Balancing energy generation and crop productivity: A modeling and validation study on alfalfa agrivoltaics

Gabriel Marçal da Cunha Pereira Carvalho[2], Michele Moretta[1], Riccardo Rossi[1], Marco Moriondo[2], Luisa Leolini[1], Gloria Padovan[1], Aldo dal Prà[2], Giuseppe Mario Lanini[2], Enrico Palchetti[1], Giovanni Argenti[1], Marco Bindi[1]

[1] Department of Agriculture, Food, Environment and Forestry (DAGRI), University of Florence, Florence (Italy)

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

Abstract

Agrivoltaic systems (AVS) offer a promising solution to land-use competition by combining renewable energy production with agriculture. This study applied an integrated modeling framework linking the three-dimensional radiation and crop growth model GroIMP with PVsyst to optimize row spacing in a fixed AVS cultivating alfalfa (*Medicago sativa* L.). Simulations evaluated pitches ranging from 4 to 16 m to explore trade-offs between energy yield and biomass production. Dense configurations, such as 6 m spacing, increased energy output by 20% relative to the 8 m baseline with minimal impact on biomass (1% loss), whereas wider spacing, such as 10 m, enhanced biomass by 40% at the expense of a 19% reduction in energy. In conditions of limited water availability, as represented by half of the observed precipitation in 2023, the shading provided by AVS partially offset the drought stress, thereby transforming the energy–biomass trade-off into a synergy. The 10-meter pitch resulted in a +12% biomass gain relative to the full-sun (FS) control, with a maximum gain of +14% observed at 16 meters. These findings demonstrate that AVS can simultaneously optimize renewable energy generation, crop productivity, and climate resilience, and that the proposed integrated framework provides a robust tool for guiding system design under variable environmental conditions.

Keywords: Pitch optimization, Drought resilience, Trade-off, Mutual shading, AVS

1. Introduction

The global imperative to address climate change while ensuring food security has intensified the search for innovative land-use solutions that can simultaneously optimize agricultural production and renewable energy generation (Bazilian et al., 2011). Agrivoltaic systems (AVS) have emerged as a promising response to this dual-use challenge, enabling the coexistence of photovoltaic electricity generation and crop cultivation within the same spatial footprint (Barron-Gafford et al., 2019). These systems create complex spatial and temporal patterns of radiation distribution through panel shading, fundamentally altering the microenvironmental conditions that drive plant physiological responses and agricultural performance. Consequently, the reshaped light availability and energy balance have cascading effects on crop growth dynamics, water-use efficiency, and overall system productivity (Dal Prà et al., 2025). This spatial heterogeneity presents both opportunities and challenges for management practices, as moderate shading levels can enhance crop performance under certain conditions, whereas excessive shading may limit photosynthesis and reduce yield potential.

Alfalfa (*Medicago sativa* L.) represents a particularly compelling crop for AVS integration due to its high nutritional value as livestock feed, perennial growth habit (Argenti et al., 2021) and demonstrated adaptability to variable light regimes (Moretta et al., 2025b). Field studies have revealed that moderate shading levels (25-30%) can improve alfalfa performance under water-stressed conditions, while maintaining acceptable productivity compared to full-sun cultivation (Edouard et al., 2023). However, the extent to which these beneficial effects can be maximized through AVS design optimization, such as adjustments in panel spacing or orientation, has not yet been fully explored. Addressing this question requires a comprehensive

10.18086/swc.2025.06.06 Available at http://proceedings.ises.org

understanding of how dynamic shading patterns influence alfalfa physiological processes and biomass accumulation throughout the growing season.

In this context, advanced modeling approaches capable of capturing the multiscale processes governing system behavior are essential to represent the complex interactions between photovoltaic infrastructure and crop performance (Amaducci et al., 2018). Traditional crop models, while effective under homogeneous field conditions, face significant challenges when predicting plant responses under the heterogeneous radiation environments characteristic of AVS. The development of integrated modeling frameworks that couple three-dimensional (3D) radiation model with dynamic crop growth simulations represents a critical advancement for AVS design and optimization (Zainali et al., 2025). Integrating these biophysical models with industry-standard photovoltaic (PV) simulation tools is essential for a holistic assessment of both agricultural and energy productivity (Bellone et al., 2024). Such a coupled modeling strategy enables the simulation of diverse AVS configurations, allowing for quantitative evaluation of system-level trade-offs and identification of optimal design prametes.

Building on these premises, this study employs a validated, integrated modeling framework to assess the effects of PV row spacing on overall AVS productivity. The analysis extends beyond baseline performance metrics to examine the role of AVS in modulating crop performance and resilience under water-limiting scenarios, using detailed three-dimensional representations of fixed AVS layouts with dynamic simulations of radiation distribution and crop growth processes.

2. Materials and methods

2.1 Study sites and experimental setup

The modeling framework was developed using data from two distinct sites in Italy. Crop growth model calibration was performed using data from an open-field control site in Montese (44.4579° N, 10.5899° E), while AVS simulations and subsequent validation were based on a 35 MW commercial-scale solar farm in Ravenna (44.51019° N, 12.1552° E), where PV power generation is co-located with 70 hectares of alfalfa cultivation. This installation reports a specific yield of 1,285 kWh/kWp. The PV infrastructure, which serves as the baseline for this study, consists of south-oriented, fixed-tilt panels with a 35° tilt angle, an 8-meter inter-row spacing (pitch), and a table height of 3.3 meters.

Field data for model calibration (open-field, 2019) and validation (AVS, 2023) were collected via dedicated sampling campaigns. Above-ground biomass was periodically sampled using standardized 0.5 × 0.5 m quadrats, and samples were oven-dried to determine total dry matter (DM) content, adhering to established protocols (Mikhailova et al., 2000). Detailed information on field methodologies, including sampling frequency and spatial arrangement for validation, is detailed in Moretta et al. (2025a).

2.2 Crop growth modeling

The integrated modeling approach was implemented within the GroIMP plataform, implemented by Moretta et al. (2025a), combining a 3D radiative module with a dynamic crop growth model. The framework operates at hourly time steps throughout the entire growing season, utilizing local meteorological data (i.e. global horizontal irradiance, wind speed, precipitation, air temperature and relative humidity) as driving variables for both radiative and physiological processes. The model accounts for positive inputs to the soil water balance, including rainfall, as well as losses due to runoff, drainage, and evapotranspiration. The radiation model incorporates a dynamic light source that tracks solar trajectory for direct beam radiation, complemented by static light sources distributed to represent diffuse sky radiation.

Biomass estimation is based on a mechanistic approach, incorporating dynamic partitioning coefficients that redistribute assimilated carbon among leaves, stems, and roots throughout the growing season. Following the radiation use efficiency concept introduced by Monteith (1977), the hourly biomass increment under optimal environmental conditions is calculated by multiplying the incident global solar radiation, the fractional interception of photosynthetically active radiation by the canopy architecture (fPAR), and the radiation use efficiency (RUE) for DM production.

Spatial heterogeneity is represented through a tessellated ground model, where individual computational cells simulate discrete plant entities. This framework enables explicit tracking of growth responses across variable radiation microenvironments and facilitate mechanistic upscaling from plant-level physiological processes to field-scale productivity assessments, while preserving information about local environmental gradients and their influence on crop development patterns.

2.2 Photovoltaic modeling

PV energy yield was simulated using the industry-standard software PVsyst (Version 7.2). The analysis centered on the 'Near Shading' module to accurately model the complex irradiance patterns and inter-row shading effects inherent to AVS.

A detailed 3D scene was constructed replicating the Ravenna site's baseline parameters: south-oriented, 35° fixed-tilt tables equipped with 420 Wp monofacial modules. Simulations were performed at an hourly time step using Typical Meteorological Year (TMY) data sourced from PVGIS. The key metrics quantified for each scenario were the final AC energy yield delivered to the grid (kWh) and the specific yield (kWh/kWp). Furthermore, the simulation explicitly isolated mutual shading losses to assess the direct impact of pitch on system efficiency, thereby clarifying the trade-off between land use intensity and energy capture.

2.3 Experimental treatments and validation approach

To validate the integrated model's ability to accurately simulate the impact of heterogeneous shading on crop performance, a field sampling campaign was conducted at the Ravenna commercial site (8 m inter-row spacing).

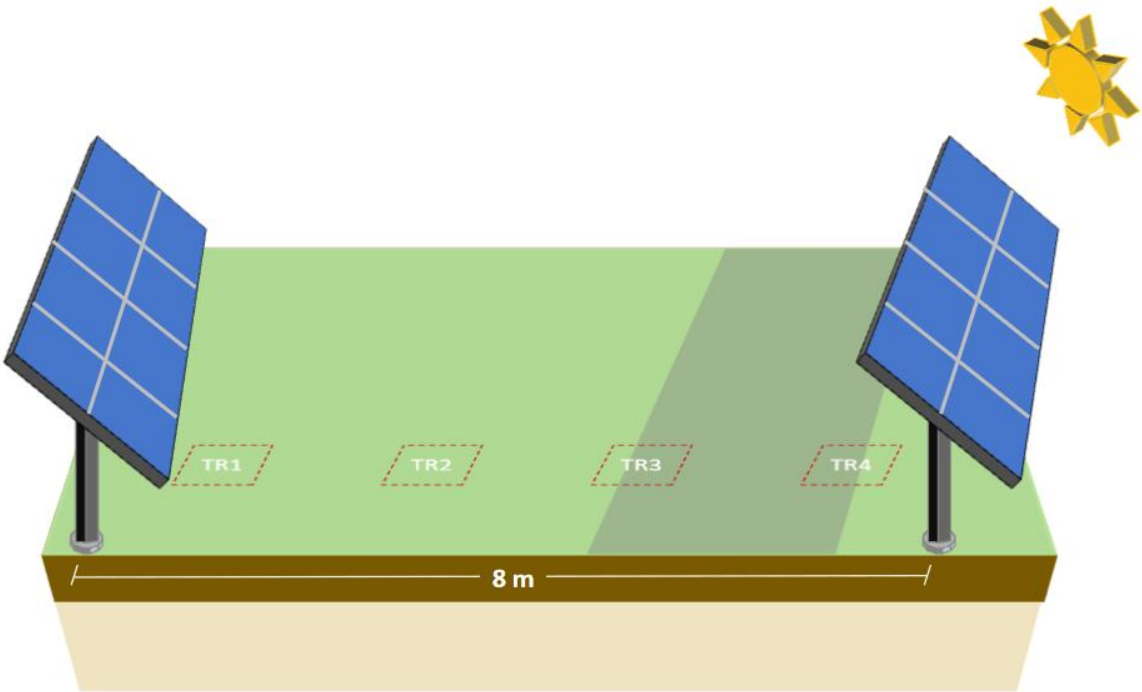

Figure 1. Representation of the fixed AVS highlighting the spacing between rows of solar panels and treatment areas.

As illustrated in Figure 1, four experimental treatment plots (TR1, TR2, TR3, TR4) measuring 1 m² were established. TR1 was placed on the inferior edge of the solar panel and received runoff from the solar panel surface. TR2 and TR3 were placed in the uncovered space, and TR4 was placed under the superior edge panel.These plots were arranged in a spatial transect within the 8-meter pitch, located between the first and second panel rows. The positions were set at 2-meter intervals relative to the support structure of the first panel row.

This layout was designed to capture the full gradient of radiation conditions, from the heavily shaded area near the panel to the more illuminated central alleyway. Annual shading percentages were calculated by the model for each specific location based on cumulative daily shadow coverage throughout the growing season.

2.4 Simulation scenarios and analysis

To evaluate the microclimatic impact of AVS on crop resilience and productivity, a comprehensive scenario analysis was conducted. Alfalfa biomass production was simulated across systematically varied AVS pitches and precipitation conditions. Seven AVS configurations were considered, with inter-row spacing (pitch) ranging from 4 to 16 m in 2 m increments. The entire set of simulations was run under two contrasting water regimes: a non-limiting water (100% Precip.) scenario using observed 2023 precipitation, and a limiting water (50% Precip.) scenario defined as half of the recorded 2023 precipitation. Performance of all AVS configurations was benchmarked against a full-sun (FS) control simulation under both water regimes.

For all AVS scenarios analyzed (Sections 3.1 and 3.2), the resulting agricultural yield was consistently quantified by calculating the average biomass production of the four defined treatments.

3. Results

3.1 Energy and agricultural productivity trade-offs

The impact of pitch variation in the AVS was evaluated by simulating the seven configurations using 2023 observed meteorological data. This analysis quantified the total energy production of the PV plant and the averaged biomass yield of treatments. The simulated scenarios revealed the fundamental trade-off between energy yield and agricultural productivity, with all results benchmarked against the 8 m baseline configuration (Figure 2).

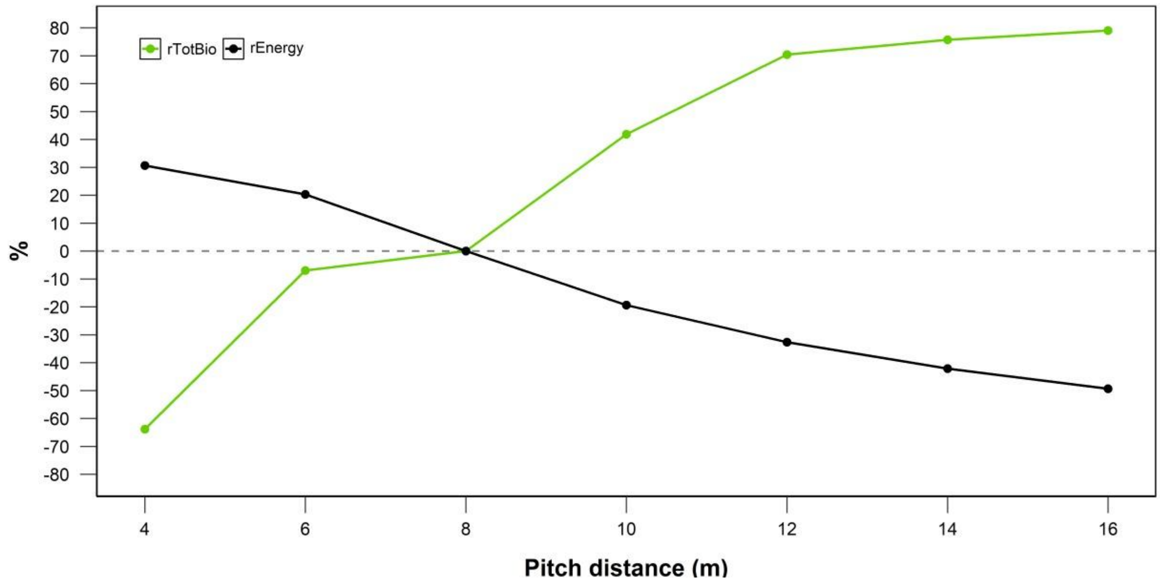

Figure 2. Relative change in total annual energy yield (rEnergy) and total annual biomass yield (rTotBio) across the simulated pitch scenarios, relative to the 8 m baseline, illustrating the core trade-off where reducing the pitch increases energy generation while decreasing biomass.

From an energy perspective, total yield was predominantly influenced by power density (kWp/ha). Higher-density configurations produced substantially greater energy output, despite increased losses from mutual shading. Specifically, the 6 m pitch scenario generated a 20% increase in total energy, while the 4 m configuration achieved a 31% gain, representing the maximum production observed. In contrast, wider spacing reduced power density, resulting in a 19% decrease in energy yield at 10 m and a 49% decrease at 16 m.

Agricultural performance exhibited an inverse trend relative to energy yield. Wider spacing, while incurring an energy penalty, enhanced biomass production: the 10 m pitch increased biomass by 40%, and the 16 m pitch achieved a 64% gain, approaching open-field levels. Conversely, the high-density configurations imposed substantial agricultural costs, with the 4 m spacing reducing annual biomass by 60%, whereas the 6 m spacing prioritized energy production and incurred only a 1% loss in biomass for a 20% gain in energy yield.

3.2 Influence of shading under water-stress conditions

A comparative analysis was performed for all seven pitch configurations using both the 2023 recorded meteorological data (100% Precip.) and the simulated drought scenario (50% Precip.). Results from simulation under this conditions revelad in the densest configurations (4 m and 8 m pitch), severe light limitation remained the dominant factor, resulting in a net yield penalty compared to the FS control. However, the results indicate that the water-conserving benefits of shading partially mitigated this loss under drought conditions, with the 4 m configuration penalty reduced from -74% under the 100% precipitation scenario to -64% under the 50% precipitation scenario.

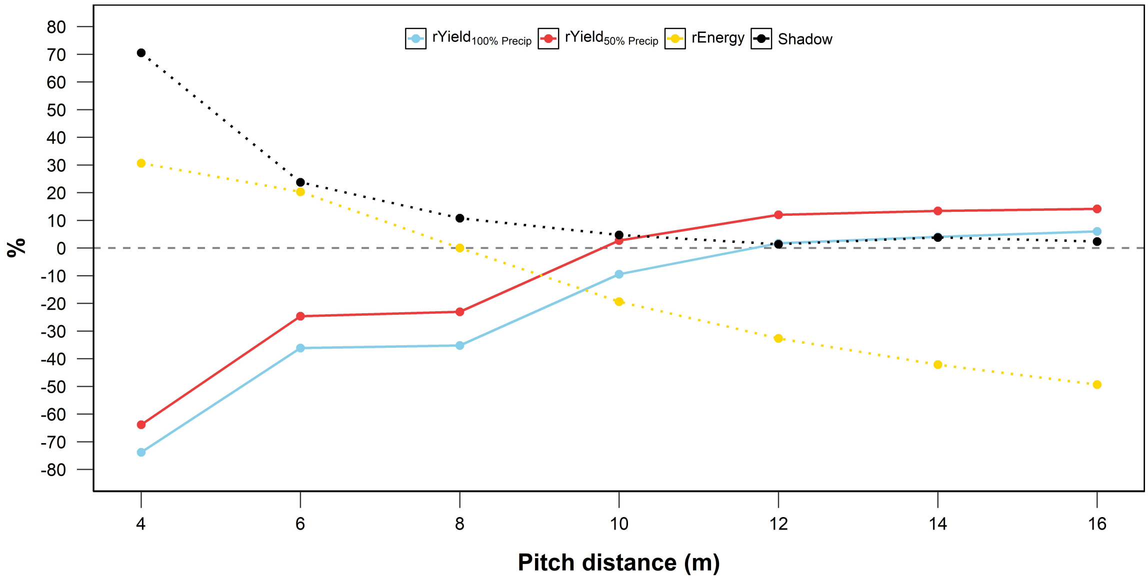

Figure 3. Relative annual biomass yield (rYield, average of TR1-TR4 vs. FS control) under 100% precipitation ($rYield_{100\% \text{ Precip}}$) and 50% precipitation ($rYield_{50\% \text{ Precip.}}$) conditions, alongside relative energy yield (rEnergy vs. 8m baseline) and shading percentage (Shadow), all varying with pitch. The beneficial impact of AVS on biomass yield is substantially amplified under drought conditions across most pitches, while energy yield decreases monotonically with increasing pitch.

When benchmarked against the FS control, the average AVS yield (across the treatments) showed modest gains under the 100% precipitation scenario, ranging from +2% at 12 m and peaking at +6% at the 16 m pitch. In contrast, this beneficial effect was substantially amplified by drought conditions. Under the 50% precipitation scenario, these yield gains were significantly higher, exhibiting a +12% gain at the 12 m pitch, +13% at 14 m, and reaching a maximum observed benefit of +14% at the 16 m pitch, relative to the stressed FS control.

This finding underscores the capacity of the system to promote crop resilience in conditions of water scarcity (50% Precip.). Concurrently, Figure 3 reiterates the energy trend previously observed (Section 3.1), showing a consistent decline in relative energy production (rEnergy) as pitch increases due to lower power density.

4. Discussions

The integration of photovoltaic energy generation and agriculture in AVS requires a balance in land use to achieve optimal productivity. This study used an integrated and validated modeling framework to specifically investigate this balance in alfalfa cultivation under fixed AVS, focusing on the pitch parameter. Our findings not only quantify the inherent trade-offs under standard conditions but also reveal a compelling synergistic relationship under drought scenarios.

Our simulations under non-limiting water conditions (100% Precip.) demonstrated the trade-off driven by pitch distance. Reducing the pitch increases the density of photovoltaic modules per unit of land area, thus increasing total energy generation, despite greater mutual shading losses (Bellone et al., 2024). Our results show a substantial energy gain of 31% at the narrowest pitch (4 m) compared to the baseline (8 m). Conversely, this densification significantly reduces the availability of photosynthetically active radiation (PAR) reaching the crop, which leads to a severe biomass penalty of 60% for alfalfa at the 4 m pitch caused by 71% shading. This aligns with the meta-analysis by Laub et al. (2022), which identified that no agrivoltaic study showed a production gain in situations of 60% shading when compared to the open-field control.

Wider pitches naturally alleviate light limitations for the crop, allowing biomass production to approach FS control levels (e.g., +64% biomass gain at 16 m pitch vs. 8 m baseline), but at the cost of significantly reduced energy production (-49% energy at 16 m). This inverse relationship highlights that pitch selection represents a strategic decision that can be used to balance AVS priorities. The simulation results show that a 6 m pitch offers a 20% energy gain with only a 1% biomass loss, suggesting an "energy-priority" sweet spot for alfalfa. In contrast, the 10 m pitch, increasing biomass by 40% while reducing energy by 19%, represents an "agriculture-priority" strategy. However, these definitions derived from these configurations are specific to each AVS, since alfalfa's productivity responses to shading are not uniform and depend critically on prevailing environmental conditions (particularly water availability) and the AVS configuration. For example, the study by Edouard et al. (2023) obtained a +10% biomass gain relative to the FS control by imposing 22-44% shading with a dual-axis tracker AVS in France. However, the same results are not observed in our simulations, in which the AVS with 22% shading (obtained with the 6 m pitch) exhibits a -36% drop in biomass production relative to full sun. This discrepancy is fundamental and can be attributed to critical differences in system design and environmental conditions. The dual-axis system in Edouard et al. (2023) creates dynamic and diffuse shading patterns, vastly different from the more constant and deep shading of our fixed-tilt system.

Transcending the pitch assessment, the evaluation of the drought scenario (50% Precip.) transforms the AVS paradigm from a land-use trade-off to a climate adaptation tool. The observed synergy confirms that AVS provides crop resilience in climate change situations (Amaducci et al., 2018). Although shading reduces PAR, it confers microclimatic benefits, such as: reduced soil evaporation, lower canopy temperatures, and increased water use efficiency (WUE) (Amaducci et al., 2018; Barron-Gafford et al., 2019; Scarano et al., 2024; Sturcchio et al., 2025). This effect is also observed on a smaller temporal scale, whereby AVS can mitigate midday photosynthetic stress, reduce water stress, and maintain equal or better productivity compared to the FS control (Barron-Gafford et al., 2025).

Our simulations show that, although dense configurations (4–8 m) still incurred a yield penalty relative to the FS control at 50% precipitation, the penalty was significantly attenuated under drought compared to non-limiting conditions (e.g., penalty at 4 m reduced from -74% to -64%). Most notably, for pitches of 10 m and wider, the AVS effectively produced more biomass than the FS control under stress (+12% at 10 m, reaching +14% at 16 m). This demonstrates a clear synergistic benefit where the AVS structure enhances crop resilience to drought. This finding provides quantitative support for the hypothesis that AVS can mitigate climate-related stresses (Barron-Gafford et al., 2019) and suggests that in water-scarce environments or during drought periods, AVS use may be more productive overall than conventional open-field agriculture.

In this context, the integrated modeling of alfalfa productivity and energy generation, by simulating different pitches, provided a quantitative analysis of the balance between energy generation and crop productivity. This approach allowed for an in-depth assessment of the complex interrelationship between the crop water balance, dynamic shading, and radiation availability. The framework's flexibility allows for its application to test various abiotic conditions and AVS configurations. This validated modeling framework thus provides a robust tool to guide the optimization of AVS for specific contexts, balancing renewable energy goals with sustainable and adaptive agricultural production.

5. Conclusions

This study applied an integrated 3D modeling framework (GroIMP/PVsyst) to evaluate AVS performance, capturing the interactions between energy generation and alfalfa productivity. These interactions were strongly influenced by pitch geometry: dense configurations (4–6 m) maximized energy yield but limited biomass, while wider spacings (10–16 m) enhanced crop production at the expense of energy output. The effects of shading were further modulated by water availability, with drought conditions amplifying the benefits of AVS and partially compensating for light limitation. Overall, the results demonstrate that appropriately designed AVS can balance energy and agricultural objectives, transforming potential competition into synergy under water-limited conditions.

The proposed framework could thus enable stakeholders to quantitatively assess how different system geometries influence both energy and biomass outcomes under varying climate scenarios, thereby supporting the predictive optimization of AVS designs to achieve specific objectives in food production and renewable energy generation.

6. References

Amaducci, S., Yin, X., Colauzzi, M., 2018. Agrivoltaic systems to optimise land use for electric energy production. Applied Energy 220, 545-561. http://dx.doi.org/10.1016/j.apenergy.2018.03.081.

Argenti, G., Parrini, S., Staglianò, N., Bozzi, R., 2021. Evolution of production and forage quality in sown meadows of a mountain area inside Parmesan cheese consortium. Italian Journal of Agrometeorology 19, 43-52. http://dx.doi.org/10.15159/ar.21.061.

Barron-Gafford, G. A., Murphy, P., Salazar, A., Lepley, K., Rouini, N., Barnett-Moreno, I., Macknick, J. E., 2025. Agrivoltaics as a climate-smart and resilient solution for midday depression in photosynthesis in dryland regions. Npj Sustainable Agriculture, 3, 32. https://doi.org/10.1038/s44264-025-00073-1

Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L. et al., 2019. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nat Sustain 2, 848-855. http://dx.doi.org/10.1038/s41893-019-0364-5.

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R.S.J., Yumkella, K.K., 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. Energy Policy 39, 7896-7906. http://dx.doi.org/10.1016/j.enpol.2011.09.039.

Bellone, Y., Croci, M., Impollonia, G., Nik Zad, A., Colauzzi, M., Campana, P. E., Amaducci, S., 2024. Simulation-Based Decision Support for Agrivoltaic Systems. Applied Energy, 369. https://doi.org/10.1016/j.apenergy.2024.123490

Dal Prà, A., Dainelli, R., Santoni, M., Lanini, G.M., Di Serio, A., Zanotti, D., Greco, A., Ronga, D., 2025. Impact of different shading conditions on processing tomato yield and quality under organic agrivoltaic systems. Horticulturae 11, 319. http://dx.doi.org/10.3390/horticulturae11030319.

Edouard, S., Combes, D., Van Iseghem, M., Ng Wing Tin, M., Escobar-Gutiérrez, A.J., 2023. Increasing land productivity with agriphotovoltaics: Application to an alfalfa field. Applied Energy 329, 120207. http://dx.doi.org/10.1016/j.apenergy.2022.120207.

Laub, M., Pataczek, L., Feuerbacher, A., Zikeli, S., Högy, P., 2022. Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis. Agronomy for Sustainable Development, 42. https://doi.org/10.1007/s13593-022-00783-7

Mikhailova, E.A., Bryant, R.B., Cherney, D.J.R., Post, C.J., Vassenev, I.I., 2000. Botanical composition, soil and forage quality under different management regimes in Russian grasslands. Agriculture, Ecosystems & Environment 80, 213-226. http://dx.doi.org/10.1016/S0167-8809(00)00148-1.

Monteith, J.L., 1977. Climate and Efficiency of Crop Production in Britain. Philosophical Transactions of the Royal Society London B 281, 277-294. http://dx.doi.org/10.1098/rstb.1977.0140

Moretta, M., Moriondo, M., Leolini, L., Padovan, G., Staglianó, N., Palchetti, E., Lanini, G.M., Bindi, M., Rossi, R., 2025. Towards crop monitoring in agro-photovoltaic systems: An image-driven modeling approach for fAPAR-derived biomass estimation. European Journal of Agronomy 170, 127748. http://dx.doi.org/10.1016/j.eja.2025.127748.

Moretta, M., Rossi, R., Padovan, G., Staglianò, N., Palchetti, E., Bindi, M., Campana, P.E., Moriondo, M., 2025. The Impact of Photovoltaic on Permanent Grassland Composition and Productivity in Central Italy. AgriVoltaics Conference Proceedings, 3. http://dx.doi.org/10.52825/agripv.v3i.1372.

Zainali, S., Lu, S.M., Fernández-Solas, Á., Cruz-Escabias, A., Fernández, E.F., Zidane, T.E.K., Honningdalsnes, E.H., Nygård, M.M., Leloux, J., Berwind, M., Trommsdorff, M., Amaducci, S., Gorjian, S., Campana, P.E., 2025. Modelling, simulation, and optimisation of agrivoltaic systems: a comprehensive review. Applied Energy 386, 125558.