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Enhancing sustainable and climate-resilient agriculture: Optimization of greenhouse energy consumption through microgrid systems utilizing advanced meta-heuristic algorithms

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ABSTRACT

Greenhouses offer controlled microclimates that enable year-round cultivation, improving food security and agricultural productivity. However, greenhouses are energy-intensive, with heating accounting for a significant portion of the associated costs. This study explores optimal microgrid configurations, economic viability, and policy recommendations for sustainable greenhouse agriculture in Nigeria. An in-depth energy assessment of a reference greenhouse in a South Korean facility is conducted. Distinct climatic differences between South Korea and Nigeria are highlighted, emphasizing the need for tailored greenhouse designs and energy solutions. Shifting focus to Nigeria, this study investigates the feasibility of hybrid renewable energy systems with a focus on wind and solar power across six geopolitical zones in Nigeria. The analysis encompasses technical, economic, and policy aspects, providing a holistic perspective on renewable energy adoption. Notably, the study uses an advanced optimization model, Teaching and Learning–Based Optimization algorithm, to assess the net present cost and baseload supply reliability, offering valuable insights for investors and policymakers. The result indicates diverse energy requirements across Nigeria, with total monthly peak energy demands ranging from 5374.80 kWh in the Southeast to 17,115.76 kWh in the Northwest, and a notable variation in the Levelized Cost of Electricity (LCOE), with the lowest at $0.07327 in Kano. Specifically, in Ogun, the net present cost for the WT-PV-ESS system stood at $520,935.45, while the PV-ESS system cost was substantially lower at $500,444.41. This confirms the effectiveness of location-specific analysis and shows the suitability of photovoltaic–battery energy storage systems for Nigeria's diverse regions, with unique considerations for specific areas. Policy recommendations, including feed-in tariffs, renewable portfolio standards, net metering, research support, and market development, provide a holistic framework for the adoption of renewable energy and sustainable agriculture. Improving infrastructure, market access, and financing for smallholder farmers is integral for improving food

Abbreviations: greenhouse gas, (GHG); renewable energy source, (RES); hybrid renewable energy source, (HRES); net-zero energy greenhouse, (NZEG); net present cost, (NPC); photovoltaic, (PV); wind turbine, (WT); teaching and learning–based optimization, (TLBO); air-to-water heat pump, (AWHP); energy storage system, (ESS); feed-in tariff, (FiT); renewable portfolio standard, (RPS).

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security and standards of living in rural Nigeria. In conclusion, Nigeria can leverage renewable resources to revolutionize its energy and agriculture sectors, setting an example for a sustainable and resilient future.

1. Introduction

Greenhouse farming involves using structures made of transparent materials such as glass or plastics to create a controlled microclimate for plants. It facilitates the sustainable cultivation of fresh, high-quality crops throughout the year, thereby improving food security, a key factor for increasing farmers' earnings and the overall productivity of the agricultural sector [1]. In modern agriculture, the significance of greenhouse farming is growing, particularly in areas characterized by harsh environmental conditions or restricted arable land. Managing the indoor environment, especially during unfavorable weather conditions, is vital for successful crop growth in greenhouses [2,3]. The energy required to regulate indoor air conditions accounts for approximately 50 % of the total expenses associated with greenhouse production in numerous countries [4,5]. As a result, greenhouse agriculture is considered one of the most energy-intensive segments of agriculture, carrying substantial economic and environmental consequences [6].

The primary challenge of greenhouse crop production is substantial production costs, primarily driven by the high energy consumption of greenhouse heating, accounting for approximately 90 % of the total energy demands of greenhouses [6–8]. Energy-efficient strategies that do not require active systems have helped decrease the energy consumption of greenhouses. These strategies involve the use of high-performance materials for greenhouse coverings and the utilization of thermal screens to control the amount of sunlight that crops receive in the summer and minimize heat loss in the winter [6]. The use of thermal screens can reduce heat loss by approximately 23%–24 % [8]. These screens can be positioned either inside or outside the greenhouse to create a favorable microclimate for crops [9,10]. One of many related studies focusing on the use of sustainable energy sources and energy-saving systems in greenhouses has indicated that implementing basic measures such as the installation of energy screens in traditional greenhouses or improving existing setups in small-scale greenhouses is insufficient for the sustained and optimized use of energy [11]. In regions like Africa, where rural electrification remains a significant challenge, reliable and sustainable energy is crucial for agricultural development. Renewable energy microgrids using wind and solar power, complemented by battery storage, offer a practical solution for powering greenhouse farming, particularly in areas with limited access to conventional electricity [12,13].

1.1. Literature review

Although numerous studies have investigated greenhouse energy consumption and various proposed energy-saving strategies, greenhouse agriculture still heavily relies on fossil fuels [14], which is a significant challenge that needs to be addressed. The efficiency of energy usage in greenhouses is another increasingly important concern. According to Crippa et al. [15], approximately 34 % of the total greenhouse gas (GHG) emissions are attributed to our food systems. The integration of renewable energy sources (RESs), such as solar, wind, and geothermal energy in agriculture can result in positive outcomes for both the environment and farmers. RESs can serve various purposes in greenhouses, including water pumping from wells or other sources. Their use could not only reduce the reliance on fossil fuels but also lower energy expenses, decrease GHG emissions, and conserve water [16].

A considerable number of studies have employed various simulation methods to decrease GHG emissions as shown in Table 1,through the implementation of RESs [17–21]. Same et al. [22] focused on alleviating power shortages in remote and vulnerable communities, including refugee camps, through the utilization of hybrid RESs (HRESs). These systems are considered reliable because of their technical, economic, and environmental benefits. Specifically, Same et al. assessed the feasibility and techno-economic performance of HRESs tailored to the energy needs of a refugee camp. In a related study, Ukoima et al. [23] performed a comprehensive techno-economic evaluation of a hybrid wind turbine (WT)–photovoltaic (PV) power generation system to satisfy the energy needs of the rural community of Okorobo-Ile Town in Rivers State, Nigeria. In addition, various researchers have employed RETScreen software, an energy simulation tool, to design RESs for diverse applications and locations [24–26]. The use of RESs, particularly solar power, for cooling purposes in various buildings has also been explored, with a particular focus on greenhouses [3,8]. In these studies, RESs were used to create more favorable conditions for plant growth and alleviate stress on crops during hot seasons, ultimately leading to improved crop yields. Additionally, solar energy can be used for heating greenhouses, enabling farmers to extend the growing season and cultivate crops that would not typically thrive in the local climate [27–29]. This practice can diversify crop options and increase overall farm

Table 1
Comparative analysis of renewable energy systems in Nigerian geopolitical zones.

Configuration	System Type	Evaluation criteria	Methodology	Location
PV/Wind/Diesel/Battery [53]	Off-grid	RF	HOMER	Maiduguri, Enugu, Nigeria
PV [54]	Grid	GHG, NPV	RETScreen	Northeastern, Nigeria
PV/Battery/Diesel [55]	Off-grid	GHG, COE, ROI	HOMER	Ibadan, Nigeria
Fuel cell/Wind/PV/Battery [56]	Off-grid	TNPC, capacity shortage, COE	HOMER and CRITIC COPRAS (Criteria Importance Through Intercriteria Correlation-weighted complex Proportional Assessment)	Lagos, Nigeria
PV/Battery/Diesel/Wind [57]	–	Operating cost, GHG	AIMMS (Advanced Interactive Multidimensional Modelling System)	Nigeria
Multiply power systems [58]	–	GHG, NPC,	Multi-objective optimization	Nigeria
PV/Wind/Diesel/Battery [59]	Off-grid	LCOE, LPSP	Fuzzy-logic and Particle Swarm Optimization (PSO)	Ogun, Nigeria
Biomas/PV/Wind/Battery/Hydrogen [60]	Off-grid	LPSP, LCOE, annualized system cost (ASC)	Salp Swarm Algorithm	Nigeria
PV/Wind/Battery/Diesel [61]	Off-grid	ASC, COE, SOC	Grasshopper optimization algorithm, PSO	Nigeria
Present study Wind/PV/Battery	Grid	LPSP, LCOE, NPC	TRNSYS, Teaching Learning Based Optimization (TLBO) algorithm	Rivers, Anambra, Kano, Adamawa, Nassarawa,

productivity.

Recent research in artificial intelligence and machine learning has seen substantial progress in the realm of renewable energy. Some key studies include the work of Khanmohammadi et al. [30] who introduced an AI-driven framework to optimize a combined cycle with geothermal energy. Utilizing various machine learning methods and incorporating six performance indicators and nine design variables, they identified artificial neural networks as having the best statistical correlation. Their sensitivity analysis further elucidated the effects of different cycle parameters. Zhang et al. [31] explored the optimization of an off-grid system comprising wind energy, fuel cells, and hydrogen storage. By employing three enhanced versions of the harmony search meta-heuristic method, they aimed to minimize annual costs and reduce energy wastage probabilities. Their findings revealed that the second modified version excelled in terms of accuracy, speed, and reliability. Also, Oyewole et al. [32] conducted a techno-economic analysis integrating hydrogen refueling stations with electric power generation through solar and wind energy resources. By developing the system model using Mixed Integer Quadratic Constrained Programming (MIQCP) and its linearized counterpart (MILP), and employing robust optimization via AIMMS, they assessed key indicators like levelized cost of energy (LCOE), excess energy, emissions avoided, and carbon tax. Their findings, with an LCOE ranging from \$0.0702/kWh to \$0.1125/kWh, indicated that the system was both economically feasible and environmentally advantageous. Tiv et al. [33] tackled the optimization of residential renewable energy integration using a MILP-based Energy Management System (EMS) algorithm. Their solution integrated battery storage with the power grid, optimizing consumption for greater cost efficiency. By analyzing historical residential data, they demonstrated significant energy savings compared to traditional approaches, potentially fostering more sustainable energy policies and improved grid stability. Abdelwahab et al. [34] conducted a comprehensive analysis of a hybrid energy system combining wind turbines and photovoltaic panels (PV). They utilized Particle Swarm Optimization (PSO) and Electric Eel Foraging Optimization (EEFO) to regulate power effectively. Their mathematical modeling and MATLAB/SIMULINK simulations indicated that these methods adeptly balanced loads while maintaining a consistent power supply. The optimized system proved to improve grid integration, performance, and energy output, thereby contributing to the advancement of renewable energy technology. However, The Teaching and Learning-Based Optimization (TLBO) algorithm provides notable advantages compared to other optimization algorithms mentioned in recent literature. Leveraging the concept of knowledge transfer between a teacher and students, TLBO reduces computational complexity and offers faster convergence to optimal solutions compared to the harmony search method used by Zhang et al. [31]. Unlike PSO, which requires careful parameter tuning, TLBO operates with fewer adjustable parameters, simplifying application across various problem domains. Additionally, TLBO is robust under uncertainty, reliably minimizing the NPC and ensuring consistent power supply, as demonstrated by Oyewole et al. [32].

Transitioning to RESs for greenhouse applications is becoming increasingly important. Researchers have explored innovative solutions, such as the utilization of the excess thermal energy of air and the implementation of solar thermal systems, to address the heating needs of greenhouses. These technologies have demonstrated their capability to improve nighttime greenhouse temperatures, reduce air humidity, and increase crop yields. Bazgaou et al. [35] designed a heating system powered by solar thermal energy through rock-bed thermal storage and passive solar water heating for a greenhouse in Canada. The system reduced air humidity by 10%–15 % and increased substrate temperatures by 3°C-4°C, resulting in a 49 % increase in tomato yield. In addition, He et al. [36] reported the feasibility of the use of excess thermal energy of air through a multifunctional air conditioning system. This system not only elevated nighttime greenhouse temperatures but also efficiently supplied heat energy, reducing energy consumption and GHG emissions of a greenhouse facility. Moreover, the optimization of the temperature differentials between water and air could further enhance the system's capacity to release heat, improving the energy efficiency of a greenhouse.

Heat pumps, which have been increasingly adopted recently, are a promising technology for improving the energy efficiency of greenhouses. Heat pumps can extract a significant amount of energy from the environment, thereby reducing reliance on conventional energy sources [37]. Heat pumps can use various heat sources, including air, ground, water, industrial waste, wastewater, geothermal water, flue gas, and solar heat [38]. In the pursuit of net-zero energy greenhouses (NZEGs), it is essential to explore the intrinsic factors affecting the usage of different heat pump types, such as water-source heat pumps and ground-source heat pumps. Monovalent and bivalent heat pump systems offer flexibility in meeting greenhouse heating requirements, with bivalent systems particularly suited for regions where heat pumps alone may not suffice [39]. Studies such as those conducted by Aye et al. [40] and Awani et al. [41] provide valuable insights into the performance and efficiency of various heating technologies, including air-source heat pumps, electric heaters, boilers, and water-to-air heat pumps. These comparisons shed light on the environmental impact and energy efficiency of different heating solutions, which can be instrumental in optimizing heating systems for NZEG applications [42].

The scientific aim of this work is to evaluate the feasibility and optimal configuration of HRESs incorporating wind and solar power for greenhouse agriculture in Nigeria's six geopolitical zones. The subject of the research was to develop tailored configurations of WT and PV systems, coupled with battery storage, to ensure baseload reliability and minimize net present cost. Previous studies have examined the use of RESs, such as PV or WT power, for baseload supply. However, there remains a critical need for comparisons that can assist investors and policymakers in determining the most effective pathway for deploying different RESs. This study extended existing research by:

- Developing a Transient System Simulation (TRNSYS) model, incorporating weather data and greenhouse geometry, to assess the energy demands of a greenhouse in six geopolitical zone in Nigeria (Fig. 1). Furthermore, validate the reliability of this model using an experimental multispan greenhouse in South Korea.
- Evaluating the effectiveness of the greenhouse model powered by optimally configured Hybrid Renewable Energy Systems (HRES). This includes a comprehensive investigation of the practicality of implementing wind turbine and PV systems and techno-economic comparison of WT–PV HRES configurations in Nigeria's six geopolitical zones. This assessment is crucial for determining the viability of renewable energy systems (RESs) in these regions.
- Designing sizing optimization models that aim to minimize the net present cost (NPC) while maintaining baseload supply reliability. The models employ the Teaching and Learning–Based Optimization (TLBO) metaheuristic algorithm.
- Conducting a detailed comparative analysis of different renewable energy systems across Nigeria. This comparison is essential for providing investors and policymakers with valuable insights into the most effective RES deployment strategies.
- Conducting a thorough analysis of the energy and cost of production derived from the optimization results across the six geopolitical zones. This analysis is key to understanding the economic implications of HRES deployment.

Finally, the study offers crucial insights and formulates strategic policy recommendations, specifically designed to foster and accelerate the adoption of greenhouses utilizing renewable energy systems, thereby contributing to sustainable agricultural practices and energy use.

The remaining parts of the research are as follows: Section 2 of the study discussed the methodology. The result and the discussion are

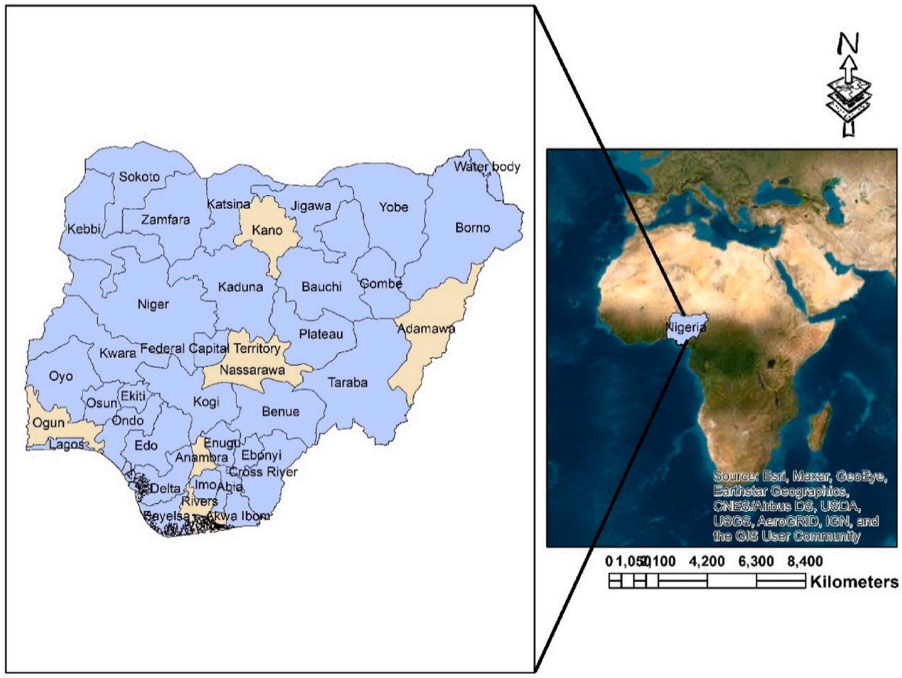

Fig. 1. The six geopolitical zones were selected as study area.

presented in Section 3. In section 4, the result and policy recommendation were summarized. Finally, the conclusion of the study is presented in Section 5.

2. Methods

2.1. Description of the case study

The experimental greenhouse at Kyungpook National University is located in Daegu, Southeastern South Korea. This greenhouse has a Venlo Roof-type design with a three-span roof structure and a 24 m × 16.3 m rectangular base. It has a height of 7.6 m and provides a floor area of 391.2 m^2. The greenhouse is oriented in a north–south direction, with coordinates 35.53° N 128.36° E and elevation of 48 m above sea level. The roofing is made of 4 mm horticulture glass and the side walls of 16 mm polycarbonate panels. Internally, the greenhouse is divided into three rectangular sections, each with a floor area of 130.4 m^2 and dimensions of 8 m × 16.3 m × 7.6 m. Two layers of thermal screens (PH-66 and Luxous) are installed beneath the roof to conserve energy and reduce the heating and cooling area. The dimensions of a single span of the greenhouse, the thermal screen position, and the sensor position are shown in Fig. 2.

Energy to the experimental greenhouse is supplied by three air-to-water heat pump (AWHP) systems, each with heating and cooling capacities of 70 and 65 kW, respectively, a 50 m^3 water storage tank, several water circulation pumps (390 W), six fan coil units with heating and cooling capacities of 27 and 18 kW, respectively, and heating pipes laid on the ground floor of the greenhouse. For illustration, the outside view of the greenhouse, the installed AWHP systems, and the storage tank are shown in Fig. 3; the thermal energy flows to the greenhouse within the energy supply systems are shown in Fig. 4.

The water storage tank was used to store hot and cold water derived from the AWHP, dispensing it to the greenhouse when the temperature in the greenhouse fell below the established set point (25 °C for cooling

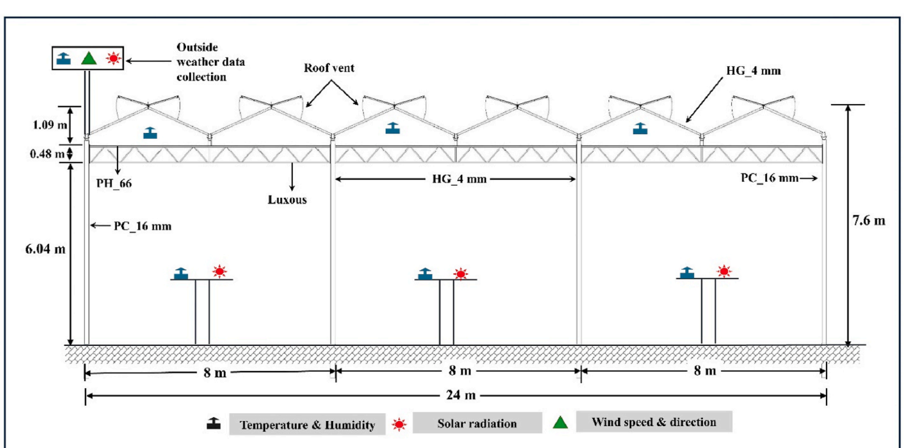

Fig. 2. The experimental greenhouse.

Fig. 3. External view of (a) greenhouse (b) heat pumps, and (c) water storage tank.

and 15 °C for heating). For heating purposes, water with a temperature of 50 °C was upheld in the storage tank, whereas for cooling, a temperature of 15 °C was sustained. The heating process involved the use of both heating pipes and fan coil unit systems, whereas only the fan coil unit was employed during cooling to exchange thermal energy with the partitioned greenhouses denoted as GH1, GH2, and GH3.

2.1.1. TRNSYS greenhouse modeling and simulation

The greenhouse was designed in TRNSYS 3D (an add-on to Google Sketchup) as multizones with 6 spans of 4 m each, a ridge height of 1.09 m, and a roof slope of 30°, as shown in Fig. 5. The 3D model was then imported into TRNbuild (a building interface for the TRNSYS program) as an Intermediate Data Format file (.idf, readable by TRNbuild). The Lawrence Berkeley National Laboratory Windows 7.7 program was used to define the properties of greenhouse materials. The program was used to create a DOE-2 file, which was imported to TRNbuild. More importantly, the greenhouse was divided into three zones separated by horizontal thermal screens to create different thermal stratifications. Thermal screens were used to simulate the shading effect of residential buildings, resulting in a reduction in the conductive and radiative heat losses of the greenhouse. Equations (1) and (2) were used to control the thermal screens depending on the solar flux.

$$\text{If } \int_{T_i<18\ ^\circ C}^{SR<150\ \mathrm{Wm}^{-1}} \textbf{then } (\boldsymbol{bool}=\mathbf{1}) \textbf{ else } (\boldsymbol{bool}=\mathbf{0}), \tag{1}$$

$$\int_{T_i<15\ ^\circ C}^{SR<100\ \mathrm{Wm}^{-1}} \textbf{then } (\boldsymbol{bool}=\mathbf{1}) \textbf{ else } (\boldsymbol{bool}=\mathbf{0}) \tag{2}$$

The Boolean controller was used to control the opening (*bool* = 1) and closing (*bool* = 0) of the screens; SR is the solar flux, and T_i is the greenhouse internal temperature.

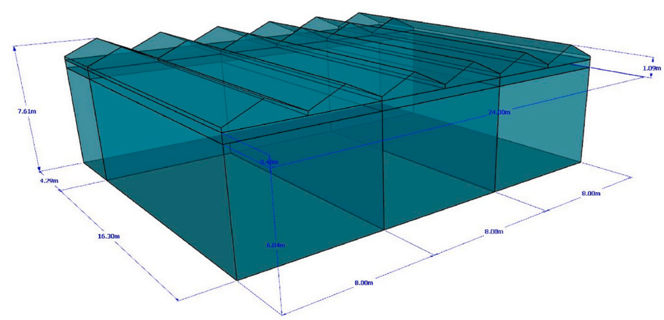

Fig. 5. 3D model of the greenhouse.

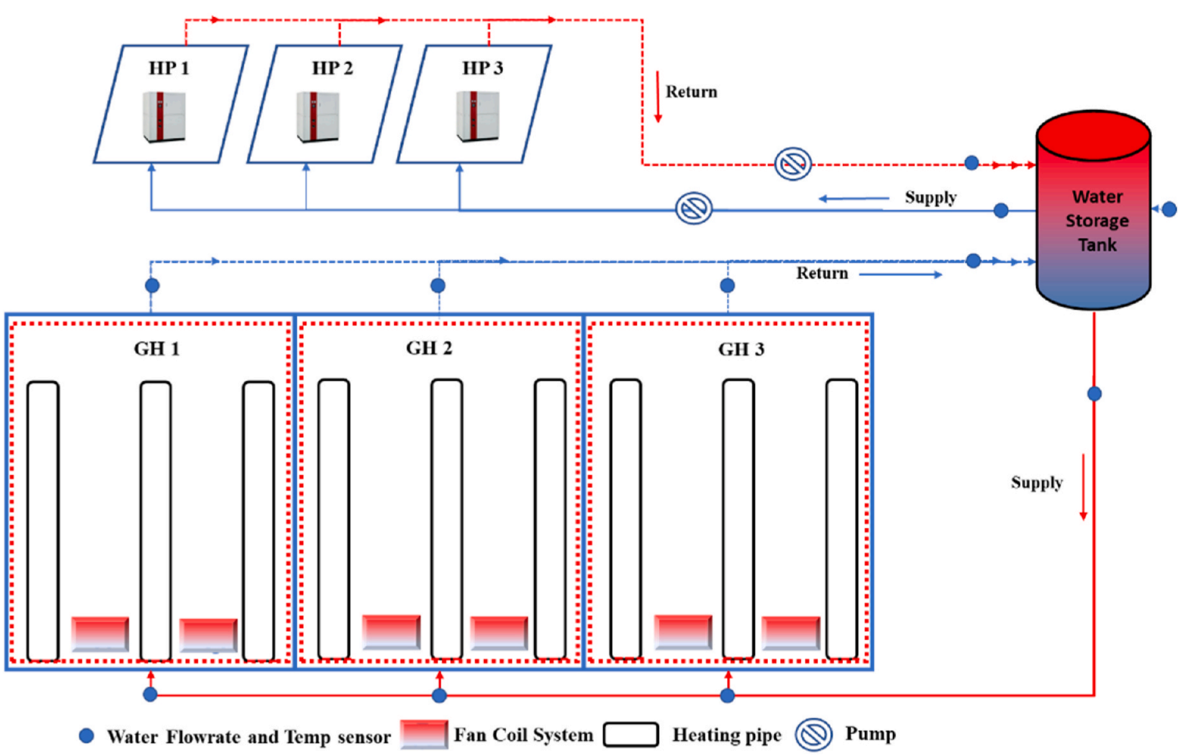

Fig. 4. Thermal energy flow from the heat pumps to the greenhouse.

2.1.2. Heat transfer

Heat transfer through the defined internal greenhouse materials depends on the coefficient of convective heat transfer and the temperature difference between the internal surface and internal air. The internal coefficient of convective heat transfer can be calculated or set to user-defined parameters (a constant, a scheduled value, or an input) in TRNbuild. Input selection permits the user to define any desired equation from the literature using the equation tools in the simulation studio. The internal calculation method, which is dependent on the temperature difference between the surface, the direction of heat flow, and the time steps, was used for this study. It is expressed mathematically in Eq. (3) [43]:

$$\boldsymbol{\alpha_{conv}} = \boldsymbol{K}\left(\boldsymbol{T_{surf}} - \boldsymbol{T_{air}}\right)^{e} \tag{3}$$

where K and e are constants depending on the surfaces and temperature difference.

The coefficient of convective heat transfer and temperature difference between the external surface and outside air determine the heat transfer through the external glass surface. Unlike the internal heat transfer coefficient, the heat transfer from the exterior is dominated by forced convection due to wind. The coefficient of convective heat transfer from the exterior was calculated using McAdam's equation based on wind speed (Eq. (4)):

$$h_{ext} = 3.6 \times (3.8(V_s) + 7.4) \tag{4}$$

where h_{ext} is the exterior convective coefficient (kJ/h) and V_s is the windspeed (m/s).

To avoid excessive heat loss through the ground floor, the 3D heat transfer model for ground temperature according to the ASHRAE F-factor in Eq. (5) was used to simulate the ground, and Eq. (6) was used to determine the heat transfer through the floor.

$$q = F_i p(T_i - T_a) \tag{5}$$

$$\boldsymbol{q} = \boldsymbol{UA}(\boldsymbol{T_i} - \boldsymbol{T_a}) \tag{6}$$

where q is the heat transfer (W), F_i is the perimeter heat lost factor, p is the exposed perimeter of the slab (m), T_i is the indoor temperature (°C), T_a is the outside temperature (°C), u is the overall heat transfer coefficient of the walls (W/m^2 • k), and A is the wall area (m^2). The F-factor was chosen based on the type of building and specifications from the ASHRAE standard [44]. For a heated slab with 12 inches of vertical R-7.5 insulation, the F-factor is 1.020 W/m • k.

2.1.3. Building simulation interface

Several components (Fig. 6) from the TRNSYS library were linked together to simulate the greenhouse environment. The necessary components were connected, and the simulation's time steps were set. The dynamic flowchart of the modeling procedure is shown in Fig. 7. The outside data needed for the simulation, such as solar radiation, temperature, relative humidity, ambient pressure, wind speed, and wind direction, were saved in the data reader (Type 9e). For the base case simulation, solar radiation, temperature, and relative humidity data were measured at the experimental greenhouse, while ambient pressure, wind speed, and wind pressure data were downloaded from the Korean Meteorological Station, Daegu (Station 143, 35.83° N 128.57° E) [45]. However, all the weather data needed for the proposed case in Nigeria was sourced from NASA [46]. It should be noted that the windspeed data were measured at a height different from that of the eave height of the greenhouse and were modified using the power law equation from

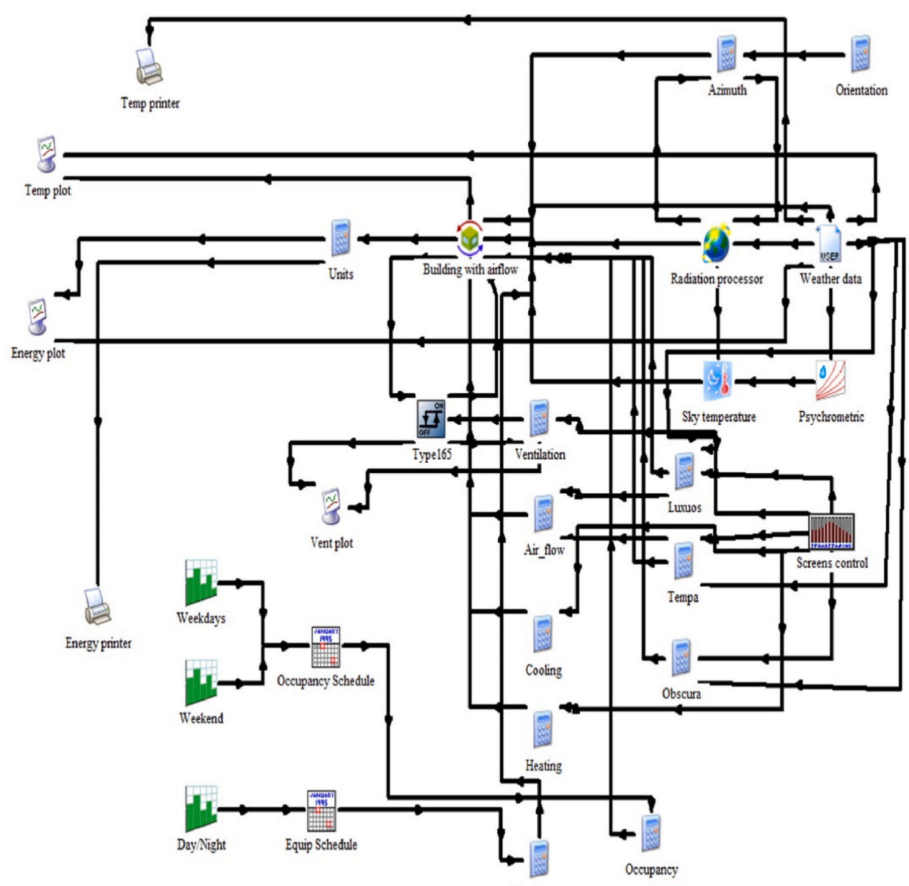

Fig. 6. TRNSYS simulation studio interface.

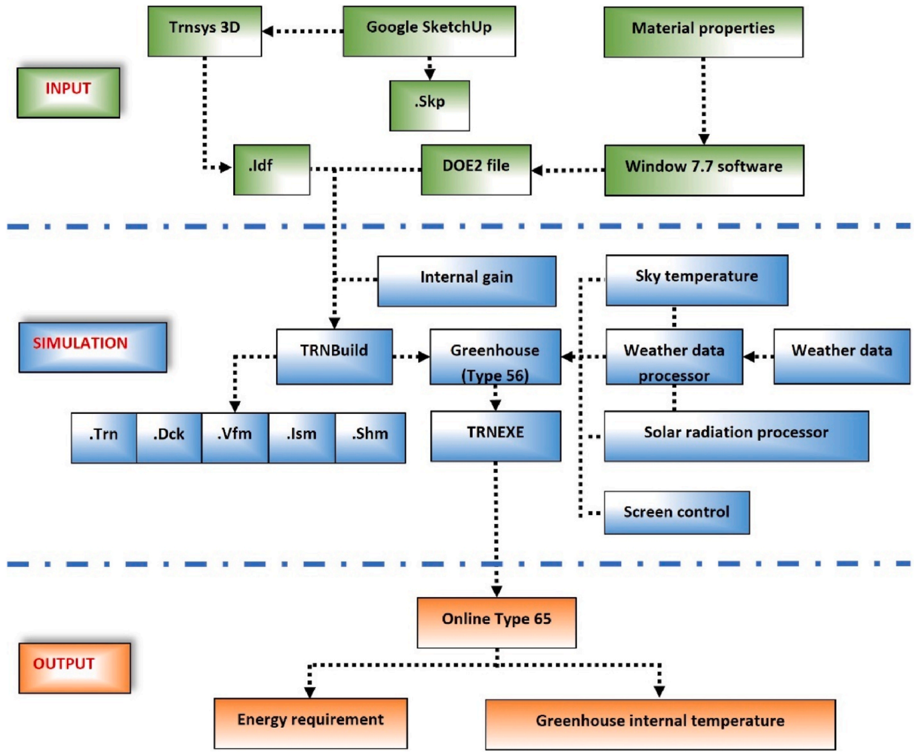

Fig. 7. Dynamic flowchart of the TRNSYS model.

Ref. [2]. Also, the observed solar flux was measured on a horizontal surface, and diffuse radiation was computed using Eq. (7) [47]:

$$\frac{I_d}{I} = 0.426kt - 0.256\sin(\alpha_s) + 0.00349T_{amb} + 0.0734\left(\frac{RH}{100}\right) \tag{7}$$

where I_d represents the diffuse radiation on the horizontal surface ($kJh^{-1}m^{-2}$), I represents the total radiation on the horizontal surface ($kJh^{-1}m^{-2}$), kt represents the clearness index, α_s represents the solar altitude angle (°), T_{amb} represents the outside temperature (°C), and RH represents relative humidity (%).

The horizontal beam radiation (I_b) was determined as the difference between the diffuse and total radiation on the surface (Eq. (8)), whereas the total radiation on the tilted surface (I_T) was determined using Eq. (9):

$$\boldsymbol{I_b = I - I_d} \tag{8}$$

$$\boldsymbol{I_T = I_b \bullet \frac{\cos\theta}{\cos\theta_z} + I \bullet 0.5(1 - \cos\beta)\rho_g + I_d \bullet 0.5(1 + \cos\beta)} \tag{9}$$

where θ represents the beam radiation incident angle (°), θ_z represents the solar zenith angle (°), β represents the surface slope (°), and ρ_g represents the ground reflectance (−).

2.2. Statistical index for model evaluation

The proposed TRNSYS model was validated using the coefficient of determination (R^2) and coefficient of variance of the root mean square error, CV(RMSE), expressed in Eqs. (10) and (11), respectively. R^2 value ranges from $-\infty$ to 1, with values greater than 0.75 showing substantial predictive potential of the model, whereas CV(RMSE) quantifies random error, with values below 15 % and 30 % being acceptable for monthly and hourly data comparison between the simulated and observed data.

$$R^2 = \left(\frac{n\left(\sum X_i^{sim}\right) - \left(\sum X_i^{mean}\right)\left(\sum X_i^{sim}\right)}{\sqrt{\left[n\sum X_i^{mean\ 2} - \left(\sum X_i^{mean}\right)^2\right]\left[n\sum X_i^{sim\ 2} - \left(\sum X_i^{sim}\right)^2\right]}}\right)^2 \tag{10}$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum\left(X_i^{exp} - X_i^{sim}\right)^2}{N-1}}}{X_i^{mean}} \times 100\% \tag{11}$$

where X_i^{exp} is the experimental data, X_i^{sim} is the simulated data, X_i^{mean} is the mean of the experimental data, and n is the total number of datasets.

2.3. Renewable systems

WT power generation primarily depends on the wind speed at the hub height, whereas the power generation of PV panels is determined by solar radiation and ambient temperature [48]. This study assumed that WTs and PV panels are equipped with maximum power point tracking (MPPT) controllers, allowing continual optimization of their performance and tracking of the maximum power points under varying meteorological conditions. Details on the MPPT control strategy may be found elsewhere [49].

2.3.1. WT model

The power output of a WT is determined by wind speed and linked to several key parameters, including factors such as the rated power of the turbine, cut-in wind speed, cut-out wind speed, and rated wind speed. The mathematical model that defines the power output of an individual turbine is as follows [50] and specifications of the WT employed is detailed in Ref. [51]:

$$P_{WP}(t) = \begin{cases} 0 & v(t) < v_{ci} \\ P_{nom} \times \dfrac{v(t)^3 - v_{ci}^3}{v_{co}^3 - v_{ci}^3} & v_{ci} \le v(t) < v_{co} \\ P_{nom} & v(t) \ge v_{co} \end{cases} \tag{12}$$

where P_{nom} is the rated power of wind power generation (kW), $v(t)$ is the local actual wind speed (m/s), v_{ci} is the cut-in wind speed, and v_{co} is the cut-out wind speed.

2.3.2. Model of PV panels

The output power of a PV panel is determined by temperature and the intensity of incident solar radiation. The energy output per PV panel was calculated using the following equation [50]:

$$P_{PV} = Y_{pv} f_{pv} \left(\frac{G_T}{G_{T,STC}} \right) \left[1 + \propto_P \left(T_c - T_{c,STC} \right) \right] \tag{13}$$

where P_{PV} is the power output, Y_{PV} is the rated capacity of the PV array (kW), F_{PV} is the derating factor (%), G_T is the solar radiation incident on the PV array (kW/m^2), $G_{T,STC}$ is the incident radiation under standard test conditions (1 kW/m^2), α_p is the temperature coefficient of power (%/°C), and Tc (°C) is the temperature of the PV cell in the current time step.

2.3.3. Battery model

Traditional battery energy storage systems are integrated into RES setups primarily to stabilize power generation in the system. They store surplus energy generated during periods of excess energy production and release it when there is a power supply deficit [22,24].

Equation (14) describes a typical battery operation model:

$$P_{Bat}(t) = P_{Bat}(t-1) \times (1 - \sigma) + \left[generated\ power - \frac{consumed\ power}{\eta_{INV}} \right] \tag{14}$$

where $P_{Bat}(t)$ is the battery state of charge at time t, $P_{Bat}(t-1)$ indicates the state of charge at time $t-1$, σ is the battery's self-discharge rate, and η_{INV} is the efficiency of the converter.

2.4. Sizing optimization model

An HRES was used to address intermittent renewable power generation and enhance power supply reliability by integrating various renewable technologies and energy storage. In the HRES, a generic energy storage system (ESS) model was implemented to effectively manage the difference between energy supply and demand, with specification as detailed in Ref. [50]. The energy management strategy of the HRES consists of storing in the battery the surplus energy generated by renewable sources. Subsequently, this stored energy is used during periods of insufficient renewable energy generation to meet load requirements. Herein, the load demand of the greenhouse, determined from TRNSYS simulations, including lighting and electrical loads, is defined as the peak load. Additionally, 40 % of the load is designated as the energy demand for the nearby farm settlement and residential community. Therefore, we assumed a baseline load of 1 MW for our analysis. The techno-economic parameters are shown in Table 2 and the optimization model was designed to achieve the lowest cost while effectively meeting the load demand [52]. This was achieved by optimizing the rated power of WTs and PV panels and the rated capacity of the battery.

The study assumed a load-following strategy that primarily focuses on the use of a renewable energy system in combination with battery. This system is adeptly designed to efficiently manage the energy supply, primarily by harnessing surplus energy generated by the RE system and storing it within the battery. This reserved energy is subsequently deployed to satisfy load requirements during instances when the generation of renewable energy is inadequate. The effectiveness of this strategy is particularly pronounced in scenarios where the RE system constitutes the primary source of power. In such situations, the battery fulfills a crucial role, providing power during periods when renewable energy resources are not available, notably during night-time. This methodology ensures a stable and reliable power supply, adeptly mitigating the inherent challenges of intermittency and fluctuations typically associated with renewable energy sources.

Table 2
Systems techno-economic parameters.

Component	Parameter	Value	Unit
Solar PV panel (Mono-Si CSUN200-72 M) [22,24]	Rated power	200	W
	Normal operating temperature	45	°C
	Open circuit voltage	45.3	V
	Temperature Coefficient	0.4 %	°C
	Initial cost	650	USD/kW
	Life span	20	year
	Efficiency	85	%
Battery (Generic Lithium-ion) [22,24]	Depth of discharge	60	%
	Initial capital cost	174	USD/kWh
	O&M	5	USD/kWh/year
	Lifetime	5	year
Wind Turbine (AWS HC) [51]	Rated power	3.3	kW
	Hub height	12	m
	Turbine diameter	4.65	m
	Rated wind speed	12.5	m/s
	Cut-in wind speed	2.7	m/s
	Cut-off wind speed	25.0	m/s
	Investment cost	1300	USD/kW
	Expected lifetime	20	year
Project Factors [57]	Interest rate	3	%
	Discount rate	8	%
	Design lifetime	20	year
	Inflation rate	2	%

In this study, the minimization of NPC was the primary economic objective. In addition, the model contained a reliability restriction, specifically defined as the maximum acceptable loss of power supply probability (LPSP). In the optimization model, the dimensions of the system components (WT, PV, and battery) were considered as variables for decision-making. The NPC, which is defined as the discounted present value of the total cost over the entire life cycle, encompasses various elements such as initial investment costs, annual operation, and maintenance (O&M) costs, replacement costs, and salvage value. Furthermore, the levelized cost of electricity (LCOE) was used to assess the cost of electricity generation. LCOE was calculated as the ratio of NPC to the lifetime energy production [62]. This measure is essential for evaluating power generation expenses and comparing them with current electricity prices.

$$LCOE = \frac{NPC}{\sum_{y=1}^{x} \frac{E_y}{(1+d)^y}} \tag{15}$$

$$NPC = C_{in} + \sum_{y=1}^{x_s} \frac{C_{O\&M}}{(1+d)^x} + \sum_{y=1x_s}^{y=x_r} \frac{C_{ch}}{(1+d)^y} - V_{sal} \tag{16}$$

where C_{in}, $C_{O\&M}$, C_{ch}, and V_{sal} are the initial investment cost, annual O&M cost, replacement cost, and salvage value, respectively; x_s is the system design lifetime, x_r is the replacement year of the components, and d is the discount rate.

2.5. Optimization algorithm

The scale of HRESs was determined by balancing economic and technical factors, both of which are crucial for constructing a cost-efficient and reliable system. The main goal was to minimize the NPC of the system, with the added constraint of ensuring an acceptable level of power supply reliability, as measured by the LPSP. Metaheuristic algorithms have been extensively applied to solve problems related to energy system planning; thus, their efficiency is firmly established [62]. Within this category of algorithms, the TLBO method has proven to be superior to genetic algorithms and particle swarm optimization [63]. Thus, the TLBO algorithm was used herein to address the optimization problem of optimal sizing. The operation of the TLBO algorithm resembles a classroom scenario, where every decision variable is considered a "student," and the solution demonstrating the highest fitness is the "teacher." The process is as follows:

The average knowledge level of a class, represented by the mean H_{mean} and can be elevated towards H_{new} through the influence of an effective teacher. An effective teacher is characterized as one who elevates their students' knowledge to closely match their own. However, realistically, a teacher can only enhance the class's mean knowledge level to a certain degree, which is contingent on the students' collective capability. This enhancement tends to occur through a stochastic process influenced by a variety of factors. Denoting H_{mean} as the mean knowledge level of the class and H_{old} as the teacher's knowledge level at any given iteration. The teacher's objective is to raise the mean knowledge level H'_{new} closer to their own level H_{old}. Consequently, the updated class mean, now referred to H_{new}, is influenced by the teacher's level. The adjustment to the mean is quantified by the equation:

$$H_{new} : r(H_{best} - T_x H_{mean}) \tag{17}$$

Here, T_x represents the 'teaching factor', which determines the extent of the mean's alteration and is a randomly generated number within the interval [0, 1]. The teaching factor can assume a value of either 1 or 2, with the specific value being determined by a heuristic process and chosen randomly with equal probability. This is expressed as:

$$T_x = round\,[1 + rand(0,1) * (2-1)] \tag{18}$$

The discrepancy identified by H_{new} is then used to update the existing solutions using the equation:

$$\text{Teacher phase} : H_{new} = H_{old} + r(H_{best} - T_x H_{mean}) \tag{19}$$

In the student phase of the learning process, knowledge enhancement occurs through two primary mechanisms: direct instruction from the teacher and mutual engagement amongst the learners themselves. Each learner engages with peers through various forms of collaborative activities such as group discussions, presentations, and formal exchanges. Through these interactions, a learner can acquire new insights and understanding, particularly when engaging with a peer who possesses a greater depth of knowledge.

The process of learner enhancement is procedurally outlined as follows:

1. Two learners, referred to as H_a and H_b, are chosen at random, ensuring that they are not the same individual (a $\neq$ b).
2. A comparison is made between their respective knowledge levels, which is quantified by a fitness function f(.). If learner H_a is found to have less knowledge than H_b (as indicated by f(H_a) < f(H_b)), then the knowledge level of H_a is augmented by the difference between H_a and H_b, scaled by a random factor r. Conversely, if H_a has more knowledge than H_b, the knowledge level of H_a is updated by the inverse of the aforementioned difference, again scaled by r. In this case, the new knowledge level of H_a is calculated as

$$\text{Student phase} : H_{new} = \begin{cases} H_{old} + r(H_a - H_b), H_a > H_b \\ H_{old} + r(H_b - H_a), H_b > H_a \end{cases} \tag{20}$$

3. The newly calculated knowledge level is then evaluated as shown in equation (20). If it results in an improvement in the fitness function value, it is accepted as the updated state of knowledge for that learner.

Notably, TLBO effectively combines elements from particle swarm optimization and differential evolution, merging these concepts to find a balance between exploration and exploitation in the search for global solutions. By simulating various hyperparameter combinations, the most effective settings were determined, as outlined in Table 3. The fundamental operations of the TLBO and the employed optimization model is shown in Fig. 8.

3. Results and discussion

The hourly average outside temperature and solar radiation flux on a horizontal surface for the reference greenhouse and different locations in Nigeria are shown in Figs. 9 and 10. The dataset of the reference greenhouse represents the measured data between June and August 2022, whereas that of the locations in Nigeria represents typical meteorological data between January and March 2022. The disparity between the two periods is associated with the difference between the climatic conditions in the two regions. For instance, South Korea has a warmer and more humid summer, whereas Nigeria has dry weather, Harmattan winds, and lower humidity. To ensure a comprehensive investigation, a consistent weather pattern was maintained for both regions, despite their climatic disparities. Table 4 outlines the weather conditions for the reference greenhouse in South Korea and the selected zones in Nigeria. The hourly maximum solar radiation recorded in the reference greenhouse, as shown in Table 4, occurred in July. In contrast, the maximum solar radiation for the southwest, south–south, southeast, northwest, northeast, and north–central regions of Nigeria occurred in February. Nonetheless, the results indicate that the maximum energy demand of the reference greenhouse is in August, whereas the maximum energy demand of greenhouse facilities in Nigeria is expected in March. More importantly, compared with South Korea, where the heating load is more predominant and natural ventilation is often used in the summer [64], horticultural facilities in Nigeria require year-round active cooling.

3.1. *Comparative analysis of energy demand*

The energy performance of a greenhouse depends on the features of the greenhouse envelope and crop requirements. In Nigeria, the common crop grown year-round is tomatoes, with an optimum growth temperature between 12°C and 32°C [65]. Paradoxically, the same thermophysical properties of the reference greenhouse are proposed for different locations in Nigeria, and all operating conditions in the developed model are the same except for the difference in the weather data of Type 9e for different locations. To adapt the model, the total monthly measured experimental and simulated energy consumptions

Table 3
Parameter settings of the metaheuristic's algorithm.

Hyperparameter	Description	Value/ Range
Population Size (N)	Number of student solutions	30–100
Max Iterations (G_{max})	Maximum number of iterations for convergence	50–200
Teacher Phase Learning Rate (r)	Learning rate in the teacher phase	0.1–0.3
Student Phase Learning Rate (r)	Learning rate in the student phase	0.1–0.3
Teaching Factor (T_x)	Influences the extent of learning from teacher	{1, 2}
Mutation Probability (P_m)	Probability of random changes in solutions	0.01–0.1

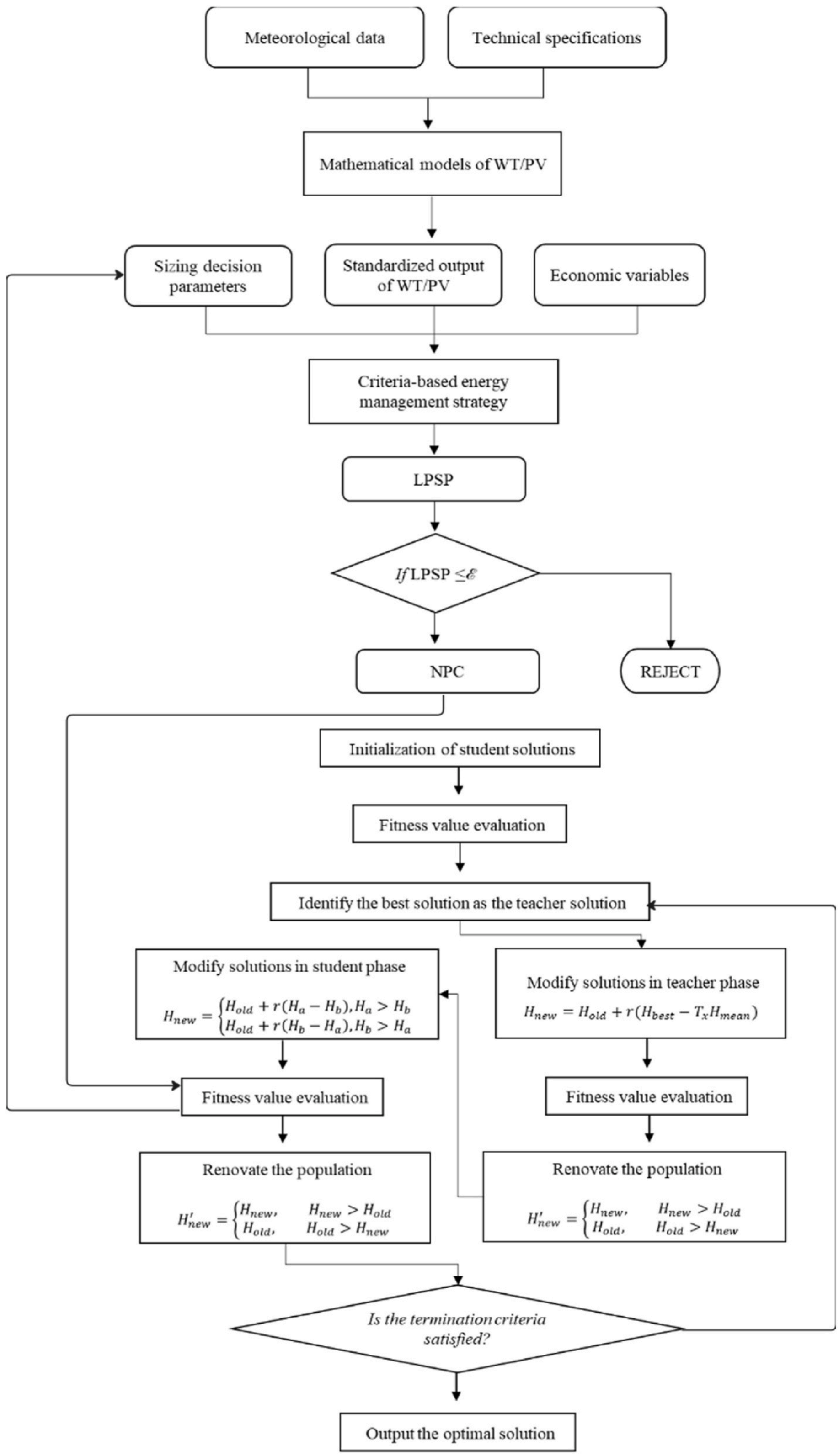

Fig. 8. The fundamental operations of TLBO and optimization model.

during the summer of 2022 were compared. Figs. 11 and 12 depict a comparison of the hourly and monthly simulated and experimental energy demand. Specifically, the hourly energy demand was examined during the month of July, from July 11, 2022, to July 19, 2022. Noticeable variations in energy consumption were observed on an hourly basis compared to the aggregated monthly energy consumption, primarily due to the on/off control of the energy supply systems and the summation of hourly energy consumption over the month. In June, July, and August, the total monthly energy use is 2.65, 4, and 4.08 MWh, while the simulated energy demand is 3.21, 4.17, and 4.57 MWh, respectively. Apparently, the energy demand increases with the increase in monthly average outside temperature from 24.3 °C in June to 27.5 °C

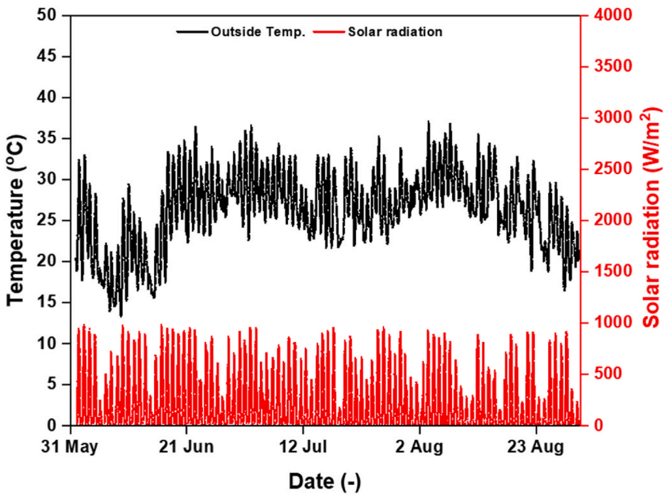

Fig. 9. Hourly outside temperature and solar radiation in Daegu, South Korea.

in July, and further slightly increases in August (by 84.91 kWh) even though the monthly average outside temperature decreases to 27.1 °C. During the three-month investigation period, the total simulated energy demand amounts to 10,732 kWh, while the experimental energy consumption is 11,949.55 kWh, resulting in a calculated R^2 of 0.95 and a CV (RMSE) of 10.99 %. Additionally, the calculated hourly R^2 and CV (RMSE) stand at 0.91 and 34.39 %, respectively. The CV (RMSE), which represents the percentage error between the simulated and experimental values, exceeds the benchmark by 4.39 % according to ASHRAE standards for hourly data model calibration [66]. This variation can be attributed to uncertainties recorded during the experiment that were not accounted for during simulation. However, the normalized mean bias

Table 4
Climatic conditions of the reference and selected greenhouse.

Zone	State	Min Temp. (°C)	Max Temp. (°C)	Max solar radiation (W/m²)
Daegu (Experimental site)	–	13.30	37.10	980.56
Southwest	Ogun	14.49	33.44	897.82
South South	Rivers	14.84	33.08	945.15
Southeast	Anambra	13.30	33.26	972.93
Northwest	Kano	6.53	39.77	1090.84
Northeast	Adamawa	13.92	44.21	1040.62
North Central	Nassarawa	15.34	39.58	1017.80

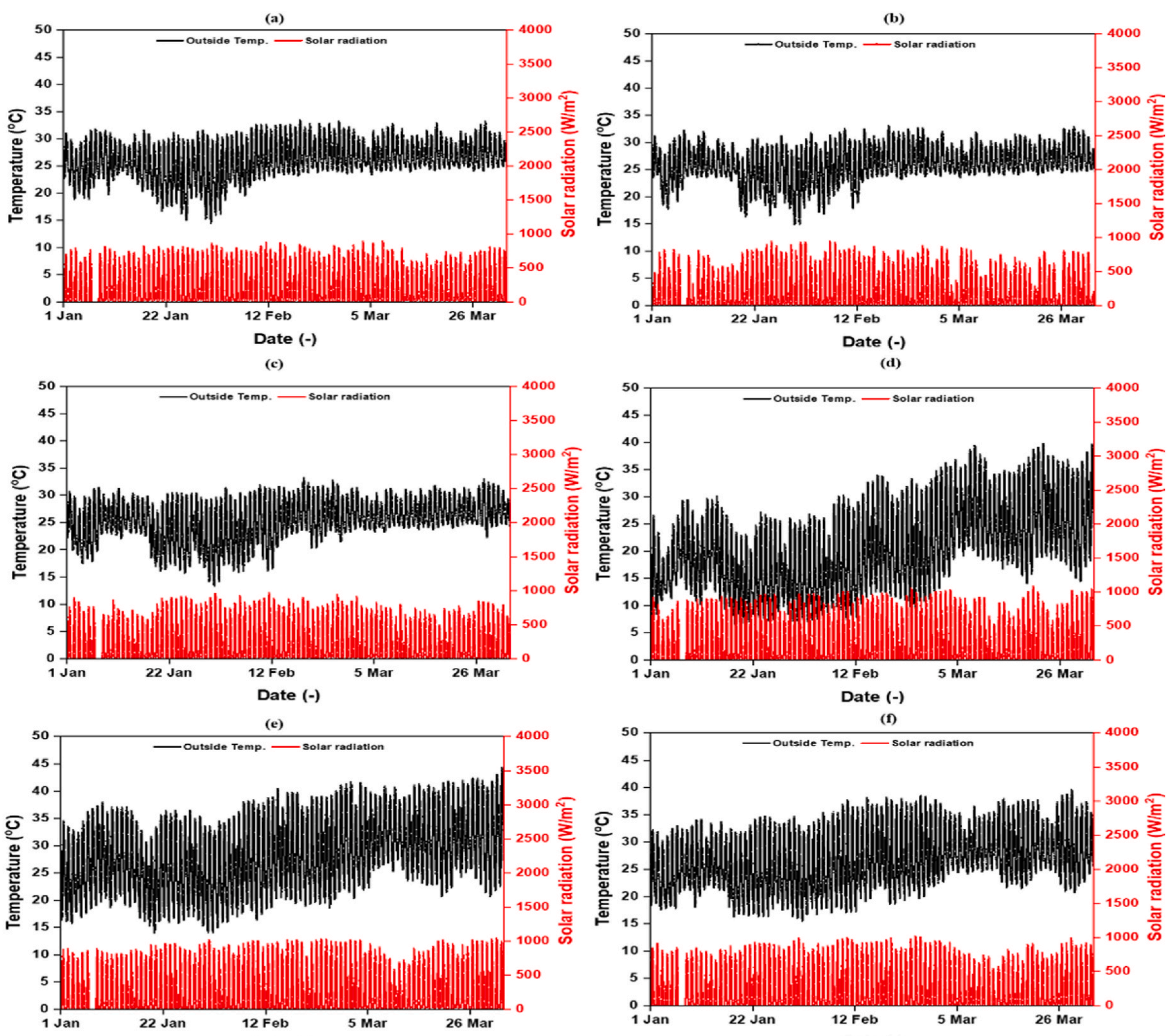

Fig. 10. Hourly outside temperature and solar radiation in Nigeria geopolitical zones (a) Southwest (b) Southsouth (c) Southeast (d) Northwest (e) Northeast (f) Northcentral

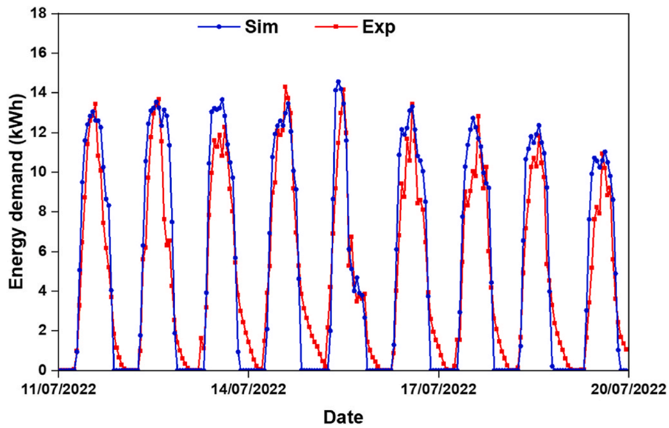

Fig. 11. Comparison between hourly simulated and experimental energy consumption.

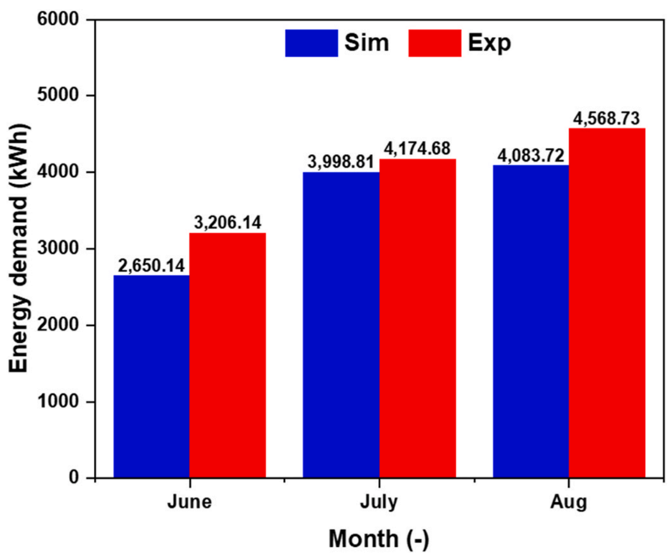

Fig. 12. Comparison between monthly simulated and experimental energy consumption.

error between the simulated and experimental data during the evaluation period is 2.57 % below the benchmark. Therefore, the overall energy analysis shows that the developed model is sufficiently accurate to predict the energy requirements of the proposed greenhouses in different regions of Nigeria, with the same crop requirements and greenhouse features. The total yearly energy demands for different locations in Nigeria are summarized in Table 5.

3.2. Economic comparison of six case studies in Nigeria

The extensive research conducted in the present study highlights the pivotal role of RESs, specifically WT and PV systems, in addressing climate change and promoting sustainable agriculture in Nigeria. The primary aim of the study was to assess the feasibility and effectiveness of these RESs across Nigeria's six geopolitical zones, with a particular focus on their application in powering greenhouses. To evaluate the possibility of using HRESs to provide baseload power, we performed an economic optimization considering reliability limitations in each of the six geopolitical zones. We employed a standardized 1 MW load profile to simulate baseload power demands, with the maximum permissible LPSP fixed at 2 % [67]. To ensure the strength and dependability of the optimal outcomes, we independently ran the TLBO algorithm [68] four times, selecting the most favorable solution from multiple optimization results. The obtained LCOE for HRESs in all six zones are listed in Table 6.

Fig. 13 provides insights into the optimal sizing of the HRES components for each zone. This comprehensive analysis allowed us to gauge the economic viability and reliability of HRESs as continuous baseload power sources across these distinct regions. As observed, most regions in Nigeria, including the selected case study locations, tend to be PV-dominated. This implies that the optimal installed capacity of PV power is generally greater than that of WTs.

At the same time, in PV-dominated zones, the optimal capacity for the ESS is typically lower than that for renewable sources, as shown in Fig. 14. This suggests that areas with abundant solar resources can attain a baseload power supply with limited energy storage capacity. Thus, HRESs that predominantly rely on PV require significantly lower energy storage capacity than those that primarily rely on WT. This trend is linked to the unique intraday properties of PV power output. In PV-dominated zones, energy storage primarily serves to supply power during nocturnal periods, when solar generation is unavailable. In contrast, in resource-rich zones, where PV output consistently satisfies both day and night load requirements, PV systems can provide baseload power supply via an increase in capacity and implementation of active energy curtailment. Consequently, regions with ample PV resources can achieve lower NPC levels because of the reduced requirement for energy storage capacity.

3.3. Technical comparison of the six case studies

In this section, a comprehensive analysis of the technological and economic aspects of different system setups, including WT–PV–ESS, WT–ESS, and PV–ESS, is presented. The optimal NPCs for each system configuration are summarized in Table 7, and Fig. 14 illustrates the optimal system configurations for each location.

Fig. 15 reveals that the PV–ESS system configuration is the optimal choice for most regions, encompassing approximately 90 % of the cases. These results highlight the advantages of integrating ESS with PV technologies, which significantly improves the cost-efficiency of providing constant power compared to individual power plants. Moreover, PV–ESS is the preferred setup in areas such as Ogun, Rivers, Kano, Adamawa, and Nassarawa, where the potential for wind resources is inadequate to generate cost-effective electricity. Anambra stands out as a unique case among the studied regions. In Anambra, the WT–PV–ESS system configuration was identified as the optimal choice because of a combination of factors, including the presence of wind resources and capacity for continuous power output, making this hybrid system the

Table 5
Total monthly peak energy requirements in different regions of Nigeria.

Zone	State	Latitude	Longitude	Energy demand (kWh)
Southwest	Ogun	7.1475 N	3.3619 E	6044.15
South South	Rivers	4.8472 N	6.9746 E	5809.09
Southeast	Anambra	6.2220 N	7.0821 E	5374.80
Northwest	Kano	11.7474 N	8.5247 E	17115.76
North East	Adamawa	9.2095 N	12.4782 E	15,643.96
North Central	Nassarawa	8.5060 N	8.5227 E	10,455.56

Table 6
Levelized cost of the optimal system.

Zone	State	WT–PV–ESS	PV–ESS	WT–ESS
Southwest	Ogun	0.1022	0.0982	0.5305
South South	Rivers	0.1058	0.1046	0.6882
Southeast	Anambra	0.1705	0.1718	0.5939
Northwest	Kano	0.07458	0.07327	0.5612
North East	Adamawa	0.8526	0.08445	0.7278
North Central	Nassarawa	0.07458	0.07327	0.5612

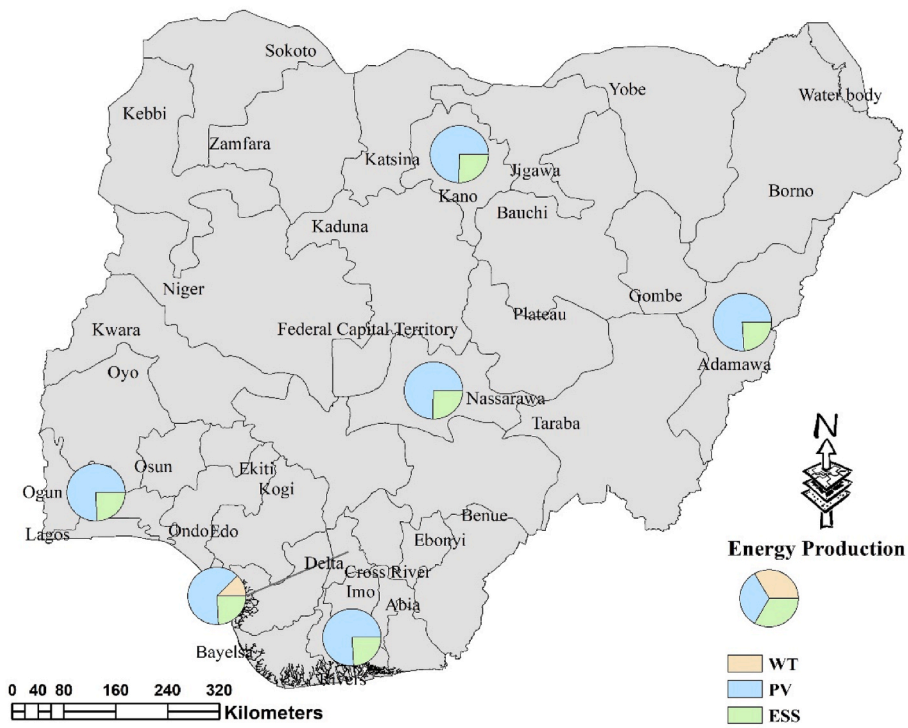

Fig. 13. Location-specific energy production by the system.

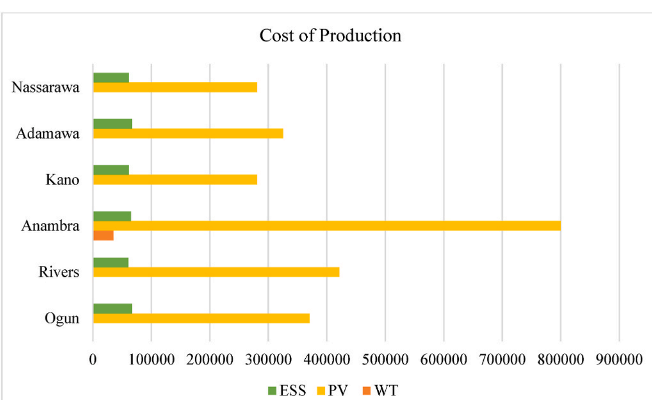

Fig. 14. Location-specific cost of production by the system.

Table 7
NPC of optimal systems.

Zone	State	Optimal NPC ($)		
		WT–PV–ESS	PV–ESS	WT–ESS
Southwest	Ogun	520,935.45	500,444.41	2,194,054.25
South South	Rivers	539,008.95	532,973.35	3,507,084.23
Southeast	Anambra	868,558.14	875,325.55	3,024,859.32
Northwest	Kano	380,026.26	373,371.24	2,858,561.69
North East	Adamawa	434,243.84	430,271.94	3,706,989.88
North Central	Nassarawa	380,026.26	373,371.24	2,858,561.69

most cost-effective solution for the area.

In analyzing the feasibility and challenges of implementing these diverse system configurations, several factors need to be considered. These include the initial capital cost, the availability of local resources, maintenance costs, system reliability, and the regulatory environment. Challenges such as technical expertise for installation and operation, the integration of systems into existing infrastructure, and potential environmental impacts also play critical roles. Each region's specific energy resource availability and demand patterns necessitate tailored approaches to ensure that the selected system configuration maximizes cost-efficiency and sustainability. This nuanced understanding aids in making informed decisions about the deployment of renewable energy systems across diverse geographical locations.

3.4. Policy recommendations to accelerate renewable development

This section presents a structured set of policy recommendations designed to leverage the findings of our research to foster sustainable energy practices and agricultural development in Nigeria. These recommendations aim to facilitate the adoption and integration of hybrid renewable energy systems within the agricultural sector, addressing both immediate and long-term sustainability goals.

As humanity grapples with the multifaceted and dynamic challenge of climate change, Nigeria is at a critical juncture. The escalating climate crisis poses a serious threat to the nation's sustainable development. In response, the Nigerian government has pledged unwavering commitment to a proactive stance, devising and enacting a suite of multidimensional mitigation and adaptation strategies [69]. This commitment is expressed as a dynamic policy framework, which was meticulously crafted to effectively address climate change. The evolution of the global climate discourse since the inception of the National Climate Change Policy and Response Strategy in 2012 has been meteoric, ushering in a new era of climate initiatives. Nigeria has astutely adopted these initiatives, crafting a robust and resilient national response aimed at diminishing the adverse impacts of climate change and fostering an adaptive society.

Also, the deteriorating energy infrastructure in Nigeria, plagued by frequent outages and shortages, necessitates innovative solutions for enhancing the agricultural sector. This study proposes a greenhouse powered by renewable energy sources specifically PV and wind turbines as a sustainable alternative to the unreliable national grid. Implementing a hybrid system that combines PV and wind energy is critical for

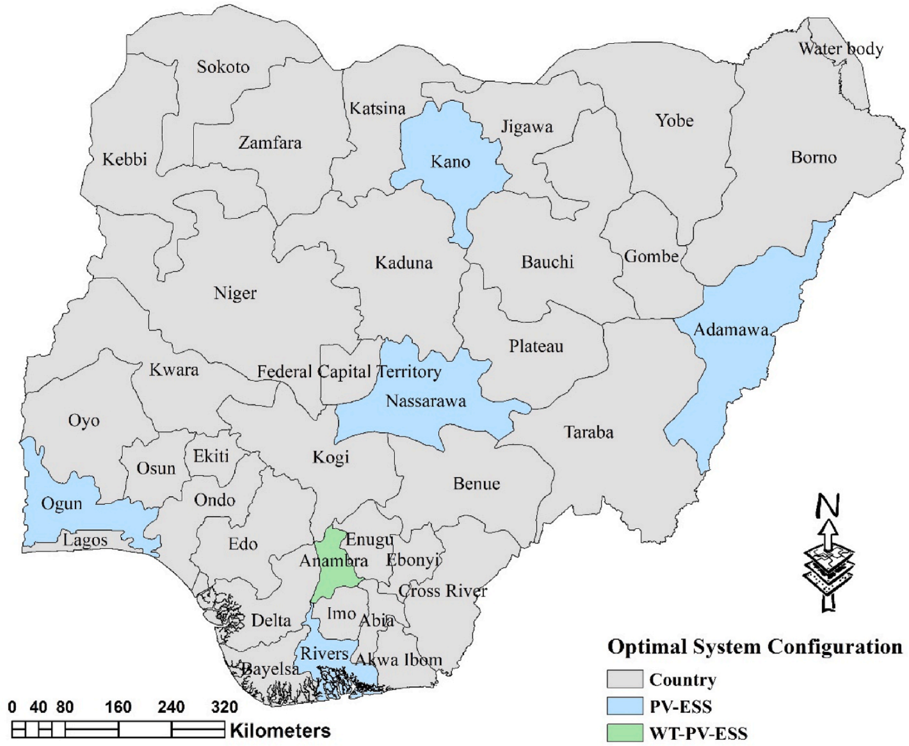

Fig. 15. Location-specific optimal system configuration.

ensuring a reliable and efficient power supply, facilitating year-round crop cultivation, boosting food production, and providing surrounding communities with improved access to electricity. This scenario highlights the urgent need for policy formulation aimed at integrating renewable energy systems into the agricultural sector. By developing policies that support the creation of off-grid, renewable energy-powered greenhouses, we can guarantee a dependable energy supply for agricultural production and promote the broader adoption of hybrid renewable energy systems.

Furthermore, introducing a hybrid system powered by PV and wind turbines offers significant benefits beyond enhancing the agricultural sector; it presents a viable solution for reducing greenhouse gas (GHG) emissions that would otherwise result from grid-supplied power. By calculating the GHG emissions savings achieved through this renewable energy setup, these savings can be converted into tradable carbon credits. This mechanism not only boosts the profitability of deploying such systems but also enhances their appeal to investors and stakeholders. The potential to earn carbon credits serves as a compelling incentive, encouraging investment and participation in renewable energy projects. This approach highlights the dual benefits of renewable energy systems: contributing to sustainable agriculture and playing a pivotal role in climate change mitigation by reducing reliance on fossil fuel-based energy sources.

In this manuscript, we propose a series of policies designed to promote RESs and sustainable agriculture in Nigeria. Although similar policies have been suggested by other researchers, we believe our tailored approach is crucial for guiding Nigeria towards a toward a greener, more sustainable future.

3.4.1. Feed-in tariffs (FiTs)

FiTs is a policy mechanism designed to accelerate investment in renewable energy technologies by offering long-term contracts to renewable energy producers, typically based on the energy generation cost. In Nigeria, the implementation of FiTs could significantly promote the adoption of solar PV systems, WTs, and other renewable technologies. The tariffs guarantee a fixed price for electricity generated from RESs above the standard rate for a set period, often 15–20 years. This price security can attract investors and encourage the development of renewable energy infrastructure. FiTs can be particularly effective in rural areas, providing a steady income stream for households and businesses that invest in RESs [70].

3.4.2. Renewable portfolio standards (RPSs)

RPSs require electricity suppliers to source a certain percentage of their power from renewable sources. In Nigeria, an RPS policy could be a catalyst for diversifying the energy mix and reducing the reliance on fossil fuels. Setting clear, ambitious targets for renewable energy generation, with interim milestones, would attract investment and drive the development of the sector. The RPS could include specific sub-targets for various renewable sources, such as solar, wind, and biomass, to ensure a balanced and resilient energy portfolio. Compliance could be monitored through the issuance of renewable energy certificates can be traded to meet sourcing obligations [71].

3.4.3. Net metering

Net metering allows consumers who generate their electricity using renewable technologies to feed excess electricity back into the grid and get credited for it. In Nigeria, the implementation of a net metering policy could incentivize homeowners, businesses, and farmers to install solar PV systems and other renewable technologies. By allowing consumers to sell excess energy at a favorable rate, net metering can improve the economics of investing in renewable energy and promote distributed generation. This policy can also reduce the load on the grid during peak times and contribute to a more stable and resilient energy supply [72].

3.4.4. Research and innovation

Investment in research and innovation is crucial for advancing renewable energy technologies and sustainable agricultural practices. In Nigeria, establishing research centers and funding initiatives focused on renewable energy can lead to the development of more efficient and cost-effective technologies. Collaboration with universities, international research institutions, and the private sector can drive innovation in solar PV materials, WT design, and bioenergy conversion. In agriculture, research can focus on the development of climate-resilient crops, improvement of soil health, and optimization of water use. Innovations resulting from research can increase productivity, reduce environmental impact, and make renewable energy and sustainable agriculture more accessible and affordable for all Nigerians.

3.4.5. Market access and infrastructure development

Market access and infrastructure development are pivotal for making Nigeria's agricultural sector profitable and sustainable. Rural infrastructure, such as roads, storage facilities, and processing centers, requires significant improvement to reduce postharvest losses and facilitate the efficient transportation of goods from farms to markets. Investment in cold storage and warehousing can help maintain the quality of perishable produce, thereby resulting in better prices and reducing waste. Furthermore, establishing farmer cooperatives can strengthen market access through produce aggregation, higher bargaining power, and the use of shared resources for marketing and logistics. Digital platforms and mobile technology can also play a role in connecting farmers directly with consumers, wholesalers, and exporters, thereby ensuring transparency and fair pricing. By bolstering market access and infrastructure, Nigeria can empower its farmers to meet both domestic and international demand, increase their income, and contribute to the nation's economic growth.

Finally, access to financing is a critical factor in making Nigeria's agricultural sector sustainable because smallholder farmers, who constitute the majority of Nigeria's agricultural workforce, often lack the capital necessary to invest in advanced technologies, high-quality inputs, and climate-resilient practices. To address this, Nigeria could implement a multifaceted financial support program. This program would include low-interest loans, credit guarantees, and microfinance options tailored to the needs of small-scale farmers. In addition, insurance schemes, such as weather-indexed insurance, could protect farmers against the risks posed by climate variability and extreme weather events. Additionally, government-led initiatives could encourage private investment in sustainable agriculture by offering incentives and reducing investment risks. With easier access to financing, farmers can adopt more productive, sustainable, and climate-resilient agricultural practices, ultimately improving food security and quality of life in rural areas. To strengthen the role of renewable energy in Nigeria's agricultural sector, we propose actionable policy recommendations.

- Legislative Support and Regulation: New laws should mandate the integration of renewable energy in agricultural development plans and simplify the approval processes for renewable energy projects. Financial Incentives: We suggest implementing tax reliefs and creating grant programs that cover up to 50 % of costs for setting up renewable energy systems, especially in underserved rural areas. Technical and Infrastructure Support: There should be collaborations with tech providers and educational institutions to bring affordable renewable technologies to farmers and develop infrastructure that supports the deployment and maintenance of these systems.
- Capacity Building and Education: Initiatives must include training programs for local farmers on the management of renewable energy systems, supported by ongoing technical assistance from agricultural extension services. Monitoring and Evaluation: A robust framework should be established to monitor the effectiveness of renewable energy policies and their impact on agriculture, with adjustments made based on regular evaluations. Environmental Benefits and Carbon Credits: Policies should encourage the certification of carbon credits, creating additional revenue streams for farmers and promoting further investment in green technologies. The expected impacts of these policies include enhanced agricultural productivity, improved rural electrification, reduced carbon emissions, and strengthened economic resilience among farming communities, positioning Nigeria as a leader in sustainable agricultural practices on the African continent.

In summary, the detailed policies and strategic implementation guidelines we propose are pivotal in steering Nigeria towards becoming a resilient and sustainable society, capable of confronting the myriad challenges brought about by climate change. The adoption of these measures is expected to significantly enhance agricultural productivity and expand rural electrification, thereby fostering a substantial reduction in carbon emissions, improving the sustainability of food production systems, and bolstering economic resilience across farming communities. These transformative steps will not only benefit Nigeria but will also set a precedent for sustainable agricultural practices across Africa. By executing these policies, Nigeria positions itself as a leader in the integration of renewable energy in agriculture on the continent, demonstrating a commitment to environmental stewardship and progressive agricultural strategies. This leadership is essential for inspiring similar advancements in neighboring countries, contributing to a broader regional shift towards sustainability.

4. Conclusion

The present study is a comprehensive analysis of the feasibility and effectiveness of the implementation of HRESs in Nigeria, focusing on wind and solar power in Nigeria's six geopolitical zones. The research offers optimal configurations, economic viability, and policy recommendations to guide Nigeria toward sustainable and resilient energy. Our analysis included an in-depth energy assessment of a reference greenhouse facility and a comparison with various Nigerian climates. We recorded minimum and maximum temperatures and solar radiation levels, highlighting the distinct climatic differences between South Korea and Nigeria. This comprehensive approach allowed us to accurately adapt the model to each considered geopolitical zone, considering local weather patterns and energy needs.

The findings revealed notable variations in temperature and solar radiation across Nigeria, which significantly affected the energy requirements of greenhouse operations. In contrast to South Korea's heating-dominated climate, Nigeria's climate necessitates consistent active cooling for horticulture, highlighting the importance of tailoring greenhouse designs to suit local environmental conditions and crop needs. In addition, the simulation results indicated a close alignment between the experimental and simulated energy consumption, validating the accuracy of the developed model in predicting the energy requirements of greenhouses across Nigeria. This reliability is crucial for the planning and implementation of effective HRESs in these regions.

Furthermore, the primary contribution of the present study is a meticulous evaluation of WT–PV hybrid systems for baseload supply, employing the TLBO algorithm. By considering both the NPC and baseload supply reliability, this study provides crucial guidance for investors and policymakers seeking to effectively harness renewable energy resources. In terms of economic feasibility, the LCOE for the PV-ESS varied across the zones, from as low as $0.07327/kWh in Kano to $0.8526/kWh in Adamawa, demonstrating the impact of regional factors on the cost-effectiveness of renewable energy technologies. Furthermore, the NPC analysis showed that PV-ESS configurations were most cost-effective, with costs ranging from $373,371.24 in Ogun to $500,444.41 in Nassarawa. Additionally, in Ogun, the NPC for WT-PV-ESS was $520,935.45, whereas for PV-ESS, it was significantly lower at $500,444.41. The analysis reveals a predominant preference for PV systems across Nigeria's regions, driven by their lower energy storage requirements and abundant solar resources. The TLBO algorithm played a pivotal role in minimizing NPC and ensuring reliable baseload supply, emphasizing the significance of this approach for renewable energy decision-making.

The results of location-specific analysis further confirmed the suitability of PV–ESS systems for Nigeria's diverse regions, with special considerations for areas such as Anambra. Tailoring renewable energy solutions to local resource availability and demand is essential for optimizing energy production. In addition to the technical and economic aspects, the present study suggested policies, the implementation of which is crucial for Nigeria's energy transition and agricultural sustainability. The proposed policies, FiTs, RPSs, net metering, research and innovation support, and market access development, align with global best practices. They provide a holistic framework that encompasses both renewable energy advancements and sustainable agricultural practices. Furthermore, the improvement of infrastructure, market access, and access to financing for smallholder farmers is integral for increasing food security and quality of life in rural Nigeria. Despite these benefits, the study has some limitations. The analysis was based on simulation models and reference greenhouse data, which may not fully account for all the complexities and unique challenges in each geopolitical zone. Variations in infrastructure, local energy policies, and regional renewable resource availability may impact the practical implementation of the recommended HRES configurations. Remarkably, the results of the present study demonstrate that Nigeria can leverage renewable energy resources to revolutionize its energy sector and agricultural practices. By adopting the recommended policies and embracing sustainable technologies, Nigeria can navigate the challenges posed by climate change and set an example for other nations striving for a sustainable and resilient future.

4.1. Future work

Considering the limitations of this study, future research should focus on conducting pilot projects that implement the recommended HRESs in actual greenhouse facilities in different regions of Nigeria. These pilot projects can provide valuable real-world data on the performance, cost-effectiveness, and challenges associated with HRES deployment in diverse climatic conditions. In addition, long-term monitoring and evaluation of these pilot projects will help refine the energy management strategies and policy frameworks, ensuring continuous improvements in sustainability, energy efficiency, and agricultural productivity.

CRediT authorship contribution statement

Abdulfatai Olatunji Yakub: contributed to writing, Software, Methodology, Formal analysis, Validation. **Misbaudeen Aderemi Adesanya:** contributed to writing, Software, formal analysis. **Same Noel Ngando:** contributed to, Data curation, writing, and formal analysis. **Anis Rabiu:** contributed to software, Visualization, and validation, contributed formal analysis and editing. **Deepak Chaulagain:** contributed to, Data curation, Formal analysis, reviewing and editing, contributed formal analysis and editing. **Qazeem Opeyemi Ogunlowo:** contributed to. **Abdulhameed Babatunde Owolabi:** contributed formal analysis and editing. **Jaebum Park:** contributed to revision and editing. **Jeong-Ok Lim:** contributed to revision and editing. **Hyun-Woo Lee:** contributed to investigation and supervision. **Jeung-Soo Huh:** contributed to the investigation, Supervision, Funding acquisition, editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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