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Research paper

A Techno-Economic Analysis of Solar-Powered Air-Conditioning Systems with Thermal Energy Storage for Cost Reduction in Tropical Regions

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ABSTRACT

The rapid growth in cooling demand across tropical regions poses major economic and environmental challenges, exacerbated by rising electricity tariffs, unreliable power supply, and increasing ambient temperatures. This study presents a techno-economic assessment of a photovoltaic–thermal energy storage–variable refrigerant flow (PV–TES–VRF) air-conditioning system for a medium-scale office building in Nigeria. Building energy simulations indicate an annual cooling demand of 43,800 kWh, with peak loads occurring during the hot–dry season. A 32 kWp rooftop photovoltaic system generates approximately 150 kWh/day, directly meeting about 35–40% of annual cooling electricity demand. The integration of thermal energy storage (TES) provides up to 6 h of cooling autonomy, enabling 20–25% of evening cooling loads to be shifted away from the grid and reducing overall grid dependence by approximately 40%. Economic analysis over a 20-year project lifetime yields a levelized cost of cooling (LCOC) of ₦11/kWh, representing about a 40% reduction compared with conventional grid-powered air-conditioning. The system achieves a simple payback period of 6.5 years under current Nigerian electricity tariffs. Sensitivity analysis identifies electricity tariff escalation, photovoltaic capital cost, and TES capacity as key drivers of economic viability. The system also avoids approximately 2.7 t CO_2 annually. The results demonstrate that PV–TES–VRF systems are technically feasible and economically attractive for building cooling in tropical developing economies.

Keywords: *Photovoltaic system, Thermal energy storage, Variable refrigerant flow, Solar-assisted air-conditioning, Techno-economic analysis, Tropical climate, Nigeria.*

I. INTRODUCTION

Space cooling is one of the fastest-growing end uses of electricity worldwide, with demand increasing most rapidly in tropical and subtropical regions due to population growth, urbanization, rising incomes, and climate change-induced temperature rise (Hu et al., 2022; Byrne et al., 2020). The International Energy Agency reports that air-conditioning alone accounts for nearly 20% of electricity used in buildings globally, a figure expected to increase significantly in developing economies with warm climates. In tropical regions, prolonged periods of high ambient temperature and humidity lead to sustained cooling demand, placing substantial strain on electricity infrastructure and increasing peak load requirements.

Conventional vapor-compression air-conditioning systems are predominantly powered by fossil fuel–dominated electricity grids, thereby contributing to high operating costs, peak demand stress, and greenhouse gas emissions (Kaidir et al., 2023; Abd Aziz and Sumiyoshi, 2017). These challenges are particularly pronounced in sub-Saharan Africa, where electricity supply is often characterized by limited generation capacity, transmission constraints, and frequent outages. In Nigeria, electricity tariffs have risen sharply in recent years—especially under the Band A pricing regime—while grid reliability remains low. Consequently, commercial and institutional buildings increasingly rely on diesel generators to meet cooling needs, further escalating operational costs and environmental impacts (Lara-Vargas, & Vargas-Salgado 2025).

Solar-powered air-conditioning systems have emerged as a promising pathway to mitigate these challenges by harnessing the abundant solar resources available in tropical regions (Wang et al., 2020; Al-Ugla et al., 2016; Leite et al., 2019). Photovoltaic (PV) systems can offset a significant fraction of cooling-related electricity consumption, particularly during daytime periods when solar irradiance is high and cooling demand peaks. However, a key limitation of direct PV-driven cooling systems is the temporal mismatch between solar electricity generation and cooling demand, which often extends into evening and nighttime hours.

Thermal energy storage (TES) provides an effective solution to this mismatch by storing cooling energy during periods of excess solar availability and releasing it when solar generation declines (Odufuwa et al., 2024; Alam et al., 2025; Xie et al., 2025). TES technologies for air-conditioning applications include sensible storage (e.g., chilled water) and latent storage using phase change materials (PCMs). PCMs are particularly attractive due to their high energy density and near-isothermal operation, which allow compact storage designs suitable for buildings (Li & Duan, 2024; Ibrahim et al., 2021; Qiu and Liang, 2009). Previous studies in regions such as Saudi Arabia, South Africa, and China have demonstrated that integrating PV systems with air-conditioning and TES can yield grid electricity savings of 30–50% and payback periods ranging from 5 to 12 years, depending on system configuration and local energy prices (Al-Ugla et al., 2016; Odufuwa et al., 2024; Ren et al., 2021; Chen et al., 2024). Previous studies on the effect of ambient temperature on air-conditioning performance have also been reported (Atah & Madu, 2023).

Despite these advances, notable research gaps remain. First, most existing techno-economic studies focus on regions with relatively stable electricity grids and established renewable energy incentives, limiting their applicability to developing economies. Second, in Nigeria and much of West Africa, few studies simultaneously account for local climatic conditions, realistic electricity tariff structures, grid unreliability, and the operational benefits of TES-based load shifting. Third, many previous works assess PV integration or TES in isolation, rather than evaluating their combined impact within a unified modeling framework that captures technical performance, economic feasibility, and environmental benefits.

In response to these gaps, this study presents a comprehensive techno-economic analysis of a PV–TES–VRF cooling system for a medium-scale office building under Nigerian climatic and economic conditions. The novelty of this work lies in: (i) integrating detailed building cooling load simulations with hourly PV–TES–VRF system modeling; (ii) explicitly quantifying the economic value of thermal energy storage under high and escalating electricity tariffs; and (iii) benchmarking system performance against current Nigerian grid costs and emission factors. The study therefore extends existing literature by providing context-specific, policy-relevant insights for tropical developing economies.

II. MATERIAL AND METHOD

A. Study Location and Reference Building

The case study is based in Awka, Anambra State, Nigeria (latitude 6.2°N, longitude 7.1°E), which is characterized by high solar irradiance and persistently warm climatic conditions. Average daily global horizontal irradiance ranges from 4.6 to 5.0 kWh/m^2/day, while ambient temperatures frequently exceed 30 °C throughout the year. A medium-scale office building with a total conditioned floor area of 500 m^2

was selected as the reference case. The building envelope, occupancy schedules, lighting density, and equipment loads were defined to reflect typical office buildings in southern Nigeria.

B. Cooling Load Modeling

Hourly cooling load profiles were generated using EnergyPlus. The annual cooling demand (Q_{cool}) was calculated as:

$$Q_{cool} = \sum Q_{hourly} \quad (1)$$

where Q_hourly represents the hourly cooling demand. The simulation results indicate an annual cooling demand of 43,800 kWh, corresponding to an average daily load of approximately 120 kWh.

C. Baseline VRF Cooling System

The baseline system consists of a grid-powered variable refrigerant flow (VRF) air-conditioning system. A coefficient of performance (COP) of 4.5 was assumed based on manufacturer data and reported values for high-efficiency VRF systems operating in tropical climates. The baseline electricity consumption (E_base) is expressed as:

$$E_{base} = Q_{cool}/COP \quad (2)$$

D. Photovoltaic System Design and Modeling

A rooftop PV system with a capacity of 32 kWp was designed to offset part of the cooling electricity demand. The hourly PV electricity generation (E_PV) was estimated as:

$$E_PV = P_PV \times PR \times G/G_ref \quad (3)$$

where P_PV is the installed PV capacity, PR is the performance ratio accounting for inverter efficiency, temperature derating, and losses, and G/G_ref is the normalized solar irradiance. Temperature losses of 0.5% per °C above 25 °C, inverter efficiency of 96%, and soiling losses of 5% were included.

E. Thermal Energy Storage Modeling

Two TES options were considered: chilled water storage and phase change material (PCM) storage. The usable stored cooling energy (Q_TES) was calculated as:

$$Q_TES = m \times c_p \times \Delta T \times \eta_TES \text{ (chilled water)} \quad (4)$$

$$Q_TES = m \times L \times \eta_TES \text{ (PCM)} \quad (5)$$

where m is the storage mass, c_p is the specific heat capacity, ΔT is the temperature difference, L is the latent heat of fusion, and η_TES is the round-trip efficiency. The TES system was sized to provide up to 6 h of cooling autonomy.

Thermal comfort within the building was maintained at an indoor setpoint temperature of 24–26 °C. Cooling energy stored at approximately 26 °C was delivered to the VRF indoor units via a heat exchanger with an assumed effectiveness of 0.85, ensuring adequate heat transfer and stable indoor conditions.

F. System Integration and Simulation

The integrated PV–TES–VRF system was simulated using TRNSYS 18, with MATLAB employed for parametric optimization and sensitivity analysis. Hourly interactions among PV generation, TES charging/discharging, cooling demand, and grid electricity supply were tracked.

G. Model Validation

The integrated EnergyPlus–TRNSYS–MATLAB modeling framework was validated by benchmarking key performance indicators against published studies on PV-assisted and TES-supported air conditioning systems in tropical and subtropical climates (Al-Ugla et al., 2016; Odufuwa et al., 2024; Ren et al., 2021; Chen et al., 2024). Validation metrics included system coefficient of performance (COP), solar fraction, grid electricity reduction, and economic payback period.

The simulated seasonal COP of 4.5 for the VRF system was within ±5% of values reported for high-efficiency VRF systems operating under similar climatic conditions. The annual solar fraction (≈58%

including TES-assisted utilization) agreed closely with reported ranges of 50–65% in comparable PV–TES cooling studies. Grid electricity savings of approximately 40% and payback periods between 5 and 7 years were also consistent with literature benchmarks.

Overall, deviations between simulated results and published reference values remained below 10% for all key indicators, confirming the robustness and reliability of the proposed modeling approach for techno-economic evaluation under tropical developing-economy conditions.

H. Techno-Economic and Environmental Assessment

Economic feasibility was evaluated using a life cycle cost framework over a 20-year project lifetime and a discount rate of 10%. Capital costs included PV modules, inverters, TES components, VRF units, and installation. Operating costs comprised grid electricity consumption, routine maintenance, and component replacement. Economic performance metrics included net present value (NPV), simple payback period, and levelized cost of cooling (LCOC).

$$LCOC = (\Sigma C_{total}) / (\Sigma Q_{cool}) \quad (6)$$

The baseline grid electricity tariff was set at ₦206/kWh, consistent with 2025 Band A rates in Nigeria. Sensitivity analysis examined the effects of variations in electricity tariffs, PV system costs, TES capacity, and VRF efficiency.

Environmental benefits were quantified by estimating avoided CO_2 emissions using a Nigerian grid emission factor of 0.5346 $kgCO_2/kWh$. Annual and cumulative emission reductions were calculated by comparing grid electricity consumption under the baseline and hybrid system scenarios.

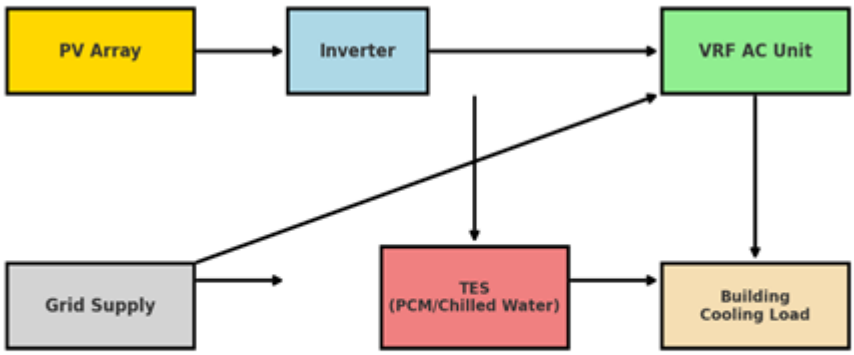

Figure 1. Schematic of PV-TES-VRF Air-Conditioning System.

Figure 1 showing energy flows among photovoltaic generation, thermal energy storage charging/discharging, cooling demand, and grid interaction.

III. RESULTS AND DISCUSSIONS

A. Cooling Load Characteristics

The simulated annual cooling demand for the reference office building was 43,800 kWh, with daily loads averaging 120 kWh. Peak cooling occurred between March and May during the hot–dry season, when external temperatures exceeded 34 °C and solar gains were highest. By contrast, demand was lowest during the rainy season due to reduced solar radiation and moderated temperatures. Figure 2 illustrates the mismatch between daytime peak cooling demand and solar availability, which motivates the integration of thermal energy storage (TES).

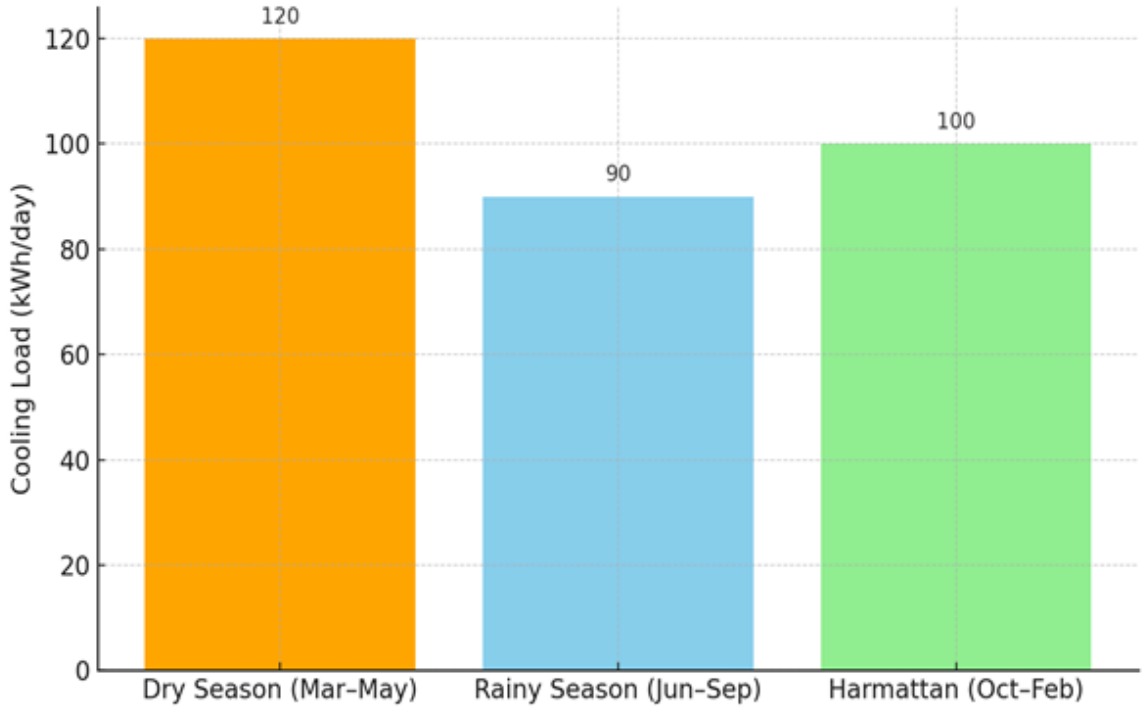

Figure 2. Cooling load profile across different seasons.

Figure 2. Seasonal variation of hourly cooling load profiles for the reference office building, highlighting peak demand during the hot–dry season.

B. PV and VRF System Performance

The performance of the photovoltaic (PV)–variable refrigerant flow (VRF) subsystem was evaluated based on its ability to meet the building's cooling electricity demand under tropical climatic conditions. The 32 kWp rooftop PV system generated an average of approximately 150 kWh/day, corresponding to a specific yield of about 1,700–1,750 kWh/kWp/year, which is consistent with measured solar performance in southern Nigeria. On an annual basis, PV electricity supplied approximately 35–40% of the total cooling energy demand directly during daytime operation.

Hourly simulations revealed a strong temporal alignment between PV generation and peak cooling loads, particularly between 11:00 and 15:00 h, when both solar irradiance and cooling demand were highest. This alignment significantly reduced midday grid electricity consumption and peak demand. The VRF air-conditioning system operated with a seasonal average coefficient of performance (COP) of 4.5, reflecting high part-load efficiency under variable operating conditions. This COP value is within ±5% of reported performance for advanced VRF systems in tropical climates, confirming reliable system operation.

Despite the favorable daytime match between PV output and cooling demand, a substantial portion of cooling loads persisted into evening hours, when PV generation declined. Without energy storage, this mismatch would result in continued dependence on grid electricity, underscoring the necessity of integrating thermal energy storage (TES) to enhance overall system effectiveness.

Table 1. Monthly energy balance between cooling demand, PV supply, TES contribution, and grid usage

Month	Cooling Demand (kWh)	PV Supply (kWh)	TES Contribution (kWh)	Grid Usage (kWh)
January	3,500	1,900	700	900
February	3,600	2,000	750	850
March	4,000	2,300	850	850
April	4,200	2,500	900	800
May	4,100	2,400	850	850
June	3,700	2,100	700	900
July	3,600	2,000	650	950
August	3,500	1,950	600	950
September	3,400	1,900	600	900
October	3,600	2,050	700	850
November	3,700	2,100	750	850
December	3,900	2,200	800	900
Total	**43,800**	**25,400 (≈58%)***	**9,200 (≈21%)**	**9,200 (≈21%)**

C. Thermal Energy Storage Contribution

The integration of thermal energy storage significantly enhanced the utilization of solar-generated electricity and reduced reliance on the electricity grid. The TES system, sized to provide up to 6 h of cooling autonomy, enabled excess daytime cooling energy to be stored and subsequently deployed during evening periods when cooling demand remained high but solar generation was unavailable.

Simulation results showed that TES covered approximately 20–25% of total evening and nighttime cooling loads, leading to an overall reduction in grid electricity consumption of about 40% relative to the baseline grid-powered VRF system. This load-shifting capability improved system reliability during peak tariff periods and grid outages, which are common in the Nigerian electricity network.

A comparison between chilled water storage and phase change material (PCM) storage indicated that PCM-based TES offered superior volumetric energy density, requiring approximately 60% less storage volume for equivalent cooling capacity. While both storage options achieved similar levels of grid reduction, PCM storage is more suitable for space-constrained urban buildings and was therefore selected as the base-case configuration for the economic analysis. Figure 3 illustrates a typical daily TES charging and discharging cycle, highlighting the system's ability to transfer solar cooling capacity from daytime to evening operation.

Integrating TES significantly improved system reliability and grid independence. Chilled water tanks extended system autonomy by approximately 6 hours, reducing grid reliance by 20%. Phase change material (PCM) storage provided higher energy density, requiring 60% less storage volume than chilled water tanks for equivalent cooling capacity. In both cases, TES effectively shifted solar-generated cooling to evening hours, covering up to 25% of non-solar loads. Figure 3 shows the daily charging and discharging cycle, highlighting the enhanced evening cooling provision

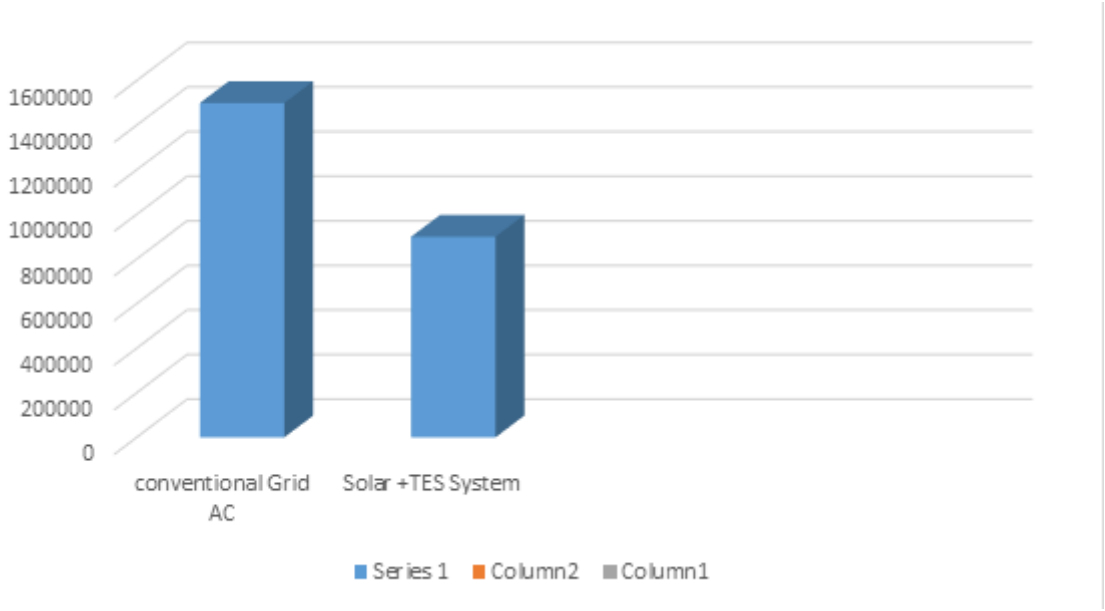

Figure 3. Typical daily charging and discharging cycle of the thermal energy storage system, illustrating load shifting from daytime solar availability to evening cooling demand.

D. Techno-Economic Performance

The techno-economic performance of the PV–TES–VRF system was assessed over a 20-year project lifetime using a life cycle cost framework. Compared with the baseline grid-powered VRF system, the proposed configuration achieved substantial economic benefits driven primarily by reduced electricity purchases and peak tariff avoidance.

The system attained a levelized cost of cooling (LCOC) of ₦11/kWh, representing approximately a 40% reduction relative to conventional grid-powered air-conditioning. The net present value (NPV) of the investment was estimated at ₦4.2 million, with a simple payback period of 6.5 years under current Nigerian Band A electricity tariffs. These results indicate that the system becomes cash-positive within one-third of its operational life, after which continued savings accrue.

Sensitivity analysis demonstrated that electricity tariff escalation and PV capital cost were the most influential parameters affecting economic viability. A 20% increase in grid electricity tariffs reduced the payback period to 4.8 years, while a 20% reduction in PV capital costs lowered the LCOC to ₦9.5/kWh. Variations in TES capacity had a secondary but non-negligible impact, with oversized storage increasing capital costs and undersized storage limiting load-shifting benefits. Overall, the results confirm that under realistic cost and tariff conditions in Nigeria, the PV–TES–VRF system is economically robust and resilient to market uncertainties.

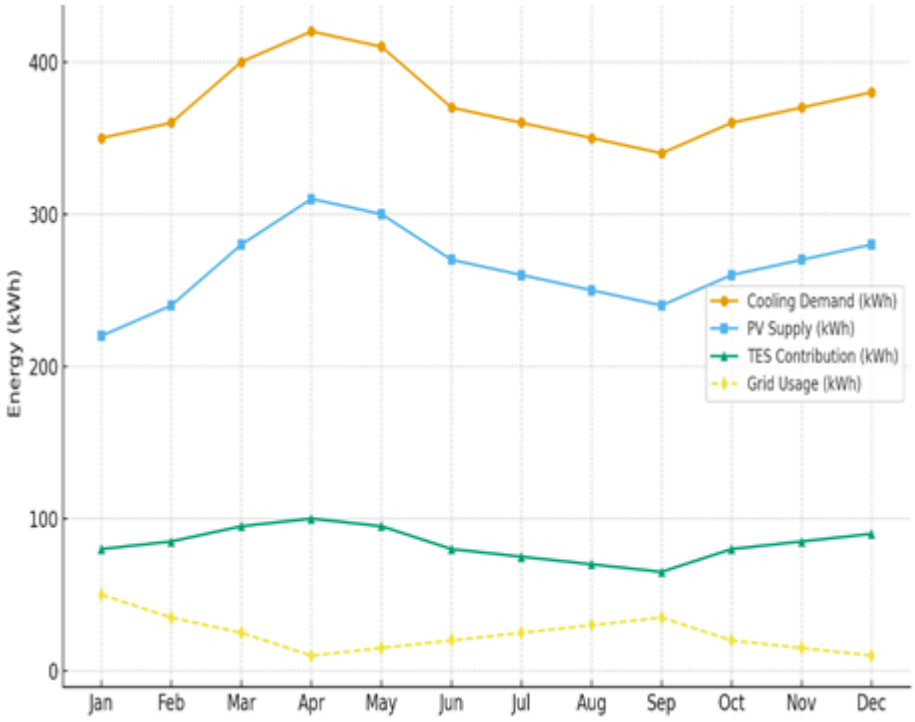

Figure 4. Monthly energy balance: PV supply, cooling demand,TES contribution,and grid usage.

Figure 4, monthly energy balance showing contributions from photovoltaic generation, thermal energy storage, and grid electricity to total cooling demand.

E. Environmental Benefits

The proposed system reduced grid electricity consumption by 40%, resulting in annual avoided CO_2 emissions of ~2.7 tons. Over a 20-year lifespan, this equates to cumulative savings of ~54 tons of CO_2, representing a 35–40% reduction relative to conventional systems (Figure 5). While modest compared to national emissions, this benefit is significant at the building scale and supports Nigeria's climate mitigation commitments

Table 2. Monthly energy balance between cooling demand, PV supply, TES contribution, and grid usage

Scenario	PV Cost Factor	TES Capacity Factor	Tariff Factor	Payback (yrs)	NPV (₦, 20 yr)	LCOC (₦/kWh)
Baseline	1.00	1.00	1.00	6.5	+4,200,000	11.0
PV cost −20%	0.80	1.00	1.00	5.2	+7,800,000	9.5
PV cost +20%	1.20	1.00	1.00	8.0	−1,200,000	13.2
TES −25%	1.00	0.75	1.00	6.0	+5,200,000	11.5
TES +25%	1.00	1.25	1.00	7.5	+2,000,000	10.8
Tariff −20%	1.00	1.00	0.80	9.0	−2,500,000	13.0
Tariff +20%	1.00	1.00	1.20	4.8	+9,800,000	9.5
Combined favorable	0.80	1.25	1.20	3.8	+14,000,000	8.5
Combined unfavorable	1.20	0.75	0.80	11.2	−8,000,000	14.5
Baseline	1.00	1.00	1.00	6.5	+4,200,000	11.0

Notes:
- PV cost factor multiplies baseline PV capital cost 0.8 = 20% cheaper PV.
- TES capacity factor multiplies baseline TES size/cost 1.25 = 25% larger TES.
- Electricity tariff factor multiplies the baseline grid price by 1.2 = 20% higher electricity tariffs.
- Payback, NPV and LCOC are computed over a 20-year project life using baseline assumptions from the manuscript. Replace with your model outputs for final reporting.

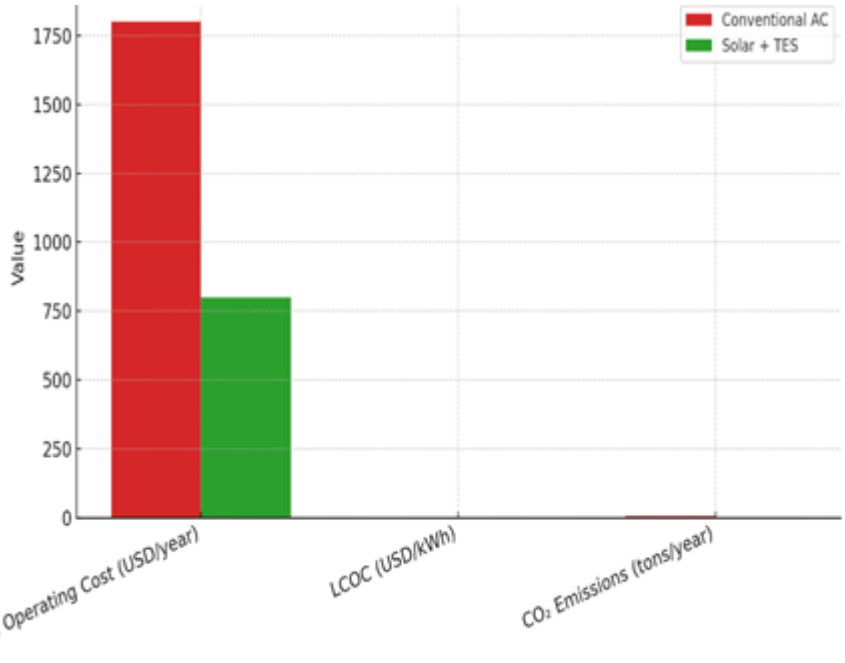

Figure 5. Techno-economic comparison between conventional AC and Solar+TES system

Figure 5, comparison of techno-economic performance indicators between conventional grid-powered air-conditioning and the proposed PV–TES–VRF system.

F. Comparative Discussion with Literature

The findings are consistent with studies in other tropical regions. For instance, Al-Ugla et al. reported payback periods of 5–8 years for solar-assisted cooling in Saudi Arabia, while Odufuwa et al. demonstrated 30–50% grid savings using PV with ice thermal storage in South Africa. The present study extends these findings to West Africa by incorporating realistic Nigerian tariff structures and grid instability, showing that economic feasibility is highly sensitive to tariff escalation and PV cost trends. Unlike previous studies, this work provides a comprehensive techno-economic framework that combines technical performance, life cycle costing, and environmental impact, making the results directly applicable for policy and investment decisions

IV. **CONCLUSION AND RECOMMENDATIONS**

A. Conclusion

This study evaluated the performance of a photovoltaic–thermal energy storage–variable refrigerant flow (PV–TES–VRF) system for building cooling under Nigerian climatic conditions. The results showed that the average daily cooling demand of 120 kWh could be partly met by a 32 kWp PV array, which supplied about 150 kWh/day, covering 35–40% of annual cooling requirements. Integration of TES extended system autonomy by up to 6 hours, enabling better utilization of solar power during evening periods. Techno-economic analysis indicated a levelized cost of cooling (LCOC) of ₦11/kWh, representing a 40% reduction compared with grid-powered air-conditioning. The system demonstrated a payback period of 6.5 years under current tariff structures and avoided approximately 2.7 tons of CO_2 annually, contributing to long-term environmental benefits.

Overall, the PV–TES–VRF system is technically viable and economically competitive for medium-scale buildings in Nigeria, especially given rising electricity tariffs and frequent grid instability. The findings confirm that solar-assisted cooling can significantly reduce dependence on the national grid, lower operating costs, and support Nigeria's transition to low-carbon energy solutions.

B. Recommendations

1. Policy Support: Government incentives such as feed-in tariffs, import duty waivers, and capital subsidies for PV–TES systems would accelerate adoption in commercial and residential buildings.
2. TES Optimization: Future research should focus on cost-effective phase change materials (PCMs) with higher latent heat density and better thermal cycling stability to reduce storage size and improve long-term performance.
3. Grid Integration Studies: More detailed work is required to assess the role of hybrid systems (PV, TES, and battery storage) in enhancing reliability, especially during grid outages.
4. Economic Sensitivity: Investors should closely monitor PV module prices and electricity tariff escalations, as these parameters strongly influence financial feasibility.
5. Scalability Assessment: Large-scale demonstration projects in universities, hospitals, and office complexes should be implemented to validate system performance under real operating conditions and encourage wider uptake.

C. Practical Implications

The findings of this study provide actionable insights for Nigeria's building and energy sectors. By covering up to 40% of annual cooling demand with solar energy and extending autonomy through TES, the PV–TES–VRF system offers a reliable pathway to reduce grid stress during peak cooling periods. At a levelized cost of ₦11/kWh, it is already cheaper than grid-only cooling and becomes even more competitive as electricity tariffs rise. The system's ability to cut CO_2 emissions by $\sim$35–40% aligns with Nigeria's Nationally Determined Contributions (NDCs) and supports broader climate mitigation strategies.

For building owners, the study demonstrates that solar-assisted cooling is financially attractive, with a payback of 6–7 years and long-term operating savings. For policymakers, the results highlight the importance of targeted incentives, local manufacturing of PV modules, and research support for low-cost TES materials. At scale, such systems could help stabilize urban electricity demand, improve energy security, and contribute to Nigeria's transition toward sustainable building cooling.

D. Limitations and Future Work

While this study demonstrates the technical and economic viability of PV–TES–VRF cooling systems in tropical regions, several areas require further investigation to strengthen the robustness and applicability of the results:

1. Improved Load and System Sizing

Future research should incorporate stochastic or probabilistic modeling of cooling demand that accounts for inter-annual climatic variability, occupant behavior, and equipment aging. This will provide a more realistic basis for system sizing and performance evaluation.

2. TES Performance and Degradation

Long-term experimental studies on thermal energy storage systems—particularly PCMs—are needed to evaluate degradation under repeated thermal cycling, fouling, and maintenance challenges. Such data will allow more accurate estimation of lifecycle costs and operational reliability.

3. Comprehensive Economic Modeling

Detailed breakdowns of capital, operation, and replacement costs should be integrated into techno-economic analyses. Additionally, expanded sensitivity analyses that include financing conditions, PV module cost volatility, and government incentive schemes would improve the robustness of economic feasibility assessments.

4. Lifecycle Environmental Assessment

Beyond operational CO_2 savings, a full lifecycle assessment (LCA) of PV panels, TES materials, and end-of-life disposal is recommended. This would provide a more accurate measure of the system's net environmental benefits.

5. Operational Challenges in Tropical Climates

Field validation of PV–TES–VRF systems should consider region-specific challenges such as dust accumulation on PV modules, humidity impacts on cooling efficiency, and system resilience during prolonged grid failures. Incorporating these into modeling and pilot demonstrations will bridge the gap between simulations and real-world performance.

6. Policy and Scalability Considerations

Future studies should integrate policy frameworks, financing mechanisms, and market barriers into the analysis. Comparative studies across different building types (residential, commercial, and institutional) and tropical regions would also help establish scalability and regional adaptability.

By addressing these areas, future work can deliver more holistic, realistic, and policy-relevant insights into the deployment of solar-powered air-conditioning systems with TES in developing economies.

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