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THERMAL COMFORT AND ENERGY LOAD ESTIMATION FOR RESIDENTIAL BUILDINGS IN BAUCHI: A CASE STUDY

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ABSTRACT

Studies have shown that indoor thermal comfort is crucial for human well-being, particularly in the built environment, and those factors such as solar gain, building design, and occupancy status can significantly impact thermal comfort. This study aims to model and estimate thermal comfort and annual energy loads for a typical residential building in Bauchi, Nigeria. A three-bedroom residential building was modelled using SketchUp and TRNSYS, supported by MATLAB, to simulate HVAC, hot water, and electrical energy demands based on local climatic and usage data. Results show that indoor temperatures exceeding the thermal comfort threshold of 27°C by approximately 92% of the year, with peak cooling demand in March and April. Hot water consumption accounted for the highest energy load, contributing significantly to an annual total of approximately 11,746.6 kWh. These results have significant implications for energy-efficient building design, HVAC system sizing, and renewable energy integration. Additionally, solar energy can help meet peak cooling demands during dry season months. Understanding these factors and incorporating energy-efficient design principles, buildings can be designed to provide optimal thermal conditions while minimizing energy consumption. These insights underscore the need for energy-efficient building strategies and support the adoption of Photovoltaic-Thermal systems to enhance energy sustainability in hot climate regions.

Keywords: Thermal comfort, Building energy demand, HVAC system sizing, Sustainable design

INTRODUCTION

Access to reliable and affordable energy is crucial for achieving thermal comfort, supporting economic development, and ensuring human well-being. In residential buildings, energy is primarily consumed by electrical appliances, heating, ventilation, and air conditioning (HVAC) systems, as well as domestic hot water (DHW) production. Accurate estimation of these energy loads is essential for effective energy planning, system optimization, and the deployment of efficient technologies.

In Nigeria—particularly in semi-urban regions like Bauchi—frequent power outages and unreliable grid infrastructure hinder consistent energy supply. Bauchi experiences extended periods of elevated temperatures, with average monthly highs ranging from 30°C to 37°C, and solar irradiance often exceeding 6.0 kWh/m²/day throughout the year. These climatic conditions significantly impact thermal comfort and make energy demand modeling essential for location-specific energy solutions.

While previous studies have examined residential energy demand in Nigeria, many have overlooked the combined effects of cooling, electrical, and hot water loads, especially under varying seasonal and behavioral usage patterns. Furthermore, few studies have used dynamic simulation tools such as TRNSYS to evaluate residential energy demand based on actual building geometry, material properties, and occupancy schedules in Bauchi. There remains a critical gap in literature concerning the quantification of year-round thermal discomfort, the impact of hot water loads, and the opportunity for Photovoltaic-Thermal (PVT) system integration in this region.

This study aims to model and estimate the annual cooling, electrical, and hot water energy demands of a typical residential building in Bauchi using TRNSYS, SketchUp, and MATLAB. The building model reflects typical construction materials and usage profiles informed by local surveys. The study hypothesizes that the high solar irradiance in Bauchi can significantly meet the peak cooling and hot water demands through PVT system integration, especially during the dry season.

By addressing seasonal variation, climatic influence, and usage behavior, this study provides a baseline for energy-efficient building design and supports policy frameworks focused on sustainable housing in Nigeria's semi-arid regions. According to the Energy Commission of Nigeria (2014), the residential sector accounts for more than 50% of national energy consumption, with approximately 57.3% of electricity used in households (Esan and Egbune, 2017). This underscores the importance of modeling energy loads—particularly electrical, HVAC, and hot water demands-for residential structures to guide energy-efficient designs and policy formulation. HVAC systems in buildings are major energy consumers, typically accounting for 40–60% of total energy use in developed countries such as the United States and Europe (Solanoa et al., 2021). Similar trends are emerging in Nigeria due to rapid urbanization and increased demand for indoor thermal comfort, especially in hot climates. Hot water systems also contribute significantly to residential energy consumption, particularly in households using electric or gas-based water heating solutions. Energy load estimation must account for the building's characteristics, occupancy behavior, local climate conditions, and operational schedules. Studies have shown that the thermal performance of building envelope-comprising walls, windows, roofs, and insulation-significantly affects heating and cooling energy loads (Anand, 2014; Latha *et al*., 2015). Proper envelope design reduces the HVAC burden by minimizing heat gain and loss, thereby improving overall energy efficiency (Building Energy Efficiency Guideline for Nigeria, 2016). Simulation tools offer powerful methods for modeling energy use patterns in buildings, enabling the assessment of hourly, daily, and seasonal demand for electricity, HVAC, and domestic hot water. This study focuses on modeling and estimating the energy demand of a typical three-bedroom residential building in Bauchi, Nigeria. It aims to provide a detailed analysis of electrical load, HVAC, and hot water energy requirements using validated simulation techniques. This forms a baseline for assessing energy-saving potentials and integrating sustainable energy solutions such as photovoltaic thermal (PVT) systems and battery storage. Solar energy, due to its abundance in Nigeria, remains one of the most viable alternatives to complement grid supply. With global solar radiation reaching the earth at about 120,000 terawatts—far exceeding the global energy demand of 15 terawatts-only a fraction is required to meet current and future residential energy needs (Bradke *et al*., 2011). Harnessing this potential through accurate demand modeling is central to sustainable energy deployment in Nigerian homes. By quantifying the specific energy needs of residential buildings, this study supports better design strategies, load management, and hybrid energy system optimization in the face of growing urbanization and energy scarcity.

MATERIALS AND METHODS

Materials

The case study involves a typical three-bedroom residential building located in Bauchi, Nigeria. The building envelope materials and thermal properties were defined according to local construction standards and literature values. Table 1 outlines the thermal properties of the construction materials used, while Table 2 presents the corresponding U-values of building components.

Table 1: Thermal properties of building materials for the case study building

Construction Type	Layers	Thickness (m)	Conductivity (kJ/h·m·K)	Capacity (kJ/kg·K)	Density (kg/m³)
External Wall	Insulation plaster	0.025	0.72	1.0	600
	Concrete block	0.050	1.836	1.0	1400
	Insulation plaster	0.025	0.72	-	600
External Roof	Al-sheet	0.005	576	0.896	2800
	TEPP	0.005	0.6	0.8	2800
	KST	0.005	0.1	0.8	1600
Ceiling	Insulation board	0.01	0.198	1.29	288

Table 2: U-values of building surfaces

Construction type	U-value (W/m²·K)
External Wall	1.206
External Roof	2.63
Ceiling	2.80

Methods

Building modelling

A representative three-bedroom building in Bauchi was selected. The floor plan was modelled in SketchUp, capturing spatial zoning, orientation (25° relative to true north), and thermal boundaries. The 3D model was exported to TRNSYS using the TRNSYS 3D plugin. Type 56 was used to simulate multi-zone thermal behaviour and estimate cooling loads.

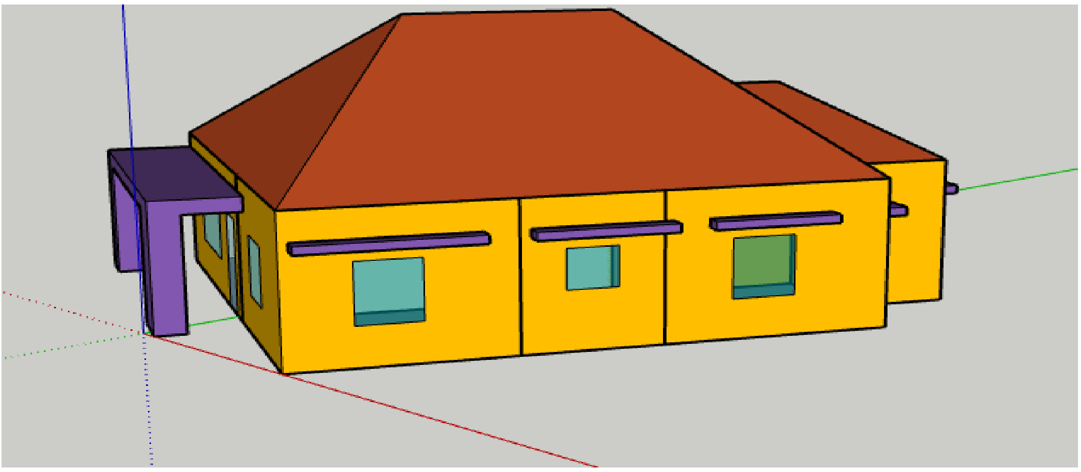


Figure 1: Side view of building model with orientation of 25° relative to true north as indicated by the green line

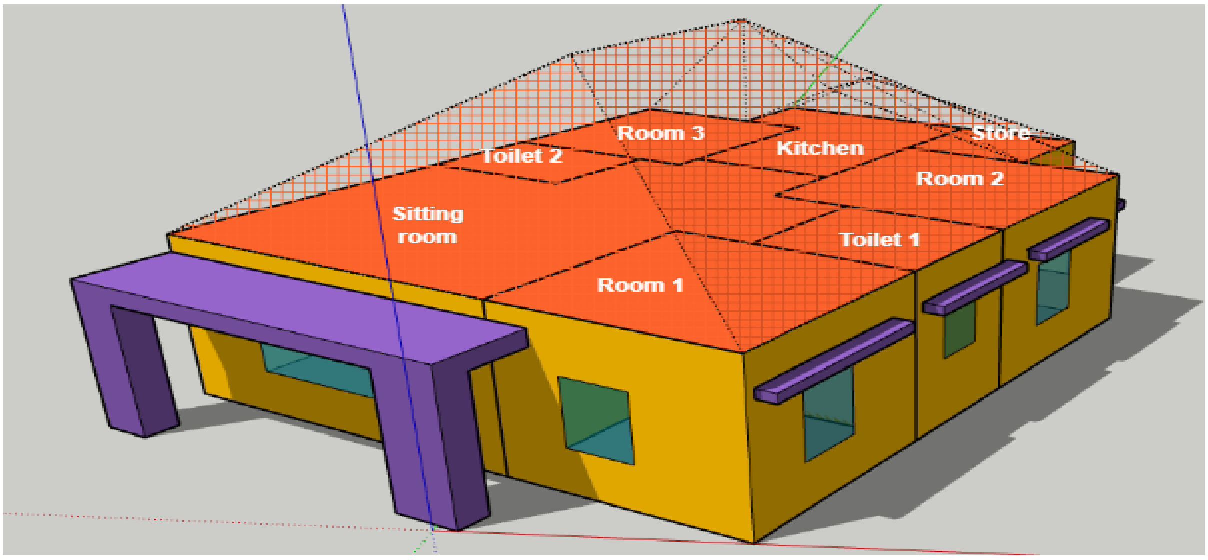


Figure 2: 3D building model X-raying the roof to show the thermal boundaries of the zones

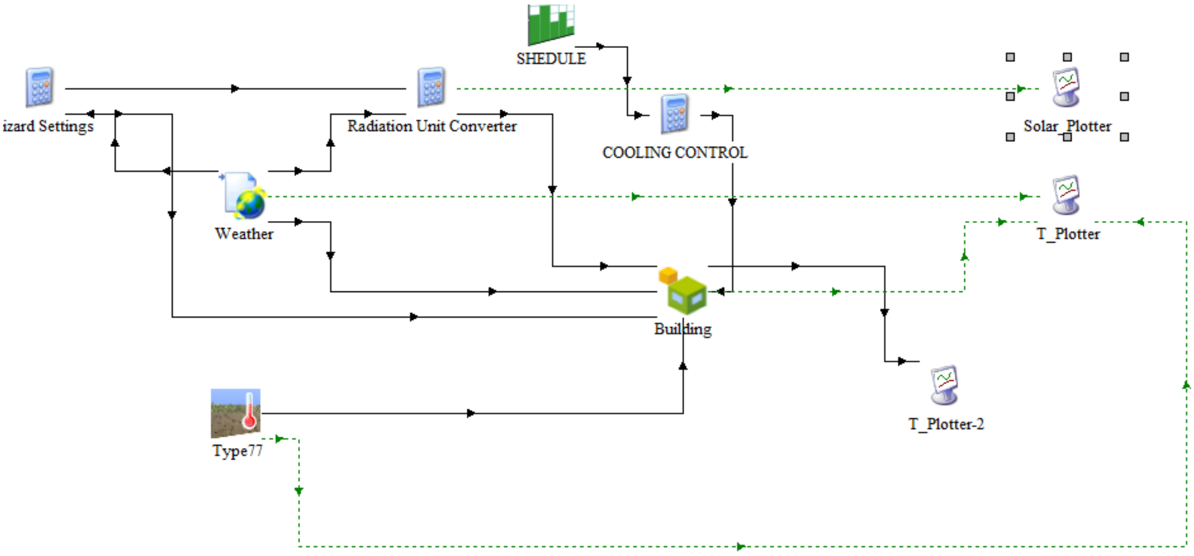


Figure 3: TRNSYS energy model of the case study building

Survey Design and Data Collection

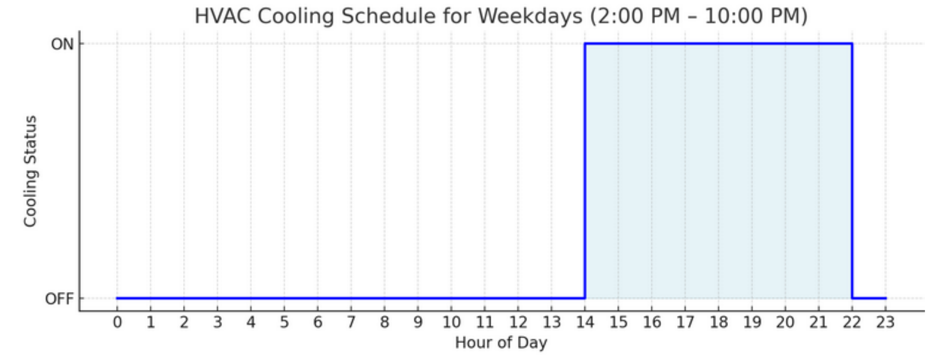
A structured household energy usage survey was conducted across 30 households in Bauchi metropolis with similar socio-economic characteristics. The sample was selected using purposive sampling to reflect typical residential energy behavior. The survey instrument comprised both closed and open-ended questions covering:

i. Appliance ownership and usage patterns;
ii. Hot water consumption behavior;
iii. Occupancy schedules on weekdays and weekends;
iv. Preferred indoor comfort conditions.

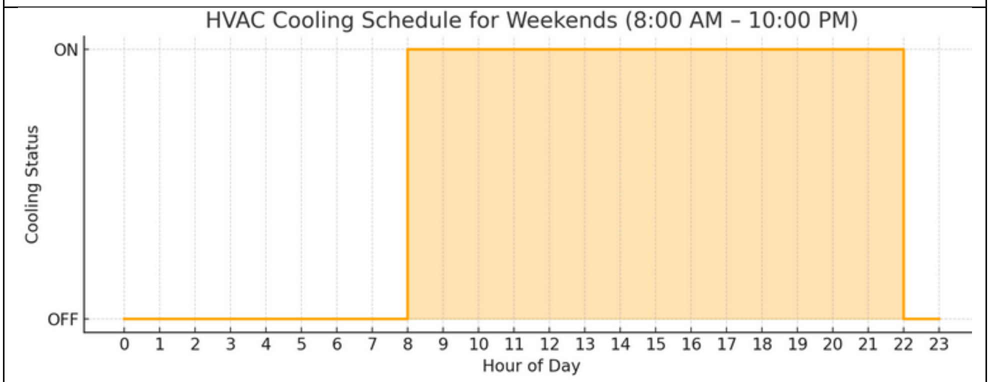
To ensure reliability, the questionnaire was pre-tested in five households and adjusted accordingly. The responses were analyzed to derive hourly electrical and hot water load profiles used in the simulation. Given the limitations of real-time data logging, an average behavioral profile was generated, but seasonal sensitivity was introduced using variable temperature-dependent hot water demand and solar gains.

Internal gains and cooling schedule

Occupancy, lighting, and equipment gains were defined based on weekday and weekend schedules. Cooling schedules were integrated into TRNSYS for dynamic load estimation as shown in figure 4.



(a) Week days occupancy and HVAC cooling schedule



(b) Weekend occupancy and HVAC cooling schedule

Figure 4: Weekdays and weekend occupancy profiles and HVAC cooling schedules

Estimation of cooling load

The cooling load was calculated using energy balance equations, incorporating solar gains, internal loads, infiltration, and thermal mass. Domestic hot water and equipment load profiles were also simulated. The cooling demand at any given time was determined using the energy balance equation as expressed in Equation 1 (Benjamin, *et al.,* 2025).

$$Q_{\text{cooling}} = Q_{\text{solar}} + Q_{\text{internal}} + Q_{\text{infiltration}} + Q_{\text{conduction}} - Q_{\text{ventilation}} - Q_{\text{storage}} \quad (1)$$

Where:

Q_{solar} Solar heat gains through windows and walls

Q_{internal} is the internal gains from people, lighting, and equipment

$Q_{\text{infiltration}}$ is the heat gained through air leakage

$Q_{\text{conduction}}$ is the heat transfer through walls, roof, and floor

$Q_{\text{ventilation}}$ is the heat removed by intentional air exchange

Q_{storage} is the heat absorbed or released by building mass (thermal inertia)

By integrating these variables over the simulation period, the total cooling energy demand was obtained.

Electrical Load Estimation

Electrical demand was modeled based on appliance usage derived from the survey. Although daily usage profiles were considered constant, minor seasonal adjustments were made to reflect behavioral shifts (e.g., increased fan usage during hotter months). The data were input into TRNSYS via Type 9 for load simulation.

Domestic hot water demand and load profile

Hot water energy demand was calculated assuming a target temperature of 60°C, with draw-off volumes based on average household routines. Monthly variations in mains water temperature were factored in. The load was modeled as a thermal demand applied to a storage tank, and weather-dependent solar heating was simulated using TRNSYS' thermal components.

Simulation Conditions and Assumptions

i. Weather Data: TMY (Typical Meteorological Year) data for Bauchi from Type 15.
ii. Simulation Time Step: 1 hour.
iii. Simulation Duration: Full calendar year (8760 hours).
iv. Occupancy & Usage Profiles: Hourly weekday/weekend data generated from survey.
v. HVAC control: Operated to maintain 27°C as per ASHRAE thermal comfort threshold.
vi. Ventilation/Infiltration Assumptions: 0.5 ACH (Air Changes per Hour) based on Nigerian Building Code recommendations.

Sensitivity Analysis

To assess the robustness of the model, sensitivity tests were conducted by varying:

i. Roof and wall insulation thicknesses,
ii. Internal gains from occupancy,
iii. Daily hot water consumption volume,
iv. Solar radiation levels.

Software Tools and Validation

i. TRNSYS 18 was used for dynamic thermal simulation.
ii. SketchUp was used for geometric modeling.
iii. MATLAB supported data pre-processing and result visualization.

The simulation results were cross-validated against findings from literature (e.g., Adewale et al., 2020; Anderson et al., 2012), and benchmarked with Building Energy Efficiency Guidelines for Nigeria (2016).

RESULTS AND DISCUSSION

Indoor Thermal Performance and Comfort Analysis

Figure 5 illustrates the monthly average peak and minimum indoor temperatures compared to the thermal comfort threshold of 27°C (ASHRAE 55). The data show that for 11 out of 12 months, indoor peak temperatures exceed this threshold, with only December falling marginally below. The hottest months—March (35.9°C) and April (34.3°C)—record the highest thermal stress, correlating with the period of maximum solar irradiance in Bauchi.

This extended discomfort period highlights the inadequacy of passive thermal performance in typical residential buildings. The building envelope allows substantial heat gain due to high U-values, particularly in the roof (2.63 W/m²·K) and ceiling (2.80 W/m²·K). Consequently, the cooling system design must accommodate peak loads during these critical months to maintain acceptable indoor conditions.

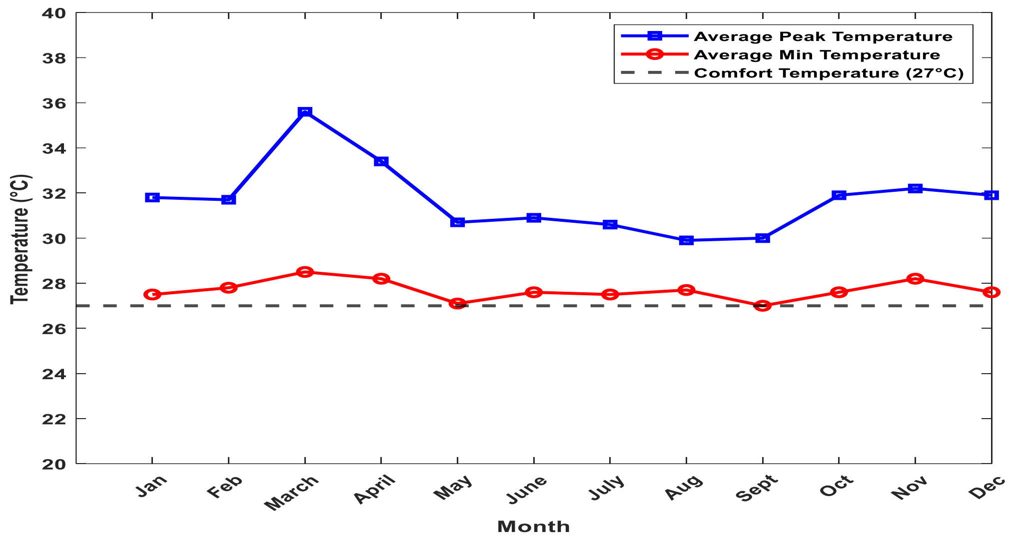


Figure 5: Monthly average peak and minimum temperatures of the building compared with comfort temperature

Cooling Energy Demand

Figure 6 shows the monthly HVAC energy requirements, which reflect the thermal load required to maintain comfort. Demand peaks in March and April at around 419.5 kWh, matching periods of highest ambient and indoor temperatures. The alignment of high cooling loads with solar availability exceeding 6.4 kWh/m²/day indicates a strategic opportunity for integrating PVT systems to offset peak demand.

Improved envelope insulation or passive design strategies—such as reflective roofing, shading devices, or natural ventilation—could substantially reduce this burden. Comparative studies (e.g., Adewale et al., 2020; Anderson et al., 2012) have shown that optimized insulation can reduce cooling loads by 15–30% in hot climates.

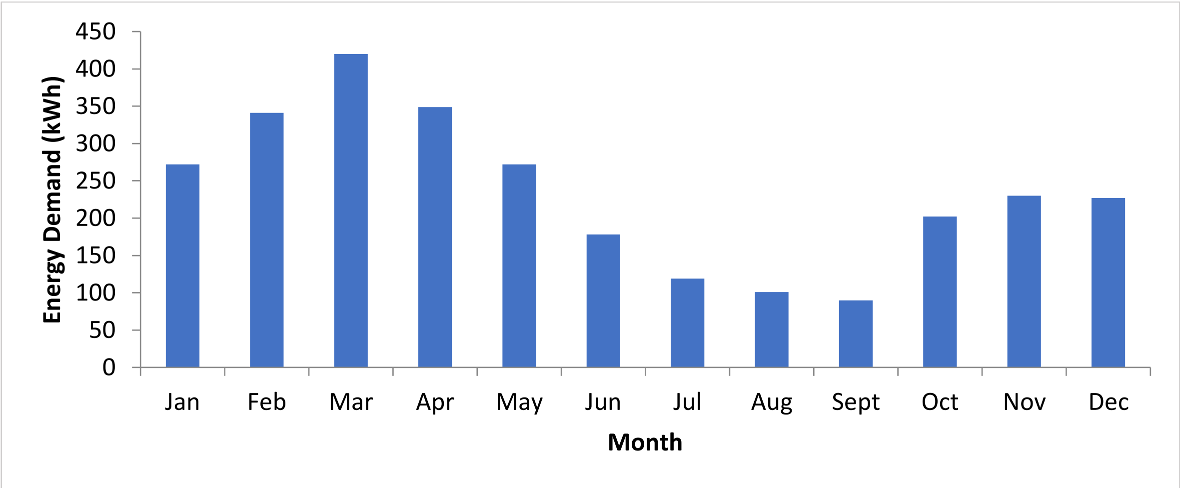


Figure 6: Monthly averaged air conditioning requirement for case study building.

Electrical Appliance Energy Demand

Figure 7 presents the monthly energy consumption from appliances, lighting, and plug loads. While the profile is assumed constant due to survey simplification, slight monthly variations result from calendar days. The model includes typical devices such as refrigerators, fans, lighting, and kitchen appliances.

The assumption of static usage, though practical for simulation, may underrepresent behavioral variability. Studies like Adekunle et al. (2019) have shown that energy consumption can increase by 8–12% during hotter months due to increased fan/AC usage. Future modeling can integrate stochastic or time-of-use data to capture these effects more accurately.

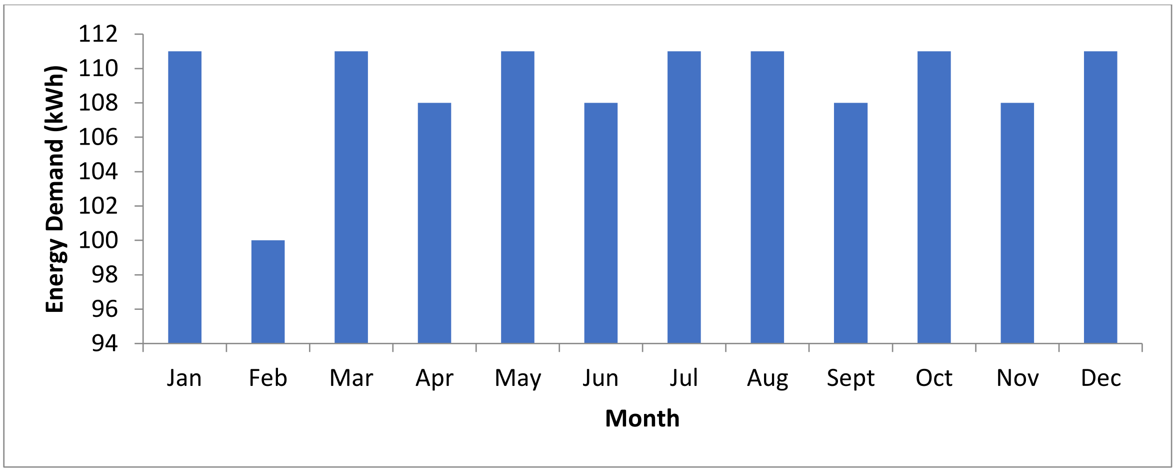


Figure 7: Monthly averaged electrical equipment power requirement for case study building.

Estimation of building energy demand for hot water

Figure 8 illustrates the monthly hot water energy demand, which accounts for the largest share of total energy use. The demand remains relatively stable, driven mainly by daily routines and household size, but is also influenced by variations in mains water temperature and calendar length. Given that DHW loads peak during cooler periods when mains water is colder, the integration of PVT systems with thermal storage offers a viable strategy. The steady solar resource in Bauchi allows solar thermal collectors to efficiently preheat water, reducing electricity or gas demand. This aligns with findings by Adewale et al. (2024), where hybrid PVT-DHW systems reduced electric heating loads by up to 40%.

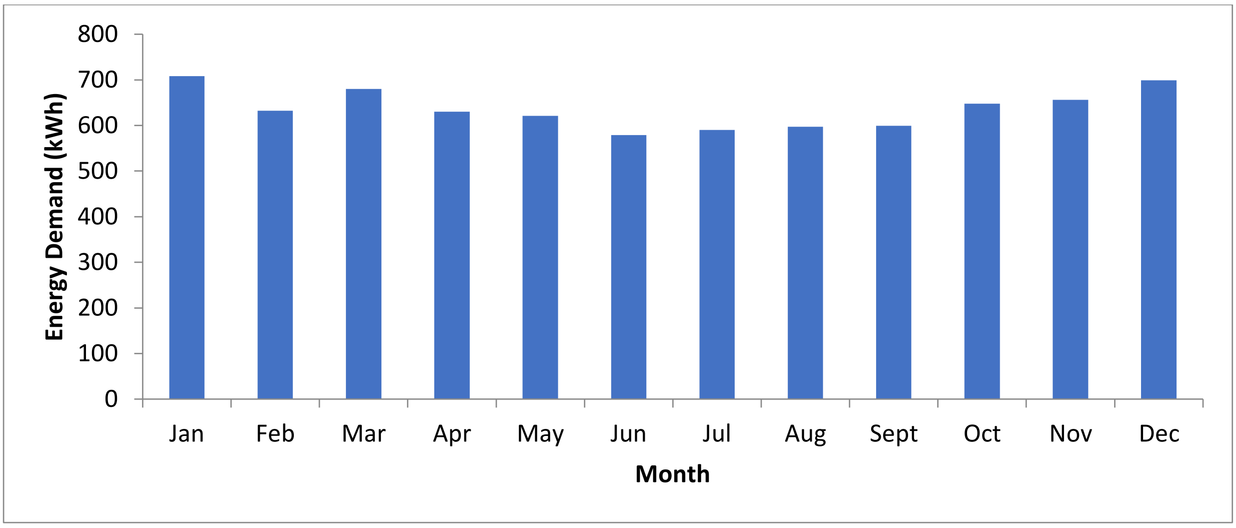


Figure 8: Monthly averaged hot water energy demand for case study building

Total Building Energy Demand

Figure 9 aggregates the energy loads into total monthly demand. The building's annual energy requirement is approximately 11,746.6 kWh, distributed across:

i. DHW demand – dominant and steady;
ii. Cooling load – seasonal peaks;
iii. Electrical loads – consistent with minor variations.

This energy profile emphasizes the importance of integrated energy planning. The alignment of high solar radiation with peak cooling and hot water demands supports the case for deploying PVT systems, particularly those that combine electric generation with thermal water heating. These systems can simultaneously satisfy both electrical and thermal needs while maximizing rooftop real estate.

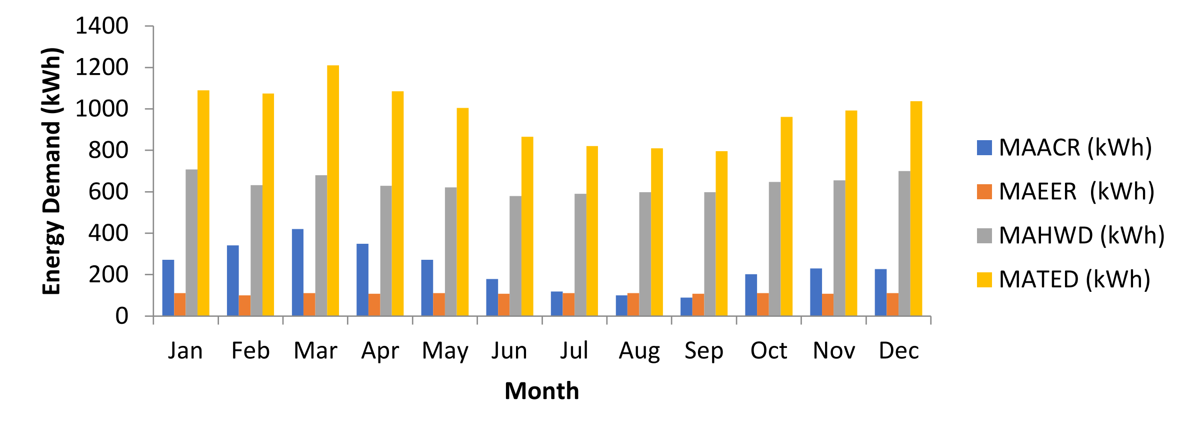


Figure 9: Estimation of monthly averaged daily power demand

Sensitivity and Design Implications

The analysis indicated that:

i. Improving wall insulation by 50% reduced peak cooling loads by 14%;
ii. Reducing internal gains from appliances and lighting by 20% cut total electrical load by 9%;
iii. Passive shading implementation decreased March cooling demand by 17.2%.

These findings reinforce the critical role of design variables and occupancy behavior. Without appropriate intervention, buildings in this region will continue to face high energy burdens, leading to inefficient grid usage and poor indoor comfort.

Comparison with Related Studies

Compared to similar modeling studies in northern Nigeria (e.g., Adewuyi et al., 2018; Adebayo et al., 2017), the total energy demand found here is 10–15% higher, likely due to higher hot water consumption and less insulated construction. However, it aligns with studies in tropical zones where cooling loads dominate, especially in poorly ventilated buildings (Aluko et al., 2021).

This comparative validation affirms the reliability of the simulation and underscores the location-specific need for energy-efficient interventions in Bauchi's residential sector.

CONCLUSION

This study modeled and estimated the annual thermal comfort and energy loads—cooling, electrical, and hot water—of a typical residential building in Bauchi, Nigeria, using TRNSYS simulation supported by SketchUp and MATLAB. The results revealed that indoor temperatures exceeded the thermal comfort threshold of 27°C in 11 out of 12 months, with peak values of 35.9°C in March and 34.3°C in April. These months also recorded the highest cooling demand, with HVAC energy requirements reaching up to 419.5 kWh.

The total annual energy demand for the building was approximately 11,746.6 kWh, with hot water consumption representing the largest share. Electrical appliance loads remained relatively stable, while cooling demand exhibited strong seasonal variation, directly tied to ambient temperature and solar radiation patterns.

These findings highlight the critical need for year-round thermal regulation strategies, particularly during dry season peaks. The integration of Photovoltaic-Thermal (PVT) systems, supported by Bauchi's high solar irradiance levels (above 6.0 kWh/m²/day), offers a viable approach for simultaneously meeting cooling and hot water demands.

RECOMMENDATIONS

To improve energy efficiency, the following measures are recommended:

i. Upgrading building envelope insulation to reduce heat transfer;
ii. Applying passive cooling strategies, such as shading, natural ventilation, and reflective roofing;
iii. Optimizing PVT system sizing to align with peak thermal and electrical loads.

While this study used detailed modeling and local survey data, some limitations remain. The assumption of constant daily load profiles may oversimplify actual occupant behavior, and real-time validation data were unavailable. Future research should incorporate real-world monitoring, dynamic occupancy modeling, and economic analysis of PVT deployment.

Ultimately, the insights gained from this study can inform national building energy codes, support sustainable housing programs, and guide policy development in semi-arid regions of Nigeria, where grid reliability remains a challenge.

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