energies

MDPI

Article

Optimisation of Tilt Angle, Orientation, and Building Aspect Ratio for Rooftop Solar Photovoltaic Energy Performance in a Tropical Climate: A Case Study of Lagos, Nigeria

Kehinde Zacheaus Babalola [1,2], Rolains Golchimard Elenga [1,3], Paolo Vincenzo Genovese [1,4,5,*], Chibesa Kalinso [5], Hong Wu [1] and Moses Akintayo Aborisade [6,*]

[1] School of Architecture, Tianjin University, Tianjin 300072, China; babalolazacheaus@gmail.com (K.Z.B.); rolains.elenga91@gmail.com (R.G.E.); wuhong960229@163.com (H.W.)
[2] Department of Architecture, Faculty of Environmental Science, Nnamdi Azikiwe University, Awka 420007, Nigeria
[3] College of Civil Engineering, Shandong Jianzhu University, Jinan 250101, China
[4] International Centre of History, Critics of Architecture and Restoration of Historical Heritage, Hangzhou 310027, China
[5] College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310027, China; ckalinso@gmail.com
[6] School of Civil Engineering, Guangzhou University, Guangzhou 510006, China
* Correspondence: pavic@zju.edu.cn (P.V.G.); aborisademoses@yahoo.com (M.A.A.)

Abstract

With the rapid advancement of solar energy, accurate solar irradiance data at different tilt angles are increasingly needed for PV system design. However, measuring irradiance at all possible angles is impractical, necessitating simulation-based approaches to identify optimal PV configurations. To overcome this limitation, a hybrid model is proposed that uses complementary approaches to estimate solar power generation at different angles, the energy performance of different orientations and the impact of aspect ratio on building geometry energy performance. Hence, the generation of clean energy through solar photovoltaic (PV) panels has been attracting significant global attention in recent decades. Understanding the relationship between tilt angle, building orientation, and aspect ratio can enhance the performance of electricity output in solar PV energy systems for buildings. This study aims to evaluate the impact of optimal tilt angle (OTA), orientation, and building aspect ratio with respect to electricity production. The results from modelling and simulating a 100 m^2 floor area show that square-shaped buildings (10 × 10 m) yielded the best energy demand compared to rectangular ones. South-facing PV modules at a tilt angle of 10° yielded optimal energy production of 52.8% (3040 kWh). The optimised design achieved a 12.18% increase in annual energy production compared with the baseline, thereby enhancing the building's renewable energy contribution and overall energy performance under the tropical African climate of Lagos, Nigeria. The results indicated that understanding the relationship between these parameters can lead to a more efficient system configuration, reduce energy wastage, and enhance sustainable energy demand in buildings.

Keywords: solar photovoltaic; building orientation; building aspect ratio; tilt angle optimization; Lagos; Nigeria

Check for updates

Academic Editor: Armando Oliveira

Received: 20 August 2026
Revised: 30 September 2026
Accepted: 20 October 2026
Published: 29 October 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

The surge in population and urbanisation has tremendously increased the global energy demand and intensified environmental issues, such as climate change and global

 https://doi.org/10.3390/en19215158

warming [1,2]. As a result, the growing demand for sustainable energy solutions has driven unprecedented growth in photovoltaic (PV) energy technologies. This has gained global attention due to their ability to harness abundant renewable sources of energy in nature for electricity generation [3–5].

This electricity output from solar PV is greatly influenced by a series of factors, which include optimal tilt angle (OTA), ambient temperature, solar intensity, dust particles, and wind speed [6]. Thus, to achieve maximum output from PV modules, finding the optimal tilt angle for efficient energy production and natural cleaning by rainwater, which reduces the accumulation of soil or dust particles, cannot be underestimated. Determination of OTA contributes greatly to annual electricity generation, whereas a sub-optimal tilt angle decreases the total annual energy production, giving rise to inefficiency of the energy configuration and techno-economic losses [7].

Solar energy is an alternative to fossil fuels due to its techno-economic viability, safety, efficiency, and environmental sustainability. It is generally believed that the prices of renewable energy technologies could be significantly lower than those of conventional energy technologies due to their efficiency and growing demand. It is also forecasted that renewable energy would account for 3/5th of global electricity demand by the mid-21st century, transitioning into a renewable energy-driven economy and cutting down CO_2 emissions to 75% compared to the 1985 equivalent by 2050 [8,9]. In the last century, it was estimated that the global Earth's surface temperature surged by 0.60 °C, and as a result, the sea level would have risen by approximately 20 cm. This prediction indicates that the continued combustion of fossil fuels may increase Earth's temperature by 4 °C in the next few decades. Realising this forecast could raise the sea level by about 60 cm by the end of this century, threatening the survival of the entire population through flooding of coastal regions. Hence, this global hazard depends on energy consumption. Shifting to renewable energy (RE) options could dramatically lower the risk. Renewable energy infrastructure is becoming competitive compared to conventional power sources, driven by high efficiency in operation [9]. Therefore, RES presents itself as one of the most effective and efficient energy solutions [8].

Many researchers have evaluated PV tilt angle under varying meteorological conditions. Significant insight was provided on the tilt angle for the efficient production of solar energy in a harsh desert climate in Jeddah, Saudi Arabia. The results revealed that the optimal tilt position varies from one season to another. Due to a lack of rain for natural cleaning of the PV surface during the dry season, the power generation dropped from 80% to 60% with tilt angles of 0° to 25° [10], respectively. As a result of space constraints in urban areas, [6] proposed a baseline, overhead reflector, and overhead panel PV configurations in the densely populated hot arid desert climate of Cairo, Egypt, in North Africa. The PV array produced 12.54 MW, 12.77 MW, and 12.53 MW, respectively. The authors of Ref. [3] studied the variability of PV tilt angles, spacing, and sizing concerning the levelised cost of energy in three distant locations, showcasing the effect of latitude on solar PV energy production.

1.1. Background and Motivation

Globally, solar light has significant uses in both nature and for human life. Solar energy is a form of solar radiation that sustains every living thing on Earth through photosynthesis and is a key driver of Earth's weather and climate. Through photosynthesis, plants manufacture their food by capturing a quantity of sunlight through stomata, by the reaction of carbon dioxide and water to synthesise glucose and release oxygen as a byproduct [8].

Fundamentally, all forms of energy on Earth have their origin in the solar system. Coal, oil, and natural gas are products of biochemical reactions within the Earth's crust over a long period of time. In the past century, most energy came from fossil fuels until recent

times, when concerns about environmental pollution and degradation from fossil energy consumption were raised. Essentially, a solar cell captures sunlight and generates electricity for various uses in buildings, appliances and means of transportation, which is generally referred to as a solar photovoltaic (PV) panel. The advantages of solar energy compared to other sources of energy are that it is clean and eco-friendly, without anthropogenic emissions or pollution into the environment [8].

Despite substantial research and the availability of various tools for assessing PV orientation and tilt angle, further investigation remains relevant for identifying location-specific configurations that maximise electricity generation under local climatic and building conditions. More narrowly, the tropical African climate is blessed with abundant solar radiation for power generation. Hence, this study focuses on simulating the orientation of solar PV, tilt angle and building aspect ratio to maximise clean electricity generation in a tropical climate, particularly in Lagos, Nigeria. Moreover, a comprehensive review of studies in Table 1 demonstrates that PV tilt angle and orientation significantly influence solar energy yield, with the optimal configuration varying with geographical location, climatic conditions, building aspect ratio, and system characteristics. Various approaches, including numerical modelling, GIS, machine learning, experimental methods, and optimisation algorithms, have been adopted to determine PV configurations across different regions. However, limited research has simultaneously integrated PV tilt angle, orientation, and building geometry in tropical African urban environments, highlighting the need for climate-responsive optimisation studies such as the present research in Lagos, Nigeria.

Table 1. Summary of the related literature reviewed for this study.

Ref.	Year	Location	Software	Method	Key Findings
[11]	2018	Worldwide (Hong Kong as a case study)	Clear-sky model (ASHRAE 1972)	Contour maps of the plan-of-array (POA) irradiation were used as functions of tilt and azimuth to determine the recommended range.	Using a clear-sky model produced plan-of-array (POA) irradiation predictions that were very similar to the results under real weather conditions. It gives designers a wide, flexible range of acceptable tilt and azimuth angles for PV installations.
[12]	2025	Europe	QGIS (open-source GIS software) with Python extensions	Direct, diffuse and ground-reflected irradiance, Ground Coverage Ratio and Ground albedo optimisation were used to determine the optimal tilt angle.	Optimal tilt angles increase with latitude showing that higher latitudes benefit from tilts due to sun path differences. Higher ground coverage ratio (GCR) (i.e., closely spaced rows) leads to lower optimal tilt angles.
[9]	2025	United States	Isotropic sky model	Thirteen machine learning (ML) models were configured to predict optimal tilt angles.	Support Vector Machine with Gaussian Kernel (SVMG) performed best for monofacial systems, and k-Nearest Neighbours Regression (KNN) performed best for bifacial systems. The ML approach offers a fast, scalable, and computationally efficient way to estimate optimal tilt angles at many locations without needing repeated physical simulations.

Table 1. *Cont.*

Ref.	Year	Location	Software	Method	Key Findings
[13]	2025	Lebanon	MATLAB	Numerical MATLAB-based method.	The method quantifies energy gains from monthly and seasonal tilt adjustments and demonstrates economic and environmental benefits relative to fixed tilt panels and grid electricity. This can increase energy yield by roughly 4–6% in Lebanese cities.
[3]	2021	Lebanon, France, and Morocco	MATLAB	Novel Mathematical Model, monthly Tilt Angle Optimisation, and Economic Evaluation.	Monthly adjustment of tilt angle significantly reduced LCOE across all studied locations, increasing power production and energy cost reduction.
[14]	2023	China	Collares-Pereira and Rabl hourly solar radiation model and solar radiation models	Inverse Distance Weighting (IDW) method.	Annual photovoltaic power generation potential ranges from roughly 117 to 483 kWh m^{-2}, with optimal tilt angles varying widely across China. The simplified β_{opt} model (latitude + altitude) offers a practical tool for preliminary design and planning of PV systems.
[15]	2026	Worldwide	ANSYS Fluent/ANSYS CFX, COMSOL Multiphysics, MATLAB, TRNSYS/Energy Plus	Systematic literature review of experimental, numerical, and hybrid studies on PCM thermal behaviour under different tilt angles and natural convection effects during melting and solidification.	Tilt angle strongly influences PCM heat transfer and vertical orientation is not always optimal. The research gap is the lack of unified correlations linking tilt angle, Rayleigh number, and melting time.
[16]	2025	India	Experimental field study; High-precision I-V tracer, Radiation sensors, and Infrared thermal imaging camera	A bifacial PV module was installed on a rooftop, with the ground surface painted white to increase reflected irradiance (albedo).	The maximum daily average power output occurred at a 30° tilt, producing about 316.85 W under the tested conditions. This study has implications for urban rooftop PV integration where albedo enhancement (e.g., white roofs) is feasible.
[17]	2025	Turkey	Engineering Equation Solver (EES)	A photovoltaic (PV) system coupled to a proton exchange membrane (PEM) electrolyser for green hydrogen production and a photovoltaic-thermal (PVT) system coupled to a PEM electrolyser, with cooling water mass flow.	Lower tilt angles (10°) favoured electricity and hydrogen production daily during summertime. Also, higher tilt angles (40°) with proper cooling improved energy and exergy efficiencies, and the cooling flow rate significantly enhanced PVT performance, hydrogen output, carbon savings, and economic outputs. This study provides a detailed multi-objective comparison of PV and PVT systems for renewable hydrogen production under varying operational conditions.

Table 1. *Cont.*

Ref.	Year	Location	Software	Method	Key Findings
[18]	2022	France and Italy	PVGIS-SARAH platform data, climate-based empirical modelling, and Optimisation algorithms	Data Collection & Preprocessing using PVGIS-SARAH database, Climate-Based Correction Model, and optimisation of Tilt and Azimuth.	This study provides a large-scale, climate-informed analysis of optimal PV tilt and azimuth configurations across France and Italy. The authors enabled efficient tilt optimisation and showed that even modest adjustments can produce measurable gains in annual energy yield.
[19]	2024	China	Long-term hourly solar radiation data from the ERA5 climate reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) were used	The study calculates optimal fixed tilt angles (annual and monthly) for every grid cell in China by maximising total surface solar radiation received across multiple periods, using the long-term ERA5 radiation dataset.	Using long-term, data-driven optimisation of PV tilt angles significantly improves solar energy yield across China, as simple latitude-based rules can cause substantial annual power losses.
[20]	2026	Saudi Arabia	Performance modelling tools and numerical optimisation techniques	Performance model and used simulations to optimise the tilt, azimuth, and installation of bifacial PV modules, comparing their energy yield to monofacial modules.	Optimally oriented bifacial PV modules achieve higher energy yields than monofacial modules, with rear-side irradiance and ground reflectance being critical, highlighting the importance of site-specific design in high-irradiance regions.
[21]	2025	Mali	Rhino/ClimateStudio	Parametric energy simulation for evaluation of aspect ratio, WWR, and orientation.	Seven aspect ratios (1:1–4.2:1) were assessed, with 1.3:1–1.5:1 achieving the lowest energy consumption.
[22]	2024	Iran	Validated building-energy simulation software	Energy simulation of different aspect ratios and orientations to minimise energy consumption.	A 1:4 aspect ratio with east–west elongation minimised energy consumption, highlighting the influence of aspect ratio and orientation.
[23]	2024	19 European cities	SketchUp, OpenStudio, EnergyPlus, Python/Eppy	An NSGA-II optimisation of building geometry, orientation, and WWR to minimise heating and cooling energy demand.	Compact, self-shading geometries reduced energy demand, achieving 4.58–19.84 kWh/m^2·yr.

The aforementioned literature review shows the tilt angles of various locations. Still, there is more work to be done on PV module orientation and building aspect ratio, especially in tropical African climates, such as Lagos, Nigeria, to achieve optimal performance of solar technologies, which is the main goal of this paper. The design and modelling techniques are aided by the DesignBuilder modelling tool.

1.2. Related Studies and Research Gap

The review of the current energy-related literature for this study reveals the following gaps:

1. Limited research focuses on tropical African regions: Most of the existing research is conducted in non-tropical climates, which limits the applicability of their findings to African regions such as Lagos, Nigeria.

2. Insufficient integration with building design: Current research primarily concentrates on optimising PV tilt and orientation, with little consideration given to building-related factors such as roof configuration, aspect ratio, and the impact of building geometry in the tropical African climate.
3. Limited simulation studies in Lagos: Many studies rely on idealised or non-African conditions, with limited simulation-based assessment of the interaction between building characteristics, solar availability, energy demand, and PV integration under Lagos's tropical climate.

1.3. Research Objectives

The objectives of the research include the following:

- To investigate PV system optimisation under tropical climatic conditions: This objective aims to evaluate the performance of PV systems in a tropical environment, with a focus on Lagos, Nigeria, to provide context-specific design recommendations.
- To develop an integrated building PV optimisation approach: This study seeks to incorporate building design parameters, including roof configuration, aspect ratio, and urban shading, into the optimisation of PV tilt orientation.
- To assess PV performance under urban constraints: This objective focuses on analysing the impact of practical urban conditions, such as building orientation limitations and building geometry, on PV system performance in dense urban settings.
- To evaluate the amount of direct and indirect employment opportunities solar energy infrastructure development can create for Lagosians to improve their living standards and boost their socio-economic activities.

The remaining sections of this paper are structured as follows. Section 2 provides the methods and materials for the study. Section 3 details the experimental results, focusing on the impact of varying tilt angle, orientation, and clean energy production. Section 4 discusses the findings and identifies the optimal tilt angle (OTA) for the system configuration, while Section 5 concludes the study and presents the deductions from the findings.

2. Materials and Methods

2.1. Building Descriptions

For this study, a crystalline silicon photovoltaic (PV) system positioned on 100 m^2 building floor area, 3 m height, with PV an active area of 1.26 m^2, a rated power of 250 W, and consisting of 10 modules, giving a total installed capacity of 2.50 kWp, was used for the tropical climate of Lagos, Nigeria, facing south, north, west, and east with tilt angles of 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45°. This study examines the relationships between tilt angle, orientation, aspect ratio, and annual electricity production. The design, modelling, and simulation are carried out using the DesignBuilder program [24] as presented in Figure 1. The building geometry modelling is a crucial part of the building envelope. In DesignBuilder, it involves a series of settings, configured systematically. The building is drawn based on the thermal zones rather than a detailed architectural drawing. For this study, the building footprint is 100 m^2, and weather files for temperature, wind velocity and solar radiation at the location were imported into the simulation engine.

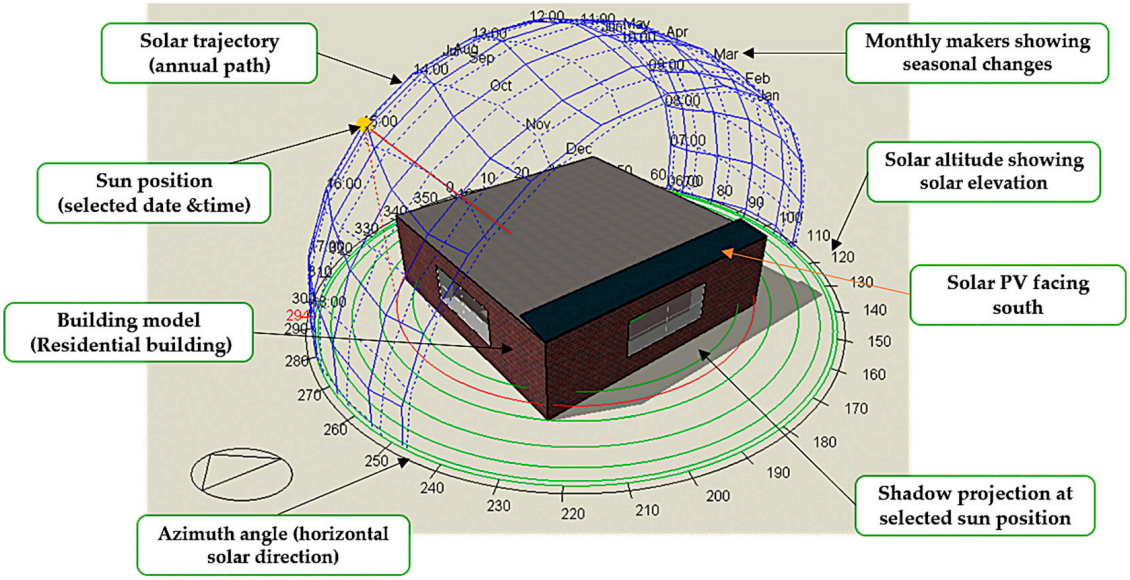


Figure 1. Sun-path and shading analysis of the residential building model.

Moreover, the baseline model represents a residential building floor area of 100 m^2 with a 3.0 m floor-to-ceiling height, aspect ratio of 1:1, and a 120.0 m^2 gross wall area, reflecting typical Nigerian residential construction. Located in Lagos, Nigeria, the building falls within ASHRAE zone 1A and the Köppen Aw tropical savanna classification (WMO Station 65201). It operates at standard atmospheric pressure of 101.3 kPa with an airflow rate of 0.29 m^3/s. The building envelope incorporates concrete block, cast concrete, brickwork, plasterboard, screed, asphalt, mineral glass wool, XPS, and urea-formaldehyde foam insulation to enhance thermal resistance and overall energy performance, as detailed in Table 2.

Table 2. Envelope materials of the baseline building.

Envelope Material	Thickness (m)	Conductivity (W/m·−K)	Density (kg/m^3)	Specific Heat (J/kg K)	Thermal Resistance (m^2·K/W)
Urea-formaldehyde foam	0.1327	0.040	10.00	1400.0	3.318
Cast concrete	0.10	1.130	2000.0	1000.0	0.0885
Floor/Roof screed	0.0	0.41	1200.0	840.0	0.1707
Asphalt	0.01	0.700	2100.0	1000.0	0.01429
MW glass wool	0.1445	0.04	12.00	840.0	3.612
Plasterboard	0.013	0.250	2800.0	896.0	0.0520
Brickwork	0.1	0.84	1700.0	800.0	0.1190
XPS (extruded polystyrene)	0.18	0.034	35.0	1400.0	5.294
Concrete block	0.26	0.510	1400.0	1000.0	0.5098

2.2. Study Area and Climatic Conditions

Lagos State, located in southwest Nigeria, lies within the tropical savanna climate zone at 6.35° N and 3.45° E, at an elevation of 39.40 m above sea level and an altitude of 5 m [25]. Lagos is bounded to the north by Ogun State and to the south by the Atlantic Ocean. Despite Nigeria's abundant energy resources, urban and rural areas face significant electricity challenges, with over 90 million people lacking access to power nationwide. The city experiences prolonged power outages even in grid-connected areas, and reliance on diesel generators increases operational costs. These challenges highlight the urgent need for alternative and renewable energy solutions to ensure a sustainable energy supply in Lagos. Furthermore, Lagos, Nigeria, is a metropolitan city in the southwestern region of

the country. It is generally known as the commercial hub or commercial capital of Nigeria. To cope with the growing population and urbanisation of the state, the need for sustainable energy solutions cannot be overemphasised [26].

The Lagos Economic Development Update (2025) reports a severe electricity supply deficit in Lagos State, Nigeria's economic hub, where demand of approximately 9000 MW far exceeds the 1000 MW supplied by the national grid. With a population exceeding 23 million, over 80% of residents and businesses rely on off-grid generators, primarily powered by petrol and diesel. These generators collectively produce about 15,000 MW daily, but at significantly higher costs (₦ 130/kWh) than grid electricity (₦ 50/kWh), resulting in an estimated annual economic burden of ₦ 5.3 trillion. As of 2020, only 31% of households were connected to the national grid. The report projects electricity demand to rise to 29,212 MW by 2030, highlighting the urgent need for sustainable and resilient energy solutions in Lagos [27,28].

Additionally, the site receives high solar radiation, with an estimated annual average global horizontal irradiance (GHI) of 5.47 kWh/m^2/year, a wind speed of over 3.81 m/s, a daily temperature of 26.4 °C, and a clearness index of 0.61. For the study location, data from the NASA Prediction of Worldwide Energy Resource (POWER) database, which contains over 22 years of meteorological records, were utilised. Hence, the site is richly blessed with renewable energy resources to generate sustainable electricity [26]. Figure 2 shows the meteorological data in the area: solar radiation (kWh/m^2/day), wind speed (m/s), daily temperature (°C) and clearness index of Lagos, Nigeria.

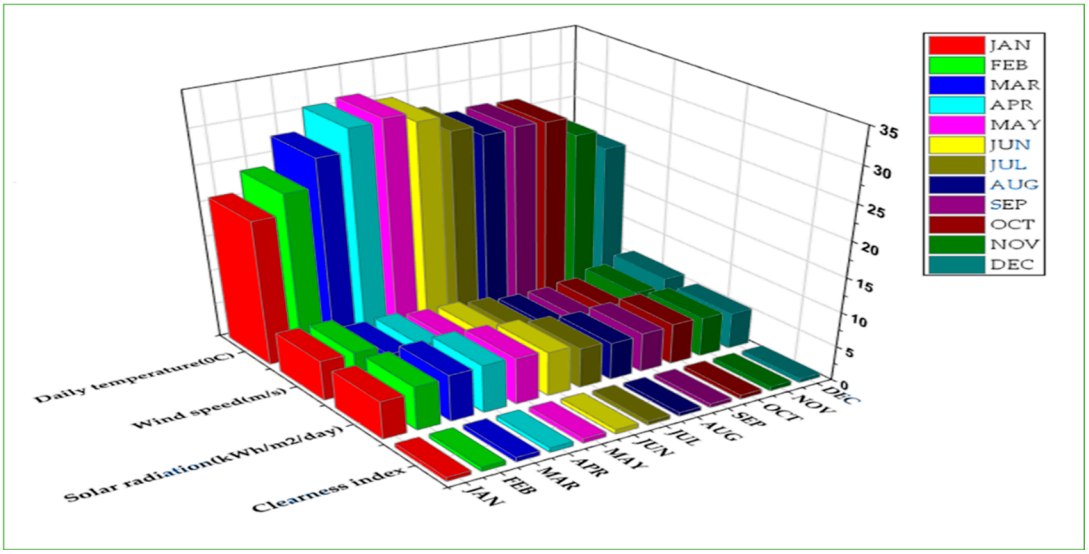


Figure 2. Meteorological data in the area. Solar radiation (kWh/m^2/day), wind speed (m/s), daily temperature (°C), and clearness index of Lagos, Nigeria.

Moreover, the methodological flowchart illustrates a sequential optimisation process involving building geometry (aspect ratio), solar PV orientation, and PV tilt angle to identify the optimal energy performance configuration. The process is repeated iteratively until an energy solution is achieved, after which results are evaluated and discussed. The simulation programme models hourly building energy performance by integrating geometry, climate, and system operation using physical and energy balance principles, while accounting for transient energy flows through building components over the full simulation period. Energy use associated with meeting thermal and other operational loads is also determined at the same time step. The results from each calculation are transferred to the subsequent

time step and recorded in the output file. Figure 3 illustrates the proposed methodological flowchart of the energy system performance under study.

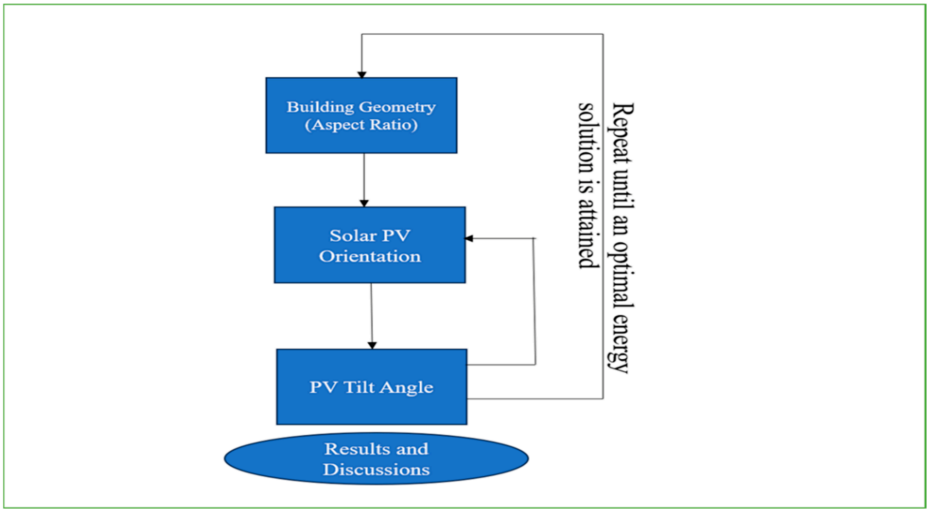


Figure 3. The methodological flowchart of this study.

2.3. Solar PV System Configuration

The PV module used in this study was selected from the DesignBuilder PV module library as the BP Solar 5170. In the DesignBuilder library, it is defined as a crystalline-silicon module with an active area of 1.26 m^2 and a rated electrical power of 250 Wp. The module was modelled as a rooftop-mounted PV system on a 10 × 10 m single-zone building model. A single-sided roof was adopted to isolate the effects of PV orientation and tilt angle. Although other roof configurations are common in the region, multiple roof orientations were outside the scope of this study. These specifications represent the parameters assigned to the module within the DesignBuilder simulation environment. Roof-mounted PV systems are typically modelled under simplified assumptions, including fixed tilt and orientation, uniform roof geometry, negligible shading, and constant system efficiency. These assumptions facilitate simulation but may not fully represent real-world conditions, particularly in dense urban environments.

2.4. Tilt Angle and Orientation Scenarios

The solar PV tilt angle is crucial to total clean energy generation; these angles range from 0° to 45° to receive sufficient solar radiation across four basic orientations: south, west, east, and north. This is to examine which of the orientations and tilt angles would yield maximum power. Hence, the optimal tilt angle is the inclination of a solar photovoltaic panel that maximises solar energy capture and electrical energy production for a specific location and over a given period. Solar PV panels are significantly affected by the tilt angle of the solar radiation. Additionally, the choice of tilt angle has a crucial impact on annual energy output. A sub-optimal tilt angle reduces electricity production, lowering efficiency and incurring economic losses. Therefore, an optimal tilt angle is essential in achieving maximum solar energy capture by the photovoltaic system [19]. The tilt angle is determined based on prevailing meteorological conditions and long-term climatic data for Lagos to maximise solar radiation captured for electricity generation. Solar energy systems with optimal tilt angles contribute meaningfully to cost savings and carbon emission reduction. Generally, the optimal solar photovoltaic (PV) angle depends on the position of the sun, the geographical latitude of Lagos State, local climate data, and other related parameters. This

study uses a fixed tilt angle system throughout the year, which is economical compared to an auto sun-tracker system that is techno-financially infeasible for the Lagos economy [19].

2.5. Simulation Tools and Modelling Approach

DesignBuilder Software Ltd. develops user-friendly building simulation software that enables fast, accurate assessment of environmental performance. Its tools support integrated analysis of energy [29]. Additionally, DesignBuilder offers high-accuracy, whole-building energy simulation by using the internationally validated EnergyPlus engine, enabling integrated analysis of envelope, HVAC, lighting, occupancy, and renewable systems. Its climate-responsive modelling, advanced passive design features, and user-friendly 3D interface make it well-suited for evaluating energy-efficient buildings in Nigeria's diverse climates. In addition, its robust reporting, scenario comparison, and thermal comfort analysis provide reliable, research-grade results that support compliance assessment and policy-relevant decision-making [30]. This study utilises DesignBuilder (version 7.3.1.003 with inbuilt EnergyPlus 9.4) for modelling and simulations. It has a user-friendly interface that enables the authors to model building aspect ratio, building orientation, and integration of renewable energy, such as solar PV. Building design variables were selected to model a 100 m^2 building envelope with a headroom of 3 m, using nine aspect ratios to determine the optimal model with the lowest energy consumption. Moreover, a monocrystalline silicon PV array is modelled and integrated at the rooftop, positioned facing north, south, west and east and simulated with tilt angles ranging from 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, and 45° to establish the optimal tilt angle (OTA).

2.6. Building Aspect Ratio

Building aspect ratio is defined as the ratio of the length to the breadth of the building. Additionally, building aspect ratio is defined as the ratio of the longest dimension to the smallest dimension of a building, especially for rectangular building forms. The software tools utilise these weather files to extract hourly environmental conditions to run the simulation algorithm, and annual energy performances were recorded for all the aspect ratios, which include square and rectangular forms starting from S1, S2, S3, S4, S5, S5, S6, S7, S8, and S9 as depicted in Table 3. This study examines the impact of aspect ratio on the building's energy performance. Various aspect ratios were modelled for a floor area of 100 m^2, and energy performance was analysed for the Lagos weather location using a window-to-wall ratio (WWR) of 30% as the default setting during the simulation processes. In this section, the impact of building aspect ratio on the energy performance is evaluated. The building is modelled using the DesignBuilder tool with different aspect ratios, for a single-storey residential building area of 100 m^2. The simulation is conducted to compare the energy demand under Lagos' meteorological conditions. Reducing the building surface area minimises energy demand [31]. Therefore, nine building aspect ratio scenarios are modelled for this study to investigate the optimal aspect ratio that minimises energy consumption and provide an appropriate orientation. The same floor area, but with a different aspect ratio, was examined in this study, along with its energy performance.

Additionally, the aspect ratio significantly affects the building's relative energy consumption (REC). Mathematically, the relationship between aspect ratio and the annual energy consumption is governed by the equation [31]:

$$REC = \left(\frac{E_{aspect}}{E_{1:1}} - 1 \right)\% \quad (1)$$

where E_{aspect} is the energy consumption of a particular aspect ratio, and $E_{1:1}$ is the energy consumption of a 1:1 aspect ratio. Technically, a positive relative energy consumption

(REC) shows an increase in energy demand, while a negative REC means a decrease in energy demand.

Table 3. Building aspect ratio for a 100 m^2 floor area.

S/N	Length, l (m)	Breadth, b (m)	Aspect Ratio (l:b)	Floor Area, l × b (m^2)
S1	50	2	9	100
S2	33.33	3	8	100
S3	25	4	7	100
S4	20	5	6	100
S5	16.7	6	5	100
S6	14.3	7	4	100
S7	12.5	8	3	100
S8	11.11	9	2	100
S9	10	10	1	100

2.7. Optimal Tilt Angle (OTA)

The PV tilt angle is the angle of inclination of the solar PV modules to the horizontal plane. Additionally, the PV tilt angle will be negative if the module is positioned toward the north or south poles, whereas a positive tilt angle indicates the module's plane is oriented toward the equator. Hence, the solar irradiance intensity that strikes a tilted surface is expressed mathematically as [32]:

$$\overline{H}_T = \overline{H}_b \overline{R}_b + \overline{H}_d \left(\frac{1 + \cos\beta}{2} \right) + H_\rho \left(\frac{1 + \cos\beta}{2} \right) \tag{2}$$

where $\overline{H}_T$ is the monthly average solar irradiance on the tilted PV module, $\overline{H}_b$ is the monthly average daily beam irradiation of the sun on the tilted PV panels, and $\overline{H}_d$ is the monthly average daily diffuse solar irradiation. The following mathematical formulation governs the optimal tilt angle (OTA) from the fixed orientation [32]:

$$\frac{d}{d\beta}\left(\overline{H_T}\right) = 0 \tag{3}$$

$$\frac{d}{d\beta}\left(\overline{R}_b\right) = 0 \tag{4}$$

$$\overline{R}_b = \frac{\sin(\varphi - \beta)\cos\delta\sin\omega_s - \left(\frac{\pi}{180}\right)\omega_s \cos(\varphi - \beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + \left(\frac{\pi}{180}\right)\omega_s \sin\varphi\sin\delta} \tag{5}$$

$$\beta = \varphi - \tan^{-1}\left(\frac{\left(\frac{\pi}{180}\right)\omega_s \sin\delta}{\cos\delta\cos\omega_s} \right) \tag{6}$$

where $\overline{R}_b$ denotes the horizontal surface, and the diffuse solar irradiance is negligible. β,ω_s,φ, and δ represent the surface slope to the horizontal, time, a specific latitude, and inclination, respectively. Hence, the tilt angle is optimised as the angle that produces the highest total solar radiation at each grid point, ranging from 0° to 45° [19].

2.8. Solar PV Power Output Computation

The solar PV energy production depends on factors, namely: the installed capacity of the PV and the power generation potential (*PVpot*). The *PVpot* is a dimensionless parameter that describes how PV modules perform relative to their rated capacity under prevailing ambient conditions. Consequently, instantaneous PV output is expressed as [19]:

$$PVpot = P_R \frac{I_t}{I_{ref}} \tag{7}$$

where I_t is the hourly distribution of total solar radiation striking the tilted surface. I_{ref} denotes the standard reference condition ($I_{ref} = 1000\ W/m^2$) while P_R is the performance ratio and also accounts for variation in PV cells' efficiency, resulting from temperature changes, given as [19]:

$$P_R = 1 + \lambda\ [T_{cell} - T_{ref}] \quad (8)$$

where T_{ref} is the reference temperature at a value of 25 °C, λ is the cell coefficient, typically at 0.0045 °/C for a monocrystalline silicon cell, and T_{cell} is the cell temperature.

2.9. PV Optimisation Problems

Many researchers have studied the optimal PV tilt angle and provided valuable recommendations applicable to many regions and countries, including Lagos State in Nigeria. Hence, Duffie and Beckman provided a useful formulation where output will be negative during summer and positive during winter periods, as presented in Table 4 [32].

Table 4. Optimum tilt angle in relation to the latitude, data from [33,34].

Formulation	Remarks	Ref.
$(\phi + 15^\circ) \pm 15^\circ$	Positive for the winter season	[33]
$(\phi + 15^\circ) \pm 15^\circ$	and negative for summer	[33,34]
$(\phi - 10^0)$	season.	[33]
$\phi + 15^0, \phi - 15^0, 0.9\phi$		[33]
$(\phi + 20^0)$		[33]
$(\phi + 10^0)$		[33]
$(\phi \pm 15^0)$		[33]
$\phi + (10^0 \rightarrow 30^0)$		[33]
$(\phi + 20^0)$		[33]

3. Results

3.1. Baseline Model

The simulation results show an annual electricity consumption of 19,508.81 kWh. The photovoltaic (PV) system contributes 40.62% of the building's total energy demand. The baseline parameters establish a reference model for assessing the effectiveness of subsequent energy-efficiency measures and optimisation strategies.

3.2. Energy Demand of Aspect Ratios

In this study, various aspect ratios and energy demand are being investigated through simulation. Thus, for a square building, the aspect ratio is 1, whereas that of a rectangular building varies with the ratio of the longer to the shorter footprint dimension. The square shape with dimensions of 10 × 10 m yielded lower energy consumption, especially for cooling electricity demand, compared to a rectangular building footprint. Figure 4 presents various aspect ratios as applied to building energy consumption. The square building form S9 (10 × 10 m) shows optimal energy performance compared to rectangular forms. Hence, the square form is more economical in terms of energy demand [24].

Additionally, the building aspect ratio significantly influences energy consumption, with total electricity demand increasing as the building geometry changes from S9 (10 × 10 m) to S1 (2 × 50 m). The elongated building configuration (S1) records the highest energy consumption, primarily due to increased cooling and lighting loads resulting from the greater facade exposure to solar radiation. In contrast, the more compact configuration (S9) exhibits the lowest energy consumption because its reduced surface-area-to-volume ratio minimises heat gain and cooling demand. This trend indicates that compact building forms are more energy-efficient and can significantly reduce operational electricity con-

sumption, as presented in Table 5. For Lagos, Nigeria, where cooling accounts for a major share of building energy use due to the tropical climate, optimising the building aspect ratio can substantially improve energy efficiency. Lower building energy demand also reduces the required capacity of solar PV systems, making clean energy deployment more cost-effective and increasing the share of renewable energy that can meet building loads. Therefore, integrating energy-efficient building design with solar PV technology represents a practical strategy for achieving sustainable buildings and supporting Lagos State's clean energy transition and carbon emission reduction goals.

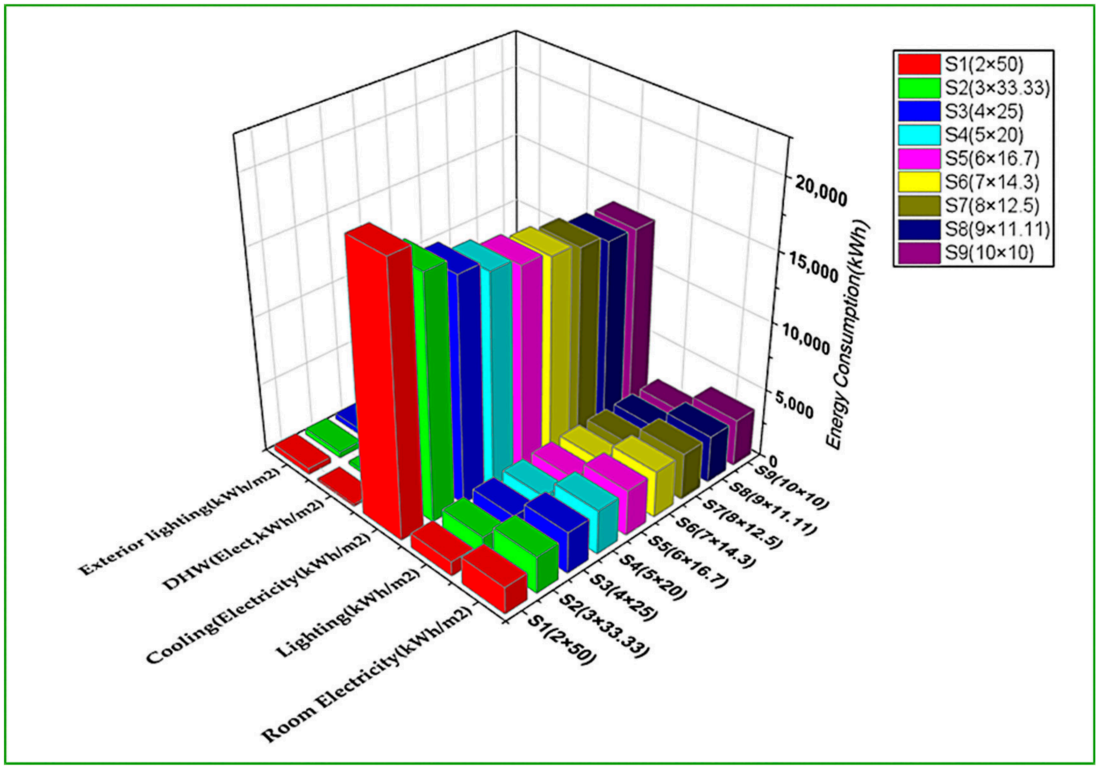


Figure 4. Energy consumption of nine building configurations (S1–S9) with different aspect ratios.

Table 5. Effect of building aspect ratio on annual energy consumption.

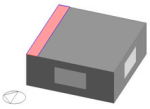
Scenario	Aspect Ratio (m)	Energy Consumption (kWh)
S1	50:2	23,204.97
S2	33.3:3	21,776.68
S3	25:4	21,776.08
S4	20:5	21,263.02
S5	16.7:6	20,851.07
S6	14.3:7	20,550.57
S7	12.5:8	20,245.47
S8	11.11:9	19,708.17
S9	10:10	19,626.17

3.3. Solar PV Orientation

Positioning solar PV modules for optimal tilt angle is a herculean task. However, the orientation and tilt angle of PV modules are important parameters for maximising electricity generation. In this study, azimuth represents the horizontal direction of the PV modules (west, east, south, or north), while tilt angle represents their inclination from the horizontal plane. Each azimuth orientation was evaluated at tilt angles ranging from 0° to 45° to determine the optimum configuration. A PV area of 12.6 m^2 was assessed for the four

orientations. As shown in Table 6, the optimal tilt angle was 10° for the west and south orientations and 0° for the east and north orientations. The south-facing configuration at 10° produced the highest electricity contribution (52.8%), followed by the north-facing configuration at 0° (52.1%), while west and east orientations produced 40.6% and 40.1%, respectively. These differences demonstrate the combined effects of azimuth and tilt angle on PV electricity generation.

Table 6. Solar PV azimuth orientation and optimal tilt angle for electricity generation.

Orientation	West	East	South	North
Position of solar PV				
Solar PV size (m^2)	12.6	12.6	12.6	12.6
Optimal angle (°)	10	0	10	0
Percentage of electricity Produced (%)	40.6	40.1	52.8	52.1

Overall, the results indicate that low tilt angles (0–10°) were favourable at the study location, with the south-facing PV system at a 10° tilt identified as the optimum configuration, supplying 52.8% of the building's electricity demand.

3.4. Annual Electricity Production with Tilt Angle

In this study, the annual electricity generation of the PV system was evaluated for four orientations (south, west, east, and north) at tilt angles ranging from 0° to 45°. The results show that the south-facing orientation produced the highest electricity generation, with an optimal tilt angle of 10° and a maximum output of 3040 kWh, as shown in Figure 5. The north-facing orientation achieved its maximum output of 2309.8 kWh at 0°, while the west and east orientations reached 2339 kWh at 10° and 2309.8 kWh at 0°, respectively.

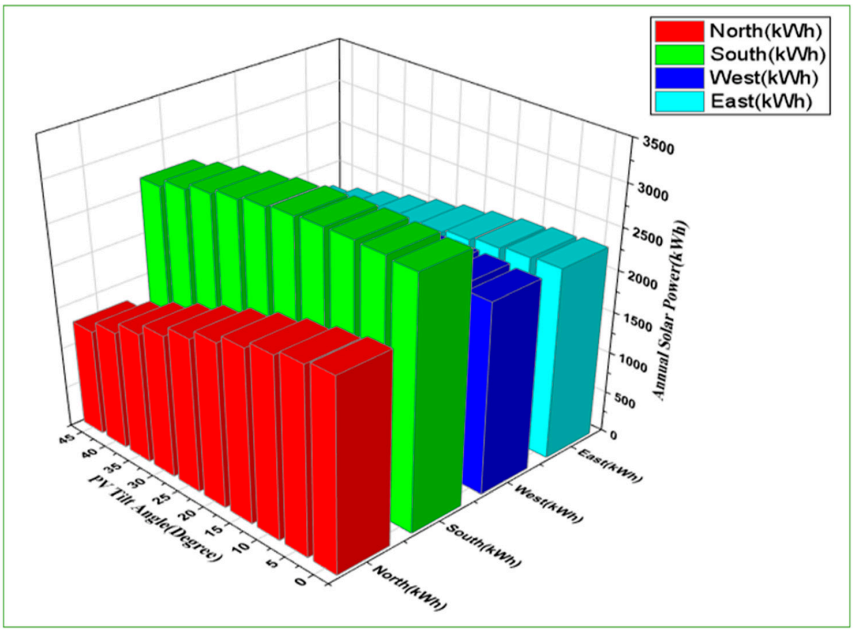


Figure 5. The relationship between PV tilt angle and solar power generation.

Electricity generation generally decreased as the tilt angle increased, particularly at higher angles. For example, south-facing generation decreased from 3040 kWh at 10° to

2676 kWh at 45°, while north-facing generation decreased from 2309.8 kWh at 0° to 1295 kWh at 45°. These results indicate that low tilt angles are more suitable for the study location, with the south-facing system at 10° providing the highest annual electricity generation. Hence, the optimised design achieved a 12.18% increase in annual energy production relative to the baseline, thereby enhancing the building's contribution from renewable energy sources.

4. Discussions

4.1. Influence of Building Aspect Ratio on Energy Demand

The findings demonstrate that integrating building geometry with photovoltaic system configuration can substantially influence the energy performance of residential buildings in tropical climates. The results show that a 10 × 10 m square building (S9) had the lowest energy demand compared with the rectangular configurations. Its compact form reduces the exposed surface area relative to the enclosed floor area, thereby limiting unwanted solar heat gain through the building envelope and reducing cooling loads. In particular, the optimised configuration achieved a 12.8% increase in annual PV energy production compared with the baseline, demonstrating the potential of climate-responsive PV integration in buildings to support sustainable energy transition in Lagos, Nigeria. This indicates that building compactness can play a crucial role in improving energy efficiency in tropical climates.

The findings are consistent with previous research showing that building geometry and aspect ratio influence energy consumption and thermal performance. In the Lagos context, the adoption of compact forms can therefore support climate-responsive residential design by reducing cooling loads while maintaining functional floor space. Integrating aspect-ratio considerations at the early design stage can consequently contribute to more energy-efficient and sustainable residential buildings.

4.2. Impact of PV Tilt Angle and Orientation on Energy Production

The optimisation results for PV tilt angle and orientation indicate that south-facing PV modules at a 10° tilt angle achieved the highest electricity production, approximately 3040 kWh. This performance can be attributed to Lagos' tropical location, where the low latitude and associated solar trajectory favour relatively low PV tilt angles. At 10°, the PV surface receives favourable incident solar radiation throughout the year, resulting in higher annual energy generation compared with the other configurations investigated.

Moreover, as the tilt angle increased, PV energy production declined, with the south-facing configuration decreasing from 3040 kWh to 2676 kWh at 45°. This demonstrates that increasing the tilt beyond the locally favourable range can reduce effective solar capture in low-latitude regions. The findings are consistent with previous studies showing that optimal tilt angles vary across geographical and climatic conditions, indicating Europe, China, Lebanon, and Saudi Arabia. Therefore, PV tilt angle should be optimised based on local solar conditions rather than relying solely on universal latitude-based rules.

4.3. Integrated Building PV Optimisation

The study highlights the importance of simultaneous consideration of building geometry, orientation, and PV tilt angles when optimising residential building energy performance. Unlike existing studies that have largely investigated PV tilt angle and orientation independently, this study integrates these parameters with building geometry, providing a more comprehensive approach to climate-responsive building and renewable energy design in tropical environments. Additionally, this integrated approach demonstrates that architectural design and PV system optimisation can work together to reduce building energy demand while increasing renewable electricity production. The optimised design achieved a 12.18% increase in annual energy production compared with the baseline, thereby enhanc-

ing the building's renewable energy contribution and supporting the sustainable energy transition in Lagos, Nigeria.

4.4. Comparison with Previous Studies

Table 7 presents a comparative review of previous studies that investigated the influence of building geometry and photovoltaic (PV) design parameters on building energy performance using different simulation and optimisation tools. The reviewed studies were conducted across China, Pakistan, Iran, India, and South Korea, employing software such as EnergyPlus, PVsyst, DesignBuilder, MATLAB, BIM, and GIS-based optimisation platforms. Most of the studies incorporated building geometry, PV tilt angle, PV orientation, and energy production techniques. The increasing adoption of optimisation algorithms demonstrates a growing emphasis on identifying optimal building and PV design configurations that balance energy performance and renewable energy generation. Despite these contributions, few studies have simultaneously addressed these parameters within the context of tropical residential buildings in Nigeria. Therefore, the present study addresses this research gap by integrating building geometry, PV tilt angle, PV orientation, and energy production optimisation using DesignBuilder for residential buildings in Lagos, Nigeria.

Table 7. Comparative review of previous studies on building geometry, photovoltaic design parameters, and energy performance.

Ref.	Location	Software	Method	Building Geometry	PV Tilt Angle	PV Orientation	Energy Production
[35]	China	Energy plus	Simulation	✓	X	✓	✓
[36]	Pakistan	PVsyst	Techno-economic modelling	✓	✓	✓	✓
[37]	Iran	EnergyPlus+ jEPlus+EA	Multi-objective optimisation (NSGA-II)	✓	X	X	X
[38]	India	BIM+ Energy Plus	Simulation	✓	X	✓	X
[39]	South Korea	GIS-based PV optimisation	Multi-objective Optimisation	✓	✓	✓	✓
[40]	China	MAT-LAB+PV simulation	Multi-objective Optimisation	✓	✓	✓	✓
[41]	China	Design-Builder + jEPlus	Multi-objective Optimisation	✓	✓	✓	✓
This study	Nigeria/Lagos	Design Builder	Single-objective Optimisation	✓	✓	✓	✓

4.5. Study Implication for Sustainable Energy Transition and Urban Planning

This study demonstrates that rooftop PV can support the decentralisation of urban energy generation in Lagos by enabling residential buildings to generate electricity locally, reducing dependence on the national grid. Integrating approximately oriented and optimally tilted PV systems into residential buildings can reduce dependence on conventional electricity sources and contribute to a more resilient urban energy system. This approach is particularly relevant to Lagos, where rising energy demand and unreliable electricity supply create a need for sustainable, evenly distributed energy solutions.

Architects and urban planners can integrate PV orientation, tilt angles, and building geometry in the early design stage to maximise renewable energy production and improve building energy performance, supporting a sustainable energy transition in Nigeria. These findings also support incorporating renewable energy and energy-efficiency requirements

into building regulations and approval processes, and encourage collaboration among architects, planners, engineers, and energy sector professionals to promote climate-responsive, renewable energy-integrated development in the building industry.

In addition, wider adoption of rooftop solar PV could reduce reliance on fossil-based energy sources such as petrol, coal, and diesel generators, while supporting greenhouse gas (GHG) emissions reduction, energy security, and climate-change mitigation. The integrated PV approach developed in this study can provide a useful framework for other tropical African cities with similar conditions, rapid urbanisation, and electricity supply challenges, thereby contributing to a broader transition toward sustainable and resilient urban energy systems.

4.6. Job Creation: Implications of Solar PV on Tropical Building Design

Solar energy infrastructure creates job opportunities for the young populace, either directly or indirectly, particularly for stakeholders involved in the planning, designing and construction of the built environment. Moreover, manufacturing locally produced solar PV technology creates employment opportunities for both skilled and unskilled workers, including installation, operation, and maintenance of solar energy components. Additionally, there is no doubt that increasing the share of solar energy helps reduce dependence on imported energy and contributes to climate-change mitigation. Solar energy technologies are distinctive because they create jobs directly while also stimulating indirect employment through demand for goods and services from suppliers and subcontractors. In addition, international trade plays a role in this process.

Using the mathematical relationship in Equation (9) [42], this study estimates the potential number of jobs by installing a 250 Wp PV panel system in Lagos, Nigeria. Data from [43] were utilised to estimate employment factors related to the manufacturing, installation, operation and maintenance of solar panel modules. Technically, job_x represents the number of jobs created per unit of electricity (jobs/kWh/year) for a given energy technology, and $E_{gen,x}$ denotes the energy generated by that energy component (kWh).

$$Job = \sum_{x \in comp} job_x \times E_{gen,x} \tag{9}$$

$$E_{orientation} = E_{2.5kW_p} \times \frac{G_{orientation}}{G_{2.5kW_p}} \tag{10}$$

where $E_{orientation}$ is the employment for the specific PV orientation, $E_{2.5kW_p}$ is the employment value for the (10 × 250 Wp = 2.5 kWp) reference system, is the electricity generation for the specific orientation (e.g., 3040 kWh for south), and $G_{2.5kWp}$ is the electricity generation of the 2.5 kWp reference system.

Therefore, calculations were carried out under the same conditions. The results indicate that all four PV technology orientations generate similar numbers of jobs per kWh across manufacturing, construction, installation, operation, and maintenance, with a total installed capacity of 2.50 kWp. Optimal energy production of each side-facing configuration is estimated using Equation (10) in relation to the employment factor in Equation (9). Hence, in electricity production, south-facing technology has the highest job-creation potential due to its superior capacity factors. The estimated employment created across the lifecycle of the modelled PV systems is summarised in Table 8.

The employment assessment indicates that solar PV deployment in Lagos State can support direct and indirect employment across different stages of the PV value chain. For the manufacturing, construction, and installation category, the estimated jobs range from 0.01094 to 0.01195 jobs across the four orientations, with the south-facing system recording the highest value (0.01440–0.01553 jobs). Similarly, operation and maintenance

generate approximately 0.00228–0.01200 jobs, while PV-module manufacturing contributes 0.00570–0.01750 jobs. Direct employment such as engineers, electricians, plant operators, and installers ranges from 0.02279 to 0.05000 jobs, with the south-facing configuration again showing the highest estimate. The results further show that the construction stage provides approximately 0.03267–0.04300 man-years, while the operation stage contributes approximately 0.01786–0.02350 man-years for the modelled systems. Overall, the findings demonstrate that solar PV deployment can contribute to employment generation throughout the PV lifecycle, while the higher electricity output of the south-facing configuration corresponds to greater employment potential. Increased investment in solar PV could therefore support local economic activity and contribute to Lagos State's transition toward a more sustainable and resilient energy system.

Table 8. The estimated number of jobs that the solar panel technology could create, adapted from [43].

Employment Factor [43]	Category of Job	Jobs for the PV Modelled System			
		North (2309.8 kWh)	South (3040 kWh)	West (2339 kWh)	East (2309.8 kWh)
0.0144–0.0155 jobs/MWp	Manufacturing, construction, and installation	0.01094–0.01180	0.01440–0.01553	0.01108–0.01195	0.01094–0.01180
0.0030–0.0120 jobs/MWp	O&M	0.00228–0.00912	0.00300–0.01200	0.00231–0.00923	0.00228–0.00912
0.0075–0.0175 jobs/MWp	Manufacturing of PV modules	0.00570–0.01330	0.00750–0.01750	0.00577–0.01346	0.00570–0.01330
0.0300–0.0500 jobs/MWp	Direct employment	0.02279–0.03799	0.03000–0.05000	0.02308–0.03847	0.02279–0.03799
0.0430 man-year/MW	Construction	0.03267	0.04300	0.03308	0.03267
0.0235 man-year/MW	Operation	0.01786	0.02350	0.01808	0.01786

4.7. Energy Efficiency and Sustainability Implications

The study suggests that a compact building form with south-facing PV modules at a 10° tilt angle is a suitable configuration for improving residential energy performance in Lagos, Nigeria. This provides practical guidance for architects, developers, policymakers, and renewable energy practitioners when integrating solar PV into residential design.

Moreover, applying optimisation techniques alongside long-term, high-resolution solar radiation data enables the development of highly site-specific photovoltaic (PV) system designs. This approach is essential for Lagos, Nigeria, to effectively scale up renewable energy capacity and advance toward its carbon-neutral ambition and energy transition plan (ETP). The findings also highlight the need to account for regional climatic specificities when determining optimal PV panel tilt angles.

4.8. Limitations of the Study

While DesignBuilder provides a robust physics-based approach for assessing building performance, differences between simulated and actual building performance may arise from modelling assumptions, occupant behaviour, weather variability, and operational conditions. This study is primarily simulation-based and was not validated against measured performance data from comparable residential buildings in Lagos, as such data were unavailable within the study scope. The analysis also used a single-sided roof configuration and a PV module from the DesignBuilder library rather than newer, higher-wattage commercial modules; therefore, multiple roof orientations and emerging PV technologies were not evaluated. In addition, the weather data may not fully capture extreme events, microclimatic conditions, urban heat-island effects, and short-term climate variability. Con-

struction defects, material ageing, thermal bridges, and workmanship variations are also not fully represented. Future studies intend to incorporate measured data for model validation, evaluate newer higher-wattage commercial modules, and compare results with established commercial PV modelling tools.

5. Conclusions

5.1. Key Findings

In conclusion, investigating building aspect ratio, orientation, and PV tilt angle with respect to energy demand yields substantial savings in heating and cooling energy demand. The investigation of these parameters was conducted on a modelled design of a 100 m^2 building floor area with a height of 3 m, using the DesignBuilder program, under the tropical African climate of Lagos, Nigeria. The results show that the square-shaped building S9 (10 × 10 m) yielded the lowest energy demand compared to rectangular ones, and south-facing PV modules at a tilt angle of 10° yielded optimal energy performance of 52.8% (3040 kWh) compared to sub-optimal tilt angles ranging from 0°, 5°, 15°, 20°, 25°, 30°, 35°, 40°, and 45°. In addition, the square building form S9 (10 × 10 m) shows optimal energy performance compared to the rectangular forms (S1, S2, S3, S4, S5, S5, S6, S7, S8). Hence, the square form is more economical in terms of energy demand. Moreover, the optimal tilt angle (OTA) reduces building energy demand, and understanding the relationships among these parameters can lead to a more energy-efficient design of buildings that enhances sustainable energy consumption and reduces energy wastage. Additionally, the optimised design increased annual energy production by 12.18% compared with the baseline, enhancing renewable energy contribution. The findings also indicate that solar PV deployment in Lagos can generate direct and indirect employment across the PV lifecycle, while higher energy-generating orientations offer greater employment potential and support local economic development. The method used for this study will enhance the versatility of local climate-responsive design, lowering the cost of energy, reducing greenhouse gas (GHG) emissions and enabling widespread adoption of solar PV harvesting of renewable energy in Lagos and other regions in Nigeria, to shape the future of the energy landscape for sustainable development in sub-Saharan African (SSA) countries.

5.2. Practical Recommendation

The following recommendations are proposed to promote renewable energy adoption, energy-efficient building design, and a sustainable energy transition in Lagos, Nigeria, which include:

- Implementation of policies such as the Lagos State Electricity Law, Electricity Act 2023, and National Renewable Energy and Energy Efficiency Policy (NREEEP) can support renewable-energy investment, decentralised generation, and clean-energy adoption in Lagos [44–46]. A specific action is to establish incentives for residential and commercial rooftop solar PV, including streamlined permitting and targeted financial support, to accelerate adoption, strengthen electricity supply, and reduce carbon emissions.
- Adoption of a solar-renewable-intensive future is technically feasible in Lagos, Nigeria, to bring about economic prosperity and stabilise the energy sector by diversifying the economy from oil- and gas-based to sustainable renewable fuel alternatives.
- In a grid-connected household where excess electricity is being generated by a hybrid of utility grid, battery and solar PV, the excess electricity can be sold back to the grid to generate income for the resident and thereby lower the excessive pressure on the national grid.
- There should be a renewable energy and energy efficiency guideline incorporated into building approval regulations by the building regulatory bodies (ARCON, COREN,

city planners and energy experts) on the integration of renewable energy systems, aspect ratio and orientation into new building development from the preliminary phase to the delivery phase.

- There should be collaboration between foreign international organisations and local institutions on the development of renewable energy infrastructures and technologies, on the assessment of energy options that are adaptable to the local climate and on an increase in research centres on the development of renewable fuel.

5.3. Future Research Direction

This study focused on single-story residential building stock. However, in our future study, we intend to explore multi-level residential building units with auto-tilt-angle tracking PV installation, as well as the optimisation of various building elements, including economic and lifecycle analysis. Also, future studies will evaluate emerging high-efficiency PV technologies and compare results with established commercial PV modelling tools to assess their potential for improving rooftop solar generation and validating the effects of PV orientation and tilt angle in the study region.

Author Contributions: K.Z.B.: Writing—original draft, Methodology, investigation, Conceptualisation; R.G.E.: Validation, Software, Formal analysis, Data curation; C.K.: Graphic editing, visualisation; P.V.G.: Writing—review and editing; H.W.: Visualisation, investigation; M.A.A.: Writing—review, validation, and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest concerning this article, authorship, and/or publication of this research.

References

1. Elenga, R.G.; Wang, Q.; Babalola, K.Z.; Quan, D.; Lv, H.; Wang, P. Multi-objective optimization for cost-effective low-carbon building design. *Buildings* **2026**, *16*, 3626. [CrossRef]
2. Eke, M.; Clausel, T.T.B.; Anyanwu, C.; Ojike, O.; Abam, F. Sizing and designing of an adsorption chiller with phase change material thermal storage for an office building: Case study nigeria. *Next Energy* **2025**, *7*, 100305. [CrossRef]
3. Osmani, K.; Ramadan, M.; Lemenand, T.; Castanier, B.; Haddad, A. Optimization of pv array tilt angle for minimum levelized cost of energy. *Comput. Electr. Eng.* **2021**, *96*, 107474. [CrossRef]
4. Babalola, K.Z.; Elenga, R.G.; Genovese, P.V. Swot analysis approach for renewable energy production in sub-Saharan African climate: Case study of six geopolitical states of nigeria. In *Proceedings of the 2025 5th International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Zanzibar, Tanzania, 16–19 October 2025*; IEEE: New York, NY, USA, 2025; pp. 1–5.
5. Babalola, K.Z.; Elenga, R.G.; Genovese, P.V. Energy–economic–environmental (3e) optimization of a hybrid system for a residential building in a developing country: A case of Nigeria. *Sustain. Energy Res.* **2025**, *12*, 66. [CrossRef]
6. Al-Ghussain, L.; Hassan, M.A.; Hamed, A. Modeling and techno-economic optimization of overhead panels and reflectors in near-wall mounted pv systems. *Sol. Energy* **2023**, *249*, 624–641. [CrossRef]
7. Tamoor, M.; Bano, A.R.; Farhan, M. An improved approach for enhancing the pv system efficiency through optimization of tilt angle. *Sol. Energy* **2025**, *297*, 113607. [CrossRef]
8. Duffie, J.A.; Beckman, W.A. *Solar Energy Engineering: Processes and Systems*, 4th ed.; John Wiley & Sons: Hoboken, NJ, USA, 2013.
9. Haroun, H.; Issa, J.S.; Rahme, P. Machine learning-based prediction of optimal tilt angles for monofacial and bifacial pv systems. *Sol. Energy* **2025**, *301*, 113924. [CrossRef]
10. Alzahrani, M.; Rawa, T.R.; Muhyaddin, R.; Weddell, A. Impact of dust and tilt angle on the photovoltaic performance in a desert environment. *Sol. Energy* **2025**, *288*, 113239. [CrossRef]

11. Chen, X.M.; Li, Y.; Zhao, Z.G.; Ma, T.; Wang, R.Z. General method to obtain recommended tilt and azimuth angles for photovoltaic systems worldwide. *Sol. Energy* **2018**, *172*, 46–57. [CrossRef]
12. Ferry, A.; Parenti, M.; Thebault, M.; Ménézo, C.; Fossa, M. Optimal tilt angles for bifacial photovoltaic plants across Europe based on cumulative sky and typical meteorological year data. *Sol. Energy* **2025**, *293*, 113475. [CrossRef]
13. Nahim, H.M.; Ibrahim, T.; Faraj, J.; Ali, S.; Khaled, M.; Darwiche, M. Optimizing solar panel tilt angles for enhanced energy production: Case studies in Lebanon. *Case Stud. Therm. Eng.* **2025**, *73*, 106720. [CrossRef]
14. Jing, J.; Zhou, Y.; Wang, L.; Liu, Y.; Wang, D. The spatial distribution of China's solar energy resources and the optimum tilt angle and power generation potential of pv systems. *Energy Convers. Manag.* **2023**, *283*, 116912. [CrossRef]
15. Rashid, F.L.; Kadhim, S.A.; Abdalrahem, M.K.; Ameen, A.; Al-Obaidi, M.A.; Bouabidi, A.; Ashour, A.M.; Al-Ghezi, M.K.S. Influence of tilt angle on the thermal performance of phase change materials: A comprehensive review. *Energy Convers. Manag. X* **2026**, *29*, 101489. [CrossRef]
16. Basak, A.; Chakraborty, S.; Behura, A.K. Tilt angle optimization for bifacial pv module: Balancing direct and reflected irradiance on white painted ground surfaces. *Appl. Energy* **2025**, *377*, 124525. [CrossRef]
17. Atiz, A. Evaluation of energy, exergy, economic, and carbon savings analyses, along with green hydrogen production of pvs and pvts under daily solar radiation for various tilt angles and mass flow ratios. *Int. J. Hydrogen Energy* **2025**, *98*, 657–672. [CrossRef]
18. Memme, S.; Fossa, M. Maximum energy yield of pv surfaces in France and Italy from climate based equations for optimum tilt at different azimuth angles. *Renew. Energy* **2022**, *200*, 845–866. [CrossRef]
19. Lu, N.; Qin, J. Optimization of tilt angle for pv in China with long-term hourly surface solar radiation. *Renew. Energy* **2024**, *229*, 120741. [CrossRef]
20. Al Garni, H.Z. A performance modeling and optimal orientation of bifacial pv modules: A case study from Saudi Arabia. *Results Eng.* **2026**, *29*, 109175. [CrossRef]
21. Zanjirei, S.; Davoodi, M.; Sadeghi, E.; Ansarisamani, A. Optimizing early-stage design for energy-efficient schools in Bandiagara, Mali. *Afr. J. Environ. Sci. Renew. Energy* **2025**, *18*, 70–100. [CrossRef]
22. Zafari Jurshari, M.; Yousefi Tazakor, M.; Yeganeh, M. Optimizing the dimensional ratio and orientation of residential buildings in the humid temperate climate to reduce energy consumption (case: Rasht Iran). *Case Stud. Therm. Eng.* **2024**, *59*, 104484. [CrossRef]
23. Salata, F.; Ciardiello, A.; Dell'Olmo, J.; Ciancio, V.; Ferrero, M.; Rosso, F. Geometry optimization in the schematic design phase of low-energy buildings for all European climates through genetic algorithms. *Sustain. Cities Soc.* **2024**, *112*, 105639. [CrossRef]
24. Garg, V.; Garg, J.M.; Bhatia, A. *Building Energy Simulation: A Workbook Using Designbuilder*, 2nd ed.; CRC Press, Taylor & Francis Group, LLC: Boca Raton, FL, USA, 2020.
25. Akpootu, D.O.; Salifu, S.I.; Idris, M.; Nouhou, I.; Kola, T.A.; Yusuf, A.; Agidi, O.E.; Aliyu, M.A. Evaluation of new developed models for estimation of diffuse solar radiation over Ikeja, Lagos State, Nigeria. *FUDMA J. Sci.* **2024**, *8*, 286–295. [CrossRef]
26. Babalola, K.Z.; Elenga, R.G.; Mushtaque, A.; Genovese, P.V.; Aborisade, M.A. Hybrid optimisation of pv/wind/bs standalone system for sustainable energy transition: Case study of Nigeria. *Energies* **2026**, *19*, 89. [CrossRef]
27. Omeje, I. Lagos Residents Spend n5.3tn Annually to Power Generators—Report. Available online: https://thewhistler.ng/lagos-residents-spend-n5-3tn-annually-to-power-generators-report/ (accessed on 31 January 2026).
28. RES4Africa Foundation; Enel Foundation; MicroEnergy International. *Access to Electricity in Urban and Peri-Urban Areas in Sub-Saharan Africa*; RES4Africa Foundation: Rome, Italy, 2025.
29. Ltd, D.S. About Us. Available online: https://designbuilder.co.uk/about-us (accessed on 30 January 2026).
30. Federal Ministry of Power, Works and Housing. *Building Energy Efficiency Guideline (Beeg)*; Federal Ministry of Power, Works and Housing: Abuja, Nigeria, 2016.
31. McKeen, P.; Fung, A. The effect of building aspect ratio on energy efficiency: A case study for multi-unit residential buildings in Canada. *Buildings* **2014**, *4*, 336–354. [CrossRef]
32. Mamun, M.A.A.; Islam, M.M.I.; Hasanuzzaman, M.; Selvaraj, J. Effect of tilt angle on the performance and electrical parameters of a pv module: Comparative indoor and outdoor experimental investigation. *Energy Built Environ.* **2022**, *3*, 278–290. [CrossRef]
33. Hafez, A.Z.; Soliman, A.; El-Metwally, K.A.; Ismail, I.M. Tilt and azimuth angles in solar energy applications—A review. *Renew. Sustain. Energy Rev.* **2017**, *77*, 147–168. [CrossRef]
34. Mamun, M.A.A.; Hasanuzzaman, M.; Selvaraj, J. Impact of tilt angle on the performance of photovoltaic modules in malaysia: A review. In Proceedings of the 4th IET International Conference on Clean Energy and Technology (CEAT 2016), Kuala Lumpur, Malaysia, 14–15 November 2016.
35. Wang, M.; Zhao, X.; Li, S.; Yang, Z.; Liu, K.; Wen, Z.; Li, Y.; Peng, J. Analysis of energy performance and load matching characteristics of various building integrated photovoltaic (bipv) systems in office building. *J. Build. Eng.* **2024**, *96*, 110313. [CrossRef]
36. Hasnain, S.; Hanak, D.; Ali, M.; Gomes, J.; Khan, K. Design, modeling and cost analysis of 8.79 mw solar photovoltaic power plant at national university of sciences and technology (nust), Islamabad, Pakistan. *Sci. Rep.* **2024**, *14*, 25351. [CrossRef]

37. Kabiri, E.; Maftouni, N. Multiple objective energy optimization of a trade center building based on genetic algorithm using ecological materials. *Sci. Rep.* **2024**, *14*, 9366. [CrossRef]
38. Jadhav, P.; Minde, P. Bim-based energy consumption analysis for residential buildings: Effects of orientation, size, and type of windows. *Discov. Civ. Eng.* **2024**, *1*, 110. [CrossRef]
39. Ye, Y.; Zhu, R.; Yan, J.; Lu, L.; Wong, M.S.; Luo, W.; Chen, M.; Zhang, F.; You, L.; Wang, Y.; et al. Planning the installation of building-integrated photovoltaic shading devices: A gis-based spatiotemporal analysis and optimization approach. *Renew. Energy* **2023**, *216*, 119084. [CrossRef]
40. Liu, R.; Liu, Z.; Xiong, W.; Zhang, L.; Zhao, C.; Yin, Y. Performance simulation and optimization of building façade photovoltaic systems under different urban building layouts. *Energy* **2024**, *288*, 129708. [CrossRef]
41. Ji, Y.; Lv, J.; Li, H.X.; Liu, Y.; Yao, F.; Liu, X.; Wang, S. Improving the performance of prefabricated houses through multi-objective optimization design. *J. Build. Eng.* **2024**, *84*, 108579. [CrossRef]
42. Agyekum, E.B.; Odoi-Yorke, F.; Abbey, A.A.; Adegboye, O.R.; Rashid, F.L. Techno-economic, social and environmental analysis of different photovoltaic cell technologies under tropical weather conditions. *Int. J. Thermofluids* **2025**, *27*, 101164. [CrossRef]
43. Sooriyaarachchi, T.M.; Tsai, I.T.; El Khatib, S.; Farid, A.M.; Mezher, T. Job creation potentials and skill requirements in, pv, csp, wind, water-to-energy and energy efficiency value chains. *Renew. Sustain. Energy Rev.* **2015**, *52*, 653–668. [CrossRef]
44. Lagos State Government. *Lagos State Electricity Law 2024*; Lagos State Government: Lagos, Nigeria, 2024.
45. Nigerian Electricity Regulatory Commission (NERC). *Electricity Act 2023: Institutional Roles and Regulatory Framework*; Nigerian Electricity Regulatory Commission: Abuja, Nigeria, 2023.
46. Federal Republic of Nigeria. *National Renewable Energy and Energy Efficiency Policy (NREEEP)*; Federal Ministry of Environment: Abuja, Nigeria, 2015.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.