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AGRIVOLTAICS – PERFORMANCE ENHANCING CHARACTERISTICS – OVERVIEW

BY

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Abstract. Agrivoltaic systems, which integrate solar energy conversion with agricultural production, present a promising strategy to enhance land use efficiency while contributing to both food security and the renewable energy transition. Applied in arable and vegetable farming, these systems leverage innovative design solutions – such as optimized spatial configurations, shading management, and crop selection – to ensure synergy between crop yields and photovoltaic output. Engineering considerations, including panel height, tilt, and modular installation, are critical to enabling farm operations while maximizing energy generation. Beyond technical performance, agrivoltaics offer multiple environmental and socio-economic benefits, including improved resource efficiency, increased farm profitability, reduced carbon emissions, and strengthened rural resilience. Nevertheless, challenges remain in addressing potential yield trade-offs, system costs, regulatory barriers, and farmer adoption. Scaling agrivoltaic deployment will require interdisciplinary collaboration, supportive policy frameworks, and advances in system design tailored to diverse agricultural contexts. By aligning food production with renewable energy

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generation, agrivoltaic systems represent a sustainable pathway toward resilient and resource-efficient food-energy systems.

Keywords: renewable energy, solar energy, photovoltaic system, agrivoltaic, efficiency.

1. Introduction

The defining attribute of agrivoltaics is the simultaneous utilization of sunlight by two energy conversion systems: photovoltaics (PV) and photosynthesis (Macknick *et al.*, 2022). Agrivoltaics demonstrate significant potential in providing advantages inside the water-food-energy (WEF) concept as shown in the Fig. 1 (Kabeya *et al.*, 2022).

The notion was initially developed by Goetzberger and Zastrow in 1982 in Germany. This strategy aims to alter the existing design of solar power plants to simultaneously provide food production in the same region. Consequently, PV arrays are elevated to approximately 2 meters above the agricultural area, and the spacing between rows will be increased to prevent excessive shade on the crops cultivated underneath the PV panels (Gorjian *et al.*, 2023).

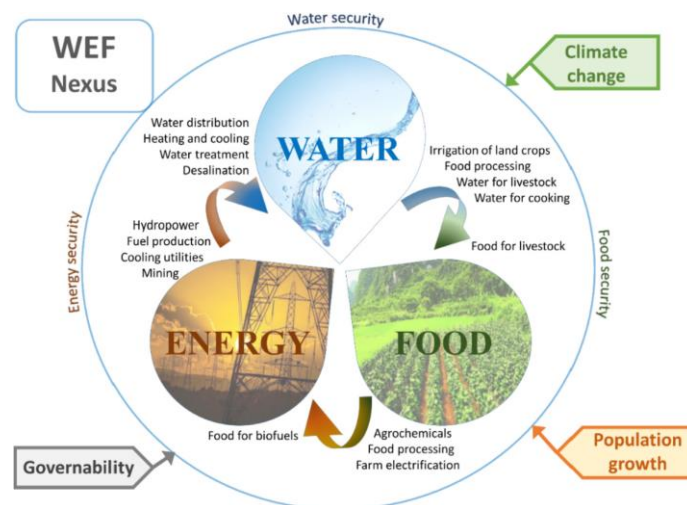


Fig. 1 – The water-energy-food (WEF) concept (Mahlknecht *et al.*, 2020).

Innovative approaches to land use are necessary to feed the world population, projected to reach 9.8 billion people by 2050 while also dealing with climate change and land scarcity. Agrivoltaic systems (AVS), promise a dual-use solution by enhancing agricultural output and use of renewable energy by combining PV panels with crop cultivation on the same land area, Fig. 2 (Saka, 2024; Barron-Gafford *et al.*, 2019; Campana *et al.*, 2021).

According to meta-analyses, crops adaptability to shade varies significantly. Although grain, legumes and maize demonstrate significant decreases in yield even under modern shade, berry crops (such as blueberries and strawberries) can often tolerate 30 – 50% shading with minimal yield penalties (Laub *et al.*, 2022).

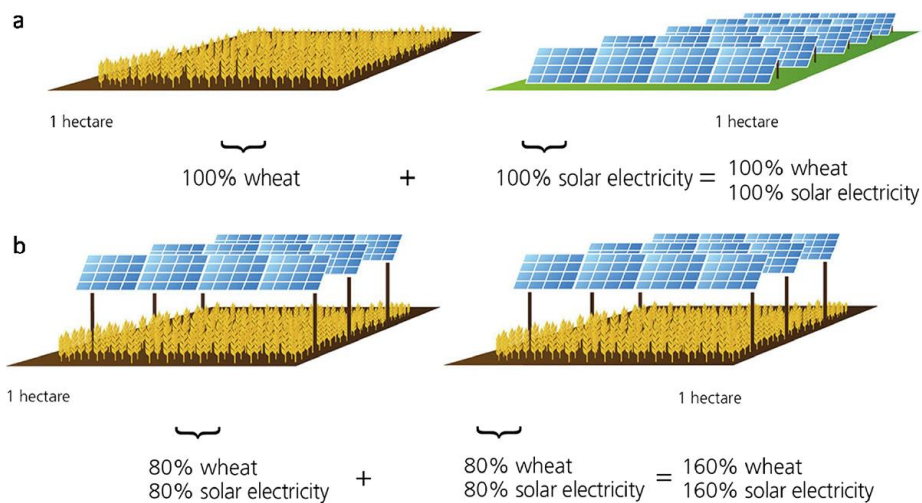


Fig. 2 – Agrivoltaics concept land use: a) separate; b) combined (Schneider, 2017).

To maximize agricultural yields and energy generation, spatial design (panel height, tilt, orientation, and inter-row spacing) and engineering parameters (ensuring proper photosynthetically active radiation - PAR, structural safety, and ease of farm operations) are crucial (Riaz *et al.*, 2022; Zainali *et al.*, 2023; Campana *et al.*, 2021).

In addition, AVS provide socio-economic and environmental co-benefits, such as decreased evapotranspiration, enhanced water-use efficiency, managed microclimates, increased resilience to temperatures and drought stress, and diversified farmer income through energy income (Barron-Gafford *et al.*, 2019; Trommsdorff *et al.*, 2025). Trade-offs in crop productivity under shade, high initial capital costs, regulatory barriers, and a lack of empirical data across crop types and climates constitute a number of the challenges. Genuine engagement with agriculture, policy incentives, and locally specific design guidelines are crucial for scaling AVS (Mehta *et al.*, 2025). Agrivoltaics may grow from pilot projects to essential strategies for durable, sustainable food-energy systems with proper technology (Dinesh and Pearce, 2016; Esetilili *et al.*, 2025).

2. Overview of Agrivoltaic Systems

System performance depends heavily on design parameters. Panel height, tilt, orientation, and spacing light distribution, micro-climate conditions, and farm machinery access, Fig. 3 (Dupraz *et al.*, 2011; Riaz *et al.*, 2022). Shading effects are crop-specific: while moderate shading can lower evapotranspiration and reduce heat stress, excessive shading reduces photosynthesis and yield, particularly in cereals and legumes (Barron-Gafford *et al.*, 2019; Elamri *et al.*, 2018). Shade-tolerant crops such as leafy greens and certain fruits often demonstrate improved outcomes in AVS (Adeh *et al.*, 2018).

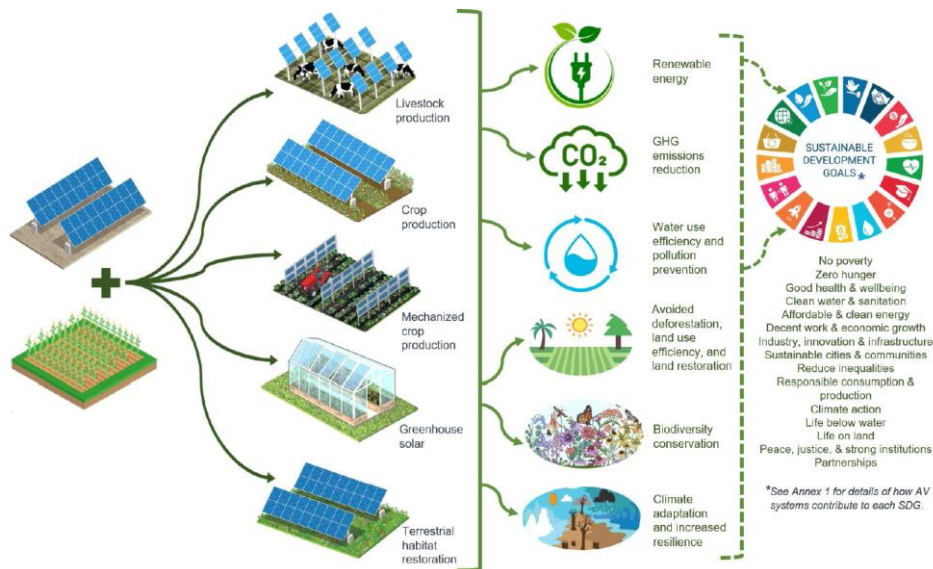


Fig. 3 – Applications and benefits of AV systems (Agrivoltaics, 2024).

Engineering and installation aspects are equally critical. Systems must ensure structural stability under wind and snow loads, integrate irrigation, and allow for efficient maintenance (Schindele *et al.*, 2020). Innovations such as bifacial modules and adjustable configurations further optimize energy capture and crop compatibility (Riaz *et al.*, 2022).

The benefits of AVS are multi-dimensional. Environmentally, they enhance water-use efficiency, moderate soil and air temperatures, and reduce carbon emissions (Amaducci *et al.*, 2018; Aroca-Delgado *et al.*, 2018). Economically, they diversify income streams through food and energy co-production, with higher land-equivalent ratios than single-use systems (Dinesh and Pearce, 2016). Socially, AVS foster rural resilience and improve acceptance of renewable technologies (Weselek *et al.*, 2019; Esetilili *et al.*, 2025).

Challenges remain, including shading-yield trade-offs, high upfront costs, limited farmer awareness, and regulatory barriers such as unclear land-use classifications (Schindele *et al.*, 2020). Future opportunities lie in regionally adapted designs, supportive policies, and participatory approaches that food and energy goals (Farmonaut, 2025).

3. Technical Configurations of Agrivoltaic Systems

The technical configuration of AVS is important for their dual efficiency in energy generation and agricultural productivity. Fundamental engineering and design components include panel orientation, tilt angle, elevation, row spacing, and array density, all of which influence solar capture, shading patterns, and crop microclimates (Dupraz *et al.*, 2011; Weselek *et al.*, 2019). Panels orientated south with tilt angles suitable for local solar incidence enhance PV efficiency, while modifications in height and spacing can mitigate excessive shade and accommodate farm machinery, Fig. 4 (Schindele *et al.*, 2020; Mehta *et al.*, 2025).

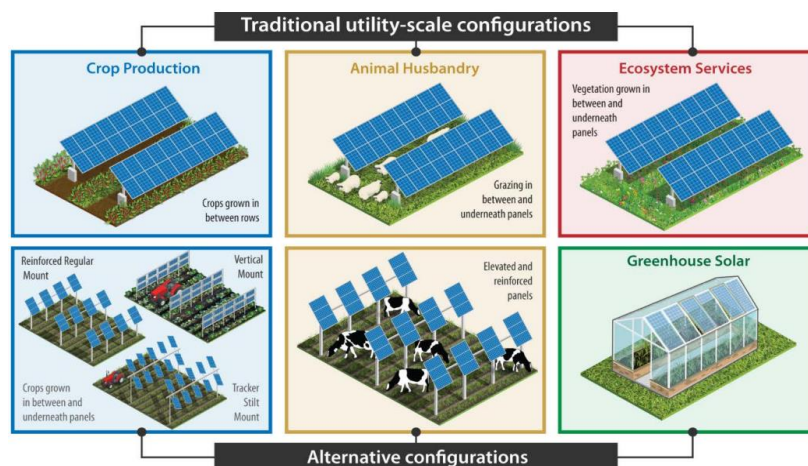


Fig. 4 – Traditional utility-scale APV to alternative APV configurations (Macknick *et al.*, 2022).

The elevation and spacing of panels are essential for assessing light dispersion and farm functionality. Elevated panels facilitate enhanced sunshine exposure and support automated agricultural methods, although they escalate structural expenses (Amaducci *et al.*, 2018). Furthermore, increased row spacing lowers shadowing intensity but may decrease total energy output per hectare (Elamri *et al.*, 2018). Optimizing array density requires integrating the land equivalent ratio (LER), an indicator of integrated food and energy productivity, with the light needs particular to each crop (Esetlili *et al.*, 2025).

Structural safety is an essential design element. Systems must endure wind and snow loads, reduce soil compaction from foundations, and utilize resilient support structures to guarantee durability in agricultural settings, as shown in the Fig. 5 (Schindele *et al.*, 2020). Integration with irrigation infrastructure is necessary. Drip irrigation under PV panels has demonstrated improved water-use efficiency and enhanced the microclimatic advantages of partial shadowing, Fig. 6 (Adeh *et al.*, 2018).

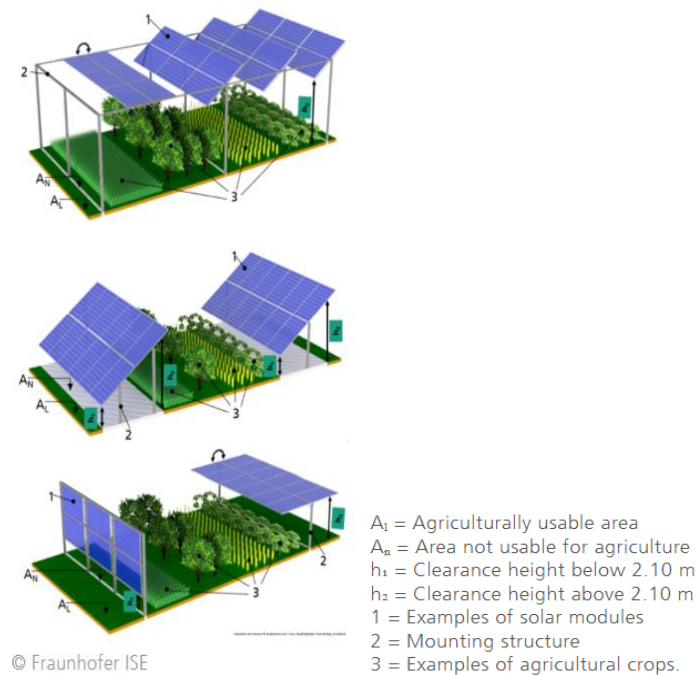


Fig. 5 – Agrivoltaics configurations (Schneider, 2017).

Technological innovations are improving AVS performance. Bifacial modules, which absorb light reflected from the ground, increase energy output without significantly modifying shade patterns (Riaz *et al.*, 2022). Adjustable and tracking systems, despite their higher cost, offer dynamic adjustment of light distribution between crops and panels, adapting seasonal crop cycles, Fig. 5 (Marrou *et al.*, 2013).

Recent field studies exemplify the significance of customized arrangements. In France, (Dupraz *et al.*, 2011) demonstrated that a 50% density PV array decreased wheat output by 19% while achieving a 73% improvement in land-use efficiency. In Arizona, (Barron-Gafford *et al.*, 2019) observed that raised AVS structures reduced air temperature and improved water-use efficiency for chiltepin peppers and cherry tomatoes, while maintaining significant PV output.

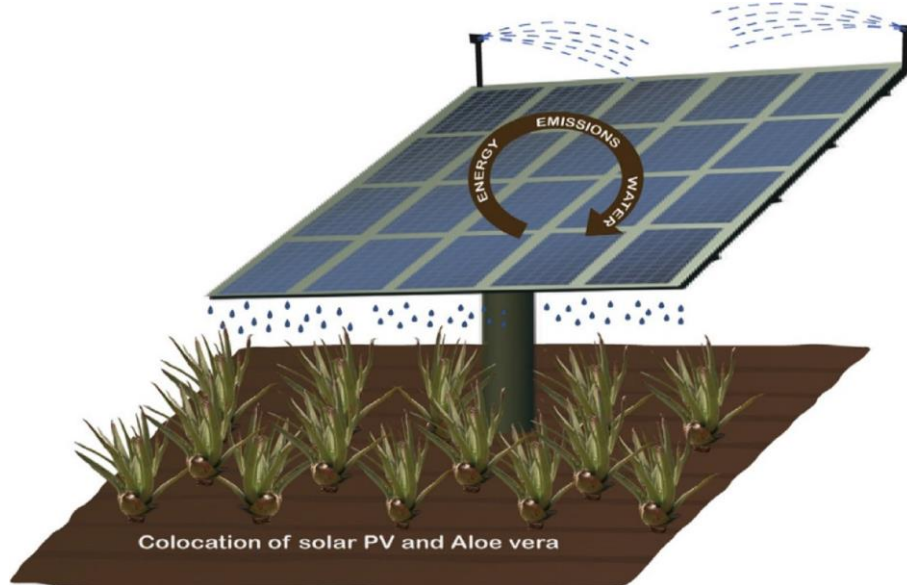


Fig. 6 – Water use efficiency (cleaning PV module and directly to irrigate crops) (Ravi *et al.*, 2016).

In essence, AVS systems require a balance between crop yields and energy production. Optimal designs are based on context, requiring adjustment to crop types, climatic factors, and socio-economic considerations. Advancements in research need the integration of structural engineering, crop physiology, and energy modeling to create resilient and scalable AVS.

4. Conclusions

AVS provide a promising solution to land-use competition by enabling simultaneous crop cultivation and solar energy generation. Research shows AVS can increase land-equivalent productivity, enhance water-use efficiency, and create dual revenue streams, supporting both food security and the renewable energy transition (Amaducci *et al.*, 2018; Aroca-Delgado *et al.*, 2018; Barron-Gafford *et al.*, 2019; Dinesh and Pearce, 2016).

Key challenges persist. Crop responses to shading vary widely, and technical design choices – such as tilt, spacing, and elevation – require balancing trade-offs between crop yields and energy output (Dupraz *et al.*, 2011). Structural and operational considerations, including wind resistance, irrigation integration, and farm machinery access, add complexity (Schindele *et al.*, 2020). Regulatory uncertainties in land classification and permitting, alongside high capital costs and limited farmer awareness, further slow adoption (Trommsdorff *et al.*, 2025).

Future opportunities include innovations such as bifacial and adjustable PV modules, regionally adapted design standards, and supportive policies that recognize dual-use benefits. Cooperative business models and participatory research with farmers can also accelerate acceptance and deployment. With these advances, AVS can evolve from experiment projects into strategies for sustainable food-energy systems globally.

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AGRIVOLTAICE – CARACTERISTICI DE ÎMBUNĂTĂȚIRE A PERFORMANȚEI – VEDERE DE ANSAMBLU

(Rezumat)

Sistemele agrivoltaice, care integrează producția de energie solară cu activitățile agricole, reprezintă o strategie promițătoare pentru creșterea eficienței utilizării terenurilor, contribuind totodată la securitatea alimentară și la tranziția către energie regenerabilă. Aplicate în agricultura arabilă și legumicolă, aceste sisteme utilizează soluții inovatoare de proiectare – precum configurări spațiale optimizate, gestionarea umbririi și selectarea culturilor – pentru a asigura sinergia dintre randamentele agricole și producția fotovoltaică. Considerentele ingineresti, inclusive înălțimea panourilor, unghiul de înclinare și instalarea modulară, sunt esențiale pentru desfășurarea lucrărilor agricole, maximizând în același timp generarea de energie. Dincolo de performanța tehnică, sistemul agrivoltaic oferă multiple beneficii de mediu și socio-economice, printre care se numără creșterea eficienței utilizării resurselor, sporirea profitabilității fermelor, reducerea emisiilor de carbon și consolidarea rezilienței mediului rural. Cu toate acestea, persistă provocări legate de gestionarea compromisurilor privind randamentele, costurile sistemelor, barierele de reglementare și adoptarea de către fermieri. Extinderea implementării sistemelor agrivoltaice va necesita colaborare interdisciplinară, cadre de politici de sprijin și progrese în proiectarea sistemelor adaptate diverselor context agricole. Prin alinierea producției agricole cu generarea de energie regenerabilă, sistemele agrivoltaice constituie o cale durabilă către sisteme alimentare-energetice reziliente și eficiente din punct de vedere al resurselor.