

MULTICRITERIA DECISION ANALYSIS OF FIXED-TILT AND SINGLE-AXIS TRACKING PHOTOVOLTAIC PLANTS USING TOPSIS METHOD

ANÁLISE MULTICRITÉRIO PARA TOMADA DE DECISÃO EM USINAS FOTOVOLTAICAS COM INSTALAÇÃO COM ESTRUTURA FIXA E RASTREAMENTO DE EIXO ÚNICO POR MEIO DO MÉTODO TOPSIS

ANÁLISIS MULTICRITERIO PARA LA TOMA DE DECISIONES EN PLANTAS FOTOVOLTAICAS DE INSTALACIÓN FIJA Y SEGUIMIENTO DE EJE ÚNICO MEDIANTE EL MÉTODO TOPSIS

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ABSTRACT

Growing electricity demand and stringent environmental regulations have shifted investment toward renewable energy. Despite its potential, solar energy accounts for less than 4% of the global matrix, necessitating optimizations in installation efficiency and financial viability. While solar panels achieve 16%–24% efficiency, performance can be enhanced through solar trackers, which adjust orientation to maximize energy capture. This study proposes a decision-support framework utilizing the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method to determine the economic viability of tracker-based systems across various geographic coordinates. The methodology integrates multicriteria analysis with field validation, allowing for the adjustment of regional economic indices and technical yields. Results demonstrate that single-axis trackers become economically advantageous for capacities exceeding 250 kWp in Southern, Southeastern, and lower Midwestern Brazilian regions, and above 300 kWp in higher Midwestern, Northern, and Northeastern regions of Brazil. Furthermore, tracker-based installations can reduce land requirements by up to 40% compared to fixed structures. The integrated financial tool aligns with real-world market conditions, providing a robust instrument for investors to optimize photovoltaic plant design and resource allocation according to regional socioeconomic variations.

Keywords: Decision Analysis. Photovoltaic Systems. Single-Axis Solar Tracking. TOPSIS.

RESUMO

O crescimento da demanda por eletricidade e o endurecimento das regulamentações ambientais

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têm direcionado os investimentos para fontes de energia renovável. Apesar de seu elevado potencial, a energia solar representa menos de 4% da matriz energética global, evidenciando a necessidade de otimizações relacionadas à eficiência de instalação e à viabilidade econômica dos sistemas. Embora os módulos fotovoltaicos apresentem eficiência entre 16% e 24%, seu desempenho pode ser aprimorado por meio da utilização de rastreadores solares, capazes de ajustar a orientação dos painéis para maximizar a captação energética. Este estudo propõe um modelo de apoio à decisão baseado no método TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) para avaliar a viabilidade econômica de sistemas equipados com rastreadores em diferentes coordenadas geográficas. A metodologia integra análise multicritério e validação em campo, permitindo a adequação de índices econômicos regionais e rendimentos técnicos. Os resultados demonstram que os rastreadores de eixo único tornam-se economicamente vantajosos para sistemas com capacidade superior a 250 kWp nas regiões Sul, Sudeste e porções inferiores do Centro-Oeste brasileiro, bem como acima de 300 kWp nas regiões de maior latitude do Centro-Oeste, Norte e Nordeste do Brasil. Adicionalmente, instalações com rastreadores podem reduzir a necessidade de área em até 40% quando comparadas às estruturas fixas. A ferramenta financeira integrada apresenta aderência às condições reais de mercado, constituindo um instrumento robusto para investidores na otimização do projeto de usinas fotovoltaicas e da alocação de recursos, considerando as variações socioeconômicas regionais.

Palavras-chave: Análise Multicritério de Decisão. Sistemas Fotovoltaicos. Rastreamento Solar de Eixo Único. Método TOPSIS.

RESUMEN

El crecimiento de la demanda eléctrica y el endurecimiento de las regulaciones ambientales han orientado las inversiones hacia fuentes de energía renovable. A pesar de su elevado potencial, la energía solar representa menos del 4% de la matriz energética mundial, lo que evidencia la necesidad de optimizar la eficiencia de instalación y la viabilidad económica de estos sistemas. Si bien los módulos fotovoltaicos alcanzan eficiencias entre el 16% y el 24%, su desempeño puede mejorarse mediante el uso de seguidores solares, capaces de ajustar la orientación de los paneles con el fin de maximizar la captación energética. Este estudio propone un marco de apoyo a la toma de decisiones basado en el método TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) para determinar la viabilidad económica de sistemas con seguidores solares en distintas coordenadas geográficas. La metodología integra análisis multicriterio y validación experimental en campo, permitiendo la adaptación de índices económicos regionales y rendimientos técnicos. Los resultados demuestran que los seguidores de un eje resultan económicamente ventajosos para instalaciones con capacidades superiores a 250 kWp en las regiones Sur, Sudeste y áreas inferiores del Centro-Oeste Brasileño, y por encima de 300 kWp en las regiones de mayor latitud del Centro-Oeste, Norte y Nordeste del Brasil. Asimismo, las instalaciones equipadas con seguidores solares pueden reducir los requerimientos de superficie hasta en un 40% en comparación con estructuras fijas. La herramienta financiera integrada muestra concordancia con las condiciones reales del mercado, constituyendo un instrumento sólido para que los inversionistas optimicen el diseño de plantas fotovoltaicas y la asignación de recursos en función de las variaciones socioeconómicas regionales.

Palabras clave: Análisis Multicriterio de Decisión. Sistemas Fotovoltaicos. Seguimiento Solar de Eje Único. Método TOPSIS.



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INTRODUCTION

The current energy demand is closely linked to industrial growth and environmental and climate concerns, driving the adoption of sustainability-oriented policies in which renewable energy sources have emerged as viable solutions.

Studies reported in [9] indicate that, by 2040, more than 37% of the global installed energy capacity will be supplied by renewable sources. According to [14], [38], [26], the solar energy incident on the Earth's surface is approximately 5.000 times greater than the current worldwide electricity consumption. Widespread deployment of photovoltaic generation systems at points of consumption could significantly reduce global dependence on fossil fuels, with PV generation complementing hydropower during periods of insufficient solar availability and nighttime operation [43].

In tropical countries such as Brazil, where solar irradiation levels exceed 5 kWh/m²/day, photovoltaic solar energy remains underexploited for electricity generation [4], [8], [14], [11], accounting for less than 22% of installed electricity capacity as illustrated in Fig. 1.

Figure 1. Brazilian Solarimetric Atlas [13]



Source: Authors

Despite the high global solar irradiance potential, large-scale PV deployment is limited by the relatively low efficiency of conventional panels (17%–25%) installed in fixed-tilt configurations oriented toward true geographic north [6].

To optimize energy yield throughout the day and across different seasons, solar tracking systems represent an effective solution. These systems follow the periods of highest solar

irradiance from sunrise to sunset, accounting for the Earth's declination angle, thereby increasing energy production and improving return on investment [11], [15].

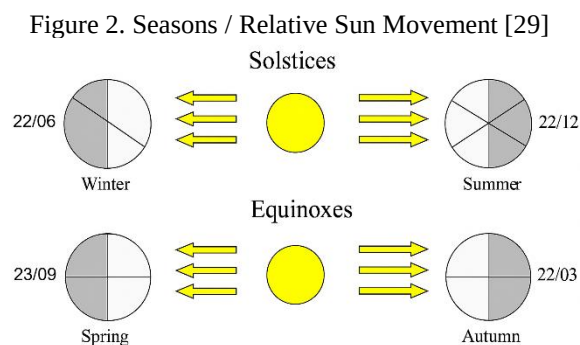
The paper aims to determine, using a multicriteria decision-making model, the installed power range (kWp) at which ground-mounted photovoltaic plants become economically viable with either fixed-tilt or solar tracking systems, according to geographic location. The study evaluates the performance of fixed and tracking configurations using solar geometry, manufacturer data, and field measurements; demonstrates the influence of local solar irradiation and system size on investment decisions; and develops an investor-oriented financial assessment tool based on the TOPSIS method applicable to both configurations.

Although the literature demonstrates consistent energy gains associated with both single- and dual-axis solar tracking systems, existing studies primarily focus on relative performance improvements and mechanical configurations. None of the reviewed works establishes power-based economic thresholds or evaluates the viability of tracking systems as a function of installed capacity. This gap is addressed in the present study through a combined technical and multicriteria economic analysis.

The remainder of this article is organized as follows. Section II presents the theoretical foundations of solar energy and tracking systems. Section III describes the TOPSIS methodology. Section IV presents results and discussion. Finally, Section V concludes the article.

TECHNICAL OVERVIEW

A major global challenge is the provision of electricity while minimizing the environmental impacts of energy generation [46]. The Sun delivers approximately $5,45 \times 10^{24}$ J ($1,51 \times 10^{18}$ kWh) of energy annually to the Earth's atmosphere, which is more than sufficient to meet global energy demand [12]. Solar radiation is defined as the solar energy incident on a surface over a given period and is expressed in Wh/m² or kWh/m² [43]. Atmospheric dispersion reduces the average extraterrestrial irradiance of approximately 1.367 W/m² to about 1.000 W/m² at the Earth's surface under ideal conditions, known as direct normal irradiance, a key parameter in photovoltaic system assessment [3], [35]. These solar geometry principles form the basis for the analyses performed, including the evaluation of seasonal variations shown in Fig. 2.



Source: Authors

Solar Tracker

Solar tracking systems increase photovoltaic (PV) energy yield by adjusting module orientation to maximize solar radiation incidence, outperforming fixed-tilt configurations, particularly in regions with high direct normal irradiance. Trackers are classified by degrees of freedom and axis orientation: single-axis systems typically employ a horizontal north–south axis with east–west rotation, while dual-axis trackers control both azimuth and elevation. Although dual-axis trackers offer higher gains, their greater complexity, cost, and maintenance requirements generally restrict their application to small-scale installations [23], [30].

Horizontal single-axis trackers with a north–south axis and east–west rotation are a common choice, offering 15% to 30% annual energy gains over fixed-tilt systems, depending on latitude, climate, and ground coverage. They are most effective in equatorial and mid-latitude regions with moderate seasonal variations in solar path.

Tracking systems also improve land-use efficiency. By increasing energy production per kilowatt-peak, single-axis trackers reduce land area requirements, offsetting their higher initial investment. Thus, their economic viability depends on energy yield, land cost, solar availability, and system scale [35].

Despite significant research, there is no clear definition of the power thresholds at which tracking systems outperform fixed-tilt systems economically, according showing in Table I. This study addresses this gap by integrating performance and economic metrics into a multicriteria decision-making framework.

Table 1. Summary of Solar Tracking Technologies and Reported Energy Gains

Author(s) / Year	Tracking Technology and Configuration	Application	Energy Gain
[2] Yadav (2013)	Solar tracking system (general concept)	PV modules with increased direct irradiance	Significant increase in energy yield
[11] Paiva (2009)	Single-axis tracker (horizontal or polar axis, $\sim 120^\circ$ rotation)	Ground-mounted PV systems	Not quantified
[27] Kacira <i>et al.</i> (2004)	Dual-axis solar tracker	Ground-mounted PV system (Turkey); optimized tilt	30–35% gain compared to fixed system (June)
[19] Karimov <i>et al.</i> (2005)	Dual-axis tracker powered by PV DC output	Self-powered PV tracking system	Not explicitly quantified
[32] Vilela <i>et al.</i> (2003)	Single-axis horizontal tracker (east–west)	PV-powered water pumping system	19–24% gain over fixed systems
[19] Karimov <i>et al.</i> (2005)	Polar-axis tracker with sensor-based control ($\pm 10^\circ$ accuracy)	Ground-mounted PV	Not quantified
[47] Li <i>et al.</i> (2010)	Single-axis tracker with optical sensors (LDR)	Active solar tracking PV system	Not quantified
[24] Abouzeid (2001)	Single-axis tracker with stepper motor (7.5° step)	Ground-mounted PV systems	Not quantified
[22] Navarte and Lorenzo (2008)	Single- and dual-axis trackers	Ground-mounted PV without shading	18–25% (single-axis); 37–45% (dual-axis); ~ 2 -year payback reduction
[34] Roth <i>et al.</i> (2004)	Dual-axis tracker with DC motors	Solar radiation measurement (pyrheliometer)	Not quantified
[16] Canãda <i>et al.</i> (2007)	Dual-axis tracker with stepper motors	Spectro radiometric measurements	Not quantified
[43] Poulek and Libra (2000)	Dual-axis tracker with bifacial modules (360° rotation)	Terrestrial and satellite PV applications	14% gain compared to single-axis control

Source: Authors

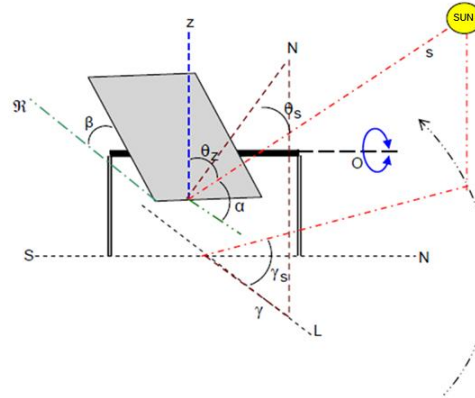
Previous studies consistently report that solar tracking systems increase photovoltaic energy yield by enhancing the incidence of direct solar radiation on the module surface. Depending on the configuration, reported gains range from approximately 18% to over 40% when compared with fixed-tilt installations. Single-axis trackers, particularly those with horizontal north–south axes and east–west rotation, typically achieve gains between 18% and 25% [19], [45], whereas dual-axis systems may reach gains above 35% under favorable conditions [18]. Several works also explore different actuation and control strategies, including stepper motors [24], DC motors [7], sensor-based control using optical devices [18], [37] and self-powered tracking architectures [47].

Trackers With Horizontal Axis (South-North Direction and East-West Movement)

This configuration is the focus of the present study to compare efficiency with fixed structure. It is a mounting system very similar to one shown on the horizontal axis oriented in east-west direction and north-south movement, with good conversion efficiency, as it

accompanies the highest radiation with east-west orientation, as shown in Fig. 3:

Figure 3. Solar Tracker with horizontal axis south-north [10], [28]



Source: Authors

TOPSIS METHOD

The economic and technical comparison between fixed-tilt and solar tracking photovoltaic (PV) systems was performed using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), a well-established multicriteria decision-making method widely applied in energy planning and engineering problems [1], [36], [44]. TOPSIS enables the ranking of alternatives by evaluating their relative proximity to an ideal solution that maximizes benefit criteria and minimizes cost criteria.

Definition of Alternatives and Criteria

For calculation, two alternatives were evaluated:

- (i) ground-mounted photovoltaic plants with fixed-tilt structures and
- (ii) ground-mounted photovoltaic plants equipped with single-axis solar trackers.

The selection of evaluation criteria was based on a combination of technical relevance, economic significance, and practical considerations observed in large-scale PV projects [1], [21].

The criteria adopted in the analysis are include:

- Initial capital expenditure (CAPEX);
- Ground area requirement;
- Installation complexity and O&M (operation and maintenance);

- Annual energy generation;
- Net Present Value (NPV);
- Internal Rate of Return (IRR).

Cost-related criteria (CAPEX, ground area, and O&M complexity) were treated as minimizing criteria, whereas energy production and financial indicators (annual energy, NPV, and IRR) were treated as maximizing criteria [26], [30].

Criteria Weighting

Criteria weights were derived from a structured survey of 22 photovoltaic system integrators in the Brazilian market, selected based on their experience in medium- and large-scale PV projects. Participants assigned relative importance to each criterion, reflecting practical investment priorities. The responses were normalized and aggregated to obtain the final weight vector, and result robustness was verified through sensitivity analysis by varying the weights within reasonable limits and assessing ranking stability.

TOPSIS Computational Procedure

The TOPSIS method was implemented following the classical procedure proposed [1], [6]. First, a decision matrix was constructed using the performance values of each alternative under the selected criteria. The matrix was then normalized to eliminate dimensional inconsistencies, and the weighted normalized matrix was obtained by applying the criteria weights [25], [40].

The positive ideal solution (PIS) and negative ideal solution (NIS) were subsequently determined [20], [40]. The PIS represents the hypothetical alternative with the best performance across all criteria, while the NIS represents the worst-case scenario. Euclidean distances between each alternative and the PIS and NIS were calculated, allowing the computation of the relative closeness coefficient for each alternative [44].

Ranking and Decision Interpretation

Alternatives were ranked by their closeness to the ideal solution, with higher values indicating more favorable options. The TOPSIS results indicate that fixed-tilt systems are preferred for smaller capacities due to lower costs and simplicity, while single-axis tracking systems achieve higher rankings as capacity increases, driven by superior energy yield and land-use efficiency despite higher CAPEX [31], [40]. By integrating technical, spatial, and financial criteria, the proposed framework provides a transparent and reproducible decision-support tool for large-scale PV investment analysis under varying conditions.

RESULTS AND DISCUSSION

This section presents the performance, land-use, and economic results obtained for fixed-tilt and single-axis tracking photovoltaic (PV) systems. The analysis combines annual solar-geometry simulations [6], controlled field measurements, and a multicriteria economic assessment based on the TOPSIS method.

Energy Yield Assessment

Annual simulations show that horizontal single-axis trackers with a north–south axis and east–west rotation significantly increase energy yield relative to fixed-tilt systems. For the evaluated sites, gains of 22%–25% were observed, in agreement with literature for similar configurations [19], [39], [47]. Solar-geometry analysis under representative conditions, including Julian day 80, confirms that tracking systems maintain near-optimal incidence angles throughout the day, whereas fixed-tilt systems suffer higher losses during morning and afternoon periods, resulting in lower cumulative energy output [42].

Experimental Validation

Field measurements were conducted over eight months in São Paulo (latitude -23.57°) using two identical 370 W PV modules, one mounted on a fixed-tilt structure and the other on a single-axis north–south tracker, as illustrated in **Fig. 4**. The measured hourly and daily energy

yields are summarized in **Table II**.

Figure 4. 370 W PV module mounted on a north–south single-axis tracker with east–west rotation



Source: Authors

Table 2. Measured Daily Energy Yield for a 370 W PV Module - Fixed and Tracking Configurations

Time	Fixed System		Solar Trackers North–South Axis with east–west rotation	
	Hourly average (%)	Average energy (kWh)	Hourly average (%)	Average daily energy (kWh)
06h - 07h	7,88%	0,01	9,77%	0,02
07h - 08h	24,29%	0,04	30,12%	0,05
08h - 09h	48,15%	0,08	59,71%	0,10
09h - 10h	71,40%	0,11	88,53%	0,14
10h - 11h	90,26%	0,14	111,60%	0,18
11h - 12h	99,41%	0,16	113,60%	0,18
12h - 13h	98,13%	0,16	112,00%	0,18
13h - 14h	89,29%	0,14	111,90%	0,18
14h - 15h	73,90%	0,12	91,64%	0,15
15h - 16h	50,13%	0,08	62,17%	0,10
16h - 17h	26,47%	0,04	32,82%	0,05
17h - 18h	7,96%	0,01	9,88%	0,02
18h - 19h	1,26%	0,00	1,56%	0,00
-	-	1,1	-	1,34

Source: Authors

The tracking system achieved an average energy gain of **21,31%** relative to the fixed configuration, which is slightly lower than the theoretical value of **22.93%** estimated using the Angström–Prescott model [29], [41]. This deviation of approximately **7.6%** is attributed to real-world losses, including mechanical tolerances and non-ideal atmospheric conditions, which are not fully captured in the theoretical model. Nevertheless, the experimental results confirm the validity of the simulation outcomes and the expected performance advantage of the tracking system.

Land-Use Implications

The increased specific energy production of the tracking configuration directly impacts land-use efficiency. For equivalent installed capacity, tracker-based PV plants can reduce the required ground area by up to **40%** compared with fixed-tilt systems, depending on layout assumptions and ground coverage ratio [17], [39], [45]. This reduction is particularly relevant for utility-scale projects, where land availability and cost are critical constraints.

Multicriteria Economic Analysis (TOPSIS)

The economic comparison between fixed and tracking systems was performed using the TOPSIS multicriteria decision-making method [1], [5]. The evaluated criteria include initial investment, occupied space, installation and maintenance complexity, Net Present Value (NPV), Internal Rate of Return (IRR), and annual energy generation.

Criterion weights were derived from a structured survey conducted with 22 photovoltaic integrators across Brazil, as summarized in **Table III**.

Table 3 Answers to Topsis Index Weights (Criteria)

Criteria	Answers	Weights
Initial investment	8	35%
Occupied Space	10	20%
Installation/Maintenance	7	15%
NPV	11	10%
IRR	8	10%
Energy Generated (year)	7	10%

Source: Authors

The results show that initial investment and land occupation are the most influential criteria, followed by installation/maintenance and financial indicators. According to the TOPSIS rankings in **Table IV**, fixed-tilt systems are favored for small installations, while tracking systems become dominant as plant size increases. Under the analyzed Southern Hemisphere conditions, trackers become economically viable above approximately 250 kWp at higher latitudes and 300 kWp at lower latitudes, reflecting the combined effects of higher energy yield, improved land-use efficiency, and economies of scale.

Table 4. Power Limits (Simulation in the South Hemisphere)

(kWh / month)	Power (kWp)		TOPSIS Decision
	Fixed	Tracker	
420	4,49	3,6	59,3% fixed
3.740	40	32,09	60,68% fixed
29.000	310,14	248,8	100% solar tracker
370.300	3.960,19	3.176,89	87,17% solar tracker

Source: Authors

Overall, the results demonstrate that the decision between fixed and tracking configurations cannot be based solely on traditional financial metrics. Spatial efficiency and operational criteria play a decisive role, particularly for large-scale projects. The proposed framework therefore provides a structured and market-consistent basis for selecting PV system configurations according to geographic conditions and project scale.

CONCLUSIONS

This study demonstrated that single-axis solar tracking systems provide significant performance and economic advantages for ground-mounted photovoltaic (PV) plants when properly aligned with geographic and solarimetric conditions. Simulation results confirmed energy yield gains between 22% and 25% compared with fixed-tilt systems, enabling a reduction of up to 40% in land requirements while maintaining equivalent power output. These findings reinforce the central role of solar geometry in PV system design and validate the effectiveness of horizontal single-axis trackers with north–south axis and east–west rotation tracking configurations, particularly under conditions of low solar declination.

The proposed multicriteria decision-support framework, based on the TOPSIS method, proved capable of integrating technical, geographic, and financial parameters in a coherent and market-consistent manner. Results indicate that tracker-based PV systems become economically viable for installed capacities above 250 kWp in higher-latitude regions and above 300 kWp in lower-latitude regions, highlighting the decisive influence of latitude and solar irradiance on investment thresholds. Beyond conventional financial indicators, spatial efficiency and operational considerations were shown to play a critical role in investor decision-making.

Overall, the methodology provides a robust analytical basis for optimizing land use and guiding strategic investments in large-scale photovoltaic generation. Its applicability can be extended to other geographic regions and emerging PV configurations, supporting a more efficient and sustainable expansion of solar energy worldwide. Future research may enhance the

proposed framework by incorporating additional variables affecting long-term PV performance, such as operation and maintenance costs, module degradation, and irradiance variability, as well as by extending the analysis to bifacial modules, floating systems, and hybrid renewable plants supported by long-term operational data.

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