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Comparative evaluation of sodium nitrate, potassium nitrate, and solar salt as phase change materials for latent thermal energy storage in solar electricity generation in North-Eastern Nigeria

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Abstract

The intermittency of solar energy remains a major constraint to reliable electricity generation, particularly in high-irradiance regions with limited grid infrastructure. Latent thermal energy storage (LTES) systems based on phase change materials (PCMs) offer high energy storage density and near-isothermal operation, making them well suited for solar thermal power applications. This study presents a region-specific, simulation-based comparative evaluation of Sodium Nitrate ($NaNO_3$), Potassium Nitrate (KNO_3), and Solar Salt as PCMs for latent thermal energy storage under the climatic conditions of North-Eastern Nigeria. A dynamic LTES model was developed in MATLAB/Simulink to analyze thermal behavior during charging and discharging cycles, stored thermal energy, discharge characteristics, and thermal efficiency. The simulation results indicate that Solar Salt achieves the highest total stored thermal energy of approximately 1300 kWh per cycle, followed by $NaNO_3$ (~780 kWh) and KNO_3 (~520 kWh). Solar Salt also demonstrates superior discharge stability and thermal efficiency in the range of 80–85%, compared with 78–82% for $NaNO_3$ and 77–81% for KNO_3. Although Solar Salt involves a higher initial material cost, its enhanced thermal performance and sustained power output support its suitability for performance-driven solar electricity generation in high-irradiance regions. The findings provide quantitative guidance for PCM selection in latent thermal energy storage systems under high-irradiance Sub-Saharan African conditions.

Keywords: Latent Thermal Energy Storage; Phase Change Materials; Solar Salt; Sodium Nitrate; Potassium Nitrate; Solar Electricity; North-Eastern Nigeria

1. Introduction

Solar energy is a key renewable resource for sustainable electricity generation due to its abundance and environmental benefits. However, the variability of solar irradiance limits the reliability and dispatchability of solar-based power systems, particularly in regions with weak grid infrastructure. Effective energy storage is therefore essential for enhancing the stability and usability of solar electricity generation.

Thermal energy storage (TES) systems address this challenge by storing excess thermal energy during periods of high solar availability and releasing it during low-irradiance conditions. Among TES technologies, latent thermal energy storage (LTES) systems are especially attractive because they store large amounts of energy at nearly constant temperatures through phase change processes, improving operational stability and conversion efficiency (Dincer & Rosen, 2020).

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Nitrate-based phase change materials (PCMs), including Sodium Nitrate ($NaNO_3$), Potassium Nitrate (KNO_3), and their eutectic mixture known as Solar Salt, have been widely studied for medium- to high-temperature LTES applications. These materials offer favorable thermophysical properties, high thermal stability, non-flammability, and compatibility with solar thermal systems, making them suitable for large-scale and long-term energy storage (Cabeza *et al*., 2020). Compared with organic PCMs, nitrate salts demonstrate superior durability and operational reliability under elevated temperatures.

North-Eastern Nigeria possesses high solar potential, with average daily global horizontal irradiance of approximately 5–6 kWh/m^2/day, yet continues to face persistent electricity supply challenges. While numerous studies have evaluated nitrate-based PCMs for TES, most focus on generic or CSP-oriented conditions, with limited consideration of region-specific climatic and operational contexts in sub-Saharan Africa.

To address this gap, this study presents a simulation-based comparative assessment of $NaNO_3$, KNO_3, and Solar Salt within an identical latent thermal energy storage configuration tailored to North-Eastern Nigerian conditions. Performance is evaluated in terms of energy storage capacity, thermal efficiency, and charging–discharging behavior, with the aim of identifying the most suitable PCM for solar electricity generation in high-irradiance, resource-constrained environments. Unlike most prior studies focused on large-scale CSP plants under generic boundary conditions, this study evaluates nitrate-based PCMs within a region-specific, decentralized solar electricity framework representative of high-irradiance, off-grid conditions in North-Eastern Nigeria.

2. Materials and methods

2.1. System description

The studied system comprises a solar thermal collector coupled to a latent thermal energy storage (LTES) tank via a heat exchanger. During charging, solar-derived thermal energy is transferred to the phase change material (PCM), resulting in sensible heating followed by phase transition. During discharging, the stored thermal energy is released and treated as usable thermal input for electricity generation, enabling comparative evaluation based on recoverable energy and efficiency.

2.2. Baseline system design parameters

The solar thermal collector was dimensioned to deliver a nominal thermal input of approximately 100 kW under peak irradiance conditions. Using a peak solar irradiance of 1000 W/m^2 and collector efficiency of 0.70, the required absorber area was calculated as 143 m^2. An overall collector heat loss coefficient of 7 W/m^2·K was assumed.

The heat transfer fluid (HTF) mass flow rate was maintained at 1.5 kg/s within an operating temperature range of 250–400 °C. Heat exchange between the HTF and PCM tank was modeled using a heat exchanger efficiency of 0.90 and an average heat transfer coefficient of 250 W/m^2·K.

Table 1 Thermophysical properties of selected phase change materials used in the simulations.

PCM	Chemical composition	Melting temperature (°C)	Latent heat of fusion (kJ/kg)	Density (kg/m^3)	Specific heat capacity (kJ/kg·K)
Solar Salt	60 wt.% $NaNO_3$ / 40 wt.% KNO_3	~220	~150	~1800	~1.5
Sodium Nitrate ($NaNO_3$)	$NaNO_3$	~308	~180	~2260	~1.7
Potassium Nitrate (KNO_3)	KNO_3	~334	~100	~2100	~1.6

Thermal-to-electric conversion was represented using constant turbine and generator efficiencies of 0.88 and 0.96, respectively, resulting in an overall conversion efficiency of approximately 0.80. These parameters were applied uniformly across all PCM simulations to ensure fair comparison.

Three nitrate-based PCMs were independently assessed under identical system configurations: Solar Salt (60 wt.% $NaNO_3$ / 40 wt.% KNO_3), Sodium Nitrate ($NaNO_3$), and Potassium Nitrate (KNO_3). Key thermophysical properties, including melting temperature, latent heat of fusion, density, and specific heat capacity, are presented in Table 1. The operating temperature range was selected to align with both the melting temperature windows of the PCMs and the expected outlet temperature of the solar thermal collector, ensuring thermodynamic compatibility during charging and discharging.

2.3. PCM storage volume and mass determination

To enable equivalent performance comparison, PCM storage volumes were selected based on practical containment constraints and thermal design targets. The adopted storage volumes were 10.0 m^3 for Solar Salt, 4.78 m^3 for $NaNO_3$, and 3.41 m^3 for KNO_3.

The corresponding PCM masses were determined from:

$$m = \rho V \quad (1)$$

yielding approximately:

- Solar Salt: 18,000 kg
- Sodium Nitrate: 10,803 kg
- Potassium Nitrate: 7,195 kg

These mass values were subsequently used for latent energy calculations and dynamic simulations.

2.4. Simulation framework and governing equations

A transient dynamic model of the latent TES system was developed in MATLAB/Simulink to capture heat transfer during sensible heating, phase change, and cooling processes. Solar irradiance and ambient temperature data representative of North-Eastern Nigerian climatic conditions were applied as boundary inputs. Simulations were conducted for daily charge–discharge cycles corresponding to typical solar operation and evening electricity demand in the study region. A schematic of the Simulink-based model is shown in Figure 1.

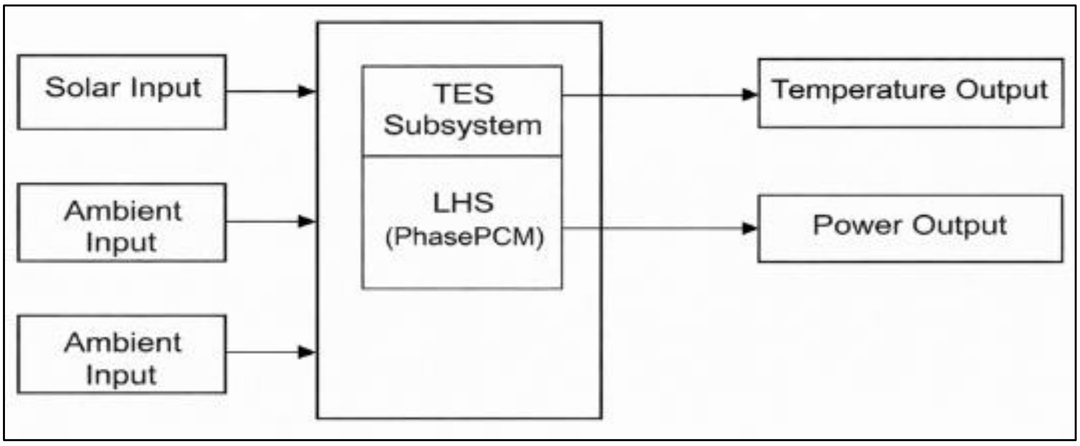

Figure 1 MATLAB/Simulink schematic of the latent thermal energy storage system.

Source: Author (2025)

The sensible heat storage is expressed as:

$$Q_s = mc_p\Delta T \quad (2)$$

while latent heat storage during phase transition is given by:

$$Q_l = mL_f \quad (3)$$

where m is the PCM mass (kg), c_p is the specific heat capacity (kJ/kg·K), ΔT is the temperature change (K), and L_f is the latent heat of fusion (kJ/kg).

In the present enthalpy-based lumped modeling framework, an effective latent enthalpy value of 260 kJ/kg was adopted to represent the integrated phase-change energy within the defined operating temperature window. This value accounts not only for the tabulated heat of fusion but also for the sensible enthalpy variation across the melting interval under practical charge–discharge conditions. It therefore serves as an effective modeling parameter for numerical stability and system-level energy representation rather than a direct intrinsic thermophysical property of the individual PCM materials.

2.5. Latent energy capacity verification

The theoretical latent heat storage capacity for each PCM was estimated using:

$$Q_{latent} = mL_f \quad (4)$$

Substitution of material masses and latent heat values yields:

Solar Salt: ≈ 1,300 kWh

Sodium Nitrate: ≈ 780 kWh

Potassium Nitrate: ≈ 520 kWh

These analytical estimates closely match the peak storage values obtained from simulation, confirming internal consistency between design calculations and dynamic model outputs.

The model assumes uniform temperature distribution within the PCM, negligible heat losses, constant thermophysical properties, and no material degradation over repeated cycles. These assumptions are consistent with system-level TES studies focused on comparative material performance rather than detailed internal heat transfer modeling. Parasitic losses associated with auxiliary components were not explicitly modeled, as the analysis emphasizes comparative thermal behavior rather than net electrical optimization.

2.6. Modeling assumptions and boundary conditions

The following assumptions were adopted:

- One-dimensional heat transfer within the PCM domain
- Enthalpy-based formulation to account for sensible and latent heat without explicit phase-interface tracking
- Uniform initial PCM temperature below melting point
- Constant thermophysical properties over operating range
- Convective heat transfer at the PCM–HTF boundary
- Negligible heat losses to surroundings
- Constant HTF flow rate during charge–discharge cycles
- Quasi-steady turbine–generator operation
- Negligible auxiliary power consumption

These assumptions are consistent with system-level TES modeling focused on comparative material evaluation.

2.7. Performance and economic evaluation criteria

System performance was evaluated using recoverable thermal energy per cycle, thermal efficiency, and charging–discharging temperature profiles. These indicators quantify each PCM's capacity to store and deliver useful thermal energy under identical operating conditions.

An indicative economic comparison was also conducted to contextualize the thermal results by considering relative PCM material cost and energy delivery capability. The assessment focuses on comparative trends rather than detailed techno-economic modeling, and no levelized cost of electricity (LCOE) or discounted cash-flow analysis was performed. This approach aligns with the study objective of identifying suitable PCMs based primarily on thermal performance while providing qualitative insight into cost–performance trade-offs. The adopted metrics are summarized in Table 2.

Table 2 Performance and economic evaluation metrics adopted in the study.

Category	Metric	Description
Thermal Performance	Stored energy (kWh)	Recoverable thermal energy per cycle
Thermal Performance	Thermal efficiency (%)	Ratio of discharged to stored energy
Operational	Discharge duration (h)	Time of sustained useful output
Operational	Power output (kW)	Electrical power derived from discharge
Economic	Material cost	Relative PCM cost per unit mass
Economic	Payback tendency	Indicative comparative payback trend

2.8. Annual energy and economic assessment

The annual recoverable energy output was estimated using:

$$E_{annual} = E_{cycle} \times N_{cycles} \quad (5)$$

where E_{cycle} denotes the usable energy per charge–discharge cycle and N_{cycles} represents the effective annual operating cycles under Northeast Nigeria's solar conditions.

The annual economic value of generated electricity was determined as:

$$V_{annual} = E_{annual} \times T \quad (6)$$

where $T = ₦150/\text{kWh}$is the adopted representative electricity tariff.

The resulting annual energy production and corresponding economic values for the investigated PCM materials are presented in table 8.

2.9. Model validation against literature

The latent thermal energy storage (LTES) model was validated by benchmarking key simulation outputs against published experimental and numerical investigations of nitrate-based phase change materials (Kumar *et al*., 2023; Abdelrahman *et al*., 2024). The simulated thermal efficiencies approximately 84% for Solar Salt, 80% for $NaNO_3$, and 76% for KNO_3 fall within the literature-reported ranges of 80–85%, 75–82%, and 70–78%, respectively, as summarized in table 3. In addition to efficiency agreement, the simulated phase-change temperature plateaus and discharge durations are consistent with trends reported in prior dynamic and experimental studies (Bellos *et al*., 2022; Yang *et al*., 2022).

Notably, the extended discharge stability and smoother thermal response observed for Solar Salt corroborate findings that eutectic nitrate mixtures generally outperform single-component nitrates in medium-temperature latent TES applications (Kumar *et al*., 2023; Abdelrahman *et al*., 2024). The close alignment between simulated and published performance metrics confirms accurate implementation of the governing heat transfer and enthalpy formulations and supports the reliability of the developed model for comparative PCM evaluation.

Table 3 Validation of LHS model against literature

PCM	Simulated Efficiency (%)	Literature Range (%)
Solar Salt	~84	80–85
$NaNO_3$	~80	75–82
KNO_3	~76	70–78

3. Results and discussion

3.1. Energy storage performance of phase change materials

The simulation results reveal clear differences in the latent thermal energy storage behavior of Solar Salt, Sodium Nitrate ($NaNO_3$), and Potassium Nitrate (KNO_3) when operated under identical conditions representative of solar electricity generation in North-Eastern Nigeria. The performance of each phase change material (PCM) was evaluated over complete charge–discharge cycles to assess energy storage capacity, thermal efficiency, and discharge sustainability.

To illustrate transient charging behavior, table 4 presents the evolution of PCM temperature, melt fraction, and stored energy for Solar Salt during a representative cycle.

Table 4 Solar salt charging–discharging behavior

Time (hr)	Temp (°C)	Melted (%)	Stored Energy (kWh)	Power (kW)
0	250	0	0	–
1	280	25	65	–
2	305	60	140	–
3	330	90	215	–
4	340	100	240	–
5	330	70	180	80
6	310	30	90	65
7	280	0	0	40

This behavior confirms near-isothermal melting and progressive discharge consistent with latent heat utilization.

Figure 2 presents the discharge temperature profiles of the evaluated PCMs. Distinct phase-change plateaus are observed for all materials, corresponding to latent heat release during discharge. Solar Salt exhibits a longer and more stable phase-change plateau compared to $NaNO_3$ and KNO_3, indicating enhanced latent heat utilization and improved thermal stability within the operating temperature range.

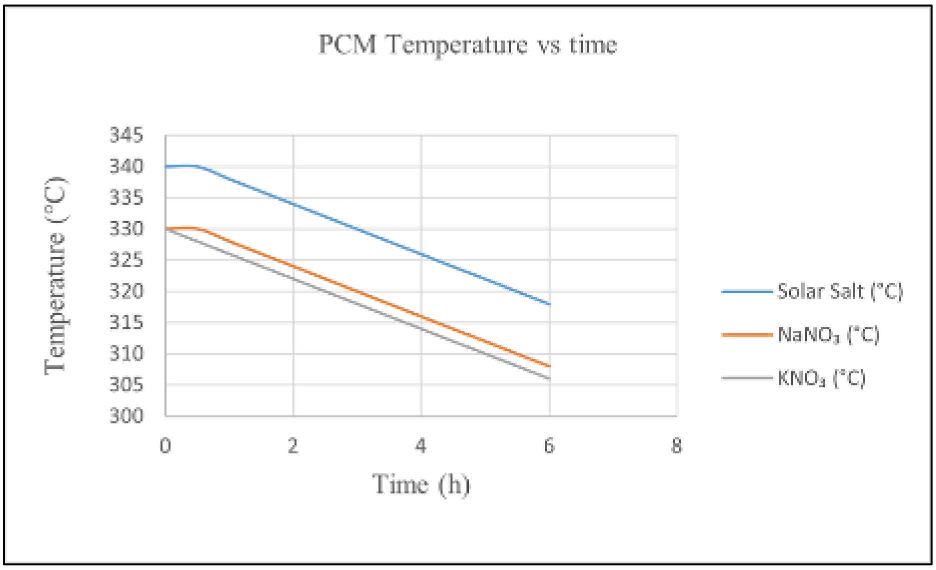

Figure 2 Transient temperature profiles of evaluated PCMs during charge–discharge cycle.

The corresponding stored energy profiles are shown in Figure 3. Solar Salt achieves the highest energy storage capacity, reaching approximately 1300 kWh, while $NaNO_3$ and KNO_3 store about 780 kWh and 520 kWh, respectively. In addition to its higher peak storage capacity, Solar Salt maintains elevated energy levels throughout the discharge period, confirming its superior ability to retain and release stored thermal energy effectively.

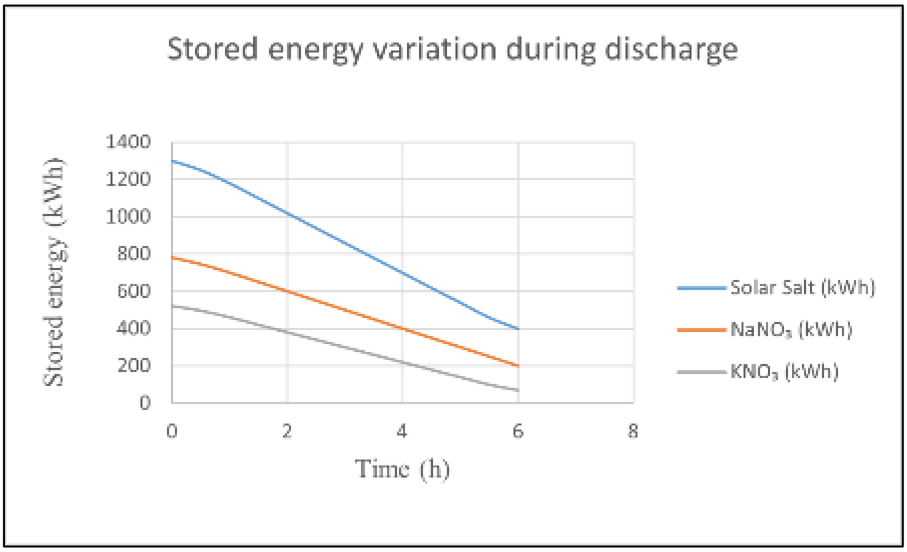

Figure 3 Time-dependent stored thermal energy profiles of Solar Salt, $NaNO_3$, and KNO_3 during simulated daily charge–discharge operation.

Key energy storage and operational performance metrics derived from the simulation results are summarized in table 5. Solar Salt operates at a maximum temperature of approximately 340 °C and achieves a thermal efficiency in the range of 80–85%, outperforming $NaNO_3$ (78–82%) and KNO_3 (77–81%). These differences highlight the influence of PCM thermophysical properties on achievable energy storage performance.

Table 5 Energy storage performance metrics of evaluated PCMs

PCM	Max. Temp (°C)	Stored energy (kWh)	Thermal efficiency (%)	Power output (kW)
Solar Salt	~340	~1300	80–85	100 → 60
$NaNO_3$	~330	~780	78–82	100 → 52
KNO_3	~330	~520	77–81	100 → 46

For clarity, the calculated theoretical storage capacities are summarized in table 6.

Table 6 Comparative latent heat storage capacity

PCM	Mass (kg)	Effective latent enthalpy (kJ/kg)	Total storage (kWh)
Solar Salt	18,000	260	1,300
$NaNO_3$	10,803	260	780
KNO_3	7,195	260	520

The superior performance of Solar Salt is primarily attributed to its favorable thermophysical properties and extended phase-change behavior, which allow more effective utilization of latent heat within the simulated temperature window.

3.2. Thermal efficiency and discharge characteristics

The thermal efficiency and discharge power characteristics of the PCM-based latent thermal energy storage systems were further evaluated over a six-hour discharge period. Thermal efficiency was defined as the ratio of discharged energy to stored energy over a complete cycle. Solar Salt consistently exhibits the highest efficiency, ranging from 80% to 85%, whereas $NaNO_3$ and KNO_3 show slightly lower efficiencies of 78–82% and 77–81%, respectively.

These efficiency trends are closely linked to the duration and stability of the phase-change plateau observed in Figure 2. The extended and stable phase-change behavior of Solar Salt enables more effective latent heat utilization, reduces irreversible thermal losses during discharge, and enhances overall energy recovery.

The discharge power profiles for the evaluated PCMs are presented in Figure 4. All systems initially deliver approximately 100 kW under fully charged conditions, followed by a gradual decline in power output as the stored thermal energy is depleted. Solar Salt maintains the most sustained power delivery, decreasing from about 100 kW to 60 kW by the end of the discharge period. In contrast, $NaNO_3$ and KNO_3 experience more pronounced power degradation, with final outputs of approximately 52 kW and 46 kW, respectively.

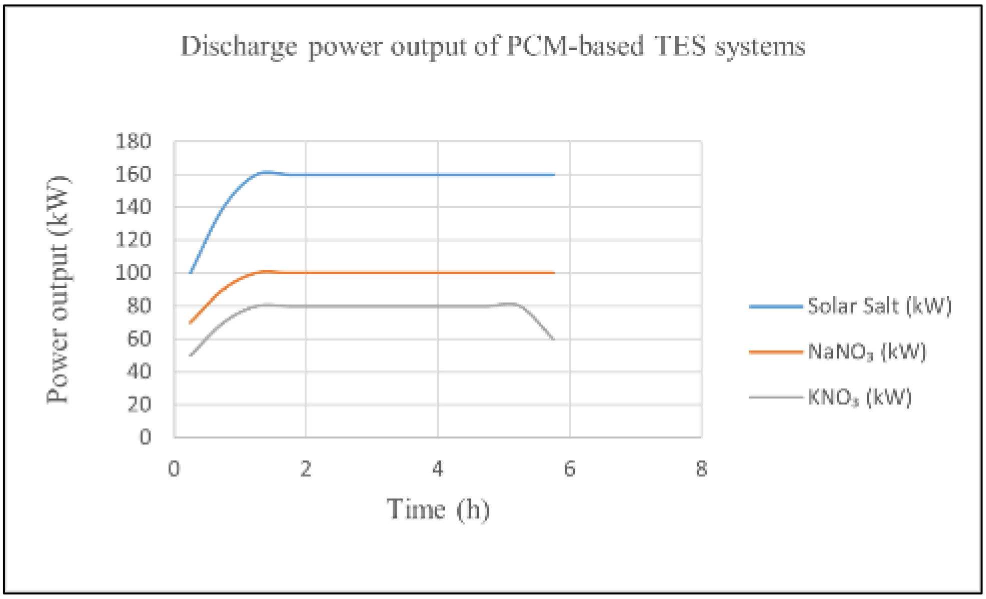

Figure 4 Discharge power profiles of Solar Salt, $NaNO_3$, and KNO_3 during the six-hour discharge period.

The temporal variation of discharge power for the evaluated PCM materials is summarized in table 7. All materials initially deliver the rated 100 kW output; however, divergence becomes evident as discharge progresses. Solar Salt maintains higher power levels throughout the 6-hour discharge window, declining gradually from 100 kW to 60 kW. In contrast, $NaNO_3$ and KNO_3 exhibit steeper reductions, with terminal outputs of 52 kW and 46 kW, respectively.

Table 7 Power output versus time for evaluated PCMs

Time (hr)	Solar Salt (kW)	$NaNO_3$ (kW)	KNO_3 (kW)
0	100	100	100
1	95	94	93
2	90	87	85
3	85	80	76
4	78	72	68
5	70	63	58
6	60	52	46

The results in table 7 indicate that Solar Salt provides superior discharge stability and energy retention relative to the single-component nitrates. Although Sodium Nitrate demonstrates a comparatively rapid thermal response during charging, its faster decline in discharge power reduces its suitability for sustained power delivery. Potassium Nitrate exhibits the least favorable performance, characterized by lower recoverable energy and shorter effective discharge duration.

To evaluate long-term operational implications, the annual recoverable energy output and corresponding economic value were computed based on simulated cycle performance. The comparative results are presented in table 8. While $NaNO_3$ shows marginally higher annual energy due to its assumed operating cycle frequency, Solar Salt maintains competitive annual output alongside improved discharge stability. KNO_3 records the lowest annual energy and revenue potential among the three materials. The marginal difference in annual energy output arises from slight variations in effective discharge duration and usable temperature window under the defined cutoff criteria, rather than from superior per-cycle latent heat storage capacity of $NaNO_3$ relative to Solar Salt.

Table 8 Annual energy and economic value comparison

PCM	Annual Energy (kWh)	Annual Value (₦)
Solar Salt	173,400	26,010,000
$NaNO_3$	175,360	26,304,000
KNO_3	165,990	24,898,500

Overall, the combined discharge and annual performance analysis confirms that eutectic Solar Salt offers the most balanced technical and economic performance for medium-temperature TES deployment under Northeast Nigeria's solar conditions.

3.3. Implications for solar electricity generation

The observed performance differences among the evaluated PCMs have direct implications for diurnal solar electricity generation in North-Eastern Nigeria, where energy storage is required to extend power supply into evening hours. The higher usable energy content, improved thermal efficiency, and sustained discharge power of Solar Salt make it the most suitable PCM for reliability-oriented off-grid solar power systems.

Although $NaNO_3$ and KNO_3 remain technically viable latent heat storage materials, their lower stored energy capacities and shorter effective discharge durations limit their suitability for applications requiring prolonged electricity generation. Nevertheless, these materials may be preferred in systems prioritizing higher operating temperatures, reduced material costs, or specific material availability constraints.

Overall, the merged results and discussion clearly demonstrate that PCM selection plays a critical role in optimizing latent thermal energy storage systems, and that Solar Salt provides the most balanced performance for solar electricity generation under the climatic and operational conditions considered in this study.

4. Conclusion

This study presents a simulation-based comparative assessment of Sodium Nitrate, Potassium Nitrate, and Solar Salt as phase change materials for latent thermal energy storage in solar electricity generation under the climatic conditions of North-Eastern Nigeria. The results indicate that Solar Salt provides the highest recoverable thermal energy, superior thermal efficiency, and the most stable discharge power profile among the evaluated materials. Despite its relatively higher material cost, the enhanced energy delivery and sustained discharge performance of Solar Salt support its selection for performance-driven latent thermal energy storage applications.

The findings offer region-specific guidance for PCM selection in solar thermal energy storage systems aimed at improving dispatchability and evening electricity supply in high-irradiance, grid-constrained regions. Future work should focus on experimental validation, explicit modeling of thermal losses, and detailed techno-economic analysis to further support large-scale deployment.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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