Climate change impact on fixed, one-axis, and two-axis solar PV technologies in Brazil

Paula Conde Santos Borba[1,2], André Rodrigues Gonçalves[1], Rodrigo Santos Costa[1], Francisco José Lopes de Lima[1], Meiriele Alvarenga Cumplido[1], Hallan Souza de Jesus[1,2], Felipe Husadel Poyer[1], Fernando Ramos Martins[1,2]

[1] Laboratory of Modeling and Studies on Renewable Energy Resources, INPE, São José dos Campos - SP

[2] Institute of Marine Science, Federal University of São Paulo (UNIFESP), Santos – SP

Abstract

Solar energy is a key driver of the global energy transition, with photovoltaic (PV) capacity expanding rapidly worldwide. However, climate change is expected to alter renewable resources, including solar irradiation, in spatially and seasonally heterogeneous ways. These variations, combined with the different performance of fixed-tilt and tracking PV systems, can lead to positive or negative shifts in electricity generation and influence the regional cost of solar energy deployment. This study quantifies the performance gains of one- and two-axis tracking systems relative to fixed-tilt configurations under current and future climate conditions in Brazil. A geospatial analysis was also conducted to identify suitable areas for utility-scale PV installations and to evaluate their corresponding levelized cost of electricity (LCOE) across the country. Results show that tracking systems provide an annual energy yield 34–43% higher than fixed panels, with the greatest advantage observed between April and July. Under climate change scenarios, solar generation potential increases across most of Brazil, except in the South, where a slight decline is projected. Overall, the effects of climate change are modest but predominantly beneficial, leading to LCOE reductions of approximately 0.6–1.1 US$/MWh in large portions of the country and reinforcing Brazil's strong potential for resilient, low-cost solar expansion.

Keywords: solar energy, climate change, tracking systems

1. Introduction

Solar energy is rapidly becoming a major component of the global energy transition, growing by 25% in 2023 and reaching 1,600 TWh of electricity generation worldwide (IEA, 2024). It recorded the highest expansion among all renewable technologies, driven by declining costs and robust policy support. Despite this growth, the long-term performance of solar technologies under climate change conditions remains insufficiently explored in the context of energy system planning.

The variability in solar energy production and the performance differences among photovoltaic technologies can be affected by climate change, as it alters solar resources unevenly across regions and seasons. Previous studies have evaluated the capability of CMIP6 climate models to reproduce and project surface solar irradiance in various parts of the world (de Lima et al., 2024; Hou et al., 2021). These simulations suggest that while climate change is likely to have only a modest impact on the overall renewable energy potential, it will alter the spatial and temporal distribution of electricity generation. Such changes should be explicitly considered in the design and planning of future power systems.

Understanding these dynamics is particularly important when assessing the performance of different photovoltaic configurations. Solar PV systems can be designed with various tracking mechanisms to maximize energy capture by following the sun's apparent motion across the sky. Fixed-tilt systems are stationary and set at an optimal angle, offering simplicity and lower costs but limited adaptability to seasonal solar angle changes. In contrast, one-axis tracking systems rotate along a single axis, enhancing energy yield by approximately 15–25% depending on location and season (Alonso-Abella et al., 2014). Two-axis systems, which track both horizontal and vertical solar movements, can maintain near-perpendicular orientation to sunlight year-round, achieving gains of 30–40% or more over fixed systems, especially in regions with high solar variability (Li et al., 2018). These gains could result in a smaller dedicated area for solar farms.

10.18086/swc.2025.03.11 Available at http://proceedings.ises.org

The combined effects of climate change and PV technology configuration are often analyzed in isolation or limited to a single system setup, leaving critical knowledge gaps in how these factors interact over space and time. Climate change can modify the regional availability of solar resources and consequently affect the levelized cost of electricity (LCOE), leading to cost increases in some regions and reductions in others. These spatial disparities highlight the need to evaluate how shifting climatic conditions influence both generation potential and investment competitiveness. Since the LCOE is strongly driven by capacity factor variations and local resource quality, incorporating these spatially differentiated impacts into energy planning is essential for identifying resilient and cost-effective areas for future solar deployment.

The analysis of the impact climate change is particularly relevant for Brazil, since solar energy deployment has accelerated significantly in recent years. The installed capacity of centralized photovoltaic systems has reached 18 GW, while distributed solar PV expanded from almost zero to 42 GW (ABSOLAR, 2025). This expansion reflects the country's favorable solar resources, supportive policies, and rapid decrease in technology costs. As solar energy becomes a key pillar of Brazil's electricity system, its growing dependence on weather and climate variability raises important questions about long-term reliability and resilience.

This study addresses this gap by evaluating the benefits of considering tracking systems over the fixed ones. Then, the monthly impacts of climate change on solar electricity generation across Brazil, considering three configurations (fixed-tilt, one-axis tracking, and two-axis tracking systems). Using reanalysis data from 2,267 locations, climate change correction factors are applied to hourly solar irradiance time series to estimate future electricity output. The next steps consist of evaluating the available areas for the deployment of utility-scale PV, and the associated LCOE distributed spatially. The results provide insights for improving the accuracy and resilience of long-term energy planning, supporting more informed investment and policy decisions in Brazil's evolving solar sector.

2. Methods

The methods include the steps indicated in Figure 1. ERA5 climate reanalysis data and PV-GIS panel performance information were used to estimate the electricity generation of fixed, one-axis, and two-axis tracking photovoltaic systems. The overperformance of one- and two-axis tracking systems relative to fixed-tilt configurations was evaluated. Climate change factors were then applied to quantify variations in solar performance under different climate scenarios. From these results, the available areas for solar farm deployment were identified, excluding unsuitable or restricted lands. The resulting spatial distribution of the Levelized Cost of Electricity (LCOE) under climate change scenarios was used to construct supply curves.

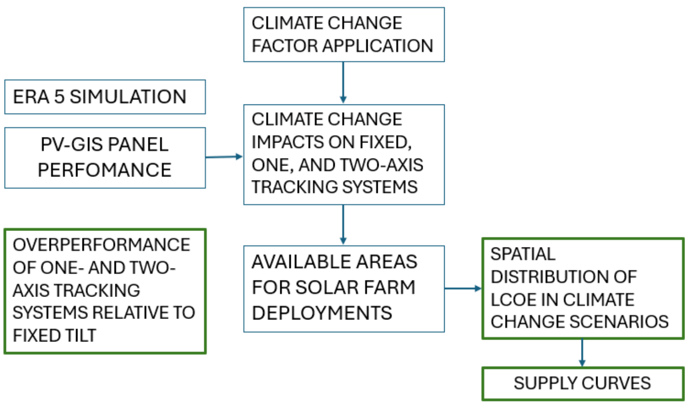

Figure 1: Workflow of the analysis for assessing climate change impacts on solar energy systems.

2.1. Simulation of solar output

This study employs ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts

(ECMWF) to simulate solar energy production across 2,267 coordinate points distributed throughout the Brazilian territory, using a spatial resolution of 0.5º in latitude and 0.625º in longitude. The selected reference year for this analysis is 2013, which represents a typical climatological year in terms of solar radiation patterns.

To estimate the electricity output from solar irradiation data, we use the Photovoltaic Geographical Information System (PVGIS) API, a widely recognized tool developed by the European Commission's Joint Research Center. The PVGIS API allows for hourly performance simulation of photovoltaic systems by incorporating meteorological input, solar geometry, and system losses. In this study, we evaluate three types of solar tracking configurations: (i) fixed-tilt systems, (ii) one-axis tracking systems (rotating along the horizontal North-South axis), and (iii) two-axis tracking systems, which follow the sun in both azimuth and elevation for maximum energy capture.

For all simulations, we assume crystalline silicon (c-Si) photovoltaic modules, which are the most commercially adopted PV technology globally due to their maturity, efficiency, and cost-effectiveness. System losses are accounted for according to PVGIS default parameters, including inverter efficiency, temperature losses, and soiling. The inclusion of different tracking technologies enables an assessment of potential performance gains across Brazil's diverse climate zones and supports more detailed energy planning under current and future climate scenarios.

2.2 Climate change factors

The study evaluates the potential impacts of climate change on solar energy resources in Brazil by applying Climate Change Factors (CCFs) developed by the Laboratory of Energy Modelling and Renewable Resources (LABREN) at INPE, as presented in De Lima et al. (2024). These CCFs are derived from an ensemble of climate model projections that simulate variations in solar irradiation under two Shared Socioeconomic Pathways (SSPs): SSP2-4.5 (intermediate scenario) and SSP5-8.5 (high-emissions scenario). The projections are provided for two future time slices, 2015–2040 and 2041–2070, capturing both near- and mid-century climate dynamics.

The original CCF data has a high spatial resolution of 30x30m, however, the data are spatially aggregated into pre-defined geographical zones in this work. Within each zone, the CCFs were averaged to generate representative mean values that reflect the expected change in solar resource availability. This spatial processing was carried out using QGIS, an open-source Geographic Information System software. The resulting aggregated CCFs were then applied to the original solar radiation time series to simulate the expected performance of PV systems under future climate scenarios.

2.3 Analysis of power gains and losses

To assess the impact of climate change on solar power generation, the monthly Climate Change Factors (CCFs) were applied multiplicatively to the historical hourly solar capacity factor time series associated with each predefined zone. To facilitate interpretation, the final results were aggregated by Brazil's five macro-regions (North, Northeast, Central-West, Southeast, and South). This regional aggregation highlights spatial trends in the expected gains or losses in photovoltaic performance under different climate scenarios, allowing clearer insights for regional energy planning and investment decisions.

2.4 Suitable areas for solar farms and supply curve

To find the available areas exclusion zones were applied according to environmental, social, and technical considerations to identify suitable areas for utility-scale photovoltaic (PV) installations. Protected areas, public forests, and selected land-use categories were excluded with a 1 km buffer. Land-use restrictions followed MapBiomas classes, allowing only classes 4 (savanna), 12 (grasslands), 15 (pasture), 21 (mosaic of agriculture/pastures), and 39 (soybean crops) (MMA, 2023). The following land-use classes were excluded: forest formation, mangrove, floodable forest, wooded sandbank vegetation, wetland, hypersaline tidal flat, rocky outcrop, herbaceous sandbank vegetation, temporary crop, sugarcane, rice, cotton, other temporary crops, coffee, citrus, palm oil, other perennial crops, forest plantation, beach, dune and sand spot, urban area, mining, other non-vegetated areas, river, lake and ocean, aquaculture, and not observed (MapBiomas, 2023). Indigenous and quilombola territories, as well as urban areas, were excluded with a 1 km buffer to avoid conflicts with traditional and densely populated areas (INCRA, 2023; MMA, 2023).

Sites with slope greater than 10% were excluded, as steep terrain substantially increases construction and maintenance costs (TOPODATA, 2012). Airports were buffered by 3 km to prevent conflicts with aviation safety. Existing utility-scale PV plants and onshore wind farms were also excluded to avoid double counting of already occupied land (EPE, 2023). For existing PV plants, exclusion areas were estimated based on the current installed capacity and a capacity density of 33 MW/km², applying a square buffer from each coordinate point.

After identifying the available land area, the levelized cost of electricity (LCOE) was computed using the average historical capacity factor. The formulation used to calculate the LCOE is presented in Equation (1):

$$\text{LCOE} = \frac{\text{Capex}*\text{CRF}+\text{Opex}}{8760*\text{CF}} \quad \text{(eq. 1)}$$

where *Capex* represents the capital cost per installed megawatt (US$/MW), assumed to be 756,000 US$/MW; *Opex* is the annual fixed operation and maintenance cost (US$/MW-year), assumed to be 0.01134 US$/MW; *CF* is the capacity factor (ranging from 0 to 1); and *CRF* is the capital recovery factor. The *Capex* and *Opex* values were obtained from EPE (2025).

Equation 2 estimates the CRF:

$$CRF = \frac{r*(1+r)^N}{(1+r)^N-1} \qquad \text{(eq. 2)}$$

where *r* is the real weighted average cost of capital (WACC), and *N* is the project lifetime, here assumed to be 25 years. For the WACC, a baseline value of 5% was adopted, while a sensitivity analysis was performed considering intermediate (8%) and high (10.75%) values, the latter following the estimate provided by the IEA (2023). By combining the LCOE results obtained under different WACC assumptions with the spatially available areas for solar farm deployment, a supply curve was developed. This curve represents the cumulative installable capacity as a function of the corresponding generation cost, illustrating how financing conditions affect the economic potential of solar expansion.

3. Results and discussion

3.1. Gains of tracking systems

The capacity factor for fixed-tilt photovoltaic systems has a seasonal variability throughout the year, with a clear reduction in electricity generation observed during May to July as shown in Figure 1. The highest average capacity factors are generally recorded between January and March, and again in the final quarter of the year (October to December), with regional differences. For instance, the Northeast consistently shows higher values across most months, while the South experiences the most intense seasonal drop, highlighting the influence of regional climate conditions on solar energy performance. These patterns emphasize the importance of considering temporal and spatial variability in energy planning and PV system design across Brazil.

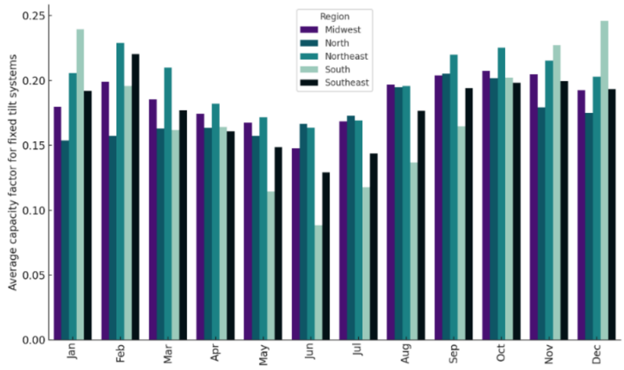

Figure 2: Annual average capacity factor for five Brazilian regions.

One-axis and two-axis tracking systems outperform the fixed ones by an annual gain of 33.8% and 42.8%, respectively. These gains are, however, not constant over the months and regions as indicated in Figure 2. The gain from tracking is highest in months like April and July, and lower in January and December, possibily due to optimal sun angles already aligning well with fixed systems during these months. For two-axis systems, percentage gains over the fixed systems may achieve 86% in July for the Southern region.

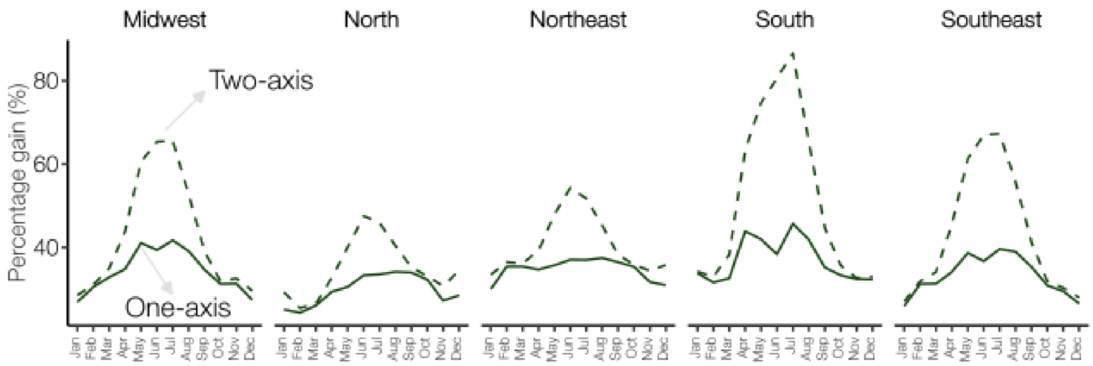

Figure 3: Percentage gain over the fixed systems. The dashed line indicates the two-axis tracking system gain over the fixed one and the solid line represents the gain of one-axis tracking system.

4.2 Climate change effects on fixed and tracking systems

Across most regions and technologies, the projected changes in PV performance are slightly positive, except for the Southern region, where a decrease is observed. Climate change under the scenario SSP5 8.5 is expected to lead to increases in solar capacity factors, with absolute increments ranging from -0;70% to 1.5% (percentage point) for the long-term (2040-2070) and -0.70% to 1.2% for the medium term (2015-2040). The gains and losses are moderate in scenarios SSP2 4.5, varying from -0.2% to 0.9% in both time horizons.

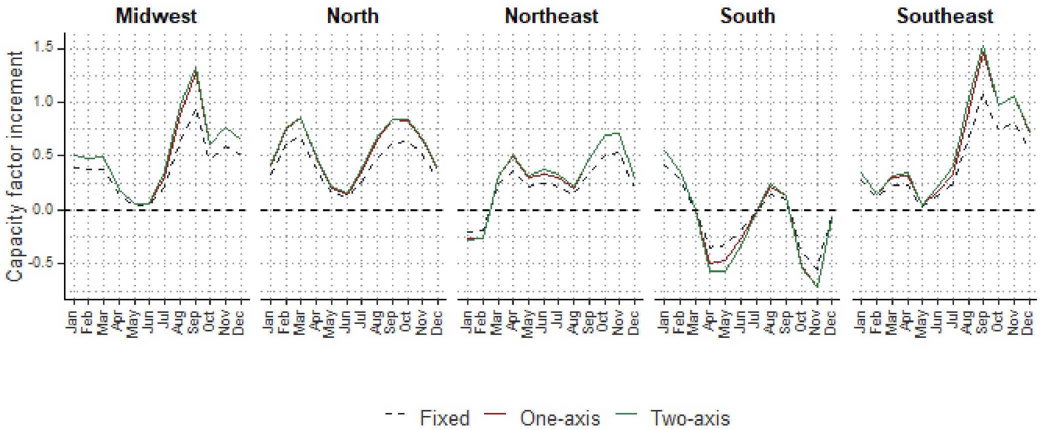

Figure 4: Absolute capacity factor increments over the reference year for climate change scenario SSP5 8.5 2040-2070.

The results indicate that regions have a different response of solar resources under climate change. March to August tends to have more pronounced gains, particularly for Midwest and Southeast regions. For the South, the negative increment (losses) occurs in April and November in all scenarios.

Although the direction of change is generally positive, the magnitude of improvement remains modest. The capacity factor increases, but are not substantial enough to drive major system-level changes without considering other planning factors. Nevertheless, these results support the notion that PV systems, especially those with tracking capabilities, may experience small but beneficial performance shifts in a changing climate, if losses in the efficiency due to the increase of temperature are ignored.

4.2 Available lands for utility-scale PV and the impacts of climate change on costs

Figure 4 presents the supply curves of LCOE for utility-scale photovoltaic (PV) projects under different WACC assumptions, considering fixed-tilt systems. After applying land-use exclusions, the estimated technical potential for utility-scale PV deployment reaches approximately 65 TW. However, this value should be interpreted with caution, as the analysis does not account for transmission infrastructure or grid connection constraints, which could significantly limit the feasibility of new solar park installations.

The results show a clear sensitivity of LCOE to financing conditions. As the discount rate increases from 5% to 10.75%, the average generation cost rises substantially, shifting the entire supply curve upward. At a 5% WACC, the LCOE ranges from roughly 35 to 55 US$ MWh^{-1}, whereas at 8% and 10.75% WACC the range widens to 44–69 and 53–84 USD MWh^{-1}, respectively. The shape of the curves reflects the least-cost ordering of potential sites. Low-cost areas are exploited first, followed by progressively more expensive locations as cumulative installed capacity increases. The cost escalation is relatively smooth until the upper tail, where the marginal cost of additional deployment grows sharply, indicating that only a limited share of potential sites remains economically competitive under higher discount rates. Overall, the analysis highlights the critical role of financing conditions in determining the economic feasibility of large-scale renewable energy expansion.

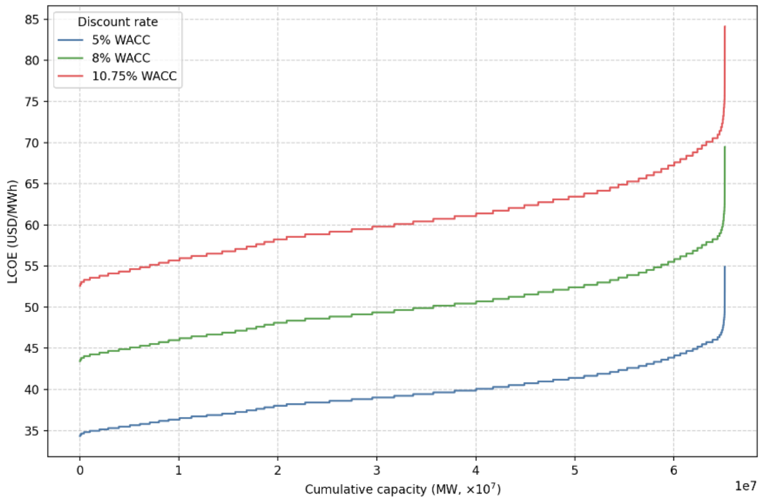

Figure 5: Supply curves of LCOE for different discount rates. The sharp increase at the upper end of the curves indicates that only a limited portion of the remaining potential is economically viable under high financing costs.

The spatial distribution of the LCOE for utility-scale photovoltaic (PV) generation under different climate scenarios is presented in Figure 5. In the baseline period (2040–2070), the lowest costs (below 37 US$/MWh) are concentrated in the Northeast region, where high solar irradiance favor PV performance. Moderate LCOE values (38–40 US$/MWh) extend across the Midwest and part of the Southeast, while higher costs (above 41 US$/MWh) occur mainly in the South and in the Amazon, where lower solar resource availability prevails.

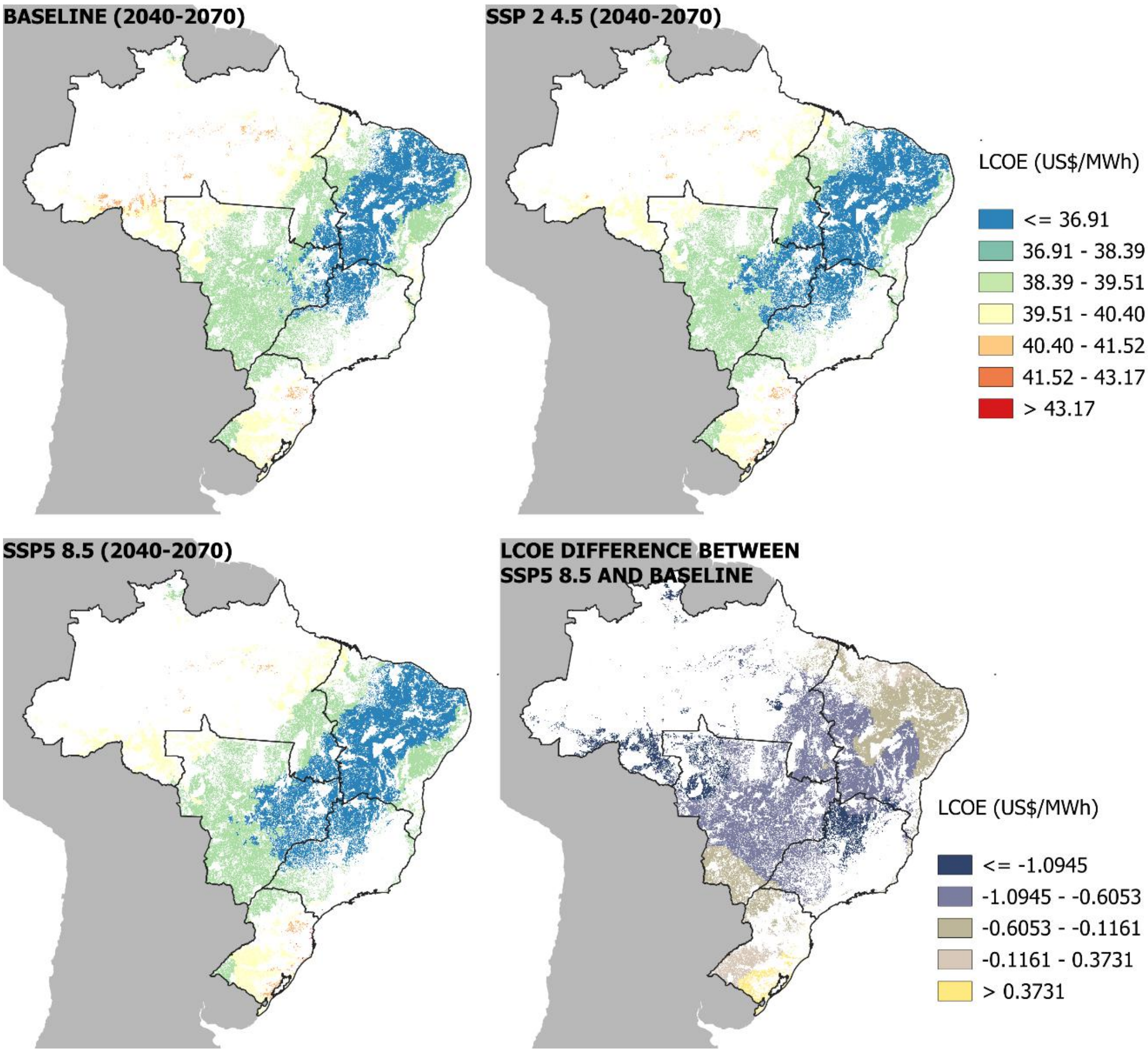

Figure 6: Available land for utility-scale PV deployment and corresponding levelized cost of electricity (LCOE). The first map shows the LCOE in the baseline scenario for 2040–2070. The second map shows LCOE under the climate change scenario SSP2-4.5 for 2040–2070. The third map LCOE under the climate change scenario SSP5-8.5 for 2040–2070. The fourth map LCOE change in SSP5-8.5 relative to the baseline scenario, highlighting the impact of climate change.

Under the SSP2-4.5 scenario, smaller variations are observed relative to the baseline (Figure 5), with minor cost reductions in the Northeast and Midwest (Figure 5B). In the SSP5-8.5 scenario, this pattern becomes more pronounced, showing a broader area of reduced LCOE across central and northeastern Brazil.

Figure 5 highlights the difference in LCOE between SSP5-8.5 and the baseline scenario, revealing a general reduction of up to 1.1 US$/MWh, especially in the interior Northeast and northern Minas Gerais. Although the overall change represents a modest decrease, it indicates that climate change could slightly enhance PV performance in several high-irradiance regions of Brazil. Conversely, localized cost increases are observed in the South, where the overall performance is expected to decrease.

Overall, the results suggest that the impacts of climate change on PV economics in Brazil are spatially heterogeneous but predominantly beneficial, reinforcing the robustness of solar energy as a long-term mitigation option even under high-emission scenarios.

4. Conclusion

This study provides an assessment of how climate change may affect the performance and spatial economics of different photovoltaic (PV) configurations in Brazil. By combining ERA5 reanalysis data, PV-GIS performance simulations, and climate change factors derived from CMIP6 models, it was quantified how fixed, one-axis, and two-axis tracking systems respond under future climate scenarios (SSP2-4.5 and SSP5-8.5).

In a scenario that does not consider climate change, tracking technologies show significant gains over fixed-tilt systems, improving electricity generation by 34% to 43% under current conditions. These advantages persist under climate scenarios, suggesting that dynamic tracking can enhance system resilience against seasonal and regional irradiance variability. Under climate change scenarios, most Brazilian regions, particularly the Northeast and Midwest, are expected to experience slight increases in solar potential, while the South may see declines.

By integrating spatial land-use restrictions with LCOE calculations, the study also identified suitable areas for solar farm deployment and constructed supply curves under different financing assumptions. The results reveal that economic feasibility remains highly sensitive to the weighted average cost of capital (WACC), with costs ranging from 35 US$/MWh to 80 US$/MWh depending on financing conditions. Nonetheless, even under conservative assumptions, large areas remain cost-competitive for solar deployment, confirming Brazil's strong potential for sustained solar expansion.

Overall, the findings highlight that climate change will not undermine, and may even modestly enhance, Brazil's solar energy potential. The combination of favorable irradiance patterns, tracking technology adoption, and effective spatial planning ensures that solar power can continue to play a central role in Brazil's energy transition. However, this study investigate exclusively the impact of climate change on the electricity generation from solar resource and does not account for the impacts of temperature on PV efficiency. For solar energy, however, if no technological improvements occur in the long term, these gains might be offset by rising temperatures. The impacts of extreme weather events due to climate change are also not considered. The costs are associated with the deployment of the solar park. Costs related to grid connection and transmission lines expansion are excluded. Future research should incorporate these issues and explore system-level interactions with hydropower and storage, advancing the understanding of climate-resilient renewable systems.

5. Acknowledges

This work was supported by the São Paulo Research Foundation (FAPESP), process nº 2024/02007-7.

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