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Hybridization of energy systems for air conditioning application in an educational building

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Abstract

This study reports the hybridization of energy systems for an air conditioning (AC) application in an educational building, using the Faculty of Engineering Lecture Theaters at Rivers State University, Port Harcourt, Nigeria as case study. It includes conceptual design of a hybrid energy system of thermoelectric and solar energy, analysis of cooling load to select suitable air conditioning system for the building using Carrier's Hourly Analysis Program (HAP) software, analysis of the required energy to drive the air conditioning system, and techno-economic analysis of the system. The analysis carried out shows that a total of 4 packaged rooftop air conditioners each of 10.6kW (30,000 Btu/h) capacity would be required to handle the building's cooling load of 38.28kW, and would require 344.5kWh of energy per day, out of which 249kWh/day would be generated from the thermoelectric generator (TEG) modules, and the remaining 95.5kWh/day would be generated from the photovoltaic (PV) modules. The 249kWh/day of energy required from the thermoelectric energy system would require a total of 1600 TEG modules of 26W each, and the 95.5kWh/day of energy required from the solar system would require a total of 65 PV modules of 330W each. The energy generated would be stored in a 679kWh capacity battery storage system which contains 72 batteries of 48V and 200Ah capacity each, which are wired into 3 parallel strings, which would supply the AC system. The techno-economic analysis carried out shows that the system designed can be implemented at a cost of ₦98,558,000, with a payback period of 9years, and would mitigate 72,050.5kg of CO_2 emissions annually.

Keywords: Air Conditioning System; Cooling Load; Hybrid Energy System; Solar Energy; Thermoelectric Energy

1. Introduction

Air Conditioning (AC) is the provision of an acceptable thermal environment within a building. It includes, cooling, humidifying, dehumidifying, filtering, and distribution of air at suitable conditions for the maintenance of human comfort [1]. In tropical climate, the AC system plays an important role to foster a comfortable environment for improved work efficiency in educational buildings. As the climate change indicators are projecting rising global average temperature that is associated with extreme weather conditions such as heat waves, AC systems have become an essential commodity for educational buildings [2]. In order to design an AC system, the appropriate cooling, heating, and other environmental loads must first be calculated, other factors such as initial and running costs, distribution space, control requirements and energy required to drive the system must be assessed [1].

AC systems substantially consume large amounts of energy, often account for approximately 87% of total building energy consumption, and add over 1.9 million tons of greenhouse gas emission annually [3]; thus necessitating that energy supply to the AC systems should be derived from sustainable energy systems. Sustainable energy is energy from sources that can be replenished, and meet our current energy needs without causing long-term damage to the environment. Sustainable energy includes all renewable energy sources, such as hydro, biofuel, thermoelectric, wind, and solar energy sources [4]. Variable weather and environmental conditions limit the ability of renewable sources to

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supply energy continuously, when only one source is considered. Such problems would be averted by integrating various energy sources into hybrid energy systems, that would greatly reduce the irregularities and uncertainties of the energy generation [5]. Thus, this study reports the hybridization of energy systems for air conditioning application in an educational building.

2. Literature Review

In the face of internationally tightened requirements for the regulation of greenhouse gas emissions to tackle climate change, transiting to renewable energy, and reducing reliance on fossil fuels, has become one of the effective ways to tackle climate change. Thus, hybridization of renewable energy systems for various applications, has become one of the most significant research interests. Several research studies have reported on this subject, some of which are reviewed as follows:

Nakomcic-Smaragdakis and Dragutinovic [6] carried out an assessment on the potential and cost-effectiveness of hybrid renewable energy system for heating/cooling purposes and power supply application in a residential building in Serbia. They proposed a hybrid system consisting of geothermal heat pump for heating/cooling, solar photovoltaic panels and small wind turbine for power supply of the building. The hybrid renewable energy system analysis was conducted with the help of RETScreen software. The results showed that the hybrid system was able to meet the heating/cooling and electrical energy needs of the building in a sustainable way. Also, the techno-economics analysis carried out shown that investing in geothermal heat pump and photovoltaic panels was cost-effective.

Ani [7] reported the experience acquired with a photovoltaic (PV) hybrid system simulated as an alternative to a diesel generator system for a residential home located in Southern Nigeria. The hybrid system was designed to overcome the problem of climate change, to ensure a reliable supply of energy, and to improve the overall system efficiency by the integration of a battery bank. The system design was done using conventional simulation tools and representative insolation data. The analysis of the energy flows through the system was carried out to quantifies all the losses caused by PV charge controller, battery storage round-trip, rectifier, and inverter conversions. A simulation was run to compare the PV/diesel/battery with the diesel/battery and the results showed that the capital cost of a PV/diesel hybrid solution with batteries was nearly three times higher than that of a generator and battery combination, but the net present cost, representing cost over the lifetime of the system, was less than one-half of the generator and battery combination.

Assadi *et al*. [8] developed and integrated a solar hybrid system into a conventional AC system to handle the same cooling load, but with considerably less electricity demand. In the paper, a solar evacuated tube and a DC compressor were set up to compressed the refrigerant in the AC system. A three-dimensional simulation and analysis of the thermal performance was carried out for the set-up using the solar ray-tracing model provided by the ANSYS-FLUENT software. The results showed that the DC compressor reduced the air conditioning electricity consumption by up to 45%, and contributed up to 25% of energy saving.

Mbarek *et al.* [9] proposed a design for hybrid solar AC, ventilation, humidification, dehumidification and desalination system. The design was proposed to produce both thermal comfort and desalinated water for residential buildings. Mathematical models that govern the heat and mass transfer in the different compartments of the proposed design and within the conditioned space were developed. A numerical investigation was carried out to assess the heat and mass transfer performance of the designed hybrid system, as well as the produced thermal comfort within the conditioned space. All numerical simulations were carried out under the realistic climatic conditions of the region which was located in Gafsa, Tunisia. Results show that the performance of the proposed design was within the AC standards. It was concluded that buildings in hot and arid regions can fully benefit from the design.

Farajat and Abu-Zaid [10] designed a solar power AC system for the engineering building at Mutah University, Jordan. In the design, a suitable cooling system to cater for the required load was analyzed using climatic variables, Cooling Load Temperature Difference (CLTD), Solar Cooling Load (SCL) and Cooling Load Factor (CLF). A solar power plant was designed to provide power for the system. The results showed that the solar power system generated sufficient power to handle the cooling load, and was more economical powering the AC system from the solar power system than from the grid for the first ten years.

Al–Okbi *et al.* [11] reported a new solar hybrid air conditioner designed to demonstrate the potential of using solar energy to improve AC system performance and economize electrical energy. In the design, a solar thermal collector was added to the compressor to add thermal energy to the system and reduce the energy consumption of the compressor. Modern simulators were used to determine the optimal set points for the temperature of the refrigerant leaving the water storage tank and entering the condenser as a reference temperature. The experiments on the test apparatus were carried out in three cases, first conventional, second with a 2-ton compressor and with a solar collector, and third with a solar collector but with replacing the compressor by another one of size 1.5 ton. Coolpack computer software was used to analyze the data obtained from the experiment, and the results showed that the refrigeration cycle system of the new design provided higher coefficient of performance (COP) when compared with the traditional system. Thus, the design demonstrated the possibility of using solar energy to improve system performance and reduce electrical energy consumption by an air conditioning system.

Shalgar *et al.* [12] designed a hybrid air conditioning system for sleeper commercial vehicles using a combined conventional compression and phase change material. The system included a cold storage heat exchanger which was designed for transferring heat between the three fluids—refrigerant, phase change material, and air. Thermal energy was stored in the phase change material during vehicle operation by extracting latent heat from the conventional compression system's refrigerant and reused during engine shutdown by exchanging it with air for cooling. The designed cold storage heat exchanger was evaluated using a computational fluid dynamics tool by varying various parameters and optimizing for operation time. The use of hybrid air conditioning systems was found significantly useful for sleeper cabins for prolonged operation time, reducing driver fatigue, and enhanced thermal comfort.

Al-Yasiri *et al.* [13] reviewed the main solar cooling and air-conditioning systems driven by solar thermal energy that were used for building applications. The primary operation method, and some recent developments of solar cooling and air-conditioning systems were discussed and highlighted. From the several literatures reviewed, they concluded that solar cooling and air-conditioning systems were installed for commercial buildings more than residential buildings with high capacities, even though their performance still lags compared with the traditional systems driven by convectional energy sources. They also recommended new numerical and experimental studies considering novel advances to improve solar collectors, creating new sorption materials, developing hybrid cycles and heat transfer components.

Having reviewed literatures, due to increase in enrollments of students every year, and projected rising global average temperature, the most emphasized aspects of educational buildings that are essential to meeting students need include space cooling controlled through AC systems. However, AC systems are contributing increasingly to global energy demand, and adding to greenhouse gas emissions, without adequate action to address energy efficiency and demand for space cooling that is expected to triple by 2050. Thus, this paper reports the hybridization of energy systems for air conditioning application in educational buildings, using the Faculty of Engineering Lecture Theaters at Rivers State University, Port Harcourt, Nigeria, as a case study.

3. Material and methods

The materials for this study include climate and solar irradiation data of Port Harcourt, design information of the building, standard design data and stipulated guideline by ASHRAE [14], Carrier's Hourly Analysis Program (HAPv6), and a 2000kVA diesel generator set catalog by Caterpillar [15]. The methods that have been used in the study are discussed in the following sections:

3.1. Description of the Building

The Faculty of Engineering Lecture Theaters at Rivers State University, Port Harcourt, Nigeria, under study was designed to house teaching activities and services necessary for the proper functioning of university programs. The building is composed of four classrooms, namely: LT1, LT2, LT3 and LT4, which was designed to function with an air conditioning system. From the building survey conducted, the structure of the building consists of a reinforced concrete prefabricated construction system. The roof has clay tiles with acoustic and thermal insulation. Table 1 summarizes the building survey report.

Table 1 Building Survey Report

Building Characteristics	**Values**
Location	Port Harcourt with Coordinates 4.9 °N, 7.1 °E
Orientation	59 ^{o}NE
Floor-to-ceiling Height	5.4m
Wall thickness	0.61m
Window	0.9m x 0.75m glass-window

Door	1.8m x 2.1m metal door
Occupancy	60 persons per classroom
Lighting	600W per classroom
Working hours:	8:00am to 4:00pm
Outdoor dry bulb	36 °C
Outdoor wet bulb:	26 °C
Indoor design temperature:	18 °C
Outside relative humidity	78%
Inside relative humidity	50%
Average wind velocity	7.5m/s

Source: Building Survey Report conducted by the authors

3.2. Designing of Thermal Zone

Thermal zone is occupied space or spaces within a building with similar heating or cooling requirements so that comfort conditions can be controlled by a single thermostat. Designing of thermal zone is the dividing of the building into separate spaces and each space's air conditioning is controlled independently [16]. According to McDowall [17] designing of thermal zone with less number of zones and fewer thermostats is considered an effective design. The building under study is divided into 4 thermal zones to simplify the cooling calculation process. The schematic diagram and detail description of the building thermal zoning design are shown in Table 2 and Figure 1.

Table 2 Description of the Building Zoning Design

Zone	Name	No of Walls per Room Facing Sun	Wall Facing Sun	Wall Gross Area Facing Sun (m^2)	No of Rooms per Zone	Roof/Floor Gross Area (m^2)
1	LT1	2	NW,SW	37, 78	1	97.92
2	LT2	1	NW	37	1	97.92
3	LT3	2	NW,NE	37, 78	1	97.92
4	LT4	3	NE,SW,SE	78, 78, 37	1	97.92

Source: Building Survey Report conducted by the authors

3.3. Designing of Air Conditioning System

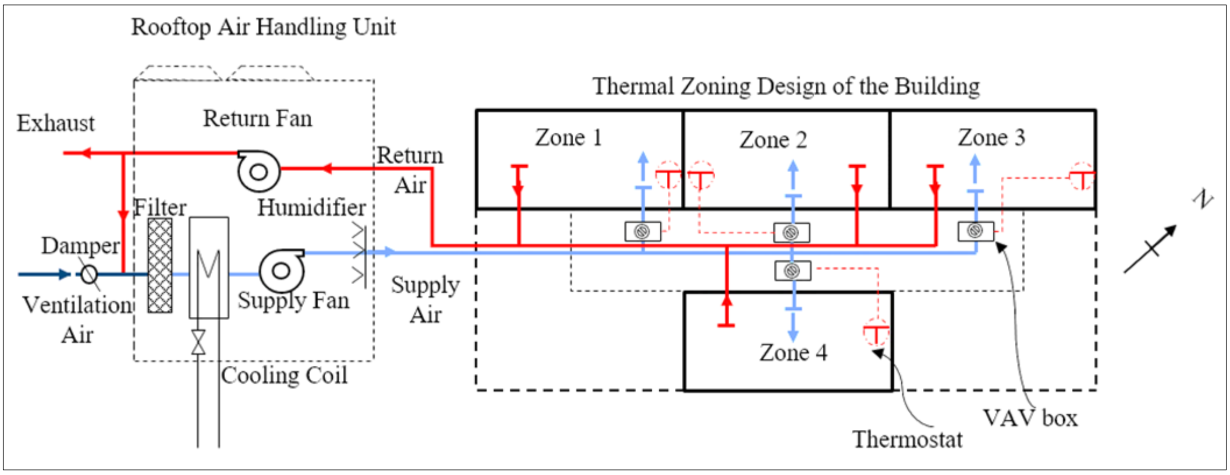

Figure 1 Schematic of the Air Conditioning System

In air conditioning design, different sizes and systems are considered depending on a variety of factors such as the space to be cooled, application type and aesthetic preferences. The rooftop variable air volume (VAV) system is used in this study. This system is used to provide comfort in a wide range of building types and climates. The VAV system consists of a central air handling unit which provides supply air to the VAV terminal control box that is located in each zone to adjust the supply air volume, as shown in Figure 1. The VAV terminal control box in each zone is controlled by a temperature sensor [18]. The size of an air conditioning system is determined by the cooling load, whose calculation is the first step in the air-conditioning system design procedure [19, 20].

3.4. Cooling Load Calculation

Cooling load is the total heat required to be removed from a space in order to bring it to the desired temperature and relative humidity by the air conditioning system. The cooling load calculation is used to select the size or capacity of air conditioners required during the period of high temperatures, and also the energy capacity required to drive the system [16]. There are multiple methods used to calculate the cooling load and are documented in Chartered Institution of Building Services Engineers [21], ASHRAE [14], and McQuinston and Parker [22]. Also, various computer programs and software have been developed for cooling load calculation, including the Carrier's Hourly Analysis Program (HAP) which is a commercial software that performs the cooling/heating load calculation on hourly basis and can be used for any building design [23]. Thus, HAP program is used to calculate the cooling load of the building under study. The calculation was carried out on February 26th at 1300 hours. February is the usual design month, being a hot and humid month that is peculiar to Nigeria due to her location in the tropic.

3.5. Cooling Capacity of the Air Conditioner

The selection of air conditioner of adequate cooling capacity to maintain the required comfort conditions within the space under the normal range of climatic conditions for the region is based on the cooling load [1]. Packaged rooftop air conditioners, which are designed for ducted systems that enable their installation on the rooftop are used in this study. According to Daikin [24] packaged rooftop air conditioners are designed from the ground up to include the features and benefits that are ideal for offices, schools and libraries. The total capacity of the air conditioners can be determined by the formula:

$$C_{TAC} = Q_{Total} \times sf \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where Q_{Total} = Total cooling load, sf = Safety factor. A safety factor of 1.1 to 1.2 would be applied to the calculation to account for errors and variations from design. The number of air conditioners required is given by [25]

$$n = \frac{C_{TAC}}{C_n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where c_n = nominal capacity of the air conditioner. The nominal capacity of commercial packaged rooftop air conditioners usually ranges from 36,000Btu/h (10.6kW) to 300,000Btu/h (87.9 kW) [24]

3.6. Energy Requirement

The energy required depends on the cooling capacity of the air conditioners and the controls employed to maintain the comfort conditions. The daily energy consumption of the air conditioners expressed in kilowatt hour per day (kWh/day) is calculated using the formula:

$$E_{AC} = C_{TAC} \times UH_{AC} \quad \ldots\ldots\ldots\ldots\ldots(3)$$

where UH_{AC} = usage hours of the AC equipment (h)

3.7. Description of the Hybrid Energy System

Hybrid energy systems combine multiple types of energy generation and/or storage or use two or more kinds of fuel for power generation. A hybrid energy system is a valuable method in the transition from fossil fuel-based power generation, and it can capitalize on existing energy infrastructure and add components to help reduce costs and environmental impacts [26]. The system employed in this study combines a diesel generator, thermoelectric energy and solar energy sources, and operates as explained in the schematic diagram of Figure 2. The system components include the PV array, thermoelectric generator modules, energy storage system (ESS), inverters, charge controller, diesel generator and other installation hardware.

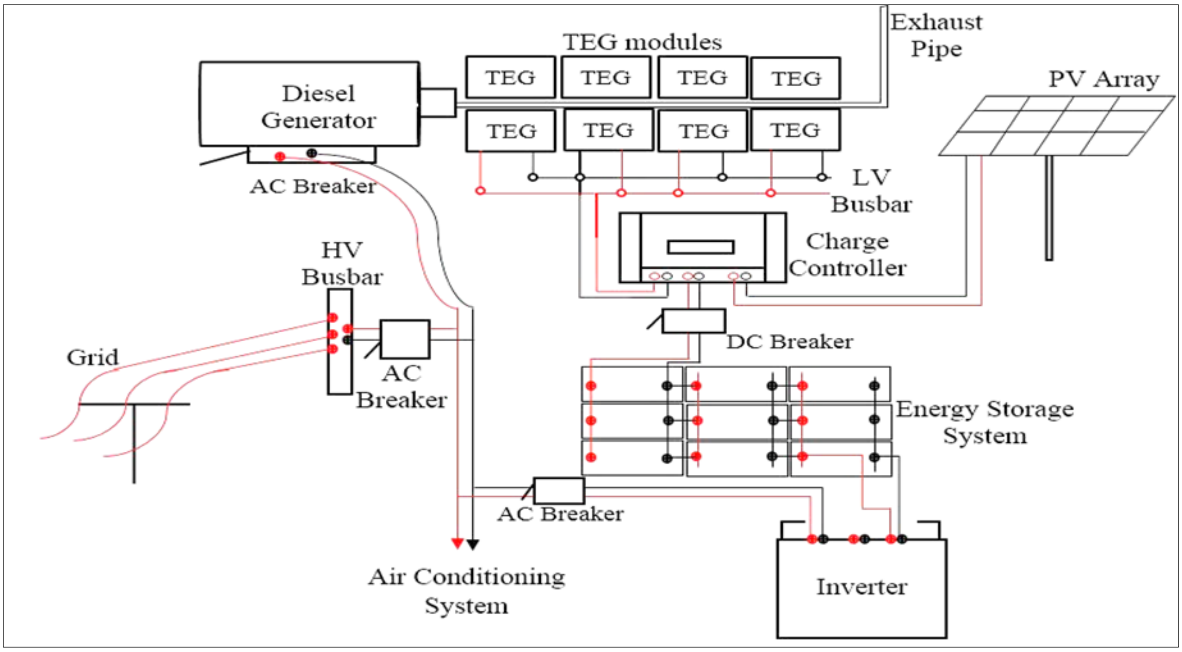

Figure 2 Schematic Diagram of Hybrid Energy System Operation

3.7.1. Diesel generator energy

The hybrid energy system in this study capitalizes on the existing 2000kVA diesel generator that supplies energy to the university, when there is no supply from the grid. The waste heat in the exhaust gas of the diesel generator would be converted to useful energy by the thermoelectric generators. The detail specification of the diesel generator is obtained from Caterpillar [15]. The quantity of waste heat in the exhaust gas is a function of the specific heat, temperature and the mass flow rate of the exhaust gas. The quantity of available waste heat flow in an exhaust gas can be calculated using the formula [27].

$$\dot{Q}_e = \dot{m}_e \times C_{pe} \times (T_e - T_c) \quad ....(4)$$

where $\dot{m}_e$ = exhaust gas flow rate, C_{pe} = specific heat of exhaust gas, T_e = exhaust stack gas temperature, T_c = cold side temperature of the TEG module.

3.7.2. Thermoelectric energy

Thermoelectric energy generation is the conversion of temperature difference into electrical energy using thermoelectric generators (TEG). A TEG module is specifically designed and manufactured to convert high temperature heat sources directly into electricity. The bismuth-telluride (Bi_2Te_3)-based TEG module can operate at temperatures as high as 400 °C intermittently. The TEG *et al.*, module generates DC electrical power, and the power generated is proportional to the temperature difference across the module [28]. The TEG modules generally have low energy conversion efficiency, typically in the range of 3 -7% [29]. As illustrated in Figure 2, the waste heat in the exhaust gas is transferred to the hot side of the TEG modules that convert it into electrical energy whenever the diesel generator is running. The electrical energy is harvested and stored in the energy storage system (ESS). The power generated by thermoelectric modules is given by [30].

$$P_{TEG} = \eta_{TEG} \times \dot{Q}_e \quad .... (5)$$

where η_{TEG} = TEG module energy conversion efficiency. The number of TEG modules required for the system is given by [30]

$$N_{TEGm} = \frac{P_{TEG}}{p_{TEGm}} \text{ ....(6)}$$

where p_{TEGm} = power rating of TEG module. The energy available from the TEG modules is calculated using the formula

$$E_{TEG} = P_{TEG} \times OH_{gen} \text{ ....(7)}$$

where OH_{gen} = Operating hours of the diesel generator (h). From the survey conducted, the diesel generator in the university is run for an average of 10 hours daily.

3.7.3. Solar energy

The solar energy system uses photovoltaic (PV) modules to convert sunlight into electricity. The required size of the PV array depends on the energy requirement and the solar irradiation available at the area. The energy required from the PV array (E_{PV}) is the difference between the energy consumption of the air conditioners (E_{AC}) and energy available from the TEG modules (E_{TEG}). The PV array area (A_{PV}) and the peak power (P_{PV}) are, respectively, given as [31].

$$A_{PV} = \frac{E_{PV}}{G_{av} \times \eta_{PV} \times TCF} \text{ ....(8)}$$

and $$P_{PV} = A_{PV} \times G_{ref} \times \eta_{PV} \text{ ....(9)}$$

where G_{av} = daily average irradiation on a horizontal surface (kW/m^2), η_{pv}= PV energy conversion efficiency, TCF = temperature correction factor, G_{ref} = solar irradiation at standard test condition amounting to $1kW/m^2$. According to energy sector management assistance program [32], the global horizontal irradiation for Port Harcourt is $4.2kWh/m^2$ per day. TCF that corresponds to the average annual ambient temperature of 26.5 $°C$ experienced in Port Harcourt is 1.07 [33].

The total number of modules (N_m) in the PV array is given by [34].

$$N_m = \frac{A_{PV}}{A_m} \text{ ....(10)}$$

where A_m = area of each module (m^2).

3.7.4. Energy Storage System (ESS)

The energy harvested from the PV and TEG modules are stored in the ESS. The required energy storage capacity of the ESS expressed in Watt-hour (Wh) and Ampere-hours (Ah), respectively, are given as [35].

$$C_{Wh} = \frac{E_{TEG} + E_{PV} \times DOA}{DOD \times \eta_b \times \eta_{inv}} \text{ ....(11)}$$

and $$C_{Ah} = \frac{C_{Wh}}{V_{PV} + V_{TEG}} \text{ .... (12)}$$

where C_{Wh} = energy storage capacity (Wh), DOA = numbers of days of autonomy, DOD = battery depth of discharge, η_b= battery efficiency ($\%$), η_{inv} = inverter efficiency ($\%$), C_{Ah} = energy storage capacity (Ah). V_{TEG} = TEG module open circuit voltage (V).

The number of batteries to be connected in series and parallel of the BSS are given respectively as [34]

$$N_{BS} = \frac{V_{PV} + V_{TEG}}{V_b} \text{ .... (13)}$$

and $N_{BP} = \frac{C_{Ah}}{C_b}$ ………………… (14)

where N_{BS} = number of batteries to be connected in series, V_b = voltage rating of a single battery (V), N_{BP} =number of batteries to be connected in parallel, C_b = energy capacity of a single battery (Ah).

The total number of batteries (N_B) required for BSS is then given as [34]

$$N_B = N_{BP} \times N_{BS} \text{ ………………… (15)}$$

Energy stored in DC source is converted to AC using inverters. The number of inverters (N_{inv}) required for the system is given as [34]

$$N_{inv} = \frac{Pf \times (P_{PV} + P_{TEG})}{P_{inv}} \text{ …………… (16)}$$

where Pf = power factor, P_{inv} = power capacity rating of a single inverter (kVA).

3.7.5. Techno-economic Analysis

Techno-economic analysis is a widely practiced approach used for evaluating the technical performance and economic feasibility of a technology [36]. The techno-economic metrics used in this study include payback period and carbon emission mitigation.

3.7.6. Payback Period

Payback period determines the number of years the energy savings from a renewable energy system would offset the initial cost of the investment. Payback is calculated using the formula [37].

$$PbP = \frac{I \times (1 + Cf_{OM})}{U_{kWh} \times (E_{TEG} + E_{PV})} \text{ ……………….. (17)}$$

where PbP = payback period (year), I = installation cost of the system (₦), Cf_{OM} = operation and maintenance cost factor U_{kWh} = unit cost of energy (₦/kWh). The average unit cost of grid electricity in Nigeria is ₦88.58/kWh [38]. The annual operation and maintenance cost of utility infrastructure which includes the energy project is expressed as a percentage of its investment cost, and typical values range from 1% to 4% [39].

3.7.7. Carbon Emission Mitigation

Using renewable energy systems for power generation is one of the effective strategies to mitigate carbon emission. The amount of carbon emission mitigated is calculated by [40].

$$A_{EM} = (E_{PV} + E_{TEG}) \times Ef_{grid} \text{ …………..(18)}$$

where AEM = amount of carbon emission mitigation ($kgCO_2$), Efgrid = Electricity emission factor (kgCO2eq/kWh). An electricity emission factor refers to a CO_2 emission factor which would be associated with each unit of electricity provided by an electricity system. Nigeria's average carbon emission factor for grid electricity is 0.573kgCO2eq/kWh [41].

4. Results and discussion

The results of the study are presented and discussed as follows:

4.1. Analysis of the cooling load

The cooling load calculation for the thermal zones of the building was implemented in the HAPv6 software developed by Carrier Corporation, and the results are summarized in Figure 3.

Zone Sizing Summary for VAV System

Project Name: Faculty of Engineering Lecture Theaters at Rivers State University, Port Harcourt, Nigeria — 26/02/2023
Prepared by: Bumag Energies — 1:45PM

Air System Information

Air System Name .... VAV System
Equipment Class .... PKG Roof
Air System Type .... VAV

Number of zones 4
Floor Area 391.68m²
Location .... Port Harcourt, Rivers State

Sizing Calculation Information

Calculation Months .... Feb to May
Sizing Data .... Calculated

Zone CFM Sizing .... Peak zone cooling load
Space CFM Sizing .... Individual peak space load

Space Loads and Airflows

Zone Name / Space Name	Mult.	Cooling Load (kW)	Time of Peak Sensible Load	Air Flow (L/s)	Heating Load (kW)	Zone Floor Area (m²)	Space (L/s-m²)
Zone 1 – LT1							
LT1 - Typical Classroom	1	7.9	Feb 1300	588	0.0	97.92	6
Zone 2 - LT2							
LT2 - Typical Classroom	1	6.8	Feb 1300	588	0.0	97.92	6
Zone 3 - LT3							
LT3 - Typical Classroom	1	7.9	Feb 1300	588	0.0	97.92	6
Zone 4 - LT4							
LT4 - Classroom	1	9.3	Feb 1300	588	0.0	97.92	6

Figure 3 Snapshot of HAP Report for the Cooling Load Calculation

4.2. Analysis of the capacity of the air conditioners and energy requirements

Applying equation 1, where Q_{Total} = 7.9 + 6.8+ 7.9+ 9.3 = 31.9kW (from Figure 3), *sf*= 1.2

$$C_{TAC} = 31.9 \times 1.2 = 38.28kW$$

Also, applying equation 2, $C_n = 10.6kW$

$$n = \frac{38.28}{10.6} \approx 4$$

Using equations 3, where $C_{TAC} = 38.28kW$, $UH_{AC} = 9h$ (from Table 1)

$$E_{AC} = 38.28 \times 9 = 344.5kWh/day$$

From the analysis, a total of 4 packaged rooftop air conditioners of 10.6*kW* (30000 *Btu/h*) capacity each, would be required to handle the building's cooling load of 38.28kW. The 4 packaged rooftop air conditioners would require 344.5*kWh* of energy per day.

4.3. Analysis of quantity of waste heat in the exhaust gas

Applying equation 4, the quantity of waste heat in the exhaust gas is calculated as follows: $m_e = 2.536kg/s$, $C_{pe} = 1.185kJ/kgK$, $T_e = 763.3K$ [15], $T_c = 303K$ (from Table 3)

$$\dot{Q}_e = 2.536 \times 1.185 \times (763.3 - 303) = 1383.3kW$$

4.4. Analysis of energy generated by the TEG modules

Applying equation 5 and 6, the total power generated by the TEG modules and the number of TEG modules required to harvest the waste available in the exhaust gas are determined, respectively, as follows: $\eta_{TEG} = 0.031$ (from Table 3), $Q_e = 1383.3kW$, $P_{TEGm} = 26W$

$$P_{TEG} = 0.031 \times 1383.3 = 41.5\text{kW}$$

and

$$N_{TEGm} = \frac{41500}{26} \approx 1600$$

Applying equation 7, the energy generated by the TEG modules is thus calculated as: P_{TEG} = 41.5kW, OH_{gen} = 6h

$$E_{TEG} = 41.5 \times 6 = 249kWh$$

From the analysis, out of the 344.5kWh/day of energy required to power the air conditioners, 249*kWh/day* would be generated from the thermoelectric generators, and the remaining 95.5kWh/day would be generated from the PV array. The 249*kWh/day* of energy required from the thermoelectric energy system would require a total of 1600 TEG modules of 26*W* each.

4.5. Analysis of energy required from the PV array

Using Equation 8, the PV array area is calculated as follows: E_{PV} = 95.5*kWh/day*, G_{av} = 4.2$kWh/m^2/day$, *TCF* = 1.07, η_{pv} = 0.168 (from Table 3)

$$A_{PV} = \frac{95.5}{4.2 \times 0.168 \times 1.07} \approx 127\text{m}^2$$

Applying Equation 9, where A_{pv} = 127m^2, G_{ref} = 1kW/m^2, η_{pv} = 0.168, we obtain the peak power from the PV array

$$P_{PV} = 127 \times 1 \times 0.168 = 21.3kW$$

Using Equation 10, the total number of modules in the PV array is calculated as follows: A_{PV} = 127m^2, $A_m = 1.956m \times 0.995m = 1.946m^2$ (from Table 2)

$$N_m = \frac{127}{1.946} \approx 65$$

The 95.5*kWh/day* of energy required from the solar system would require a total of 65 PV modules, covering an array area of 127m^2.

4.6. Analysis of the required capacity of BSS

Applying Equations 11 and 12, where E_{TEG} = 249kWh, E_{PV} = 95.5kWh, DOA = 2, DOD = 0.80, η_b= 0.90, η_{inv} = 0.9, V_{pv} = 1000V, $V_{TEG} = 40 \times 4.4 + 4.4 = 184.4V$ (from Table 3), the energy storage capacity in Watt-hour and Ampere-hour are respectively, calculated thus:

$$C_{Wh} = \frac{249 + 95.5 \times 2}{0.8 \times 0.9 \times 0.9} \approx 679kWh$$

and $$C_{Ah} = \frac{679000}{1000 + 184.4} \approx 573Ah$$

Applying Equations 13, 14 and 15 noting that V_{PV} = 1000V, V_{TEG} = 184.4V, V_b = 48V (from Table 3), C_{Ah} = 573Ah, C_b = 200Ah, the total number of batteries required for BSS are calculated thus:

$$N_{BS} = \frac{1000 + 184.4}{48} \approx 25, \; N_{BP} = \frac{573}{200} \approx 3$$

$$N_B = 24 \times 3 = 72$$

The 679*kWh* energy storage capacity of the BSS contains 72 batteries of 48*V*, 200*Ah* capacity each, which are wired into 3 parallel strings.

4.7. Analysis of the required number of inverters

Applying Equation 16, where P_{PV} = 21.3kW, P_{TEG} = 41.5kW, Pf = 1.25, P_{inv} = 40kVA (from Table 3), the total number of inverters required for the system are respectively calculated thus:

$$N_{inv} = \frac{1.25 \times (21.3 + 41.5)}{40} \approx 2$$

Thus, a total of 2 inverters of 40kVA capacity is required for the system

Table 3 Specifications of TEG Module, PV Module, Battery, and Inverter

Component	Parameter	Value
TEG Module (GM250-127-28-12)	Material	Bismuth Telluride (Bi_2Te_3)
	Hot side temperature	523K
	Cold side temperature	303K
	Output voltage	4.4V
	Power	26W
	Efficiency	3.1%
	Dimension	62mm x 62mm x 4mm
PV Module (330W Mono Solar Panel)	Maximum power voltage	37.4V
	Maximum system voltage	1000V
	Short circuit current Panel efficiency	9.39A 16.80%
	Dimension	1956mm x 995mm x 40mm
Battery (LiFePo4 battery)	Voltage	48V
	Capacity	200Ah
	Depth of Discharge	80%
	Efficiency	90%
Inverter (sine wave inverter)	Capacity Efficiency	40kVA 90%

4.8. Analysis of Payback Period and Carbon Emission Mitigation

Applying Equation 17 and 18 the payback period and amount of carbon emission mitigation are calculated, respectively, as: I = ₦126,698,000 (Table 4), Cf_{OM} = 0.015 [39], E_{PV} = 95.5kWh/day x 365$day/year$ = 34857.5$kWh/year$, E_{TEG} = 249kWh x 365$day/year$ = 90885$kWh/year$, U = ₦88.58/kWh [38], Ef_{grid} = 0.573$kgCO_2eq/kWh$

$$PbP = \frac{98558000 \times (1 + 0.015)}{88.58 \times (34857.5 + 90885)} \approx 9years$$

and $A_{EM} = (34857.5 + 90885) \times 0.573$ = 72,050.5$kgCO_2eq/year$

From the analysis, the system would be implemented at a cost of ₦98,558,000. 00 with a payback period of 9years, and would mitigate an average of 72,050.5kg of CO_2 emissions annually.

Table 4 Summary of Cost of Installation

S/N	Description	Quantity	Rate (₦)	Cost (₦)
1.	Rooftop air conditioners	4	602,000	2,408,000
2	Duct and Accessories		Lump sum	50,000
3	TEG modules	1600	4500	7,200,000
4	PV modules	65	55,000	3,575,000
5.	Charge controller	1	135,000	135,000
6.	Inverter	2	2,150,000	4,300,000
7.	Battery	72	1,120,000	80,640,000
8.	Cable and Accessories		Lump sum	100,000
9.	Reconstruction of exhaust pipe for TEG		Lump sum	50,000
10.	Installation Labour		Lump sum	50,000
11.	Miscellaneous		Lump sum	50,000
	Total			98,558,000

5. Conclusion

This study reports the hybridization of energy systems for air conditioning application in an educational building, using the Faculty of Engineering Lecture Theaters at Rivers State University, Port Harcourt, Nigeria as case study. The findings of this study are summarized as follows:

- The energy requirements of the air conditioning system would be generated from the hybrid energy system of thermoelectric and solar energy system.
- Cooling load was analyzed to select suitable air conditioning system for the building using Carrier's Hourly Analysis Program (HAP) software.
- The analysis carried out shows that a total of 4 packaged rooftop air conditioners of 10.6kW (30,000 Btu/h) capacity each would be required to handle the building's cooling load of 38.28kW, and would require 344.5kWh of energy per day, out of which 249kWh/day would be generated from the thermoelectric generators, and the remaining 95.5kWh/day would be generated from the solar power system.
- The 249kWh/day of energy required from the thermoelectric energy system would require a total of 1600 TEG modules of 26W each, and the 95.5kWh/day of energy required from the solar system would require a total of 65 PV modules of 330W each.
- The energy generated would be stored in a 679kWh capacity battery storage system which contains 72 batteries of 48V, 200Ah capacity each, which are wired into 3 parallel strings, from which it would be supply to the AC system.
- The techno-economic analysis carried out shows that the designed system can be implemented at a cost of ₦98,558,000, with a payback period of 9years, and would mitigate 72,050.5kg of CO_2 emissions annually.

In conclusion, therefore this study will redound to the benefit of society as it would improve the energy efficiency of a building, reduce environmental impact, enhance indoor comfort, and would be an attractive option for many buildings, particularly in areas with hot climates and fluctuating energy supply.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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