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Multidimensional Role of Agrovoltaics in Era of EU Green Deal: Current Status and Analysis of Water–Energy–Food–Land Dependencies

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Abstract: The European Green Deal has set climate and energy targets for 2030 and the goal of achieving net zero greenhouse gas emissions by 2050, while supporting energy independence and economic growth. Following these goals, and as expected, the transition to "green" renewable energy is growing and will be intensified, in the near future. One of the main pillars of this transition, particularly for Mediterranean countries, is solar photovoltaic (PV) power. However, this is the least land-efficient energy source, while it is also highly competitive in food production, since solar parks are often developed in former agricultural areas, thus resulting in the systematic reduction in arable lands. Therefore, in the context of PV energy planning, the protection and preservation of arable lands should be considered a key issue. The emerging technology of agrovoltaics offers a balanced solution for both agricultural and renewable energy development. The sustainable "symbiosis" of food and energy under common lands also supports the specific objective of the post-2020 Common Agricultural Policy, regarding the mitigation of and adaptation to the changing climate, as well as the highly uncertain socio-economic and geopolitical environment. The purpose of this study is twofold, i.e., (a) to identify the state of play of the technologies and energy efficiency measures of agrovoltaics, and (b) to present a comprehensive analysis of their interactions with the water–energy–food–land nexus. As a proof of concept, we consider the plain of Arta, which is a typical agricultural area of Greece, where we employ a parametric analysis to assess key features of agrovoltaic development with respect to energy vs. food production, as well as water saving, as result of reduced evapotranspiration.

Keywords: water–energy–food–land nexus; renewable energy; green transition; PV panels; dual land use; solar radiation; shading; crop efficiency; evapotranspiration; water saving

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1. Introduction

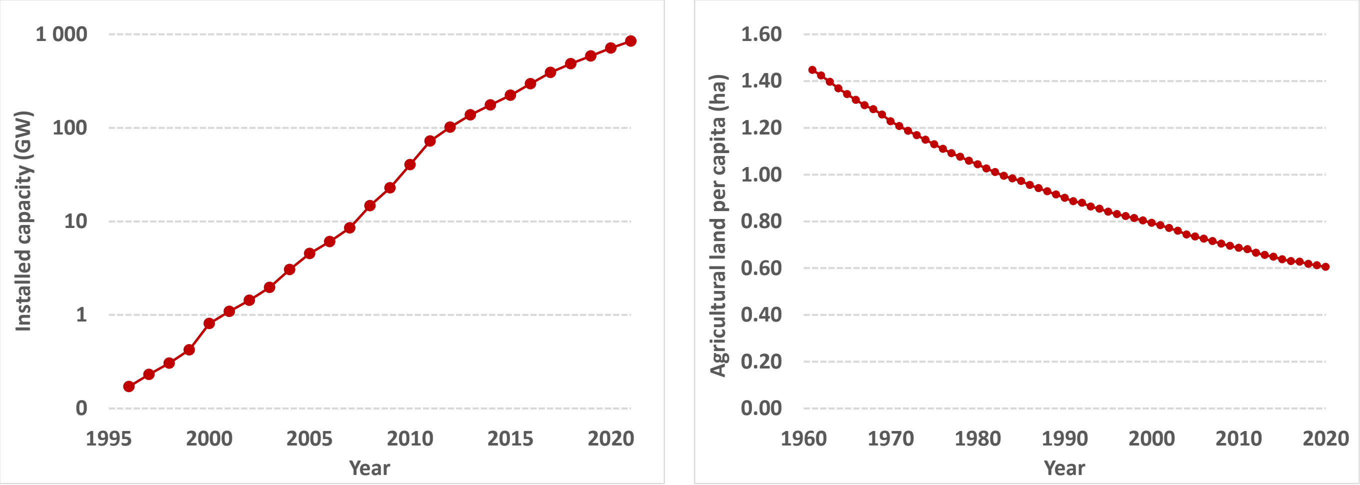
In the past decades, the four axes of humanity development, i.e., water, energy, food and land, have had significant stressors imposed on them by the increase in population and the improvement of standards of living as well. Since all aforementioned resources are, more or less, interrelated, their exploitation and management should be handled under the nexus approach.

In particular, energy is strongly associated with the water and food industries, as a key element throughout their entire life cycles. Energy is also interrelated with water through hydroelectric projects, which offer energy regulation and storage at a large scale. In this respect, water and energy can be considered two complementary resources. On the other hand, energy and food have both synergies and conflicts, in terms of land occupation.

A relatively new dimension to the role of energy with respect to water, food and land has arisen from the challenge of transitioning electrical power systems from fossil fuels towards low-carbon sources. With regard to this, Europe has set the goal of increasing renewable energy prevalence to 45% of the gross final consumption by 2030 [1], while also aiming to reduce greenhouse gas (GHG) emissions by 55% [2]. Green energy is essential for food security, since it significantly affects food production [3,4]. However, the replacement of conventional sources with renewables is expected to further intensify competition for land resources, particularly agricultural ones that are reserved for food production. Interestingly, the hypothetical land surface required to replace fossil fuels with bio-fuels widely exceeds the agricultural areas of the planet [5].

One of the dominant forms of renewable energy refers to solar photovoltaics (PVs), with their global cumulative capacity already exceeding 800 GW (Figure 1a), while their market share is expected to increase to up to 70% by 2030 [6]. From a landscape approach, PV systems' direct and total land occupation are almost equal [7]. However, a key constraint on their development, with respect to other popular renewable energy sources, particularly wind energy, is their requirement of extensive land use, competing against agriculture, which is the predominant land use form, currently accounting for 12% (1.6 billion ha) of land globally [8]. In theory, the current global electricity consumption could be supplied by photovoltaics covering only 0.3% of the Earth's land surface, which is about 13 billion ha [9,10], or, equivalently, 2.4% of the agricultural one. However, this percentage may be substantially larger if we focus on specific areas where PV systems work, in fact, to the detriment of arable lands [11–14]. Extensive resource exploitation can lead to land degradation and reduced soil productivity [15,16]. Such changes to the occupation of land can bring great imbalances in the water–energy–food–land nexus, given the already significant decrease in the area of agricultural land over the past decades (Figure 1b).

One of the key findings of the Common Agricultural Policy (CAP)'s legislative texts, published by the European Parliament in November 2020, indicates that "EU agriculture and food practices are currently not on the right track to meet the Green Deal ambition, objectives and quantitative targets related to climate, environment, nutrition and health issues" [17]. The incorporation of solar power can enhance the resilience of agricultural systems and help mitigate climate change, given that nearly every state of food production currently relies on gas and oil [18].



(**a**) (**b**)

Figure 1. Global evolution of (**a**) cumulative solar PV capacity, and (**b**) agricultural land per capita. The original data were retrieved from [9,19].

The competition between solar energy and land uses imposes the need for advanced technologies that are able to combine the transition to clean energy and the sufficiency of land for food production. Following this, agrovoltaics (AVs) can minimize this gap, since it is a novel synergistic approach that combines agricultural production with the generation of renewable energy through photovoltaic (PV) systems. It involves installing solar panels above cropland or grazing areas, allowing dual land use, namely the coexistence of agricultural activities and renewable energy production, finding great applicability in countries with limited open space. The main objective of agrovoltaics is to maximize land-use efficiency by providing additional benefits, such as reduced water requirements, increased crop yields, and reduced soil erosion, while simultaneously addressing the energy needs of society.

There are several factors that may explain how the integration of photovoltaics can increase crop productivity. To some extent, the shade provided by panels is considered beneficial, since only a small fraction of sunlight is required for crops to achieve their maximum photosynthesis levels, while too much light hinders their growth and can lead to adverse results, causing serious damage to plant DNA [20]. Another crucial factor is the reduced water evaporation caused by the panels' shade. Depending on the level of shade, agrovoltaics can achieve water savings of 14–29% [21].

Due to all the aforementioned reasons, agrovoltaics are in line with the Farm to Fork Strategy [22], which has the general aim of making food systems in the EU fair, healthy and more environmentally sustainable. In particular, agrovoltaics are a promising solution for sustainable land-use management and can contribute to a reasonable transition in the EU agriculture and land use sector. Their involvement in improving crop quality, increasing biodiversity, and reducing water requirements for crop growth offers a rapid increase in the speed and scale of actions required to reduce the risks of climate change, creating new economic opportunities and ensuring a reasonable transition in the EU agriculture and land use sector. A recent land eligibility analysis of NUT-2 regions in Europe showed that the majority of countries have a share of between 12–29% of eligible land for agrovoltaics [23]. Financially, the combined crop and energy output from an agrovoltaic system can enhance land productivity by up to 70% [24]. According to the European Bank for Reconstruction and Development (EBRD) "a just transition seeks to ensure that the substantial benefits of a green economy transition are shared widely, while also supporting those who stand to lose economically" [25].

In terms of their significant solar potential, Mediterranean countries with limited arable land resources, such as Greece, are expected to be strongly beneficial for the employment of agrovoltaics. In this vein, this research study has two major objectives. The first objective is to employ a brief overview of the state of the art of AV systems, emphasizing the design challenges and their technoeconomic assessment. These issues are discussed in Sections 2–5. A second, parallel, objective is to investigate the role of AVs across the water–energy–food–land nexus, by means of a proof of concept in a typical agricultural area of Greece. The analyses are presented in Section 6 and discussed in Section 7, while the key findings of this research are outlined in Section 8.

We remark that in our case study, the issue of economic feasibility is not accounted for, since our emphasis is on revealing the role of AV systems with respect to the water–energy–food land nexus. To our knowledge, this kind of integrated analysis in the broader field of renewable energy, which considers the synergies and conflicts between all components of the nexus, is not usual in the literature, with few exceptions, e.g., Abdali et al. [26] who studied the nexus approach in bioenergy development.

2. Historical Development of Agrovoltaic Systems

The concept of the coexistence between photovoltaics and crops was first introduced by Goetzberger and Zastrow [27]. In their study, a theoretical configuration prioritizing energy production was proposed comprising PV modules installed at a height of 2 m, in rows of three times their height, in order to achieve nearly uniform radiation, approximately equal to two-thirds of the global radiation. The first agrovoltaic prototype was not developed until 2004, when Akira Nagashima designed different configurations to match the variating shade tolerance of each cultivated crop [28].

The first agrovoltaic pilots of Europe were implemented in 2010 in Montpellier, France, where two different layouts were tested on wheat crops by changing the density of the solar panels: (1) full-density (optimal spacing for electricity production) and (2) half density, to account for crop growth and productivity [29]. The results showed that the half-density layout had almost no impact on wheat production. However, it was also proven that the assumption of Goetzberger and Zastrow about the global radiation value reaching the ground was too optimistic, as less than 50% of solar radiation actually reached the ground. The first commercial agrovoltaics were installed in Northern Italy in 2012 under the name "Agrivoltaico". Amaducci et al. [30] simulated the operation of Agrivoltaico for different radiation and shading conditions and crop development and found that the best configuration produced twice as much energy per unit area compared to that produced using ground-mounted solar panels, without negatively affecting crop productivity.

Since 2014, more than 2200 agrovoltaic systems have been installed. By the end of 2022, their power capacity was approximately 2.8 GW [31]. However, this is still only a minor fraction (about 0.3%) of the total capacity of PVs across the globe.

3. Technological Advances

Agrovoltaics entail sharing solar radiation to produce both food and energy on the same land. Therefore, designs of such systems must aspire to alleviate the reduction in crop profitability, and adapt to local climate conditions, crop types and energy needs. Technological advancements have contributed to different types of photovoltaic modules, increasing their versatility and applicability in agriculture. Bifacial PV cells absorb solar radiation from both sides of the cell to produce energy, as facilitated by their anti-reflective coatings, reaching an efficiency of up to 24% [32]. Specifically, global radiation is absorbed on the front side, while the rear side absorbs the reflected radiation caused by the ground's albedo [6]. Dullweber and Schmidt [33] proved that bifacial PV cells can increase the energy yield by up to 30% compared to monofacial PV cells, thus reducing the relative cost of surface area. In parallel with bifacial cells, concentrator photovoltaic (CPV) modules are another emerging technology. They selectively transmit sunlight in a specific spectral range essential for plant growth, while also concentrating the remaining sunlight for power generation. Sato and Yamada [34] examined different types of CPV cells and found that they exhibit higher electricity yields compared to the partially transparent modules. However, even though these modules are more efficient, they are provided at a significantly higher cost, since manufacturer processes for mass production are yet to be implemented [35].

In addition to these technologies, semi-transparent solar panels absorb blue and green light, thus allowing red light to be absorbed by crops for photosynthesis. Thompson et al. [36] examined the integration of tinted semi-transparent solar panels in spinach and basil crops, and found consistently increased levels of protein in both crops. Furthermore, Fernández et al. [37] developed a novel dual APV model for agriculture greenhouses and evaluated its performance in four locations worldwide, in terms of photovoltaic irradiance and the associated energy yield. Their results showed that such systems ensure a transparency of up to 68%, without significantly affecting crops, and could achieve annual energy production of up to 200 kWh/m^2. However, even though semi-transparent photovoltaics are a promising and constantly developing technology, their overall efficiency is much lower than that of the other types of modules [38]. Detailed analyses, including comprehensive graphs outlining the efficiency of all known types of solar cells, industrial as well as experimental, are provided by [39].

4. Design Parameters

The rational design of agrovoltaic systems requires a transdisciplinary approach, where different optimization approaches must be implemented, depending on the system's primary purpose. Toledo and Scognamiglio [40] distinguished these with three basic categories: (1) minimizing shadows on crops, (2) maximizing electricity generation and (3) social acceptance. Design parameters and factors that influence the operation of an agrovoltaic system are outlined below. While the first two categories can be achieved by fine-tuning the different design parameters, it is important to also include the social acceptance category in AV system planning, given that mathematical models have been developed to evaluate aesthetics [41].

4.1. Panel Height

Agrovoltaic systems fall into two basic structural layouts. Specifically, the first one includes photovoltaic arrays on stilts of a 2–5 m height, enabling the use of conventional agricultural machinery and cattle to roam underneath. Higher elevated arrays reduce their surface soiling from dust, which is created by farming equipment. Dust affects the electricity output, since it diminishes the transmittance capacity of the module's transparent collectors [42]. It is a common practice for AVs to implement a system that ensures both crop irrigation and the cleaning of the modules' surface [43]. However, as the arrays' height increases, so does the investment cost, which is also due to the requirement of additional wind reinforcements.

The second layout consists of placing the arrays at a relatively lower elevation, while also widening the space between the rows to allow crop growth. Although the panel density is decreased, leading to reduced energy production, this layout requires lower initial investments and minimizes the system's impact on the landscape [5].

4.2. Panel Tilt Angle and Orientation

The performance of photovoltaic panels is influenced by their tilt angle and orientation, which affect the amount of energy produced. Specifically, this angle is adjusted in order to maximize the panels' efficiency during winter, when the incoming radiation is low. A common (yet not the most effective) practice involves installing the panels at an angle equal to the region's latitude. Nevertheless, small angles are avoided to prevent dust accumulation. The first agrovoltaic systems were installed under a fixed tilt angle in order to account for crop development. In further studies, it was found that crop development remains unhindered by the installation of photovoltaics, provided that the necessary amount of radiation reaches the ground [44]. Following this, variable tilt angle systems were suggested to guarantee crop development, while also maximizing energy production for the remainder of crops' life cycles by ensuring that the PV surface is perpendicular to the striking solar angle during operation [45]. Valle et al. [46] performed a comparative analysis between dynamic and stationary photovoltaics, which found the former to exhibit very high productivity per land area unit. However, the array density is the factor that mostly influences crop yield, rather than the tilt angle, which was also shown in the agrivoltaico system [30].

In order to maximize energy production, the majority of installed photovoltaics have an azimuth of 180°, directed towards the south. Such layouts result in ununiform radiation being reflected on the ground, a phenomenon that intensifies during late spring and early summer. This heterogeneity is reduced through rotating the panels by 30° southeast or southwest. The most uniformly distributed ground radiation is achieved by directing the panels towards the north (0° azimuth), which is a less cost-effective practice [47].

A different approach to an agrovoltaic system is provided through the use of vertical solar panels. Vertical photovoltaics, usually utilizing bifacial cells in order to produce energy from both sides, are placed in appropriately distanced arrays so that crops can develop, and heavy agriculture machinery can operate between them. Contrary to the aforementioned layout, their optimal orientation has an azimuth of 90°, directed from the west to the east. For this reason, their energy yield peak occurs during the morning and afternoon hours [48].

In all cases, the selection of the system's tilt angle and orientation should depend on several other factors, such as the system's primary purpose, the available landscape and the overall social acceptance. For instance, Scognamiglio [49] highlighted the effect of the pitch angle and orientation of agrovoltaics, across three different geographical areas (Bergen, Munich, and Trapani). This analysis showed that a low tilt angle provides more freedom in the choice of orientation (azimuth angles), allowing better use of land at the expense of a slight loss in normalized energy generation.

4.3. Array Density

The density of the installed photovoltaic arrays is a crucial design parameter, as it determines the amount of radiation that reaches the ground. The greater the array density is, the higher the energy production will be. However, the crop yield is expected to be less, especially for shade-intolerant crops. Dinesh and Pearce [50] examined two different densities of photovoltaic arrays, i.e., the full (3.2 m distance of array rows) and the half one (6.4 m distance). The second layout resulted in greater overall land productivity. Contrary to photovoltaics installed at a tilt angle, vertical photovoltaics increase energy yield as the arrays' density decreases. Specifically, in an agrovoltaic layout located in Sweden, the crop yield was reduced by 50% when the distance of the rows was narrowed down from 20 to 9 m [51].

4.4. Other Situational Factors That Influence the Operation of an AV System

Mamun et al. [8] outlined an extensive list of local factors that influence the operation of agrovoltaic systems. Most of them concern meteorological processes (e.g., air temperature, humidity, wind velocity, soil temperature and moisture), while others concern crop-related properties (e.g., crop growth rate, and photosynthetically active radiation). The type of crop also plays a pivotal role in the system's overall efficiency. The cultivation of plants with increased shade tolerance (e.g., field crops) exhibits higher overall system efficiency compared to that of orchards. In a recent study, Sekiyama and Nagashima [42] examined the performance of corn, which is a shade-intolerant crop, and found that its yield for a low-density configuration was higher than that without any modules. However, this study was conducted in a small experimental farm; thus, a larger scale investigation is encouraged in order to also ensure that the microclimate of that specific region did not favor the crop cultivation.

5. Performance and Evaluation of AV Systems

In order to evaluate the performance of the different examined layouts, several metrics and key performance indicators (KPIs) were developed. They can be distinguished with two basic categories: (1) performance metrics and (2) economic indicators.

5.1. Performance Metrics

5.1.1. Ground Coverage Ratio (GCR)

This metric is defined as the ratio of the area of photovoltaic panels with respect to the cultivated surface. High GCR values lead to a higher energy yield and lower crop yield, as the amount of solar radiation reaching the crops will be lower due to the shading from module arrays [52].

5.1.2. Agricultural and Energy Yield

The agricultural yield denotes the total amount of agricultural produce in a selected area (kg/ha) and strongly depends on local climate conditions, soil quality and the availability of water [53]. The energy yield (MWh/ha) is the produced energy per land unit and is heavily dependent on various meteorological variables (solar radiation, temperature, and microclimate) as well as technical variables (efficiency and cable losses). Willockx et al. [54] stated that agrovoltaic systems are expected to have greater cable losses compared to ground mounted photovoltaics, due to the increased module spacing.

5.1.3. Water Usage Efficiency

The impact of agrovoltaics can also be quantified through determining water usage efficiency (WUE). WUE is calculated as a unit of biomass per unit of water used against the biomass produced in a zone which is not under the influence of photovoltaics [55].

5.1.4. Land Equivalent Ratio (LER)

The LER evaluates land productivity. It was initially used to compare mixed cropping systems with respect to sole crops, while later it was also utilized in agrovoltaic systems [56]. LER values above 1 indicate that the integrated system of agrovoltaics is more effective than separate crop production and energy production for the same area. For example, a LER value of 1.7 would mean that an agrovoltaic farm of 1 ha can produce as much electricity and crops as a 1.7 ha farm that separates the aforementioned productions [29].

However, using LER exhibits some limitations. For instance, it does not differentiate between energy and crop production, meaning that a high LER can derive from high energy production and a low crop yield [40]. Moreover, environmental effects (e.g., soil fertility, biodiversity) are not accounted for. Therefore, while evaluating an AV system, it is important to describe the crops' performance characteristics and the landscape.

5.2. Economic Indicators

5.2.1. Price Performance Ratio (PPR)

The PPR is a measure used to define if the project is financially viable, which is estimated as the ratio between the price of the implementation of the agrovoltaic system and the derived performance benefits. The first term results from the adaptation of solar panels while maintaining cropland and enabling techno-economic synergies. On the other hand, the benefits are expressed in terms of annual revenue from the harvest of crops and the energy yield. The smaller the ratio, the more favorable the project. However, even a ratio close to 1 can be considered attractive, since the projects contribute to a clean energy transition and a reduction in the carbon footprint [57]. However, if the PPR is larger than 1, the agrovoltaic system is considered not sustainable.

5.2.2. Levelized Cost of Electricity (LCOE)

This metric accounts for the full life-cycle costs (fixed and variable) of a power-generating technology per unit of electricity (MWh). In particular, it allows a comparison of the energy generation costs of conventional plants with respect to renewables [58]. LCOE is used to calculate the price of the implementation of the agrovoltaic system. The higher the shade tolerance of the crop, the lower the LCOE, since a decreased light requirement results in a larger GCR and, thus, a larger power capacity and energy yield, for the same fixed structural costs [56].

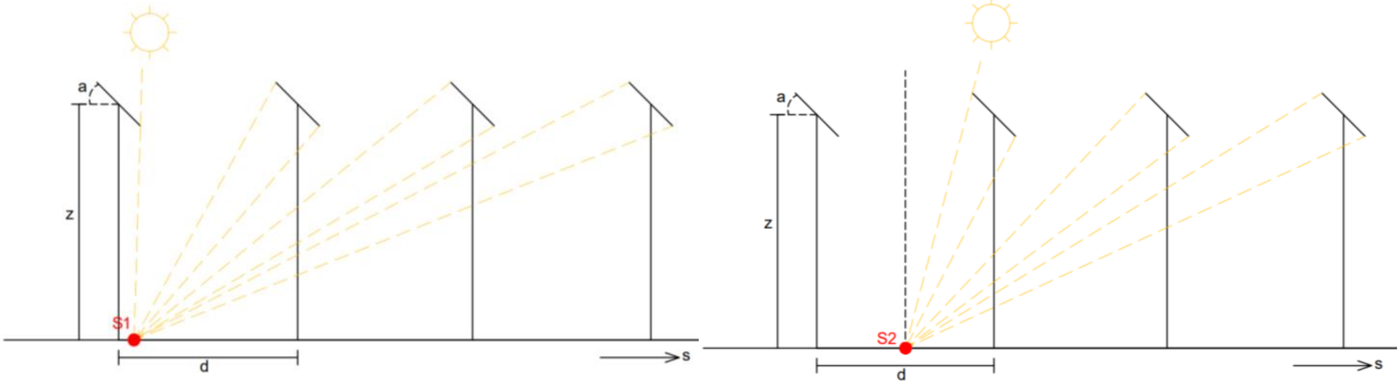
6. Proof of Concept: Arta Plain, Western Greece

6.1. Problem Setting

In order to assess the sustainability of agrovoltaic systems with respect to the water-energy–food–land nexus, and to reveal their potentials in Greece, we investigate a hypothetical AV system located in the plain of Arta, Western Greece. In particular, we assess the variation of several performance metrics across the water–energy–food–land nexus against three key design characteristics of the system, namely the array density, the tilt angle and the installation height of the panels, and for three different crops (corn, alfalfa, and winter wheat). Our analyses are based on the simulation of three processes of interest, namely the power production through the photovoltaic panels, the food production, and the potential evapotranspiration, which is the driver of associated water needs.

The essential meteorological data for the representation of the aforementioned processes are solar radiation, relative humidity, wind speed and temperature. In our analyses, we retrieved hourly time series for the recent years from the pilot monitoring station at Kostakioi, operated by the University of Ioannina. The data were available through the Open Hydrosystem Information Network (OpenHi; https://openhi.net; accessed on 13 May 2023), which is an open-access large-scale water and environmental monitoring infrastructure [59].

The general layout of the system and its characteristic geometrical properties are shown in Figure 2, while the technical features of the selected PVs are summarized in Table 1. Specifically, we assume monocrystalline south-oriented PVs, placed at height *z*, with a tilt angle, *a*, in arrays of distance, *d*. The examined values range from 1 to 5 m for *z*, 30 to 50° for *a*, and from 1.345 to 10 m for *d*. We remark that the minimum array distance is derived from an empirical rule, implying that this should equal at least twice the modules' height. In order to assess the impacts of shadowing, we consider two representative points, one below the panel (S1) and one between the panels (S2), as shown in Figure 2.



(**a**) (**b**)

Figure 2. The examined points. The dashed yellow lines represent the direction of direct radiation for different sunlight angles; (**a**) Point S1 is located under a PV module, and (**b**) Point S2 is located between two PV arrays.

Table 1. PV modules' key characteristics.

Nominal power (W)	400
Total efficiency (%)	22.6
Dimensions (mm)	1046 × 1690 × 40
Operating temperature (°C)	−40 to +85
Power temperature coefficient (%/°C)	−0.29

6.2. Ground Radiation

One of the most crucial issues regarding AV systems is the shade created by the PV modules. The shade level is a decisive factor for crop quality and development and for the reduction in evapotranspiration. In open-sky conditions, each point on the ground receives both direct and diffuse radiation. However, the installation of PVs hinders direct radiation from reaching the ground, depending on the sun's position during the season and time of day in contrast to the panel's geometry (height and till angle). The mathematical framework for calculating the shadowing effects is explained by Mamassis et al. [45].

In our analysis, we assume that Point S1 receives all diffuse radiation and partial direct radiation, according to actual shadowing conditions, while Point S2, which lies in the middle of the panels, receives all incoming radiation. We highlight that the observed meteorological data concern the total radiation, and not its individual components. In order to determine them, we utilize the empirical formula by Angström (1956) [60]:

$$R_s = R_a\ (a + b\ n/N) \tag{1}$$

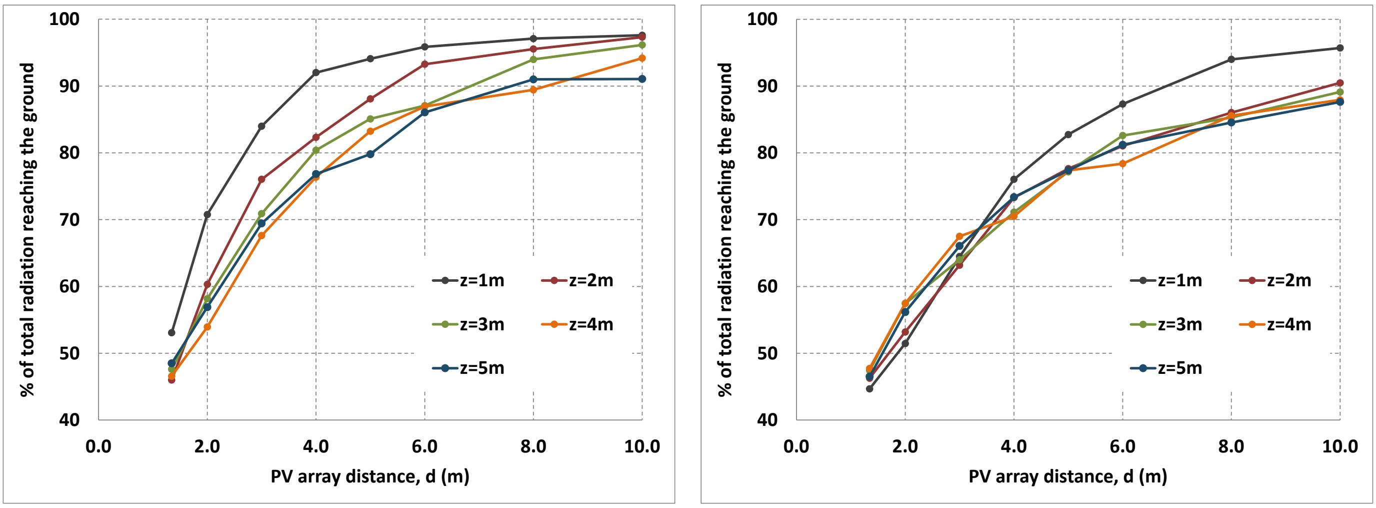
where R_s is the total (also referred to as global) radiation arriving at the terrain surface, R_a is the so-called extraterrestrial radiation, i.e., the solar radiation received at the top of the Earth's atmosphere above a horizontal surface, which is a function of latitude and time, n is the actual duration of sunshine, N is the maximum potential daylight hours (which are also a function of latitude and time), a is a regression constant, expressing the fraction of extraterrestrial radiation reaching the Earth on overcast days ($n = 0$), and $a + b$ is the fraction of extraterrestrial radiation ideally reaching the earth under clear-sky conditions ($n = N$). Parameters a and b depend on the location, the season and the state of the atmosphere, and they are related to the distribution of direct and diffuse radiation. In our analyses, we apply their typical values, i.e., $a = 0.25$ and $b = 0.50$, as indicated by Brutsaert [61]. Under this premise, we consider that 25% of the extraterrestrial radiation is converted to diffuse radiation; thus, the direct radiation is easily estimated as the difference between the observed global radiation and the diffuse one. Next, we adjust the direct radiation to shadowing conditions, following the rationale by Mamassis et al. [45], while, for simplicity, we consider that the diffuse component is not affected by the installation of panels.

Initially, we account for the impacts of the PVs' tilt angle on radiation, which is examined for three distance values and two placement heights (Table 2). The results outline that this design characteristic has too limited an impact on the radiation reaching the ground. Thus, for the next analyses, we assume a standard tilt angle value of 40°, which ensures optimal energy production.

Next, we assess the radiation received by points S1 and S2 for various module heights and array distances (Figure 3). As expected, as the distance and the height increase, the effects of shadowing become less intense, and thus the radiation that reaches the ground becomes more uniform. It is important to notice that for array distances larger than 4 m, the change in ground radiation does not exceed 30%, while it becomes insignificant for distances larger than 6 m. On the other hand, the different PV placement heights have smaller impacts on shadowing, since they generally exhibit less than a 10% change in radiation values (except for the rather small height of 1 m). This indicates that this design characteristic is not crucial from the radiation perspective, and should be mainly selected on the basis of the crop type and the size of the agricultural machinery to be used. For this reason, all the next analyses are employed for a standard panel height of 5 m, in order to not impose barriers to crop development.

Table 2. Percentage of total radiation reaching the ground for point S1 (%).

Array Distance (m)	Tilt Angle (°)					
	Height 1.0 m			Height 5.0 m		
	35	**40**	**45**	**35**	**40**	**45**
1.345	53	53	54	48	48	49
5.0	94	94	94	80	80	79
10.0	98	98	98	91	91	91



(**a**) (**b**)

Figure 3. Impact of design parameters on ground radiation (**a**) under the PV modules (point S1); (**b**) between two arrays (point S2).

6.3. Energy Yield

The energy yield, in terms of monthly and annual power production per acre, is calculated for various array densities (Table 3), by accounting for the technical characteristics of the PVs (Table 1), the incoming radiation, and the adjustment of the total efficiency to the temperature. In Figure 4, we contrast the annual power production with respect to distance. The two variables follow a power-type relationship with the shape parameter of −0.80, indicating that as we move away from the theoretically optimal distance of 1.345 m (which is two times the height of the panels), the solar energy production is exponentially decreased. For instance, at a distance of 3 m, the energy production is 57% with respect to the optimal one, while at 10 m this percentage is only 20%.

Table 3. Impact of array distance on energy production (MWh/acre).

Month	Panel Distance, *d* (m)						
	1.345	**3.0**	**4.0**	**5.0**	**6.0**	**8.0**	**10.0**
January	6.9	3.9	3.1	2.5	2.2	1.7	1.4
February	8.1	4.6	3.6	3.0	2.6	2.0	1.6
March	12.0	6.8	5.4	4.4	3.8	2.9	2.4
April	18.3	10.3	8.2	6.8	5.8	4.5	3.6
May	19.6	11.1	8.8	7.2	6.2	4.8	3.9
June	22.3	12.6	10.0	8.3	7.0	5.4	4.4
July	24.8	14.0	11.1	9.2	7.8	6.1	4.9
August	21.6	12.2	9.7	8.0	6.8	5.3	4.3
September	15.0	8.5	6.7	5.5	4.7	3.7	3.0
October	10.9	6.2	4.9	4.0	3.4	2.7	2.2
November	7.3	4.1	3.2	2.7	2.3	1.8	1.4
December	7.9	4.4	3.5	2.9	2.5	1.9	1.6
Total	174.6	98.6	78.1	64.6	55.1	42.6	34.7

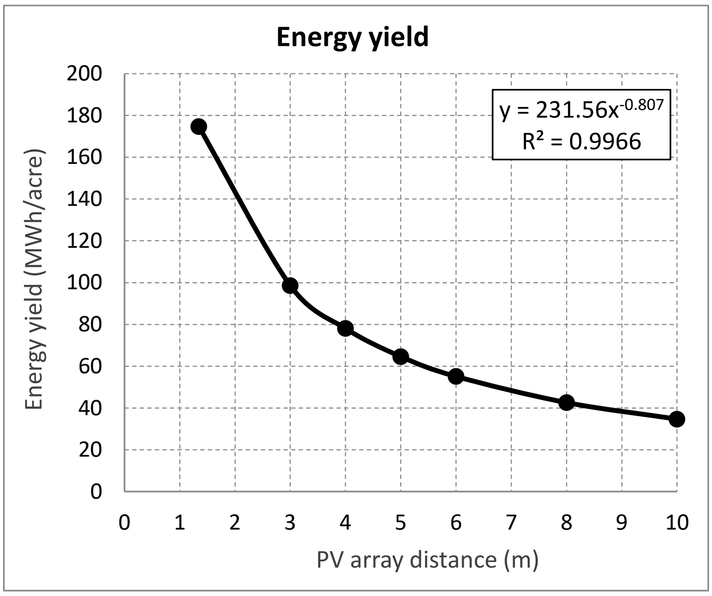


Figure 4. Impact of array distance on PV energy yield.

6.4. Crop Yield

Crop yield is expressed in terms of produced dry matter (kg/acre), which is a common metric with which to define a crop's productivity. As mentioned in Section 6.1, in our AV system, we assess the development of three crops, namely corn, alfalfa and winter wheat (Table 4), for which we investigate different PV array densities. All analyses are performed for a PV height of 5 m, in order to account for the full development of corn crops.

Table 4. Crop characteristics and optimized shape parameters of empirical relationship (3).

	Growth Period	Days of Development	Radiation Use Efficiency (RUE)	Dry Matter under Full Sun, DM$_{max}$ (kg/acre)	Shape Parameters	
					a	*b*
Corn (C4)	10 April to 9 September	150	2.49	424.7	0.468	2.466
Alfalfa (C3)	Perennial crop	-	1.77	507.9	0.381	1.788
Winter Wheat (C3)	15 October to 1 June	225	2.00	266.0	0.449	1.653

Following the global classification standards, the three examined crops fall into two categories, C3 and C4, depending on the photosynthetic processes they undertake [62]. Corn belongs to category C4, which is more efficient than C3 plants at photosynthesis and resource usage, particularly in hot climates, where the potential for productivity is high [63]. The crop productivity, in terms of dry matter (SM), is estimated by the following:

$$DM = RUE \times IPAR \tag{2}$$

where RUE (radiation use efficiency) is a typical measure of the conversion of intercepted radiation into biomass (dimensionless), and IPAR (intercepted photosynthetically active radiation) is the amount of light available for photosynthesis ([64–66]). The remaining radiation is either consumed for plants' metabolism, reflected to other plants or converted into heat [67]. On the basis of the classical work carried out by Monteith [68], referring to tropical and temperate latitudes, and the findings of more recent studies [69], we assume that the IPAR is 50% of the global solar radiation [70]. On the other hand, for the estimation of RUE across each examined crop, we apply the values proposed by Gosse et al. [65].

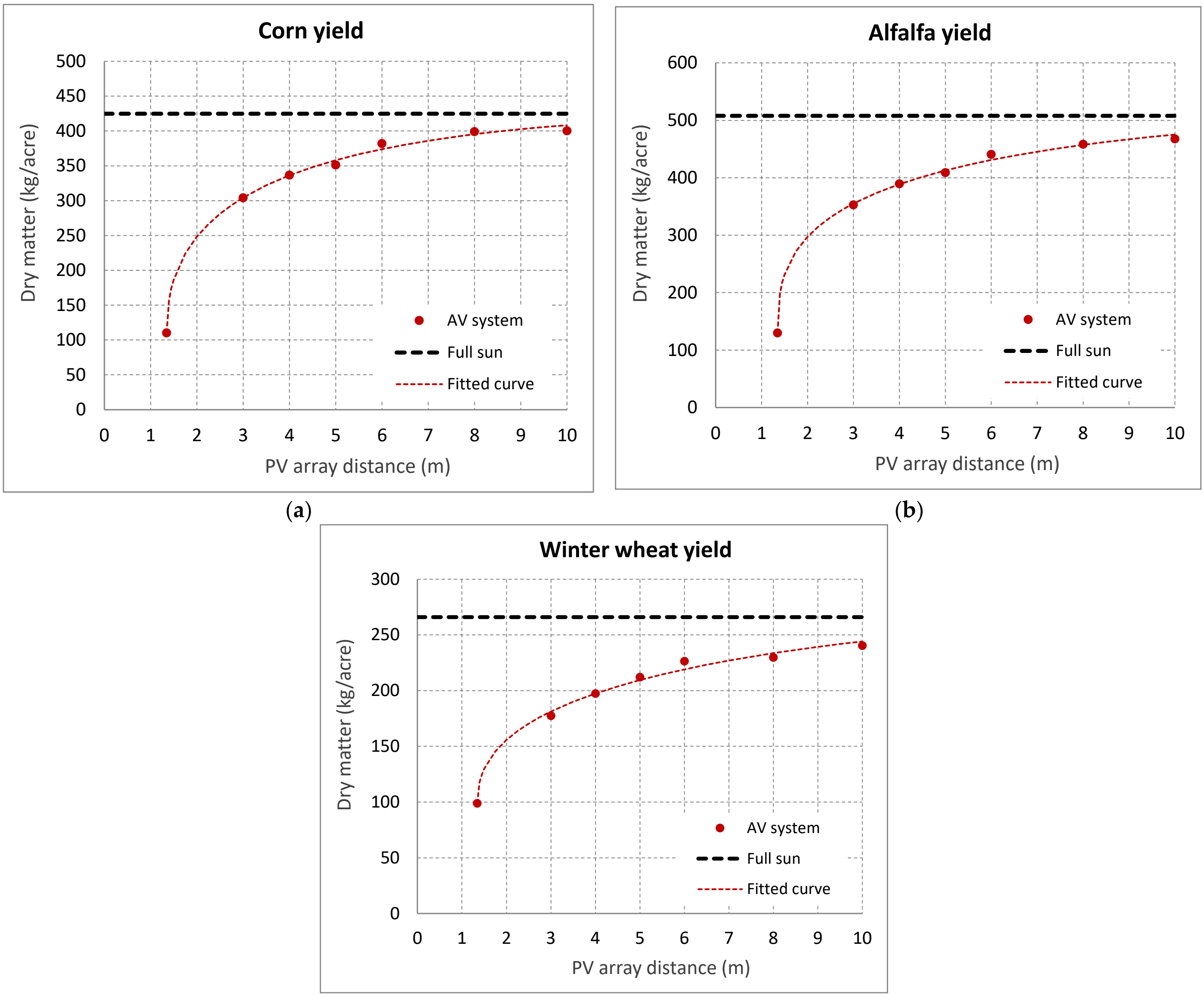
The outcomes of crop productivity analysis with respect to the PV array distance are summarized in Figure 5. For each crop, we contrast the estimated DMs under different shading conditions, due to the PV's layout, with their theoretical value under full-sun conditions. As the distance increases, the actual DM values tend towards the theoretical one, through a nonlinear relationship of the generic form:

$$\mathrm{DM} = \mathrm{DM}_{\min} + [1 - (1 - u^{a})^{b}]\,(\mathrm{DM}_{\min} - \mathrm{DM}_{\max}) \tag{3}$$

where $\mathrm{DM}_{\min}$ and $\mathrm{DM}_{\max}$ are the extreme values of dry matter under a full array density, and under full-sun conditions, respectively, u is the dimensionless distance, and a and b are shape parameters. Quantity u is estimated as

$$u = (d - d_{\min})/(d_{\infty} - d_{\min}) \tag{4}$$

where $d_{\min}$ = 1.345 m (full array density) and d_{∞} is a large enough distance, practically ensuring full-sun conditions. In our case, for convenience, we set d_{∞} = 20 m.



(**a**) (**b**) (**c**)

Figure 5. Impact of PV array distance on dry matter production for (**a**) corn; (**b**) alfalfa and (**c**) winter wheat, and fitting of empirical relationship (3).

The results for the three examined crops are summarized in Table 5. As shown in Figure 5, the empirical relationship (3) is fitted very well to the data, while its optimized parameters are given in Table 4.

Table 5. Impact of array distance on crop yield, in terms of dry matter (kg/acre).

Array Distance (m)	Corn	Alfalfa	Winter Wheat
1.345	110.5	129.8	98.9
3.0	304.2	352.9	177.5
4.0	336.8	389.6	197.4
5.0	351.4	409.0	212.1
6.0	382.1	440.7	226.4
8.0	399.2	458.2	229.8
10.0	400.6	467.8	240.3

Since the three crops have different growth periods and days of development, their productivity varies; thus, the optimal array distance is different for each crop.

6.5. Water Demand

The agricultural water demand is determined using two main pillars. The first one concerns the theoretical needs of each crop, which are the footprint of the combined effects of evaporation and transpiration, which are generally accounted for as a unique process, called evapotranspiration. In particular, plants receive water through their roots by means of rainwater, soil moisture and capillary action, thus absorbing the necessary nutrients and subsequently ejecting the remaining moisture through the transpiration process. In parallel, water evaporates from the soil and plants' surface. This process is highly influenced by the existence of PVs due to shadowing effects.

On the other hand, the second driver of agricultural demand is associated with water availability, which in turn depends on local hydroclimatic and soil conditions, irrigation management practices and associated technologies, as well as water losses across water conveyance and delivery networks. The development of AVs generally limits the range of applicability of irrigation practices to "drop by drop" methods, through micro-sprinklers. Additionally, all other aforementioned factors are not influenced by the existence of AVs.

In this respect, our analysis regarding the water component across the full nexus (i.e., water–energy–food–land) emphasizes the impacts of shadowing by AVs to the theoretical water needs of two of our examined crops, i.e., corn and alfalfa (by definition, winter wheat is not irrigated). In this vein, we utilize the FAO Penman–Monteith method [71], which introduces the key concept of crop evapotranspiration, which is estimated by the following:

$$\mathrm{ET}_c = k_c \times \mathrm{ET}_0 \tag{5}$$

where ET_0 is a climatic variable, called reference-crop evapotranspiration, and k_c is a crop coefficient, which depends on the specific crop type and the season.

In particular, ET_0 is defined as the evapotranspiration rate from a reference surface, covered with a hypothetical grass crop with specific properties, which resembles that of green, well-watered grass of uniform height, actively growing and completely shading the ground. The governing equations make use of local geographical information (latitude and elevation) as well as meteorological data, in terms of air temperature, relative humidity, solar radiation, and wind velocity. Table 6 summarizes the mean monthly values of ET_0 for different paned distances, and thus different solar radiation values due to shadowing effects. For convenience, we repeat calculations for full-sun conditions (infinite distance; last column).

Table 6. Impact of array distance on reference crop evapotranspiration.

	Panel Distance, *d* (m)							
ET_0 (mm)	1.345	3.0	4.0	5.0	6.0	8.0	10.0	Infinite
January	18.4	22.0	41.3	41.5	41.8	42.5	42.3	42.9

February	27.0	31.5	48.4	52.3	51.5	52.1	51.9	53.6
March	36.8	43.5	62.5	60.5	62.9	61.5	63.9	64.4
April	58.0	85.5	98.7	91.3	100.1	95.7	102.2	103.5
May	57.4	78.1	80.1	95.1	89.6	94.7	97.9	103.5
June	83.5	98.8	89.0	119.9	122.3	130.3	126.1	144.3
July	82.1	108.2	109.8	137.4	135.2	144.2	144.6	160.2
August	81.1	123.1	131.6	132.8	135.5	135.8	145.7	148.6
September	49.5	63.4	94.8	86.8	95.2	90.4	95.6	97.1
October	33.9	45.2	61.9	67.4	65.2	66.7	67.7	69.6
November	21.1	25.5	45.9	46.9	47.3	48.0	47.8	48.6
December	17.7	18.5	39.5	39.4	39.3	39.7	39.9	40.2
Annual	566.5	743.3	903.6	971.1	985.9	1001.6	1025.6	1076.6

Next, the reference crop evapotranspiration is multiplied by the crop coefficient, in order to determine the theoretical water needs of the two crops of interest (Table 7). Since alfalfa is a perennial crop, the impacts of seasonality are neglected; thus, the associated coefficient is considered constant, and equal to $k_c = 0.85$. Contrarily, corn's needs exhibit significant seasonal variability depending on its development stage. On the basis of FAO standards, we assign the following values:

- First stage (25 days): $k_c = 0.45$;
- Second stage (40 days): $k_c = 0.70$;
- Third stage (60 days): $k_c = 1.05$;
- Fourth stage (25 days): $k_c = 0.60$.

Table 7. Estimation of theoretical water needs per crop type, by means of potential evapotranspiration, for various AV layouts.

Distance (m)	Theoretical Water Needs, ET_c (mm/y)		
	Reference Crop	Corn	Alfalfa
1.345	566.5	264.4	481.5
3.0	743.3	354.9	631.8
4.0	903.6	365.7	768.0
5.0	971.1	421.7	825.5
6.0	985.9	427.0	838.1
8.0	1001.6	442.4	851.4
10.0	1025.6	450.9	871.8
Infinite	1076.6	487.4	915.1

The results indicate that at the maximum PV density (i.e., $d_{min} = 1.345$ m), the annual crop needs, in terms of potential evapotranspiration, are halved, which is a significant advantage of AVs from the perspective of water saving. However, for array distance values over 5 m, this change is not notable.

6.6. Overall Performance

In order to summarize the findings of our analyses, and quantify the conflicts between the four vital resources, i.e., water, energy, food and land, we estimate and contrast three dimensionless key performance indices (KPIs) against all examined distance values and three crops of interest (Table 8).

Table 8. Summary of the case study's key findings.

Array Distance (m)	PV Modules /Acre	Ground Coverage Ratio (GCR)	Land Equivalent Ratio (LER)			Water Saving Index (WSI)	
			Corn	Alfalfa	Winter Wheat	Corn	Alfalfa
1.345	276	0.37	1.260	1.256	1.372	0.458	0.474
3	156	0.21	1.281	1.260	1.232	0.272	0.310
4	123	0.17	1.240	1.214	1.189	0.250	0.161
5	102	0.14	1.197	1.175	1.167	0.135	0.098
6	87	0.12	1.215	1.183	1.167	0.124	0.084
8	67	0.09	1.184	1.146	1.108	0.093	0.070
10	55	0.07	1.142	1.120	1.102	0.075	0.047

The first index is the so-called ground coverage ratio (GCR, see Section 5.1.1), which accounts for the energy–food conflict in terms of the land portion occupied for energy production by AV's. We observe that if the panel cells are installed at the technically minimum distance of 1.345 m, the portion of occupied land is up to 37%, which is diminished to only 7% for the distance of 10 m.

The second KPI is the land equivalent ratio (LER, see Section 5.1.4), which is an overall productivity metric that evaluates the sharing of the same land by photovoltaic panels and crops. In our case, LER is function of distance, d, and crop type, i_c, which is estimated by the following:

$$\mathrm{LER}(d, i_c) = e^*(d)/e^*(d_{\min}) + \mathrm{DM}(d, i_c)/\mathrm{DM}(d_\infty, i_c) \tag{6}$$

where $e^*(d)$ is the energy yield per unit land cover (MWh/acre) of AV systems installed at distance d, and $\mathrm{DM}(d, i_c)$ is the dry matter associated with the crop type i_c. The two terms of eq. (6) are conflicting, while their maximum value is a unit. In particular, the first term is maximized at the minimum AV distance of 1.345 m, while the latter is maximized for full-sun conditions, and thus at the conventionally maximum distance, d_∞. It is remarkable that for winter wheat, LER is optimized at the minimum distance of cell panels, whilst for the other two crops this metric is marginally better at a distance of 3.0 m.

The last performance metric, herein referred to as the water saving index (WSI), is an original one, and attempts to introduce the water dimension within the overall assessment of AV's. This is defined as the relative reduction in theoretical crop needs, which are expressed in terms of crop evapotranspiration, with respect to full-sun conditions, i.e.,

$$\mathrm{WSI}(d, i_c) = [\mathrm{ET_c}(d_\infty, i_c) - \mathrm{ET_c}(d, i_c)]/\mathrm{ET_c}(d_\infty, i_c) \tag{7}$$

We remark that WSI is calculated only for corn and alfalfa, since winter wheat is a non-irrigated crop. From Table 8, it is evident that from the water-saving perspective, it is clearly beneficial to set the panels at their technically minimum distance. This outcome is in line with that of the productivity analysis using the LER index, thus highlighting that for the examined study area, the symbiosis of energy and food, through AV systems, is highly sustainable.

6.7. Issues of Uncertainty

The key objective of this proof of concept was the assessment of AV systems under the integrated prism of the water–energy–food–land nexus. Although the general findings were not surprising, the anticipated synergies and conflicts between the four components have been further justified, by providing quantitative estimations, in terms of graphs and KPIs.

Apparently, these estimations are subject to multiple facets of uncertainty that span all aspects of such systems. Following the rationale of Sakki et al. [72], these can be classified into two major categories, namely external and internal.

External uncertainties are associated with the four meteorological inputs, driving the calculations of the incoming solar power and evapotranspiration (solar radiation, relative humidity, wind speed and temperature). This kind of uncertainty originates from the inherent variability of the corresponding physical processes, which is impossible to be adequately interpreted in the small historical records of a few years that were used in this study. In fact, the more consistent approach with which to quantify external uncertainties is the stochastic simulation approach, which allows the generation of long-enough synthetic time series that reproduce the probabilistic properties of the parent data, thus representing their overall variability, and statistical dependencies as well, across multiple scales of interest (daily, seasonal, annual, and multi-annual, also referred to as climatic).

On the other hand, internal uncertainties refer to all kinds of conversions, which are represented through empirical formulas and models. These are subject to several assumptions, and they also make use of parameters derived from field experiments under site-specific conditions. For instance, in our study we employed such modelling approaches to convert the input meteorological drivers into PV power production (e.g., [73]), crop productivity (e.g., [74]) and irrigation needs, through the FAO Penman–Monteith method (e.g., [75]). A detailed analysis of all these individual sources of uncertainty and their propagation across the various system components is a challenging research target to be addressed.

7. Discussion

As the world's population continues to rise, water and food security and energy supply are greatly threatened. Agricultural production relies both on soil quality and water availability. The former depends on arable land, the availability of which may be out-competed by other uses, including energy production. On the other hand, water availability is often the critical element of agricultural development. However, in arid and semi-arid climatic areas, such as the Mediterranean ones, this factor is under significant stress, also due to the systematic degradation of groundwater resources, as result of over-pumping.

Lack of food and water security can lead to equity issues and loss of welfare for lower social classes [53]. In parallel, in an attempt to reduce the carbon footprint and mitigate climate change, there has been a global increase in the power capacity of renewable systems. This has raised concerns due to their extensive land use, especially regarding PVs.

With regard to all the aforementioned points, AV systems provide ample opportunities to achieve a sustainable energy–food combination, while also reducing irrigation needs. This dual land use outperforms separate production and enables synergistic techno-ecological and techno-economic effects, such as fulfilling the energy needs of agriculture, and a reduction in water requirements, due to the favorable shading conditions that reduce crops' evapotranspiration. We should remark that the development of crops under PV panels also contributes to cooler microclimate conditions, thus favoring their efficiency.

As also shown in our proof of concept, AV systems are subject to multiple complexities that span numerous techno-economic issues, and thus their rational design requires a transdisciplinary approach. For instance, panel siting and sizing, and crop type selection are crucial factors, as the combined land-use efficiency is heavily dependent on agricultural yield. AVs are more efficient in the south, due to higher solar insolation, and, thus, a higher capacity factor. Moreover, while shade-loving crops (e.g., leafy vegetables) exhibit higher yields in AV systems, some shade-intolerant crops have also been effectively tested [42]. Nevertheless, further experimental research is encouraged to determine the performance of various crop types [31].

Further improvisation is also required to maximize PV efficiency and, simultaneously, mitigate the contribution of PVs to overall landscape degradation. For instance, a dynamic tilt angle is recommended to account for optimal energy production during winter solstice and crop phenological stages during spring and summer [29]. The effectiveness of such designs can be investigated via modeling the heterogeneity of PV decisional dimensions through digital twins [76].

In a more general economic context, the investment cost of AV systems is relatively higher, compared to that of traditional PV configurations. However, this advanced technology offers positive environmental externalities that are difficult to account for in economic terms, since they provide an acceptable trade-off between land use and green energy. Most of the financial analyses performed focus on short-term outcomes, with little focus on the discounted cash flow [8]. The capital costs of the system's installation are expected to be fully depreciated within a time frame of less than five years [77–79]. To this end, it is essential to adopt an AV layout that maximizes energy production, with respect to crop development [80].

Finally, from a social perspective, landholders are hesitant to adopt AV systems due to the potential constraints imposed on future agricultural activities (i.e., loss of flexibility, land degradation and crop quality decline). Thus, it is essential to develop a policy framework to provide tentative solutions, viable recommendations and standard operating procedures to ensure the AV systems' wider social acceptance from key stakeholders.

8. Conclusions

Over the last years, AV systems have attracted increasing attention, due to their multidimensional benefits. In fact, they have the potential to become an essential and indispensable element of the water–food–energy–land nexus, since they are affiliated with all of its pillars.

In the present study, we implemented a comprehensive performance analysis for various AV system layouts and for three crops with different characteristics (in terms of shade tolerance, development time, irrigation needs, etc.). As a first step, we investigated the influence of several PV design variables such as the module height, tilt angle and array distance on the radiation reaching the ground. The clearly most decisive factor was found to be the array distance, which was then selected as the sole design quantity within our parametric analysis.

Next, we evaluated the multiple and multidimensional dependencies across the water–energy–food–land nexus, and quantified them by means of KPIs, applied for the three crops of interest. As expected, higher array densities work in favor of energy yield and, subsequently, against crop productivity, and vice versa. While these two major aspects of the system's performance seem conflicting, they are in fact synergistic, since they share the same resource, i.e., land. Therefore, in order to assess them from the synergy perspective, we applied a typical literature metric, i.e., the land equivalent ratio (LER), which accounts for their combined performance.

On the basis of LER values, winter wheat performs better in a combined AV system, since it seems to exhibit higher shade tolerance with respect to that of the other two crops (corn and alfalfa). However, we emphasize that a high LER does not necessarily indicate a combined system that produces both high energy and crop yield. For instance, a high LER value can derive from increased energy production yet low dry matter, and vice versa. Nevertheless, this index should be carefully interpreted when comparing different crops.

Another interesting find is that the two irrigated crops, i.e., corn and alfalfa, exhibit relatively small variability across quite different distance values, while the difference between the technical minimum distance of 1.345 m and the distance of 3.0 m is practically negligible. In order to ensure a clearer insight into the system's performance, we introduced the dimension of water, by means of a novel dimensionless metric, called the water saving index (WSI). By including this information in our comparative analysis, we concluded that, for the system in study, the full array density is the most favorable. In fact, apart from the increased land productivity, a full array density layout results in a significant decrease in evapotranspiration (more than 50% compared to that in individual agricultural crop fields), thus reducing crop irrigation needs.

Since the issue of irrigation water saving is of major importance in climate-stressed areas suffering from water scarcity, we strongly recommend integrating this crucial aspect into AV development studies. In this context, WSI can be applied as one of the fundamental KPIs within the techno-economic assessment of AV systems.

9. Patents

Not applicable.

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