Strategic Integration of Emerging Energy Crops and Agrivoltaic Systems: A Comprehensive Analysis of Agronomic, Economic, and Regulatory Opportunities in Brazil

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ABSTRACT

The convergence of agricultural production and photovoltaic energy generation—termed agrivoltaics (AgriPV)—represents a paradigm shift in land-use efficiency, addressing the dual crises of food security and energy transition. This study provides an exhaustive analysis of the synergies between specific emerging crops (*Brassica carinata*, *Sorghum bicolor*, *Sesamum indicum*, *Vigna radiata*, and *Humulus lupulus*) and photovoltaic infrastructure within the Brazilian context. The analysis synthesizes physiological data, economic modeling, and recent regulatory frameworks, including Law 14.300 and the "Fuel of the Future" Law (14.993). Evidence suggests that while shading induces theoretical yield penalties in C4 crops like sorghum, physiological plasticity and gains in Water Use Efficiency (WUE) under photovoltaic panels can offset these losses, particularly in semi-arid regions and during the "safrinha" (second crop) season. Furthermore, winter oilseeds such as *Brassica carinata* offer a strategic pathway for Sustainable Aviation Fuel (SAF) production, benefiting from the microclimatic regulation provided by solar arrays. The report concludes that Brazil is uniquely positioned to leverage AgriPV to decentralize power generation, secure water resources, and lead the global bioenergy market.

Keywords — Agrivoltaics, AgriPV, *Brassica carinata*, Sorghum, Land Equivalent Ratio, Solar Energy, Biofuels, Law 14.300.

I. INTRODUCTION

The global imperative to decarbonize energy matrices while increasing food production has led to the emergence of agrivoltaics—the co-location of agriculture and solar photovoltaic (PV) systems. In Brazil, a nation characterized by high solar irradiance and a dominant agribusiness sector, this technology offers a transformative solution to land-use competition.[1] Unlike in Europe or Asia, where land scarcity is the primary driver, AgriPV in Brazil is propelled by the need for climate resilience, water security, and rural energy stability.

A. The Land Equivalent Ratio (LER) Concept

The central metric for evaluating AgriPV efficacy is the Land Equivalent Ratio (LER). An LER greater than 1.0 indicates that the combined production of food and energy on the same land area exceeds the production achievable if the activities were spatially separated.

$$LER = \frac{Yield_{AgriPV}}{Yield_{Monoculture}} + \frac{Electricity_{AgriPV}}{Electricity_{FV}}$$

Research indicates that AgriPV systems can increase total land productivity by 60–70% through synergistic interactions.[3] In tropical environments, the primary driver of this synergy is microclimate modification. Solar panels reduce excessive direct irradiance, lowering soil temperature and evapotranspiration rates, which is critical for regions suffering from water scarcity or dry spells (*veranicos*), such as the Brazilian Northeast and Central-West.[1]

B. The Brazilian Context: From Caatinga to Cerrado

Brazil's diverse biomes present unique opportunities. In the semi-arid Caatinga, water retention is the limiting factor for agriculture. AgriPV systems have been shown to reduce irrigation needs by up to 30% by mitigating the "midday depression" in photosynthesis caused by excessive heat and high Vapor Pressure Deficit (VPD).[4] In the Cerrado and Southern regions, the focus shifts to land-use intensification during the off-season (*safrinha*) and crop protection against frosts.[6] The regulatory landscape, with Law 14.300 (Distributed Generation Legal Framework) and the recently sanctioned Law 14.993 (Fuel of the Future), creates a favorable environment for integrating biomass production for biofuels with green electron generation.[8]

II. PHYSIOLOGICAL FOUNDATIONS IN AGRIVOLTAIC SYSTEMS

Agronomic viability depends on the physiological response of plants to altered light and microclimate conditions.

A. Radiation and Light Saturation

Plants do not utilize all available sunlight. Radiation above the Light Saturation Point causes photoinhibition and thermal stress.[10] AgriPV filters this "excess," keeping C3 crops like *Brassica carinata* in a more efficient physiological zone.[11] For C4 crops like Sorghum, improved water status often compensates for photon reduction, preventing stomatal closure during the tropical midday.[12]

B. Microclimatic Buffering and Water Use Efficiency (WUE)

Panels act as a shield, reducing the VPD and decreasing evapotranspiration by 20–30% in semi-arid environments.[4] This soil "water battery" effect is crucial for the *safrinha* in the Cerrado, where rains cease abruptly.[14]

C. Thermal Regulation

Crops cool the panels via transpiration (increasing PV efficiency), while panels protect crops from extreme heat events that can abort flowers, preserving yield quality in oilseeds.[15]

III. *BRASSICA CARINATA*: THE STRATEGIC ANCHOR FOR BIOFUELS

Brassica carinata (Ethiopian Mustard) is central to the global Sustainable Aviation Fuel (SAF) strategy.

A. Agronomic Profile and Climate Suitability

Characterized by a deep taproot system and indehiscence (resistance to pod shattering) [16], *Carinata* is positioned as a winter cover crop. AgriPV arrays can increase nocturnal soil temperatures by 2–4°C, acting as a passive heating system that reduces frost risk in Southern Brazil [6], while mitigating heat spikes in the Cerrado.[17]

B. Response to Shading

Carinata exhibits plasticity to shading; wider inter-row spacing in AgriPV systems promotes branching, compensating for lower plant density.[18] Shading preserves high oil content (>40%) and the favorable fatty acid profile required for biojet fuel, preventing heat-induced degradation.[15]

C. Business Model and Carbon Economy

Cultivation under AgriPV lowers Carbon Intensity (CI) scores by utilizing zero-emission solar energy for irrigation/processing and enhancing soil carbon sequestration.[19] This allows for a triple revenue stream: energy credits, biofuel feedstock, and carbon removal credits.[19]

IV. *SORGHUM BICOLOR*: RESILIENCE IN THE SECOND CROP

For the Northeast and Cerrado transition zones, Sorghum offers unparalleled resilience against erratic rainfall patterns exacerbated by climate change.

A. The C4 Paradox: Light vs. Water

Despite being a C4 plant, Sorghum maintained an LER of 1.54 in AgriPV configurations, allocating more energy to grain filling rather than vegetative expansion when shaded.[12] Soil moisture conservation compensates for reduced light availability, stabilizing yields during drought years.[12]

B. Water Use Efficiency

AgriPV mimics "deficit irrigation" strategies, allowing cultivation in areas with low water tables.[7] Sorghum outperforms maize in productive stability under the water stress conditions typical of the Brazilian *safrinha*.[23]

C. Sweet Sorghum and Ethanol

Sweet sorghum maintains sugar production under moderate saline and water stress. Partial shading from AgriPV can reduce soil salt evapoconcentration, protecting the rhizosphere.[24] Integration with ethanol plants and PV energy creates a virtuous bioenergy cycle.[25]

V. HIGH-VALUE AND ROTATION CROPS

A. Sesame (*Sesamum indicum*)

Sesame is highly valuable but sensitive to thermal stress during germination. PV shading protects seedlings from soil temperatures >40°C.[26] Although yield reductions (approx. 19–20%) have been observed in static systems, the prevention of total crop failure during heatwaves justifies the system, particularly with dynamic trackers.[27]

B. Mung Bean (*Vigna radiata*)

Ideal for rotation, Mung bean under AgriPV showed increased plant height, leaf number, and pod count due to reduced leaf temperature (3–9%) and increased relative humidity, outperforming full-sun cultivation in tropical environments.[28]

VI. *HUMULUS LUPULUS*: HIGH-TECH HORTICULTURE

A. Infrastructure Synergy

PV modules mounted on top of hop trellises (up to 6m) turn a structural cost into an energy-generating asset and improve air circulation, reducing fungal diseases.[29]

B. Photoperiod and Lighting

In Brazil, hops require artificial lighting to complete a ~17h photoperiod. Energy generated by the AgriPV system powers LED supplementation at night, closing the energy loop and significantly reducing operational costs.[30]

VII. TECHNOLOGICAL SYSTEMS AND PROCESSING

A. Vertical Bifacial Systems

Vertical panels allow large agricultural machinery (tractors, harvesters) to operate between rows, capturing albedo from crops and preserving operational efficiency in large-scale Cerrado farming.[1]

B. On-Farm Micro-Plants

Decentralized generation enables local processing. Modular micro-plants for oil extraction (Carinata, Sesame) can be powered directly by the PV array. This adds value (selling crude oil instead of seeds) and retains the press cake for animal feed.[32]

VIII. REGULATORY AND ECONOMIC LANDSCAPE

A. Law 14.300: Distributed Generation Framework

Brazil's legal framework allows for Remote Self-Consumption and Shared Generation, essential for the "Solar-Biofuel" business model. Future valuation of environmental benefits by the National Energy Policy Council (CNPE) may further favor AgriPV by recognizing reduced transmission losses.[8]

B. Law 14.993: Fuel of the Future

This law establishes mandates for SAF and Green Diesel, creating a guaranteed market for *Carinata* and vegetable oils. Increased ethanol and biodiesel blending targets strengthen demand for sorghum and oilseeds.[9]

C. Financing and Economics

Credit lines such as "Pronaf Bioeconomia" fund implementation. With PV system costs falling (~7.5% drop in H1 2025), the payback for rural projects is estimated between 4 to 7 years.[36]

IX. CONCLUSION

Brazil possesses the ideal climatic, agronomic, and regulatory conditions to become a global leader in Agrivoltaics. The integration of *Brassica carinata*, Sorghum, and Sesame transforms AgriPV from a niche experiment into a scalable industrial solution. Yield penalties associated with shading in C4 crops are physiologically offset by gains in water efficiency and economically surpassed by energy and carbon revenues. The strategic recommendation is to deploy Integrated Energy-Food Systems, leveraging the "Fuel of the Future" incentives to position Brazilian agribusiness at the forefront of sustainable intensification.

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