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Determining the optimal orientation for solar panels – a comparison amongst selected software

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Abstract
The angle of tilt between solar panels and the horizontal plane determines the amount of solar radiation falling on the panel. Therefore, selecting an optimal tilt angle is essential to maximize captured solar irradiance. Due to the complexity and cost of solar tracking systems, it is often preferable for panels to be installed at a fixed tilt angle especially for large array of panels. In this work, the optimal tilt angle for a 600kW solar system is investigated using Okorobo-Ile town, Andoni Local Government Area of Rivers State (Latitude/Longitude: 4.47N, 7.54E) as a case study. The software used for this investigation are: Photovoltaic Geographic Information System (PVgis), Renewable Energy and Energy Efficiency Technology Screening Software (Retscreen), Photovoltaic System (PVsyst) and Hybrid Optimization of Multiple Energy Resources (Homer). The results show that all the software yield a tilt angle of 8°, while the azimuth angles range from 0° to 41°. Among the software reviewed, PVGIS demonstrated the highest ease of use and the fastest response time for determining optimal angles.

Keywords: Optimal tilt, orientation, software, solar panels, homer

1. Introduction

The generation efficiency of PV-based generating units is primarily influenced by the amount of solar radiation incident on PV panels (Akhlaghi et al., 2017). Solar radiation magnitude incident on panels depends on two critical factors: the direction and tilt angle of the panels. The optimal tilt angle varies based on the sun's position relative to Earth, changing daily, monthly, and yearly. Furthermore, the optimal angle is location-specific, making it essential to maintain an optimal tilt angle throughout the year to maximize energy generation. For determining the optimal tilt angle of a specific area, latitude, climate conditions, solar radiation characteristics, and utilization period play pivotal roles (Akhlaghi et al., 2017). In solar energy harvesting systems, azimuth orientation typically follows a basic rule: in the Northern Hemisphere, panels oriented south have an azimuth angle of 0°, while in the Southern Hemisphere, panels oriented north have an azimuth angle of 180°. The inclination maximizing received solar energy is the optimal tilt angle, influenced by factors such as the day of the year, cloud cover, altitude, and site latitude (Nabila et al., 2017; Mark and Vijaysinh, 2018; Ukoima, 2025c). As such, determining the optimal orientation (tilt and azimuth angle) of photovoltaic systems remains a complex task.

While several studies have proposed mathematical models for calculating optimal tilt angles based on the sun’s geometry, including works by Anthony et al. (2022) and Ahunim et al. (2022), these models often simplify real-world factors. Some studies, such as Kallioğlu et al. (2020) and Hassan et al. (2021), have demonstrated location-specific variations in optimal tilt and azimuth angles, highlighting the need for robust tools that integrate seasonal and geographic influences. Despite these advancements, the practical application of these models often necessitates specialized software for accurate determination of optimal orientation. Tools like PVWatts (NREL, 2017), PVGIS, RETSCREEN, PVSYST, and HOMER are increasingly utilized for this purpose. However, a direct comparison of their performance, usability, and computational efficiency remains underexplored.

This study is novel in its comparative evaluation of four widely used software tools—PVgis, Retscreen, PVsyst, and Homer—in determining optimal tilt and azimuth angles for PV panels. By investigating their simplicity, response time, and resulting outputs, this work bridges a critical gap in the literature, offering practical insights for researchers and system designers. Unlike previous studies that focus solely on mathematical models or individual tools, this research provides a comprehensive assessment of software performance for Okorobo-Ile, Rivers State, Nigeria. The findings aim to guide the selection of appropriate tools based on project-specific needs and constraints.

However, this study is not without limitations. Only one geographic location was evaluated, potentially limiting the generalizability of the findings. Additionally, the analysis relies on built-in solar radiation databases within the software, which may vary in accuracy and resolution across different regions. Despite these constraints, the results contribute to optimizing PV system performance and advancing the practical application of solar energy technologies.

2. Materials and method

2.1. Site of study

The study area is named Okorobo-Ile in Andoni Local Government Area of Rivers State, Nigeria. It is located at 4.47N and 7.54E.

2.2 Data

Data was obtained from the solar radiation data was obtained from resources within the software under review.

2.3 Software

2.3.1 PVsyst

Tilt optimization in PVsyst can be performed in any of three ways:

1. From the preliminary or new design tab, as illustrated in Figure 1.
2. From the transposition factor tab within the tools menu, as shown in Figure 2. The Transposition Factor (TF) is the ratio of the incident irradiation (GlobInc) on the panel to the horizontal irradiation (GlobHor), indicating gains or losses from tilting the panel. An optimal TF value is typically ≥ 1. Both approaches involve manual optimization, where various tilt angles are input manually, and the energy output effects are displayed graphically.
3. Using the optimization tool, as demonstrated in Figures 3 and 4. Here, a range of tilt angles and step sizes is defined, and the software conducts automatic optimization. The process duration ranges from a few minutes to several minutes, depending on the range and step size specified.

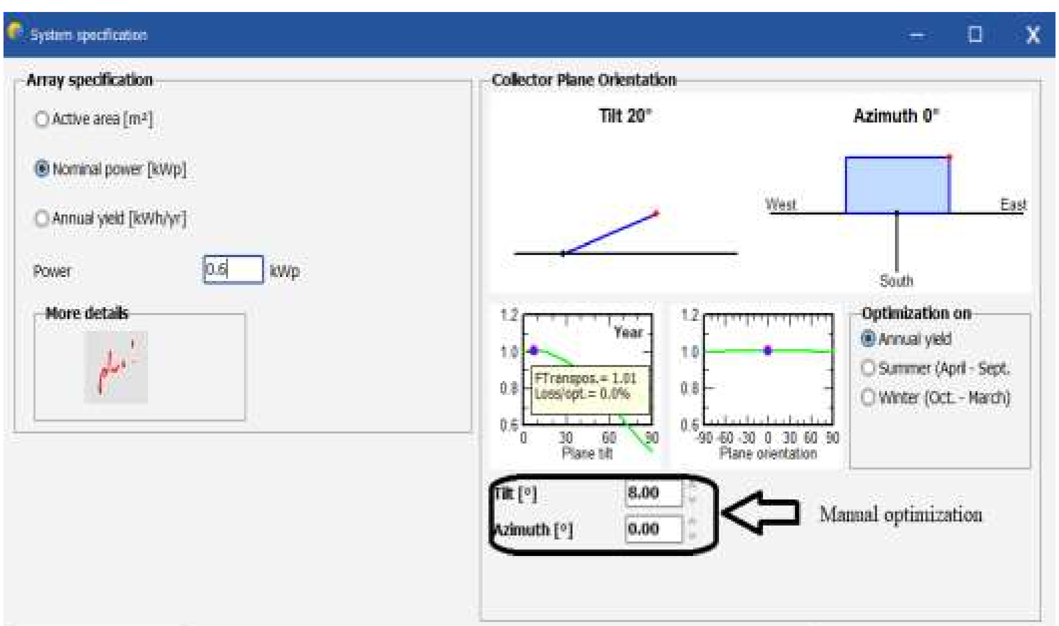

Figure 1: System specification in preliminary design tab

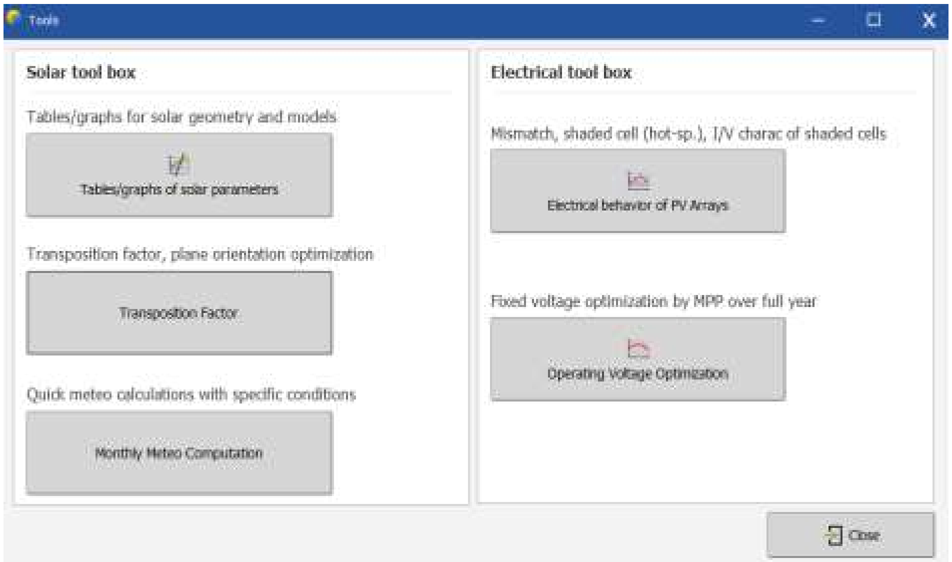

Figure 2: Transposition factor tab in PVsyst

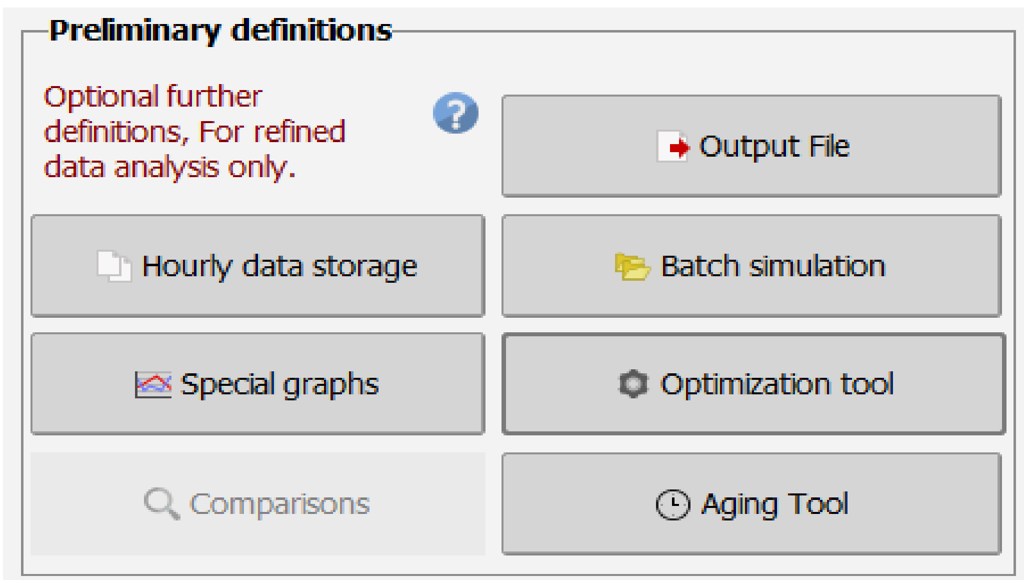

Figure 3: Automatic optimization tool

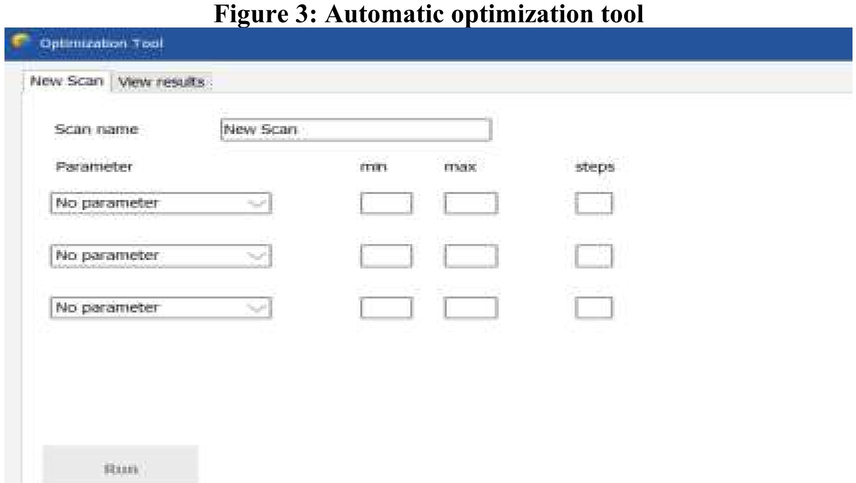

Figure 4: Range and step sizes input in the optimization tool

2.3.2 PVgis

PVgis provides a means of accessing the solar energy resources and electricity generation from photovoltaic systems via maps. Here, the performance of a photovoltaic system in the area under investigation can be estimated for any geographical location. Combined with a system for accessing the data interactively via the Internet, the results are made available for interested users. Optimal panel orientation can be determined by selecting either "Optimize Slope" for tilt angle alone or "Optimize Slope and Azimuth" for both tilt and azimuth angles, as shown in Figure 5.

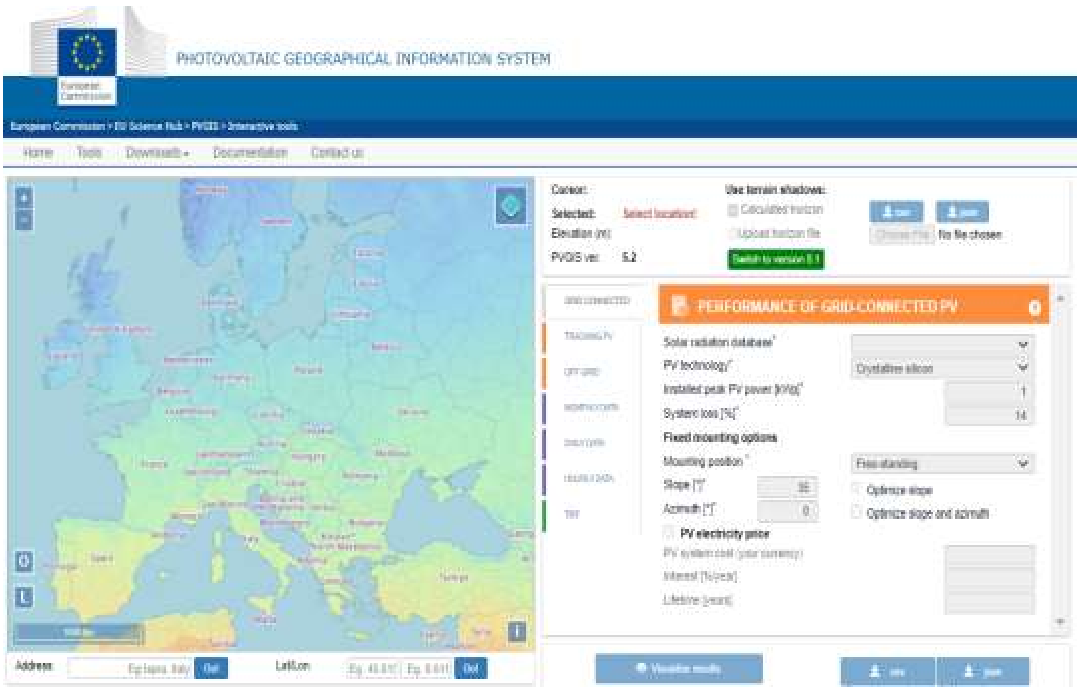

Figure 5: Snapshot of PVgis

2.3.3 Retscreen

Retscreen utilizes manual optimization, akin to PVsyst, where different tilt angles are input manually. The resultant energy output is displayed in tabular form, as illustrated in Figure 6.

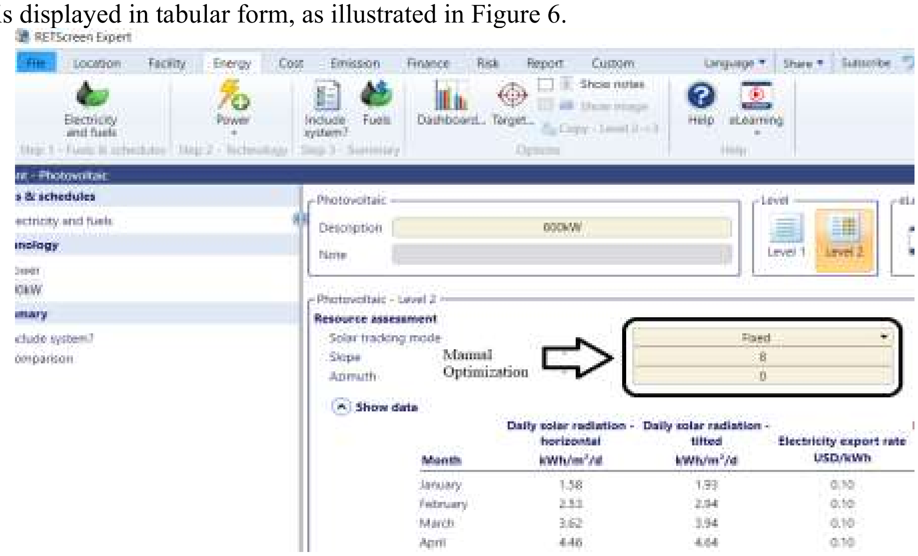

Figure 6: Retscreen software

2.3.4 Homer

Homer uses sensitivity analysis to optimize tilt and azimuth angles, as shown in Figure 7. Users specify a range of values for tilt and azimuth angles in the sensitivity analysis section, and Homer calculates optimal orientations upon simulation. A summary of the optimization process of the considered software is presented in Table 1.

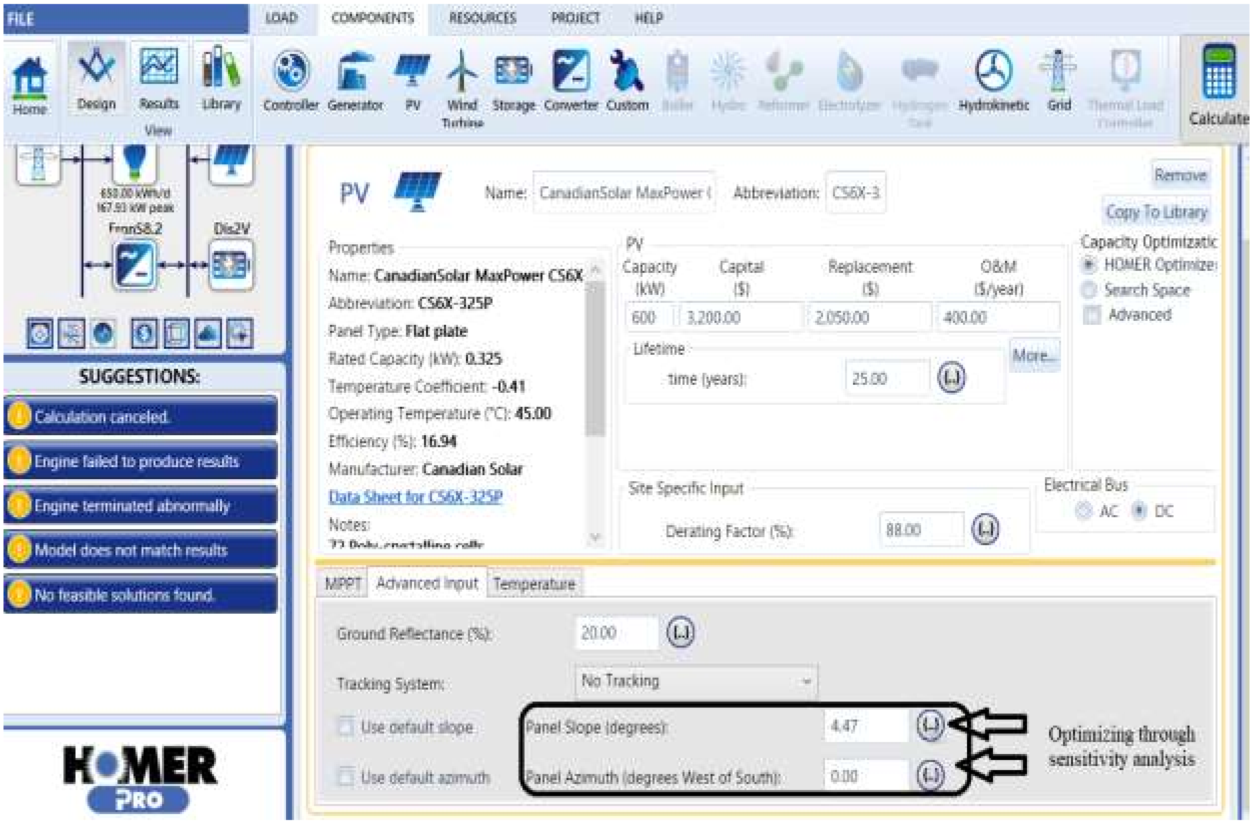

Figure 7: A snapshot of homer software

Table 1: Summary of the optimization process

Software	Optimization method	Ease of use	Time required
PVsyst	Manual (Preliminary Design Tab or Transposition Factor Tab) and Automatic (Optimization Tool)	Moderate - Manual setup for two methods; Automatic tool requires input ranges.	Varies: Few minutes to several minutes depending on range and step size.
PVgis	Automatic (Optimize Slope/Optimize Slope and Azimuth)	High - User-friendly interface; intuitive options.	Quick - Highly responsive.
Retscreen	Manual (Input tilt angles and observe tabular outputs)	Low - Extensive manual entry required.	Quick - Responsive once values are entered.
Homer	Automatic (Sensitivity Analysis with range input for tilt and azimuth)	High - Intuitive for sensitivity analysis setup.	Varies - Depends on range and simulation complexity.

3. Results

3.1 Result from Retscreen

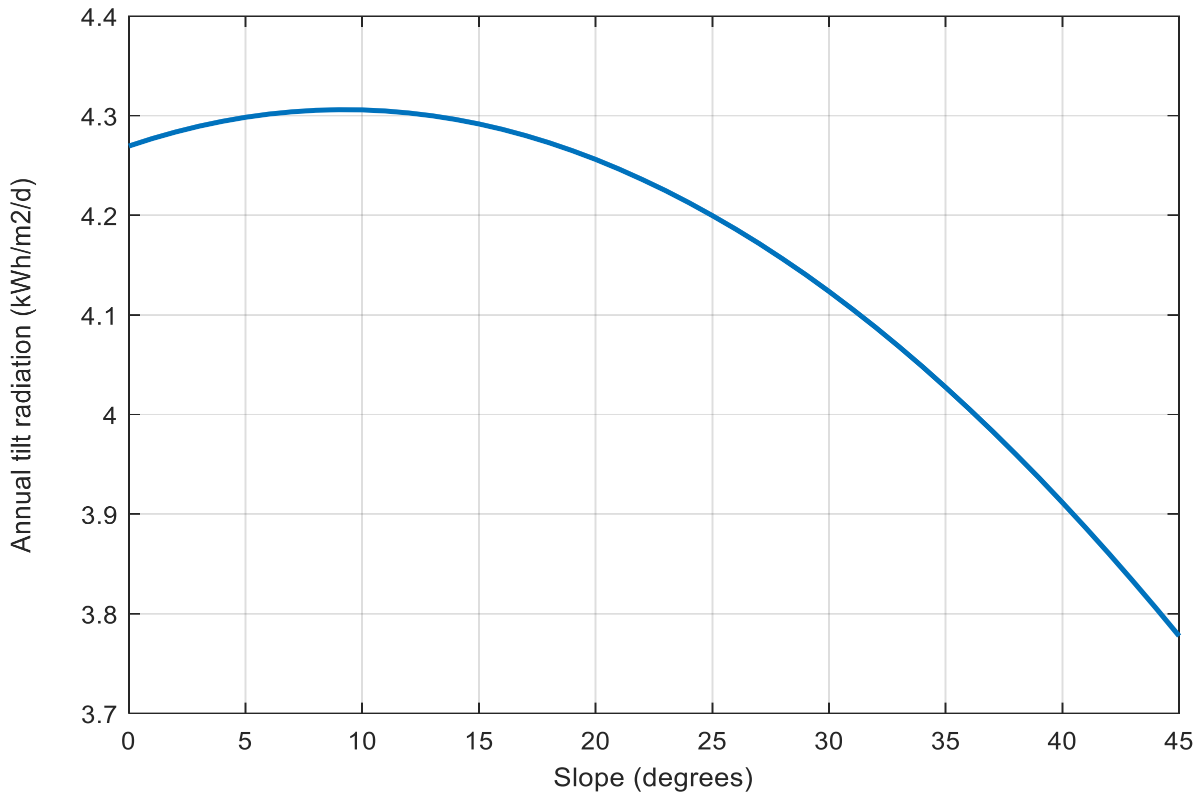

Figure 8: Optimal tilt angle at 0° azimuth for Andoni LGA in Retscreen

In Figure 8, the curve peaks at 8°, indicating this is the optimal tilt angle for capturing the maximum solar irradiance.

3.2 Result from PVsyst

Table 2: Yearly transposition factors and Losses with respect to the optimal tilt in PVsyst from method 1 (preliminary or new design tab)

Tilt	Ftrans	Loss/opt
0 – 4	1	0%
5-9	1.1	0%
10-14	1	0%
15	1	-0.1%
16	1	-0.3%
17	1	-0.5%
18	0.99	-0.7%
19	0.99	-1%
20	0.99	-1.2%

Table 2 shows that for tilt angles between 5° and 9°, the transposition factor peaks at 1.1, with no associated losses (0% Loss/opt). This indicates maximum efficiency in harnessing solar energy, showing the optimal tilt angle range lies within this interval.

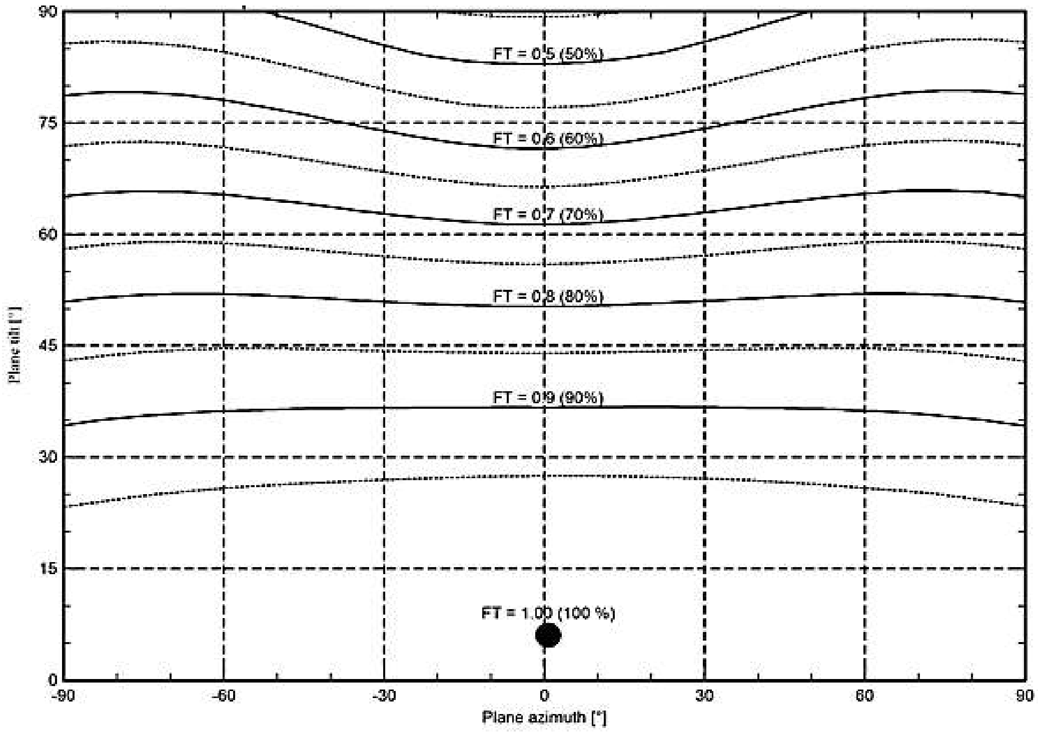

Figure 9: Transposition factors obtained from the transposition factor tab in PVsyst (method 2)

The transposition factor (TF) in PVsyst represents the ratio of the solar radiation received on a tilted surface to the radiation received on a horizontal surface. It is a crucial metric for evaluating the effectiveness of different tilt angles in optimizing solar energy capture. In Figure 10, the transposition factors are plotted against various tilt angles and azimuth orientations. The optimal tilt angle corresponds to the point where the transposition factor is maximized (close to TF = 1.0), indicating the highest efficiency in converting solar radiation into usable energy. The graph reveals a peak TF value at a tilt angle of 8° with an azimuth orientation of 0°.

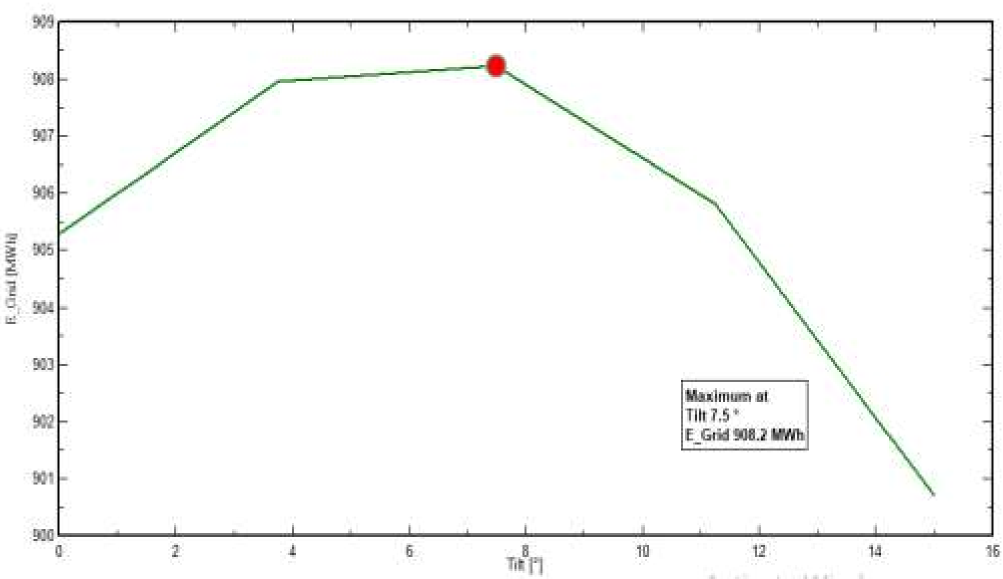

Figure 110: Optimal tilt angle obtained from the optimization tool box in PVsyst (method 3)

Figure 11 shows that 8° is the optimal tilt angle yields the maximum annual electricity generation of 908.2 MWh for the region.

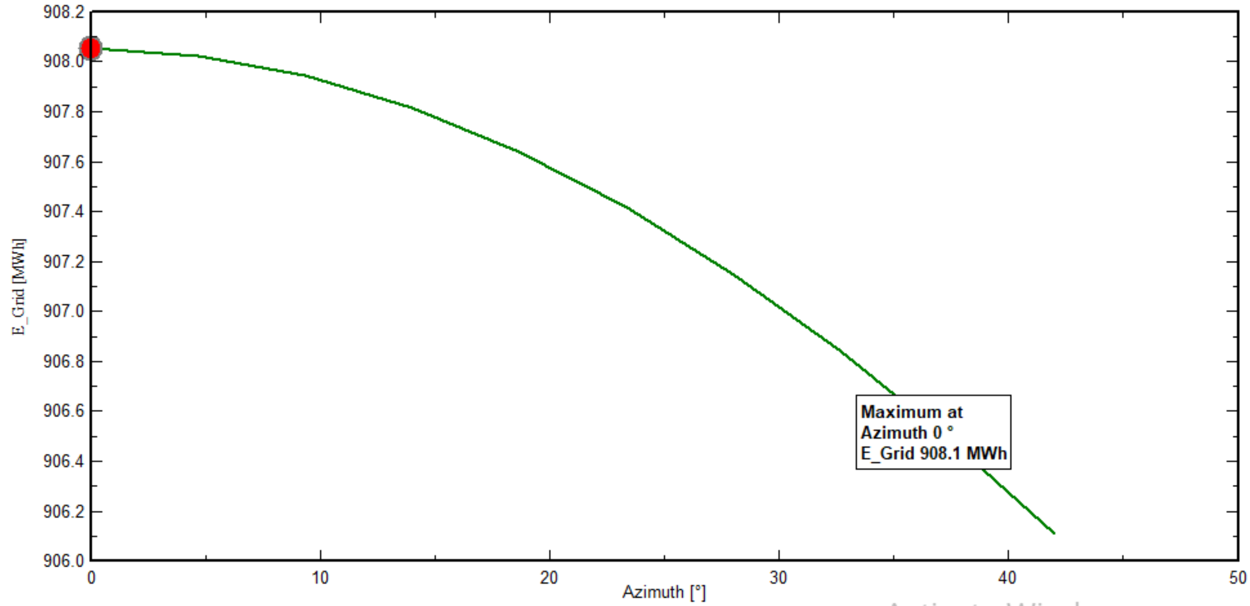

Figure 11: Optimal tilt angle obtained from the optimization tool box in PVsyst (method 3)

Similarly, Figure 12 also shows 8° as the optimal tilt angle. This represents the peak efficiency point for solar energy harvesting, as increasing or decreasing the tilt angle results in reduced electricity output.

3.3 Result from PVgis

Table 3: Optimal slope at 0°azimuth in PVgis

Month	E_d	E_m	H(i)_d	H(i)_m	SD_m
Jan	3420.95	106049.52	5.96	184.69	10835.06
Feb	3398.26	95151.34	5.93	165.92	8264.77
Mar	2995.92	92873.58	5.23	162.02	6252.35
April	2959.39	88781.64	5.16	154.77	3430.02
May	2584.69	80125.48	4.5	139.37	4247.64
June	1961.89	58856.61	3.43	102.81	6788.16
July	1828.72	56690.4	3.2	99.18	5293.71
Aug	2098.53	65054.53	3.66	113.48	8036.8
Sept	2259.48	67784.35	3.95	118.38	5647.29
Oct	2536.87	78642.99	4.42	137.03	2539.32
Nov	2852.91	85587.27	4.96	148.84	4908.16
Dec	3301.36	102342.03	5.73	177.69	7272.95
Year	**2679.29**	**81494.98**	**4.67**	**142.02**	**1805.93**

Table 3 presents monthly and yearly metrics for the PV system at an optimal slope with 0° azimuth using PVgis. January exhibits the highest daily energy output (3420.95 Wh/day) and solar irradiance (5.96 kWh/m²/day), while July records the lowest values (1828.72 Wh/day and 3.2 kWh/m²/day). The total annual energy output (E_m) is 81494.98 Wh, with a yearly average daily energy of 2679.29 Wh/day. Seasonal variations are evident, with peak performance in the dry months due to higher irradiance levels. This analysis underscores the importance of considering monthly and yearly fluctuations in solar conditions to optimize PV system design for consistent energy generation.

Table 4: Optimal orientation in PVGIS (slope = 0°; azimuth = 41°)

Month	E_d	E_m	H(i)_d	H(i)_m	SD_m
1	3380.23	104787.01	5.88	182.37	10516.96
2	3382.41	94707.44	5.89	165.06	8077.78
3	3006.67	93206.87	5.24	162.54	6169.82
4	2989.17	89675.09	5.21	156.32	3398.17
5	2634.62	81673.1	4.58	142.02	4305.16
6	2008.04	60241.23	3.5	105.11	7047.15
7	1864.53	57800.48	3.26	100.98	5393.5
8	2130.0	66029.99	3.71	115.09	8139.54
9	2290.88	68726.43	4.0	119.96	5735.28
10	2551.92	79109.57	4.44	137.76	2456.84
11	2839.47	85184.16	4.93	148.04	4910.29
12	3259.47	101043.47	5.66	175.34	6856.88
Year	**2690.92**	**81848.74**	**4.69**	**142.55**	**1776.29**

E_d: Average daily energy production from the given system (kWh/d); E_m: Average monthly energy production from the given system (kWh/mo); H(i)_d: Average daily sum of global irradiation per square meter received by the modules of the given system (kWh/m2/d); SD_m: Standard deviation of the monthly energy production due to year-to-year variation (kWh)

Similar to Table 3, Table 4 presents monthly and yearly metrics for the PV system at an optimal slope with 41° azimuth. Both tables highlight seasonal variations, with January showing the highest energy outputs and July the lowest. The total annual energy output is slightly higher for the system with an azimuth of 41° (81848.74 Wh) compared to 0° azimuth (81494.98 Wh). Similarly, the average daily energy output is marginally greater at 41° azimuth (2690.92 Wh/day) versus 0° azimuth (2679.29 Wh/day). These findings suggest that adjusting the azimuth to 41° offers a small but measurable improvement in energy generation for the region.

3.4 Result from Homer

Table 5: Optimal orientation obtained from sensitivity analysis in homer

Azimuth (°)	Slope (°)	Production (kWh/yr)
0	0	454151.1
0	11	459840.9
0	4.47	454670.5
0	8	457699.0
41	0	454151.1
41	11	463936.6
41	4.47	456004.7
41	8	464177.2

The findings in Table 5 indicate that adjusting the azimuth to 41° and maintaining an 8° slope significantly enhances energy generation.

Table 6: Comparison of the different software used in this study

Software rank	Monthly Opt	Yearly Opt	Free access to software	Slope Opt	Azimuth Opt	Auto. Slope and azimuth	Result
PVgis	√	√	√	(automatic and manual	(automatic and manual)	√	8° slope, 41° Azi
Homer	X	√	First 30 days	(manual)	(manual)	X	8° slope, 41° Azi
PVsyst	√	√	First 30 days	(manual)	(manual)	X	8° slope, 0° Azi
Retscreen	X	√	First 30 days	(manual)	(manual)	X	8° slope, 0° Azi

Table 6 provides a comparison of four software tools used in this study highlighting their features and capabilities in determining optimal PV system orientation. Notably, PVgis and PVsyst provide both monthly and yearly outputs, giving a detailed performance overview, whereas Homer and Retscreen focus solely on yearly results.

4. Discussion

The optimal orientation for photovoltaic systems is influenced by the methodologies and algorithms of the software used. While the raw data from these tools identifies tilt and azimuth angles for optimal solar energy harvesting, their usability vary significantly. Retscreen employs manual entries for tilt and azimuth angles, ranging from 0–45° and -45° to 45°, respectively. For each tilt angle, analyses were conducted across the azimuth range. Results indicate that a tilt of 8° and an azimuth of 0° yield optimal orientation and maximum energy generation (Figures 8 and 9). Retscreen's manual approach demands substantial user input, making it less efficient and user-friendly, particularly when compared to other software options. However, its granular approach may appeal to users performing detailed feasibility studies focused on small-scale or individual projects. This aligns with findings by Ukoima et al. (2023), who utilized Retscreen to analyze a solar hybrid electricity generation system in Okorobo-Ile Town, Rivers State, Nigeria. Their study highlighted Retscreen's ability to assess energy generation potential based on solar irradiance data and location-specific parameters, emphasizing the importance of optimal tilt angle determination.

PVsyst, as discussed in Section 2.3, provides three optimization methods: the preliminary design tab, the transposition factor tab, and the optimization toolbox. Results from the preliminary design tab indicate an optimal tilt angle range of 0–14°, with losses increasing as angles deviate from this range (Table 2). The transposition factor tab offers graphical optimization and identifies a yearly optimal tilt of 7.5° and azimuth of 0° (Figure 9). The optimization toolbox automates the process, allowing users to input angle ranges and step sizes. Though automated, this method's time response depends on input precision—smaller step sizes result in longer computation times. The observed optimal orientation of 8° tilt and 0° azimuth (figures 10 and 11) aligns with findings from Retscreen. PVsyst's detailed modeling tools are best suited for advanced users, as its flexibility comes at the cost of increased complexity and time commitment. These findings align with Ukoima (2025a), who explored the use of PVsyst for performance analysis of a solar photovoltaic system for the region.

PVgis stands out for its simplicity and efficiency. The software provides optimal orientation values with minimal user input—either by optimizing slope alone or slope and azimuth simultaneously. Results, presented both graphically and in tabular form, indicate an optimal tilt angle of 8° and azimuth angle of 41° (Tables 3 and 4). Notably, optimizing both slope and azimuth yields a 0.43% increase in average daily energy generation compared to slope optimization alone. PVgis's user-friendly interface and rapid processing make it ideal for quick assessments, confirming its position as the simplest and fastest tool among those reviewed. These findings are consistent with evaluations by Ukoima et al. (2024a), and Anthony et al. (2022), which praise PVgis for its intuitive design and robust functionality.

Homer employs sensitivity analysis to determine optimal orientation. Tilt angles ranged from 0–25°, while azimuth angles were tested between 0–45°. The results (Table 5) identified a tilt angle of 8° and azimuth angle of 41° as optimal. Homer's sensitivity analysis allows for comprehensive exploration of scenarios, making it suitable for hybrid system designs where flexibility and adaptability are critical (Hassan et al., 2021; Ukoima et al., 2024b; Ukoima et al., 2024c; Ukoima et al., 2024d). However, its simulation process can be time-consuming, placing it behind PVgis in terms of speed.

4.1 Comparative insights

The differences in optimal azimuth angles—0° for Retscreen and PVsyst versus 41° for PVgis and Homer—highlight variations in how these software tools calculate solar irradiance. Retscreen and PVsyst prioritize annual average values, often simplifying analysis by focusing on yearly summaries. Retscreen uses climate data from sources like NASA and applies a straightforward approach for feasibility assessments, while PVsyst employs hourly meteorological data for more detailed simulations, though its default focus on annual averages often results in a 0° azimuth recommendation. In contrast, PVgis and Homer incorporate seasonal and geographic factors more comprehensively. PVgis utilizes high-resolution satellite data to model the sun's position throughout the year, resulting in a more seasonally optimized azimuth angle of 41°. Similarly, Homer performs detailed simulations considering seasonal load variations, geographic specifics, and hybrid system dynamics, which also leads to the identification of an optimal azimuth angle of 41°.

The usability rankings presented in Table 6 align with observed software characteristics. PVgis's single-click optimization process ranks it first, followed by Homer's intuitive sensitivity analysis. PVsyst, though versatile, demands more user intervention, placing it third. Retscreen's reliance on manual entries makes it the least user-friendly option.

5. Conclusion

The aim of this study is to compare and contrast the optimal azimuth and tilt angles generated by PVgis, Retscreen, PVsyst, and Homer software. Specifically, an evaluation is made regarding the simplicity, time response, and user interface of each software in generating optimal orientation angles. The results reveal variations in the complexity of user inputs and the speed at which results are generated. Among the software compared, PVgis stands out for its simplicity, as it requires minimal user input and generates angle values with the fastest response time. Homer follows, combining ease of use with moderate input requirements, while PVsyst, despite offering detailed simulations, is comparatively slower. Retscreen necessitates significant manual entries to produce results, making it less efficient in terms of user-friendliness. Additionally, experimental findings by Ukoima et al. (2025b) validate the results obtained for the studied region, underscoring the relevance of region-specific analyses.

However, the conclusions drawn from this study must be considered in light of certain limitations. Each software relies on internal databases, which may incorporate different assumptions and methodologies. Assumptions related to seasonal variations, geographic factors, and load profiles influence the outputs. These differences underscore the importance of understanding the contexts and constraints of each tool when interpreting results. The findings of this study highlight the critical role of optimizing tilt and azimuth angles in maximizing solar energy generation. For instance, minor deviations in orientation can lead to significant energy gains or losses over the course of a year. This has substantial implications for the efficiency of solar installations, particularly in regions with variable solar irradiance patterns. Future research could expand upon this work by exploring the accuracy of these tools using real-time performance data from diverse geographic regions. Such studies could also delve deeper into the economic and environmental impacts of tilt angle optimization on photovoltaic system efficiency and longevity.

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