Agrovoltaic as an Answer to the Difficult Relationship Between Land Use and Photovoltaics. A Case Study from Apulia Region

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Abstract. Decarbonization in the electricity production sector represents a fundamental step for reducing greenhouse gas emissions and achieving the objectives set by the Paris Agreements for 2050. Reflecting on the use of rural areas in the 21st century is an extremely central topic in the debate on the long-term development of renewable energies. While cities show a model of energy consumption in constant growth, rural areas assume a significant role in terms of potential development regarding renewable energy sources. This new specialization of these areas could represent both an effective response to climate change and a reduction in dependence on fossil fuels to mitigate respective economic and environmental impacts. The proposed contribution aims, as a first step, to describe the different impacts caused by the implementation of renewable energy sources in rural areas with reference to the Tavoliere della Puglia study area. This research will take into account the economic, energy, and geographic factors underlying the localization of some photovoltaic parks. In addition, the experience of some companies in the sector, active for several years in designing, building and managing innovative plants for the production of electricity from renewable sources, will also be considered. By analyzing the official cartography (e.g. Regional Territorial Landscape Plan) and participatory cartography (e.g. OpenStreetMap) at the municipal scale in a GIS-based approach, the main changes in land use and the impact of photovoltaic parks will be estimated, also in relation to a dimension of planning and environmental management. The first results obtained would finally highlight a clear contrast between the conservation of land with strong agricultural potential and the massive expansion of renewable energy production in rural areas.

Keywords: Agrivoltaic system · Land Use · Renewable energy · Apulia

The paper is the result of the joint work of the two authors. However, Claudio Sossio de Simone wrote paragraphs 2–3, while Andrea Gallo wrote paragraphs 4–5. The paragraph 1 was written togheter.

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1 Introduction

By definition, fossil fuels are non-renewable sources [1]. The excessive consumption of these energy sources is producing negative externalities both for the environment [2], in reference to climate change, and for the problem of resource scarcity and the inevitable economic impact on the energy resource market. This has highlighted the importance of decarbonization through the transition to renewable and clean energy sources, in which solar energy represents the primary resource [3]. Photovoltaic technologies have experienced a rapid technological upswing in recent years, improving their efficiency and significantly lowering production and installation costs [4]. Today, photovoltaic energy represents the best possible tool for meeting the constantly increasing global energy demand. The IEA estimates that, to meet the energy demand, by 2050 over 16% of the energy produced will need to come from photovoltaic sources [5]. However, the photovoltaic technology poses a concrete problem that we will try to analyze in this contribution: due to the relatively widespread nature of solar energy, large surfaces are needed to be covered with photovoltaic panels. Part of this demand can be met by integrating photovoltaic modules into traditional buildings and through photovoltaic roofs. However, to achieve the set goals, the key role that ground-based plants will assume appears fundamental. The use of large tracts of land for solar power plants will increase competition for land resources, as food production demand and energy demand are growing and competing for limited land resources [6]. These coupled land challenges can be mitigated by using the concept of agrivoltaics, that is, the joint development on the same surface of a photovoltaic solar power plant integrated with conventional agriculture [7].

Land consumption continues to transform the Italian territory at high speed. In the last year, new artificial covers affected 69.1 km^2, or an average of about 19 ha per day. This increase shows a clear acceleration compared to the data collected in the recent past, sharply reversing the trend of reduction in recent years and causing our country to lose 2.2 m^2 of land every second. More precisely, at the national level, the artificial cover of the land can now be estimated at about 21,500 km^2 (86% of which are located on useful soil), to which another 624 km^2 of areas subject to other forms of direct alteration due to artificial land cover (such as non-paved greenhouses and bridges) must be added, which are not considered as causing land consumption [8]. The relationship between land consumption and population dynamics confirms that the link between demography and processes of urbanization and infrastructure is not direct, and there is an increase in artificial surfaces even in the presence of stabilization or, in many cases, a decrease in the resident population, with an increase in land consumed per capita from 2020 to 2021 of 3.46 m^2/person and 5.46 m^2/person in two years (Fig. 1).

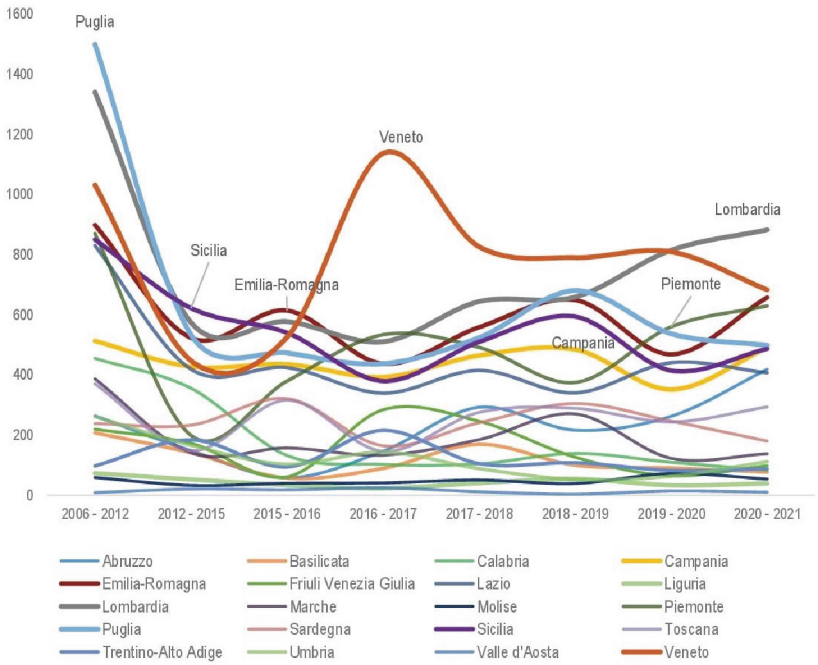


Fig. 1. Regional net annual land consumption trend from 2006 to 2021. Source: ISPRA elaborations on SNPA cartography (Source: ISPRA, 2022)

2 Solar Power Plants and Land Consumption in Italy: A Complex Relationship

Among the causes of land consumption in our country, according to what is reported by Superior Institute for Environmental Protection and Research [8], photovoltaic installations can be considered. It should be noted that according to the data collected in the National Land Consumption Map, a distinction is made between ground-mounted installations, which are identified in a specific class, and those present on non-ground surfaces (buildings, warehouses, sheds, greenhouses, etc.) which fall into other classes. Focusing on ground-mounted installations, according to the Photovoltaic Solar Statistics Report [9], the factors that determine the incidence of ground-mounted photovoltaic installations are multiple, including geographic location, morphological characteristics of the territory, weather conditions, and availability of suitable areas. As a result, the distribution of installed photovoltaic panel power by location among the different regions is highly heterogeneous. Indeed, according to GSE data (2021) [9], at the national level, only 36% of the 22,594 MW installed at the end of 2021 is located on the ground, while the remaining 64% is distributed on non-ground surfaces.

The greater penetration of ground-mounted photovoltaic panels is observed in the southern regions, and in particular in Puglia and Basilicata, where there is a relatively high incidence of ground-mounted installations (respectively, 72% and 64% of the regional total). In contrast, in the northern regions, there is widespread penetration of the capacity

of non-ground installations, with maximum values observed well beyond 90% in Liguria, Lombardy, Valle d'Aosta, and in the provinces of Trento and Bolzano. In general, considering the ISPRA [8] data and the GSE report (2021) [9], the new ground-mounted photovoltaic installations (detected between 2020 and 2021) will have a total of 70 ha of land consumption corresponding to a power of about 37 MW. Indeed, in 2022 the total area occupied by ground-mounted photovoltaic panels is 644,9 ha corresponding to a power of 365 MW [10]. Overall, at the national level, ground-mounted PV occupies between 15,200 and 17,560 ha, for a total power output greater than 25 GW [10] (Fig. 2).

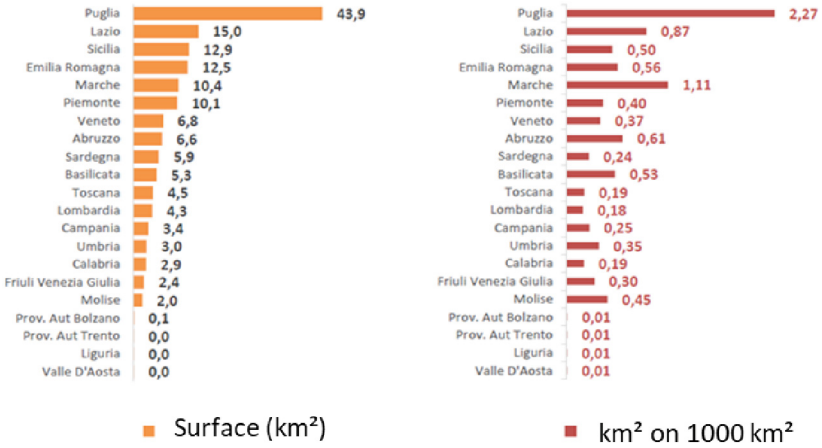


Fig. 2. Distribution of the ground-mounted PV in the Italian regions at the end of 2021 (Source: GSE, 2021).

On the other hand, the obsessive focus on renewable energy and the growing need for decarbonization is profoundly changing energy policies both internationally and nationally [11]. In line with the European Energy Plan (Repower EU)[1], Italy's Ecological Transition Plan (PTE)[2] envisages that by 2030, 70% of electricity will come from renewable sources, mainly from photovoltaic solar energy. This goal is already partly outlined in the Integrated National Plan for Energy and Climate (Pniec)[3], which in 2019 hoped to add about 30 GW of capacity to the national photovoltaic capacity of 22 GW, to exceed a capacity of 50 GW [12]. According to some estimates by ISPRA [15], this direction would lead to an 8-fold increase in total net annual land take (Fig. 3).

[1] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en. Last accessed 24/03/2023.

[2] https://www.italiadomani.gov.it/en/il-piano/missioni-pnrr/rivoluzione-verde-transizione-ecologica.html. Last accessed 24/03/2023.

[3] https://www.mise.gov.it/images/stories/documenti/it_final_necp_main_en.pdf. Last accessed 24/03/2023.

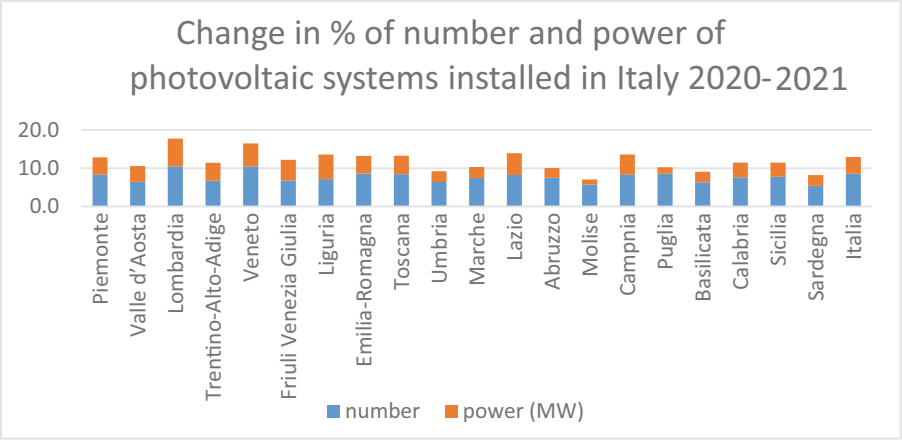


Fig. 3. Change in % of number and power of photovoltaic systems installed in Italy 2020–2021 (Source: GSE, 2021; by Author).

3 Observation and Analysis From Apulia Region: The Case of Foggia Area

An exemplary case of this challenging relationship, between renewable energy installations and land consumption is Apulia and in particular the Foggia administrative province.

It is to be recalled, that in the area is located the Tavoliere, one of the symbols of Southern Italy's rural identity. Indeed, between the sixteenth and eighteenth centuries, this area was one of the protagonists of the "great transhumance" between Abruzzo and Puglia [13]. In addition, the area is among the main intervention zones of the land reform of the early 1950s, which strengthened the supremacy of arable land and woody crops. In today's Tavoliere, traces of these processes can still be seen, remnants of a heritage not entirely lost [14]. This heritage contributes to vitalizing the richness and variety of the agricultural and productive structures of the region, which stand out from the rest of Italy [16].

Within the framework of the Regional Territorial Landscape Plan[4], the region has defined particular measures for the location and installation of plants powered by renewable sources, including photovoltaic plants, in ecological safeguards of the rural heritage [17, 18]. On the other hand, Apulia with reference to the regional distribution of the number and power of photovoltaic plants (at the end of 2020) takes the Italian leadership in terms of installed capacity. A total of 2,900 MW is produced here, accounting for 13.4% of the national photovoltaic capacity. In the region is registering, moreover, the highest average size of installations (53.4 kW), of which 72% of these are on the ground (GSE, 2021). However, in 2022 Italy produced 28.161 GWh, which 4.194 GWh from the Apulia region [10]. Moreover, to consider that between 2006 and 2021, there are an estimated 13,000 ha of land consumed in the region, and there are about 5,000 ha occupied by ground-mounted PV installations [8],

[4] https://www.sit.puglia.it/portal/portale_pianificazione_regionale/Piano%20Paesaggistico%20Territoriale.

On observing the trend at a local scale, this is even more exemplified. According to Aretano *et al*. (2022) [19], it is evaluated in relative terms (in thousandths, ‰) the loss of land taken to ground-mounted photovoltaic installations compared to the total area of municipalities in the province of Foggia. Indeed, on the geographical distribution of PV farms of Tavoliere area, using a GIS approach [35][5], we created the land take map (Fig. 4) of the municipalities of Foggia.

The range of estimated land take across the entire set of municipalities is between 0.18‰ and 10.53‰. Considering only municipalities (28 on the 64) with PV farms, the average of loss in soil is 0.82 ‰ and an average of 33 ha of PV in each municipality. Conversely, the average Pv size is 3.8 ha, and most plants do not outgrow the size 1.8 ha.

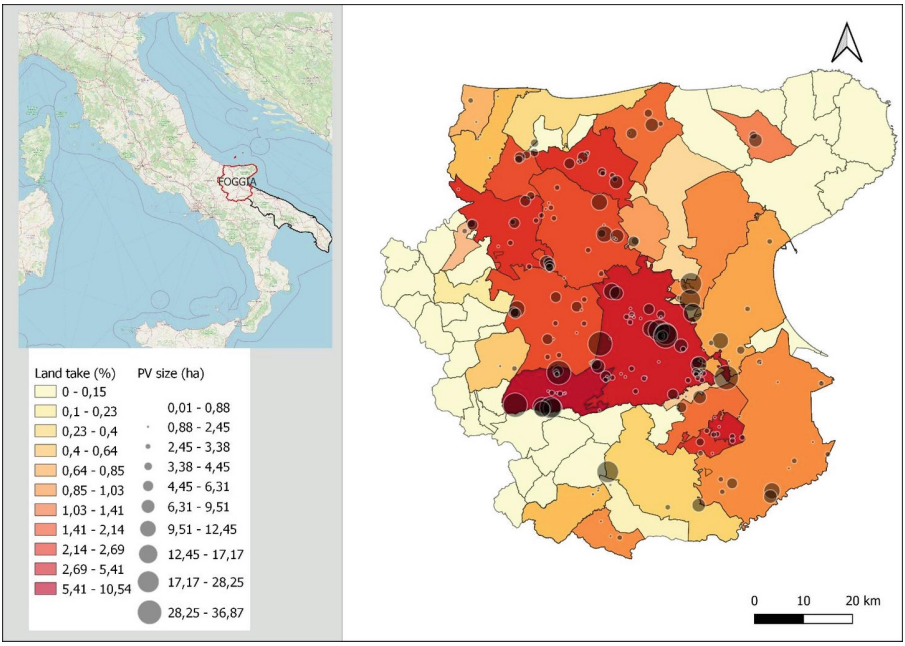
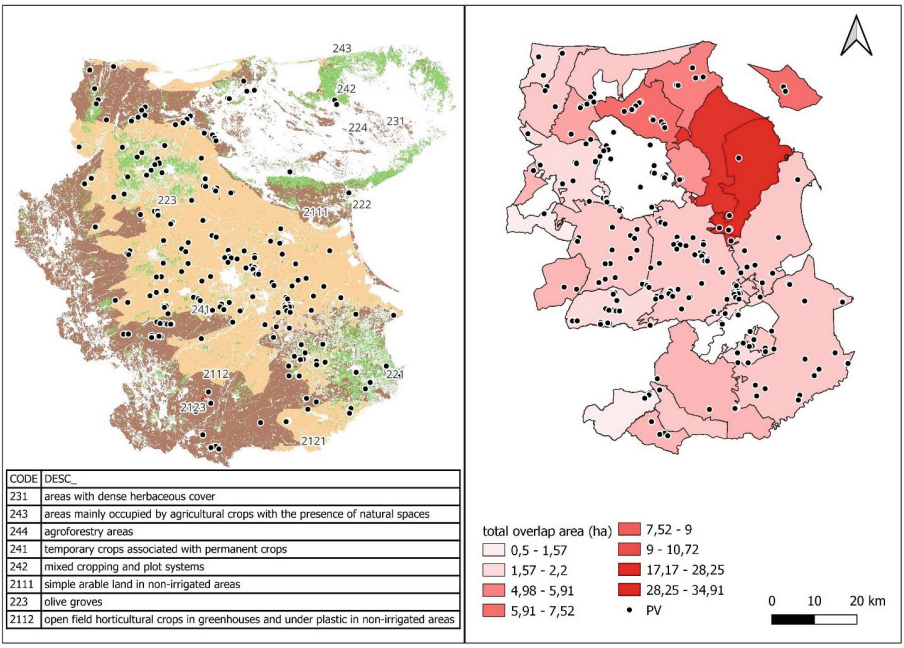


Fig. 4. Change The Land take (‰) at municipality level (Author: De Simone).

In this scenario, a remarkable transformation of the rural landscape is clearly evident. As reported by Arpa Puglia, moreover, in the Foggia area 830 ha of agricultural land has been lost [19]. The overlaying information layers of ground-mounted photovoltaic (National Land Use Map, 2021) and map of agricultural land (Land use map SIT Puglia, 2011) confirmed the prevision. Indeed, out of about 1,000 registered hectares of PV 541 of them are on agricultural land which means that on average 43% of each individual plant is located on agricultural land (Fig. 5)[6].

[5] In QGIS software (3.28), the tools of Map Algebra and Raster Analysis were used both to geolocalisation data from the National Land Use Map (2021) about ground-mounted photovoltaic installations both to extract the municipal level share of land take.

[6] The projection is taking into account the period 2011–2021.



CODE	DESC_
231	areas with dense herbaceous cover
243	areas mainly occupied by agricultural crops with the presence of natural spaces
244	agroforestry areas
241	temporary crops associated with permanent crops
242	mixed cropping and plot systems
2111	simple arable land in non-irrigated areas
223	olive groves
2112	open field horticultural crops in greenhouses and under plastic in non-irrigated areas

Fig. 5. The overlaying of ground-mounted photovoltaic (National Land Use Map, 2021) on map of agricultural land (Land use map SIT Puglia, 2011) (Author: De Simone).

With regard to agricultural landscape, in addition, it is favorable to compare the location of ground-mounted photovoltaic with the land use capacity map of the Regional (LCC), aimed at assessing the productivity of soils for agro-sylvo-pastoral uses. Also in according to Arpa Puglia prevision, the 44% o PV fall in the Apulia are classified as having no limitation for agricultural use and that would have required greater attention to the agronomic characteristics of the soils favorable to silvo-agro-pastoral activities [19]. Moreover, at municipality level, more than 70% of PVs are located on arable and arboreal land (II s class on LCC Map) (Fig. 6).

On that basis, rural areas assume a relevant role in terms of potential development with regard to renewable energy sources. This new specialization of such areas could be an effective response in the fight against climate change and a reduction of energy dependence on fossil sources. In this perspective, they can take a key rule to mitigate the economic and environmental impacts on a national scale. What is the price, however, in terms of land take and loss of identity heritage of our country's rural areas?

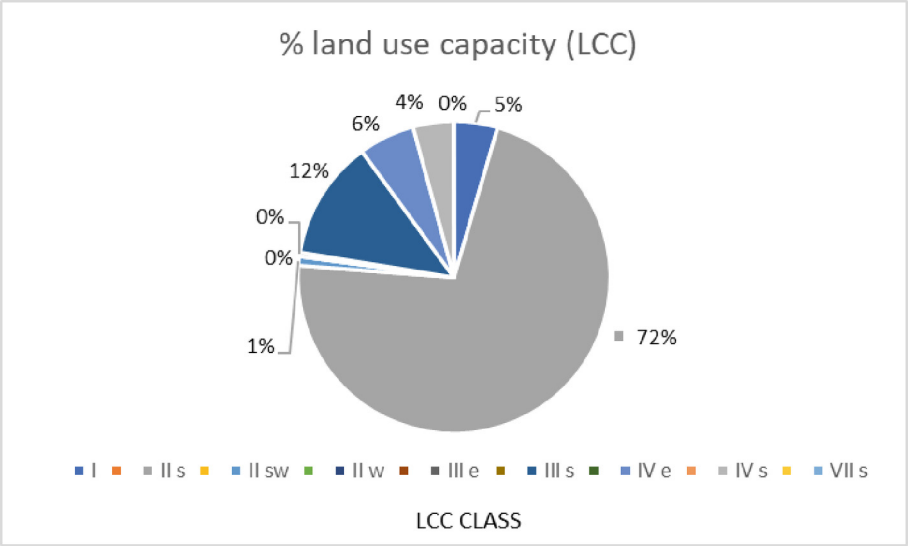


Fig. 6. Proportion of Land Use Capacity data (LCC) of research area (Author: De Simone)

4 Agrovoltaics Practice-Techniques and Classification

Agrovoltaics is a system that combines agricultural production with that of renewable energy. This is done through the installation of modular solar panels placed on raised supports, using the space below for traditional cultivation of plants, vegetables, fruits and vegetables [20]. The fundamental aspect of agrovoltaics derives from the maximization of the potential of the soil used, as the same area will be allocated ambiguously to the production of renewable electricity and agricultural production [32]. The replacement of traditional agricultural activity and the introduction of photovoltaic systems are motivated by several competitive advantages: firstly, the use of photovoltaic panels can be useful in providing shade to crops, which subsequently translates into a reduction in water consumption, with savings that can reach up to 20% [21]; photovoltaic panels can also protect the crops underneath from adverse weather conditions such as heat waves, strong winds, or torrential rains and hail [31]. In light of these benefits for the agricultural sector, it should be emphasized that the renewable energy generated by photovoltaic panels can be used to power irrigation systems, agricultural equipment and lighting systems, reducing dependence on fossil fuels, lowering greenhouse gas emissions and generating positive economic impact, not only in terms of energy cost savings but also as a source of profit from self-produced energy not consumed and fed into the distribution network [22].

However, in light of these numerous advantageous aspects, it is also necessary to consider some critical issues associated with the use of agrovoltaics: the installation of photovoltaic panels mounted on mobile trackers at various heights would cause shading of the agricultural land, reducing the amount of solar radiation received by the crops [23, 34]. The photovoltaic system will therefore require careful and accurate planning in the

inclination of the panels in order to find the combination capable of maximizing energy and agricultural productivity [21]. The second aspect to consider is the management and maintenance costs of the photovoltaic systems, and finally the most significant problem is the installation costs of the systems, which can be up to 40% higher than common ground-based photovoltaic systems. Agrovoltaic systems commonly used can be classified based on their different characteristics and applications. A first distinction is that of open or closed systems: a closed system refers to photovoltaic modules installed on the roofs of greenhouses. In contrast, open systems are those in which the photovoltaic system is positioned in an open area [24]. There are then three different structural possibilities for agrovoltaic systems: the construction of a tensile structure between 3 and 5 m in height, under which traditional agricultural practices are adopted; the insertion of ground-mounted photovoltaic panels, increasing the distance between different rows of vegetables, and finally, the installation of vertically inserted photovoltaic panels between rows [25]. While the dual use of the land will lead to economic and productive benefits, it must be considered that these installations will inevitably have a significant visual environmental impact [26, 33]. Regarding photovoltaic systems mounted on a raised structure, it should be noted that these will usually be mounted on mobile trackers, capable of adapting their angle to obtain the best possible exposure for both electricity production and agricultural needs [24].

Another classification of agrovoltaic systems is based on the different agricultural practices adopted: field crops, referring to traditional field crops following a highly mechanized supply chain, or orchards, which refer to fruit tree cultivation planted in a specific arrangement based on rows and requiring some protection from adverse weather conditions.

To evaluate the efficiency of different agrovoltaic systems, it is possible to use some indicaTo evaluate the efficiency of different agrovoltaic systems, it is possible to use some indicators, which we will now proceed to present [27].

The first indicator under analysis is the Ground Coverage Ratio (GCR): the ratio of the area covered by photovoltaic panels to the cultivated agricultural land. This indicator can be expressed by the following formula: $GCR = \frac{A_{PV}}{A_{Agr}}$.

The second indicator is the energy and agricultural yield of the land. The energy produced Y_{el} (expressed in MWh/hectare) represents the amount of solar energy produced during a year per hectare. Y_{Agr} on the other hand, indicates agricultural production expressed in kg per hectare (kg/ha).

The third key indicator for evaluating the efficiency of photovoltaic systems is the so-called "spatial efficiency," a measure that was created to measure the increase in land efficiency by installing a photovoltaic system and allocating the land for agricultural use at the same time. The indicator used to measure land efficiency is the Land Equivalent Ratio (LER). This index is constructed from the following formula: $LER = \frac{Y_{Agr,AGR}}{Y_{Agr,N}} + \frac{Y_{el,AGR}}{Y_{el,N}}$.

In this indicator, Y_{Agr} denotes traditional agricultural production (N) or using an agrovoltaic system (AGR), while Y_{el} represents electricity production using agrovoltaic particles compared to traditional production. If the LER index is greater than 1 then the use of agrovoltaics will imply an increase in overall land productivity, otherwise this practice will be inefficient [27].

4.1 Contextualization of the Regulatory Framework in Italy

The recent GUIDELINES (2022) from the Ministry of Ecological Transition and Sustainable Development (MITE) regarding agrovoltaic installations attempt to provide a unique definition and describe the characteristics of such installations, with the aim of experimenting with new practices and new design solutions. The Simplification Bis Decree (Decree-Law 77/2021) and the corresponding Law (108/2021) passed in the same year have already been important in this regard.

Moreover, the National Recovery and Resilience Plan (PNRR) includes a mission called "Green Revolution and Ecological Transition" which aims to incorporate this legislation and allocate 1.1 billion euros to achieve a production capacity from agrovoltaic installations of 1.04 GW.

According to the available data, the MITE predicts a cost of around 750 €/kW for traditional type installations (800 €/kW with single-axis tracking) and up to about 1,200 €/kW for systems with seed crops (with a variability of about 375 €/kW) and 950 €/kW for systems with permanent crops (with a variability of about 270 €/kW). On average, there is a 60% increase compared to a traditional installation for a seed crop system, and a 25% increase for a permanent crop system. On average, there is a 13% reduction in O&M costs compared to a traditional installation for an agrovoltaic system. As for the cost of generating electricity (LCOE), starting from 55–69 €/MWh for ground-mounted single-axis tracking installations, there is a range of 73–93 €/MWh for agrovoltaic systems with seed crops and 60–76 €/MWh for systems with permanent crops. These values also include a variability of about 25 €/MWh for systems with seed crops and 15 €/MWh for systems with permanent crops due to possible variations in investment costs. It should be noted that, while the cost difference with ground-mounted installations is quite significant for systems with seed crops (on average around 35%), it is rather moderate for systems with permanent crops (10%). Finally, the monitoring system for the production of electricity from agrovoltaic installations, as evaluated in paragraph 3.3, does not involve any extra costs compared to those associated with monitoring a photovoltaic installation. This monitoring system involves the collection of data already widely shared in real-time by thousands of installations throughout the country through a portal managed by the GSE.

5 Conclusions and Final Consideration

Meeting the constantly increasing global energy demand, assisted by a growing push towards an ecological transition and the search for renewable energy sources [25], represents one of the most daring and pressing challenges to face, with the awareness that this process can only happen by moving away from the use of non-renewable fossil energy sources in favor of sustainable energy production. In the current economic and social landscape (from the current war in Ukraine, to the pandemic, etc.), market uncertainty and the high volatility of commodity and energy prices have highlighted the need and urgency to try to pursue the goal of independence from non-renewable energy sources. For these reasons, we have decided to present this contribution on an innovative practice such as agrovoltaics [28]. Common solar photovoltaic systems require large areas due to the relatively dispersed nature of solar energy. Part of this demand can be met

by using photovoltaic systems integrated into buildings and roofs, but ground-mounted photovoltaic parks are the primary driver of growth and development in the widespread use of these renewable energy sources. The use of large plots of land for the construction of solar parks generates, as a direct consequence, a decision-making process in the land-use destination, as food production and energy production currently compete for the limited resources of the land. To address this important debate, this decision-making process could be overcome by using the emerging concept of agrovoltaics: developing a photovoltaic park on the same area of land, built on a tensile structure at a significant height above the ground (from 2.5 to 5 m), to allow traditional agriculture to develop in the underlying soil [29]. This technological solution thus allows sharing agricultural land with photovoltaic energy production, enabling the farmer to continue producing crops using commonly used techniques (such as tractors, harvesters, etc.) and allowing the same area to be used for a photovoltaic system as well. Photovoltaic panels mounted on mobile trackers that follow the daily course in order to modulate shading and favor crop growth. Through the first applications of the agrovoltaic production model, an initial measurement of the technical potential has suggested that the value of energy production combined with shade-tolerant crop production has generated an increase in value that ranges between 30% and 60% of the economic value of farming businesses that implement such agrovoltaic systems instead of conventional agriculture. The use of shade-tolerant crops allows minimizing crop yield losses and thus maintaining crop price stability. Furthermore, this dual use of agricultural land can have a significant effect on national photovoltaic production.

Agrovoltaic systems therefore incorporate efficient dual use of agricultural land resources, namely arable land for agricultural and photovoltaic production, or pasture for animal breeding and photovoltaic production. There are various test sites and some commercial installations around the world to reduce pressure on agricultural spaces. This combined use would allow a reduction in conflicts regarding land use between the energy and agricultural sectors. It is expected that total soil productivity could increase significantly due to the effects of shading and altered water availability. This could even develop beneficial effects for all, such as reducing heat stress and providing more consistent water supply to plants during the summer to improve the resilience of agricultural systems in a changing climate [30]. Agrovoltaic systems could contribute to promoting regional development in the agricultural and energy sectors. By making the agricultural sector more attractive (ensuring higher profits per hectare), the younger generation can be encouraged to stay in rural areas, thereby strengthening infrastructure and the economy. In the EU, urbanization and energy dependence can be combated while supporting the transition towards decentralized energy supply. The potential of these dual production systems for both the agricultural and photovoltaic sectors has resulted in the inclusion of agrovoltaics in the PNRR, with an investment of 2.6 billion euros in the sector. This once again highlights how such practices can represent a fundamental driver of sustainable development for the future.

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