Simulation-Based Analysis of Energy Optimization in Solar Tracking Using SunCalc, NASA POWER Data Access Viewer, and PVsyst

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***Abstract*— This study focuses on designing and formulating a dual-axis solar tracking system that integrates such as SunCalc algorithm, NASA POWER meteorological data, and PVsyst simulation software to optimize solar energy capture. Solar tracking technology improves the efficiency and energy yield of photovoltaic (PV) systems by continuously adjusting panel orientation to follow the Sun's trajectory, significantly increasing energy absorption. Dual-axis solar tracking systems can enhance energy output to 30-40% compared to fixed-panel systems, making them increasingly popular in both residential and and commercial solar installations. Computational solar tracking systems employing astronomical algorithms overcome limitations of sensor-based systems by eliminating the need for physical sensors and reducing mechanical wear. This study aims to enhance solar energy efficiency, reduce carbon emissions, and provide a cost-effective solution for large-scale solar energy applications.**

***Keywords*— Carbon Emission, Dual-Axis Solar Tracking, Energy Efficiency, Photovoltaic Systems, Simulation**

I. INTRODUC TION

The global shift towards sustainable energy solutions has intensified research and development efforts in renewable energy technologies. Among these, solar power stands out as minimal environmental impact, and long-term economic benefits [4]. However, traditional fixed solar panel systems suffer from inefficiencies as they do not adjust to the Sun's movement, leading to suboptimal energy capture [5]. This limitation underscores the need for solar tracking systems, which dynamically reorient panels to maximize solar exposure throughout the day. Solar tracking technology improves the efficiency and energy yield of photovoltaic (PV) systems by continuously adjusting panel orientation to follow the Sun's trajectory, significantly increasing energy absorption [8]. Dual-axis solar tracking systems can enhance energy output by 30-40% compared to fixed-panel systems [3], making them increasingly popular in both residential and commercial solar installations. The rising dependence on fossil fuels has caused environmental issues such as greenhouse gas emissions, resource depletion, and air pollution [6].

Solar energy provides a clean and renewable alternative that addresses these concerns. Governments worldwide have promoted solar adoption through incentives and policies aimed at reducing reliance on non-renewable sources [7]. Despite its promise, solar energy transition faces challenges, notably the low efficiency of fixed panels that are installed at fixed tilt angles and thus cannot adjust to the Sun's changing position [7]. Renewable energy, particularly solar, is crucial for energy security and environmental sustainability [5]. Efficient solar tracking systems are pivotal to this transition. Dual-axis trackers offer cost-effective means to maximize energy generation by maintaining optimal sunlight exposure regardless of seasonal or geographic variations [1]. However, conventional sensor- based tracking systems face challenges including environmental interference, mechanical wear, and high maintenance costs due to their reliance on physical sensors such as light-dependent resistors (LDRs) [16]. To overcome these limitations, computational solar tracking systems employing astronomical algorithms have been proposed. These systems calculate the sun's position based on geographic location, time, and date, eliminating the need for physical sensors and reducing mechanical wear [13]. This study focuses on designing and simulating a dual-axis solar tracking system that integrates the SunCalc algorithm, NASA POWER meteorological data, and PVsyst simulation software to optimize solar energy capture. The efficiency of solar energy systems depends on solar radiation, which varies with the Sun's position throughout the day and seasons. Fixed systems cannot capture maximum radiation at all times, resulting in energy loss [5]. Large-scale solar farms benefit significantly from tracking systems, with potential annual energy yield increases up to 40% compared to fixed systems [3]. Solar tracking mechanisms are broadly categorized into single-axis and dual-axis systems. Single-axis trackers adjust panels along one axis, while dual-axis trackers allow movement along both azimuth and elevation axes, ensuring optimal alignment with the Sun's position [1],[2]. The latter is particularly advantageous in regions with significant seasonal solar angle variation. Sensor-based tracking systems face drawbacks including susceptibility to environmental factors such as dust and cloud cover, sensor degradation, and mechanical stress from continuous movement, leading to higher maintenance costs and energy consumption [12]. Computational tracking systems provide a more reliable and efficient alternative by using solar positioning algorithms to direct panel orientation without physical sensors [13]. This research develops and simulates a dual-axis solar tracker using computational techniques and integrates SunCalc, NASA POWER data, and PVsyst software to evaluate its performance. The study aims to enhance solar energy efficiency, reduce carbon emissions, and provide a cost-effective solution for large-scale solar energy applications.

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II. METHODOLOGY

A. Research Environment

The experiment is conducted at Cebu Technological University – Danao Campus (Oval), located at G23J+6P7, Poblacion, Danao City, 6004 Cebu. This location offers optimal sunlight exposure, making it suitable for efficiently capturing solar energy and for obtaining reliable data in evaluating the performance of the dual-axis solar tracker. The site was selected due to its high potential for energy yield, as it provides a spacious, unobstructed area with no nearby buildings or large trees that may cause shading—making it an ideal location for simulation.

Fig. 1. Map of Cebu Technological University – Danao Campus within Sabang, Danao City, Cebu.

B. Data Collection

Using reliable open-source platforms such as SunCalc and the NASA POWER Data Access Viewer, the researchers will collect hourly data on solar position, irradiance, and ambient environmental conditions. From the SunCalc platform, solar position data—including the movement of the sun's path—will be obtained using azimuth and declination angle calculations. Meanwhile, the NASA POWER Data Access Viewer will be used to gather key meteorological parameters such as Global Horizontal Irradiance (GHI), Ambient Temperature, and Diffuse Horizontal Irradiance (DHI).

C. PV System Configuration in PVsyst

Two PV system configurations are modeled and simulated using the same dataset parameters, including PV module type and specifications, inverter model, system capacity (in kWp), site location, time, and terrain, to ensure fair and accurate comparison of the two configurations.

1. Fixed PV System: Oriented at an optimal tilt angle based on the site's latitude.
2. Dual Axis Solar Tracking System: Continuously adjusts both azimuth and elevation to maintain perpendicular alignment with the sun.

D. Derived Parameters and Supporting Calculations

The section presents the standard formulas used to compute key solar and environmental parameters, which were obtained from SunCalc and NASA POWER Data Access Viewer. Including these formulas ensures transparency in how the data were generated and provides a basis for understanding how each value is determined within the simulation. Parameters such as solar declination, solar azimuth angle, global horizontal irradiance (GHI), and ambient temperature adjustments follow established solar energy and meteorological models.

Azimuth Angle

$$Az = tan^{-1}\left(\frac{-\sin h}{\cos(h)\cdot \sin\emptyset - \tan\delta\cdot\cos\emptyset}\right) \quad \text{Eq. 1}$$

Where:

□: Hour angle (in radians), calculated as:

□ = 15° × (Local Solar Time − 12)

$\emptyset$: Latitude of the observer (in radians)

δ: Solar declination (in radians)

Declination angle

$$\delta = 23.45 \cdot \sin\left(\frac{360}{365}\cdot(N-81)\right) \quad \text{Eq. 2}$$

N is the day of the year (ex: January 1 = 1, December 31 = 365).

Global Horizontal Irradiance

$$GHI = DHI + DNI \cdot cos(\theta z); \quad \text{Eq. 3}$$
$$where: cos(\theta z) = sin(\alpha)$$

DHI = Diffuse Horizontal Irradiance

DNI = Direct Normal Irradiance

α = solar altitude angle

Diffuse Horizontal Irradiance

$$DHI = GHI \cdot \left(\frac{DHI}{GHI}\right) \quad \text{Eq. 4}$$

DHI = Diffuse Horizontal Irradiance

GHI = global Horizontal Irradiance

Ambient Temperature (°C)

$$T(t) = Tmin + (Tmax - Tmin)\cdot sin\left(\frac{\Pi(t - t_{sunrise})}{t_{sunset} - t_{sunrise}}\right) \quad \text{Eq. 5}$$

T(t) = Ambient temperature at time **t**

T*min* = minimum daily temperature

T*max* = maximum daily temperature

t = time of the day (in hours)

$t_{sunrise}$ = time of sunrise

t_{sunset} = time of sunset

Specific Yield

$$Specific\ Yield = PE \times El \times TA \times T \quad \text{Eq. 6}$$

PE= Panel efficiency

EI= Effective irradiance on panel

TA= Temperature adjustment factor

T = Time duration (hours)

$$Improvement(\%) = \frac{Y_{tracker} - Y_{fixed}}{Y_{fixed}} \times 100 \quad \text{Eq. 7}$$

Performance Ratio

$$PR = \frac{Y_f}{Y_r}; Where: Y_r = \frac{H_{POA}}{G_{STC}} \quad \text{Eq. 8}$$

Y_f = Final yield
Y_r = Reference yield
H_{POA} = Irradiance in the plane of array (kWh/m^2)
G_{STC} = Standard irradiance under STC (1000 W/m^2)

Carbon Emission

$$CO_2\ Reduction(kg) = E_{AC} \times EF \qquad \text{Eq. 9}$$

E_{AC} = Total AC energy output (kWh)

$EF = Emission\ factor\ (kg\ CO_2/Kwh)$

E. Flowchart

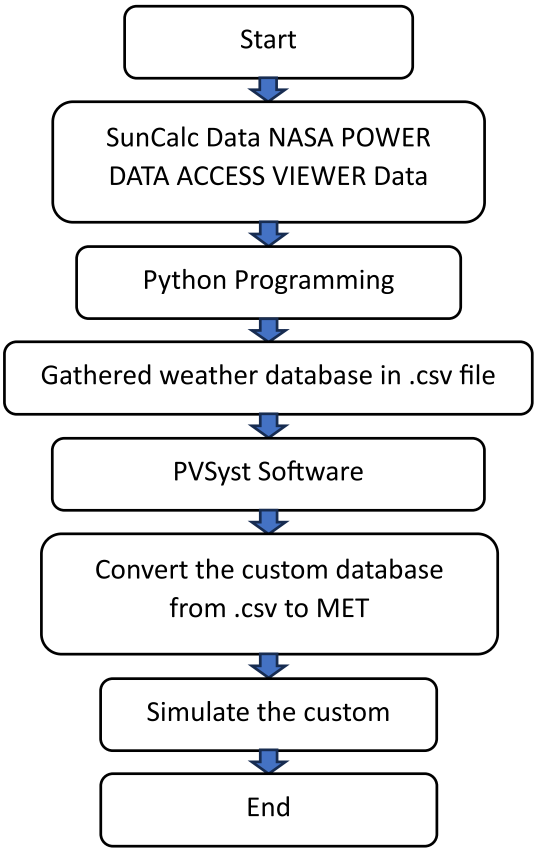

Fig. 2. Flowchart

F. Systems and Specifications:

TABLE I: PV MODULE CHARACTERISTICS

Manufacturer	Trina Solar
Model	TSM-DE-19-550Wp Vertex
Unit Nominal Power	550Wp
Number of PV Modules	11.00 KWp
Modules	1 strings x 20 In series
Pmpp	10.06 kWp
U mpp	573 V
I mpp	18 A
Total PV Power	
Nominal (STC)	11 kWp
Total	20 modules
Module area	52.3 m^2

TABLE II: INVERTER CHARACTERISTICS

Manufacturer	Growatt New Energy
Model	MOD 11KTL3-X
Unit Nominal Power	11.0 kWac
Number of inverters	1 unit
Total power	11.0 kWac
Operating Voltage	140-1000 V
Pnom Ratio (DC:AC)	1
Total inverter power	
Total power	11 KWac
Number of Inverters	1 unit

TABLE III: MODEL DIMENSIONS

Length:	2384 mm	2.384 m
Width:	1096 mm	1.096 m
Height (Depth):	35 mm	0.035 m
Weight: 28.6 kg		
Volume: (L x W x H)		0.0914 cubic meters
Density	28.6 kg /0.0914 m^3	313kg/m^3

III. ANALYSIS AND INTERPRETATION OF DATA

A. Key Outcomes from the Monthly Database (July 1, 2023-July 1, 2024)

TABLE IV: *KEY OUTCOMES FROM THE MONTHLY DATABASE (JULY 1, 2023-JULY 1, 2024)*

	GlobHorr kwh/m²	DiffHorr kwh/m²	T_Amb °C	GlobInc kwh/m²	GlobEff kwh/m²	EArray kWh	E_Grid kWh	PR
July.23	217.8	86.2	27.75	272.3	272.1	2438	2401	0.802
Aug. 23	220.7	80.55	27.79	283	282.9	2450	2412	0.775
Sep. 23	209.8	81.42	27.93	274.3	274.3	2324	2288	0.758
Oct. 23	207.1	68.35	27.98	288.2	288.1	2394	2358	0.744
Nov. 23	187	53.97	27.65	287.7	287.7	2366	2330	0.736
Dec. 23	182.9	57.35	27.19	293.2	293.2	2425	2388	0.74
Jan.24	188.8	64.55	26.52	290.5	290.5	2408	2370	0.742
Feb. 24	196.2	59.75	26.66	288.8	288.7	2329	2293	0.722
Mar. 24	226.8	59.83	27.93	315.9	315.9	2522	2483	0.715
Apr. 24	225.3	60.92	29.66	300.3	300.2	2430	2393	0.724
24-May	227.7	70.17	30.45	292.5	292.3	2481	2442	0.759
24-Jun	212.2	80.89	29	264.7	264.5	2361	2324	0.798
Year	2502.3	823.95	28.04	3451.3	3450.4	28928	28482	0.75

Legends:

GlobHor – Global Horizontal Irradiation
DiffHor – Horizontal Diffure Irradiation
T_Amb – Ambient Temperature
GlobInc – Global Incident in Collector Plane
E_Grid – Energy Injected into the Grid
PR – Performance Ratio
GlobEff – Effective Global Irradiation, corrected for IAM and shadings

B. Produced Energy of Dual-Axis Solar Tracking Systems vs, Fixed PV Systems

TABLE V: RESULT OF PRODUCED ENERGY IN KWH/YEAR

Photovoltaic (PV) System	Produced Energy in kWh/year
dual-axis solar tracking systems	**28,482**
Fixed PV systems	**21,781**

The significant increase in energy output is due to the dual-axis tracker's ability to follow the sun's position dynamically throughout the day and year, maintaining optimal solar incidence on the PV modules. Conversely, fixed PV panels are limited to a single tilt and azimuth, resulting in less solar exposure during non-optimal hours. This finding aligns with [15], who reported a 30-40% improvement in specific yield for dual-axis systems versus fixed systems globally. The dual-axis trackers enhance direct and diffuse radiation capture, especially during mornings and evenings, where fixed systems underperform [10].

C. Performance Ratio (PR) of Dual-Axis Solar Tracking vs. Fixed PV Systems

TABLE VI: RESULTS OF PERFORMANCE RATIO

Photovoltaic (PV) System	Performance Ratio (PR)
dual-axis solar tracking systems	**75.02%**
Fixed PV systems	**78.07%**

The fixed PV system had a higher PR (78.07%) than the dual-axis system (75.02%), suggesting better use of installed capacity and representing a 3.05% difference. The Performance Ratio (PR) reflects the overall system losses relative to the theoretical energy output under standard test conditions, including thermal losses, inverter inefficiencies, wiring losses, and auxiliary consumption. The slightly lower PR in the dual-axis system is due to tracking motor energy use and mechanical inefficiencies [11], [15]. However, its higher energy yield outweighs these losses. The total energy output and site conditions are more important than PR alone [10].

D. Saved CO2 Emissions of Dual-Axis Solar Tracking vs. Fixed PV Systems

TABLE VII: RESULTS OF SAVED CO_2 EMISSIONS

Photovoltaic (PV) System	Total Saved Emission in tCO_2
dual-axis solar tracking systems	**333.5**
Fixed PV systems	**249.8**

Dual-axis tracking systems reduced CO_2 emissions by about 33.4% more than PV systems due to higher energy generation displacing more fossil-fuel use. Studies support this: noted improved emissions tracking [9]; highlighted greater efficiency in hot climates, reducing grid dependence [14].

IV. CONCLUSION

A. Summary of Findings

The findings of this study indicate that dual-axis solar king systems significantly outperform fixed photovoltaic systems in terms of energy generation and environmental act under comparable conditions. The dual-axis system aced an annual energy output of 28,482 kWh, representing 71% increase over the fixed system's 21,781 kWh. While fixed system exhibited a marginally higher performance (78.07%) compared to the dual-axis system (75.02%), this difference is primarily attributed to the energy consumption and mechanical losses associated with the tracking components. Nonetheless, the enhanced energy yield of the dual-axis system effectively offsets these losses. Furthermore, the dual-axis system achieved a 33.4% greater reduction in CO: emissions, totaling 333.5 tons, compared to 249.8 tons from the fixed system. This demonstrates its superior effectiveness in reducing carbon emissions. The improved capture of solar irradiance and increased conversion efficiency further affirm the dual-axis system's overall enhanced performance, despite minor thermal and inverter-related losses.

B. Conclusions

The results affirm that dual-axis solar tracking technology optimizes solar energy capture by continuously aligning panels with the sun's movement, thereby maximizing daily and seasonal energy yield. Despite slightly lower performance ratios caused by the tracking system's energy use and maintenance demands, the substantial increase in net energy output and CO: savings makes dual-axis tracking a more effective and sustainable option than fixed PV systems. These findings support existing research and underscore the potential of dual-axis trackers to improve renewable energy generation, especially in regions with high solar potential and variable sunlight angles.

C. Recommendations

1. Consider Operational Costs and Maintenance by performing detailed cost-benefit analyses, as the tracking mechanisms require additional energy and upkeep that affect overall efficiency and economics.
2. Future research and development should prioritize enhancing the efficiency of dual-axis tracking systems by reducing the energy consumption of tracking mechanisms and addressing the mechanical inefficiencies.
3. Adopt Dual-Axis Tracking Systems where maximizing solar energy output and environmental impact is a priority, given their proven 30.71% increase in energy yield and significant CO_2 reduction.

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