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Design and Optimisation of Solar Panel Angle and Orientation for Maximum Energy Generation

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Abstract
This study focuses on the optimisation of solar panel tilt and azimuth angles to maximise photovoltaic (PV) energy generation, with Lusaka, Zambia, serving as the reference location. Solar energy potential in Zambia remains underutilised despite the country's abundant solar irradiance, primarily due to a lack of locally adapted optimisation models. In order to address this gap, the project developed and implemented a low cost, data driven system capable of simulating, analysing and optimising solar panel orientations using computational tools that were freely available.
A synthetic solar irradiance dataset covering one year of hourly data for 2024 was generated to represent the solar resource profile of Lusaka. These were used to calculate plane of array irradiance and corresponding DC and AC power outputs. Data cleaning, transformation and exploratory analysis were conducted in Python using pandas, matplotlib, and seaborn, while the system modeling and optimisation were implemented using pvlib library.
An interactive user interface was developed using Streamlit to allow users to upload their own irradiance datasets in CSV format. This design made sure that the optimisation process could be replicated across different regions with minimal configuration and no internet dependence, thereby maintaining accessibility in low resource environments. The optimisation process identified an optimal tilt angle of 15 degrees for Lusaka, which produced the highest annual energy output compared to other configurations.

Keywords: Azimuth, NASA POWER, Solar Irradiance, PV Tilt Optimisation, PV lib, PV Watts

1. Introduction

Renewable energy has become a central part of Africa's development scheme, driven by the need for cleaner and more reliable energy systems. The rapid increase in solar energy adoption across the continent reflects global concerns about climate change, environmental degradation, and the long term instability of fossil fuel based energy systems. Recent studies show that Africa has some of the World's highest solar irradiation levels, giving it exceptional potential for solar power development (Ebhota & Tabakov, 2023) [3].

Prolonged droughts, driven by climate change, have periodically reduced water levels in major reservoirs, leading to chronic load shedding that lasts up to 21 hours per day in some regions. The adoption of solar energy is especially important in countries facing electricity shortages, unreliability of grids, and limited accessibility to traditional power infrastructure. Research indicates that renewable energy technologies, in particular solar home systems and mini grids have become crucial alternatives for addressing Africa's persistent energy access gap (Moner-Girona *et al*., 2021) [6].

Despite this potential, many PV systems in Zambia deliver suboptimal performance because installation decisions especially tilt and orientation are often based on generic rules of thumb rather than local empirical data. However, despite their potential, the rollout of solar technologies is often constrained or limited by financial barriers, infrastructure limitations, and unequal access to modern energy services, especially among low income and rural households (Trotter *et al*., 2020) [10]. These inefficiencies contribute to poor user satisfaction, increased payback periods, and underutilisation of solar resources.

This study aims to close this gap by providing a structured, data-driven analysis of optimal tilt and azimuth angle configurations for Lusaka. Through the use of long-term solar data and validated PV performance models, the study presents a replicable methodology suitable for households, technicians, installers, and policymakers.

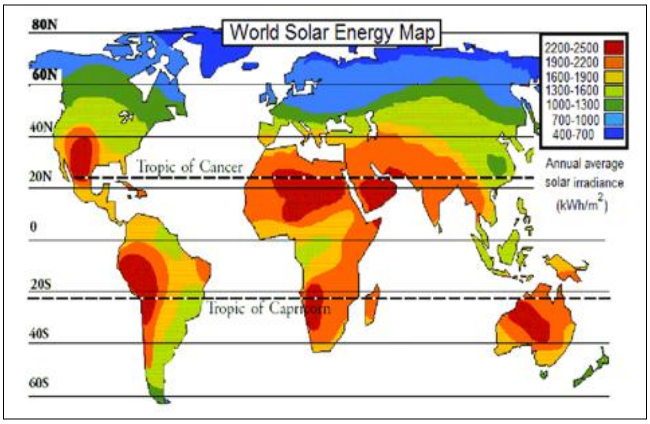

Fig 1: Showing solar irradiance potential

1.1 Background of the Study

The landscape of energy production worldwide has undergone through significant changes and transformations within the recent years, specifically with the rise of renewable energy sources as a response to increasing demand globally for sustainable and clean energy.

In many developing countries including Zambia, the adoption of solar energy has accelerated as a pragmatic response to persistent electricity supply challenges. However, this rapid deployment has often overlooked the crucial aspect of optimization, with many systems installed using standardized, non-site-specific guidelines. This results in systems that underperform, leading to substantial energy losses and a lower return on investment for end-users. This highlights a significant problem: the lack of practical, context-specific guidelines for solar panel installation in regions like Lusaka, Zambia.

Climate Change and Its Impact on Zambia's Energy Sector

Zambia's energy structure is dominated by hydroelectric power, which accounts for more than ninety of the country's electricity generation. This heavy dependence, makes the country's energy supply highly vulnerable to the impacts of climate change. Recent study shows that over the past few decades, Zambia has experienced a rise in mean yearly temperatures and a steady decrease in rainfall, leading to more frequent and severe periods without rainfall.

Technical and Empirical Background of Zambia

The theoretical optimal tilt angle for solar panels in the southern regions of the world is typically set to the local latitude to maximize yearly energy gains. However, empirical studies have shown that local climatic and environmental barriers can cause a significant move away from these general recommendations. A study on solar panels in the Zambian market found that they experience a power output drop as high as 45% when tested under local outdoor conditions, far exceeding the recommended 16.5% drop (Chiyesu, 2018) [2].

Social and Economic Barriers to Solar Utilization

Apart from policy and climate considerations, large-scale adoption of solar technology in Zambia is limited by major socioeconomic challenges. One of the major areas of challenge is the high installation cost of solar PV systems, which is still a major hurdle for most Zambian homes and microenterprises. According to a study conducted on solar adoption across Rhodes Park, Lusaka, a situation where awareness of benefits of solar energy existed for 75% of respondents, adoption remained low based on a limitation of funds. The study concluded that, of all critical challenges, high costs were principal, as indicated by respondents, where a majority of 63% saw it as a serious challenge (Kumar & Sikalumbi, 2025) [4]. That is complicated by a dearth of customized available financings, an aspect necessary for potential adopters to raise needed funds for installation purposes.

1.2 Problem of the Statement

Zambia faces a grave and long-lasting energy crisis, mainly for being itself greatly dependent on hydroelectric energy, notoriously exposed to climate change-triggered droughts.

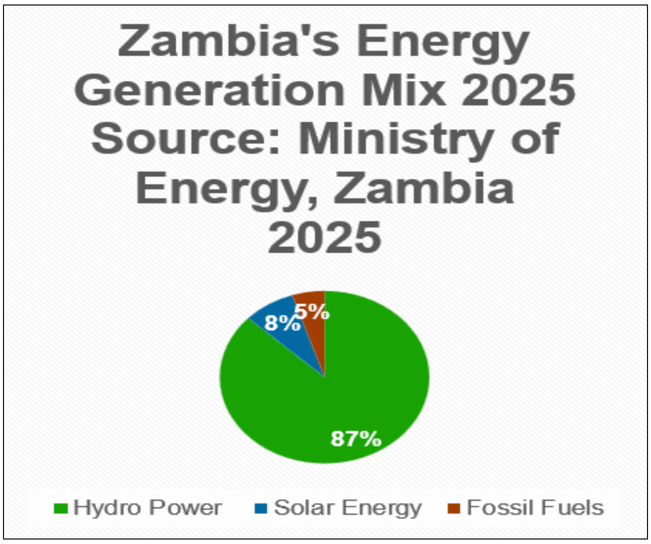

Fig 2: Showing energy generation composition as of 2025

Academic research confirms Zambia's immense solar energy potential. A study assessing the solar energy distribution found that Zambia receives an average of 2109.97 kWh/m2 of solar energy per year (Mwanza & Ulgen, 2021) [5].

While the Zambian government has actively promoted the adoption of solar photovoltaic (PV) systems as a key component of its energy diversification strategy, a critical technical and practical challenge persists. Despite a high solar irradiance potential, a significant portion of solar installations in Lusaka are not optimized for the local climatic conditions. Many installers rely on general, rule-of-thumb guidelines for panel tilt and orientation, without conducting site-specific analyses. This oversight leads to a considerable gap between a system's theoretical energy potential and its actual output, resulting in substantial energy losses.

The single annual optimum tilt sacrifices the maximum possible energy during the rainy season's lower DNI, further exacerbating the national energy deficit when hydropower dams are recovering. Research in Tanzania, a neighboring equatorial country, has shown that monthly or quarterly tilt adjustments can lead to a 5% to 11% annual energy gain compared to a fixed annual angle (Pfenninger, S. *et al.* (2021) [7], 2025). No such protocol exists for Zambia.

2. Related Work

PV tilt optimization has been extensively studied globally. The commonly used "latitude rule," which recommends tilting a PV module at an angle approximately equal to the site's latitude, provides a general estimate but often fails to consider localized climatic conditions such as dust, cloud cover, atmospheric humidity, and seasonal sun paths (Tlijani, 2025). Research conducted in North Africa, Tunisia, Indonesia, and Ecuador demonstrates that optimized angles frequently deviate from simple latitude-based assumptions (Sholihah, A. *et al*., 2025) [8].

In Sub-Saharan Africa, unique environmental constraints including high temperatures, airborne particulates, and irregular irradiance patterns, significantly influence PV performance. Empirical studies conducted in Lusaka show that module performance degrades via thermal inefficiencies and dust accumulation, causing energy losses exceeding international norms.

However, despite Zambia's rapidly growing solar market, there is little published local research providing specific installation guidelines. This study builds upon global literature while providing the first structured tilt-optimization analysis tailored to the Lusaka region.

2.1 Theoretical Foundations

This section outlines the core theoretical principles and established models that underpin this research. Providing the scientific foundation for the study's methodology, demonstrating a clear understanding of the physics and engineering concepts that govern solar energy capture and conversion. The models and theories discussed here provide a conceptual lens through which the empirical data and simulation results will be interpreted, ensuring the validity and rigor of the final conclusions.

Solar Geometry and the Sun-Path Model

Understanding how the sun moves across the sky is fundamental for optimising solar panel tilt and orientation. This field, known as solar geometry, shows why aligning panels as perpendicular to the sun as possible helps maximise energy capture. This is governed by several key astronomical and geographical angles:

i. Solar Declination Angle (δ): This is the angle between the sun's rays and the plane of the Earth's equator. It varies seasonally due to the Earth's axial tilt, ranging from $+23.45^\circ$ on the summer solstice to -23.45° on the winter solstice. This variation is a primary driver for the optimal tilt angle, especially when considering seasonal adjustments.

ii. Latitude (ϕ): The geographical latitude of the study location is a critical parameter. For Lusaka, Zambia, at approximately 15.4°S, the sun is always north of the observer, which makes a northward-facing orientation the most effective for maximum annual yield.

iii. Solar Hour Angle (ω): This angle measures the sun's position east or west of the local meridian and is a direct function of time. A zero-degree hour angle corresponds to local solar noon. This angle is essential for calculating the sun's position at any given time of day.

iv. Solar Zenith Angle (θ_z): This is the angle between the sun's rays and a vertical line (the zenith). The zenith angle is inversely related to the solar altitude and is a key parameter for calculating the amount of solar radiation that reaches the Earth's surface after passing through the atmosphere.

These angles are used to create sun-path diagrams, which are graphical representations of the sun's daily and seasonal movement across the sky for a specific location. These diagrams are indispensable tools for visually identifying the sun's position at any given time of year, helping to predict shading and to select optimal fixed or seasonally adjusted angles. A common "rule of thumb" is to set the fixed tilt equal to the latitude. However, this does not always account for local factors like dust or temperature.

Physics of Solar Irradiance and the Angle of Incidence

The power that is generated by solar panel depends on the solar irradiance received by its surface. Solar irradiance is made up of:

i. Direct Normal Irradiance (DNI): This is the sunlight that travels in a straight line from the sun to the Earth's surface. DNI is the most powerful and desired form of solar radiation for energy generation.

ii. Diffuse Horizontal Irradiance (DHI): This is the radiation that has been scattered by the atmosphere, clouds, and other particles. It comes from all directions in the sky and can still be captured by a solar panel, albeit less efficiently than DNI.

The central theoretical principle connecting a panel's orientation to its output is the Angle of Incidence (θ_i). This is the angle between the sun's rays and a line perpendicular to the surface of the solar panel. According to the cosine law, the power output of a solar panel is proportional to the cosine of this angle ($Power \propto \cos\theta_i$). Maximum power is achieved when the angle of incidence is 0°, meaning the sun's rays are perfectly perpendicular to the panel's surface.

Theoretical Models of PV System Losses

Beyond the primary factors of tilt and orientation, the performance of a solar PV system is subject to various losses that must be accounted for in a comprehensive theoretical framework. These losses are what create the significant gap between a system's ideal output and its real-world performance.

Temperature Losses: As a panel's temperature rises, its efficiency drops. In hot climates like Lusaka, modeling this effect is critical. Therefore, a theoretical model must correct for this temperature-induced efficiency drop to provide realistic energy yield estimates.

Soiling Losses: Soiling refers to the accumulation of dust, dirt, and other particles on the surface of the solar panels. This creates a physical barrier that prevents sunlight from reaching the PV cells. Soiling losses can be highly variable depending on the location and can cause a significant drop in power output, ranging from 5% to as high as 60% in very dusty conditions. While your simulation may not directly model soiling, the theoretical framework acknowledges it as a critical factor that justifies the need for local research and regular maintenance protocols. In a climate with distinct rainy and dry seasons, soiling is a significant and variable factor.

Mismatch Losses: In a solar array, multiple panels are connected in series. If one panel's performance is reduced due to soiling, shading, or a manufacturing defect, it can act as a resistor and reduce the output of the entire series string. This phenomenon, known as mismatch loss, can be significant and is a primary reason why a single shaded panel can cripple an entire array's output. The use of Maximum Power Point Tracking (MPPT) technology in inverters is a common mitigation strategy to reduce these losses.

Ohmic Losses: These are resistive losses that occur in the wiring and electrical connections of a PV system. According to Ohm's Law, the voltage drop across a circuit is proportional to the current, and power loss is proportional to the square of the current.

3. Methodology

3.1 Research Design

The study employs a computational simulation design rather than field experiments, enabling analysis of multiple tilt and azimuth scenarios across the entire year. This approach ensures greater flexibility, reproducibility, and scalability.

3.2 Data Sources

Solar irradiance and meteorological data were obtained from the **NASA POWER API**, a globally recognized dataset used for renewable energy modeling [9]. Key variables included:

- Global Horizontal Irradiance (GHI)
- Direct Normal Irradiance (DNI)
- Diffuse Horizontal Irradiance (DHI)
- Air temperature
- Solar zenith angle

These variables are required for accurately modeling PV performance as they influence the energy received by the panel and the system's thermal efficiency.

3.3 Simulation Tool (PVWatts)

The **NREL PVWatts v8** model was selected due to its reliability, widespread academic adoption, and suitability for fixed-tilt systems [10]. The system modeled was a standard 1-kW crystalline silicon PV array. The following parameters were varied:

- Tilt angle: 0° to 90°
- Azimuth: −90° (east), 0° (north), +90° (west)
- System losses: 14% (default), with sensitivity runs at 20–25% to reflect Lusaka's dust conditions

3.4 Data Processing Tools

Analysis was conducted using Python:

- **Pandas** for dataset processing
- **NumPy** for mathematical operations
- **Matplotlib** for visualizing irradiance and performance curves
- **Jupyter Notebook** for code reproducibility and exploratory analysis

These tools enabled creation of energy-tilt response curves and seasonal performance plots.

3.5 Optimisation Strategy

Three optimization procedures were conducted:

1. Annual Optimization

Determine the tilt angle that maximizes yearly energy generation.

2. Seasonal Optimization

Identify optimal angles for dry and rainy seasons to examine whether adjustment improves performance.

3. Azimuth Sensitivity Analysis

Evaluate energy losses associated with east- and west-facing misalignment.

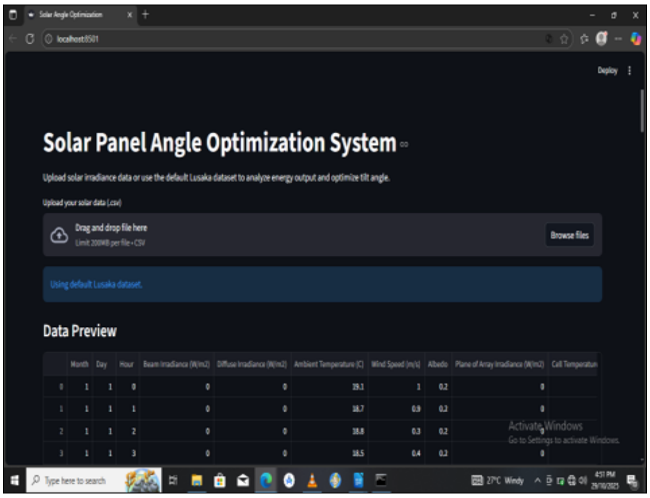

Fig 3: Streamlit User Interface for region based simulation

4. Results and Discussion

Tilt and Azimuth Optimisation Results

Configuration	Tilt Angle (°)	Azimuth Angle (°)	Annual AC Energy (kWh)	Improvement (%)
Default	0	180	6,820	-
Optimised	15	180	7,268	+6.6

Analysis revealed that energy Output increases as tilt is adjusted closer to the position's latitude angle (approximately 15° for Lusaka). Panels installed horizontally captured less direct irradiance, while those tilted between 10° and 20° obtained higher total annual energy yield.

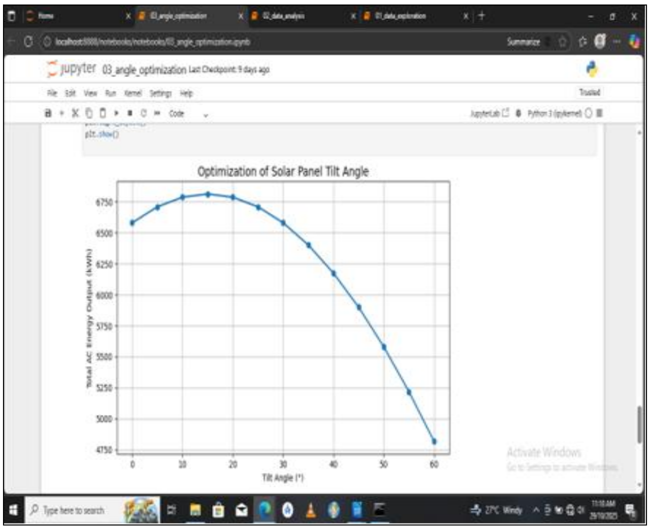

Fig 4: Plot of AC energy output in Kw/h versus titlt angle from the system

4.1 Annual Energy Optimization

Analysis revealed that the maximum annual output occurs at a tilt angle of:

15° Facing True North

This value aligns closely with Lusaka's latitude (≈15.4°S), yet is slightly lower due to:

- High yearly solar elevation
- Strong direct irradiance component
- Reduced effectiveness of steeper angles in low-latitude regions
- Temperature effects reducing panel efficiency at higher tilt angles

The energy-tilt response curve exhibited a clear global maximum at 15°, confirming this angle as optimal for fixed installations.

4.2 Seasonal Optimisation

Lusaka's climate is divided into:

- **Dry Season (May–October):** high DNI, higher dust, higher temperatures
- **Rainy Season (November–April):** greater cloud cover, higher diffuse radiation, lower temperatures

Simulations showed:

- **Dry Season Optimum: 18°–20°**
- **Rainy Season Optimum: 10°–12°**

Implementing a two-angle system (20° dry, 10° rainy) improves annual output by:

5–8% compared to a single fixed angle.

This improvement is significant for small household systems, often ranging from 1–3 kW.

4.3 Azimuth Misalignment Sensitivity

North-facing panels performed best, while misalignment resulted in noticeable losses:

- East-facing: **12% annual reduction**
- West-facing: **10% reduction**
- South-facing: **>35% reduction** (unusable in southern hemisphere)

These findings confirm that installers should carefully align modules to true north to maximize yield.

5. Conclusion and Recommendations

The study was divided into three main objectives which were developing a solar irradiance dataset for the target location, modeling solar position and energy output for static angles and calculating the optimal tilt and azimuth angles for maximum energy generation. Each objective contributed progressively to the building of a functioning optimisation system that transforms environmental data into actionable design insights.

In addressing objective 1, the research successfully developed a comprehensive solar irradiance dataset for Lusaka using a combination of radiation data that was available, weather variables and modeled estimates. The dataset included important parameters such as beam irradiance, diffuse irradiance, ambient temperature, albedo, wind speed, plane of array irradiance and the resulting DC and AC power outputs. Data cleaning, validation as well as resampling were carried out to ensure consistency and accuracy, producing a processed dataset suitable for analysis. The resulting data revealed a consistent seasonal change in solar irradiance, with higher energy availability between August and November and lower levels during the rainy months.

As for objective 2, the study modeled solar position and energy output based on static tilt and azimuth configurations. The static model provided an initial baseline for system evaluation, allowing the research to quantify daily and monthly energy generation patterns. The analysis showed us that even under fixed conditions, solar panels in Lusaka can achieve significant energy yields, though efficiency varies across the year due to changing sun angles and weather patterns. Visualisation of this data through daily and monthly energy plots confirmed the expected patterns and provided an essential foundation for optimisation.

The final and most significant step, Objective 3 involved optimisation of the solar tilt and azimuth angles to achieve maximum annual energy output. Through calculations that were done in an iterative manner and performance evaluation, the study identified a tilt angle that yielded the highest total energy generation for the given dataset. Although the observed percentage improvement over the baseline appeared minimal, this finding itself was meaningful, it demonstrated that the initial dataset and installation orientation were already well positioned with the site's optimal solar installation standards while providing a scalable methodology that could be extended to other regions for comparative analysis.

This study provides a structured, locally relevant guideline for optimizing PV panel tilt and orientation in Lusaka, Zambia. Using NASA POWER data and the PVWatts simulation tool, it identifies a fixed annual tilt angle of 15° facing true north as the most effective configuration. Seasonal adjustments can further increase performance by up to 8%, representing an accessible and low-cost strategy for improving energy output. In a country facing ongoing hydropower shortages, these findings support improved installation standards and greater reliability of distributed solar systems. Future work should include field validation, expanded modeling across other provinces, and exploration of tracking systems.

The project successfully implemented a functional solar panel angle optimization system

For permanent installations the gains in energy output justify the initial cost

Future recommendations can incorporate a live weather API to adjust the panel angle on cloudy days or to slow them down during hail storms

Run the system for a full year to gather seasonal data and refine the angle adjustment

Implement an ML algorithm that learns from historical power output data to find local optimals.

6. Acknowledgment

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