EXTENDED SUMMARY

Investigation of agrivoltaic systems development in Greece.

1. Introduction

The increasing demand for energy and the need to reduce the environmental impacts of conventional energy production have accelerated the development of renewable energy technologies, particularly photovoltaic (PV) systems. However, the expansion of large-scale photovoltaic installations raises concerns regarding land availability and competition with agricultural production. At the same time, agriculture faces increasing pressure to maintain food production while managing limited land and water resources.

Within this context, agrivoltaic systems offer an alternative approach by enabling the simultaneous production of electricity and agricultural crops on the same land. Nevertheless, the presence of photovoltaic panels alters the amount and distribution of solar radiation reaching the crops, potentially affecting their productivity and water requirements.

The performance of these systems depends on local climatic conditions, crop characteristics, and photovoltaic installation parameters. In particular, panel transmittance and inter-row spacing influence both agricultural and energy production.

The present study investigates the potential for agrivoltaic development in Greece through the assessment of different photovoltaic configurations and selected crops across ten locations.

2. Study Design and Methodology

The present study examined different agrivoltaic system configurations across ten locations in Greece. Two crops were selected for each location, considering local agricultural activities, their suitability for cultivation under agrivoltaic conditions, and the availability of the required data. A consistent calculation methodology was applied to all study areas to enable comparisons between the examined cases.

Hourly meteorological data for 2022 were obtained from the Open-Meteo Historical Weather API for each study area, including air temperature, relative humidity, wind speed, and incoming shortwave solar radiation. Based on the selected locations and their climatic characteristics, twelve agrivoltaic configurations were examined, combining four photovoltaic panel types with three inter-

row distances. The panel types included one conventional (opaque) panel and three semi-transparent panels with light transmittance levels of 40%, 50%, and 70%, while the distances between photovoltaic rows were set at 4, 5, and 6 m. Following Roxani et al. (2023), the panels were installed at a height of 5 m, facing south, with a tilt angle corresponding to the latitude of each location.

To assess the effect of these configurations on the solar radiation available to crops, three representative spatial positions were considered within each arrangement. Incoming solar radiation was separated into direct and diffuse components, while solar position and panel geometry were used to determine the shading conditions at each position. This approach allowed the estimation of radiation availability under different panel transmittance levels and inter-row distances.

Crop production was estimated using the Radiation Use Efficiency (RUE) approach, based on the photosynthetically active radiation available under each agrivoltaic configuration and crop-specific parameters. Crop water requirements were assessed by calculating reference evapotranspiration (ET_o) using the FAO Penman–Monteith method, followed by the estimation of crop evapotranspiration (ET_c) using the corresponding crop coefficients (K_c). Electricity generation was estimated considering the incident solar radiation, photovoltaic panel characteristics, and temperature-dependent conversion efficiency.

Finally, two indicators were used to evaluate the performance of the examined configurations. The Water Saving Index (WSI) quantified the reduction in crop evapotranspiration relative to full-sun conditions, while the Land Equivalent Ratio (LER) assessed the combined efficiency of agricultural and electricity production relative to their respective reference systems.

3. Results and Discussion

3.1 Solar Radiation Availability

Solar radiation availability increased with both inter-row spacing and panel transmittance at all examined spatial positions (S1–S3). However, panel transmittance consistently exerted a stronger influence, with an average effect approximately 2.6 times greater than that of inter-row spacing across the ten study locations, within the examined parameter ranges. Furthermore, increasing panel transmittance reduced the monthly variability of available solar radiation at the examined spatial positions.

3.2 Electricity Generation

An opposite trend was observed in electricity generation per unit of land area, which decreased with increasing inter-row spacing and panel transmittance. Wider spacing reduced the number of installed photovoltaic panels per unit area, while semi-transparent panels had lower rated power. Across the examined locations, panel transmittance exerted an approximately 2.3 times greater influence on electricity generation than inter-row spacing, highlighting its dominant role in determining energy production.

3.3 Agricultural Production

Estimated crop production followed the same trend as solar radiation availability, increasing with both inter-row spacing and panel transmittance and gradually approaching the corresponding production under full-sun conditions. Across the twenty examined crop cases, panel transmittance exerted, on average, approximately 2.5 times greater influence on estimated crop production than inter-row spacing, within the examined parameter ranges. However, this relationship varied among crops, with the relative influence ranging from approximately 1.9 to 3.7 times. These differences highlight the importance of crop-specific characteristics in agrivoltaic system design.

3.4 Crop Water Requirements and Water Savings

The assessment of crop water requirements revealed an additional benefit of shading provided by photovoltaic panels. Estimated crop evapotranspiration was lower under configurations with narrower inter-row spacing and lower panel transmittance, gradually increasing as conditions approached full sunlight. This trend was also reflected in the Water Saving Index (WSI), with higher values generally occurring under configurations providing stronger shading. Across the 19 examined crop cases, panel transmittance exerted, on average, approximately 2.3 times greater influence on WSI than inter-row spacing, within the examined parameter ranges. These findings highlight the trade-off between crop productivity and water savings, emphasizing the importance of considering both when selecting an appropriate agrivoltaic configuration

3.5 Land Equivalent Ratio (LER)

The Land Equivalent Ratio (LER), which assesses the efficiency of combined agricultural and electricity production relative to their separate land uses, exceeded unity in all examined

configurations, indicating an advantage of combined land use under the adopted reference conditions. The energy component had a greater influence on LER than relative crop production, with the highest values generally observed in configurations combining conventional panels and narrower inter-row spacing, despite their lower agricultural productivity. These findings highlight the importance of interpreting LER through its individual components rather than using it as a standalone criterion for evaluating agrivoltaic performance.

3.6 Comparison Between Study Locations

The comparison of identical crops across different locations revealed relatively small differences in estimated agricultural production under corresponding agrivoltaic configurations. For instance, tomato production in Ilia was 1.6–2.3% higher than in Boeotia, while alfalfa production differed by less than 0.3% between Boeotia and Aetolia-Acarnania. However, crop water requirements showed more pronounced regional differences, reflecting the influence of local meteorological conditions. Despite these variations, the response of individual crops to the examined configurations remained consistent, while LER values were nearly identical across locations for the same crops and configurations.

4. Conclusions and Future Research

The present study highlighted a clear trade-off between electricity generation, agricultural production, and water savings, demonstrating the potential of agrivoltaic systems for combined land use in Greece. Although no universally optimal configuration was identified, adapting photovoltaic arrangements to crop characteristics and local conditions can support the effective coexistence of agricultural and energy production.

Future research should focus on validating the findings through experimental field studies in Greece, assessing the economic feasibility of agrivoltaic installations, and conducting multi-year investigations to evaluate their long-term performance under varying climatic conditions.