Using agrivoltaic systems to generate income in areas susceptible to desertification

Gabriel Marçal da Cunha Pereira Carvalho[1], Fernando Luiz Marcelo Antunes[2] Menaouar Berrehil El Kattel[2]; Ingo Stadler[3]

[1]Institute of Bioeconomy of the National Research Council (CNR-IBE), Florence (Italy)

[2] Department of Electrical Engineering, Federal University of Ceará, Fortaleza (Brazil)

[3] TH Köln, Köln (Germany)

Abstract

The transition to renewable energy sources presents unique challenges and opportunities, especially in arid regions that combine high solar radiation potential with socioeconomic vulnerabilities such as desertification and poverty. This article proposes and evaluates an 88 kWp agrivoltaic system model designed specifically for the conditions of the Brazilian semi-arid region. The model integrates photovoltaic energy generation with subsistence agricultural production and a rainwater harvesting mechanism. The methodology includes the selection of priority locations using AHP-TOPSIS-2N multi-criteria analysis, the definition of a modular support structure that allows water harvesting, and the simulation of technical and financial performance using PVsyst software. The case study, centered on the municipality of Moraújo, demonstrates that the proposed system can generate a minimum monthly income of R$ 1,480 for a family of four, which is sufficient to lift them above the poverty line. The financial analysis reveals a positive cash flow from the first year of operation, validating the business model based on the leasing of generation assets for consumption by government units. The system has the potential to be scaled up to 494 similar projects, in line with the state government's energy demand. The results indicate that the agrivoltaic model is a synergistic and viable solution, transforming solar energy infrastructure into a key factor for sustainable socioeconomic development.

Keywords: Agrivoltaic, Desertification, Poverty, Government project, Multiple-criteria decision analysis.

1. Introduction

The growing demand for clean energy has driven the expansion of photovoltaic solar energy on a global scale. In Brazil, and particularly in the state of Ceará, this source has grown exponentially, favored by one of the highest rates of solar radiation in the country, with averages of 6.5 kWh/m² (Silva et al., 2010). However, the same climatic conditions that favor solar generation also impose high temperatures that reduce the efficiency of photovoltaic panels and an irregular water regime which, combined with unsustainable anthropogenic land use practices, makes the territory of Ceará completely susceptible to desertification (Carvalho et al., 2009).

This scenario is aggravated by profound social vulnerability. In 2023, 48.7% of the population of Ceará lived in poverty, concentrated mainly in rural and semi-arid areas (IBGE, 2023). Soil degradation limits agricultural productivity, the main source of subsistence for many communities, creating a vicious cycle of poverty and environmental degradation (Barbler, 1998).

In this context, systems that integrate different land uses synergistically become essential. The agrivoltaic system (AVS), which combines solar energy generation and agricultural production in the same area, emerges as a promising solution (Dupraz et al., 2011). Studies in arid ecosystems show that the co-location of photovoltaic panels and agriculture creates mutual and synergistic benefits (Barron-Gafford et al., 2019). The partial shade of solar panels creates a cooler and more humid microclimate, mitigating extreme environmental conditions (Rouini et al., 2025).

This work stands out by proposing a government project model focused on using an agrivoltaic system

10.18086/swc.2025.06.34 Available at http://proceedings.ises.org

as a direct tool for generating income for populations living in extreme poverty. The objective is to assess the technical, financial, and regulatory feasibility of a modular agrivoltaic system designed to generate clean energy, enable food production, capture rainwater, and, fundamentally, guarantee a stable source of income that allows beneficiary families to rise above the poverty line.

2. Methodology

The methodology aimed to model an agrivoltaic system capable of capturing rainwater, allowing the cultivation of plants adapted to the caatinga and generating electricity through an agrivoltaic system. The analysis involved defining assumptions, including the selection of agricultural crops, determining the areas of implementation, structuring the photovoltaic system arrangement, designing the water collection mechanism, and developing the business model.

The process was divided into three main stages: defining the assumptions for the agrivoltaic system, simulating the proposed system, including photovoltaic generation, agricultural production, and water collection, and conducting a financial analysis of the project. The choice of agricultural crop was guided by three main criteria: added value, familiarity of the region with production, and adaptation of the crop to the region susceptible to desertification.

1.2. Selection of the implementation area

To objectively define the priority cities for project implementation, a multi-criteria decision-making (MCDA) methodology was used. A hybrid method called AHP-TOPSIS-2N was applied, which combines the Analytic Hierarchy Process (AHP) with the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The following criteria were considered for all cities in Ceará: average annual rainfall, average annual reference evapotranspiration, and ratio of the area susceptible to desertification to the total area of the city.

The application of MCDA resulted in a priority ranking among the cities in Ceará for the implementation of the program. The analysis, which weighed factors such as precipitation, solar radiation, and susceptibility to desertification, ranked the 20 most relevant cities for the project. The city with the highest score, considered the highest priority, was Moraújo, followed by Jaguaretama and Miraíma. These are cities with low rainfall, high evapotranspiration, global horizontal irradiance, and high susceptibility to desertification.

1.3. Agrivoltaic system design

The proposed support structure was conceived with a modular Y-shaped design, a choice that is intended to simplify maintenance, optimize costs, and ensure the replicability of the system at different scales. Each structural module was designed to support 20 photovoltaic panels, totaling 8.8 kWp per unit. The panels are arranged in two rows with converging 10º inclines, a configuration that not only optimizes solar exposure but also facilitates efficient rainwater runoff and collection in a central drain.

To maximize energy performance, the system uses 445 Wp monocrystalline solar panels with bifacial and half-cell technology, which improve efficiency in high temperature and diffuse light conditions. Energy conversion is performed by microinverters, selected for their modularity, high efficiency, and ability to optimize generation individually per panel, a crucial factor in agrivoltaic systems where partial shading can occur. To validate the proposal, a case study of an 88 kWp plant, consisting of 10 of these modular structures, was dimensioned and simulated in PVsyst software.

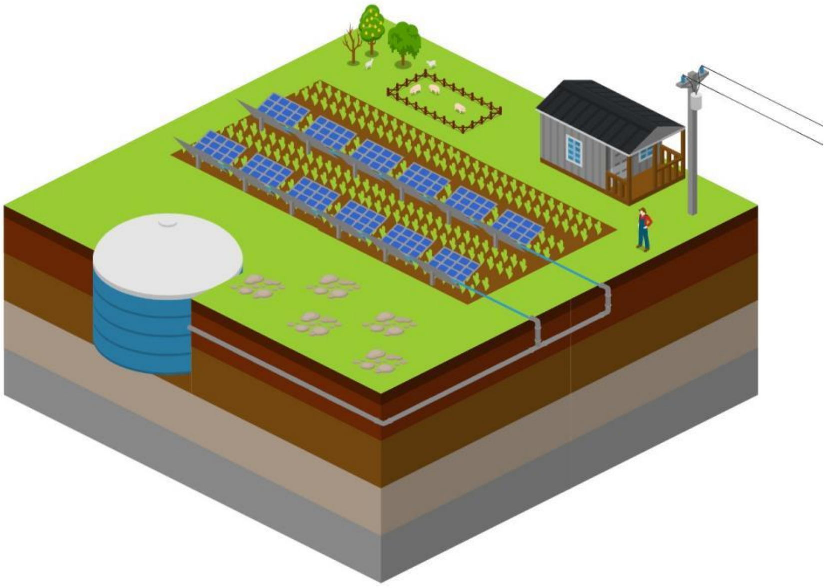

Figure 1: Modeling of the proposed agrivoltaic system, highlighting the modular support structure and the convergent inclination of the panels.

The selection of agricultural crops was based on criteria of added value, familiarity with local production, and, crucially, the species' adaptation to conditions in areas susceptible to desertification. In this context, cowpea (*Vigna unguiculata*) emerged as the ideal alternative. This legume is not only widely cultivated in these regions (IBGE, 2024), which attests to its resilience, but also adapts to multiple cropping systems, such as intercropping and crop rotation, allowing for the optimization of available resources.

1.4. Government project

The business model was structured as a government program to ensure viability and social impact. Under this model, poor farmers who own land also become owners of the agrivoltaic system through subsidized financing. The energy generated is fed into the grid and used to offset the consumption of public buildings owned by the state government through Brazil's net metering policy, the Sistema de Compensação de Energia Elétrica (SCEE).

The operational management of the program is centralized in a Project Management Unit (PMU), responsible for bidding, installation, operation, and maintenance of the systems, ensuring technical efficiency, standardization, and quality control. This structure transforms public spending on electricity into a payment mechanism for the lease of photovoltaic equipment, generating a continuous and direct income stream for rural beneficiaries.

From a financial perspective, the model was designed to be self-sustaining after the initial investment. The capital cost (CAPEX) of an 88 kWp system is fully financed by a state credit agency, with an interest rate of 6% per annum and a repayment term of 20 years. The monthly revenue from government payments for offset energy and the sale of carbon credits is sufficient to cover operating costs (OPEX), depreciation, and financial charges (Table S1).

Financial simulations indicate that, even considering all expenses, the system generates a minimum net income of R$ 1,480 per month for the beneficiary family (four people). This amount is higher than the poverty line defined by the World Bank (R$ 665.02 *per capita*/month) and, when combined with the Bolsa Família Program (average income of R$ 696.76/month in northeastern Brazil in 2023), allows the family group to rise above the poverty line from the first year of operation. The projected cash flow remains positive throughout the project's life cycle, ensuring long-term financial resilience and energy inclusion.

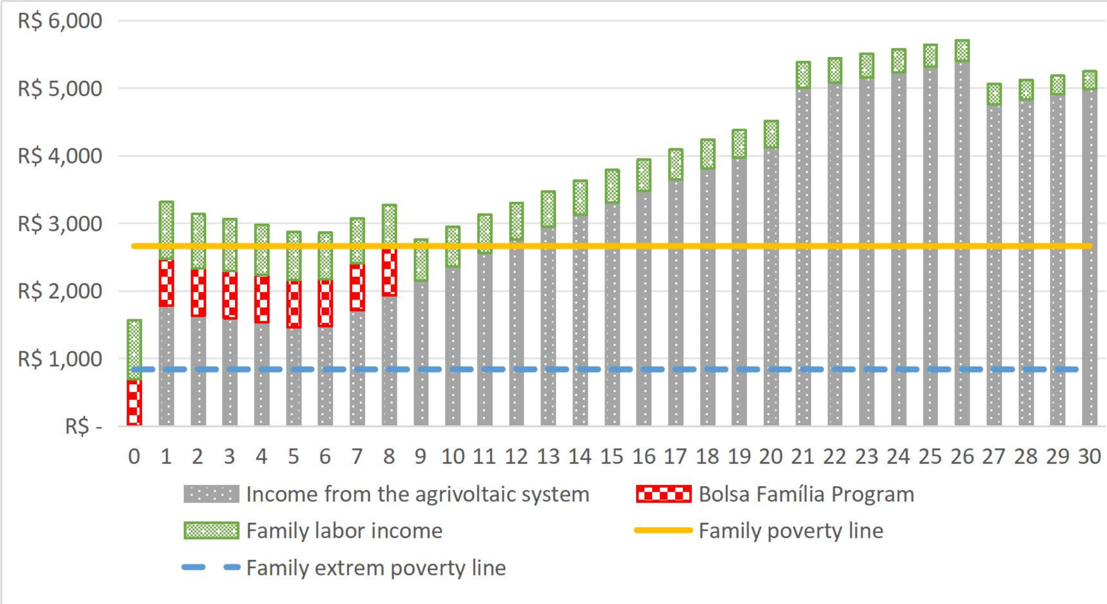

Figure 2. Evolution of family income over the years of operation of the system, considering the components of labor income, social benefits (Bolsa Família Program), and income from the agrivoltaic system in present value. The horizontal lines indicate the poverty and extreme poverty thresholds.

It is particularly significant that, without the agrivoltaic system, families living in extreme poverty are able to exceed the extreme poverty threshold defined by the World Bank with the support of the Bolsa Família Program, but still remain vulnerable, below the poverty line. The introduction of income from the agrivoltaic system substantially changes this condition, since the family exceeds the poverty line in the first year of operation and, from the ninth year onwards, reaches this level independently, without the need for support from the Bolsa Família Program. This result highlights the model's potential to promote productive inclusion and reduce dependence on social transfers, contributing to a lasting transition towards economic autonomy.

3. Results

The energy performance simulation indicated an annual generation of 136.98 MWh for an agrivoltaic system with an installed capacity of 88 kWp. The case study was developed for a family of four living in the rural area of Moraújo (CE), with an initial monthly income of R$ 872.00. To exceed the national poverty line (R$ 665.02 per capita/month), this family, a beneficiary of the Bolsa Família Program, would need an additional income of R$ 1,271.24/month. The project's cash flow analysis showed that, even after deducting operating, maintenance, interest, and financing amortization costs, the system generates net profit from the first year of operation.

As shown in Figure 2, the average monthly income generated for beneficiary families reaches a minimum value of R$ 1,480 in the sixth year (due to the tariff transition rule of Federal Law 14,300/22) and grows consistently in subsequent years. From the ninth year of operation onwards, the family is able to remain above the poverty line without the support of the Bolsa Família Program, demonstrating that the income generated by the agrivoltaic system provides long-term economic stability.

In addition, the system offers additional benefits that reinforce the sustainability of the model. The structure was designed to act as a water and food security tool. In Moraújo, an 88 kWp system has the capacity to collect up to 410,037 liters of rainwater per year, supplying four times the family's water demand and opening up opportunities for use in irrigating string bean crops. The area under the panels is used to grow shade-adapted crops, diversifying food production and enhancing the family's food security.

4. Discussion

The results demonstrate that the proposed agrivoltaic model is not only a renewable energy solution, but also a tool for socioeconomic transformation through basic income security, food production, and access to water. The generation of a minimum income of R$ 1,480, exceeding the established target, proves the viability of the system as a mechanism to contribute to poverty eradication. The family's ability to achieve independence from social assistance programs after the ninth year shows that the solution provides long-term economic autonomy.

This financial sustainability is reinforced by the fact that income is linked to electricity generation, an asset whose historical appreciation in Brazil tends to exceed inflation (Fioravante, 2022), protecting the purchasing power of beneficiary families. In this sense, by allowing beneficiaries to gradually leave the Bolsa Família program, it contributes to alleviating the public budget, allowing resources to be directed to families in greater vulnerability. This reinforces the self-sustaining nature and redistributive potential of the proposed public policy.

The synergy between the components of the water-energy-food nexus is another key element. The collection of a significant volume of water and food production in the same area as energy generation demonstrate how the system optimizes land use and increases households' resilience to extreme weather events, such as droughts. The proposed model therefore has high potential for scalability. To offset the 62.7 GWh of annual consumption by the Government of Ceará, 494 systems would be needed, directly impacting around 2,000 people. This positions the proposal as a high-impact public policy, capable of promoting rural development, reducing carbon emissions, and strengthening the local economy in an integrated and sustainable approach.

5. Conclusion

This study investigates an agrivoltaic model as an integrated and viable solution to the energy, water, and social challenges of the Brazilian semi-arid region, going beyond a technical project to establish a self-sustaining business model that uses solar infrastructure as an income-generating asset for vulnerable populations. The results indicate the technical feasibility of the 88 kWp system and add the crucial function of water collection in arid regions. Financially and socially, the proposed business model proves to be robust, generating a monthly income of at least R$ 1,480 for a family, enough to overcome the poverty line, with positive cash flow from the first year of operation. The program has significant potential for expansion and can be replicated to serve hundreds of families and align the decarbonization of the public sector with the fight against social inequality. The agrivoltaic model presented here is a promising approach to the water-energy-food nexus, contributing to a just energy transition, the recovery of degraded areas, and the strengthening of rural communities' resilience to climate change.

6. References

Barbler, E. B., 1998. Deforestation, land degradation and rural poverty in Latin America: Examining the evidence. Planejamento e Políticas Públicas, 18, 171–200. https://repositorio.ipea.gov.br/handle/11058/16508

Barron-Gafford, G. A., Pavao-Zuckerman, M. A., Minor, R. L., Sutter, L. F., Barnett-Moreno, I., Blackett, D. T., Thompson, M., Dimond, K., Gerlak, A. K., Nabhan, G. P., Macknick, J. E., 2019. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nature Sustainability, 2, 848–855. https://doi.org/10.1038/s41893-019-0364-5

Carvalho, E. B. S., Medeiros, C. N. de, Magalhães, K. A., Soares, R. B., 2009. Índice de vulnerabilidade à desertificação e sua correlação com o desenvolvimento dos municípios cearenses (Nota Técnica nº 41). Instituto de Pesquisa e Estratégia Econômica do Ceará – IPECE, Fortaleza. https://www.ipece.ce.gov.br/wp-content/uploads/sites/45/2012/12/NT_41.pdf

Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., Ferard, Y., 2011. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. Renewable Energy, 36, 2725–2732. https://doi.org/10.1016/j.renene.2011.03.005

Fioravante, D. G., 2022. O preço da energia: o descontrole do abuso de controle. Radar: tecnologia, produção e comércio exterior, 70. http://repositorio.ipea.gov.br/handle/11058/11423

Instituto Brasileiro de Geografia e Estatística – IBGE, 2023. Síntese de indicadores sociais: Uma análise das condições de vida da população brasileira: 2023 (Coordenação de População e Indicadores Sociais). IBGE, Rio de Janeiro. https://biblioteca.ibge.gov.br/visualizacao/livros/liv101052.pdf

Instituto Brasileiro de Geografia e Estatística – IBGE, 2024. Produção agropecuária: Feijão – Ceará. https://www.ibge.gov.br/explica/producao-agropecuaria/feijao/ce (Accessed on October 16, 2025)

Rouini, N., Salazar, A., Murphy, P., Lepley, K., Barron-Gafford, G. A., 2025. High-shade dryland agrivoltaic conditions enhanced carbon uptake and water-use efficiency in zucchini (Cucurbita pepo). Frontiers in Sustainable Food Systems, 9. https://doi.org/10.3389/fsufs.2025.1686773

Silva, R. A., Silva, V. de P. R. da, Cavalcanti, E. P., Santos, D. N. dos., 2010. Estudo da variabilidade da radiação solar no Nordeste do Brasil. Revista Brasileira de Engenharia Agrícola e Ambiental, 14, 501–509. https://doi.org/10.1590/S1415-43662010000500007

APPENDIX

1. City Selection Methodology (AHP-TOPSIS-2N)

The criteria and their respective weights, defined by the AHP method, were:

- Ratio of area susceptible to desertification (%ASD): Weight of 59%, with the objective of maximizing;
- Average Annual Precipitation: Weight of 47%, with the objective of minimizing;
- Global Horizontal Irradiance (GHI): Weight of 36%, with the objective of maximizing; and
- Evapotranspiration: Weight of 7%, with the objective of maximizing.

2. Technical Specifications and Simulation in PVsyst

PV module: Longi LR4-72HBD-445M; and Inverter: APsystems 1.20 kWac microinverters (25% overload).

3. Assumptions of Financial Analysis

Table S1. Key Assumptions of the Financial Analysis

Parameter	Assumption
CAPEX	R$ 6,04/Wp
OPEX	2.70% of CAPEX per year
Funding	100% of CAPEX, 6% interest per annum, 20-year term (SAC)
Energy Tariff (Year 1)	R$ 0,8195/kWh
Annual Revenue Adjustment	6%
Carbon Credit Price	R$ 290.9 per ton of CO_2
Emission Factor	0,09 kg of CO_2/kWh
Degradation of PV Modules	2.5% (year 1), 0.5% (subsequent years)
Investor Replacement	In the 10th year, at a cost of R$ 3.00/Wp