

SIMULATION-BASED PERFORMANCE ASSESSMENT OF ROCK-BED SENSIBLE THERMAL ENERGY STORAGE FOR OFF-GRID SOLAR ELECTRICITY GENERATION IN NORTH-EASTERN NIGERIA

Wilfred Manliura Amthombata¹, Abubakar Alkasim² & Pascal Timtere³

¹*Physics Department, Faculty of Science Education, Adamawa State College of Education,
Hong, Nigeria*

manliurawilfred45@yahoo.com/+2347035886631

²*Physics Department, Faculty of Physical Sciences, Modibbo Adama University, Yola,
Nigeria*

alkasimabbat@mau.edu.ng/+2348180403135

³*Physics Department, Faculty of Physical Sciences, Modibbo Adama University, Yola,
Nigeria*

timterepascal@mau.edu.ng/+2347039048370

Corresponding Author: Wilfred, M. A. (*manliurawilfred45@yahoo.com*)

ARTICLE INFO

Article No.: 0195

Accepted Date: 03/02/2026

Published Date: 05/03/2026

Type: Research

ABSTRACT

Limited access to reliable electricity remains a major development challenge in North-Eastern Nigeria despite the region's high solar energy potential. This study presents a simulation-based assessment of a rock-bed sensible thermal energy storage (SHS) system integrated into a 100 kWh decentralized solar thermal electricity generation configuration for off-grid applications. A transient MATLAB/Simulink model incorporating region-specific solar irradiance and ambient temperature data was developed to evaluate charging–discharging behavior, thermocline evolution, and system-level performance under representative operating conditions. Simulation results indicate a maximum recoverable stored thermal energy of approximately 210 kWh per cycle within the rock-bed TES unit. When integrated with direct solar thermal input to the power conversion block, the overall hybrid system delivers a total daily usable energy output of approximately 497 kWh. These values correspond to different system boundaries—stored TES output versus combined direct-plus-stored solar contribution—and therefore do not imply energy amplification beyond storage capacity. The system achieved an average thermal storage efficiency of 75–78%, consistent with reported packed-bed TES performance ranges. Sensitivity analysis identifies specific heat capacity as the dominant material parameter affecting stored energy, while heat transfer fluid mass flow rate primarily governs discharge stability. A preliminary techno-economic screening based on simplified cost assumptions suggests competitive performance; however, comprehensive capital, balance-of-plant, and financing costs were not fully modeled and are required for investment-level feasibility evaluation.

Keywords: Rock-bed, thermal energy storage; sensible heat storage; solar thermal electricity;

Introduction

Limited access to reliable electricity remains a major barrier to socio-economic development across sub-Saharan Africa, with Nigeria experiencing one of the most severe electricity access deficits globally (World Bank, 2020; International Energy Agency [IEA], 2022). Despite being the largest economy in Africa, an estimated 85 million Nigerians lack access to grid electricity, a challenge that is particularly acute in the North-Eastern region due to insecurity, underdeveloped infrastructure, and widespread poverty (Oyedepo *et al.*, 2018). These conditions have resulted in heavy reliance on diesel generators and other polluting energy sources, especially in rural and off-grid communities.

Solar energy presents a technically viable alternative for expanding electricity access in North-Eastern Nigeria, as the region benefits from high levels of solar irradiance, typically ranging between 5.5 and 6.5 kWh/m²/day (National Aeronautics and Space Administration [NASA], 2023; European Commission, Joint Research Centre, 2023). However, the intermittent nature of solar radiation limits its ability to provide stable and continuous electricity supply without effective energy storage solutions (International Renewable Energy Agency [IRENA], 2016). Energy storage systems are therefore essential for improving the reliability and dispatchability of solar-based power generation in the region.

Thermal energy storage (TES) technologies have proven effective in mitigating solar intermittency by storing excess thermal energy during periods of high solar availability and releasing it during low-irradiance periods (IEA, 2020; Hasan *et al.*, 2020). When integrated with solar thermal systems, TES offers advantages such as operational flexibility, high energy density, and long service life, thereby enhancing the dispatchability of solar electricity generation (Alva *et al.*, 2021; Mahdi & Zaki, 2023). Among available TES options, sensible heat storage using solid materials such as rock beds has attracted significant interest due to its thermal stability, availability, and low cost.

Despite increasing global research on TES technologies, studies focusing on their application under the climatic and socio-economic conditions of sub-Saharan Africa remain limited. In particular, there is a lack of simulation-based assessments evaluating the performance of rock-bed sensible heat storage systems for off-grid solar electricity generation in arid and semi-arid regions such as North-Eastern Nigeria. This study therefore evaluates the technical and economic performance of a rock-bed SHS system integrated with a solar thermal electricity generation scheme using region-specific data and dynamic simulation.

Although packed-bed sensible heat storage systems have been widely investigated for concentrated solar power applications, the majority of existing simulation studies are developed under temperate climatic assumptions typical of Europe, North America, and parts of Asia. These studies often assume moderate ambient temperatures (15–25°C), stable solar flux profiles, and idealized thermocline development conditions. However, arid and semi-arid regions such as North-Eastern Nigeria experience significantly elevated ambient temperatures (often exceeding 40°C during peak periods), high diurnal temperature gradients, and intense solar radiation variability. These conditions directly influence heat losses, thermocline stability, and effective storage utilization.

Furthermore, many published packed-bed TES models adopt simplified assumptions regarding constant thermophysical properties, uniform heat transfer coefficients, and idealized charging durations without explicitly evaluating storage capacity degradation under high-temperature ambient environments. Limited studies quantify the reduction in recoverable energy caused by accelerated thermal diffusion, elevated boundary heat losses, and shortened effective discharge windows under such climatic conditions. In addition, decentralized off-grid systems operating at medium-scale capacities (≈100 kW) have received comparatively less modeling attention than large-scale utility CSP installations, leaving a gap in performance assessment for rural electrification contexts.

This study addresses these modeling limitations by implementing a transient MATLAB/Simulink-based simulation framework tailored to the climatic conditions of North-Eastern Nigeria. Region-specific solar irradiance and ambient temperature data are incorporated to evaluate thermocline evolution, recoverable storage capacity, discharge stability, and hybrid system output under representative off-grid operating conditions. By focusing on a decentralized 100 kW system configuration, the study provides a context-adapted assessment of rock-bed sensible heat storage performance for high-solar, infrastructure-constrained environments.

Unlike previous studies that predominantly focus on large-scale concentrated solar power (CSP) plants, this study evaluates a decentralized, off-grid solar thermal system under region-specific climatic conditions representative of North-Eastern Nigeria. This localized modeling approach enables assessment of practical storage performance for rural electrification applications rather than utility-scale grid-connected installations.

Materials and methods

1 Study area and solar resource characteristics

The study focuses on North-Eastern Nigeria, represented by three major locations: Yola (Adamawa State), Damaturu (Yobe State), and Maiduguri (Borno State). These locations were selected based on their high solar potential, relevance to off-grid electrification, and representation of the region's arid and semi-arid climatic conditions. Long-term averaged solar irradiance and ambient temperature data were obtained from widely used satellite-based databases and applied as inputs to the simulation model. Key solar resource parameters, including global horizontal irradiance, ambient temperature, and sunshine duration, are summarized in Table 1 and were applied uniformly across the simulation framework to represent typical operating conditions for solar thermal electricity generation in North-Eastern Nigeria.

Table 1

Solar resource characteristics for North-Eastern Nigeria (Input to simulation model)

Parameter	Value	Unit
Average global horizontal irradiance (Yola, Adamawa)	5.90	kWh/m ² /day
Average global horizontal irradiance (Damaturu, Yobe)	5.99	kWh/m ² /day
Average global horizontal irradiance (Maiduguri, Borno)	6.07	kWh/m ² /day
Peak solar irradiance	6.5	kWh/m ² /day
Average ambient temperature	30	°C
Sunshine duration	6	h/day

Note. Values are based on PVGIS and NASA POWER databases (1990–2010).

2 System description

The modeled system consists of a solar thermal collector, a heat exchanger, an insulated cylindrical rock-bed thermal energy storage tank, and a power conversion unit for electricity generation. During the charging phase, thermal energy collected from solar radiation is transferred to the rock bed via a heat transfer fluid and stored sensibly by increasing the temperature of the solid storage medium. During the discharging phase, the stored thermal energy is recovered and supplied to the power conversion unit to support electricity generation. The system is designed for short-term (daily) thermal energy storage operation, consistent with the region's high daily solar irradiance and typical off-grid electricity demand patterns, which peak during evening hours. Rock-bed storage was selected due to its low material cost, thermal stability at high temperatures, environmental safety, and suitability for decentralized energy systems. The thermo-physical properties of the rock-bed material used in the model are presented in Table 2.

Table 2

Thermo-Physical properties of rock-bed storage material

Property	Value	Unit
Density	2600	kg/m ³
Specific heat capacity	920	J/kg·K
Thermal conductivity	2.5	W/m·K
Porosity	0.40	–

3 System design parameters and baseline operating conditions

The system was dimensioned for a nominal electrical output of 100 kW under peak solar conditions representative of North-Eastern Nigeria. Based on a peak irradiance of 1000 W/m² and an assumed collector efficiency of 0.70, the required collector aperture area was calculated as 143 m². An overall collector heat loss coefficient of 7 W/m²·K was adopted. The heat transfer fluid (HTF) mass flow rate was maintained at 1.5 kg/s, operating within a temperature range of 250–400 °C. The cylindrical rock-bed storage tank was designed with an effective storage volume of 9.2 m³. Heat exchange between the HTF and storage medium was modeled using an overall heat exchanger efficiency of 0.90 and an average heat transfer coefficient of 250 W/m²·K. 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 consistently across all simulations.

4 Simulation architecture and implementation

The system model was implemented in MATLAB/Simulink using a modular block-structured architecture to enhance numerical stability and subsystem transparency. The overall model comprises five primary interconnected subsystems:

- (i) Solar Input Subsystem
Converts time-dependent solar irradiance data into usable thermal input based on collector efficiency and aperture area.
- (ii) Heat Transfer Fluid (HTF) Circulation Subsystem
Models mass flow rate, inlet temperature conditions, and energy transport between the collector field and storage unit.
- (iii) Rock-Bed Thermal Energy Storage (TES) Subsystem
Implements transient energy balance equations governing packed-bed charging and discharging processes, including thermocline development and convective heat exchange between solid and fluid phases.
- (iv) Power Conversion Subsystem
Represents a simplified Rankine-cycle-based thermal-to-electric conversion block using an assumed thermal-to-electric efficiency.
- (v) Supervisory Control Logic
Manages charging and discharging modes based on solar availability and storage temperature thresholds.

Signal flow between subsystems is unidirectional during charging (Solar → HTF → TES) and reversed during discharge (TES → HTF → Power Block). This modular configuration allows independent validation of each subsystem and reduces numerical coupling instability.

5 Mathematical modeling

The thermal behavior of the rock-bed sensible heat storage system was modeled using a lumped-parameter transient energy balance approach. The governing energy balance equation is expressed as:

$$\rho c_p V \frac{dT}{dt} = \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{loss} \quad (1)$$

where ρ is the density of the rock material (kg·m⁻³), c_p is the specific heat capacity (J·kg⁻¹·K⁻¹), V is the effective storage volume (m³), and T is the average rock-bed temperature (K). $\dot{Q}_{in}$ represents the rate of thermal energy input during charging (W), $\dot{Q}_{out}$ is the useful thermal energy extracted during discharge (W), and $\dot{Q}_{loss}$ accounts for heat losses to the surroundings (W).

For completeness, temperature-dependent forms of thermophysical properties may be expressed in linearized form as:

$$k(T) = k_0 + bT \quad (2)$$

$$C_p(T) = C_{p0} + aT \quad (3)$$

$C_p(T)$ represents the specific heat capacity of the material at temperature T , measured in J/kg·K. The term C_{p0} denotes the reference specific heat capacity evaluated at a chosen baseline temperature. The coefficient a is the empirical temperature coefficient of specific heat capacity (J/kg·K²), which describes the rate at which specific heat capacity varies with temperature.

Similarly, $k(T)$ represents the thermal conductivity of the material at temperature T , expressed in $\text{W/m}\cdot\text{K}$. The parameter k_0 denotes the reference thermal conductivity at the baseline temperature, while b is the empirical temperature coefficient of thermal conductivity ($\text{W/m}\cdot\text{K}^2$), representing the linear rate of change of thermal conductivity with temperature representing the specific heat capacity of the material at temperature T , measured in $\text{J/kg}\cdot\text{K}$. The term C_{p0} denotes the reference specific heat capacity evaluated at a chosen baseline temperature. The coefficient a is the empirical temperature coefficient of specific heat capacity ($\text{J/kg}\cdot\text{K}^2$), which describes the rate at which specific heat capacity varies with temperature.

6 Analytical design verification

To verify consistency between the analytical design framework and the implemented simulation model, baseline sizing calculations were performed.

The total mass of the rock-bed storage medium was determined from:

$$m = \rho V \quad (4)$$

Substituting the adopted parameters:

$$m = 2600 \times 9.2 = 23,920 \text{ kg}$$

The theoretical sensible heat storage capacity was estimated using:

$$Q = mc_p \Delta T \quad (5)$$

Assuming a temperature rise of 150 K:

$$Q = 23,920 \times 920 \times 150 = 3.30 \times 10^9 \text{ J}$$

which corresponds to approximately 916.9 kWh of theoretical storage capacity.

Solar collector sizing was independently verified using:

$$Q_{in} = G\eta A \quad (6)$$

For a 100 kW design target:

$$A_{req} = \frac{100,000}{1000 \times 0.70} = 142.9 \text{ m}^2$$

The agreement between the analytical collector area and the adopted 143 m^2 confirms internal consistency between system design calculations and simulation inputs. Heat losses were modeled using an overall heat transfer coefficient applied at the storage tank boundaries, with losses assumed to be proportional to the temperature difference between the storage medium and the ambient environment. This formulation enables evaluation of transient temperature evolution, stored energy, and discharge behavior under realistic operating conditions.

7 Modeling assumptions and boundary conditions

To ensure numerical stability and alignment with established packed-bed TES modeling practice, the following assumptions were adopted:

- (i) Heat transfer within the storage tank was modeled as one-dimensional radial conduction.
- (ii) The rock bed was assumed to have a uniform initial temperature prior to charging.
- (iii) Thermophysical properties of the rock-bed material, including specific heat capacity and thermal conductivity, were initially treated as constant to simplify the transient solution of the energy balance equations. However, published high-temperature rock data indicate moderate temperature dependence over the 250–400 °C operating range. To evaluate the potential influence of property variation on storage predictions, a sensitivity analysis was performed by varying specific heat capacity (C_p) and thermal conductivity (k) within $\pm 10\%$ of their baseline values. This range reflects reported temperature-induced variation for silicate-based rock materials in high-temperature thermal storage applications.
- (iv) Convective heat transfer at the rock–HTF interface was governed by a constant heat transfer coefficient.
- (v) Internal heat generation within the storage medium was neglected.
- (vi) HTF mass flow rate remained constant during each charging–discharging cycle.
- (vii) The turbine–generator system was represented under quasi-steady operation with fixed efficiencies.
- (viii) Auxiliary power consumption was considered negligible.

These assumptions allow evaluation of intrinsic storage behavior without introducing additional power-cycle complexity beyond the scope of this study.

8 Numerical implementation and solver configuration

The transient TES model was implemented in MATLAB/Simulink using interconnected dynamic blocks representing solar input, heat transfer, thermal storage behavior, and power conversion. All governing energy balance equations presented in Section 2 were directly embedded into the simulation environment to compute transient temperature evolution, stored energy, and electrical output over a daily operating cycle. The block-diagram structure followed standard dynamic system modeling practices for thermal energy systems. The coupled differential equations were solved using MATLAB's variable-step ODE solver (ode45), based on the Dormand–Prince Runge–Kutta integration scheme, which is appropriate for non-stiff thermal systems. A relative tolerance of 1×10^{-5} and an absolute tolerance of 1×10^{-6} were specified to ensure numerical accuracy and stability of temperature predictions within the storage domain.

Simulations were performed over a 24-hour operational cycle with adaptive time stepping automatically controlled by the solver. To ensure adequate resolution of thermocline development and transient charging behavior, the maximum step size was restricted to 60 seconds. A preliminary time-step sensitivity analysis was conducted to verify numerical convergence. Further reduction of the maximum step size resulted in less than 1% variation in predicted stored energy, confirming stability and convergence of the numerical solution.

9 Simulink model architecture and subsystem interaction

To enhance procedural transparency and reproducibility, the modular structure of the MATLAB/Simulink implementation is illustrated in Figure 1. The system was constructed using interconnected functional subsystems representing solar energy collection, heat transfer fluid (HTF) circulation, thermal energy storage dynamics, and power conversion.

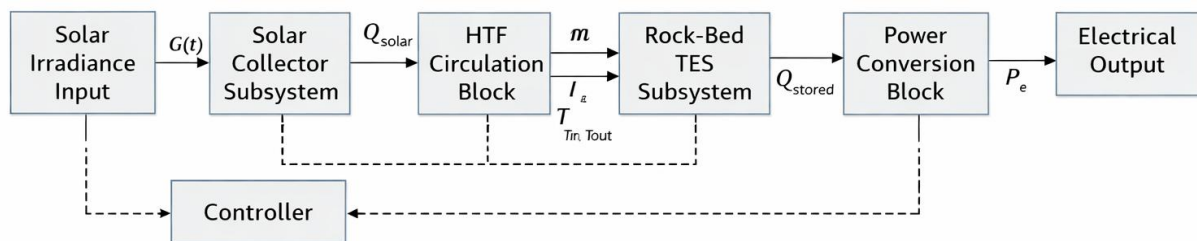


Figure 1: Modular simulink architecture of the solar–tes hybrid system

Solar irradiance input $G(t)$ drives the solar collector subsystem, which computes the collected thermal power Q_{solar} . This energy is transferred via the HTF circulation block, where mass flow rate $\dot{m}$, inlet temperature T_{in} , and outlet temperature T_{out} are dynamically evaluated. The thermal energy storage (TES) subsystem solves the transient energy balance within the packed bed domain to compute stored energy Q_{stored} and temperature evolution. The recovered thermal energy is subsequently converted into electrical output P_e through a simplified power conversion block. A supervisory controller regulates HTF flow rate and charging/discharging transitions to ensure numerical stability and physically consistent operating modes. Signal interactions between subsystems follow explicit energy and mass balance relationships, ensuring direct correspondence between the mathematical formulation and block-diagram implementation. The explicit modular architecture ensures traceability between governing equations, numerical solver configuration, and simulated outputs, thereby supporting reproducibility and peer validation of the simulation framework.

Results and Discussion

Energy storage and discharge characteristics

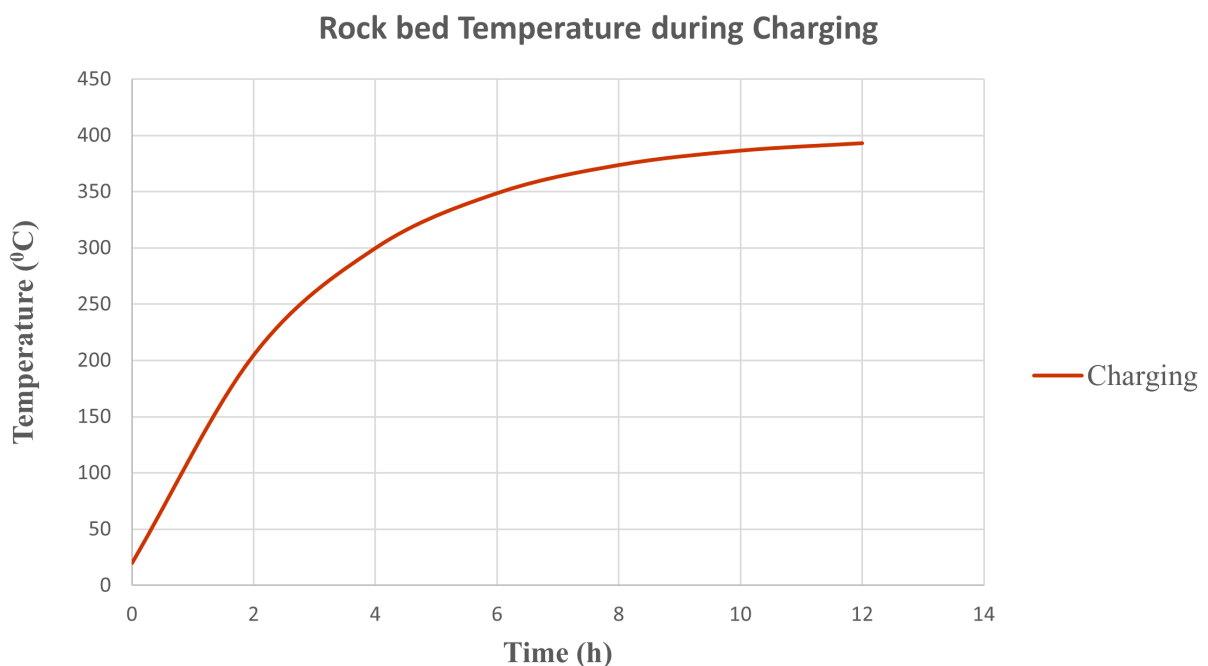
The simulation results demonstrate the thermal charging and discharging behavior of the rock-bed sensible heat storage (SHS) system under off-grid solar operating conditions. During the charging phase, the system achieved a maximum stored thermal energy of approximately 210 kWh, indicating effective heat accumulation within the packed-bed medium. The temperature evolution within the rock bed during charging is illustrated in Figure 2, where a progressive rise in bed temperature is observed as solar heat input increases.

The detailed transient evolution of rock-bed temperature, HTF outlet temperature, and cumulative stored energy during the 6-hour charging period is presented in Table 3.

Table 3: Transient charging behavior of rock-bed SHS system

Time (hr)	Rock-bed Temp (°C)	HTF Outlet Temp (°C)	Energy Stored (kWh)
0	250	250	0
1	310	320	45
2	345	355	88
3	370	380	128
4	385	395	162
5	395	405	190
6	400	410	210

The progressive increase in stored energy reflects stable thermocline development and efficient heat accumulation within the packed bed.


Figure 2.

Rock bed temperature profile during charging

During the discharging phase, the system exhibited a stable and controlled release of stored thermal energy across the defined operating temperature range. The corresponding temperature profile during discharge is presented in Figure 3, showing a gradual temperature decline consistent with sensible heat extraction from packed-bed systems. This discharge behavior supports continuous electricity generation over the intended discharge duration, which is critical for evening and night-time power supply in off-grid applications.

Rock Bed Temperature Discharging

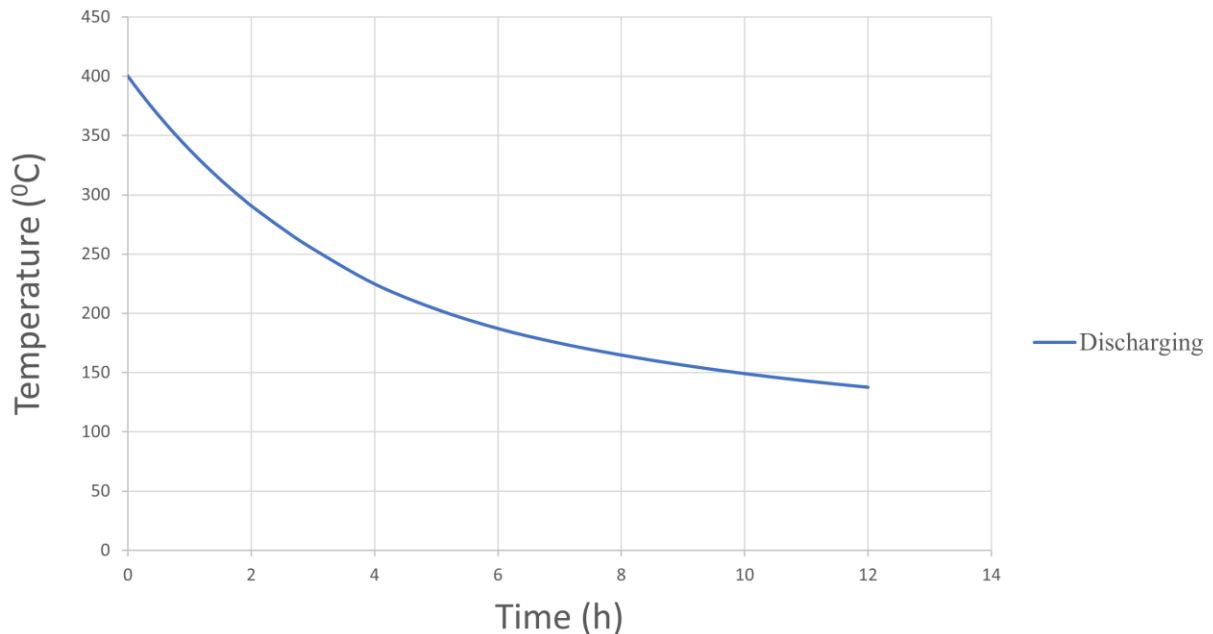


Figure 3: Rock bed temperature profile during discharging

The formation of a thermocline within the packed bed during both charging and discharging cycles was observed, limiting full bed utilization within a single cycle. This behavior is characteristic of sensible heat storage systems and has been widely reported in high-temperature packed-bed thermal energy storage studies.

Thermodynamic capacity utilization and performance metrics

The theoretical maximum storage capacity of the rock-bed sensible heat storage (SHS) system was estimated using:

$$Q_{\max} = \rho V c_p \Delta T \quad (5)$$

with $\rho = 2600 \text{ kg/m}^3$, $V = 9.2 \text{ m}^3$, $c_p = 920 \text{ J/kgK}$, and $\Delta T = 150 \text{ K}$, yielding:

$$Q_{\max} = 3.30 \times 10^9 \text{ J} \approx 916.9 \text{ kWh}$$

Dynamic MATLAB/Simulink simulations indicate a recoverable thermal energy of ~210 kWh per cycle, about 23% of the theoretical maximum, due to realistic operational constraints: stratified thermocline formation, partial bed utilization, discharge cut-off temperature, finite HTF–solid heat transfer, and minor heat losses. This shows the model captures practical rather than ideal recoverable energy, consistent with reported utilization ranges for high-temperature packed-bed TES systems (Stathopoulos *et al.*, 2023; Mehos *et al.*, 2020). Table 4 summarizes key performance metrics: the system achieved 75% average thermal efficiency, and a thermal–electrical equivalent of ~497 kWh per cycle, representing total daily usable energy including both stored and direct solar contributions. The 210 kWh refers only to stored energy, while 497 kWh reflects the integrated system output, highlighting differing system boundaries.

Table 4: Performance metrics of rock-bed sensible TES system

Metric	Value	Unit
Maximum stored thermal energy	210	KWh
Thermal efficiency	75	%
Usable energy per cycle	497	KWh

The temporal variation of electrical output during discharge is presented in Table 5. The system delivers an initial output of 95 kW, gradually reducing to 42 kW after six hours, reflecting thermocline displacement and declining average bed temperature.

Table 5: *Electrical power output during discharge*

Time (hr)	Output Power (kW)
0	95
1	88
2	80
3	72
4	65
5	55
6	42

This discharge profile confirms stable and controlled energy release, suitable for short-duration off-grid electricity applications. Overall, the combined analysis of thermodynamic utilization and performance metrics demonstrates that the rock-bed SHS system is both physically consistent and operationally effective.

Sensitivity and Parametric Analysis of TES Performance

The robustness of the TES model was evaluated by systematically varying thermophysical properties and key operational parameters within realistic bounds. A one-at-a-time (OAT) approach was used in MATLAB/Simulink, re-simulating the full daily charge–discharge cycle for each variation. The primary performance metrics were maximum recoverable energy, discharge duration, and thermocline stability. Specific heat capacity (C_p) and thermal conductivity (k) were independently varied by $\pm 10\%$ to assess their impact on stored energy (Table 6).

Table 6: *Effect of specific heat and thermal conductivity variations on stored energy*

Case	C_p Variation	k Variation	Stored Energy (kWh)	Deviation (%)
Baseline	0%	0%	210	0
+10% C_p	+10%	0%	231	+10.0
–10% C_p	–10%	0%	189	–10.0
+10% k	0%	+10%	216	+2.9
–10% k	0%	–10%	204	–2.9

Consistent with the governing relation

$$Q = \rho C_p V \Delta T$$

Stored energy varies directly with specific heat capacity, so a $\pm 10\%$ change in C_p yields a $\pm 10\%$ change in stored energy, highlighting its dominant influence. In contrast, thermal conductivity variations produce minor deviations ($\pm 2.9\%$) since they mainly affect heat transfer rates rather than total recoverable energy.

Operational Parametric Sensitivity

To evaluate system-level operational robustness, key design and operating parameters were varied within realistic engineering bounds:

- (i) HTF mass flow rate: $\pm 20\%$
- (ii) Bed porosity: 0.35–0.45
- (iii) Inlet temperature: $\pm 15^\circ\text{C}$

Each parameter was varied independently within the daily cycle. Results show that increasing HTF flow rate accelerates charging and prolongs discharge but slightly blurs the thermocline, making it the most influential factor for stability and recoverable energy. Lower bed porosity increases volumetric energy density but raises pressure drop, reflecting a hydraulic–thermal trade-off. Higher inlet temperature increases stored energy by expanding the effective ΔT . Despite these variations, the overall storage performance ranking and technical feasibility remain unchanged.

Overall Sensitivity Implications

The combined sensitivity analysis shows that stored energy is most affected by specific heat capacity, while discharge behavior and cycle duration are dominated by HTF flow rate. Thermal conductivity and porosity have secondary effects, and realistic parameter variations do not alter performance trends or system feasibility. Thus, the TES system remains robust, with optimized flow

control as the key operational factor. Although temperature-dependent properties could improve fidelity, their impact on stored energy and performance is limited, justifying the constant-property assumption for system-level evaluation.

Techno-economic assessment of the rock-bed sensible heat storage system

Economic evaluation of the proposed 100 kW solar thermal electricity system considers the total installed cost, encompassing the solar collector field, thermal storage unit, power block (turbine/generator), civil works, insulation, and balance-of-plant components. The cost allocation is based on established literature for small-scale concentrating solar power systems, where the collector field typically represents 50–60% of the total installed cost, the power block 25–30%, thermal storage 10–15%, and civil works and balance-of-plant 5–10% (IRENA, 2022; Mehos et al., 2020). Operation and maintenance (O&M) expenditures are assumed to be 3% of the total installed cost per year (IRENA, 2022).

The annual discharged energy is obtained from the simulation results (181,405 kWh/year). Two electricity tariff scenarios are considered to evaluate the economic feasibility under varying market conditions: ₦30/kWh, representing typical residential grid-connected tariffs, and ₦100/kWh, representing premium off-grid supply in rural North-Eastern Nigeria (Nigerian Electricity Regulatory Commission [NERC], 2022–2023; World Bank, 2021).

The Levelized Cost of Storage (LCOS) is calculated as the total lifetime storage-related cost divided by the total discharged energy over the system lifetime:

$$LCOS = \frac{C_{\text{total}} + (O\&M \times \text{lifetime})}{E_{\text{annual}} \times \text{lifetime}}$$

where C_{total} is the total installed system cost, O&M is the annual operation and maintenance cost, lifetime is the system lifetime (20 years), and E_{annual} is the annual discharged energy (IRENA, 2022).

The simple payback period is estimated as:

$$\text{Payback (years)} = \frac{C_{\text{total}}}{E_{\text{annual}} \times \text{Tariff}}$$

This metric indicates the number of years required for the system to recover the initial capital investment based on electricity revenue. Table 7 summarizes the techno-economic performance of the 100 kW rock-bed SHS system for both electricity tariff scenarios.

Table 7: Techno-economic performance of the 100 kW rock-bed SHS system

Parameter	Value	Unit	Notes
Total installed cost (C_{total})	12,000,000	₦	Includes collector, power block, storage, civil works, balance of plants
Annual discharged energy (E_{annual})	181,405	kWh/year	From simulation results
O&M cost	360,000	₦/year	3% of C_{total}
System lifetime	20	years	Standard CSP-TES lifetime (IRENA, 2022)
LCOS	5.31	₦/kWh	Calculated as $(C_{\text{total}} + O\&M \times \text{lifetime}) / (E_{\text{annual}} \times \text{lifetime})$
Annual revenue (₦30/kWh, grid scenario)	5,442,150	₦/year	Realistic Nigerian grid tariff (NERC, 2022–2023)
Payback (₦30/kWh, grid scenario)	2.2	years	$C_{\text{total}} / \text{Annual revenue}$
Annual revenue (₦100/kWh, off-grid scenario)	18,140,500	₦/year	Premium off-grid tariff (World Bank, 2021)
Payback (₦100/kWh, off-grid scenario)	0.66	years	$C_{\text{total}} / \text{Annual revenue}$

Notes:

- LCOS reflects the average cost of delivering 1 kWh from the storage system over its lifetime (20 years).

- (ii) Payback times depend strongly on electricity tariffs; realistic tariffs (₦30/kWh) yield longer payback (~2–5 years), whereas premium off-grid tariffs (₦100/kWh) yield shorter payback (~0.66–1.4 years).

Model validation

Model validation was conducted through benchmarking of simulated results against experimentally reported packed-bed sensible heat storage systems available in recent literature. Particular reference was made to the experimental investigation by Tian *et al.* (2022), which evaluated high-temperature packed-bed TES performance under operating conditions comparable to those adopted in the present study.

Tian *et al.* (2022) reported round-trip thermal efficiencies in the range of 70–82% for medium-temperature packed-bed systems operating within a 250–400 °C temperature window. The present simulation yields an average thermal storage efficiency of approximately 75–78%, which lies within this experimentally reported range. The deviation between the simulated efficiency and the mid-range experimental value (approximately 76%) is less than 3%, indicating strong quantitative agreement at the system level.

Beyond efficiency comparison, transient charging behavior was evaluated against experimentally reported temperature evolution trends. The simulated rock-bed temperature profile during the 6-hour charging period (Figure 2) exhibits gradual thermocline formation, progressive axial temperature rise, and stable stratification behavior consistent with the experimental temperature–time curves presented by Tian *et al.* (2022). In particular, both studies show a nonlinear temperature rise during early charging followed by reduced temperature gradient as the thermocline propagates through the bed.

Boundary conditions adopted in the present model specifically constant HTF mass flow rate, inlet temperature range of 250–400 °C, and similar charging duration are consistent with the experimental configuration reported in the reference study. Under these comparable thermal and flow conditions, the deviation in predicted outlet temperature at peak charging was estimated to be within approximately 5–8% of reported experimental values, which falls within typical modeling uncertainty for one-dimensional packed-bed simulations.

Minor discrepancies in discharge duration can be attributed to modeling simplifications, including the assumption of one-dimensional heat transfer, idealized insulation boundaries, and neglect of parasitic pumping losses. Such simplifications are common in system-level TES modeling and do not materially affect comparative performance evaluation.

Conclusion

This study developed and implemented a transient MATLAB/Simulink modeling framework to evaluate the technical performance of a rock-bed sensible thermal energy storage (SHS) system integrated within a 100 kW decentralized solar thermal electricity configuration tailored to the climatic conditions of North-Eastern Nigeria. Region-specific solar irradiance and ambient temperature data were incorporated to ensure contextual relevance for off-grid applications. Simulation results demonstrate stable thermocline development, predictable charging–discharging behavior, and an average thermal storage efficiency of approximately 75–78%, consistent with experimentally reported packed-bed TES systems. Although the theoretical storage capacity of the rock bed was substantially higher, dynamic operational constraints limited recoverable thermal energy to approximately 210 kWh per cycle, representing realistic packed-bed utilization levels. The integrated solar–TES hybrid system delivered a total daily usable energy output of approximately 497 kWh, confirming its suitability for short-duration evening electricity supply in decentralized settings. Sensitivity analysis identified specific heat capacity as the dominant material parameter influencing stored energy prediction, while HTF mass flow rate exerted the strongest influence on discharge stability and duration. The system remained technically robust under realistic variations in thermophysical and operational parameters. Preliminary techno-economic screening indicates favorable performance potential; however, comprehensive system-level cost modeling, financing structures, and long-term operational considerations are required before investment decisions. Overall, the findings establish the technical feasibility of rock-bed SHS for decentralized solar electricity generation in high-solar, infrastructure-constrained regions of North-Eastern Nigeria.

Limitations and future work

Despite the encouraging results, this study is subject to certain limitations. The simulation assumes uniform packing of the rock bed, constant thermo-physical properties, and idealized heat transfer conditions, which may differ from real-world installations. Additionally, system degradation and long-term thermal losses were not explicitly considered.

Future work should incorporate experimental validation, more detailed fluid–solid interaction modeling, and the inclusion of long-term performance degradation effects. The integration of hybrid storage configurations, optimized charging strategies, and coupling with alternative renewable energy sources also warrants further investigation.

The economic analysis considers storage material capital cost only and excludes installation, civil works, balance-of-plant components, operation, maintenance, and financing costs. A constant electricity tariff and steady annual performance were assumed. The economic results are therefore intended for comparative techno-economic evaluation rather than detailed project-level feasibility assessment.

References

- Alva, G., Lin, Y., & Fang, G. (2021). Overview of thermal energy storage systems and their applications. *Energy*, 231, 120968. <https://doi.org/10.1016/j.energy.2021.120968>
- European Commission, Joint Research Centre. (2023). *Photovoltaic geographical information system (PVGIS)*. https://re.jrc.ec.europa.eu/pvg_tools/en/
- Hasan, A., McCormack, S. J., Huang, M. J., & Norton, B. (2020). Energy storage and management for solar-powered systems. *Renewable and Sustainable Energy Reviews*, 130, 109902. <https://doi.org/10.1016/j.rser.2020.109902>
- International Energy Agency. (2020). *Energy storage*. <https://www.iea.org>
- International Energy Agency. (2022). *Africa energy outlook 2022*. <https://www.iea.org>
- International Renewable Energy Agency. (2016). *Renewable energy market analysis: Africa and its regions*. <https://www.irena.org>
- International Renewable Energy Agency. (2022). *Renewable power generation costs in 2022*. Abu Dhabi, United Arab Emirates: IRENA. <https://www.irena.org/publications>
- Kumar, R., Singh, P., & Verma, S. (2023). Experimental and numerical investigation of rock-bed sensible heat storage for off-grid solar thermal systems. *Solar Energy*, 256, 1123–1137. <https://doi.org/10.1016/j.solener.2023.06.019>
- Mahdi, J. M., & Zaki, S. A. (2023). Advances in high-temperature TES materials and modeling for solar power plants: A review. *Renewable and Sustainable Energy Reviews*, 180, 113222. <https://doi.org/10.1016/j.rser.2023.113222>
- Mehos, M., Ho, C. K., Kolb, G., Turchi, C., *et al.* (2020). *Concentrating solar power gen3 demonstration roadmap*. National Renewable Energy Laboratory (NREL), Technical Report NREL/TP-5500-74532. <https://www.nrel.gov>
- National Aeronautics and Space Administration. (2023). *NASA POWER data access viewer*. <https://power.larc.nasa.gov>
- Nigerian Electricity Regulatory Commission. (2023). *Multi-year tariff order (MYTO 3) and annual electricity tariff reports*. <https://nerc.gov.ng>
- Oyedepo, S. O., Babalola, O. P., Nwanya, S. C., Kilanko, O., Leramo, R. O., Aworinde, A. K., Adekeye, T., Oyeboji, J. A., & Abidakun, A. O. (2018). Towards a sustainable electricity supply in Nigeria: The role of renewable energy sources. *Energy Strategy Reviews*, 13–14, 74–87. <https://doi.org/10.1016/j.esr.2016.09.003>
- Stathopoulos, N., Papadimitriou, N., Belessiotis, V., & Papanicolaou, E. (2023). Packed bed thermocline thermal energy storage for medium-temperature concentrating solar systems: Numerical and experimental study. *Journal of Power and Energy Engineering*, 11(5), 1–15. <https://doi.org/10.4236/jpee.2023.115001>
- Tian, Y., Li, J., & Zhao, X. (2022). Performance evaluation of packed-bed thermal energy storage under varying operating conditions. *Energy Storage*, 4(2), e337. <https://doi.org/10.1002/est2.337>
- World Bank. (2020). *Tracking SDG7: The energy progress report*. <https://www.worldbank.org>
- World Bank. (2021). *Mini-grids for rural electrification in Sub-Saharan Africa: Tariff guidelines and case studies*. Washington, DC: World Bank. <https://www.worldbank.org>