

SIMULAÇÃO AGROVOLTAICA COM TOMATE NO SEMIÁRIDO CEARENSE INTEGRADO COM A PRODUÇÃO

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RESUMO: Este estudo avaliou a viabilidade técnica e agrônômica de um sistema agrovoltaico no município de Russas, Ceará, integrando a geração de energia solar com o cultivo de tomate (*Solanum lycopersicum*) em condições semiáridas. Utilizando modelagem computacional em Python e a biblioteca PVlib, foram simulados os dados de irradiância solar e produtividade agrícola ao longo de 12 meses. O sistema fotovoltaico, composto por 8 módulos de 550 W instalados a 2,5 m de altura, apresentou geração anual estimada de 7.030,00 kWh. A produção de biomassa vegetal total foi de 272,00 kg, com pico nos meses de junho e julho. Os resultados indicam que a integração entre produção energética e agrícola é viável, promovendo o uso eficiente da terra, redução do estresse térmico nas plantas e conservação hídrica. O modelo agrovoltaico demonstrou potencial para contribuir com a sustentabilidade ambiental e a segurança alimentar em regiões de alta incidência solar.

Palavras-chaves: Agrovoltaico, Energia Solar, Sustentabilidade, Python

AGRIVOLTAIC SIMULATION WITH TOMATO CULTIVATION IN THE SEMI-ARID REGION OF CEARÁ INTEGRATED WITH ENERGY PRODUCTION

ABSTRACT: This study evaluated the technical and agronomic feasibility of an agrivoltaic system in the municipality of Russas, Ceará, that integrates solar energy generation with tomato (*Solanum lycopersicum*) cultivation under semiarid conditions. Using computational modeling in Python and the PVlib library, solar irradiance and agricultural productivity data were simulated over a 12-month period. The photovoltaic system, composed of eight 550 W modules installed at a height of 2.5 meters, yielded an estimated annual energy output of 7,030.00 kWh. The total plant biomass production reached 272.00 kg, with peak yields occurring in June and July. The results indicate that the integration of energy and agricultural production is feasible, promoting efficient land use, reducing thermal stress on crops, and enhancing water conservation. The agrivoltaic model demonstrated strong potential to contribute to environmental sustainability and food security in regions with high solar incidence.

Keywords: Agrivoltaics, Solar Energy, Sustainability, Python

1 INTRODUCTION

One of the greatest problems worldwide is the increase in greenhouse gas emissions, which intensify global warming and cause severe environmental imbalances. In response to this challenge, several countries have adopted public policies aligned with what was agreed upon under the Paris Agreement, whose objective is to limit the increase in the average

global temperature to a maximum of 1.5°C above preindustrial levels (Brazil, 2024).

Brazil, as a signatory to the Agreement, has committed to ambitious targets to reduce its emissions and promote a sustainable development model. In 2025, the country presented the Brazil 2050 Strategy, a long-term plan that guides public policies and strategic investments focused on environmental

sustainability, social justice, and institutional strengthening (Brazil, 2025).

In 2024, the livestock sector was responsible for 54.17% of national greenhouse gas emissions, totaling more than 1.24 billion tons of CO₂ equivalent, surpassing all other sources combined (Exame, 2025). Furthermore, approximately 70% of the emissions associated with deforestation are directly linked to the expansion of livestock farming, reinforcing its central role in the environmental impacts of Brazil.

Brazil's energy transition, which is based on the expansion of renewable sources such as solar and wind power, has advanced rapidly, especially in the semiarid Northeast. Although these sources are fundamental to reducing greenhouse gas emissions, their large-scale implementation has generated significant environmental and social impacts, particularly on the Caatinga biome, which is unique to Brazil.

According to a survey by MapBiomass, the area occupied by medium- and large-scale solar power plants in Brazil increased from 822 hectares in 2016 to 35,300 hectares in 2024, with 62% of this area located in the Caatinga biome (Ihu, 2025). This accelerated growth has generated concerns regarding the suppression of native vegetation, desertification, and loss of biodiversity. In addition to ecological impacts, the expansion of solar parks has generated land conflicts and the expropriation of traditional communities, which denounce the lack of prior consultation and damage to their ways of life (Dialog Earth, 2024).

A possible solution to the territorial and environmental challenges of expanding renewable energies in Brazil lies in generating synergy between solar energy and the agricultural sector through agrivoltaic technology. This approach has already been adopted in several countries in Europe and Asia, where high population density and spatial limitations demand efficient land use (Lacerda *et al.*, 2022).

This concept was proposed in 1981 by researchers Adolf Goetzberger and Armin Zastrow and consists of using the same area for solar energy generation and agricultural production, promoting mutual benefits for both

cultivated biomass and energy efficiency (Goetzberger; Zastrow, 1982).

Agrovoltaic systems represent an eco-sustainable alternative to traditional production, promoting synergies between solar energy generation, food production, and water management (Lacerda *et al.*, 2022; Bursztyn, 2020). Furthermore, technical analyses indicate that the Brazilian semiarid region has high potential for photovoltaic generation, with opportunities for public policies focused on family farming (Dantas, 2020). Coupled with the need to optimize land use, this has driven the development of agrovoltaic systems that integrate agricultural production and energy generation (Dupraz. *et al.*, 2011). Such systems are particularly promising in semiarid regions such as Ceará, where high solar incidence allows high energy yield (Ciec, 2020).

Tomato cultivation is widespread in the region and shows promising results in terms of cultivation with partial shade. (Kujawa *et al.*, 2025). In this context, the importance of using shade-tolerant crops, such as tomatoes, stands out, as they have a greater capacity to adapt to environments with a partial reduction in direct solar radiation, maintaining their productivity under photovoltaic structures (Amazcci; Yin; Colauzzi, 2025). 2018).

This work will simulate agrovoltaic systems in the municipality of Russas, Ceará, focusing on evaluating energy generation over 12 months and the agricultural productivity of tomato crops. The Python programming language will be used, enabling computational modeling of the systems, analysis of climatic data, and processing of energy and agronomic results. This proposal aims to contribute to the development of integrated solutions that reconcile energy sustainability, food security, and efficient land use.

2 MATERIALS AND METHODS

The main library used for the analyses was PVlib, which offers advanced tools for modeling photovoltaic systems. With it, it was possible to calculate the solar position, irradiance on inclined surfaces, and optical and electrical losses and estimate energy generation

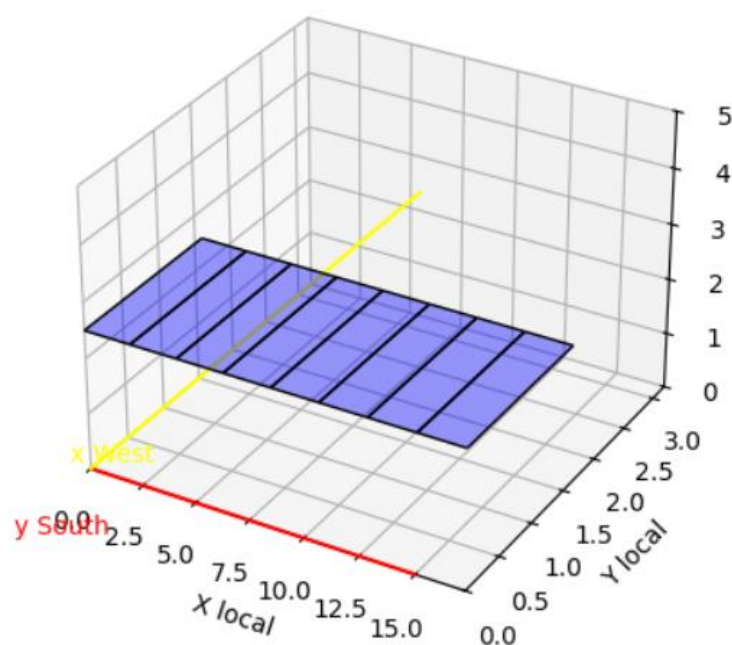
on the basis of the meteorological and technical data of the system (Holmgren). *et al.*, 2018).

In parallel, a proprietary algorithm was developed to simulate agricultural productivity. This algorithm was structured on the basis of agronomic and environmental fundamentals, considering variables such as temperature, solar radiation, soil moisture, and the physiological characteristics of the tomato crop, adapted to the semiarid context of the municipality of Russas. The approach adopted allowed for the estimation of agricultural growth and productivity in a personalized way, which was

suitable for local conditions and the objectives of the study (Lacerda *et al.*, 2022).

A simulation was performed for a typical north-facing photovoltaic (PV) array located in Russas, Ceará (latitude: 4.9397° S; longitude: 37.9739° W), characterized by a semiarid climate with high solar incidence. The array consists of 8 standard photovoltaic modules, each measuring 2.15 m wide by 1.6 m long, with a power of 550 W and installed at a height of 2.5 m at a 10° angle, totaling an installed capacity of 4.4 kWp, as shown in Figure 1.

Figure 1. Representation of solar modules.



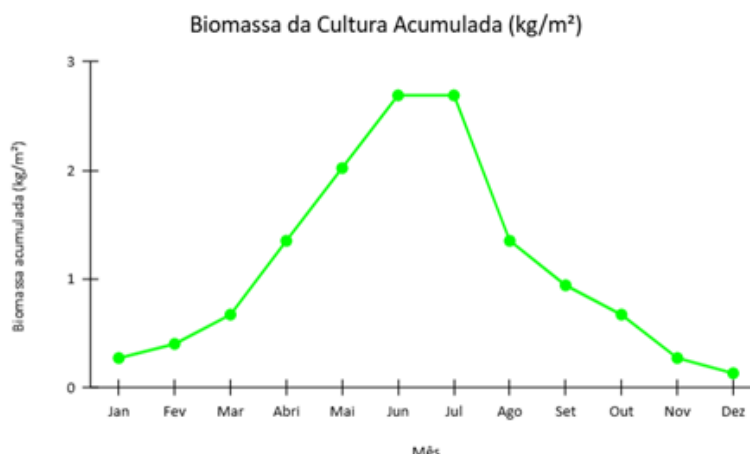
3 RESULTS AND DISCUSSION

In this research, the agronomic performance of tomato (*Solanum*) cultivation was evaluated. This study evaluated the use of **Phyllanthus lycopersicum ** in an agrovoltaic system over one year, considering an area of 27.25 m², a density of 2 plants/m², and a height of 2.5 meters. The productivity of plant biomass and solar energy generation were analyzed to understand the integrated viability of the system.

The estimated total annual biomass was 272.00 kg, corresponding to an average of 5.00 kg per plant. The monthly distribution of biomass followed the phenological pattern of

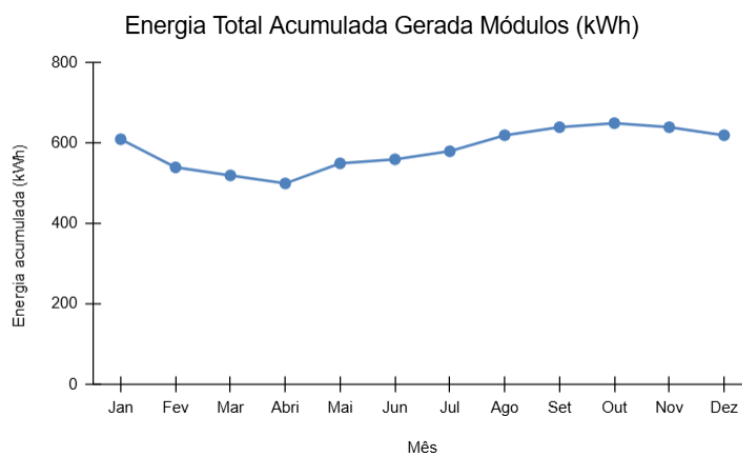
the crop, with gradual growth in the first month, peak productivity between June and July, and a decline in the final month of the year, as shown in Figure 2. The maximum productivity value was observed in July, at 2.70 kg/m², reflecting the peak of fruiting and accumulation of plant mass.

The accumulated biomass curve highlights the influence of crop cycles, with three well-defined annual cycles. Compared with conventional systems, applied shading reduced direct radiation on the plants, which may have contributed to an estimated 15% reduction in productivity but also provided benefits such as less thermal stress and greater water conservation.

Figure 2. Monthly Variation in the Accumulated Biomass of the Tomato Crop

The energy production of the photovoltaic system showed seasonal variations, with monthly values between 500 and 600 kWh, indicating significant annual generation. The accumulated energy curve remained stable throughout the year, with a slight decline in the months of lower solar radiation (March to June), followed by recovery in subsequent months, as observed in Figure 3.

The coexistence of solar panels and agricultural crops proved to be efficient and did not significantly compromise plant productivity. The 2.5 m height of the panels allowed for good penetration of diffuse light, which is essential for photosynthesis, while simultaneously ensuring adequate space for plant development.

Figure 3. Monthly Variation in the Total Accumulated Energy Generated by Photovoltaic Modules

Agrovoltáic systems are capable of reconciling agricultural production and energy generation, promoting the efficient use of land and contributing to the sustainability of cultivation. The accumulated plant biomass and the energy generated show distinct but complementary curves, reinforcing the model's potential for regions with high solar incidence, such as Northeast Brazil.

4 CONCLUSIONS

Agrovoltáic system in Russas, Ceará, demonstrated the ability to integrate solar energy generation and tomato cultivation under semiarid conditions. With an estimated annual production of 7,030.00 kWh/year and an accumulated plant biomass production of

272.00 kg over a one-year period, the model demonstrated energy and agronomic efficiency. The elevated structure of the solar panels allowed good penetration of diffuse light, which promoted plant development and contributed to a reduction in thermal stress and water conservation.

The system has shown promise in promoting the rational use of land and reconciling food production with clean energy. This approach represents a strategic alternative for semiarid Northeast Brazil, with the potential to strengthen food security and environmental sustainability in the face of climate change. The results reinforce the role of agrivoltaic systems as an innovative solution.

In future work, it is recommended that experimental field trials be conducted to validate the simulated data, in addition to an economic analysis of the model at different production scales. It is also relevant to explore other shade-tolerant agricultural crops, study cooperative arrangements aimed at rural communities, and integrate technologies such as smart irrigation and energy storage. These initiatives can broaden the social, environmental, and technological impact of agrivoltaic systems in Brazil.

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