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HORTIVOLTAICS - A ROAD TO GO OR NOT? A REVIEW

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Abstract

Climate change and disputes over land utilization are significant global obstacles. The impact of climate change on agricultural output is evident in the increasing frequency and severity of extreme weather phenomena, coupled with the ongoing escalation of temperature and carbon dioxide levels. At the same time, the increased demand for energy, especially the alternatives and greener forms, is always present.
There is hope in the form of agrivoltaic/hortivoltaic systems, a forward-thinking and truly innovative strategy. These systems integrate solar photovoltaic-based renewable energy generation with agricultural/ horticultural activities by positioning solar panels several meters above the ground.
This study aims to review these developed and implemented modern technologies, considering their long-term impact and efficiency. It will examine the dynamics of specific parameters such as abiotic stress and streamlined resource consumption, favorable microclimate through transparent photovoltaic panels, monitoring microclimate data, and early diagnosis of nutritional stress.

Key words: *photovoltaic panels, solar energy, crop production.*

INTRODUCTION

Climate change is one of the greatest challenges of the 21st century (Randers, 2021), with record global temperatures reaching approximately 1.4°C above pre-industrial averages in 2023. This rise in temperatures impacts agricultural production through increasingly frequent and intense extreme weather events, such as heatwaves, prolonged droughts, severe floods, and extended wildfire seasons, all contributing to rising sea levels (OECD, 2024). Intensive agriculture and climate change also risk soil quality and food production (Smith & Gregory, 2013; Cárceles, 2022). Food security is further endangered by the ongoing decline in arable land and the rapid growth of the global population (Durpaz, 2011). The primary driver of global warming is human activity, particularly greenhouse gas emissions (ICPP, 2023), highlighting the urgent need to expand renewable energy to meet global energy demand while replacing fossil fuels (Wydra, 2023). In this context, implementing renewable energy technologies and reducing global greenhouse gas emissions are essential measures for mitigating climate change and achieving net-zero emissions by 2050 (Kramarz, 2021; IEA, 2021). Among renewable resources, solar energy stands out for its significant potential (Lewis, 2006), with estimates indicating that by 2050, photovoltaic installations will supply over 40% of global renewable energy (IEA, 2021).

THE CONCEPT OF AGRIVOLTAICS

The attempt to produce electricity using photovoltaic systems has raised the issue of occupying arable land, thus increasing competition for limited land resources (Widmer, 2024). In this context, the combination of photovoltaic energy production with crop cultivation - often referred to as an agro-photovoltaic or agrivoltaic (AV) system - has emerged as an opportunity for the synergistic integration of renewable energy and food production (Dupraz, 2011). When crops are horticultural, we propose the term Hortivoltaic Systems (Miloș, 2022). This innovative approach maximizes land use efficiency by producing food and energy simultaneously (Dinesh & Pearce, 2016). The theoretical concept of photovoltaic systems was described as early as 1981 by Götzberger and Zastrow for a system that combines photovoltaic modules with potato production (Goetzberger et al., 1981). The first AV systems mounted on sloped spaces were invented in Japan in 2004. Small-scale AV development also began in Japan in 2011 (Nagashima, 2005; Sekiyama & Nagashima, 2019), followed by installations in Europe, with France and Italy in 2010 and 2011, respectively, as well as in Asia, Australia, and the United States of America (Barron-Gafford et al., 2019; Marrou et al., 2013; Elamri et al., 2018; Schindele et al., 2020; Toledo et al., 2022; Fraunhofer ISE, 2022; Al Mamun et al., 2022).

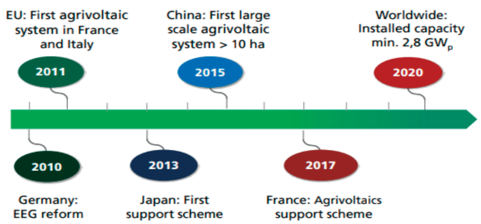

Figure 1. Development of Agrivoltaic Systems from 2010 to Present (Source: Fraunhofer Institute for Solar Energy Systems - ISE)

CLASSIFICATION OF AGRI AND HORTIVOLTAIC SYSTEMS

Agrivoltaic/hortivoltaic systems integrate agricultural/horticultural crop production with electricity generation on the same land, offering a promising sustainable energy and food production solution. However, a key challenge is the reduced light availability for crops growing under the panels, which can limit growth and yield potential. Research on shading impacts has shown that as shading intensity increases, crop yields tend to decrease (Prakash, 2023). Despite this, AV systems are particularly advantageous in hot and arid climates; strategically placed solar panels can reduce excessive thermal stress on crops during peak summer, enhancing yields and lowering water needs (Younas et al., 2019).

Central to AV systems are photovoltaic (PV) panels that convert sunlight directly into electricity using semiconductor materials, predominantly silicon-based solar cells (Dinesh, 2016; Al Mamun, 2022). These cells absorb sunlight and create electron-hole pairs, generating an electric current when connected to a circuit. Some advanced PV systems use artificial intelligence to optimize the panels' orientation and tilt, adapting to crop growth stages and weather patterns for better energy and crop performance (Klokov, 2023).

There are three primary types of agrivoltaic systems, each with distinct configurations suited to different agricultural needs (Sekiyama, 2019). The first type, *inter-row PV systems*, place solar panels between crop rows. This arrangement allows crops to grow in the spaces between the PV arrays, making it ideal for grasslands and certain crops like hay, silage, and those used for animal grazing. This setup maintains ample sunlight for crops and minimizes the shading impact on agricultural yield (Appelbaum, 2022).

Another type, *greenhouse-mounted PV systems*, incorporates PV modules onto greenhouse roofs. This system replaces part of the greenhouse's transparent covering with PV panels, which balance light transmission to support plant growth while generating electricity. This type is particularly advantageous for high-value horticultural crops, as it enables year-round production alongside energy generation (Scognamiglio, 2014).

The third type, *stilt-mounted PV systems*, involves installing solar panels on stilts above the crops. This design provides sufficient sunlight for photosynthesis, space for agricultural machinery, and easy dismantling of the structure if needed. This setup works well in larger-scale agricultural settings, allowing crops and energy production to coexist efficiently without significantly impacting crop yield (Toledo, 2021).

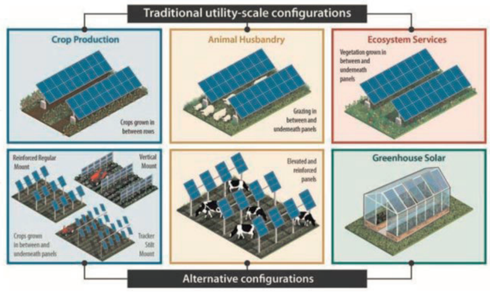

Figure 2. Types of AV systems (Wydra, 2023)

Furthermore, the types of photovoltaic panels employed can differ, each with specific characteristics and applications.

Opaque solar panels in agrivoltaic systems reduce sunlight reaching crops, helping to lower temperatures and mitigate heat stress (Uchanski, 2023). Gorjian et al. found that conventional opaque PV modules create shading that can harm crop growth (Gorjian, 2022). To mitigate this, strategies like using shade-tolerant crops, adjusting PV module layouts, employing tracking systems, and using advanced PV technologies have been tested to improve compatibility between agriculture and energy generation in AV systems (Chopdar, 2024).

Semi-transparent photovoltaic (STPV) modules represent a significant advancement in solar energy technology. They are designed to capture solar energy while permitting light transmission essential for crop growth. These modules are particularly beneficial for shade-tolerant crops such as *Rubus* spp. and *Pyrus communis* var. Conference, making them ideal for agrivoltaic applications (Reher, 2024). Innovations like Soliculture's LUMO greenhouse modules support photosynthesis by allowing specific wavelengths to pass through while converting the remaining light into electricity (Marucci, 2012; Chalgynbayeva, 2024).

Additionally, bifacial panels capture light from both sides and have proven effective in vertical configurations in countries such as Germany and Japan, increasing energy yield and optimizing land use (Younas, 2019; Li, 2021). Current STPV transparency levels are limited to 10-20%, yet research is progressing toward full transparency (Husain, 2018). Despite solar energy's promise, it currently meets only about 1% of global demand due to its low energy density. Transparent solar cells (TSCs) are being explored to transform glass surfaces into energy-generating materials, potentially increasing solar capacity and reducing reliance on non-renewable sources (Pulli, 2020).

Transparent solar panels in agrivoltaic systems balance light transmission with electricity generation, allowing sunlight to reach crops while still producing energy. These panels, often made from thin-film materials, are designed with spaces between cells to increase transparency and allow photosynthetically active radiation (PAR) to reach plants (Vasiliev, 2023).

Solar panels used in agrivoltaic systems can be fixed or adjustable, each offering specific benefits. Fixed panels, mounted with a north-south (N/S) inclination, are simple and less costly to install, providing stability and reducing maintenance costs. However, they can create an uneven distribution of light and soil moisture, which may affect crop yield (Younas, 2019). In contrast, adjustable panels allow tracking of the sun's path from sunrise to sunset, providing superior yields.

Agrivoltaic/hortivoltaic (AV) systems combine agricultural/horticultural crop production and electricity generation on the same land, with particular benefits in hot and arid climates where optimized panel coverage can protect crops from excessive heat, thereby improving yields and reducing water consumption (Younas, 2019). However, a primary challenge in AV systems is the reduced light availability for crops beneath the panels, which can restrict growth and yield. Studies indicate crop yield decreases as shading intensity increases, so choosing shade-tolerant species is crucial for successful AV integration (Prakash et al., 2023; Uchanski, 2023).

The effectiveness of AV systems relies heavily on the interaction between agricultural and photovoltaic components, particularly in managing the shading effects of panels on crops. Understanding this shading impact requires an in-depth analysis of the spatial distribution of solar radiation between the panels and crops. Pulido-Mancebo et al. (2022) introduced a methodology to estimate solar radiation distribution based on panel geometry and diffuse and direct irradiation levels. Research shows that shade-tolerant crops, which require lower light intensities, can enhance AV system productivity by preventing crop damage from

high solar intensity, often leading to scorching on leaves or fruits.
Integrating shade-tolerant crops in AV systems not only supports agricultural yield stability but can also enhance the economic value of farms by over 30% compared to conventional farming. This dual land-use strategy could significantly increase solar energy output, with potential national production gains of 40 to 70 GW (Dinesh et al., 2016).

PROGRESS IN SOLAR PV TECHNOLOGY

2010 global solar cell production ranged from 18 GW to 27 GW, reflecting a substantial increase since 2000, with yearly growth rates of 40-90%. Between 2008 and 2011, PV system costs dropped by 40%, while global electricity demand is expected to grow by 2.4% annually through 2030 (Tyagi, 2013). The worldwide installed PV capacity rose 21% from 483.1 GW in 2018 to 580.2 GW in 2019 (IRENA, 2020). Asia holds the lead in PV installations, particularly in China, Japan, and India, followed by Europe, where Germany, Italy, and the UK contribute significantly (Allouhi, 2022). By 2022, the installed capacity of agrivoltaic (AV) systems will exceed 14 GW. Deploying AV on only 1% of Europe's arable land could generate over 900 GW of solar power, vastly surpassing current installations (Klokov, 2023).
The IEA forecasts that PV power will generate around 6000 TWh by 2050, meeting about 16% of global energy needs. Due to solar energy's diffuse nature, achieving this target will require extensive land use (Denish, 2016).

AGRI AND HORTIVOLTAIC SYSTEM APPLICATIONS

The efficient functioning of agrivoltaic systems relies on effective light management and sharing between solar panels and the crops below. Tracking systems are essential in this context, as they offer the flexibility to balance energy generation with plant growth. This thesis explores various tracking optimization methods focusing on light distribution and availability. By ensuring equal emphasis on irradiation reaching both the crops and the solar panels, shading levels can be kept below 40% throughout the year, resulting in only an 8% decrease in electrical output compared to traditional backtracking setups (Bruno, 2023).
Recently, the conversion of photovoltaic installations with horizontal NeS trackers into agrivoltaic systems by cultivating orchard hedges between collector rows has been analyzed to study shading effects on the panels. A zone between the collectors was identified where the crops do not shade the panels, and a new tracking strategy was proposed to avoid shading outside this area. In a facility in Cordoba, with olive trees up to 3 meters tall, the land equivalent ratio could increase by 28.9-47.2%, making photovoltaic systems adaptable and sustainable in orchard agriculture (De La Torre, 2022).
Installing dynamic photovoltaic panels over apple orchards can address climate protection challenges and support the energy transition, but the impact of shading on apple performance needs investigation. In a three-year study (2019-2021) in southern France, 'Golden Delicious' apple trees experienced fluctuating shading (4-88% daily, averaging 50-55%). Results showed reduced air temperature and increased humidity, improved frost protection, and less alternate bearing, with more fruit-bearing trees (+31%) and higher fruit counts (+44%) in 2021. However, shading lowered photosynthetic capacity, carbohydrate storage, and dry matter content, resulting in suboptimal yields under 40 t/ha across all years (Juillion, 2022).
A study conducted in a kiwi plantation evaluated the impact of different levels of photovoltaic (PV) shading on growth, yield, and water productivity. With shading densities of 19%, 30.4%, and 38%, it was found that low shading (19%) minimally affected fruit growth and yield while improving water productivity by reducing evapotranspiration. In contrast, higher shading levels (30.4% and 38%) significantly negatively affected fruit volume and yield. The study concluded that 19% shading can support energy production and efficient agricultural yields, making it a suitable solution for isolated areas (Jiang, 2022).
The Lake Constance agrivoltaic study (2017-2018) evaluated AV system impacts on microclimate and yields for winter wheat, potato, grass-clover, and celeriac. Bifacial solar panels reduced photosynthetically active radiation by 30% and lowered air and soil

temperatures, leading to moderate yield reductions. However, during the hot, dry summer of 2018, yields for winter wheat and potatoes rose by 2.7% and 11%, respectively, highlighting AV systems' potential to stabilize yields under extreme weather conditions (Welesek, 2021).

Pascaris et al. conducted in-depth, semistructured interviews with 11 agricultural professionals to explore perspectives on agrivoltaic systems. They identified key barriers, including concerns about long-term land productivity, market uncertainties, and compatibility with current agricultural practices. Despite these challenges, participants recognized potential benefits such as increased revenue and dual land use. The study emphasizes the need for flexible system designs and strong partnerships between the solar and agriculture sectors to address concerns and promote adoption. The conclusion highlights that overcoming these barriers is crucial for successfully implementing agrivoltaic technology (Pascaris et al., 2020).

Established in 2010, the agrivoltaic experimental model in Montpellier, France, integrates photovoltaic (PV) panels with crops on 820 m². Featuring monocrystalline PV panels mounted 4 meters high at a 25° tilt, the setup includes full-density (FD) and half-density (HD) configurations. During the wheat growing season, the FD system received 43% of incident light, while the HD system received 71%. The STICS model predicted a 29% reduction in dry matter, a 19% yield reduction under FD panels, and 11% and 8% reductions under HD panels. The findings suggest significant land use efficiency and productivity improvements with agrivoltaic systems (Dupraz, 2011).

CONCLUSIONS

Hortivoltaic systems represent a promising solution to address the challenges of climate change and land-use competition, efficiently combining horticultural production with renewable energy generation. These systems are particularly beneficial in arid regions, where panel shading reduces thermal stress on crops, thus optimizing water consumption and plant yield. Additionally, hortivoltaics are ideal for crops sensitive to intense solar radiation, protecting them from burns and other adverse effects of excessive sun exposure. Technological advancements, such as semi-transparent and bifacial panels alongside artificial intelligence, ensure efficient light management. These systems provide significant economic and environmental benefits, and ongoing research can further expand their applicability in horticulture and sustainable energy.

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