

AGRIVOLTAICS FOR REGIONAL ENERGY TRANSITION: A CASE STUDY WITHIN THE MARCHE REGION, ITALY

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ABSTRACT

Agrivoltaic systems represent an integrated solution to co-locate agricultural activities and photovoltaic energy production, optimizing land use while supporting renewable energy targets. This study evaluates the technical feasibility of agrivoltaic deployment in the Marche Region of Italy, in accordance with the national guidelines outlined in the Ministerial Decree of 21 December 2023. A spatial assessment was carried out using provincial data on utilized agricultural area, combined with crop-specific suitability based on tolerance to reduced solar radiation. Land deemed suitable was quantified by applying differentiated occupation thresholds, based on crop compatibility categories. The photovoltaic potential was then estimated under two realistic land coverage scenarios. Results confirm the existence of a significant agrivoltaic potential in the region, with capacity levels sufficient to contribute meaningfully to regional energy targets, while maintaining agricultural productivity. These outcomes support the development of integrated land management strategies aligned with national decarbonization policies.

Keywords: agrivoltaics photovoltaic systems, land use efficiency, renewable energy, simulation design optimization.

1 INTRODUCTION

The growing urgency to tackle climate change and ensure energy security has prompted European countries, including Italy, to intensify the transition to renewable sources. In this context, agrivoltaics represents an integrated and multifunctional solution, capable of combining solar power generation with the continuity of agricultural activities. This approach is fully in line with the objectives outlined in the Integrated National Energy and Climate Plan (PNIEC) and the National Recovery and Resilience Plan (PNRR) [12], contributing to the decarbonisation of the energy sector and the protection of agricultural land use [1]. The availability of land for photovoltaic installations is a critical challenge, particularly in densely cultivated areas. Agrivoltaic systems offer an innovative response to this pressure, as they allow the same surface area to be used simultaneously for agricultural and energy purposes. Unlike traditional ground-mounted photovoltaic systems, which result in a net loss of land for agriculture, agrivoltaics ensure a combined and sustainable use of the land [2].

Fig. 1 highlights the high solar irradiance levels in the Marche Region, a key factor influencing the feasibility of agrivoltaic systems.

Numerous studies have also highlighted the microclimatic benefits of integrating photovoltaic modules with crops. Partial shading can reduce soil evaporation, limit plant water stress and offer physical protection against extreme weather events such as hailstorms or heat waves. In some circumstances, there are even increases in agricultural yields for shade-tolerant or shade-loving crops grown under agrivoltaic systems [3].

According to the definition contained in the Guidelines on agrivoltaic systems drawn up by the Ministry of Ecological Transition [4] and implemented in the Ministerial Decree of 21 December 2023 (known as the agrivoltaic DM), an advanced agrivoltaic system is a plant



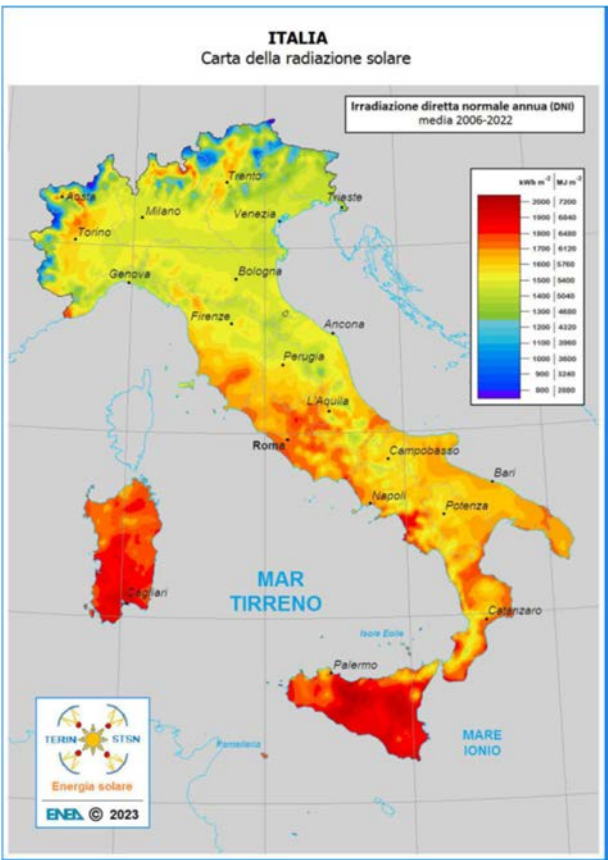


Figure 1: Distribution of average annual direct solar irradiance in Italy, with focus on central Italy and the Marche Region [8].

configuration designed to ensure the functional coexistence of agricultural production and electricity generation through specific technological and management solutions.

The minimum requirements for advanced agrivoltaic systems include: photovoltaic modules raised off the ground (to allow for the passage of agricultural machinery and crop management), module rotation or solar tracking, where applicable, monitoring of agricultural and electrical yields, compliance with Good Agricultural Practices (GAP) and maintenance of at least 70% of the area designated for agricultural activities for the entire duration of the plant [5]. Fig. 2 presents various configurations of agrivoltaic systems, illustrating design adaptations to ensure agricultural machinery access and crop continuity.

Fig. 3 shows an advanced agrivoltaic installation with raised modules, representing a benchmark configuration for compliance with ministerial requirements and agricultural best practices. Such configurations are not only compliant with regulatory standards but also directly influence the calculation of plant density, known as the Land Area Occupation Ratio (LAOR). This parameter is defined as the percentage of the area covered by the modules in relation to the total plant area, with the guidelines setting a maximum value of 40% for a system to be considered effectively agrivoltaic [6].

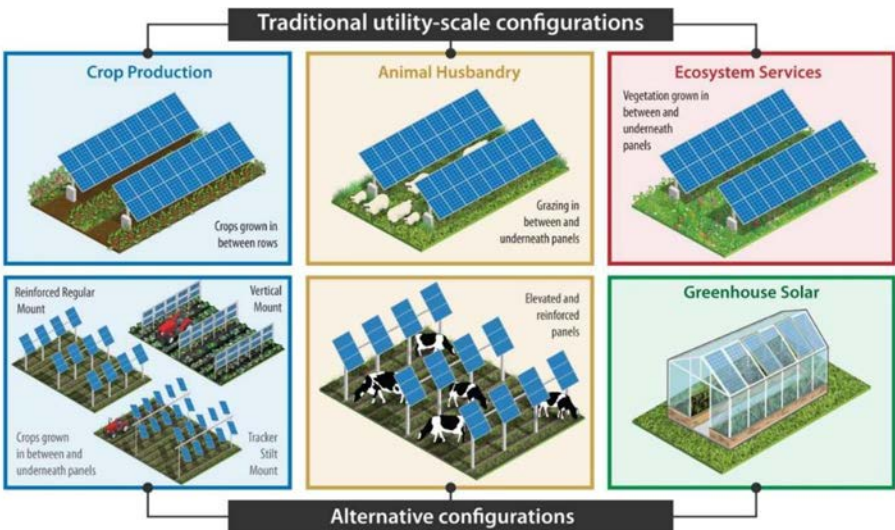


Figure 2: Configurations of agrivoltaic systems with different heights, tilts, and spacing between modules [9].



Figure 3: Advanced agrivoltaic installation with raised modules allowing machinery access and crop continuity [15].

The study aimed to assess the technical feasibility of large-scale application of agrivoltaic systems in the Marche Region, using a methodological approach based on official data on Utilised Agricultural Area (UAA) [7] and current regulatory criteria.

2 MATERIALS AND METHODS

This section outlines the methodological framework adopted to assess the agrivoltaic potential of the Marche Region. The approach integrates agricultural land data, crop classification, regulatory constraints, and technical specifications of photovoltaic systems to estimate both the available area and the corresponding installable capacity. The goal is to produce a spatially explicit and normatively compliant assessment, which can serve as a basis for energy planning and land-use policy at the regional level.

2.1 Data sources

To assess the area potentially suitable for the implementation of agrivoltaic systems in the Marche Region, a multi-criteria approach was used. Several authoritative sources of data were combined to ensure both spatial accuracy and regulatory compliance. These include official statistics from [10] ISTAT on the Utilised Agricultural Area (UAA) by province; crop classification according to their compatibility with partial shading, as detailed in the Guidelines on Agrivoltaic Systems [6]; spatial constraints outlined in Article 7 of the Ministerial Decree of 21 December 2023; and technical specifications of photovoltaic modules, assumed to have a unit power of 350 Wp [11] and an average surface footprint of 1.7 m² per module [11].

In defining land eligibility, four primary criteria were adopted:

- the land must be zoned as agricultural according to local urban and regional planning instruments (PRG or PSC);
- it must be free from restrictive environmental or cultural constraints;
- it must guarantee continuity of agricultural activity through the preservation of at least 70% of the surface for cultivation or pasture, as per Good Agricultural Practices (GAP); and
- it must be occupied by crops deemed compatible with shading.

The crop classification was derived from national guidelines, and land cultivated with incompatible species, such as maize and durum wheat, was excluded. For all compatible crops, differentiated coefficients of utilisability were applied to reflect their tolerance to partial shading and potential to maintain productivity under agrivoltaic installations: 35% for highly suitable and suitable crops, and 13% for moderately suitable crops. These coefficients define the portion of UAA that can realistically be dedicated to agrivoltaics without compromising agronomic sustainability.

2.1.1 Calculation of available area and installable photovoltaic power

The estimation procedure followed a stepwise logic. First, the total UAA per province was disaggregated by crop type. Second, the compatibility coefficients were applied to quantify the effective surface area available for agrivoltaic systems. Third, any land falling within exclusion zones, such as protected natural areas, heritage sites, or high-value landscapes, was subtracted, in line with Article 7 of the DM on suitable areas.

The result is a total of 42,176 hectares identified as potentially suitable for agrivoltaic deployment across the Marche Region. This value represents a filtered, conservative estimate aligned with current legal and agronomic requirements.

To quantify the photovoltaic potential of these surfaces, two deployment scenarios were simulated based on the land area occupation ratio (LAOR). This parameter expresses the

percentage of surface physically covered by photovoltaic modules and is typically limited to low values to ensure adequate light transmission to crops. The scenarios modelled were:

- LAOR = 1% (low-impact scenario);
- LAOR = 2% (enhanced utilization scenario).

The installable power was calculated using the following formula:

$$\text{Installed power (MWp)} = \frac{\text{Available area (ha)} \cdot 10^4 \cdot \text{LAOR}}{\text{Module area (m}^2\text{)}} \cdot 0.0035 \quad (1)$$

where

- Available area (ha) = agricultural surface suitable for agrivoltaics;
- LAOR = land area occupation ratio (e.g., 0.01 or 0.02);
- Module area (m²) = surface area occupied by a single module (e.g., 1.7 m²);
- Module power (MWp) = peak power output per module (e.g., 0.00035 MWp for 350 Wp) [11].

3 RESULTS

The above methodology was implemented through structured Excel spreadsheets, enabling province-level calculations and sensitivity analysis based on different input assumptions.

Fig. 4 displays the spatial distribution of the utilized agricultural area in the Marche Region, which underpins the assessment of agrivoltaic suitability.

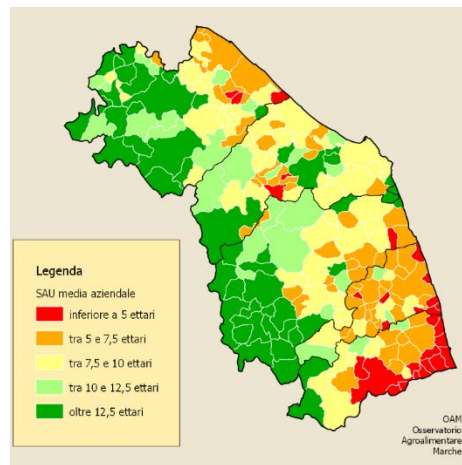


Figure 4: Geographical distribution of the utilized agricultural area (UAA) in the Marche Region [13].

Based on the spatial distribution shown in Fig. 4, the next step was to quantify the agricultural area potentially available for agrivoltaics in each province. Table 1 reports, for each province, the total UAA, the area with compatible crops and the agrivoltaic-usable surface after applying compatibility coefficients and legal exclusions.

Table 1: Total UAA, the agricultural area with compatible crops, and the usable area for agrivoltaic systems for each province.

Province (Marche Region)	UAA (ha)	Usable area for agrivoltaic systems (ha)
PU	114.864	8.640
AN	111.498	12.880
MC	140.178	13.065
FM	45.590	3.234
AP	42.968	4.355
Total	455.099	42.176

These results highlight that the provinces of Macerata and Ancona show the greatest agrivoltaic surface potential, owing to their larger share of compatible crops and fewer excluded areas. On the other hand, Fermo and Ascoli Piceno contribute more modestly due to a smaller agricultural base and greater land constraints.

Based the available surfaces, Table 2 illustrates the estimated installed capacity in each province under the two LAOR scenarios.

Table 2: Balance between maintaining agricultural continuity and increasing solar energy production.

Province (Marche Region)	Useful area (ha)	MIN installable power (MWp)	MAX installable power (MWp)
PU	8,640	177	354
AN	12,880	265	530
MC	13,065	269	538
FM	3,234	66	132
AP	4,355	89	178
Total	42,176	868	1,732

These estimates underscore the feasibility of reaching significant installed capacity in line with regional decarbonization goals, without displacing agricultural use. Even the most conservative scenario (LAOR = 1%) would nearly double the current ground-mounted capacity in the region.

According to GSE data [1], ground-mounted PV systems in the Marche Region currently cover around 962 hectares, only 0.103% of the total UAA. Compared to the 42,176 hectares identified as suitable for agrivoltaics, this represents a small fraction. The findings suggest that agrivoltaics could substantially expand renewable energy capacity while preserving primary land functions, offering an alternative path to scale without competing with food production.

4 DISCUSSION

The results of the study confirm the existence of significant agrivoltaic potential in the Marche Region. The estimated power, up to 1,732 MWp, is sufficient to contribute substantially to the regional and national energy objectives outlined in the PNIEC [14]. The use of advanced agrivoltaic systems makes it possible to increase renewable energy production without compromising existing agricultural activities, promoting multifunctional land use.



Fig. 5 depicts an agrivoltaic plant in Emilia-Romagna with modules raised 4.5 m above ground, demonstrating feasibility for large-scale agricultural contexts. Owing to similar agricultural and climatic conditions, this example offers practical insights for potential applications in the Marche Region.



Figure 5: Agrivoltaic plant in Emilia-Romagna with raised modules allowing machinery passage and continuous cultivation [16].

Despite the potential advantages, large-scale implementation of agrivoltaics presents some critical issues:

- Regulatory and landscape constraints, which can reduce the actual available surface area;
- Technical and managerial difficulties in designing systems compatible with agricultural practices;
- Social acceptance and farmers' concerns about the impact on crops and productivity;
- Lack of uniform technical standards, which complicates the authorisation and monitoring of systems.

The technological evolution of agrivoltaic systems, with the introduction of bifacial, tracking and semi-transparent modules, will increase flexibility of use and overall efficiency [17]. At the same time, greater integration between energy and agricultural policies is desirable, in particular through: alignment with the new Common Agricultural Policy (CAP), specific incentives for the construction of advanced agrivoltaic systems and monitoring systems for agricultural and energy yields to ensure the sustainability of the model [18].

In this scenario, the regions can play a key role in defining integrated territorial strategies for energy and agriculture, promoting the controlled and planned spread of agrivoltaics. Overall, the spatial analysis indicates that up to 42,176 hectares in the Marche Region could host advanced agrivoltaic systems, corresponding to an installable capacity between 868 MWp and 1,732 MWp. These figures provide the quantitative foundation for the strategic considerations discussed below.

5 CONCLUSION

The analysis conducted confirms that agrivoltaics is one of the most promising solutions for simultaneously addressing the challenges of food security, energy transition and sustainable land use. In a global context characterised by growing demand for food and an urgent need

to reduce climate-changing emissions, agrivoltaics allows for the efficient and multifunctional use of agricultural land, ensuring the coexistence of agricultural production and photovoltaic energy.

In the Marche Region, approximately 42,176 hectares of agricultural land have been identified as potentially available for the installation of agrivoltaic systems. Applying realistic coverage scenarios (LAOR of 1% and 2%), the installable photovoltaic power is estimated to be between 868 MWp and 1,732 MWp. These values are significantly higher than the power derived from ground-mounted photovoltaic systems currently present in the region, which occupy a total of 962 hectares.

The benefits of agrivoltaics are not exclusively energy-related. Recent studies show that the partial shading caused by photovoltaic modules can, under certain conditions, reduce crop water stress, improve the quality of agricultural products and contribute to soil protection. [19], [21] However, the choice of crop species, system configuration and coverage density must take into account local specificities, the type of cultivation, shade tolerance and economic objectives [20].

The effectiveness of agrivoltaics depends on careful matching between crop type, system configuration, and local conditions.

Despite its potential, the spread of agrivoltaics still faces significant obstacles, such as:

- regulatory and administrative barriers;
- economic uncertainty for agricultural operators;
- the need to define technical standards and monitoring requirements;
- social acceptance and perception of the impact on the landscape.

Overcoming these barriers requires strong institutional support through:

- the implementation of targeted incentives [5];
- the promotion of pilot projects and demonstration networks;
- the creation of data-sharing platforms between the research community, institutions and businesses;
- the full integration of agrivoltaic strategies into rural development policies and CAP measures.

If properly planned and supported, agrivoltaics can become a strategic lever for contributing to the achievement of the objectives of the European Farm to Fork Strategy [21] and the United Nations 2030 Agenda [22]. Finally, it is hoped that future technological developments (e.g. intelligent solar tracking, semi-transparent modules, integration with livestock farming) will further refine the performance of agrivoltaic systems and maximise their sustainability.

In summary, agrivoltaics is not only an innovative technology, but a true paradigm of integrated land management, capable of combining food production, energy transition and the protection of natural resources.

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