Technical and Economic Evaluation of Implementing a Photovoltaic Power Plant in Rio de Janeiro, Brazil: Fixed Structure Vs. Solar Tracker Systems

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Abstract

The transition to renewable energy sources has been driven by environmental concerns and the pursuit of greater energy security. In this context, solar photovoltaic energy stands out for its modularity, broad geographic applicability, and recent cost reductions. This study conducts a comparative technical and economic evaluation of two structural configurations for a photovoltaic plant located in the city of Iguaba Grande, RJ (Brazil): one with a fixed structure and the other with a tracker system. The analysis considers performance parameters, investment and operating costs, as well as financial indicators such as Levelized Cost of Energy (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR), and discounted payback period. The results show that the system with a tracker presents higher energy generation and net revenue, while the fixed structure demonstrates slightly more favorable financial indicators due to lower total capital expenditure (CAPEX). It is also observed that the LCOE of the tracker system is higher, reflecting the increased operational and structural costs. It is concluded that configuration selection must balance energy efficiency and economic viability, and that both alternatives are technically feasible for the studied location.

Keywords: Photovoltaic, systems, fixed structure, solar tracker, technical-economic evaluation.

1. Introduction

The transition towards cleaner and more sustainable energy sources has garnered significant momentum in recent years (De Vidovich, 2024), propelled by global concerns regarding climate change, energy security, and the volatility of fossil fuel markets (Pollitt & Shaorshadze, 2023). Among the various renewable technologies, solar photovoltaic (PV) systems have emerged as one of the most promising alternatives, attributable to their modularity, decreasing costs, and broad applicability across diverse geographic regions (IEA, 2024). In Brazil, the combination of favorable solar resources and supportive regulatory frameworks has expedited the deployment of PV systems, both in centralized and distributed generation formats (Andrade et al., 2020).

However, the optimization of efficiency and financial returns of a PV project hinges not solely on solar availability but also on meticulous design decisions, particularly concerning the type of structural support system utilized for panel installation (Torma & Aschemann-Witzel, 2024). The two predominant configurations are fixed-tilt structures, which present mechanical simplicity and reduced investment costs, and solar tracking systems (trackers), which adjust to follow the sun's trajectory throughout the day to enhance energy capture, albeit at the expense of higher capital and maintenance requirements (Bhayat et al., 2023; Kumba et al., 2024).

This study conducts a comparative technical and economic evaluation of two structural configurations for the implementation of a photovoltaic plant in Iguaba Grande, Rio de Janeiro, Brazil. Despite its relatively small size, Iguaba Grande is located in an area characterized by high solar irradiance, making it a representative location for solar energy research (Pinho & Galdino, 2014). The analysis involves comparing a plant equipped with a solar tracking system and one with a fixed structure, considering the main characteristics of the equipment comprising each installation, as well as the differences in efficiency, installation, and operating costs. Simulations are performed using PVSyst software, allowing a detailed assessment of the plants' performance. Based on the results obtained, investment costs, operating expenses, and financial metrics are analyzed to identify the most advantageous configuration, taking into account the site's specific environmental and economic conditions. The economic evaluation uses consolidated indicators, such as Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period and Levelized Cost of Energy (LCOE), to determine alternatives that offer greater attractiveness and return

10.18086/swc.2025.06.32 Available at http://proceedings.ises.org

potential for investors.

2. Methodology

The methodology employed in this study integrates a comprehensive technical and economic assessment of PV systems, structured to ensure transparency and reproducibility. Technical and economic data are sourced from reputable and verified references, including specialized literature, national energy statistics, and documented case studies of photovoltaic projects executed within Brazil. Principal references comprise solar resource assessments (Pereira et al., 2017), system configuration guidelines, and performance reports of various photovoltaic technologies (IEA, 2024). This methodological framework ensures that both the technical performance and the economic feasibility of the proposed systems are rigorously examined, supporting well-founded recommendations for the optimal deployment of photovoltaic plants in Brazil.

2.1. Simulation and Design of Photovoltaic Systems Using PVsyst

PVsyst software is employed for the simulation and sizing of photovoltaic systems, and it is distinguished by its reliability and the precision of its outcomes. Its application is justified by its capacity to incorporate essential parameters that influence system performance, such as local solar irradiation levels, system architecture, and module technology. The Hay model, implemented within PVsyst, permits the concurrent consideration of the direct and diffuse components of solar radiation incident upon inclined surfaces, thereby enabling more precise estimations of energy generation across various installation scenarios. Additionally, sensitivity analyses are conducted to evaluate the impact of variations in the detail angle and tracking configurations, thereby ensuring greater robustness of the simulation results.

2.2. Economic and Financial Analysis of Photovoltaic Systems

The economic analysis considers all financial parameters relevant to the project’s life cycle to ensure a comprehensive assessment of investment feasibility. The initial investment (CAPEX) is examined in terms of equipment acquisition and installation costs, whereas operating and maintenance expenses (OPEX) are evaluated throughout the system's operational lifespan, reflecting the ongoing expenses necessary for continuous operation and optimal performance of the photovoltaic facility. Revenues are estimated based on the energy generated annually, considering the electricity sales price and applicable tariff mechanisms. Gross Revenue is calculated based on total energy production, while Net Revenue is obtained after deducting charges and taxes, including the TUSD G component, which refers to the tariff for using the distribution system for generation. This structure allows for a realistic representation of the economic conditions of the Brazilian electricity sector. The primary indicators for assessing economic performance include the LCOE, NPV, IRR, and Discounted Payback period. The LCOE is employed to ascertain the unit cost of energy generation over temporal durations, facilitating comparisons among various system configurations. NPV and IRR serve to evaluate the investment's attractiveness by accounting for discounted cash flows and anticipated rates of return. Moreover, the Discounted Payback period signifies the duration necessary for the recovery of the initial investment, duly adjusted to reflect the time value of money. The simulations are conducted using realistic input data, reflecting current costs in the national market, local solar potential, appropriate discount rates, and the estimated useful life of the systems. This guarantees that the results obtained are congruent with Brazilian market conditions and accurately depict the profitability and economic performance of the various photovoltaic plant configurations analyzed.

2.3. Comparative Scenario Analysis

Two photovoltaic plant configurations under identical environmental and economic conditions are examined: (i) a plant with a fixed structure and (ii) a plant equipped with a solar tracking system. This methodology facilitates a comprehensive comparative analysis, emphasizing the distinctions between the scenarios regarding energy production, economic efficiency, and long-term sustainability. Such comparison enables the identification of the configuration that provides the optimal potential for financial return, the minimal levelized cost of energy, and the most effective utilization of available solar resources, thereby offering valuable insights for decision-making in photovoltaic projects.

3. Case Study

The case study presented herein delineates the location of the photovoltaic installation within the municipality of Iguaba Grande, Rio de Janeiro. It emphasizes its environmental characteristics as well as its solar potential. Additionally, the description of the plant's equipment encompasses modules, inverters, support structures, and measurement and transformation booths, with particular attention to their technical specifications and significance to system performance. Lastly, the two analyzed scenarios are elucidated: one incorporating a tracking system and the other utilizing a fixed structure. Details are provided regarding the arrangement of modules, the quantity employed in each configuration, and the distinctions between the solutions, facilitating a comparative evaluation of both technical and economic performance.

3.1. Location of the PV Plant

The proposed photovoltaic facility is situated within the rural sector of the municipality of Iguaba Grande, located in the Lakes Region of the State of Rio de Janeiro, Brazil. The designated site is proximate to the RJ-106 highway and the Araruama Lagoon, in an area distinguished by low urban density and ample space conducive to system installation. The geographic coordinates approximately are -22.828000, -42.249000, denoting an advantageous position for solar energy harnessing, as the site is subject to high average levels of global irradiation throughout the year, characteristic of the Rio de Janeiro coast. Figure 1 shows the location of the area designated for the installation of the photovoltaic plant in Iguaba Grande, RJ. This area serves as the focal point of the study, offering a representative setting for the evaluation of photovoltaic power generation under favorable climatic and environmental conditions. Figure 2 illustrates the site layout of the photovoltaic facility, delineating the designated area for system installation alongside the primary geographical references.

Figure 1: Geographical Location of the Study Area within the State of Rio de Janeiro, Brazil. Source: Google Earth.

Figure 2: Location map of the photovoltaic power plant in Iguaba Grande, Rio de Janeiro, Brazil. Source: Google Earth.

3.2. PV Plant Equipment

The photovoltaic modules are designed to be energy-efficient and lightweight, with a weight of less than 16.7 kgf/m². They are engineered to resist a minimum impact from hailstones measuring 25 mm at a velocity of 82.8 km/h and are capable of withstanding wind loads of up to 5,400 Pa on the front surface and 2,400 Pa on the rear surface.

Additionally, they feature drainage holes incorporated into their structure. The specific model employed in this context is the 540 Wp module manufactured by Canadian Solar (model CS6W-540MB-AG 1500V), which is well recognized for its reliability and high efficiency. Power conversion is conducted using ten units of 250 kWac SunGrow 250HX inverters to provide the total power for the facility. The voltage is adjusted to match the utility's distribution grid (13.8 kV) through an approved SKID, equipped with a 2,500 kVA dry-type three-phase transformer. Energy measurement is conducted within a prefabricated 15 kV cabinet, produced by an approved manufacturer and installed in accordance with the standards set by the local utility authority.

3.3. Scenario 1 – System Incorporating a Tracker

In Scenario 1, the modules are systematically arranged into 210 strings consisting of 28 modules each, resulting in a total of 5,880 modules. These modules are mounted on solar tracking systems to maximize energy collection throughout the day. Although the overall available area for the plant remains identical to that of the fixed-structure scenario, the increased spacing required between the tables to accommodate tracker movement imposes a limitation on the maximum number of modules that can be installed. The system's peak power reaches approximately 3.18 MWp, thereby enabling the assessment of energy performance and operational efficiency in relation to solar path tracking. Figure 3 illustrates the arrangement of photovoltaic modules within the configuration equipped with a solar tracking system.

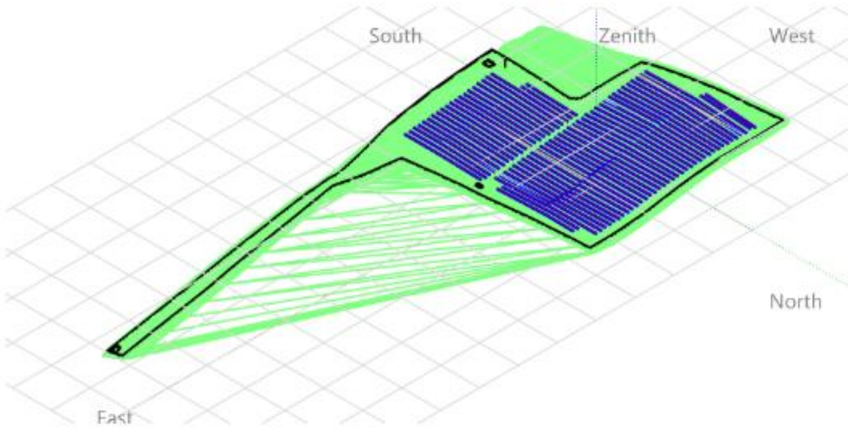

Figure 3: Diagram illustrating the layout of PV modules within the configuration employing a solar tracking system (Scenario 1).

3.4 Scenario 2 – System with Fixed Structure

In Scenario 2, the modules are organized into 240 strings comprising 28 modules each, summing to a total of 6,720 modules, mounted on fixed support structures. The reduced spacing between tables permitted in this configuration facilitates a greater number of modules within the same available area, leading to an elevated peak power of approximately 3.63 MWp. This arrangement enables a comparative assessment of energy performance and economic viability in relation to the system equipped with trackers, thereby illustrating the influence of configuration and technology on energy generation. Figure 4 illustrates the arrangement of the photovoltaic modules within a fixed structure configuration.

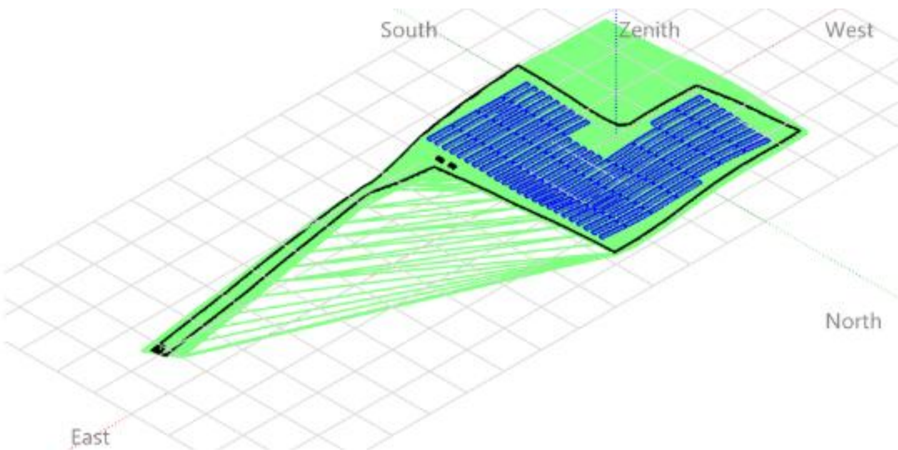

Figure 4: Diagram illustrating the layout of PV modules within the configuration utilizing a fixed structure (Scenario 2).

3.5. Methodological Assumptions

The following assumptions are used to calculate the financial indicators. The adopted exchange rate is R$5.22 per USD, with an annual discount rate of 8%, as specified by EPE (2024). Installation costs for photovoltaic plants are contingent upon their specific characteristics; reference is made to the study by GREENER (2024) for cost estimations. It is presumed that photovoltaic modules possess a lifespan of 30 years, aligning with manufacturer specifications and the total duration of the project. Additionally, an annual degradation rate of 0.4% is assumed for the modules.

3.6. Parameters for the Assessment of Photovoltaic System Performance

To evaluate the energy performance of a photovoltaic installation, parameters derived from annual system simulations are examined. Global irradiance on the horizontal plane (GlobHor) and diffuse irradiance on the horizontal plane (DiffHor) are employed to characterize the available solar resource at the location. The average ambient temperature (T_Amb) is considered due to its direct influence on the efficiency of the photovoltaic modules. Global irradiance incident on the module plane (GlobInc) and effective global irradiance (GlobEff) represent, respectively, the solar energy reaching the surface of the modules and the fraction effectively harvested after optical losses. The energy produced by the photovoltaic array (EArray) and the energy fed into the grid (E_Grid) are computed to quantify the electrical performance of the system. Finally, the Performance Ratio (PR) is utilized as a comprehensive efficiency indicator, relating the energy effectively supplied to the grid to the theoretical potential determined by the irradiance incident on the modules.

4. Results and Discussion

The results obtained in this study are presented below, detailing both the energy performance and financial indicators for each scenario analyzed. Information on annual energy generation, net revenue, and metrics such as LCOE, NPV, IRR, and discounted payback are included, allowing a clear comparison between fixed-structure and tracker configurations. The presentation of these results allows us to assess the impact of structural choices on system efficiency and the project's economic viability.

4.1. Energy Generation Results

The study indicates that the parameters of global horizontal and diffuse horizontal solar radiation, along with the annual mean ambient temperature, are identical across both scenarios. The annual global horizontal irradiance is measured at 1,625.5 kWh/m², while the diffuse irradiance amounts to 700.97 kWh/m², constituting approximately 43% of the total available radiation. Furthermore, the annual mean ambient temperature is 22.81°C, uniformly affecting the efficiency of the photovoltaic modules in both cases.

In Scenario 1, wherein modules are equipped with a solar tracker, the total incident global irradiance on the module plane attains 2,019.2 kWh/m². The effective irradiance, which accounts for optical losses, is measured at 1,913.2 kWh/m². The energy generated by the photovoltaic array amounts to 5,628.9 MWh, while the energy supplied to the electrical grid totals 5,546.9 MWh. The annual PR is recorded at 0.865, with October demonstrating the highest PR (0.881) and January the lowest (0.833). The months of January (198.9 kWh/m²) and February (180.9 kWh/m²) exhibit the highest incident irradiance values, reflecting the tracker's efficacy in optimizing solar energy capture. The monthly and annual results for Scenario 1 with solar tracking modules are presented in Table 1.

Table 1: Monthly and annual energy performance parameters of the photovoltaic system for Scenario 1 with solar tracking modules.

Month	GlobHor (kWh/m²)	DiffHor (kWh/m²)	T_Amb (°C)	GlobInc (kWh/m²)	GlobEff (kWh/m²)	EArray (MWh)	E_Grid (MWh)	PR (ratio)
January	165.9	79.98	25.27	198.9	188.6	533.7	525.9	0.833
February	153.7	65.52	25.30	180.9	180.9	522.4	514.9	0.856
March	149.1	63.86	25.08	185.2	175.1	509.8	501.2	0.852
April	128.4	49.50	23.16	164.3	156.0	461.9	454.9	0.872
May	111.6	41.54	21.37	145.0	137.2	409.1	403.2	0.876
June	107.4	33.00	20.44	143.0	134.0	405.8	398.6	0.876
July	111.0	37.51	20.25	145.7	138.1	411.9	406.7	0.878
August	128.7	44.95	21.35	164.3	156.2	466.1	459.2	0.879
September	122.1	67.40	22.64	161.3	153.6	428.1	420.2	0.864

October	143.2	70.06	24.13	173.0	164.0	491.4	484.0	0.881
November	148.2	76.20	23.36	177.6	168.5	488.8	481.6	0.854
December	156.2	82.15	24.26	182.1	174.0	508.6	499.4	0.864
Year	1625.5	700.97	22.81	2019.2	1913.2	5628.9	5546.9	0.865

In Scenario 2, with fixed modules, the total incident global irradiance on the module plane amounts to 1,730.7 kWh/m^2, while the effective irradiance measures 1,642.1 kWh/m^2. The energy produced by the array is 5,517.0 MWh, and the energy fed into the grid totals 5,437.8 MWh. The annual PR is calculated at 0.866, with December exhibiting the highest PR (0.881) and March the lowest (0.841). These figures exemplify the limitations inherent in the fixed structure, which does not modify the modules' orientation to track the solar path. The monthly and annual performance results of the photovoltaic system for Scenario 2 with fixed modules are summarized in Table 2.

Table 2: Monthly and annual energy performance parameters of the photovoltaic system for Scenario 2 with fixed modules.

Mês	GlobHor (kWh/m^2)	DiffHor (kWh/m^2)	T_Amb (°C)	GlobInc (kWh/m^2)	GlobEff (kWh/m^2)	EArray (MWh)	E_Grid (MWh)	PR (ratio)
January	165.9	79.98	25.27	149.2	140.6	473.3	466.5	0.862
February	153.7	65.52	25.30	146.8	139.0	463.1	456.6	0.857
March	149.1	63.86	24.39	154.8	146.9	479.1	472.2	0.841
April	128.4	49.50	23.16	147.8	140.9	467.5	461.0	0.859
May	111.6	41.54	21.37	141.0	134.2	448.0	442.3	0.865
June	107.4	33.00	20.44	145.1	138.1	464.0	457.5	0.869
July	111.0	37.51	20.25	145.5	138.5	465.8	459.2	0.870
August	128.7	44.95	21.35	145.5	138.5	465.8	459.2	0.870
September	122.1	56.70	21.96	131.0	124.3	419.3	413.5	0.872
October	143.2	70.06	23.36	139.1	132.4	449.7	443.2	0.874
November	148.2	76.20	23.36	135.6	128.7	437.0	430.7	0.871
December	156.2	82.15	24.26	139.7	131.5	453.3	446.8	0.881
Year	1625.5	700.97	22.81	1730.7	1642.1	5517.0	5437.8	0.866

The comparison between the two scenarios indicates that the utilization of the solar tracker in Scenario 1 enhances the irradiance incident upon the modules, thereby increasing both monthly and annual energy production in comparison to Scenario 2 with fixed modules. Although the annual PR remains similar in both scenarios, the total energy produced and fed into the grid is marginally higher in the scenario incorporating the tracker, attributable to the superior radiation capture during months with higher insolation. The variations observed in the monthly GlobInc and EArray values are attributable to the tracker's capacity for continuous optimization of the modules' orientation, whereas the fixed structure restricts capture to the orientation defined by the static tilt and azimuth.

4.2. Financial Performance Indicators

Capital expenditure (CAPEX), which signifies capital investment, includes the initial costs required for the deployment of a photovoltaic facility. It encompasses expenditures related to the procurement of photovoltaic modules, inverters, structural metal frameworks (both fixed and tracker-mounted), electrical systems, measurement and transformation stations, as well as engineering services, earthworks, engineering, procurement, and construction (EPC) activities, construction management, direct current (DC) cables, and other materials. This figure is crucial for assessing the financial viability of the project, as it directly influences the return on investment over time and serves as a benchmark for comparing different scenarios and plant configurations. To estimate the projected CAPEX, approximate reference values are sourced from Greener (2024). Table 3 delineates the estimated CAPEX for both scenarios, emphasizing the cost differences between fixed structures and solar tracker configurations.

Table 3: Estimated capital expenditure (CAPEX) values for the solar photovoltaic plant for Scenario 1 - Tracker and Scenario 2 - Fixed.

Item	Scenario 1 - Tracker	Scenario 2 - Fixed
Earthworks (USD)	63,848.02	41,399.18
Engineering, Procurement, and Construction - EPC (USD)	688,952.45	695,172.41
Construction Management (USD)	5,747.13	5,747.13
Modules (USD)	477,924.60	546,199.54
Inverters (USD)	9,578.54	9,578.54
Steel Structures (USD)	383,213.79	250,262.07
Measurement Booth (USD)	30,651.34	30,651.34
Transformation Booth (USD)	151,341.00	151,341.00
DC Cables (USD)	23,979.78	22,804.73
Others (USD)	97,061.89	110,927.87
CAPEX (USD)	1,932,298.53	1,864,083.80

Operational Expenditure (OPEX) encompasses the operating costs necessary to sustain the continuous operation and maintenance of the photovoltaic facility throughout its service life. These expenses include equipment operation and maintenance, module cleaning, vegetation control, land leasing, and administrative charges. The estimated values are determined to mirror realistic operational conditions and are vital for maintaining system performance, minimizing failure rates, and ensuring long-term durability. Furthermore, OPEX serves as a crucial parameter in the evaluation of the project's economic viability, as it directly impacts cash flow and overall profitability. The projected OPEX values are estimated based on reference data provided by Greener (2024). The estimated annual OPEX values for Scenario 1 (Tracker) and Scenario 2 (Fixed) are presented in Table 4.

Table 4: Estimated annual operating costs (OPEX) values for the solar photovoltaic plant for Scenario 1 - Tracker and Scenario 2 - Fixed.

Item	Scenario 1 - Tracker	Scenario 2 - Fixed
Operation and Maintenance (USD)	46,455.94	32,950.19
Module Cleaning (USD)	3,352.49	3,831.42
Plant Area Mowing (USD)	3,557.47	3,352.49
Land Leasing (USD)	2,643.68	2,490.42
Administrative Costs (USD)	5,172.41	5,172.41
OPEX/YEAR (USD)	61,181.99	47,796.93

Based on the CAPEX values, it is evident that certain components exhibit cost variations between the analyzed scenarios. In Scenario 1 (Tracker), the highest expenditures are associated with site preparation (earthworks) and steel structures, due to the requirement for more robust foundations and the increased complexity of the mobile structures that enable solar tracking. Additionally, DC cables present slightly higher costs, reflecting the need for supplementary cabling to accommodate module movement and monitoring systems.

In contrast, in Scenario 2 (Fixed), the most substantial expenditures pertain primarily to the photovoltaic modules and miscellaneous costs. The reduced energy capture efficiency of fixed arrays necessitates the installation of a greater quantity of modules to attain equivalent energy output, along with additional modifications to materials and installation procedures. Certain components, such as construction management, inverters, measurement booths, and transformation booths, incur identical costs across both scenarios, given their independence from structural configuration. Overall, the variations in CAPEX reflect the technical distinctions inherent to each technology: tracker systems require a higher investment in structural components and land preparation, whereas fixed structures demand a larger number of modules to compensate for diminished solar capture.

Net revenue is calculated by multiplying the net tariff of USD 150.67 per MWh by the annual energy production for each scenario. Accordingly, the Tracker scenario results in a net revenue of USD 835,764.81, whereas the Fixed structure scenario produces USD 819,326.45. These figures directly correspond to the energy performance of each configuration, demonstrating that the tracking system yields higher energy generation and, consequently, greater annual revenue compared to the fixed system.

The financial indicators demonstrate minor variations between the two scenarios. The LCOE for Scenario 1 (Tracker) is USD 0.04982 per kWh, marginally exceeding that of Scenario 2 (Fixed), which is USD 0.04688 per kWh. This disparity indicates the heightened initial investment and operational expenses associated with the tracker-based system. The NPV for the Tracker scenario is USD 4,274,667, whereas the NPV for the Fixed scenario is USD 4,319,800, demonstrating that the Fixed configuration provides a marginally greater net financial benefit over the course of the project.

Regarding the IRR, the Tracker scenario exhibits an IRR of 35.11%, in comparison to 36.26% for the Fixed scenario. A similar pattern is observed in the discounted payback period, which is 3.49 years for the Tracker and 3.36 years for the Fixed structure. Although the tracker system yields greater energy output and higher annual revenues, the Fixed configuration demonstrates marginally superior financial performance due to its lower overall capital and operational costs. Table 5 provides a comparative summary of the primary financial indicators for both scenarios, including LCOE, NPV, IRR, and discounted payback period.

Table 5: A comparative analysis of the financial indicators for Scenario 1 - Tracker and Scenario 2 - Fixed.

Financial Indicators	Scenario 1 - Tracker	Scenario 2 - Fixed
LCOE (USD/kWh)	0.04982	0.04688
NPV (USD)	4,274,667	4,319,800
IRR (%)	35.11	36.26
Discounted Payback (years)	3.49	3.36

5. Conclusions

The comparative results underscore the intricate trade-offs among simplicity, cost, and performance. Fixed-tilt systems are preferable for projects with budget limitations, as they reduce financial risk and operational complexity. They are also less prone to mechanical failures and require lower maintenance, which is particularly vital in remote locations with limited technical support. The technical analysis demonstrated that the tracking system offers an increase in energy generation over time owing to its capability to follow the solar incidence and optimize radiation capture. Nonetheless, this enhancement in efficiency entails a higher initial investment cost and increased operational expenses, arising from the necessity for supplementary maintenance and greater structural complexity.

Concerning the economic analysis, the findings indicated that, despite the superior energy efficiency of the tracking system, the plant equipped with a fixed structure exhibited more favorable economic indicators, including a reduced initial investment cost and a more compelling long-term financial return. Under the specified conditions, the fixed-tilt PV plant emerged as the most economically advantageous option, offering a more resilient and lower-risk solution for investors seeking to implement distributed generation photovoltaic projects. This outcome results not only from elevated investment and operational expenditures but also from the plant sizing considerations. The peak power of the fixed-tilt system was greater in comparison to that of the tracking system. This phenomenon occurs because, to prevent shading effects, a plant equipped with trackers necessitates a larger installation area. Consequently, for the same plot of land, the installation of additional modules was found to be more advantageous than implementing a tracking system.

This emphasizes a significant aspect in the economic feasibility analysis of a project: geographical limitations. This factor may render the use of tracking structures impractical, as they necessitate flatter terrain, and could also constrain the attainable peak power. To achieve the same installed capacity as a fixed system, a tracking system would require a larger area, which may not always be available under practical project conditions. An additional pertinent consideration is the variability across different regions. In locales characterized by high direct normal irradiance (DNI) and prolonged daylight hours, tracking systems exhibit a distinct competitive advantage. Conversely, in areas experiencing elevated diffuse radiation owing to frequent cloud cover, the relative benefit of tracking diminishes, rendering fixed-tilt systems more appropriate. This underscores the necessity of customizing system design in accordance with local climatic conditions. Furthermore, the economic feasibility of tracking systems is sensitive to financial parameters, such as discount rates and access to financing. Projects with high capital costs or limited credit availability may not fully capture the long-term benefits of increased generation. Conversely, large-scale utility projects with access to favorable financing are more likely to benefit from the tracking configuration.

In summary, the analysis demonstrates that the choice between fixed and tracking structures is not absolute but conditional. It depends on a combination of technical factors (irradiance profile, resource availability, land characteristics) and economic variables (CAPEX, O&M, financing conditions), which together define the optimal system configuration for each project. For future research endeavors, it is advisable to undertake additional analyses to further explore the findings of this study. First, an evaluation of various tracker types should be conducted, comparing single-axis and dual-axis systems to assess their effects on energy production, costs, and LCOE. Second, it is recommended to undertake plant layout optimization studies employing algorithms designed to maximize module density and energy efficiency, while taking into account shading and terrain features. Lastly, the study should be expanded to include different geographic locations, thus enabling the validation of the results' robustness across regions characterized by diverse solar irradiation and temperature profiles.

6. Acknowledgments

The authors acknowledge the support provided by the National Council for Scientific and Technological Development (CNPq, Brazil).

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