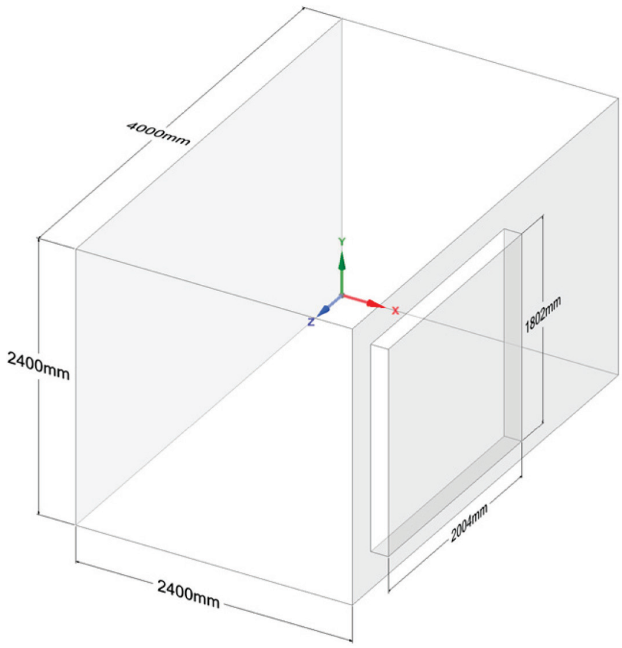

Figure 10: Dimensions of cold room

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 Voltage: 380 V Power: 5,5 kW RPM: 1 435
Compressor	V: 20,3 m3/h N: 1 450 r/min Stroke: 325 cm3 Pmax = ND(LP)/HP(HP) = 19/28 bar
Condenser	Number of tubes in the transverse direction: 11 Number of rows in the longitudinal direction: 5 Tube length (wide) = 0,83 m staggered Diameter (ID/OD) 6,25 mm
Evaporator	Number of tubes in the transverse direction: 11 Number of rows in the longitudinal direction: 5 Tube length (wide) = 1,07 m staggered Diameter (ID/OD) = 8,75 mm
Expansion device	Model: electric DC 12V PQM 1000 / 140 / 14 / 2 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]
- ρ_i is the density of infiltration air [kg/m³]
- ρ_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
- θ_p is the door open-close time, seconds per passage
- θ_0 is the time the door simply stands open [min]
- θ_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.

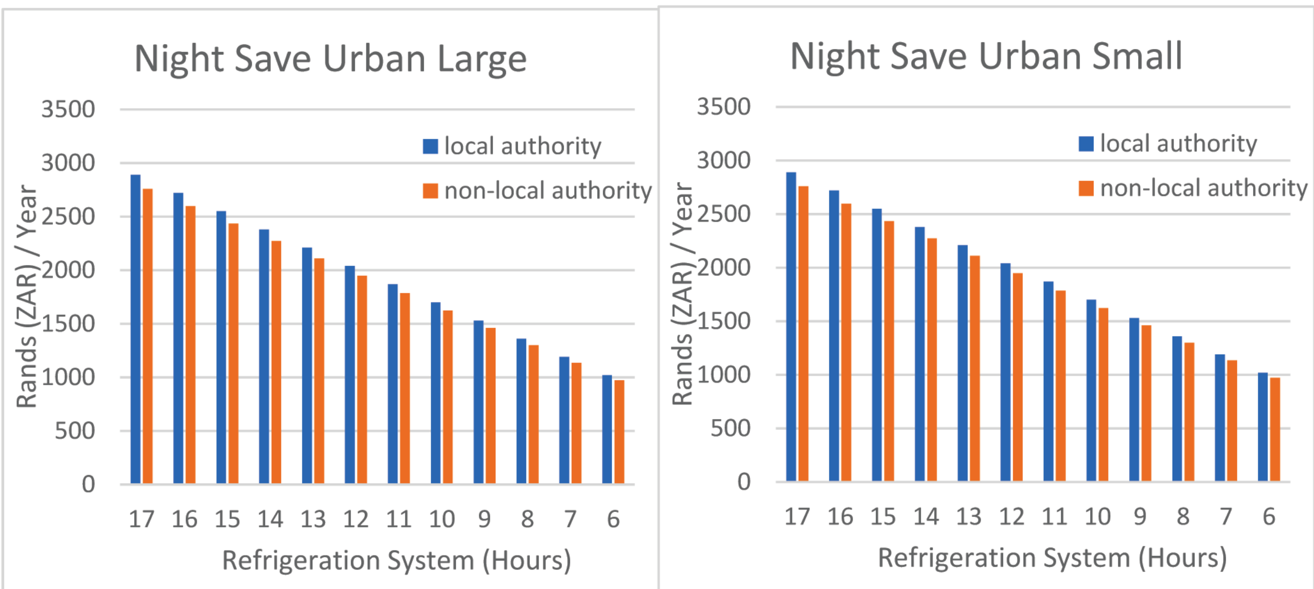

Figure 11: Tariff plan pricing for cold room operation/year

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

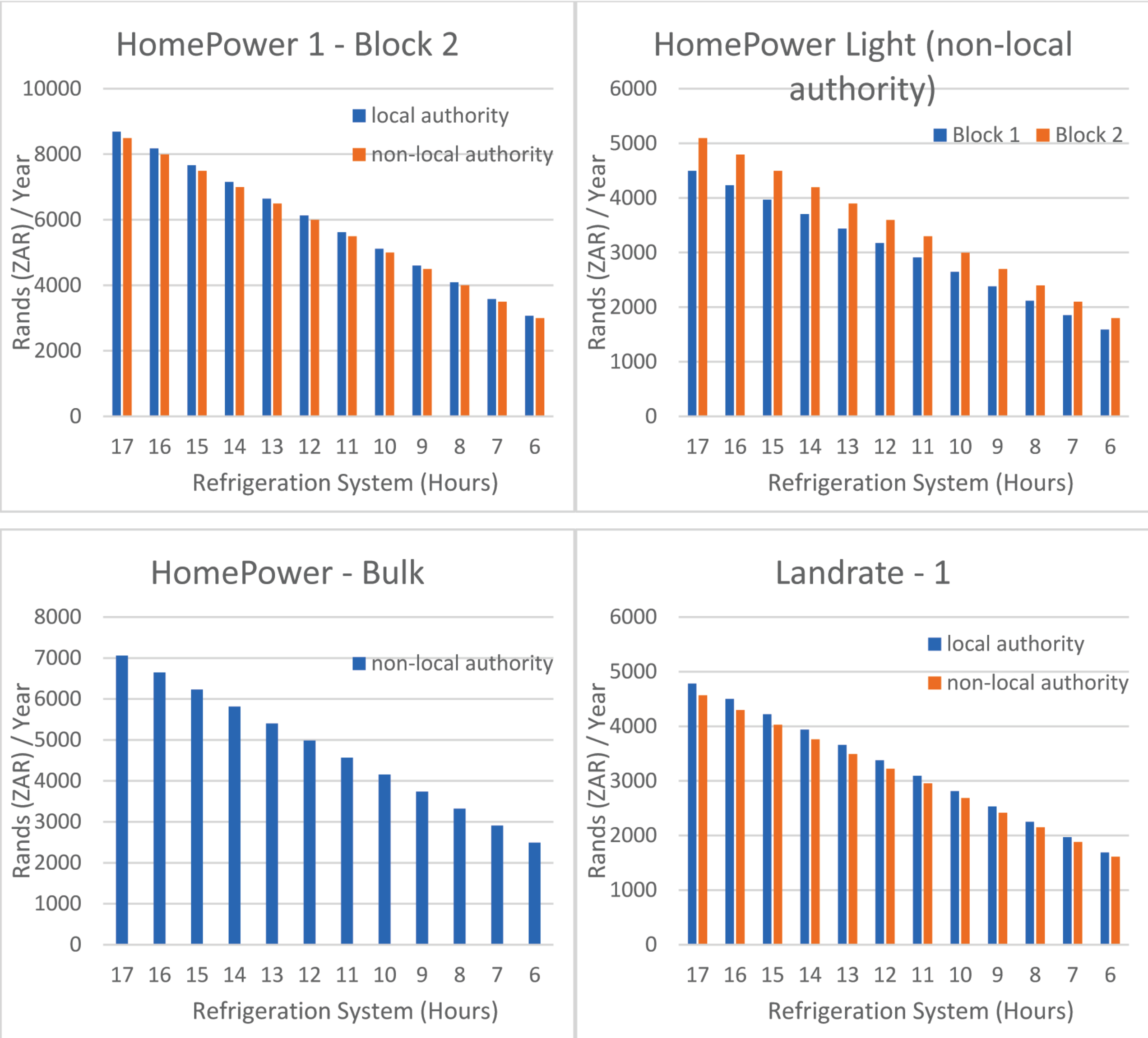

Figure 11: Tariff plan pricing for cold room operation/year *(continued)*

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.

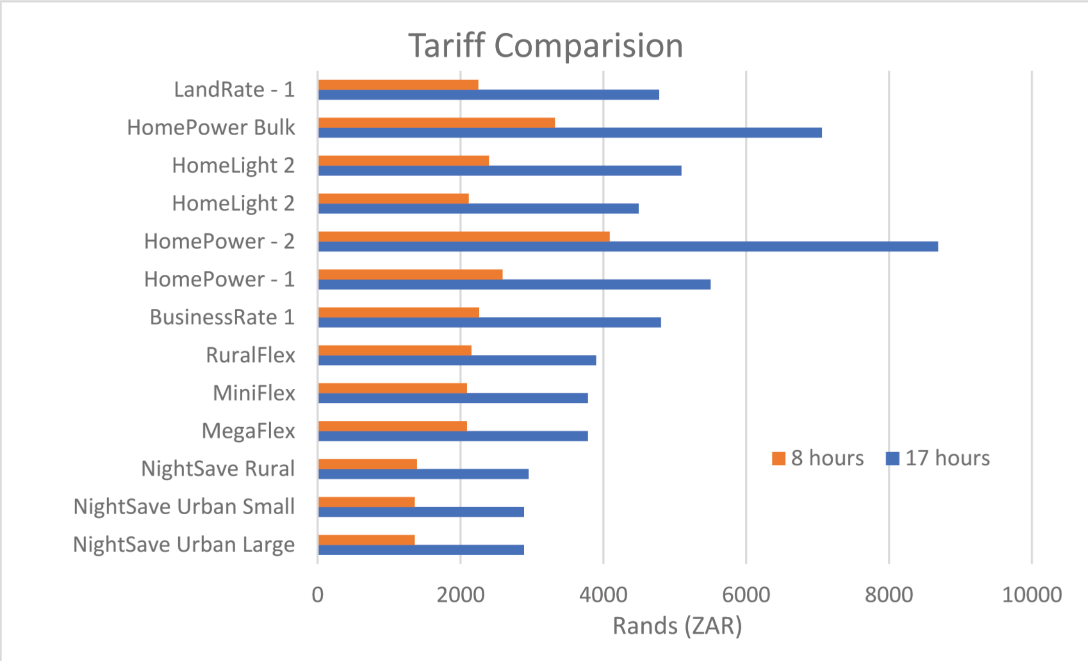

Figure 12: Tariff comparison after integrating LHTESS

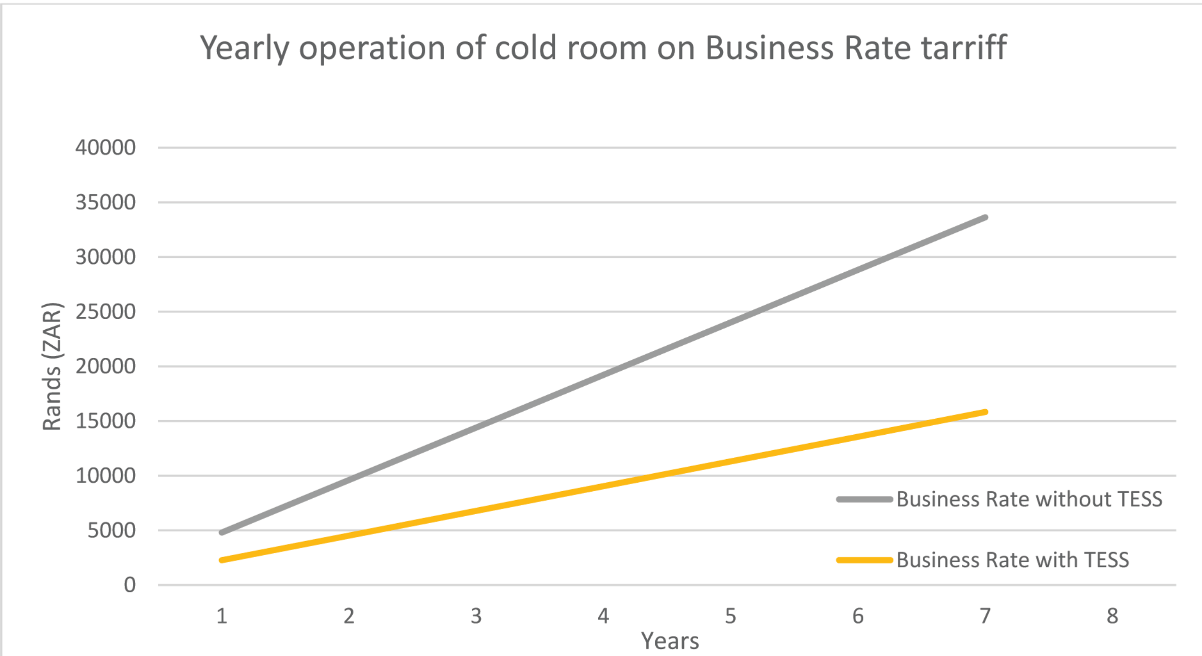

Figure 13: Yearly operation of cold room on Business Rate tariff

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

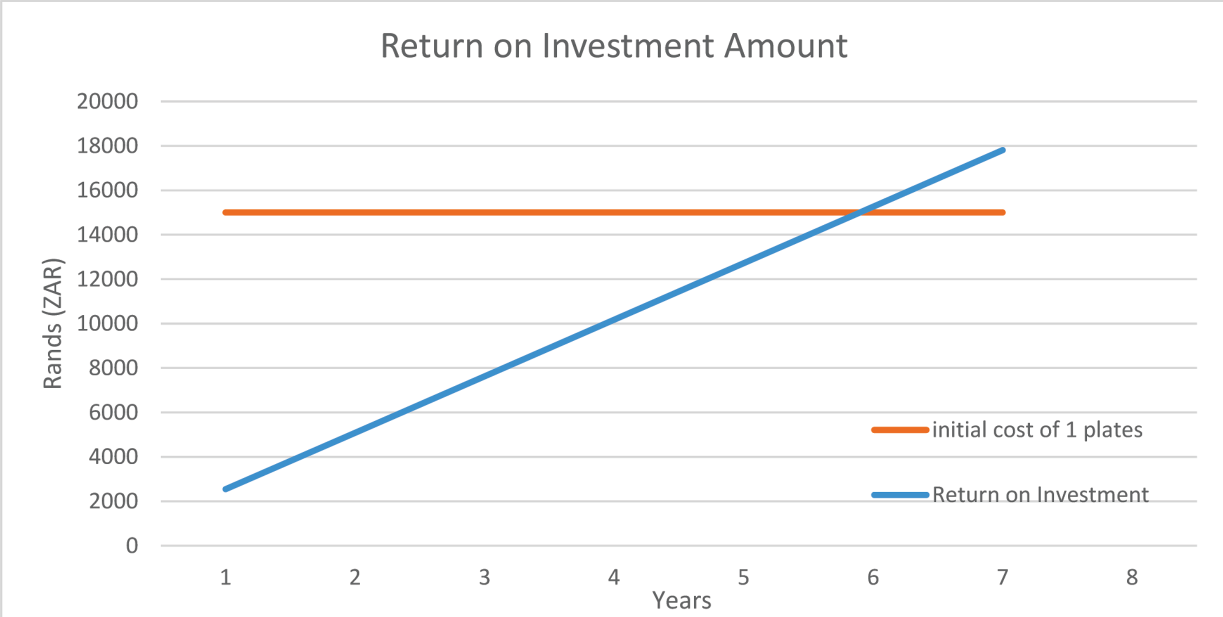

Figure 14: Return on investment amount

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.

ORCID

BT Radebe https://orcid.org/0000-0003-2796-9084

Dates

Submit: 13/05/2022
Accept: 24/11/2022
Publish: 01/06/2023

References

Cabeza, L.F., Castell, A., Barreneche, C., et al., 2011, Materials used as PCM in thermal energy storage in buildings: A review, *Renewable and Sustainable Energy Reviews* 15(3), 1675-1695. https://doi.org/10.1016/j.rser.2010.11.018.

Cabeza, L.F., Martorell, I., Miró, L., et al., 2021, Introduction to thermal energy storage systems, *Advances in Thermal Energy Storage Systems*, 1-33. https://doi.org/10.1016/B978-0-12-819885-8.00001-2.

Dincer, I. & Rosen, M.A., 2011, Thermal Energy Storage, John Wiley & Sons, Inc., Britain.

Du, K., Calautit, J., Wang, Z., et al., 2018, A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges, *Applied Energy* 220, 42-273. https://doi.org/10.1016/j.apenergy.2018.03.005.

Eskom, 2021, Eskom schedule of standard prices 2020/21, SC0207(202).

Eskom Ltd., 2021, Tariffs & charges booklet 2021/2022, 20. Available from: http://www.eskom.co.za/CustomerCare/TariffsAndCharges/Documents/ESKOM TC BOOKLET 2012-13 FINAL 3.pdf.

Evans, J., Foster, A., Huet, J.M., et al., 2014, Specific energy consumption values for various refrigerated food cold stores, *Refrigeration Science and Technology*, 74, 141-151. https://doi.org/10.1016/j.enbuild.2013.11.075.

FIC. 2019, Eutectic Plates – Accumulation systems for transport refrigeration, Italy.

FIC S.p.A. 2018, Eutectic Plates, Via Trivulzia, Available from: https://www.fic.com/en/product/eutectic-plates.

Gibb, D., Seitz, A., Johnson, M., et al., 2018, Applications of thermal energy storage in the energy transition – benchmarks and developments. Available from: https://www.eces-a30.org/publications/.

Huan, Z., 2016, Heat load calculation in refrigeration and air conditioning, first edit, pp. 134-152.

Kaygusuz, K., 2003, Phase change energy storage for solar heating systems, *Energy Sources* 25(8), 791-807. https://doi.org/10.1080/00908310390207837.

Lambert, K. & Roberto, P., 2014, 2014 Report of the refrigeration, air conditional and heat pumps technical options committee.

Lazaro, A., Delgado, M., König-Haagen, A., et al., 2020, Technical performance assessment of phase change material components, *Proceedings of the ISES Solar World Congress 2019 and IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry* 2018, 1236-1247. https://doi.org/10.18086/swc.2019.22.05.s

Liu, M., Saman, W., Bruno, F., 2012, Development of a novel refrigeration system for refrigerated trucks incorporating phase change material, *Applied Energy* 92, 336-342. https://doi.org/10.1016/j.apenergy.2011.10.015.

Maphatsoe, K., 2021, Solar viable amid power outages, *Creamer Media - Engineering News* 78.

National Cleaner Production Centre n.d., Resource efficiency and cleaner production: A guide to understanding your industrial electricity bill, Available from: http://ncpc.co.za/files/Guides/How to Read Your Electricity guide Book.pdf.

Ndanduleni, A.U.C. & Huan, Z., 2019, Review on phase change materials for sub-zero temperature application in transport refrigeration, 1-10.

Oró, E., Miró, L., Farid, M.M., et al., 2014, Energy management and CO2 mitigation using phase change materials (PCM) for thermal energy storage (TES) in cold storage and transport, *International Journal of Refrigeration* 42, 26-35. https://doi.org/10.1016/j.ijrefrig.2014.03.002.

Raam Dheep, G. & Sreekumar, A., 2014, Influence of nanomaterials on properties of latent heat solar thermal energy storage materials - A review, *Energy Conversion and Management* 83, 133-148. https://doi.org/10.1016/j.enconman.2014.03.058.

Radebe, T.B., Huan, Z., Baloyi, J., 2020, A simulation study of natural convection airflow pattern for a phase change material chamber, *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.3637981.

Radebe, T.B., Huan, Z., Baloyi, J., 2020, Simulation of eutectic plates in medium refrigerated transport, *Journal of Engineering, Design and Technology*. https://doi.org/10.1108/JEDT-02-2020-0065.

Selvnes, H., Allouche, Y., Manescu, R.I., et al., 2021, Review on cold thermal energy storage applied to refrigeration systems using phase change materials, *Thermal Science and Engineering Progress* 22, 100807. https://doi.org/10.1016/j.tsep.2020.100807.

Vadhera, J., Sura, A., Nandan, G., et al., 2018, Study of phase change materials and its domestic application, *Materials Today: Proceeding* 5(2), 3411-3417. https://doi.org/10.1016/j.matpr.2017.11.586.

Veerakumar, C. & Sreekumar, A., 2016, Phase change material based cold thermal energy storage: Materials, techniques and applications - A review, *International Journal of Refrigeration*67, 271-289. https://doi.org/10.1016/j.ijrefrig.2015.12.005.

Xu, B., Li, P., Chan, C., 2015, Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: A review to recent developments, *Applied Energy* 160, 286-307. https://doi.org/10.1016/j.apenergy.2015.09.016.

Yang, T., Wang, C., Sun, Q., et al., 2017, Study on the application of latent heat cold storage in a refrigerated warehouse, *Energy Procedia* 142, 3546-3552. https://doi.org/10.1016/j.egypro.2017.12.243.

Zalba, B., Marín, J.M., Cabeza, L.F., et al., 2003, Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications, *Applied Thermal Engineering* 23(3), 251-283. https://doi.org/10.1016/S1359-4311(02)00192-8.