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Techno-agroecological Potential of Integrated Agrivoltaic Systems in Olive Trees located in Southern Spain

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A B S T R A C T

Olivoltaics, the integration of photovoltaic (PV) systems within olive groves, offers a promising pathway to reconcile renewable energy expansion with Mediterranean agriculture. This study evaluates the techno-agroecological potential of olivoltaic systems in southern Spain, combining a structured literature synthesis with a regional case study. Scenarios for Andalusia, the world's leading olive-producing region, considering system design variables (module transparency, tilt, and height), land allocation fractions, and cultivar light responses are assessed. Results indicate that deploying olivoltaic systems on 80,000 ha of intensive and super-intensive olive groves could generate ~15 TWh/year of electricity, reduce CO_2 emissions by 3.8 Mt/year, save 12–30% of irrigation water, and create over 24,000 jobs, while maintaining land equivalent ratios above 1.3. However, uncertainties remain regarding long-term yield stability, olive oil quality, pest dynamics, and ecological effects, underscoring the need for multi-year pilot projects. The findings demonstrate the potential of olivoltaics as a regional climate adaptation and mitigation strategy, while also providing a roadmap for future empirical research and policy development.

1. Introduction

Climate change, resource scarcity, and land-use conflicts are reshaping agricultural and energy systems in the Mediterranean[1–3]. Olive cultivation, covering more than 11 million hectares worldwide, over 90% in Mediterranean countries, forms the backbone of rural economies, cultural landscapes,

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and global trade[4,5]. Spain, and particularly Andalusia, hosts the largest olive-growing area, exceeding 1.6 million hectares, but faces increasing vulnerability to rising temperatures, water scarcity, and extreme weather events [5,6]. At the same time, the rapid deployment of renewable energy, especially solar photovoltaics (PV), has intensified competition for land, raising concerns over food-energy trade-offs[2].

Agrivoltaics (APV), the dual use of land for PV energy generation and agriculture, has emerged as a promising solution to these challenges[7–11]. Global interest has accelerated in recent years, with applications in cereals, viticulture, horticulture, and, more recently, perennial tree crops[1,12–15]. Within this framework, olivoltaics, the integration of PV systems into olive groves, leverages the perennial nature, drought tolerance, and canopy structure of olives to create synergies between energy production and high-value crop cultivation[1,12],[15].

Previous research on olivoltaics has largely focused on simulation-based studies of light management, energy yields, and photosynthetic responses, complemented by initial field experiments in Spain and Italy. These studies demonstrate potential benefits such as water savings, microclimate regulation, and increased land-use efficiency. However, there still no comprehensive techno-agroecological assessment that combine literature evidence with a regional case study at scale, explicity quantifying the energy, water, carbon, and employment benefits of olivoltaic deployment in Southern Spain, the world’s leading olive region.

The novelty of this work lies in the integration of system design variables (module transparency, tilt, and height) with olive cultivar, quantifying the climate mitigation and socio-economic impacts of deploying olivoltaics across 80000 ha of olive groves and framing olivoltaics as both a regional climate adaptation and mitigation strategy.

The present paper therefore addresses these gaps by assessing the potential of olivoltaic systems in southern Spain through a dual approach: (i) a structured literature olivoltaic synthesis, and (ii) a regional case study for Andalusia that quantifies potential energy generation, CO_2 savings, water use reduction, and employment impacts under different deployment scenarios.

The article is organized as follows: Section 2 synthesis in agrivoltaics and olive cultivation; Section 3 details the methodological framework used for the regional case study; Section 4 presents the results; Section 5 discusses uncertainties, ecological and socio-economic implications, and policy relevance; and Section 6 concludes with key findings and future research directions.

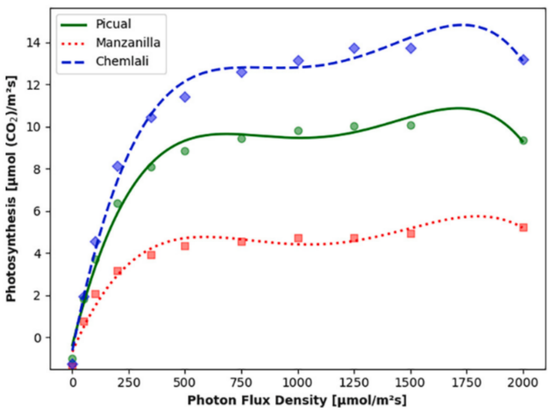
2. Overview of Agrivoltaics

Agrivoltaics, also referred to as APV, is the intentional and spatially integrated practice of combining PV systems with agricultural production on the same land. The concept, formally introduced in the early 1980s and developed further over the past decade, was driven by the fact that ground-mounted PV, while cost-effective and scalable, occupies significant areas of arable or fertile land, raising food-versus-energy land-use conflicts, especially in regions under pressure from climate change, population growth, and urban expansion[10,16]. The essential principle of agrivoltaics is to increase land use efficiency by allowing crops (or, more broadly, agricultural activities including livestock, grazing, or ecosystem services) and PV electricity production to occur simultaneously, rather than in competition[17]. A central metric is the Land Equivalent Ratio (LER), which, if above unity, indicates greater productivity than monocultures of either crop or PV alone[3,18,19].

Agrivoltaic system designs are highly varied. Overhead APV feature PV arrays mounted high above the crops (allowing mechanization and light penetration below), while interspace systems place PV modules between crop rows or animal pastures[10]. Closed systems, like PV greenhouses, integrate modules into protected cultivation[20–23]. The most widely adopted configurations globally have been tailored to local crops, farm practices, and climate[24].

Recent years have seen remarkable global growth: total APV capacity expanded from 5 MW in 2012 to 14 GW in 2021, propelled by policy incentives and government-backed pilot projects in Asia, Europe, and North America[2]. Japan and France, for example, have established clear regulatory definitions and agricultural yield requirements for APV, while other countries such as the USA operate under broader interpretations, sometimes including non-productive ecosystem services[8]. This diversity of legal and technical frameworks complicates standardization but allows for innovation and context-specific solutions.

A central technical challenge in agrivoltaics is optimizing the balance between PV-induced shading and the light requirements of crops[9]. Most crops rely on photosynthetically active radiation (PAR), which encompasses wavelengths from 400 to 700 nanometers and drives the photosynthetic process[25–27]. Particularly, the photosynthesis-light response curve for most C3 crops, which are species that use only the Calvin cycle to fix CO_2 during photosynthesis (including many cereals, vegetables, and olives) is nonlinear: photosynthetic rate rises with increasing PAR up to a certain threshold, the photosynthetic saturation point, beyond which further increases in light provide diminishing or no yield benefit[12,28]. Figure 1 shows the photosynthetic light-response curves for three typical Mediterranean olive cultivars, illustrating how CO_2 assimilation varies with incident light and highlighting differences in photosynthetic saturation among cultivars. For many temperate crops, this saturation point typically occurs at photon flux densities between 800 and 1200 $\mu mol \cdot m^{-2} \cdot s^{-1}$, or roughly 40–60% of full sunlight.



Above this point, additional light may only increase leaf temperature and evapotranspiration, rather than net assimilation.

Figure 1. Photosynthetic light-response curves of Mediterranean olive cultivars, showing tolerance to partial shading, which supports the rationale for integrating semi-transparent PV. Data from [12]

From a technical standpoint, the most significant research questions revolve around optimizing the balance between PV shading and crop light needs, the selection of suitable crops (typically those with higher shade tolerance or value), and the management of system design variables such as module height, tilt, ground coverage ratio, and transparency. Simulation studies and the first operational monitoring campaigns have shown that APV can yield environmental co-benefits beyond just dual production, including reductions in crop water demand, moderation of microclimates, improved biodiversity, and new business models for rural stakeholders[2]. Still, challenges remain: higher installation costs compared to ground-mounted PV, lack of long-term empirical data, social acceptance, and regulatory ambiguity in many regions continue to hinder large-scale uptake[8,19,29]. Despite these barriers, agrivoltaics is widely recognized as a promising pathway to reconcile food security and renewable energy expansion, especially in land-constrained, climate-sensitive regions. The next phase of APV development will rely on robust, context-adapted design, multi-annual performance data, and alignment with both agricultural and energy policies.

Olivoltaics refers to the integration of PV energy systems within olive cultivation, enabling the dual use of land for both agricultural and energy production. This approach leverages the agro ecological and socio-economic significance of the olive tree, which has been cultivated for over 6,000 years in the Mediterranean Basin and now spans all five continents, covering a global area exceeding 11 million hectares. The continual expansion of olive cultivation in recent decades has been propelled by rising demand for olive oil and the crop's adaptability to a wide variety of climates and soils [5,30].

A key feature distinguishing olive cultivation and with direct relevance to olivoltaic potential is the classification of olive groves according to planting density and associated management methods. Olive orchards are generally divided into three systems: traditional, intensive, and super intensive (hedgerow or "seto"), Figure 2.

	Traditional	Intensive	Superintensive
Density (trees/ha)	80-100	200-800	1000-1500
Height (m)	3 - 4	2 - 3	2 - 3
Frame [row x tree] (m)	10 - 12	4 - 8	2 - 3

Figure 2. Olive tree types and traditional distribution patterns and dimensions.

Traditional olive groves are the most widespread globally, accounting for roughly 63% of planted area. These systems have low planting densities (usually fewer than 80–100 trees/ha), large planting distances (10–12 meters), and tree heights typically between 3 and 4 meters. Rainfed management and manual or semi-mechanized harvesting are prevalent, resulting in higher production costs and often lower productivity. Nevertheless, traditional groves play a crucial role in supporting rural populations, maintaining biodiversity, and preserving ecosystem services such as soil protection and carbon sequestration.

Intensive olive groves represent about 32% of the global olive surface. With densities ranging from 200 to 800 trees/ha and planting frames of 4–8 meters, these systems utilize trees of 2–3 meters in height, making full mechanization feasible. Intensive groves offer higher yields per hectare, earlier entry into production, and significant reductions in harvest costs thanks to mechanization, though they often require irrigation and more intensive management.

Super intensive (hedgerow/seto) olive groves are the most modern and technically advanced system, currently making up about 5% of the global olive area but expected to grow to 23% by 2030 [31,32]. These orchards feature extremely high planting densities (over 1,000–1,500 trees/ha), tree heights generally under 3 meters, planting frames of 2 – 3 m and rely on highly mechanized, technologically optimized management, including the use of specialized varieties and precision inputs to maximize water and nutrient use efficiency[32,33]. Although still a minority of the area, their rapid expansion reflects the global trend toward greater efficiency and profitability in olive production[31].

Beyond the limited but growing body of research directly addressing agrivoltaics in olive groves, a substantial set of studies on olive tree physiology and management provide indirect insights highly relevant to olivoltaic design. For instance, long-term trials on row spacing demonstrated the strong influence of canopy architecture on radiation interception and yield formation [34], while remote sensing approaches have quantified gross primary production (GPP) as a function of photosynthetically active radiation (PAR) received by olive trees [35]. Pruning studies in high-density orchards have shown how canopy manipulation alters light penetration and thereby productivity [36], complementing controlled experiments linking fruit and vegetative growth responses to PAR during oil synthesis [37]. Architectural modeling work has further visualized the relationship between olive morphology and light interception [38]. In addition, physiological responses under stress have been characterized, such as differences in photosynthetic rates between cultivars under drought [39] and contrasting adaptive responses of sun- versus shade-adapted leaves [40]. While not agrivoltaic by itself, these contributions highlight the centrality of light management, canopy structure, and stress physiology in olive cultivation, offering a crucial scientific basis for anticipating how shading from PV modules may interact with olive growth and oil quality in olivoltaic systems.

The spatial distribution of olive cultivation remains highly concentrated in the Mediterranean, Figure 3. Europe accounts for 51.4% of global olive area, led by Spain, Italy, Greece, and Portugal. Africa, primarily Tunisia, Morocco, and Algeria, follows with 32.4%. Asia, the Americas, and Oceania together make up less than 16% of global plantings[41]. Spain alone boasts over 2.8 million hectares, half of the EU's olive area, with the traditional system making up 76% of national groves, intensive about 22%, and super intensive between 2–4% but steadily expanding[6]. The annual olive oil output in Spain can surpass 1.5 million tons in favorable years, positioning the country as the world leader. This industry not only drives national exports and rural economies but also contributes substantially to Spain's GDP.

There is a high degree of genetic and phenological diversity in olive cultivation, with over 2,600 known cultivars worldwide[30]. Key varieties of interest in olivoltaic research, including Picual, Manzanilla, Arbequina, and Chemlali, are notable for their agronomic value and adaptability to modern management systems[5,30]. Within Spain, Andalucía stands out as the dominant olive region, holding more than 60% of the country's olive area, about 1.62 million hectares[6]. At the heart of this landscape is the province of Jaén, home to the world's largest concentration of olive groves (over 600,000 hectares) and responsible for roughly a quarter of global extra virgin olive oil and half of Spain's total production.

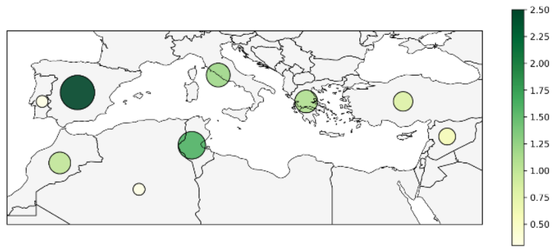


Figure 3. Distribution of olive groves in the Mediterranean in the main producing countries

Olivoltaics, therefore, must be understood against this backdrop of diverse olive systems and regional specialization. The compatibility of PV integration varies by orchard type: super intensive systems, with their uniform row structure, low canopies, and need for efficient mechanization, are particularly suited to elevated or interspace PV installations. By contrast, the ecosystem services and rural support functions of traditional systems highlight the need for careful balance between energy and cultural values. The

Mediterranean climate hot, dry summers and mild, wet winters favors olive cultivation, and the perennial, drought-tolerant olive tree is well adapted to this environment. However, this region is also a climate change hotspot, with increasing threats from rising temperatures, unpredictable rainfall, and more frequent extreme weather events. These factors imperil both yields and the long-term sustainability of olive groves, intensifying the search for resilient cropping systems.

3. Methodologies for olivoltaics

Olivoltaic systems may be designed as new plantings (greenfield) or retrofitted into existing olive groves. Two main open-field configurations are considered[1,12]:

- Overhead APV: PV modules are mounted above tree rows, typically at 3–4.5 m height, to enable machinery passage and minimize direct shading, Figure 4.
- Interspace APV: PV modules are installed between rows, using the available spacing in plantations.

Figure 4. Overhead Olivoltaic experimental setup in Jaén, Spain

Key design variables include PV module type (monofacial, bifacial, or semi-transparent), tilt and orientation, ground coverage ratio, transparency factor (fraction of module area unoccupied by cells), and the dimensions and spacing of trees and PV structures. Mechanized harvesting imposes constraints on minimum PV structure height and row width. Most published studies on Olivoltaics are simulation-based, combining solar resource assessment, geometric shading analysis, PV yield modeling, and crop light-response modeling. The main steps are as follows:

- **PV Yield Modeling**: PV productivity is estimated using commercial simulation software (e.g., PVGIS, Radiance-based ray-tracing, in-house codes) that account for hourly meteorological data, PV module parameters, system layout, shading, bifaciality, and electrical losses[1,13].
- **Crop Yield Modeling**: Crop yield is typically modeled as a function of the ratio of photosynthetically active radiation (PAR) received under the APV system compared to the open field. The crop light-response (photosynthesis–irradiance curve) for each cultivar is experimentally determined using gas exchange measurements. Simple linear or non-linear models relate absorbed PAR to oil or fruit yield[12,15].
- **LER Calculation**: The Land Equivalent Ratio is calculated as the sum of the relative yields (energy and crop) in the dual-use system compared to their respective single-use reference systems.

Recent research on Olivoltaics has primarily relied on simulation studies and case analyses concentrated in southern Spain and Italy, regions characterized by expansive, high-density olive groves and abundant solar resources[1,13]. These studies have employed a range of modeling strategies, from straightforward calculations based on light interception to advanced three-dimensional ray-tracing and parametric analyses, to explore how different system designs such as bifacial versus monofacial modules, varying panel heights (typically 3–4.5 meters), tilt angles (from vertical to 30°), and row spacing affect both olive and energy production. The most detailed approaches integrate site-specific climate data and cultivar-specific physiological responses, while others utilize empirical or analytical models for rapid scenario analysis. Financial assessments in the literature consider the full spectrum of costs (installation, operation, and maintenance) and revenue sources (crop and electricity sales), and consistently show that, when incentive frameworks or strong market conditions are present, olivoltaic systems can deliver attractive returns on investment and short payback times.

A key consensus emerges: integrating PV systems with olive groves be specially in intensive and super-intensive plantations where tree geometry and management can be finely tuned is technically viable and results in combined land productivity (measured by the LER) that significantly exceeds monoculture baselines. Most simulation studies find that olive trees exhibit moderate tolerance to partial shading, particularly when modern pruning and planting designs are used, resulting in only moderate yield reductions that are often offset by water savings and new energy-derived income. The partial shading provided by PV modules also tends to lower crop evapotranspiration, reducing overall irrigation needs an especially valuable outcome in the drought-prone Mediterranean basin.

Despite this promising outlook, studies differ substantially in their methodological complexity and underlying assumptions. Some use simple proportional yield scaling, while others incorporate detailed biophysical modeling and measured light-response data for each olive variety. There is similar diversity in the PV technologies considered, with some studies modeling conventional fixed-tilt or single-axis tracking systems and others testing advanced bifacial or semi-transparent modules to optimize light sharing and further reduce shading impacts. The ideal balance between PV transparency, spacing, and crop output remains an active area of inquiry, as does the suitability of various system types

Table 1. Summary of the studies investigating Olivoltaics. All studies are simulation based

Region Ref.	Olive varieties	PV System	Main models	Key findings	LER
Spain [14]	Hedgerow (unspecified, super-intensive)	N-S tracker, 3m height, 1.5m wide hedgerows	Geometric shading, tracking/backtracking simulation	Design can minimize mutual shading; LER gains up to 47%; geometric factors crucial for system output.	1.29 – 1.47
Italy [13]	Arbequina	N-S tracker, 3m height. Two layouts: 6m and 7.5m row spacing.	PVGIS energy yield, financial model (NPV, ROI, payback), crop yield modelling based on light response	Closer rows increase PV and profit; olive losses minor and offset; high NPV, fast payback.	-
Mediter ranean [12]	Picual, Manzanilla, Chemlali	Overhead, semi-transparent PV, 4m, transparency tuned by cultivar and site irradiance	Dual model: site specific crop light response curves(photosynthesis vs. PAR), PV energy output	Optimal transparency (57 –71%) by cultivar/site; large regional APV impact on PV capacity and jobs; co-benefits.	-
Spain [1]	Picual, Manzanilla, Chemlali (super-intensive)	Bifacial, interspace, 3-4.5m	Ray-tracing (Bifacial Radiance), cultivar specific light-response, PV performance model	Module tilt/height, bifaciality shape both yields; best LER (1.71) at 20° tilt; high APV compatibility.	Up to 1.71
Spain [15]	Hedgerow (unspecified)	N-S tracker, 3m height, 10m row spacing	Analytical PAR/crop and PV yield model	Provides design equations and guidelines; LER 1.29 –1.73; demonstrates robust gains with balanced configuration.	1.29 – 1.73

for different orchard configurations and local conditions.

Table 1 compares key olivoltaic studies, classifying them by type, assumptions, key findings and limitations. This benchmarking clarifies how the present study contributes by combining scenario modelling for Andalusia with a contextual synthesis.

For the literature synthesis, Scopus, Web of Science, and Google Scholar were searched between 2010 and 2024 using terms such as “agrivoltaic,” “olivoltaics,” “dual land use,” and “olive cultivation.” Studies were included if they contained data on PV-olive interactions, shading, water management, or land productivity. Purely economic papers without agricultural metrics were excluded.

Despite promising projections, several uncertainties remain:

- **Yield stability:** Most results derive from short-term simulations; long-term impacts on alternate bearing cycles and interannual yield variability are unknown.
- **Oil quality:** Irrigation and shading strongly influence phenolic content and oxidative stability; no multi-year data exist for olivoltaic conditions.
- **Pests and diseases:** Microclimate changes may alter pest and pathogen dynamics, but no systematic studies are available.
- **Soil and biodiversity:** Effects of sustained shading on soil carbon, microbiota, and understory biodiversity are poorly documented.
- **Social acceptance:** Farmer adoption depends on mechanization compatibility, aesthetics, and CAP (Common Agricultural Policy) alignment.

4. Discussion

Recent advances in simulation and pilot studies have established a robust technical foundation for Olivoltaics, yet they also reveal the complexity and specificity required for optimal system performance. Across multiple modeling approaches, a central consensus emerges: integrating photovoltaic arrays within olive groves, when based on informed system design, can yield substantial gains in overall land productivity, as reflected by LER that consistently exceed unity. In super-intensive and intensive systems, such as the hedgerow configurations analyzed in Spain and Italy [1,13–15], modeled LER values commonly range from 1.3 to 1.7, with best-case scenarios achieving up to 1.73. These gains are primarily attributed to the ability of precise PV placement and tracking algorithms to minimize crop shading and mutual module interference, a finding validated both by geometric shading models and by empirical yield data where available.

In particular, [14] demonstrates that adopting north-south single-axis trackers at a height of 3 meters and carefully spacing 1.5-meter-wide hedgerows enables the definition of “no-shade” zones, where olive growth is largely unimpeded. This design, validated using geometric and tracking/backtracking simulations, allows for a LER increase of 29–47% relative to monocultures, with mechanical and geometric layout factors highlighted as critical determinants of profitability. Similarly,[1] employs advanced ray-tracing (Bifacial Radiance) to compare the effects of module tilt, bifaciality, and planting pattern, revealing that optimal PV yield is achieved with latitude-tilt modules, whereas olive yield is maximized with vertical panels. The study reports that, for super-intensive groves, bifacial modules at a 20° tilt provide the best combined outcome, with LER values reaching up to 1.71 and only moderate crop shading sensitivity.

The role of PAR and crop light response modeling is another key area of methodological advancement. [12] integrates dual modeling of site-specific crop light response curves and PV energy output to demonstrate that optimal module transparency, ranging from 57% to 71% depending on the olive cultivar and site irradiance, maximizes both crop and energy yields. This fine-tuning approach, rarely applied in earlier APV literature, suggests that system designers must go beyond generic shading estimates and tailor transparency and layout to the physiological traits of target varieties (e.g., Picual, Manzanilla, Chemlali) and their location. Moreover, [12] scales these findings to the regional level, estimating that equipping just 1% of the Mediterranean’s olive groves with such optimized APV could contribute an additional 2.5% to the region’s electricity supply and generate over 560,000 jobs, while delivering notable CO_2 and water savings.

From an economic perspective, [13] provides a detailed financial assessment using PVGIS energy yield models and full project-level financial metrics as Net Present Value (NPV), Return of Investment (ROI) and payback period. The results show that tighter row spacing (6 m vs. 7.5 m) increases both PV output and net present value (NPV up to €10.4 million, ROI 276%), with minor olive yield losses that are fully offset by the additional energy revenues and land savings. The modeled payback period is rapid, around five years, underscoring the economic attractiveness of dual-use systems in suitable contexts. [15] further supports practical implementation by offering parametric equations for quick system sizing and configuration, reporting, for a typical hedgerow setup, annual outputs of 789 kg oil/ha and 891 MWh/ha, with LERs ranging from 1.29 to 1.73 depending on the energy/crop balance.

Despite these promising results, several open questions and limitations must be acknowledged. Most studies rely on simulations calibrated with short-term or idealized field data, lacking long-term empirical validation under operational, real-world conditions. For instance, while [1] and [14] demonstrate moderate to low sensitivity of olive yields to shading under optimal PV arrangements, they do not capture the full variability of weather, pest and disease pressure, or soil health dynamics across multiple years. Similarly, although water use efficiency improvements are often reported, driven by the microclimate moderation from partial PV shading, actual water savings under field conditions may vary depending on irrigation practices, local soil characteristics, and the ability to implement precision management.

Another significant gap concerns the generalizability to traditional and rainfed olive systems, which continue to represent the majority of Mediterranean olive acreage. Most simulation and economic models have favored intensive or super-intensive groves, where geometry and mechanization facilitate efficient PV integration. The challenges of adapting APV to low-density, sloped, or culturally protected landscapes remain underexplored. Moreover, while several studies model substantial regional benefits (such as the job creation and energy contribution reported by [12]), the realization of these impacts will depend on supportive policy frameworks, access to capital, and farmer engagement.

Social and operational considerations are also emerging as critical determinants of real-world adoption. Issues such as the visual landscape impact of PV installations, compatibility with existing farm machinery, maintenance logistics, and potential labor displacement need further investigation. Likewise, successful upscaling will require alignment with evolving energy market policies, stable and predictable support mechanisms, and solutions to land tenure or classification uncertainties that may impede investment.

The latest body of research highlights both the transformative potential and the practical complexities of Olivoltaics. Modeling and early pilot results make clear that, with context-adapted design, especially careful management of PAR, tracking, transparency, and economic planning, olivoltaic systems can deliver superior land productivity, climate adaptation, and diversification for Mediterranean agriculture. Yet, substantial empirical work remains to validate these outcomes across the diversity of Mediterranean agroecosystems, to optimize systems for less intensive groves, and to integrate socio-economic realities into the planning and deployment of large-scale APV. Moving forward, coordinated field trials, multi-year monitoring, interdisciplinary research, and inclusive policy design will be essential to translate the theoretical promise of Olivoltaics into a robust, resilient pillar of rural development and sustainable energy transition for the region.

4.1 Case of Andalusia

To assess the transformative potential of Olivoltaics in Andalucía, a detailed methodological framework was employed, integrating spatial, agronomic, photovoltaic, and economic data drawn from both recent simulation studies and regional statistics. The system assumptions were derived from [1,12] and uncertainty margins were incorporated by testing different climatic years and cultivar light responses. The starting point for the analysis was the official data on olive grove surface area in Andalucía, which currently exceeds 1.62 million hectares and represents over 60% of Spain's total olive cultivation. This total area was further subdivided according to the predominant grove types traditional, intensive, and super-intensive reflecting the structural heterogeneity in tree density, management practices, and suitability for photovoltaic integration. The distribution used, based on the most recent agricultural census and expert estimates [6,31,41], assigned approximately 76% of the surface to traditional systems, 22% to intensive orchards, and 2% to super-intensive hedgerow plantations. For each type, a 5% adoption rate of APV systems was chosen as a realistic medium-term goal, representing 80,000 hectares across the region.

The next analytical step involved estimating the PV capacity that could be installed under each grove type within the selected area. This was achieved by applying typical ground coverage ratios (GCRs) and module configuration parameters adapted to each management system. For example, traditional groves, with wider row spacing and taller trees were assigned a lower PV installation density per hectare compared to intensive and super-intensive systems, where more uniform, lower canopies and mechanized management enable denser PV layouts. Assumptions regarding average module efficiency, system height (minimum 3 meters to allow for mechanization), and bifacial versus monofacial technology were taken from the recent core simulation studies and aligned with commercial deployment practices[1,2,15]. Conservative deployment densities of 0.1 MW/ha were assigned to intensive and traditional systems, and 0.2 MW/ha to super intensive hedgerows[2,12]. Taking Jaén, the province at the epicenter of olive production in Andalucía, as representative of the region's solar resource, with an annual average solar yield of 1,883 kWh/kW/year[12], the scenario of 8 GW (8,160 MW) of agrivoltaic capacity installed across 80,000 hectares of olive groves would generate approximately 15.36 TWh of clean electricity each year. This output would account for nearly 40% of the total annual electricity consumption of Andalucía and about 5.5% of Spain's national electricity demand[42]. This yield estimation was then converted into avoided CO_2 emissions, based on the grid emission factors for Spain, to quantify the climate mitigation impact of the scenario. Using Spain's current grid emission factor (0.25 tCO_2 /MWh) [12], the annual reduction in greenhouse gas emissions from this APV deployment is 3.84 million tons of CO_2 per year. Figure *5* presents the estimated PV capacity and corresponding avoided CO_2 emissions under different olive grove typologies. For the scenario analyzed (80,000 ha of APV deployment), the estimated PV capacity is approximately 6.08 GW in traditional groves, 1.76 GW in intensive groves, and 0.32 GW in superintensive groves. These systems would collectively produce around 15 TWh/year of electricity, leading to an annual reduction of 3.84 $MtCO_2$. The results highlight that although intensive and superintensive groves offer higher PV efficiency per hectare, traditional groves dominate the overall mitigation potential due to their larger land area.

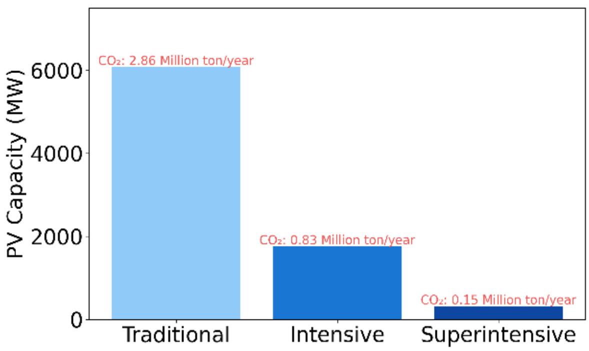


Figure 5. Scenario analysis for Andalusia: Estimated PV capacity and avoided CO_2 emissions from olivoltaic deployment in different olive grove typologies. Bars show both the potential installed capacity and the associated annual reduction in greenhouse gas emissions

A parallel modeling is estimate water savings achievable through the partial shading provided by PV modules. This was grounded in published field trials and modeling studies showing reductions in evapotranspiration and irrigation demand under APV systems, with values ranging from 15% to 30% depending on shade fraction, crop type, and local climate[2,5]. For each olive grove type, a conservative mean water savings factor was applied, and the total annual water conserved was aggregated for the 5% deployment area. Irrigation needs for traditional groves average 1,700 m³/ha/year, 2,200 m³/ha/year for intensive, and 3,200 m³/ha/year for super intensive systems[4,15]. Water savings under APV, derived from recent experimental and simulation data [1,2,5], range from 12% (traditional), 22% (intensive), to 30% (super intensive) thanks to microclimate moderation and reduced evapotranspiration. For the total assumed 80,000 ha of APV area (60,800 ha traditional, 17,600 ha intensive, 1,600 ha super intensive), this equates to 12,403,200 m³, 8,518,400 m³, and 1,536,000 m³ of water saved per year respectively, see Figure 6. For the total assumed 80,000 ha of APV area, this equates to water savings of approximately 12.4 million m³/year in traditional groves, 8.5 million m³/year in intensive groves, and 1.5 million m³/year in superintensive groves, as shown in Figure 6. The results yield a total of 22.4 million m³/year of avoided irrigation demand, equivalent to the water consumption of ~374,000 households or the irrigation of ~16,000 ha of additional crops during drought years[5,43]. With water costs for irrigation ranging from €0.20 to €0.35 per m³ in Andalucía[44], the annual direct economic value of this water saving is between €4.4 million and €7.8 million, an important margin as both costs and climate pressures rise.

Job creation multipliers from the literature (15 job-years per MW during installation, 0.4 long-term jobs per MW during operation) were applied[12]. Thus, APV deployment on 8 GW would yield approximately 120,000 construction job-years over five years (about 24,000 jobs per year during rollout), and support 3,200 permanent operational jobs, not counting indirect or induced employment in the supply chain or local services.

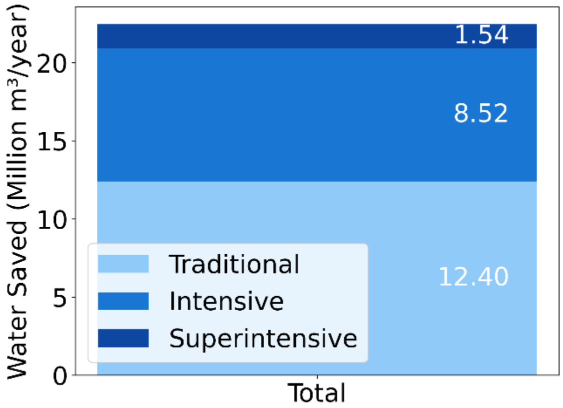


Figure 6. Annual water savings under aPV deployment in olive groves, expresses in million cubic meters per years. Bars represent total savings for each grove type assuming a deployment of 80,000 ha

Despite promising projections, uncertainties remain in yield stability, oil quality, pests and diseases, soil/biodiversity, and social acceptance. Future research should prioritize multi-year pilot projects, cultivar-specific trials, and socio-ecological monitoring to reduce these uncertainties before large-scale deployment.

5. Conclusions

Olivoltaics, the strategic integration of photovoltaic technology within olive groves, has emerged as a compelling pathway for advancing sustainable land use in the Mediterranean. This synthesis has demonstrated that, when appropriately configured, olivoltaic systems offer the potential to increase combined land productivity, enhance water-use efficiency, and generate climate-resilient income streams for farmers. The physical and physiological characteristics of modern olive cultivation, particularly in intensive and super-intensive systems, create unique opportunities for dual land use, allowing for the co-production of high-value crops and renewable energy on the same parcel of land. Partial shading from PV structures, if optimally designed, can provide significant agronomic benefits, such as reduced crop evapotranspiration and moderated microclimates, with only minor or manageable reductions in olive yield. These effects, together with the diversification of farm revenues, position Olivoltaics as a promising adaptation and mitigation strategy for regions increasingly exposed to climate extremes and market volatility.

At 5% coverage (~80000 ha), olivoltaics in Andalusia could generate ~15 TWh yr^{-1}, save 0.65-1.9 million m^3 of water, avoid 3.8 Mt CO_2, and create ~24000 jobs. LER values consistently exceed 1.2.

However, the advancement of Olivoltaics beyond the theoretical and simulation stages remains a critical challenge. The current knowledge base is predominantly informed by modeling studies and short-duration experiments, with a conspicuous lack of long-term, real-world field data. Key uncertainties persist regarding the impacts of sustained altered microclimates on olive physiology, oil quality, pest and disease dynamics, and broader ecosystem services. The economic viability of olivoltaic systems also depends on the evolution of local energy markets, agricultural policy incentives, and social acceptance among farmers and rural communities. The heterogeneity of Mediterranean agricultural landscapes further underscores the need for site-specific, adaptive approaches, rather than generic solutions.

Addressing these knowledge gaps will require the design and implementation of robust, multidisciplinary pilot projects capable of capturing yield, energy, economic, and ecological outcomes over multiple years and environmental conditions. Such initiatives must be accompanied by supportive policies, participatory research frameworks, and proactive engagement with stakeholders across the agri-energy value chain. A commitment to interdisciplinary collaboration, transparency, and knowledge exchange will be crucial for overcoming both technical and institutional barriers.

Priority research includes multi-year pilot trials, cultivar-specific physiological studies, biodiversity and soil monitoring, and integration into common agricultural policy frameworks to support farm adoption.

If these conditions are met, Olivoltaics could play a transformative role in Mediterranean rural development, contributing not only to climate mitigation and food security but also to the resilience and diversification of rural economies. As the Mediterranean region navigates the converging pressures of climate change, water scarcity, and the energy transition, the scalable and evidence-based deployment of olivoltaic systems may become a cornerstone of future-proof agricultural landscapes. This work provides a foundation and roadmap for the research, policy, and innovation required to realize the full potential of Olivoltaics, both within the Mediterranean and as a model for sustainable agri-energy integration globally.

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Nomenclature

APV	Agrivoltaics
CAP	Common Agricultural Policy
CO_2	Carbon Dioxide
ha	hectares
kWh	Kilowatt-hour
LER	Land Equivalent Ratio
NPV	Net Present Value
PAR	Photosynthetically Active Radiation
ROI	Return of Investment
TWh	Terawatt-hour

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