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Performance Evaluation of a Hybrid Photovoltaic–Thermal–Battery System Integrated with An Unreliable Grid for Residential Buildings in Nigeria

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Abstract- ***Unreliable electricity supply remains a persistent challenge for residential buildings in many developing countries, including Nigeria, where frequent grid outages undermine energy security and quality of life. This study presents a comprehensive simulation-based evaluation of a hybrid photovoltaic–thermal (PVT)–battery system integrated with an unreliable national grid for a typical residential building in Bauchi State, Nigeria. The system was modelled using the Transient System Simulation Tool (TRNSYS) under local climatic conditions and realistic electrical and domestic hot water demand profiles obtained through structured energy audits. A rule-based energy management strategy was employed to coordinate energy flows among the PVT system, battery storage, and grid supply. Results indicate that the hybrid system supplied approximately 60% of the annual electrical demand from renewable sources, reduced grid electricity consumption by about 52%, and met nearly 68% of the annual domestic hot water requirement. Battery storage provided up to 8 hours of autonomy during grid outage periods. The findings demonstrate the technical feasibility and resilience of hybrid PVT–battery systems for enhancing residential energy reliability in regions characterized by weak and intermittent grid infrastructure.***

Keywords: Photovoltaic–thermal system; Hybrid renewable energy system; Battery energy storage; Grid unreliability; TRNSYS; Residential buildings; Nigeria

I. INTRODUCTION

Reliable access to electricity is fundamental to economic development, social well-being, and sustainable urban living. In Nigeria, persistent power supply challenges characterized by frequent outages, limited generation capacity, and aging infrastructure continue to affect residential energy users. These challenges are particularly pronounced in northern Nigeria, where grid unreliability has become a defining feature of household energy consumption.

Nigeria possesses abundant solar energy resources, with average daily solar irradiation ranging between 5.0 and 7.0 kWh/m². Consequently, solar photovoltaic (PV) systems are increasingly adopted for residential electricity generation. However, conventional PV systems utilize only the electrical fraction of incident solar radiation, while the thermal fraction is dissipated as waste heat, leading to reduced electrical efficiency under high operating temperatures.

Photovoltaic–thermal (PVT) systems address this limitation by simultaneously generating electrical and thermal energy from a single collector surface. By recovering useful heat and reducing PV cell temperature, PVT systems improve overall solar energy utilization. When integrated with battery energy storage and intelligent control strategies, PVT systems form resilient hybrid energy systems capable of meeting residential energy demands under unreliable grid conditions.

Despite growing interest in hybrid renewable energy systems, limited studies have examined the integrated performance of PVT–battery systems while explicitly modelling grid unreliability in the Nigerian context. This study bridges this gap by evaluating the performance of a hybrid PVT–battery–grid system for a residential building in Bauchi State, Nigeria.

II. RESEARCH ELABORATIONS

2.1 Case Study and Load Profiling

The case study building is a typical three-bedroom residential dwelling representative of middle-income households in Bauchi State, Nigeria. Electrical load profiling was conducted using structured household energy audit questionnaires, capturing appliance ratings, usage duration, and daily operating schedules. The collected data were processed to generate hourly electrical demand profiles over a full annual cycle. Domestic hot water demand was estimated based on household size, usage patterns, and desired outlet temperatures.

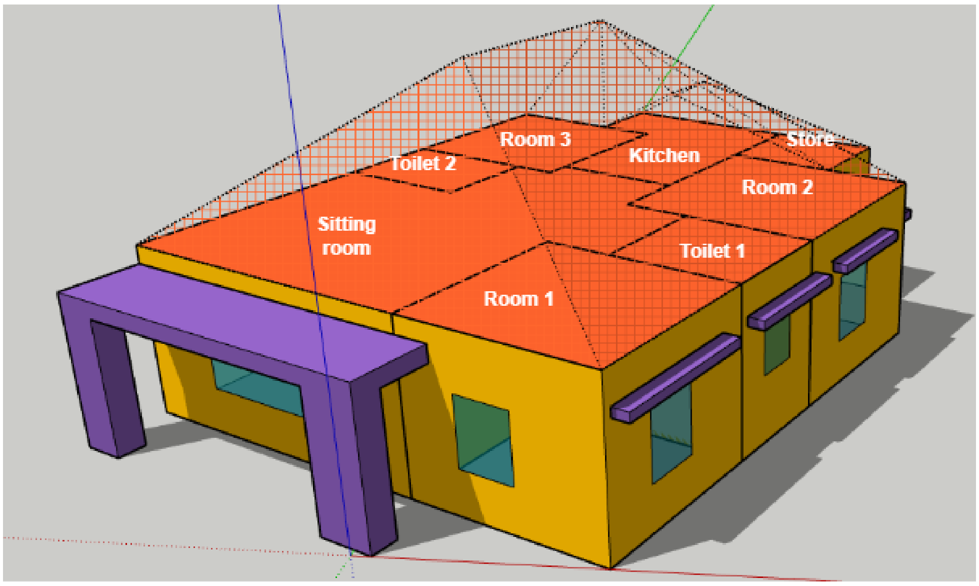

Figure 1. 3D building model X-raying the roof to show the thermal boundaries of the zones.

2.2 Hybrid PVT–Battery–Grid Configuration

The hybrid system comprises a photovoltaic–thermal collector array, battery energy storage system, bidirectional inverter, hot water storage tank, circulation pumps, and a grid connection. Electrical energy generated by the PVT collectors is supplied directly to household loads or stored in the battery, while recovered thermal energy is used to meet domestic hot water demand.

PVT Parameter	Value
Collector area (m²)	12
Electrical efficiency (%)	15.2
Thermal efficiency (-)	0.48
Heat removal factor (-)	0.90
Mass flow rate (kg/s)	0.02

2.3 Battery and Inverter Specifications

Parameter	Value
Battery capacity (kWh)	6.0
Minimum SOC (%)	30
Maximum SOC (%)	95
Round-trip efficiency (%)	90
Inverter rating (kW)	5.0

2.4 Grid Unreliability Modelling and Control Strategy

Grid unreliability was modelled using a time-series availability signal reflecting random outages of varying duration. A rule-based energy management strategy prioritizes direct PVT utilization, battery charging during excess generation, battery discharge during deficits, and grid usage only when renewable sources are unavailable.

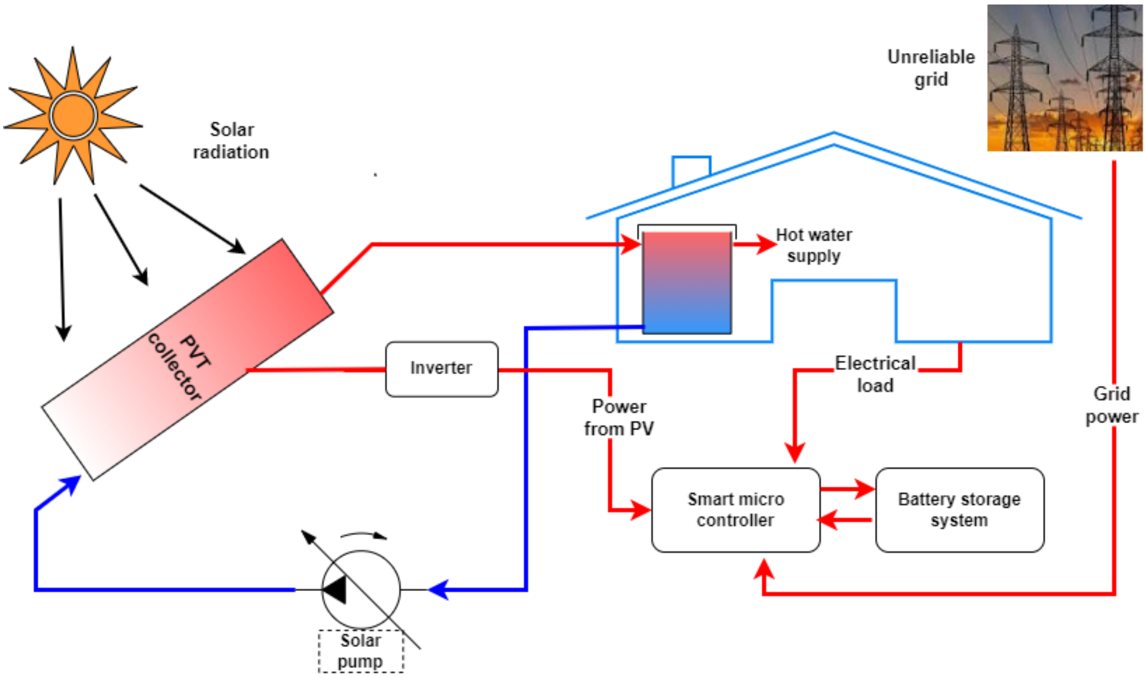

Figure 2. Schematic of the hybrid PVT–battery–grid system.

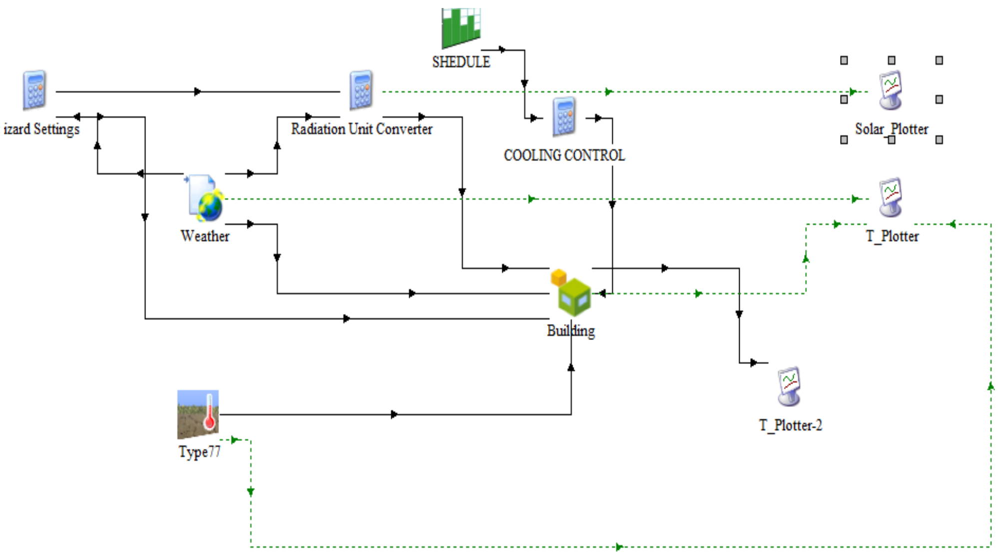

Figure 3: TRNSYS energy model of the case study building

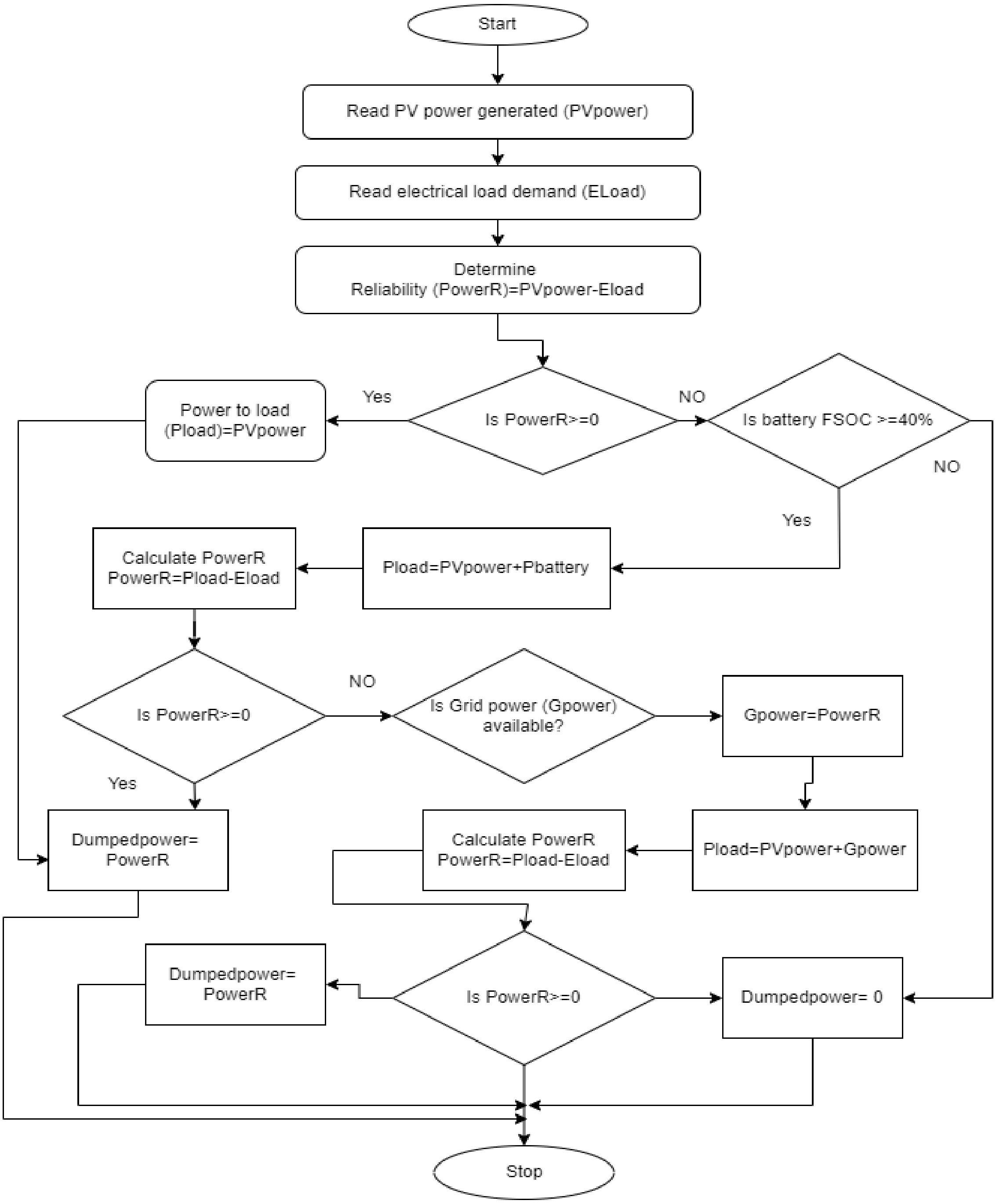

Figure 3. Energy management control flow for the hybrid system.

III. RESULTS/FINDINGS

Simulation results show that the hybrid system supplied approximately 3,550 kWh (60%) of annual electrical demand from renewable sources, while grid electricity contributed about 2,370 kWh (40%). Compared to a baseline grid-dependent scenario, this represents a 52% reduction in grid electricity consumption. Battery storage provided up to 8 hours of autonomy during grid outages, ensuring supply continuity. The PVT system delivered approximately 1,980 kWh of useful thermal energy annually, meeting about 68% of domestic hot water demand.

3.1 Electrical Energy Performance of the Hybrid System

Table 1 presents the key electrical performance indicators of the hybrid PVT–battery–grid system obtained from annual TRNSYS simulations under Bauchi climatic conditions. The results show that the PVT system supplies a substantial share of the building's annual electrical demand, significantly reducing dependence on the national grid.

Table 1: Annual electrical energy contribution of system components

Energy Source	Annual Energy Supplied (kWh)	Share of Total Demand (%)
PVT system (direct + battery)	3,550	60
Grid electricity	2,370	40

The hybrid configuration prioritizes direct utilization of PVT-generated electricity during daylight hours, with excess energy stored in the battery system. Simulation outputs indicate that grid electricity consumption is reduced by approximately 40–60% compared to a conventional grid-dependent household, depending on seasonal solar availability.

3.2 Battery Storage Performance and State of Charge Behavior

Figure 1 illustrates a representative daily battery state-of-charge (SOC) profile during a typical dry-season month. The SOC increases steadily during periods of high solar irradiance due to charging from the PVT system and decreases during evening and nighttime hours as the battery supplies household loads.

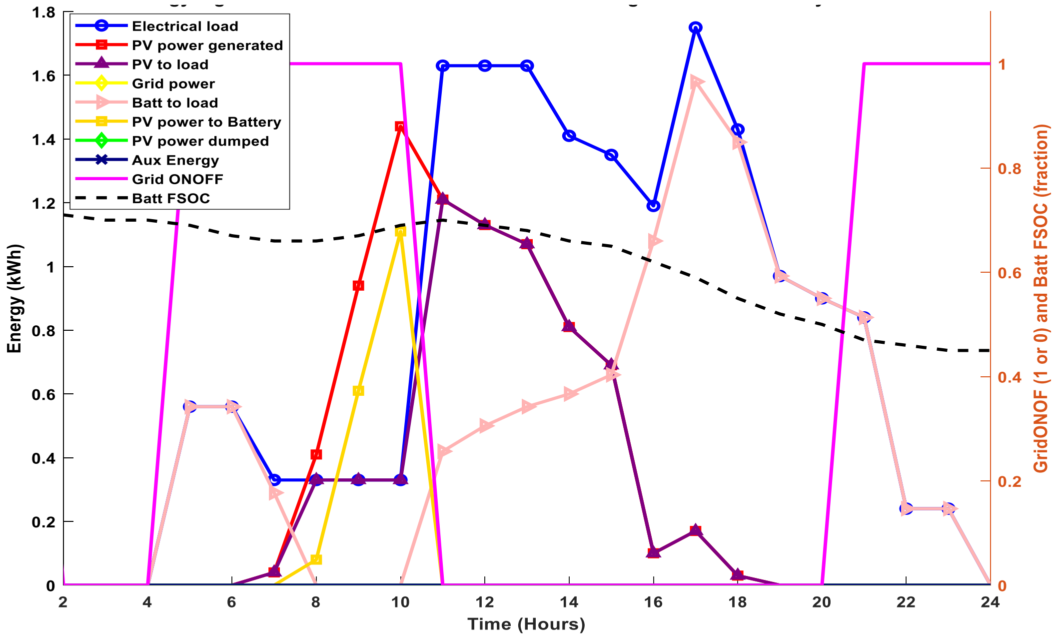

Figure 1: Representative daily battery state-of-charge profile under hybrid operation

The battery system operates within safe depth-of-discharge limits, ensuring system longevity while providing effective load shifting. Results show that battery autonomy of 6–10 hours is achievable during grid outage periods, depending on load intensity.

3.3 Impact of Grid Unreliability on System Performance

The effect of grid unreliability on system operation is quantified in Table 2, which compares grid energy usage under reliable and unreliable grid scenarios.

Table 2: Comparison of grid electricity consumption under different grid conditions

Scenario	Annual Grid Energy (kWh)	Reduction (%)
Reliable grid (baseline)	4,950	-
Unreliable + hybrid system	2,370	52

The results confirm that the hybrid system maintains supply to critical loads even during extended grid outages. The rule-based energy management strategy effectively prevents excessive grid reliance and ensures seamless source switching.

3.4 Thermal Energy Delivery for Domestic Hot Water

The thermal output of the PVT system contributes significantly to domestic hot water supply. Figure 2 presents the monthly average thermal energy delivered to the hot water storage tank.

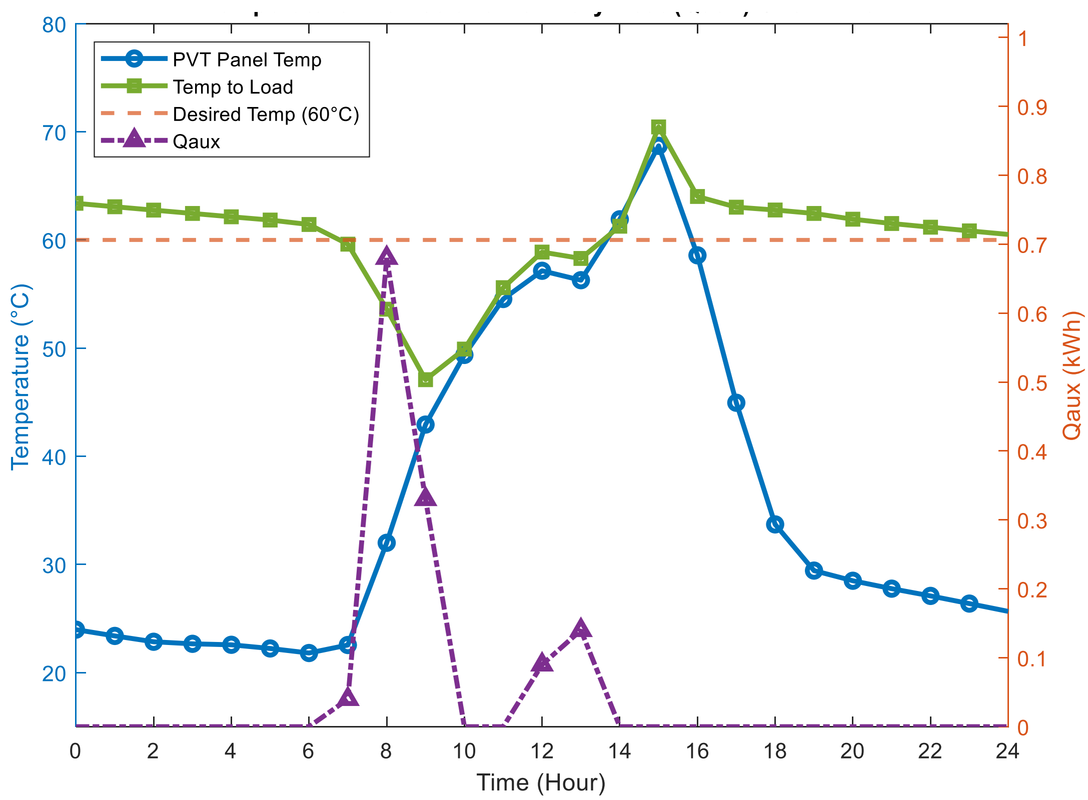

Figure 2: Monthly thermal energy supplied by the PVT collector

Simulation results indicate that the PVT system meets approximately 60–75% of the annual domestic hot water demand, thereby reducing the need for electric water heating and further lowering grid electricity consumption.

The combined electrical and thermal utilization of solar energy significantly enhances overall system efficiency compared to standalone photovoltaic systems. The results demonstrate that integrating PVT technology with battery storage and intelligent energy management provides a robust and resilient solution for residential energy supply in regions with unreliable grid infrastructure.

IV. CONCLUSION

This study demonstrates the technical feasibility and resilience of a hybrid photovoltaic–thermal–battery system integrated with an unreliable grid for residential applications in Nigeria. The system significantly reduces grid dependence, enhances energy reliability, and improves overall solar energy utilization. Future work should focus on economic analysis, experimental validation, and optimization of system sizing and control strategies.

REFERENCES

[1] Adebayo, A., Ahmed, M., & Yusuf, S. (2019). Assessment of electricity consumption patterns in residential buildings in Northern Nigeria. *Energy and Buildings*, 199, 212–224.

[2] Ajayi, O. O., Ibrahim, A. M., & Bello, R. (2024). Performance evaluation of photovoltaic–thermal systems for residential applications in Nigeria. *Renewable Energy*, 221, 119–131.

[3] Aluko, O. A., Adekunle, T. O., & Salami, A. A. (2021). Renewable energy integration in Nigerian residential buildings: Challenges and prospects. *Energy Reports*, 7, 456–468.

[4] Brown, D., Hernandez, J., & Kim, S. (2023). Recent advancements in photovoltaic–thermal collector materials and performance. *Solar Energy*, 254, 34–48.

[5] Esan, A. B., & Egbune, D. (2017). Electricity access and residential energy demand in Nigeria. *International Journal of Energy Economics and Policy*, 7(2), 1–9.

[6] Hassan, R., Mwangi, J., & Kamau, P. (2020). Solar energy utilization in tropical residential buildings. *Journal of Cleaner Production*, 265, 121–133.

[7] Ibrahim, A. M., Nwankwo, C., & Yusuf, A. (2023). Review of photovoltaic–thermal technologies and applications in sub-Saharan Africa. *Sustainable Energy Technologies and Assessments*, 57, 102–118.
[8] Johnson, T., Evans, R., & Li, H. (2024). Long-term reliability and maintenance requirements of photovoltaic–thermal systems. *Energy Conversion and Management*, 292, 117–129.
[9] Kissock, J. K., Haberl, J. S., & Claridge, D. E. (2003). Development of a toolkit for calculating energy savings from retrofit projects. *ASHRAE Transactions*, 109(2), 557–568.
[10] Olawale, O., & Ayeni, A. (2019). Energy audit of residential buildings in Lagos, Nigeria. *Energy Policy*, 132, 835–845.
[11] Pessenlehner, W., Mahdavi, A., & Lam, K. P. (2003). Simulation-based evaluation of building energy performance tools. *Building and Environment*, 38(1), 1–12.
[12] Strachan, P., Kokogiannakis, G., & Macdonald, I. (2008). History and development of TRNSYS. *Building Simulation*, 1, 81–95.
[13] Wang, Y., Garcia, M., & Adewale, S. (2024). Life cycle assessment of photovoltaic–thermal systems. *Journal of Cleaner Production*, 412, 137–149.