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Comparison and Analysis Of Different Technologies for Agrivoltaic Systems

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Abstract

Since the early 1960s, the global population has doubled and is projected to reach 9.8 billion by 2050, intensifying the challenge of food security, a crisis further worsened by climate change. Rising greenhouse gas concentrations and increasing frequencies of droughts and extreme weather phenomena, pose significant risks to agricultural stability. While solar energy is a fundamental tool for the decarbonization of the economy and the green energy transition, traditional photovoltaic plants require extensive land areas, compared to other conventional energy technologies. In densely populated regions with scarce fertile land, this creates a direct conflict between energy and agricultural sectors. Agrivoltaic technology addresses this competition by integrating food production and energy generation on the same land unit. This thesis utilizes MATLAB to estimate the energy and crop yields of an agrivoltaic plant located in southern Italy through the development of a shading model. This study evaluates the performance of three distinct crop varieties, lettuce, tomato and grape, under the three primary agrivoltaic configurations: fixed tilted, fixed vertical and tracking panels. The simulated outcomes subsequently serve as the fundamental data for the analysis of the power plant's economic viability. By assessing the Land Equivalent Ratio (LER), the optimal system configuration is identified for each agricultural scenario. The results indicate that the configuration maximizing the LER while complying with Italian national regulations is the fixed tilted system for all crops. Specifically, at an inter-row distance of 6 meters, the LER reaches 1.558 for lettuce, 1.904 for tomato and 1.714 for grape. The corresponding economic analysis reveals that at this specific distance the Net Present Values (NPV) on a 30 years period oscillates between 3.5 M€ for fixed configurations and 4 M€ for tracking systems across all crop types. Notably, the data suggests that for row distances exceeding 8 meters, the vertical panel configuration becomes more economically advantageous than the other systems for all evaluated crops.

Keywords: Agrivoltaic, yield, MATLAB, modelling, simulation

Abstract in Lingua Italiana

Dall'inizio degli anni '60, la popolazione globale è raddoppiata e raggiungerà i 9,8 miliardi entro il 2050, intensificando la sfida della sicurezza alimentare, crisi ulteriormente aggravata dai cambiamenti climatici. L'aumento delle concentrazioni di gas serra e la crescente frequenza di siccità e fenomeni meteorologici estremi rappresentano rischi significativi per la stabilità agricola. Sebbene l'energia solare sia fondamentale per la decarbonizzazione dell'economia e la transizione energetica verde, gli impianti fotovoltaici tradizionali richiedono ampie superfici di terreno rispetto ad altre tecnologie energetiche convenzionali, creando potenzialmente un conflitto diretto con il settore agricolo. La tecnologia agrivoltaica affronta questa competizione integrando la produzione alimentare e la generazione di energia sulla stessa unità di terreno. La tesi utilizza MATLAB per stimare le rese energetiche e agricole di un impianto agrivoltaico situato nell'Italia meridionale, attraverso lo sviluppo di un modello di ombreggiamento. Vengono valutate tre diverse colture, lattuga, pomodoro e vite, nelle tre principali configurazioni fotovoltaiche: pannelli fissi inclinati, pannelli fissi verticali e pannelli a inseguimento solare. I risultati delle simulazioni costituiscono i dati di base per l'analisi economica dell'impianto. I risultati individuano il sistema fisso inclinato come la configurazione che massimizza il Land Equivalent Ratio (LER) nel rispetto della normativa nazionale italiana per tutte le colture considerate; in particolare, a una distanza tra le file di 6 m, il LER raggiunge valori pari a 1.558 per la lattuga, 1.904 per il pomodoro e 1.714 per la vite. L'analisi economica evidenzia che a tale distanza il Net Present Value (NPV) su un periodo di 30 anni oscilla tra 3,5 M€ per le configurazioni fisse e 4 M€ per i sistemi a inseguimento solare, per tutte le tipologie di colture analizzate. Inoltre, emerge che per distanze tra le file superiori a 8 m la configurazione con pannelli verticali diventa economicamente più vantaggiosa rispetto agli altri sistemi per tutte le specie vegetali.

Parole Chiave: Agrivoltaico, resa, MATLAB, modellazione, simulazione

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Introduction

The European Union transition toward sustainable energy systems is increasingly defined by the necessity to reduce fossil fuel dependency and mitigate greenhouse gas emissions. The EU has established a rigorous policy framework to guide this transition, by setting the energy and environmental targets for 2030. In particular, a minimum 40% reduction in net greenhouse gas emissions with respect to 1990 levels, a 32% contribution of the renewable energy in total gross final consumption and a 32.5% saving on the energy consumption with respect to future projections on the energy consumption are expected to be achieved by the target year [1]. These objectives were further intensified following the *REPowerEU* plan in 2022 that increased the 2030 renewable energy target to 42.5% [2]. This policy shift necessitates a substantial increase in renewable energy penetration in the energy mix of all European countries [2].

In this context, the rapid evolution of solar photovoltaics, characterized by high modularity and significantly reduced costs, has positioned solar energy as one of the most adopted renewable energy technology. However, the expansion of traditional ground-mounted photovoltaic systems frequently leads to land-use concerns and often conflicts with traditional agricultural land use, due to the low power density and the consequent occupation of large areas [3].

To address the competing demands for food and energy, agrivoltaics has emerged as an innovative strategic solution that generates clean electricity and maintains agricultural productivity. While the practice of co-locating solar panels with crops dates back to 1981, contemporary research indicates that agrivoltaics offers a much broader perspective, extending its deployment with livestock management and aquaculture [4]. This dual-use strategy enhances land-use efficiency and improves crop yields by creating a beneficial microclimate. The shade provided by solar panels reduces soil temperatures, which aids in moisture retention and supports microbiological lifeforms essential for crop growth [4].

The transition to large-scale agrivoltaics has several challenges, as reported by [3]. It requires technological advancements and robust governmental support to balance rising energy demands with stable agricultural yields. Current market barriers include higher costs in terms of installation, supporting structures and maintenance, compared to conventional ground-mounted system and potential social acceptance issues if agricultural activities are deemed insufficient. Regulatory difficulties also persist due to unclear land-use status in many jurisdictions. Nevertheless, as technology advances and global awareness of the economic, environmental and social benefits of integrated systems increases, agrivoltaics is expected to play a vital role in the global transition toward more sustainable and resilient energy and agricultural infrastructures.

1 Photovoltaic Technology Operating Principles

1.1 Solar Energy

Solar energy is generated by fusion reactions inside the core of the Sun where four hydrogen (H) atoms are fused into one helium (He) atom, converting mass into energy. The power generated by Sun is equal to 3.845×10^{20} MW and the corresponding power density is 6.33×10^7 W/m²; however, the average power density that reaches the outer layer of the Earth's surface is 1367 W/m², due to the distance between Earth and Sun, that varies throughout the year [5].

The solar radiation is then attenuated by the interaction with the atmosphere that consist in the absorption by water, carbon dioxide and ozone and in two main scattering effects; in particular, particles much smaller than the light's wavelength, such as oxygen and nitrogen are responsible for the Rayleigh scattering, while large particles, such as water droplets and dust, are responsible for the Mie's scattering [5].

The cloudiness strongly affects the solar spectrum as well; in fact, the amount of radiation attenuated by the clouds depends on the type of clouds and their density: the denser and darker is the cloud the higher the attenuation effect [5].

Lastly, the tilt of the Earth relatively to the direction of solar radiation plays a key role as well; in fact, as Figure 1.1 shows, when the sun is directly overhead the local surface normal is parallel to the direction of the solar radiation that thus is spread over a small area. The opposite occurs when the Sun is not directly overhead, spreading the solar radiation over a large area [6].

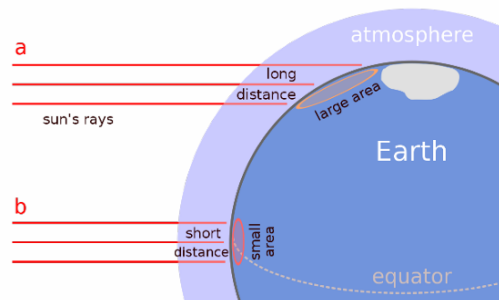


Figure 1.1: Sun radiation at different latitudes [6]

Overall, due to the orbit of the Earth, the declination angle changes throughout the year, leading to the seasonal changes in solar radiation and the cycling of seasons [6].

As Figure 1.2 shows, in tropical regions where the Sun is nearly vertical in the summer irradiance values are high. By contrast, in the polar regions where the Sun elevation is low even in summer mean solar radiation levels are low or moderate [5].

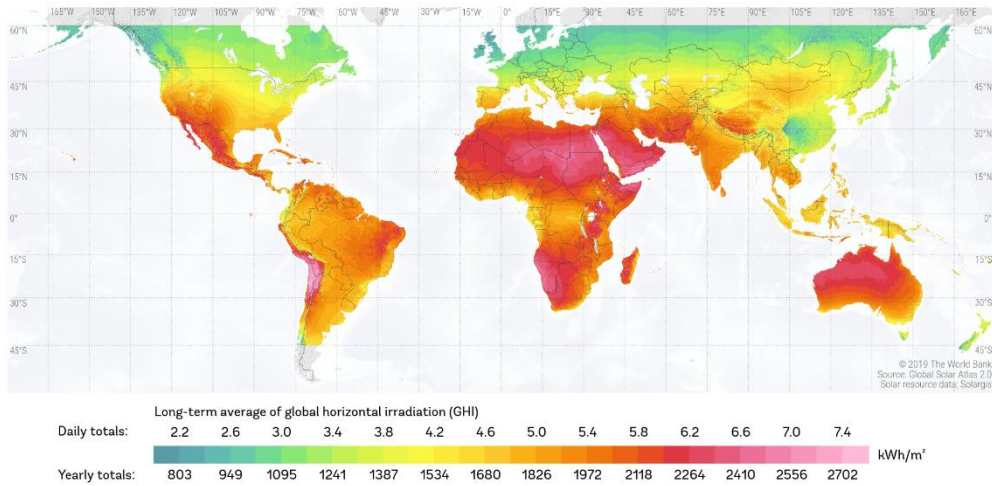


Figure 1.2: Global solar radiation. Source: Global Solar Atlas [7]

Due to the combination of these phenomena the average solar radiation at the sea level is 1000 W/m^2 according to [5]; these effects influence the solar radiation spectrum as well, as shown in Figure 1.3.

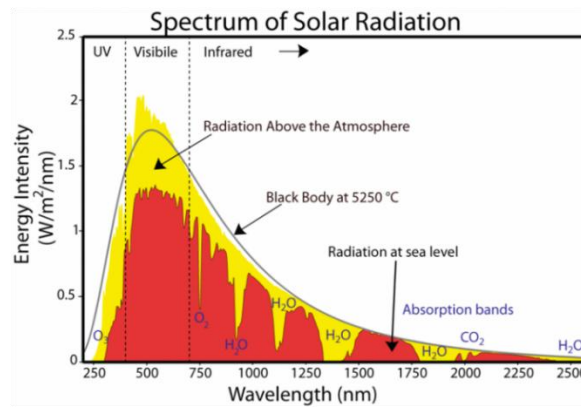


Figure 1.3: Solar spectrum [5]

The same shows that half of the solar radiation spectrum falls in the visible spectrum (380-780 nm), while the other half consists of infrared radiation (790-2500 nm), with a small fraction of ultraviolet radiation (200-380 nm). The sudden drops in the spectrum are caused by the absorption from different molecules, mainly water (H_2O) and carbon dioxide (CO_2) [5].

The previous analysis shows that the irradiance reduces significantly, while travelling across the atmosphere. Therefore, the Air Mass (AM) coefficient is defined by Equation (1), that represents length of the direct beam path along the atmosphere, compared to a vertical path at sea level [8].

$$AM = \frac{1}{\sin(\theta_z)} \quad (1)$$

In this same equation, θ_z is the zenith angle that is the angle between the Sun and a line perpendicular to the Earth's surface directly above the observer. So, when the Sun is directly overhead, the zenith angle is 0° and thus the maximum solar power is obtained, whereas as the Sun descends toward the horizon, the zenith angle increases and the solar power decreases [8].

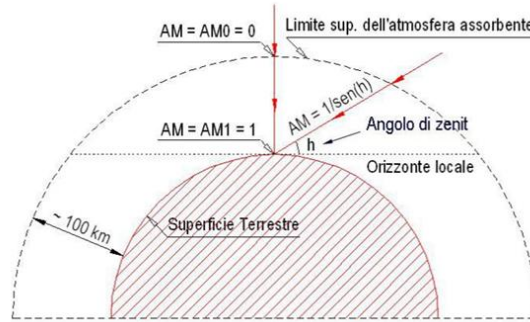


Figure 1.4: Air Mass [8]

In Figure 1.4, AM0 represents the absence of the atmosphere and AM1 indicates the standard atmosphere thickness crossed by the sun's rays in a direction perpendicular to the Earth's surface and measured at sea level.

According to [5] and [8], the radiation hitting an tilted surface can be divided in 3 main components: the direct radiation is the solar radiation received from the sun without being scattered by the atmosphere. The second component is the diffuse radiation that is the solar radiation from the sun after its direction has been changed by atmospheric scattering. Lastly, the albedo is the radiation reflected due to the ground or the surrounding environment. Equations (2), (3) and (4) report the calculation of the three contributions respectively whose sum gives the total radiation.

$$G_{dir} = DNI * \cos\theta \quad (2)$$

$$G_{diff} = DIFF * \frac{1 + \cos\beta}{2} \quad (3)$$

$$G_{diff} = GHI * \rho_g * \frac{1 - \cos\beta}{2} \quad (4)$$

In the previous equations, the Direct Normal Irradiance (DNI) is the solar flux density received by a surface maintained perpendicular to the solar beams, $DIFF$ is the diffuse radiation and GHI is the Global Horizontal Radiation. θ is the incidence angle derived via Equation (13) and β is the surface tilt angle which denotes the inclination of a generic surface relative to the horizontal plane. Lastly, ρ_g is the reflectivity of the ground.

Each material is characterized by a different albedo coefficient that describes the capacity to reflect light. For a fixed material, this value is not a constant, but it depends on the spectral and angular

distribution of light; therefore, it depends on atmospheric conditions, such as sunny or cloudy, and on the Sun position. Some typical values are reported by [9] and [8], summarized in Table 1.1.

MATERIAL	ALBEDO COEFFICIENT
Grass	0.15 –0.26
Snow	0.55 –0.98
Asphalt pavement	0.09 –0.18
Concrete pavement	0.20 –0.40
Aluminium	0,85
Copper	0,74
Urban environment	0,14-0,22

Table 1.1: Albedo coefficient [8], [9]

1.2 Solar Geometry

The design of any photovoltaic system requires a thorough understanding of the solar geometry that defines the Sun's apparent position in the sky relative to a specific location on Earth, at a given time of day, date, and latitude. As Figure 1.5 depicts, any position on the Earth surface can be univocally described by a set of geographical coordinates: latitude and longitude.

The latitude indicates whether the point lies north or south with respect to the Equator. Since the latter divides the Earth in two equal hemispheres, the latitude ranges between 0° at the Equator and 90° North or 90° South at the relative Poles, changing from one parallel to another. From a geometrical point of view, the latitude is the angular distance measured along the meridian between the Equator and the parallel passing through the point of interest [6].

On the other hand, the longitude indicates whether a location lies east or west with respect to the Greenwich meridian. Consequently, the longitude ranges from 0° to 180° East and from 0° to 180° West, changing from one meridian to another. From a geometrical point of view, the latitude is the angular distance measured along the parallel between the Greenwich meridian and the one passing through the considered point [6].

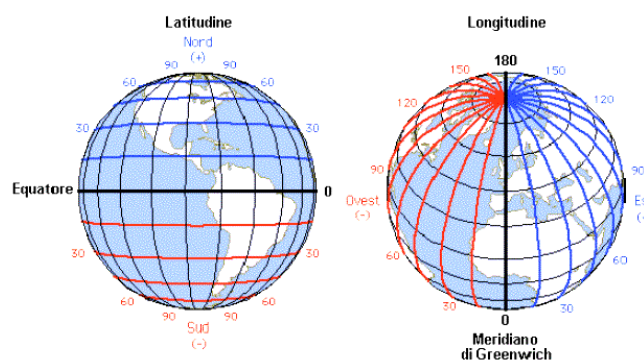


Figure 1.5: Latitude and Longitude schemes [6]

The position of the Sun is described by two fundamental angles. The first one is the solar zenith angle (θ_z), defined as the angle measured between the local vertical of the observer and the line connecting the observer to the Sun. When the Sun is directly overhead the zenith angles is 0° and, as the Sun descends towards the horizon, it increases up to 90° . It is the complement of the solar altitude (α_s), which is the angle between the horizontal plane and the line to the Sun [6]. The zenith angles and its complement can be calculated with Equations (5) and (6).

$$\cos\theta_z = \sin\delta * \sin\phi_{lat} + \cos\delta * \cos\phi_{lat} * \cos\omega = \sin\alpha_s \quad (5)$$

$$\theta_z = 90 - \alpha_s \quad (6)$$

The second one is the solar azimuth angle (γ_s) that is the horizontal angle from a cardinal direction, most commonly north or south [6]. Equation (7) reports its formula.

$$\cos\gamma_s = \frac{\sin\alpha_s * \sin\phi_{lat} - \sin\delta}{\cos\alpha_s * \cos\phi_{lat}} * \text{sign}\phi_{lat} \quad (7)$$

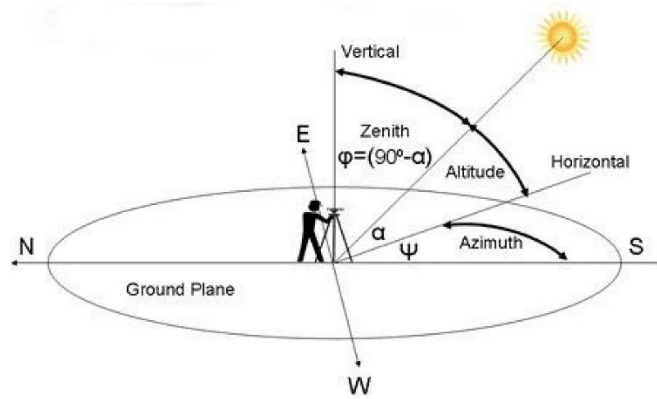


Figure 1.6: Solar geometry scheme [6]

The equations for the calculation of the zenith and azimuth angles require the knowledge of the location's latitude ϕ_{lat} , the hour angle ω and the declination angle δ .

The hour angle, defined via Equation (8) is the angular distance between the meridian of the observer and the meridian whose plane contains the sun: it is zero at solar noon and increases 15° every hour positively westward [6].

$$\omega = 15 * (t_s - 12) \quad (8)$$

t_s is the solar time that is based on the 24-hour clock, with 12:00 as the time when the sun is exactly pointing south. It differs from the local time, because the local time refers to the reference meridian for the selected Standard Time Zone (STZ) and the rotational speed of the Earth varies during the year due to the eccentricity of the Earth's orbit and the obliquity of the ecliptic [6]. The solar hour can be calculated with Equation (9).

$$t_s = t + \frac{\phi_{long} - \phi_{STD}}{15} + \frac{E_n}{60} \quad (9)$$

In the previous equation, t is the local time, ϕ_{long} is the observer longitude and ϕ_{STD} is the longitude of the STZ reference meridian, defined via Equation (10).

$$\phi_{STD} = STZ * 15 \quad (10)$$

Lastly, through Equation (11), the Equation of Time (E_n) describes the discrepancy between the apparent solar time, which directly tracks the diurnal motion of the Sun, and mean solar time, which tracks a theoretical mean Sun with uniform motion along the celestial equator. The apparent solar time can be obtained through the measurement of the current position of the Sun, as indicated by a sundial, while the mean solar time is the time indicated by a steady clock set so that over the year its difference from the apparent solar time has a mean of zero [6].

$$E_n = \left(0.000075 + 0.001868 * \cos\left(360 \frac{n-1}{365}\right) - 0.03277 * \sin\left(360 \frac{n-1}{365}\right) - 0.014615 * \right. \\ \left. * \cos\left(2 * 360 \frac{n-1}{365}\right) - 0.04080 * \sin\left(2 * 360 \frac{n-1}{365}\right) \right) \quad (11)$$

In Equation (12), the declination angle (δ) is the angle between the equator and a line drawn from the centre of the Earth to the centre of the Sun. This angle varies seasonally due to the tilt of the Earth's rotation axis and the rotation of the Earth around the Sun [6].

$$\delta = 23.45 * \sin\left(\frac{360}{365}(n + 284)\right) \quad (12)$$

In the Equation of Time and in the declination angle formula, n is the number of the day from 1 to 365.

Figure 1.7 illustrates the annual variation of the declination angle. It is equal to 0° in the vernal and autumnal equinoxes, increase to the maximum value of $+23.45^\circ$ in the summer solstice and decreases to the minimum value of -23.45° in the winter solstice.

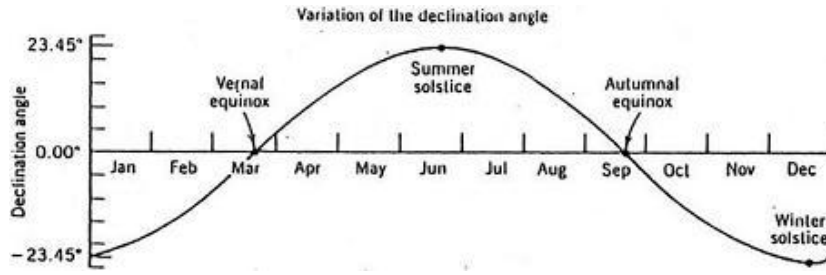


Figure 1.7: Declination Angle yearly variation [6]

Knowing the complete solar geometry, it is possible to calculate the incidence angle of the direct solar radiation hitting a surface.

$$\cos\theta = \cos\theta_z * \cos\beta + \sin\theta_z * \sin\beta * \sin\gamma_s \quad (13)$$

1.3 Photovoltaic Cell Operating Principles

A photovoltaic (PV) module is a device able to directly convert the sunlight into direct current (DC) electricity, through the photovoltaic effect. The most common PV technology is the first-generation one that includes the mono-crystalline silicon multi-crystalline silicon PV panels. The second-generation technology is based on the same physical principles, but adopts different materials, such as amorphous silicon and Cadmium telluride (CdTe) [8].

In a pure crystal, the electrons bonded in the covalent bonds to other atoms are in an energy state of valence band, whereas the electrons free to move through the material are at an energy state of the conduction band where they can generate an electric current [8].

As shown in Figure 1.8, E_v is the maximum energy level in the valence band, while E_c is the minimum energy level in the conduction band. Their difference $E_g = E_c - E_v$ is the band gap energy, necessary for an electron to break the covalent bond and reach the conduction band [8].

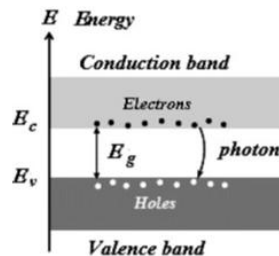


Figure 1.8: Band gap [8]

Electrons do not have the energy required to overcome the band gap and switch to the conduction band; however, when a photon hits the semiconductor, it interacts with the electrons causing their excitation. Only if the photon energy E_f is higher or equal than E_g , the electron is able to leave the covalent bond and jump to the conduction band, creating a hole in the valence band and therefore an electron-hole pair [8].

In a pure crystal, the rapid recombination of electron-hole pairs prevents the sustained flow of current. To overcome this, the crystal's conductivity is engineered through a doping process, where specific impurity atoms are introduced into the lattice [5].

Considering the silicon (Si) atoms, the impurities, which possess a number of valence electrons different from four, replace the silicon atoms in the structure, creating either an excess of free electrons or holes [5].

In a p-doped semiconductor, boron (B) atoms which have only three valence electrons are introduced. When a boron atom bonds with the surrounding silicon atoms, it creates a vacancy that can accept an electron. As nearby electrons move to fill these holes, they create new holes at their original positions, resulting in an excess of holes that behave as positive charge carriers [5].

Similarly in a n-doped semiconductor, silicon atoms are replaced with phosphorous (P) atoms that have five valence electrons. Four electrons bond with neighbouring silicon atoms, while the fifth one becomes a free electron available for electrical conduction [5].

As Figure 1.9 shows, by placing p-type silicon in contact with n-type silicon, a PN junction is created, that prevents the recombination of the electron-hole pairs and makes the electrons available to the external circuit, operating as a diode [5].

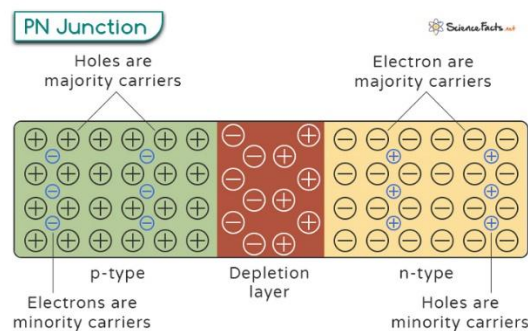


Figure 1.9: PN junction [5]

Near the PN junction, electrons diffuse from n-doped side to the p-doped side, while the holes diffuse in the opposite direction. As a result, free electrons and free holes recombine and balance the electric charge, forming the depletion layer where only the fixed charges remain; in particular, in the depletion layer, only the fixed electrons remain in the p-doped side, obtaining an excess of negative charges, and similarly for the n-doped region the fixed vacancies accumulate, creating an excess of positive charges [5].

Overall, the fixed electric charges' distribution generates an electric field. If a negative external voltage is applied to this field, the depletion layer narrows, favouring the current flow (forward bias). In contrast, if a positive external voltage is applied, the depletion layer enlarges, blocking any current flow (reverse bias) [5].

When the cell is exposed to sunlight, its energy generates electron-hole pairs. The electric field of the PN junction separates the negatively charged electrons from the positively charged holes, driving them in opposite directions. This movement of charge creates a current that flows through the external circuit [5].

However, not all the incident solar radiation is useful for the conversion process [8]. The Equation (14) shows that the photon energy E_f is inversely proportional to its wavelength λ .

$$E_f = \frac{hc}{\lambda} \quad (14)$$

As a result, photons with energy lower than the material's band gap E_g can not generate electron-hole pairs, while the photons with energy significantly exceeding E_g do contribute, but the excess energy is dissipated as heat [8]. Figure 1.10 shows that for the silicon the maximum wavelength needed is 1150 nm, beyond which the photons are not able to drive the conversion process.

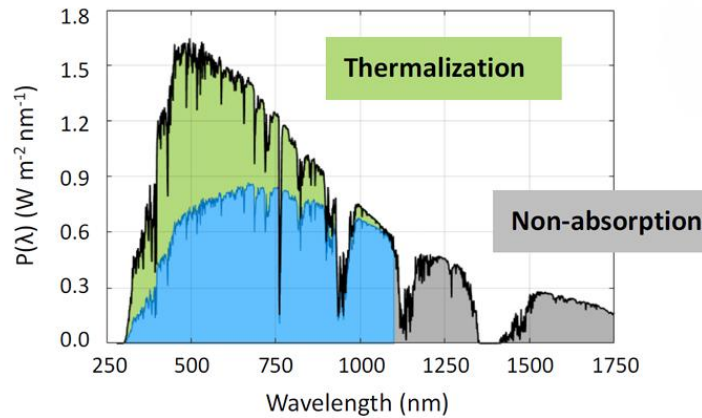


Figure 1.10: Bandgap of crystalline silicon [8]

1.4 Photovoltaic Cell Structure and Organization

A PV module consists of several interconnected solar cells encapsulated into a single, long-lasting and stable unit, with the aim to protect them and their interconnecting wires from the surrounding environment. In fact, solar cells are prone to mechanical damage, since they are relatively thin and the electrical wires may be corroded by water or water vapor.

According to [5] and [8], the most common modules have either 60 cells or 72 cells with three bypass diodes: 60 cell modules were originally designed for residential applications, while 72 cell modules for large utility installations. The lifetime of a PV module can exceed 20 years, guaranteeing that the module produces 90% of its rated output for the first 10 years and 80% of its rated output up to 25 years.

Most Si PV modules include a transparent top surface made of glass, an EVA (ethyl vinyl acetate) encapsulant and the rear layer is made Tedlar, as shown in Figure 1.11.

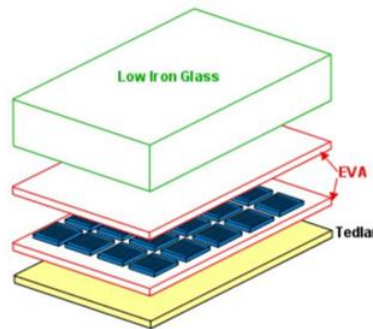


Figure 1.11: PV module structure [5]

In most modules the front surface is used to provide the mechanical strength and rigidity and thus it is usually made of acrylic, polymers and glass [5], [8]. Low-iron content tempered glass is typically adopted thanks to its low cost, stability, strength, high transparency and resistance to water and gasses.

Moreover, the front surface of a PV module must have a high transmission in the wavelengths 350 nm to 1200 nm that are useful for the solar cells. To minimize the reflection from the front surface, anti-reflection coating can be applied, or the surface can be made rough or textured; however, the first solution is not suitable for harsh environmental conditions, while the second one tends to collect more easily dust and dirt that would reduce the performance of the device [5], [8].

An encapsulant made of EVA is used to provide adhesion between the top surface, the solar cells and the rear surface of the PV module. The encapsulant should be stable at elevated temperatures and high UV exposure. It should also be optically transparent and should have a low thermal resistance [5], [8].

The rear surface is a thin polymer sheet, typically Tedlar, with a low thermal resistance, that must prevent the infiltration of water and water vapor. A final structural component of the module is the framing of the module, typically made of aluminium. The frame structure should be free of projections which could result in the lodgement of water, dust or other matter [5], [8].

Partial shading of a single cell severely reduces the current output of the entire module, as the series connection forces the current to be limited by the weakest-performing cell [10]. This leads to a significant power loss. More critically, the shaded cell, unable to produce the same current as the others, can be driven into reverse bias. In this state, it ceases to act as a generator and instead dissipates electrical energy as heat, potentially creating a destructive hotspot. To mitigate these issues, bypass diodes are connected in parallel across groups of cells within the module. Their function is to protect

non-operating cells by providing an alternative path for the current, isolating underperforming sections. The series connection of cells with the by-pass diode technology is shown in Figure 1.12.

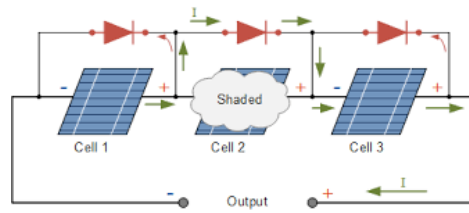


Figure 1.12: Bypass diode and shaded cell [10]

Several modules connected in series form a string that achieves the nominal voltage. A blocking diode is inserted in series to each string, to prevent reverse current flow if the power output of the individual strings is not balanced [10]. Finally, multiple strings are then connected in parallel to sum their currents and thus achieve the desired power output. The arrangement of the string is represented in Figure 1.13.

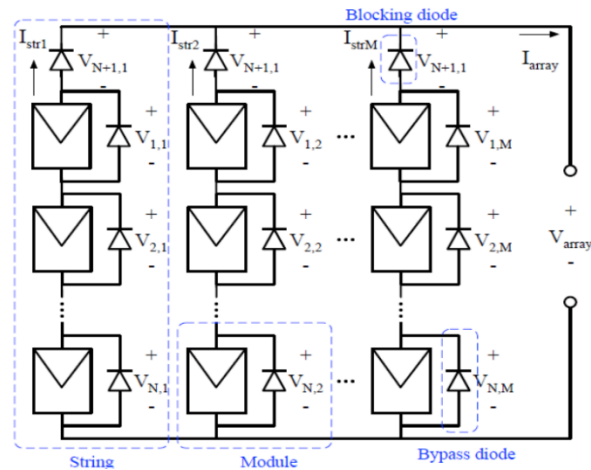


Figure 1.13: Connection of strings in parallel with bypass and blocking diodes [10]

1.5 Photovoltaic Module Characteristic Curve

The electrical behaviour of solar cells is represented by the current-voltage (I-V) and power-voltage (P-V) curves, depicted in Figure 1.14. The P-V curve is derived directly from the I-V curve by calculating the product of current and voltage at each point.

The I-V curve shows two operational extremes: the open-circuit voltage (V_{oc}), which is the maximum voltage at zero current, and the short-circuit current (I_{sc}), which is the maximum current at zero voltage; however, since power is the product of voltage and current, the power output at these two points is zero. Between them lies a specific operating point, the maximum power point (MPP), where the power output reaches its highest value for a given radiation intensity.

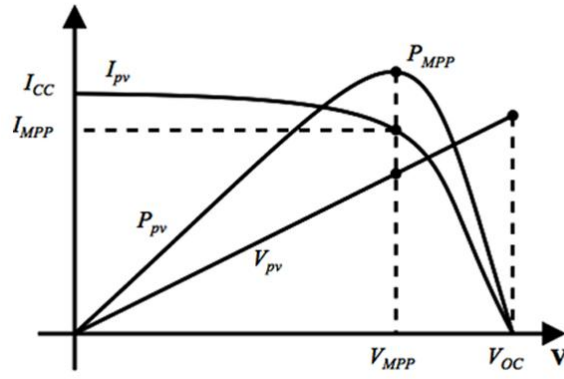
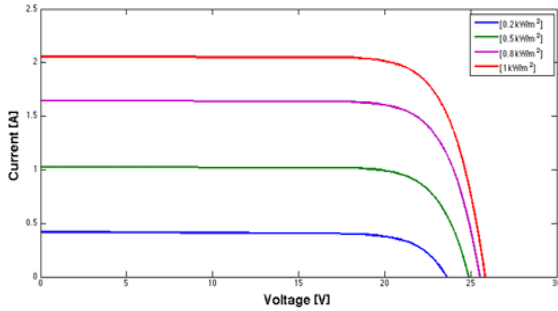
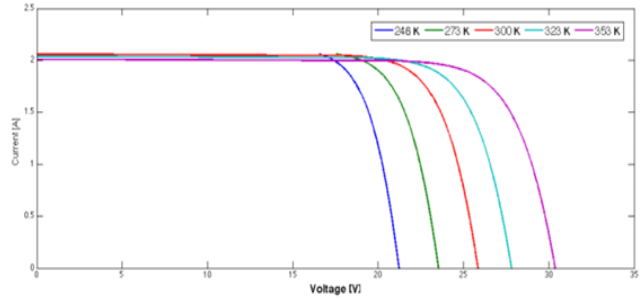


Figure 1.14: I-V and P-V curves [5]

As depicted in Figure 1.15.a and Figure 1.15.b , these curves are dynamic, as the current and thus short-circuit current are mainly influenced by the solar irradiation level, whereas the voltage and consequently the open-circuit voltage are predominantly influenced by the cell temperature. As a result, the position of the MPP is not fixed but shifts with changes in environmental conditions [5]. The effects of the ambient conditions on the electrical parameters are reported in Equations (15) and (16).



a) I-V curve at different solar irradiance values



b) I-V curve at different cell temperatures

Figure 1.15: I-V curve dependence on solar irradiance and cell temperature [5]

$$I_{sc} = I_{sc,ref} * \frac{G}{G_{ref}} * \left(1 + \alpha * (T_c - T_{c,ref})\right) \quad (15)$$

$$V_{oc} = V_{oc,ref} * \left(1 + \beta * (T_c - T_{c,ref})\right) + A * \ln\left(\frac{G}{G_{ref}}\right) \quad (16)$$

G is the solar radiation on the panel, G_{ref} is the reference solar radiation on the panel equal to 1000 W/m^2 , α and β are temperature coefficient for the short-circuit current and open-circuit voltage respectively that are reported on technical data sheet of the PV module.

Equation (16) shows a limited variation of the open-circuit voltage with the irradiance expressed by the logarithm. However, the A parameter is usually not available in the datasheet and therefore this aspect is neglected.

Equation (17) indicates that the cell temperature (T_c) depends on the ambient temperature (T_{amb}) and on the solar radiation (G).

$$T_c = T_{amb} * \left(\frac{NOCT - 20}{800} \right) * G \quad (17)$$

$NOCT$ is the Nominal Operating Cell Temperature, defined in specific conditions summarized in Table 1.2

PARAMETER	VALUE
Temperature (T_{NOCT})	20 °C
Solar radiation (G_{NOCT})	800 W/m ²
Wind speed	1 m/s
Air Mass	1.5

Table 1.2: Summary of the NOCT conditions. Source: PVsyst documentation [11]

As the short-circuit current and the open-circuit voltage, Equation (18) shows that the efficiency of the PV module (η_{PV}) deviates from the nominal conditions, as the environmental conditions change [5].

$$\eta_{PV} = \eta_{stc} * \left(1 + \beta * (T_c - T_{ref}) \right) \quad (18)$$

2 Agrivoltaic Technology Overview

Conventional photovoltaic plants are space-intensive, creating conflicts for the use of arable land for agricultural production. When biomass is utilised for energy generation, there is a risk of triggering competition between food production and energy production, as there is insufficient arable land to meet both demands.

Agrivoltaic systems (AVS) represent an innovative and synergistic approach to integrate agricultural productivity environmental sustainability and renewable energy generation, addressing critical challenges posed by resource scarcity and increasing energy demand.

The use of arable land for both AVS and food production represents a new way of farming and potentially overcomes the competition between food and energy production. Moreover AVS, by utilising excess radiation, can generate additional income for agricultural enterprises through continuous energy

production. This energy can be directly utilised in operational processes or sold back to the grid, thereby increasing the potential profitability of the plot. According to [12], the integration of agriculture and PV energy production can improve the net profits from 30 to 132 times, depending on the specific site conditions, compared to agriculture alone.

However, as stated by [13] and [14], the limited number of existing structures has restricted their adoption in agricultural enterprises, partly due to high installation costs, regulatory restrictions, and negative perceptions among farmers. Standardised models must be developed to integrate innovative farming technologies into agricultural enterprises, but there is no consensus in the scientific literature on standardised approaches for building these structures, raising concerns about structural safety.

2.1 Classification

AVS can be classified in different ways, considering the application, system organization, type of farming, photovoltaic structure. According to [15] and [16], the first classification is based on the application type, whether used for agriculture (agrivoltaics) or livestock (rangevoltaics); the second classification is based on the system type, which can be open (open field) or closed (greenhouses) for both applications.

Open AVS are installed with multiple spatial configurations and with varying degrees of integration, to maximise the productive synergy of the system (energy and food). From a configuration perspective, open AVS comprise photovoltaic modules, supporting structures and free space between and under the modules. The structures are installed to accommodate agricultural activities or other additional activities through the creation of a porous space an area where modules are absent.

Given the excessive amount of sunlight during the summer season, solutions to increase shading and reduce internal greenhouse temperature have been adopted, as cultivation could not continue otherwise. The installation of photovoltaic panels on greenhouse roofs for cultivation represents the closed agrivoltaics systems, where the panels can be arranged in a single array or in a checkboard pattern on, with partial photovoltaic coverage.

Agrivoltaics systems can be also categorized based on the agricultural practice they support: field agriculture for crops like wheat and rice, or orchard agriculture for fruits like apples, peaches, and grapes. These two categories have distinct needs, which directly influence the system's design. In field agrivoltaics, PV panels are installed also on supports near the ground or on high structures (4-6 meters) with significant clearance between rows to guarantee access for heavy machinery. Figure 2.1 shows typical arrangements of AVS for field agriculture

In orchard-based agrivoltaics systems, solar panels are typically installed on overhead structures that tower above the tree canopy. This design not only generates clean energy, but it also protects the crops from environmental phenomena such as hail and strong winds. As an alternative configuration, the panels can also be positioned in the lanes between tree rows. Figure 2.2 shows AVS for orchard agriculture.

The photovoltaic structure can be dynamic through a solar tracking system, allowing a better control of the microclimate under the photovoltaic panels, or static, with lower operating costs compared to dynamic structures.



Figure 2.1: AVS field agriculture [15]



Figure 2.2: AVS orchard agriculture [16]

2.2 Agrivoltaic Technologies

2.2.1 Fixed Tilted Panels

For fixed panels configuration, low height structures (less than 2 m of clearance height) are preferred because of their lower cost than stilted agrivoltaics and of the microclimate underneath the solar modules, so that crops can grow in between the rows of PV arrays or below the modules depending on the height of the plants and light requirements. Therefore, the area below modules may be exploited for shade-tolerant species [17].

The studies [18], [19] and [20] in this regard have already been carried out in India and Malaysia for testing species such as java tea, aloe vera or spinach (Figure 2.3.a and Figure 2.3.a), achieving higher crop yields for herbal plants while at the same time reducing the module temperature of 0.85% which may increase the annual energy production of 2.8%.

According to [21], one of the main drawbacks of fixed AVS is the lack of panel modulation, which results in several disadvantages: fixed panels do not allow for adjustable light exposure, resulting in static shading throughout the day and thus to permanent shading zones. This is particularly problematic for crops requiring direct solar radiation to optimise photosynthesis; in fact, different growth stages (germination, vegetative growth, flowering, and fruiting) require varying light exposure levels. Fixed panels cannot adjust their shading to match these requirements, which reduces yield and quality of the

agricultural products. Lastly, static shading can create high-humidity zones, favouring the development of fungal pathogens.



a) India [19]



b) Malaysia [20]

Figure 2.3: Research pilot plant with low height PV panels



Figure 2.4: Fixed panels AVS [20]

Overall, even though fixed photovoltaic panels provide advantages in terms of lower installation and maintenance costs, they offer lower adaptability to different plant phenological stages and system's management flexibility, promoting the development of shade-tolerant species and negatively affecting the yield of crops with high light demands [21]. Additionally, although they ensure a stable energy output, their efficiency remains lower than that of dynamic panel systems.

2.2.2 Tracking Panels

On the other hand, tracking AVS offer the ability to modulate photovoltaic panels or the entire system, based on the physiological needs of specific crops in response to climatic conditions; in fact, [22] shows that through the active shading regulation the panels provide greater light availability during critical physiological stages (e. g., vegetative growth and flowering) and increase shading during periods of high thermal stress, thereby reducing excessive solar exposure and improving photosynthesis.

Experimental data from [22] indicate that crop-tailored tracking systems may lead to a 35 % reduction in average shading compared to fixed panels helps maintaining optimal growth conditions, sustaining optimal photosynthetic activity and enhancing fruit size and uniformity in grapevines, strawberries and berries. Moreover, tracking AVS enhance energy yield by up to 30 %, significantly improving the overall productivity and profitability of the installation, although they entail higher installation costs, typically between 30% and 40% more than fixed panels configuration.



Figure 2.5: Tracking panels [22]

2.2.3 Fixed Vertical Panels

For open field AVS, vertical installations with bifacial PV modules facing east and west are used, leaving the areas between the rows (about 10 m) for agriculture. As documented by [23] and [24], this configuration creates a more uniform shade pattern, providing more consistent and uniform light levels for crops across the farm; in fact, the light availability across the farm varies within a much small range, preventing the creation of continuously shaded zones and achieving a higher crop yield. In contrast, the fixed tilted panels create areas with light levels below 30% and above than 90% right next to each other, compared to a purely agricultural condition, resulting in zones where some crops may struggle to grow while others receive excessive light. Moreover, the large distance between the panel rows guarantees a simple access for standard farm machinery, while the traditional tilted panels often require specialized and smaller equipment, due to the presence of the supporting structure.



Figure 2.6: Vertical bifacial panels [23]

As reported by [24], the vertical bifacial panels are characterized by energy output curve with two peaks, one in the morning and the second one in the afternoon, aligning better with typical morning and evening electricity demand peaks than the single midday peak of traditional systems, as shown in Figure 2.7. This can be advantageous for grid stability and energy pricing, reducing the need of peak-load power plants.

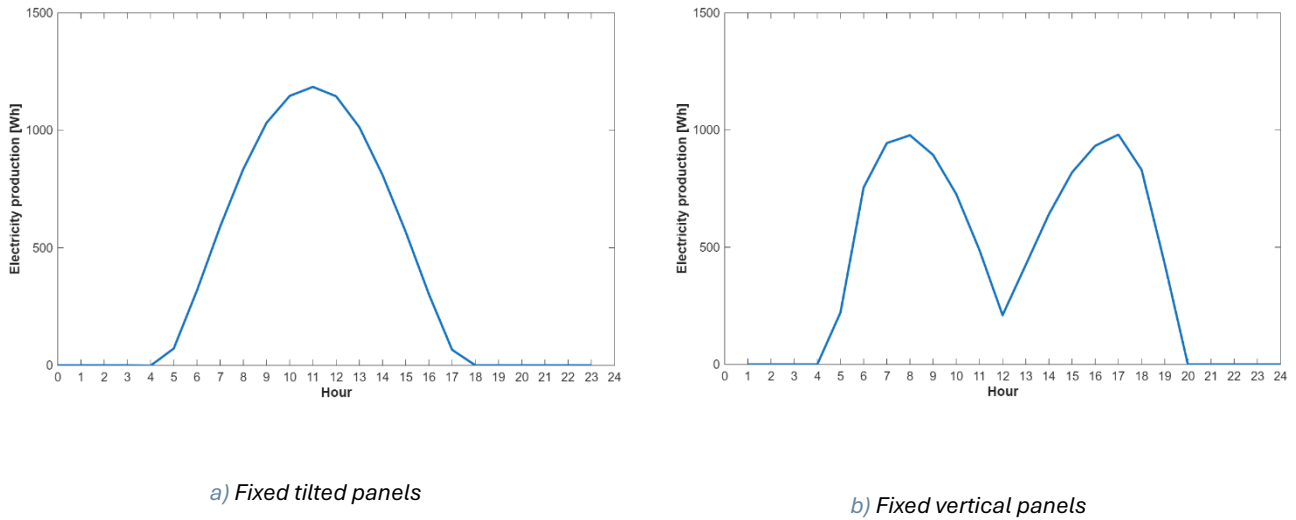


Figure 2.7: Electricity production on 21st June as a representative day in Lucera

2.2.4 Greenhouse

Depending on the location, weather conditions and land availability, crops need to grow under a controlled climate inside a greenhouse. In this case, as showed by [25], [26] and [27], the implementation of PV into the agricultural settings is through the installation of PV modules onto the greenhouse's envelope, mainly the roof.



Figure 2.8: Greenhouse photovoltaic [25]

However, conventional opaque PV modules produce shade, thereby significantly affecting the microclimate inside the structure in terms of air temperature, relative humidity, level of light and CO₂

concentration and thus the productivity. To minimize this effect, one approach is to use traditional opaque PV modules that cover only partially the greenhouse roof or PV modules with semi-transparent sections. In this way, the percentage of the greenhouse area covered by opaque PV modules is reduced in such a way that the light reaching the plants is sufficient for photosynthesis. Nevertheless, the solar irradiance is still distributed non-uniformly and varies seasonally. Therefore, it is necessary to find optimum arrangements of PV modules on the greenhouse roof, in order to define the optimal conditions for plant cultivation. The studies [28] and [29] demonstrate that the checkerboard arrangement, for instance, guarantees a better uniformity and consequently diminished the PV shading effects.

The research [30] investigated the yield estimations of 14 horticultural and floricultural crops inside four PV greenhouses (PVG), with coverage ratio ranging from 25% to 100%. The results show that all the considered species, including high light-demanding crops, can be cultivated inside PVGs with 25% coverage ratio, showing limited yield reductions below 25%, but a reduction of growth and yield occur when the coverage ratio is increased from 50% and 100%. In general, the coverage ratio of opaque PV modules should not exceed 50%, because this would provide a shading ratio that is compatible with greenhouse cultivation.



Figure 2.9: PVG with checkerboard arrangement [28]

2.2.5 Wavelength-Selective Photovoltaic Panels

Currently, a new type of solar panel suitable especially for PVG is being researched and designed for agrivoltaics systems [31],[32]. Called wavelength-selective photovoltaic (WSPV) panels, they are semi-transparent solar panels engineered to transmit only beneficial wavelengths of light to the crops below while converting the remaining wavelengths into electricity, unlike conventional opaque solar panels that block most of solar light. This system enables more sunlight to reach plants than conventional opaque solar panels

The key feature is the precise filtering of sunlight; in fact, as showed by [32], WSPV panels are designed to transmit light within the photosynthetically active radiation (PAR) region (400–700 nm), crucial for photosynthesis. Plants absorb light most efficiently in the blue (400-500 nm) and red (600-700 nm) wavelengths due to chlorophyll absorption peaks, while the green spectrum (500-600 nm) tend to be reflected instead; so, the WSPV panels, like the magenta cadmium telluride (CdTe) panels, are optimized to have high transmittance in these blue and red regions and lower transmittance in the green region.

According to [32], this feature can be achieved in different ways: thin-film PV uses an active material tuned to transmit those wavelengths of light useful for plants and absorb those less utilized wavelengths for electricity production. For the active material to be able to transmit light, it and other layers (i.e., anode and cathode) must be thin, to minimize unwanted absorption.

In Figure 2.10, the photoactive layer absorbs primarily the wavelengths of light not used for photosynthesis by plants; in fact, blue and red wavelengths are transmitted, while the remaining are reflected back.

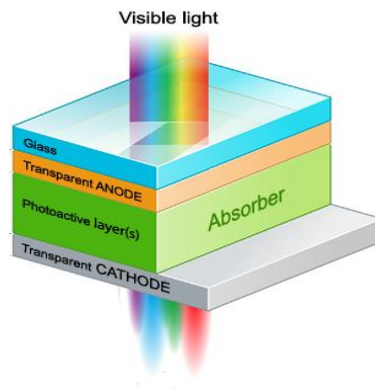


Figure 2.10: General structure of a thin-film WSPV [32]

The active material may consist of either organic or inorganic compounds. The beneficial semi-conductive properties of organic materials have been responsible for the considerable increase in solar PV research. These properties include their low cost, light weight, mechanical flexibility, low angular dependence on incident light and high molecular design tunability, which allows them to be tailored to have a localized absorbance at specific wavelengths [32].

The study [31] reports that the majority of the studies of wavelength selective OPV are in greenhouses. This is because they are manufactured on flexible and lightweight substrates, making them simple to install on the roofs of existing greenhouses. Stability issues, the need of large-area module development, and insufficient power conversion efficiency (particularly during scaling up) are among the most significant obstacles to their implementation in open-field APV systems.

Dye-sensitized solar cells (DSSCs) can also absorb light at specific wavelengths, where the dye itself is responsible for the light absorption properties in a DSSC device [32]. Comparably to OPV, DSSC has been developed for greenhouse applications, and it is characterized by low-cost, flexibility and angle-of-incidence (AOI) independence, but it also suffers from low stability and low efficiency [32].

Perovskites, that are photoactive materials with the ability to tune the band gap and thus the absorption/transmittance spectra, are also regarded as a thin-film WSPV promising technology. According to [32], they also suffer from stability problems, but opaque perovskite solar cells (PSCs) currently achieve greater efficiency. One of the main challenges in the implementation of PSCs is their limited scalability to larger sizes, with most reported studies focusing on laboratory-scale solar cells. Moreover, a major concern is the presence of toxic lead (Pb), whose leakage could have serious environmental impact.

A spatially segmented PV panel consists of conventional silicon or thin-film PV panels with spatially segmented PV cells, where the density of PV cells directly impacts the intensity of light transmitted. A translucent selectively coloured interlayer is placed beneath the PV solar cells to allow the full spectrum of incident light to reach the solar cells while filtering incident light to the plants below. Usually, this semi-transparent layer is coloured magenta due to the concentration of chlorophyll absorption maxima in the blue and red regions [32].

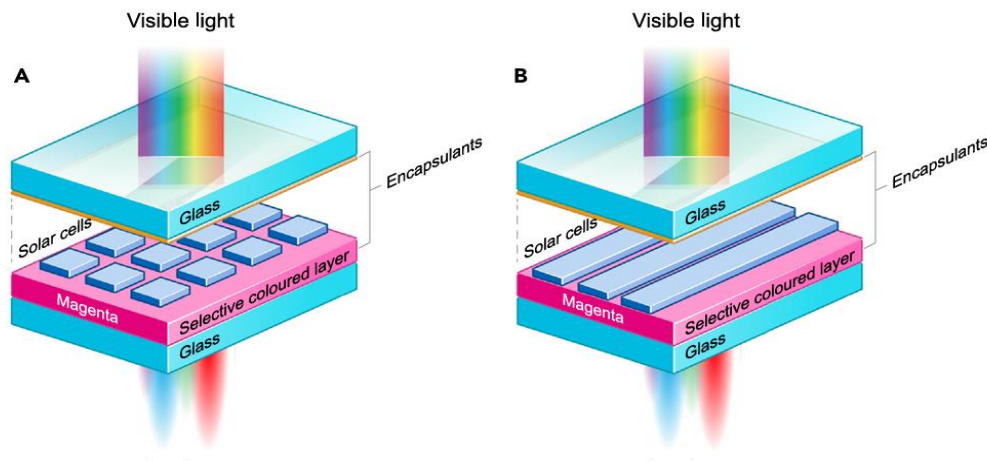


Figure 2.11: General structure of a spatially segmented PV panel with selective-coloured layer [32]

This technology has two main arrangements of the PV cells: Figure 2.11.a shows a configuration with squared PV cells, more commonly found in Si PV modules, while Figure 2.11.b shows stripes of PV cells, usually adopted for thin-film PV modules [32].

Overall, WSPV technologies offer distinct advantages compared to conventional opaque Si panels, as summarized by [32]. They are purposefully designed to transmit the necessary wavelengths of light required for plant growth and simultaneously they ensure an adequate light intensity without causing direct shading on the vegetation; however, in practice, the adoption of WSPV modules remains limited, due to their relatively recent emergence. By contrast, conventional Si technology is well-established and benefits from an efficiency between 23% and 24% that is higher than the 18% and 20% range typically observed of the WSPV technology [31], long-term stability and cost reductions over recent decades, achieving widespread market penetration. As a result, APV systems employing conventional Si PV modules and semi-transparent spatially segmented Si PV modules currently enjoy a competitive edge in the field.

Based on the current literature, it is evident that more studies, particularly experimental research, are necessary to verify the potential of WSPV technologies across diverse crops and geographical locations. While theoretical studies and numerical simulations offer valuable preliminary insights into the potential impact of WSPV technologies on both power production and crop yield, field validation remains essential for ensuring the accuracy of the theoretical models, since real field trials may still give divergent outcomes.

Currently, the implementation of all WSPV categories is still relatively rare and is usually limited to greenhouses or small-scale setups that are important to provide a basis for larger scale experiments;

moreover, many WSPV technologies are still in early stages of research and development and are at a considerable distance from being scaled up [32].

Lastly, the study [32] highlights that a non-negligible issue in the implementation of WSPV systems for agricultural applications is the presence of toxic elements, such as Pb and Cd, in some of these technologies. The potential risk of leakage would have consequences for the environment and the human health.

OPPORTUNITIES	CHALLENGES
Low material costs	Low stability over time
Lightweight	Low power conversion efficiency
Mechanical flexibility	Scarce open-field experimental implementation and limited to small-scale trials
Tuneable degree of transparency	

Table 2.1: Summary of the opportunities and challenges of the WSPV technology [32]

2.3 Agrivoltaic Regulations

The study [3] reports that agrivoltaic regulations remain fragmented worldwide, and in many countries there is no clear definition of the requirements needed to access economic incentives. This regulatory uncertainty limits the large-scale deployment of agrivoltaic systems. Nevertheless, all existing regulations share a common objective: ensuring that the integration of photovoltaic modules does not excessively compromise agricultural productivity.

According to [17], in Germany, the agricultural production under agrivoltaic systems must not decrease by more than 33% compared to the control fields. In Spain, the reduction in solar radiation beneath the panels cannot exceed 40%, except for shade-tolerant crops. In France, no reductions of the crop yield are allowed that must be maintained at 100%. In Japan, the yield losses must remain below 20% for a system to be classified as AVS. In Massachusetts (USA), the solar radiation available to crops must not fall below 50% of natural irradiation.

In Italy, the Ministry of the Environment and Energy Security (MASE) introduced specific agrivoltaic criteria in 2022 [33]. According to the *Guidelines for Agrivoltaic Systems*, at least 70% of the land area must be allocated to the agricultural production in compliance with *Good Agricultural Practices*. The total area covered by PV modules must not exceed 40%, in order to promote innovative and efficient technological solutions. Moreover, the annual energy production of an agrivoltaic system must be at least 60% of that of a conventional photovoltaic plant that occupies the same area.

To ensure the continuity of agricultural and livestock activities, the minimum installation height of the PV modules on overhead support structures must be 2.1 m for agricultural operations and 1.3 m for husbandry. These specific values try to guarantee the continuity of all activities and thus the maximum integration between the electricity and agricultural productions. Finally, the access to incentives requires the installation of appropriate monitoring systems to assess soil quality and microclimatic conditions beneath the PV modules.

ITEM	REQUIREMENT
Good Agricultural Practices (GAP)	$S_{Agricultural} \geq 0.7 * S_{tot}$
Ground Coverage Ratio (GCR)	$GCR \leq 40\%$
Minimum energy production	$El_{AVS} \geq 0.6 * E_{PV}$
Spatial configuration	$PV \text{ Modules Height} \geq 2.1m$ for agriculture $PV \text{ Modules Height} \geq 1.3 m$ for husbandry
Access to incentives	Monitoring the agrivoltaic system

Table 2.2: Summary of the guidelines for agrivoltaic plants in Italy [33]

Most AV policies so far require that the crop yield be maintained or slightly decreased and demand to measure the crop yields year after year, both under the AV system and in a control full-sun area [3]. This criterion, however, is difficult to measure and control for multiple reasons: it is quite easy to prove that the crop yield under an AV system is acceptable by reducing the yield of the full-sun crop control. The costly and labour-intensive crop yield measurements such sampling, harvesting, field and measures are not easily performed by farmers. Lastly, depending on the climate, the crop yields tend to fluctuate, resulting into year-to-year variability of AVS performance.

3 Agrivoltaic Plants and Installations

According to the study [34], the high cost of agrivoltaics systems has largely confined their adoption to developed nations in Asia, Europe, and North America. Of the fifty installations examined in the paper, two-thirds are stilt-mounted PV arrays, fifteen are integrated onto greenhouses and only two feature PV arrays interspersed among crops. The vast majority use static solar panels, with only three stilt-mounted systems employing dynamic tracking, while just two facilities utilize solar spectrum separation technology. A summary of these systems is provided in Figure 3.1. In most agrivoltaics systems, the shading area is limited to 40% or less of the total surface. This threshold is based on research indicating that a coverage of up to 25% has no negative significant impact on plant growth and quality, while exceeding 50% inhibits the growth of many species [35].



Figure 3.1: Type of AVS and solar panels used [34]

Among the crops that are adopted in the AVS considered by [34], lettuce and tomato are the most cultivated ones, followed by cereals and legumes. Only few berries have been evaluated under agrivoltaics, although these crops seem to be the most promising, while cereals and legumes would be less suitable. Figure 3.2 reports the vegetable species cultivated in the 50 agrivoltaics systems analysed.

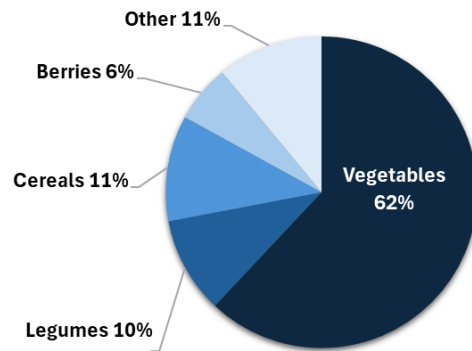


Figure 3.2: Vegetables adopted in the fifty agrivoltaics systems studied in [34]. The "Other" includes less cultivated species such as orchards and vineyards

Lettuce, the most extensively researched vegetable due to its rapid growth, manageable cultivation, and low space required, demonstrates a clear trend both in [34] and [35]. The fresh weight and yield of lettuce grown under photovoltaic panels are significantly lower compared to the full-sun condition, with yield reductions of around 50% being common. While some seasonal and varietal variations exist, most of the trends indicate that lettuce is sensitive to a reduction of light levels.

In contrast, tomato yields reported by [34] exhibit considerable inconsistency across studies. While some cases report a decrease in production and average fruit weight, others observe an increase in yield and fruit size in AVS. These divergent results show that tomato growth is not governed by shade alone; in fact, the benefits of agrivoltaics systems, such as the mitigation of heat stress which can cause physiological damage, appear to be counterbalanced by the negative effects of excessive shading on photosynthesis. The specific variety, local climate, and the degree of photosynthetically active radiation (PAR) reduction are critical factors determining the net outcome.

Maize, a crop typically classified as shade-intolerant, displayed a degree of tolerance under specific configurations. The study [36] finds that a low density of solar panels actually increases the yield by 5.7% compared to the full-sun condition. This positive effect is attributed to an optimization of the plant's light saturation point combined with reduced soil water evaporation due to partial shading. However, a further increase in solar panel density has a negative effect on yield.

For the legume's family, the study [37] observes that an increase in the level of shading negatively affects the yields of sesame, red bean and soybean. Depending on the species, a decrease in production ranging from 7% (sesame) to 26 % (red bean) is observed when the shade ratio is close to 20%. A further decrease of yield is obtained as the shading level increases. The legume family, including sesame, red bean and soybean, proves to be highly sensitive to shading. Even at a relatively low shade ratio of approximately 20%, significant yield decreases are observed, ranging from 7% for sesame to 26% for

red bean. These losses increase even more as the shading level increases, demonstrating a clear negative correlation between shade intensity and productivity for these crops.

Finally, an experimental campaign on wine grapes in Italy showed that fruit production was consistently negatively impacted by an AV installation that shaded 75% of the crop [34]. On the other hand, strawberries grown in greenhouses with partial PV panel coverage exhibited a notable increase in both crop yield and average fruit weight, suggesting that for some high-value crops, the modified microclimate of an AV system can be highly beneficial [34], [35].

CROP	EFFECT OF SHADING ON YIELD
Lettuce	Negative (-)
Tomato	Positive (+), but dependent on the specific tomato species
Maize	Positive (+) only for low shading levels
Legume	Negative (-)
Fruits	Positive (+), but depends on the specific type of fruit

Table 3.1: Summary of the shading effect on different crops. Data taken from [34], [35], [36], [37],[38]

3.1 Operating Plants

The concept of a dual-use approach for both solar photovoltaic power and agricultural production was theoretically pioneered by Goetzberger and Zastrow at the Fraunhofer Institute in Germany in 1981 [39]. However, the first ever agrivoltaic plant was open field, installed in France, close to the city of Montpellier in 2010 [39]. The prototype has mono-crystalline PV modules mounted at a height of 4 m above the ground. Since the PV modules are opaque, the main issue is the effect of the shade created by the PV on the plant growth. In order to evaluate the effect of the shadow cast by the PV, the prototype was split into different parts with two densities of solar modules: one called "full density", with optimal spacing between rows for electricity production and which transmitted on average 50% of the incident radiation to the crop, and the second called "half density", obtained by removing one PV strip out of two, leaving on average 70% of incident radiation available to the crop [39]. Additionally, to evaluate the advantages of solar-tracking technology, which allows for the adjustment of the radiation level on crops, two independent single-axis tracking PV systems were added in 2014 [40]. The experimental farm led to the exploration of the open-field AVS potential, giving rise to many scientific publications.

After several years of research and development, the global market for agrivoltaics has experienced significant growth from around 5 MW in 2012 [41] to an estimated 54 GW in 2024 [3]. This progress has been made possible mainly by government support initiatives, such as in Japan (since 2013), China (around 2014), France (since 2017), the USA (since 2018), Germany (since 2019) and Italy (since 2023) [41].

3.1.1 Agrivoltaic Plants in Europe

Since pioneering the technology in 2018, *Sun'Agri* has become France's leading agrivoltaics company, specializing in tracking solar systems. Today, the group operates 24 plants across southern France that utilize its signature dynamic technology, including few greenhouse installations [42]. The main plants of the company are summarized in Table 3.2.

NAME	POWER [MW]	EXTENSION [ha]	CROP	TECHNOLOGY
Nidolères estate	2.85	3.8	Grapes	1-Axis Tracking
le Château la Domèque	3	3.5	Grapes	1-Axis Tracking
Saint-Félix	2.27	2.6	Apricots	1-Axis Tracking
Besombes estate	1.92	2.5	Grapes	1-Axis Tracking
YoLa's farm	0.135	0.25	9 Species (tomatoes, lettuce, ...)	9 Greenhouses

Table 3.2: Main agrivoltaics systems in France. Source: Sun'Agri [42]

In Italy, agrivoltaics systems demonstrate remarkable diffusion: while they constitute only 4% of all installations, they contribute a substantial 11.5% of the nation's total installed PV capacity (approximately 2.5 GW), generated by 38,000 individual plants [43].

In 2024, the *Caviro Group* unveiled one of the largest agrivoltaics installations in Italy, integrated within a 1.5-hectare vineyard [44]. The system features nearly 1,400 bifacial solar panels equipped with tracking technology, resulting in an installed capacity of 1 MW and in an annual electricity production of 1300 MWh. Beyond clean energy production, the primary objective of this pilot project is to research the structure's potential to shield the vines from the increasing threat of extreme weather events.

The Italian company *Enel Green Power* is leading the global expansion of agrivoltaics across multiple continents, focusing mainly on 1-axis solar tracking technology, as reported in [45]. In Minnesota, USA, the 150 MW *Aurora Solar Park* employs dynamic tracking panels that not only generate electricity but also overlook fields of lavender and various herbal species, creating a thriving environment for bees and pollinator insects. Meanwhile, in Spain, the *Los Naranjos* and *Las Corchas* solar parks in Sevilla utilize bifacial PV panels to produce 100 MW overall, fostering an environment where goat grazing and beekeeping coexist with power generation. Further demonstrating this synergy, the *Totana Solar Park* in Murcia supplies 85 MW of clean energy while its panels provide the shaded conditions necessary for cultivating vegetables like peppers and broccoli and for creating a comfortable oasis for cattle.

In the Dutch town of Babberich, the *BayWa r.e.* company has established a 2.7 MW agrivoltaics farm, becoming one of Europe's largest for fruit production [46]. This innovative system is dedicated to raspberry cultivation, utilizing semi-transparent PV modules in a semi-enclosed and single-row design, to protect the fruits from harsh weather phenomena, while improving the ventilation and filtering the correct amount of sunlight [47], [46].



Figure 3.3: Babberich agrivoltaics plant (Netherlands). Source: BayWa r.e. [46]

In Germany, the *Next2Sun* company leads the development of vertical bifacial solar panels in the agricultural and civil sectors. The 480 AVS scattered across Europe, that adopt this technology, produce almost 25 MW of clean electricity [48].



a)



b)

Figure 3.4: Next2Sun operating plants with vertical bifacial solar panels: a) Neudorf an der Mur with 2 MW; b) Eppelborn-Dirmingen with 2 MW [48]

The same company uses the vertical bifacial PV panels in the solar fence configuration, for private, commercial and industrial applications, to enclose a property and at the same provide clean energy production. An important example is the 2,800-meter-long photovoltaic installation at Frankfurt Airport, able to generate up to 17.4 TWh of green electricity annually.



Figure 3.5: Solar fence by Next2Sun in Frankfurt airport. Source: Next2Sun [48]



Figure 3.6: Solar fence technology by Next2Sun in Austria [48]

NAME	POWER [MW]	CROP	TECHNOLOGY
Nidolères estate	2.85	Grapes	1-Axis Tracking
le Château la Domèque	3	Grapes	1-Axis Tracking
Saint-Félix	2.27	Apricots	1-Axis Tracking
Besombes estate	1.92	Grapes	1-Axis Tracking
YoLa's farm	0.135	9 Species (tomatoes, lettuce, ...)	9 Greenhouses
Caviro Group plant	1	Grapes	Tracking bifacial
Aurora Solar Park	150	Lavender and herbs	Tracking
Los Naranjos and Las Corchas	100	Goat grazing and beekeeping	Fixed bifacial
Totana Solar Park	85	Peppers, broccoli and husbandry	Fixed
Babberich Plant	2.7	Raspberries	Fixed semi-transparent
Neudorf an der Mur	2	Pumpkin	Fixed vertical bifacial
Eppelborn-Dirmingen	2	Hay	Fixed vertical bifacial

Table 3.3: Summary of the most relevant plants in Europe [42], [44], [45], [46], [48]

3.1.2 Agrivoltaic Plants in Asia

Subsidy programs in Japan have led to more than 4000 operational plants representing 500 MW of installed capacity [49]. Japanese agrivoltaics plants consists mainly in small-scale overhead systems with an average size of less than 0.1 hectares and often using special thin PV modules to achieve homogeneous light distribution at the crop level

These small-scale AVS address two critical national challenges: increase green energy production without consuming valuable farmable land and revitalize abandoned farmlands, converting them into sources of both food and power [49].

China's approach to agrivoltaics is distinguished by the vast scale of its installations, which far exceed those in Europe and Japan in both physical size and power capacity. By the end of 2022, the country's cumulative installed capacity for these systems had surpassed 31 GW with more than 500 operating projects, concentrating in crop cultivation, aquaculture, and greenhouses [50].

As illustrated in Figure 3.7, agrivoltaics projects are distributed across all Chinese provinces. A clear regional disparity is evident, with eastern coastal provinces generally leading in both the number and installed capacity of projects. However, the western regions, leverage their abundant land resources for large-scale installations, a prime example being Ningxia's 1 GW photovoltaic goji berry project [50].

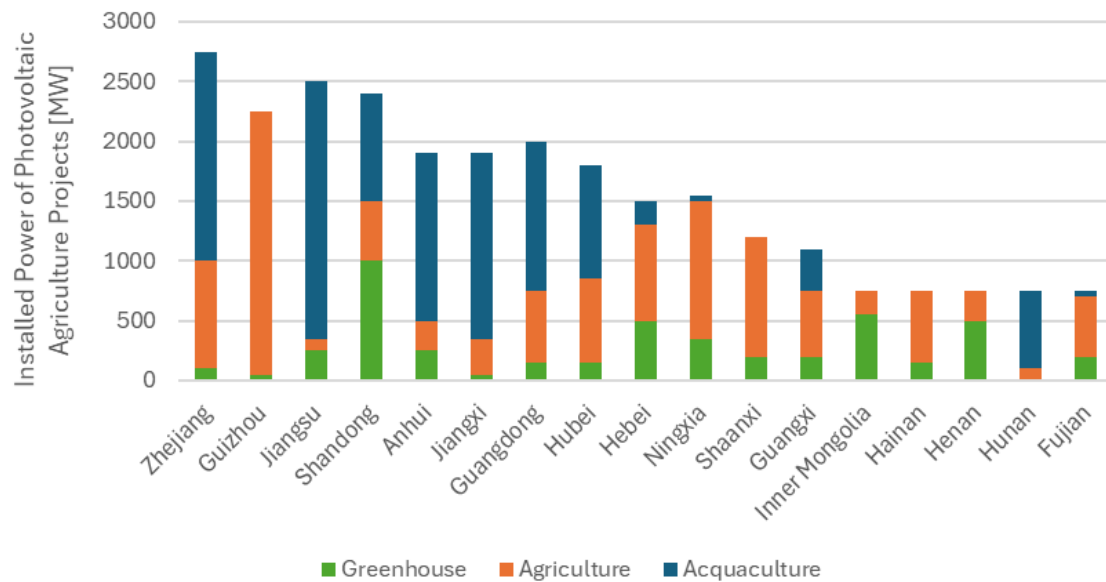


Figure 3.7: Installed power of agrivoltaics plants in China [50]. In the other provinces is lower than 500 MW

With an average size of 61 MW, Chinese AVS installations typically feature a Ground Coverage Ratio (GCR) exceeding 50% [50]. The dense arrays of PV modules limit the light and space essential for crops, whereas a much lower GCR of 20-30% is typically required to ensure acceptable yields for most vegetables and cereals. In contrast, aqua-voltaic systems demonstrate greater compatibility, as study [50] shows that fishery yields can be maintained even with a 50% GCR. This discrepancy in optimal coverage levels suggests that in many projects the agricultural output is not a primary design constraint.

However, recent Chinese policies now explicitly prioritize a diversified approach to photovoltaic development, emphasizing an integrated land use. This new directive mandates that PV projects be sited on unused or low-efficiency land, strictly prohibiting the use of high-quality farmland [50]. Agrivoltaics represents a key technology to improve the land use efficiency, ideally aligning photovoltaic infrastructure with agricultural preservation. Moreover, agrivoltaics projects serve also socio-economic purposes, such as rural revitalization, growth of economic income in rural areas and carbon neutrality [50].

In China agrivoltaics technology is adopted also to contrast the desertification phenomena and restore vegetation across the country. The company *China Huaneng Group* is involved in the construction of several large-scale agrivoltaics plants across the country [51]. The main power plants are summarized in Table 3.4.

NAME	LOCATION	POWER [MW]	EXTENSION [ha]
Suji Sandland	Inner Mongolia	2000	17000
Damao Banner	Inner Mongolia	350	2000
Jinxiang Ma miao	Shandong	100	600

Table 3.4: Agrivoltaic plants in China built by China Huaneng Group. Source: China Huaneng Group [51]

In this sense, one of the most famous projects is the 2.65 GW mountainous utility AVS in Yunnan province, whose construction started in 2023 and is still undergoing. The project site experiences an annual average solar irradiation of 1,445 kWh/m² suitable for the PV technology, but at the same time the uneven terrain and rolling hills negatively impact the material transportation and the construction efficiency, particularly in the piling and positioning of solar modules [52].



Figure 3.8: 2.65 GW mountainous utility AVS in Yunnan province, China. Source: Anhui Huasun Energy Co. Ltd [52]

4 Relevant Design Parameters

The elevation of photovoltaic modules from the ground surface is a key design parameter that directly affects the radiance available for crops. There is an inverse relationship between mounting height and solar radiation heterogeneity: lower installations result in greater variability of light exposure, while greater heights promote a more uniform distribution [47].

The use of elevated structures, however, presents significant trade-offs. Taller configurations can provoke public opposition due to their negative impact on the landscape, undermining social acceptance. Moreover, height substantially increases installation costs; in fact, according to [53], in the European context, the cost of elevating PV modules can exceed that of standard ground-mounted systems by more than double.

A standard metric for evaluating agrivoltaics system performance is the Land Equivalent Ratio (LER) [47]. The LER determines the land-use efficiency by comparing the combined agricultural and energy yield of the AVS to the yields from dedicated farmland and solar parks occupying an equivalent area.

LER is computed as:

$$LER = \frac{Y_{agri-APV}}{Y_{agri}} + \frac{Y_{energy-APV}}{Y_{PV}} \quad (19)$$

Y_{agri} is the agricultural yield of the dedicated farmland and $Y_{agri-APV}$ is the yield under the agrivoltaics system for the same area. $Y_{energy-APV}$ refers to the electricity production of the agrivoltaics systems and Y_{PV} of the standard PV system operating on the same area.

A Land Equivalent Ratio (LER) above 1 indicates that the integrated agrivoltaics system is more land-efficient than separate agricultural and solar production. In opposition, a LER equal to 1 suggests that combining agriculture and PV energy leads to no significant difference in productivity compared to separate uses. Finally, a LER lower than 1 indicates that keeping agricultural and PV activities on separate land may be more beneficial [47].

However, the primary limitation of this parameter is its failure to distinguish between the relative contributions of energy and biomass, allowing a high value to be attained even with a minimal crop yield. Therefore, a comprehensive performance evaluation must also include specific agricultural data, such as crop yield and quality. Finally, because LER is heavily influenced by local climate, technology and crop selection, its values are only directly comparable across systems with similar parameters [47].

The Ground Coverage Ratio (GCR) quantifies the proportion of a land area covered by solar panels, determining consequently the amount of shade. As shown by Equation (20), it is ratio between the area of the modules ($A_{PV \text{ modules}}$) and the area of the land that they occupy (A_{land}).

$$GCR = \frac{A_{PV \text{ modules}}}{A_{land}} \quad (20)$$

The computation of the GCR does not change when bifacial panels are used, since they do not cast more shade on crops than monofacial panels [38].

For semi-transparent panels, the GCR is adjusted to take into account the actual light transmission of the panels [38].

$$GCR_{st} = \frac{A_{PV \text{ modules}}}{A_{land}} * (1 - \tau) \quad (21)$$

In Equations (20) and (21), $A_{PV \text{ modules}}$ is the total surface of the photovoltaic panels, A_{land} is the area of the land and τ is the transmittance of the PV module.

A high value of GCR increases the photovoltaic energy production by packing the panels more densely, even though it is fundamental to take into account the effect of mutual shading that may worsen the energy performance of the system, and it creates more persistent shades and may limit the amount of sunshine and space available for the underlying crops [38]. On the other hand, a lower GCR prioritizes agricultural activities by allowing more sunlight reaching the crops and more space for farm machinery, even though it can reduce the system's ability to generate energy [38].

High GCRs are also useful to protect crops efficiently against climate hazards. While this may be true, such systems with a high GCR will not allow the farmer to replace the crops with species that require more light, reducing the farmer's options to change crop rotation in the future [47].

The Shading Ratio (SR) measures how much less sunlight reaches the crops below the PV panels [47]. As Equation (22) shows, it is given by the ratio of the shaded area to the total area available for agricultural use.

$$SR = \frac{A_{shaded}}{A_{land}} \quad (22)$$

PARAMETER	FORMULA
Land Equivalent Ratio	$LER = \frac{Y_{agri-APV}}{Y_{agri}} + \frac{Y_{energy-APV}}{Y_{PV}}$
Ground Coverage Ratio	$GCR_{st} = \frac{A_{PV \text{ modules}}}{A_{land}} * (1 - \tau)$
Shading Ratio	$SR = \frac{A_{shaded}}{A_{land}}$

Table 4.1: Summary of the main parameters of an agrivoltaic system [47], [38]

4.1 GCR - SR – Crop Yield Correlation

The main impact of photovoltaic (PV) panels on crops is their shadow, which reduces the available photosynthetically active radiation needed for photosynthesis [54]. However, the shade ratio is difficult to measure, as it varies from hour to hour and from one day to the next one, depending on the latitude and the design of the system, such as height of the panels, their orientation and tilt. The system's Ground Coverage Ratio (GCR) can be a good predictor of the shading rate and thus of crop yields in AV systems [54]

According to many authors, the shade level under an AV system is close to the GCR of the system [54], but most field measurements show that the average shade level is usually slightly higher than the GCR. Several factors increase the heterogeneity of the shading pattern at the crop level: a low elevation of the panels above the ground, a small distance between panels and crop canopy, clustered panels, such as panels arranged in lines or blocks and opaque panels. Conversely, many other factors increase the homogeneity of the shading pattern at the crop level: A high elevation of the panels above the ground,

that results in a large distance between panels and crop canopy, diffuse positioning of the panels and semi-transparent panels.

The study [38] considers thirty-five publications to ten experimental results to assess the relationship among GCR, SR and crop yield. From this analysis, emerges that for the same GCR, tracking panels cast a heavier shade on crops than fixed panels. Moreover, fixed tilted or vertical panels aligned east–west cast a more heterogeneous shade than fixed tilted or vertical panels aligned north–south.

For example, at an experimental site in Montpellier (France), the annual average shade is 28% under fixed panels with a 25% GCR and 56% under fixed panels with a 49% GCR [39]. The order of the difference between the shade ratio and the GCR is quite stable across various experimental sites; in fact, these values are supported by several papers that investigated both the system’s averaged shade ratio and its GCR [39],[55],[56].

Concerning agrivoltaic greenhouses, some studies do not compare a standard greenhouse with a photovoltaic greenhouse, lacking in the reference case, while other studies carried out in greenhouses do not provide average yields under PV panels. Drops in crop yields are recorded but cannot be included because the true control is missing. Currently, the studies regarding the crop adaptive tracking are very limited in number, not allowing to define an empirical relationship between GCR and SR and to compare it with solar tracking and fixed panels configurations [38].

TYPE OF PANEL	GROUND COVERAGE RATIO (GCR)	
	30%	60%
AVERAGE SHADING RATE		
Fixed tilted	35%	65%
Fixed vertical	35%	65%
Tracking	40%	70%
Montpellier site	28% (GCR=25%)	56% (GCR=49%)

Table 4.2: Approximate relationship between the GCR and the average annual shading ratio [38]

As a general trend, as the Ground Coverage Ratio increases, the Shading Rate increases, leading to a reduction of the crop yield. This inversely proportional relationship between GCR and CY seems to be shared by all types of AV systems, including fixed and mobile [38]. For example, a system with a GCR of 50%, typical of ground-mounted PV systems, allows a 60% average crop yield, while a system with half as many panels (GCR = 25%) allows an average crop yield of 80% [38]. Conversely, certain agricultural species, such as berries, fruits and fruity vegetables, show a positive response when cultivated in shaded environments and thus they are classified as shade-benefitting crops. Empirical evidence suggests that these varieties may realize yield improvements of 10% to 20% compared to full-sun exposure [38].

The results of the study [57] show that an average annual shading level of 50%, most annual crops experience a significant drop of around 35% in their production and even a 50% yield drop for shade-intolerant species, such as grain legumes, tuber crops, maize and cereals, while shade-tolerant crops

(forages, berries and fruit trees) and some vegetables are less sensitive. With 25% shade, the average decrease in yield was 15%.

GCR	CROP YIELD		
	Average [%]	Shade-intolerant species [%]	Shade-tolerant species [%]
50%	-42	-60	-20
25%	-22	-37	-5

Table 4.3: Relationship among GCR-SR-Crop Yield for fixed tilted panels [38]

5 Simulations

5.1 Location and Plant Characteristics

The simulations are centred on Lucera (41.423° N, 15.362° E), located within the Puglia region of Italy, a territory recognized as one of the nation's premier agricultural regions due to its significant production volume and diverse crop varieties. The convergence of high soil fertility and climatic conditions facilitates the cultivation of numerous species, most notably olive trees, tomatoes, lettuce, figs, and grapes.

Similarly to the rest of the Puglia area, this site benefits from a substantial solar resource with a mean irradiance value of 1600 kWh/m²/y, which, when coupled with the region's predominantly regular and even terrain, presents an ideal environment for the deployment of photovoltaic infrastructures. As a result, the region currently hosts a network of over 110,000 PV plants, accounting for an installed capacity of 3600 MW and an annual generation of 4600 GWh the highest recorded output for PV technology in Italy [58].



Figure 5.1: Lucera position in Puglia province, Italy

For the purposes of this study, the simulated power plant encompasses an area of 3 hectares, aligning with the average dimensions of open-field agrivoltaic systems typically found in southern France, as reported in Paragraph 3.1.1 [42]. The analysis evaluates the performance of lettuce, tomato, and grape crops across the three most prevalent solar configuration technologies: fixed-tilted, fixed-vertical, and solar-tracking systems.

Solar radiation and meteorological data are retrieved from the Photovoltaic Geographical Information System (PVGIS), a database maintained by the European Commission [59]. These datasets serve as the foundation for calculating the solar geometry and the components of solar radiation, specifically direct, diffuse and albedo radiation, across all analysed scenarios.

The modules selected for these configurations are manufactured by *Anhui Huasun Energy Co., Ltd*, a prominent leader in Chinese and global frameworks for the production of high-efficiency cells for both conventional ground-mounted and agrivoltaic applications.

For the fixed-tilted configuration, the *Himalaya G12 Series* [60] was utilized, with a peak power output of 730 W and a maximum efficiency of 23.5%. As illustrated in Figure 5.2, these panels are positioned with a minimum ground clearance (H) of 2.1 m to comply with the Italian regulatory guidelines [33]. The modules are placed in portrait configuration and they are south facing with an optimal tilt angle (Σ) derived from Equation (23), to optimize the electricity generation in the northern hemisphere as proposed by [61]. Given the site's latitude (ϕ_{lat}) of 41.43°, the calculated optimal inclination is 32.14°.

$$\Sigma = 1.3793 + \phi_{lat} * (-0.014044 + \phi_{lat} * 0.000080509) \quad (23)$$

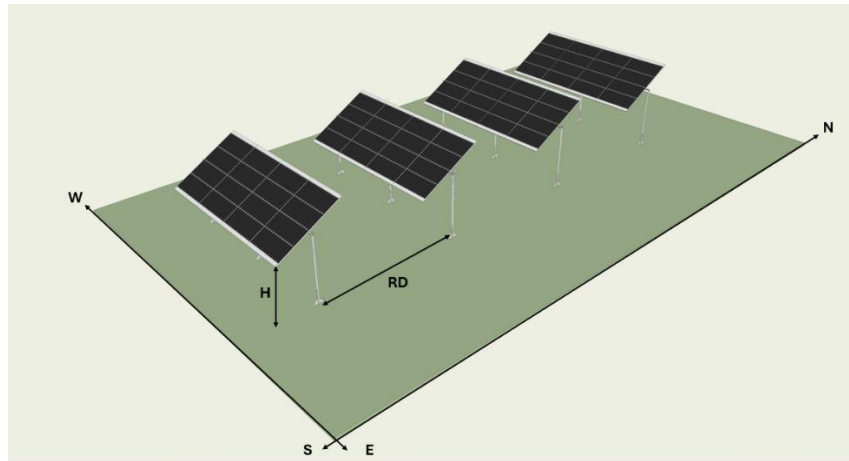


Figure 5.2: Scheme of fixed-tilted panels configuration

The second configuration, which evaluates the performance of vertical bifacial modules, utilizes the *Kunlun G12 Series* [62], a technology distinguished by a peak power output of 720 W, an electrical efficiency of 23.2%, and an ultra-high bifaciality factor of $97\% \pm 3\%$. This high bifaciality coefficient

ensures that both the front and rear surfaces of the panel operate with near-identical performance characteristics, effectively maximizing energy capture from diffuse and reflected radiation.

As illustrated in Figure 5.3, the modules are installed with a minimum ground clearance (H) of 1 m, similarly to comparable agrivoltaic systems across Europe [48], since the current Italian regulatory framework defines a limit only for AVS with overhead structures [33]. Furthermore, two identical panels are installed on top of each other in landscape configuration and they are oriented east and west facing, shifting the peak electricity generation profile from the midday peak to the early morning and late afternoon hours.

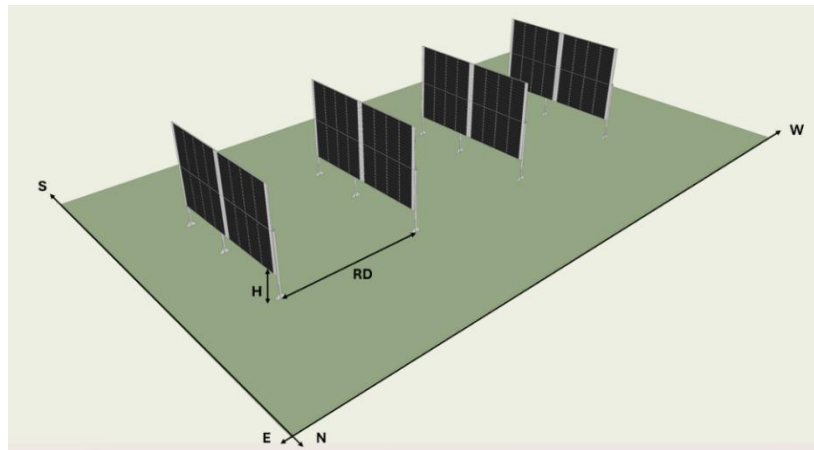


Figure 5.3: Scheme of the vertical bifacial panels configuration

The final configuration utilizes the *Himalaya G12 Series* in conjunction with a single-axis tracking system capable of a rotational range of $\pm 60^\circ$. This dynamic orientation allows the modules to transition from east to west while tracking the solar trajectory throughout the day, enhancing the total energy yield. In accordance with the previously discussed configurations, a consistent vertical clearance (H) of 2.1 m is maintained between the modules and the terrain to ensure regulatory compliance and facilitate agricultural operations [33].

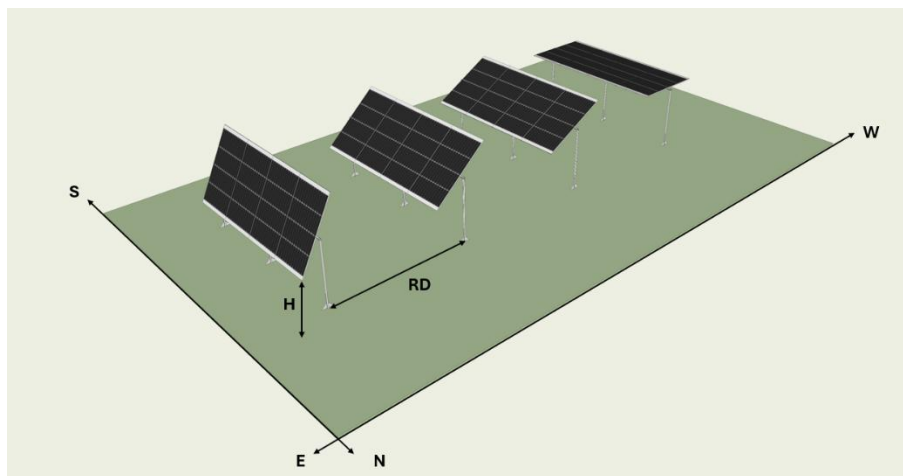


Figure 5.4: Scheme of the tracking panels configuration

Regarding long-term performance, the selected modules exhibit a power degradation rate of 1.0% during the first year of operation, which subsequently stabilizes at an annual decline of 0.3% from the second year onward, effectively guaranteeing a performance ratio exceeding 90% throughout the projected lifetime [60], [62].

PARAMETER	PANEL MODEL	
	Himalaya G12 Series	Kunlun G12 Series
Dimensions	2384 x 1303 x 33 mm	2384 x 1303 x 33 mm
Power [W]	730	720
Efficiency [%]	23.5	23.2
Temperature coefficient [%/°C]	-0.24	-0.24
Bifaciality [%]	-	97 ± 3
Yearly degradation	<1% the first year <0.3% the next years	<1% the first year <0.3% the next years

Table 5.1: Summary of the photovoltaic modules main properties [60], [62]

For the calculation of the Land Equivalent Ratio, a traditional ground mounted photovoltaic plant is established as the reference case. This reference facility employs the *Himalaya G12 Series* solar panels in a fixed and south-facing orientation with an optimized tilt angle of 32.14° derived via Equation (23). The inter-row distance (RD) is calculated as 4.72 m through Equation (24), as suggested by [61].

$$RD = L * \cos\Sigma + L * \frac{\sin\Sigma}{\tan\alpha_s} * \cos\gamma_s \quad (24)$$

In particular, L is the length of the solar panel, Σ is the tilt angle from Equation (23), γ_s is the azimuth angle and α_s is the solar altitude. To ensure a conservative design that minimizes inter-row shading under worst-case conditions, the solar geometry for the reference plant is fixed at the winter solstice (December 21st) at solar noon, representing the lowest solar elevation of the year.

In the simulations, all variables are expressed as a function of the inter-row distance, selected as the primary design variable due to its high flexibility. Since it defines the number of solar panels installed, it directly affects the electricity production, the shading level at the ground level and thus the crop yield. Knowing that the *Himalaya G12 Series* has dimensions 2.384x1.303 m, the row distance varies from 3 m to 20 m for the fixed tilted and tracking configurations. For the second simulation, the narrower interval between 5 m and 20 m is considered, to ensure sufficient space for the passage of agricultural machinery.

PARAMETER	TYPE OF CONFIGURATION		
	Fixed Tilted	Fixed Vertical	Tracking
Orientation	South and Portrait	East-West and Landscape	East-West and Portrait
Solar Panel	Monofacial	Bifacial	Monofacial
Tilt Angle [°]	32.14	90	$\pm 60^\circ$
Row Distance [m]	3-20	5-20	3-20
Clearance [m]	2.1	1	2.1

Table 5.2: Summary of the characteristics of the three agrivoltaic plants

5.2 Crop Yield Model

The growth of a crop is a very complex phenomenon that depends on the interaction between biological processes and environmental variables. Crop models are mathematical equations that simulate the plant physiology and its interaction with the surrounding ecosystem. These models can provide quantitative information about the major processes involved in plant growth and development and are essential for estimating the final state of crop yield.

So far, most of the models used in agrivoltaics adopt an empirical approach for the processes that are mostly affected by shading, such as photosynthesis, leaf structure, and the specific leaf area [3]. Empirical models might not be highly accurate, since photosynthesis and transpiration responses to environmental variables are strongly nonlinear. On the other hand, in a mechanistic approach photosynthesis and transpiration are first evaluated at the leaf level on a short time scale and then extended to the canopy level daily.

However, since AVS is still a relatively new technology and thus the research in the field are still limited, the empirical solutions generate reliable yield estimations using field observations that take into account the highly heterogeneous light environment caused by the moving shadows from solar panels [3].

The meta-analysis [57], supported by the results of [63], quantitatively assess the susceptibility of different crop types to increasing levels of Shading Rate (SR) or conversely Reduction of Solar Radiation (RSR). Crop type specific yield response curves are developed as a function of reduction in solar radiation (RSR), estimating crop yields compared to the unshaded controls.

The same meta-analysis screens a total of 613 studies, but to assure relevance of the studies chosen, only publications presenting data from field or pot trials in temperate and subtropical areas and reporting solar radiation and crop yield per area are included in the meta-analysis. The criteria for selection of the studies are reported in Table 5.3.

REASON	CRITERIA
Absence of Data	Total absence of yield information
	Absence of yield assessment on a per area base (also yield per plant is considered representative in case of an equal number of plants in shading and non-shading environments)
	Shading evaluation not conducted throughout the full growing season or exact shading period not mentioned
	No exact data reported on the mean reduction in solar radiation (RSR), photosynthetically active radiation (PAR) or level of shading
Not Acceptable cases	Data from outside of temperate or subtropical regions
	Experiments from greenhouses as the system difference to AV was considered too large
	Experiments without an unshaded control treatment
	Minor crops, such as medicinal herbs, ornamental plants or plants not relevant for temperate regions, such as rice, cotton and cocoa
	Additional implementation of treatments other than shading, which are not applied to the corresponding control case

Table 5.3: Criteria to select the papers [57]

In light of all these criteria, only 58 studies out of 613 provide proper data on the effects of shade on the yield of 38 different crop species [57]. Data on the individual crops are then aggregated into nine crop type groups based on crop physiology and data availability: berries, fruits, fruity vegetables, leafy vegetables, cereals, maize, tubers/root crops, grain legumes and forage.

While necessary due to a scarcity of studies on individual crops, the aggregation of the crops in several categories assumes significant differences in the response of one aggregated crop type compared to another, but at the same time masks heterogeneities between different crops within a given crop type and thus if the aggregated crops are heterogeneous, this leads to a higher uncertainty for the predictions of a specific crop [57].

The yields were standardized to the variable “yield under shading,” defining the unshaded control as 100% yield. The standardization is done because the focus of this study is the yield response to shading and this allows for a common scale across included publications. This is assumed to be the best manner to manage the range of site conditions and crop types in the different studies, which include different climatic zones and soil conditions [57].

The variables of interest are the crop type and attenuation in solar radiation or light intensity, which is expressed differently in the varying studies, such as reduction in PAR or shading rate. Due to the different ways that radiation and shading are represented, without always stating the baseline level of radiation, the paper uses the relative RSR compared to the control case as a standardized measure across the different studies. Accordingly, the model is constrained with a fixed intercept at the origin, based on the principle that a 100% RSR (or 0% SR) corresponds to a 100% crop yield [57]. The values RSR in the crop yield graphs are either derived from the level of shading or manually computed from the radiation under shading and the control.

Backwards elimination of fixed effects assures that only significant explanatory variables remain in the final model used to predict the response curves; in particular, the backwards elimination is done in a stepwise manner, removing fixed effects one at a time.

The process includes the systematic elimination of the variables with the highest p-values, that indicate low statistical relevance, until only those with the lowest p-values (<0.05) remain. As a result of the backward elimination, only SR and the quadratic term of SR (SR^2) are the main drivers of the crop yield models, suggesting strongly non-linear response curves [57].

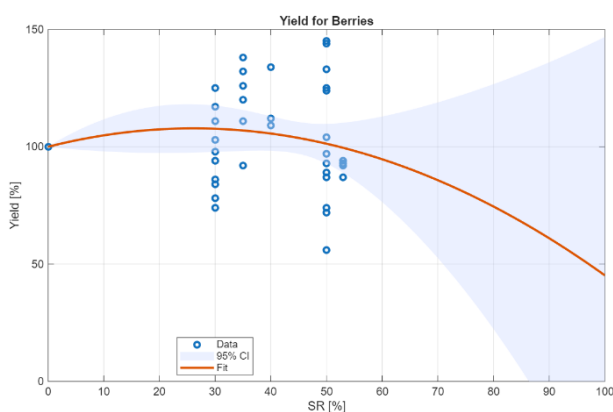
In contrast, there is no evidence of a significant difference in the response of the crop yield to RSR between intercropping and shading-only experiments or whether cloths, PV panels or nets are used for shading [57]. Moreover, absolute level of radiation does not significantly affect the response curves too.

5.3 Crop Yield Model Results

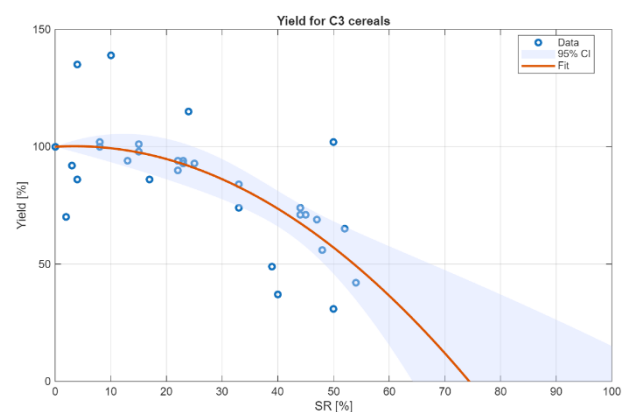
The results from [57] suggest a non-linear relationship between achieved crop yields and reduction in solar radiation for all crop types. Most of the crops tolerate a RSR or SR up to 15% showing a less than proportional yield decline. However, the response of the crops to SR results so different among crop types, that some crops may even benefit from an increase of shading level, increasing their yield.

As Figure 5.5 shows, berries, fruits and fruity vegetables benefit from a reduction in solar radiation up to 30%, 25% and 20% respectively, increasing the harvestable yield. Forages, leafy vegetables, tubers/root crops, and cereals initially show less than proportional crop yield loss, until at least 20% SR. In contrast, maize and grain legumes are most susceptible to RSR and experience strong crop yield losses even at low shade levels. At around 50% of shading, all crops show susceptibility, with a reduction of the crop yield. Estimating the shade effect on crop yields for very high levels of SR ($>75\%$) is associated with high uncertainty as it would require extrapolations beyond the range of data available; in fact, the 95% confidence intervals tend to expand significantly for high values of SR.

The results of this meta-analysis show the relationship between SR and crop yield helps that helps to optimize the level of shade in AV system. In fact, this meta-analysis includes a sufficient range to assess the suitability of crops in AV and other dual land-use systems.



a) Berries



b) Cereals

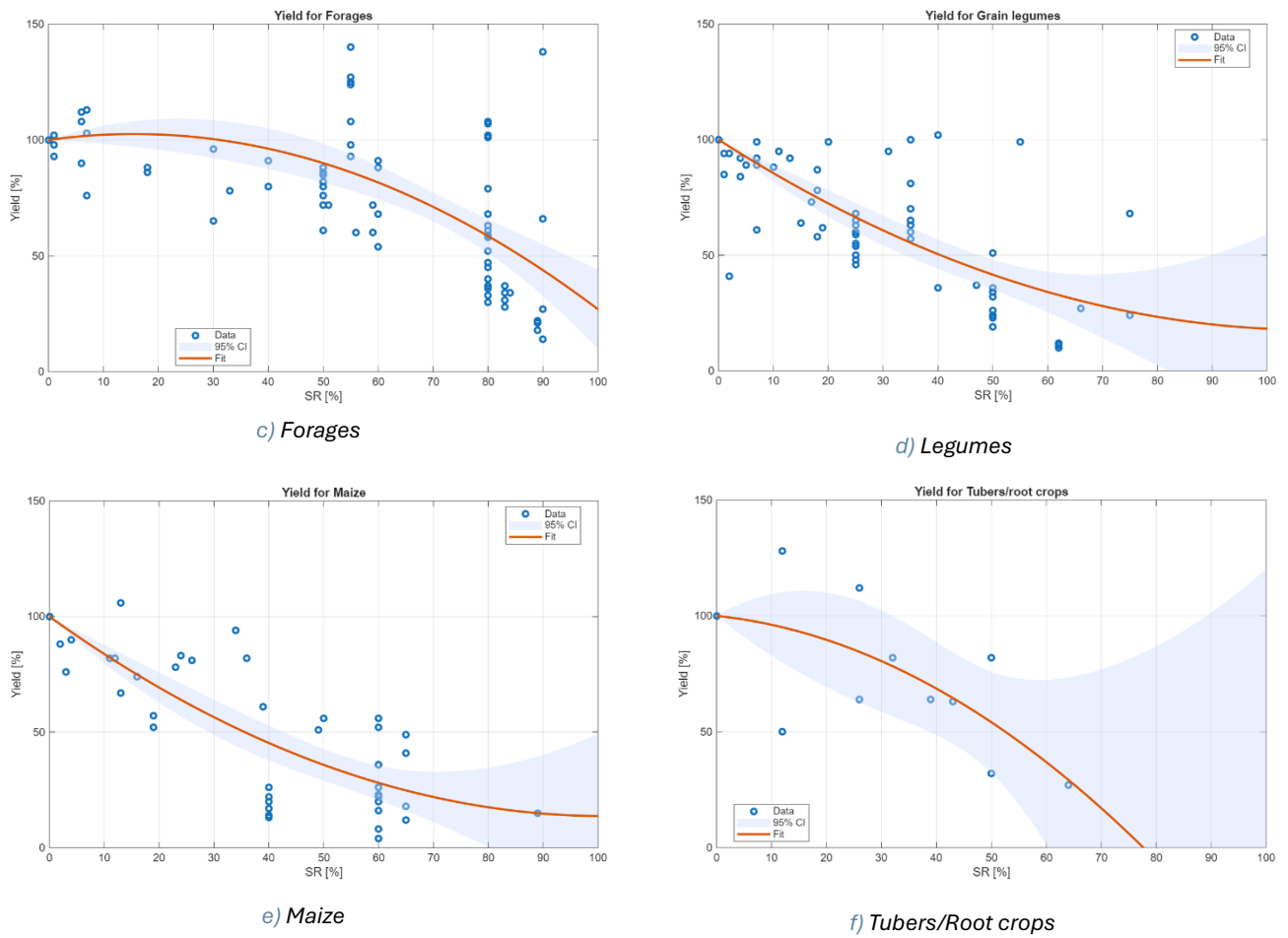


Figure 5.5: Results of the meta-analysis of several crops [57]. The light blue areas represent the 95% confidence intervals.

The level of SR of AV systems depends on the density of PV panels. In AV systems with fixed solar panels, the SR typically ranges between 28% and 50%, while PV systems optimized for electricity production, are assumed to reduce the solar radiation by 50% and more. However, AV systems rarely exceed 50% SR, because they must comply with national regulations and laws that set a maximum GCR and a minimum crop yield.

The results of the meta-analysis [57] may also contribute to the standardization and policy forming processes, in which the eligibility for support to AV systems with different levels of shading has to be determined. In some cases, AV systems are defined according to the level of yield reductions and thus the results of the analysis may help policymakers and relevant stake holders to better understand the relationship between shading and yield loss and to better defining acceptable yield reductions of AV systems or alternatively maximum levels of RSR across different AV system designs.

The main limit of the model is that it estimates the difference in the reaction to RSR between different crop types mostly based on independent experiments [57]. The ideal condition would include experiments with different levels of shade at the same sites, allowing to build a more precise yield response curves as a function of the shading level. However, synthesized knowledge on the effect of

shading on crop yields is still rare and the few studies on crop growth beneath AV systems are limited to fixed solar panels.

The choice of this model is based on the difficulty in implementing other ones that are either not accessible to the general public or require data that are complex to assess without an experimental campaign, such as soil quality, CO₂ concentration and water quality and availability.

In this thesis, leafy vegetables, fruity vegetables and fruits that consist in lettuce, tomato and fruit respectively are analysed, since they are the most suitable crops for the location selected and they are also the most studied ones in agrivoltaics systems. While lettuce represents the category of shade tolerant crop, tomato and grapes are shade-benefitting crops, as Figure 5.6.a, Figure 5.6.b, and Figure 5.6.c show [57].

Lettuce yields exhibit a non-proportional decline at low Shading Ratios (SR); however, productivity drops significantly once the SR exceeds 30%. In contrast, tomato and fruit crops respond positively to moderate shading, maintaining or even exceeding 100% yield at SR levels up to 30%.

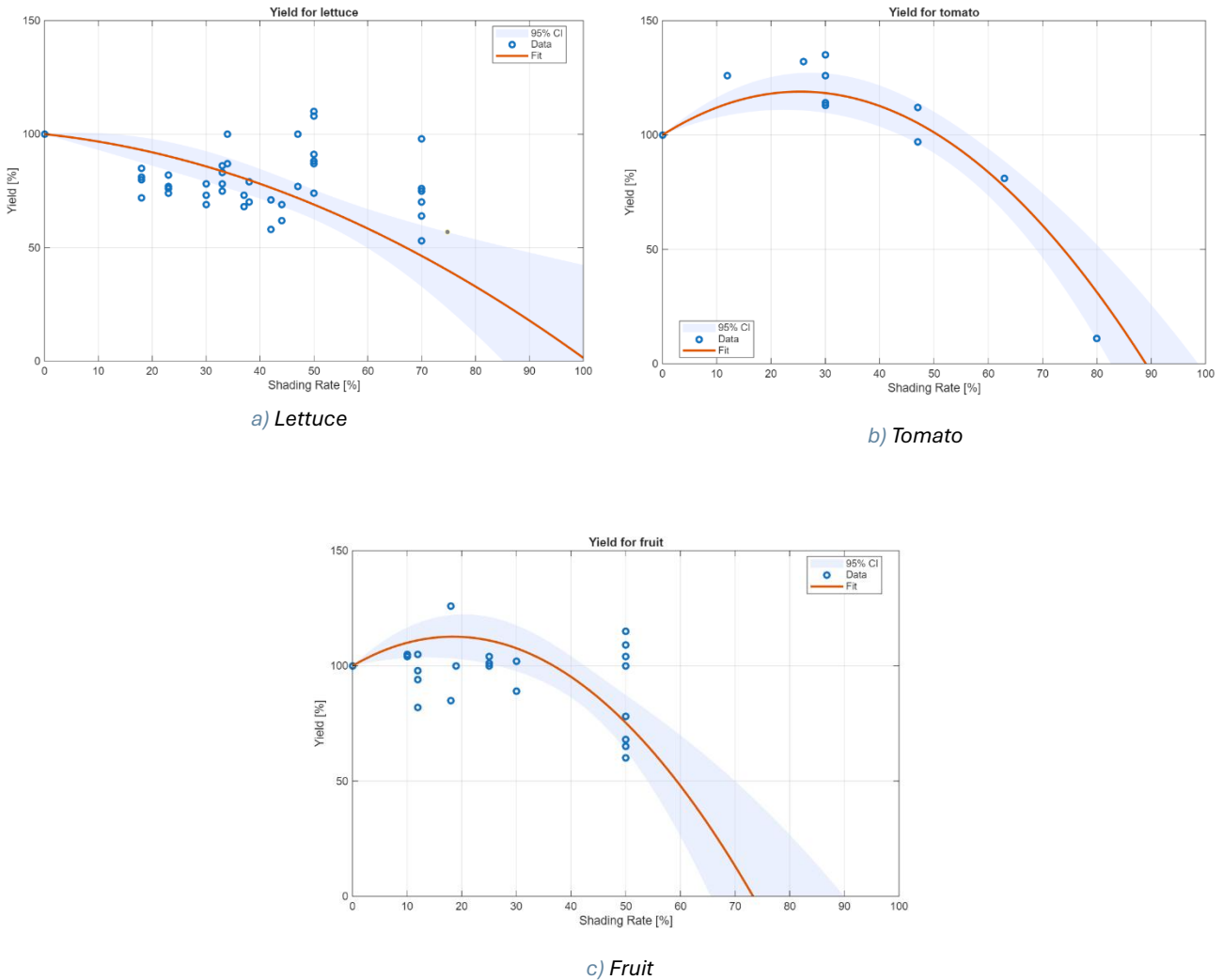


Figure 5.6: Results of the meta-analysis of the crops selected for the thesis [57]. The red curve is used for the simulations of the thesis. The light blue areas represent the 95% confidence intervals.

5.4 Shading Model

5.4.1 First Shading Model (Grid Model)

The accurate quantification of crop yield within an agrivoltaic system necessitates a robust numerical model capable of evaluating the shading rate. Following the methods proposed by [64] and [65], the first model developed in this thesis through MATLAB defines the three-dimensional coordinates of the photovoltaic arrays and projects their geometries onto the ground plane. To achieve an optimal balance between computational efficiency and resolution, the simulation employs a temporal step of one hour and a spatial resolution of 1 meter. This allows for the capture of dynamic shadow movements across the crop canopy throughout the vegetative cycle.

The computational procedure begins by determining the precise position of the Sun for a given geographic latitude, longitude and day of the year. After defined the declination angle and the hour angle, the model determines the zenith angles (θ_z), azimuth angle (γ_s) and solar altitude (α_s), with the equations presented in the Paragraph 1.2.

These parameters are the synthesized into a unitary solar vector (s) which identifies the direction of the Sun relative to the panel surface at any instant. This vector serves as the mathematical basis to dictate the trajectory along which the panel's vertices are projected toward the ground. The solar vector is constructed via Equation (25), as represented by [64].

$$s = \begin{bmatrix} \cos\gamma_s * \cos\alpha_s \\ \sin\gamma_s * \cos\alpha_s \\ \sin\alpha_s \end{bmatrix} \quad (25)$$

To model the physical structure, the solar panels are represented as rectangles without any depth, defined by four vertices. These coordinates account for the installation height, which is always kept to a minimum of 2.1 meters to comply with Italian regulatory standards for agricultural clearance, as well as the tilt and orientation of the modules.

For each time step, the model calculates the intersection of the rays originating from these vertices with the ground plane ($z=0$). The intersection point on the ground for any point on the panel is calculated in the opposite direction of the solar vector. The resulting projected points are then used to reconstruct the perimeter of the shadow on a discretized 1-m grid covering the entire field.

The model processes these projections by generating a logical matrix for every hour of the simulation. Each grid node is assigned a binary value: 1 indicates that the point resides within the polygon defined by at least one panel's shadow, while 0 signifies that the point is fully irradiated. To maintain physical consistency and avoid the numerical instability of infinite shadows during sunrise and sunset, a threshold for the solar altitude is established at 5°. Positions below this limit or behind the panel's plane are excluded. Finally, the instantaneous shading rate is calculated as the ratio of shaded points to the total number of points in the grid. This computational procedure is executed iteratively across all panels for every hour of the year, enabling the determination of the average annual shading rate.

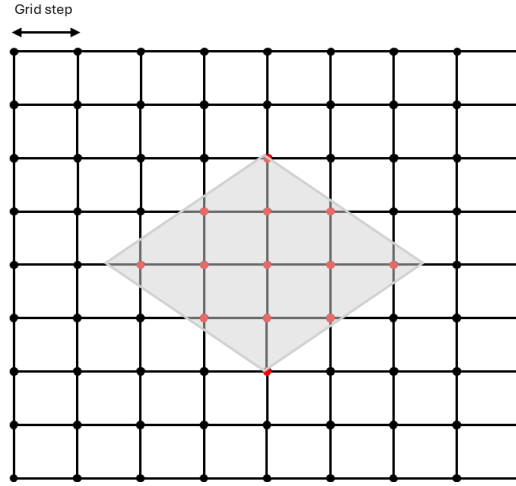


Figure 5.7: Visual representation of the Grid model. The grey area represents the shadow casted by the solar panel. The red points are regarded as shaded and will assume the binary value 1

The same model evaluates the mutual shading which occurs when one PV row casts a shadow on the row immediately behind it. This phenomenon is crucial because it directly impacts the energy production of the plant. The model calculates the mutual shading fraction based on the profile angle (ϕ_p), which is the Sun's altitude (α_s) relative to a given azimuth. The profile angle is computed in Equation (26).

$$\tan(\phi_p) = \frac{\tan(\alpha_s)}{\cos(\gamma_s - \gamma_{panel})} \quad (26)$$

If the projected shadow length on the ground (S_{ground}) exceeds the current row distance (D_{row}), there is mutual shading. The model then calculates the length of the shaded portion (L_{shaded}) along the tilted surface of the panel with Equation (27).

$$L_{shaded} = (S_{ground} - D_{row}) * \frac{\sin(\phi_p)}{\sin(\phi_p - \beta)} \quad (27)$$

In Equation (26) γ_{panel} is the azimuth angle of the panel and in Equation (27) β is the tilt angle of the pane.

Lastly, the model computes the mutual shading fraction as the ratio of L_{shaded} to the total length of the panel, that is then used to correct the electricity production of the AVS.

5.4.2 Second Shading Model (Polygon Model)

Building upon the geometric foundations of the initial model, the second version represents a significant evolution in computational methodology, transitioning from a discrete approach to a continuous technique. While both models share the same fundamental solar geometry and design parameters, the primary distinction lies in the quantification of the shaded area at the ground level.

In the original model, the shading rate is determined by discretizing the field into a 1-meter grid and building a logical matrix to check whether each point is enclosed by a shadow. However, this method is computationally very expensive and subject to discretization errors, especially for high values of the grid steps.

Instead of checking the individual grid points, the second model, through the same MATLAB tool, treats a single PV row as a large rectangle of width $N_{panels} * W_{panels}$ and for every hour with $\alpha_s > 5^\circ$ it projects the polygon onto the ground plane using the same solar vector logic as the previous model. The projected vertices form a complex polygon whose area represents the shaded region. This result is then multiplied by the number of rows, obtaining the total shaded area. This procedure is iterated for every hour of the year, enabling the determination of the average annual shading rate.

The model defines a *Field Polygon* to create the boundary of the agrivoltaic field and ensures that only the portions of the shadows falling within the actual agricultural area are considered, particularly important for the last rows whose shade are more prone to fall outside the considered field. To handle overlapping shadows and avoid counting the same area twice, the model uses the *union* function, merging all overlapping polygons into one.

The correct shaded area is calculated directly through the geometric area of the resulting unified and clipped polygons, rather than by counting grid point, guaranteeing a much higher precision.

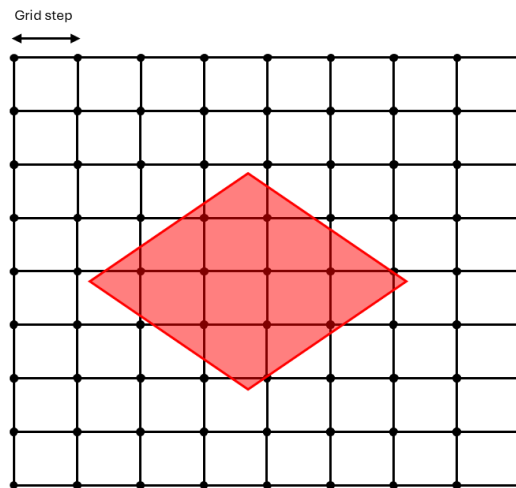
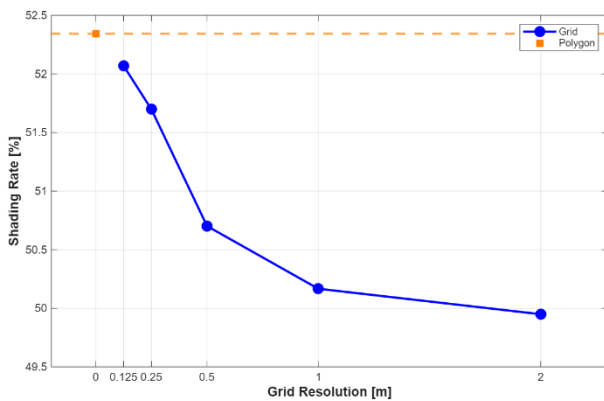


Figure 5.8: Visual representation of the Polygon model. The red area represents the area casted by the solar panel.

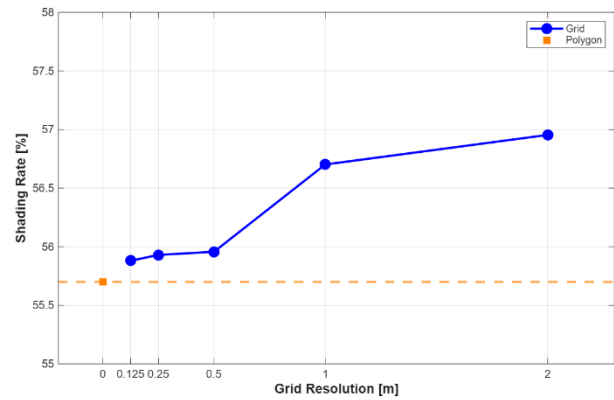
5.4.3 Choice of the Shading Model

To determine the most robust approach for estimating shading rate, a comparative analysis is performed between the *Grid* model and the *Polygon* model, both created in MATLAB. This evaluation focuses on how the spatial discretization of the grid-based approach influences the accuracy of the shading rate compared to the continuous geometric representation of the second approach.

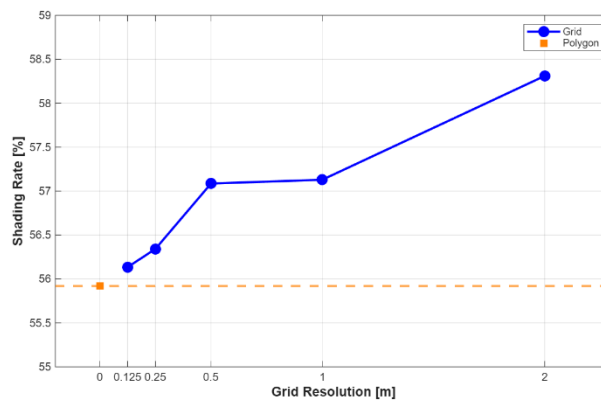
For computational efficiency during this validation phase, the simulation is constrained to a representative layout consisting of two rows spaced 5 m apart. While the *Polygon* model provides a result independently from the spatial resolution, relying only on solar geometry, local geography and analytical intersections, the *Grid* model's accuracy is strictly constrained to its resolution. Consequently, the *Grid* model is tested across four distinct spatial resolutions: 2.0 m, 1.0 m, 0.5 m, 0.25 m and 0.125 m.



c) Fixed tilted panels



d) Fixed vertical panels



e) Tracking panels

Figure 5.9: Results of the shading model comparison

As Figure 5.9.a, Figure 5.9.b and Figure 5.9.c depict, the SR values calculated by the *Grid* model asymptotically approach the value obtained from the *Polygon* one, as the grid step is refined. At the highest resolution of 2.0 m, the discretization error is significant, and it exceeds the 2 percentage points in some cases. Such a margin can lead to substantial inaccuracies in annual energy yield predictions.

On the other hand, by improving the grid resolution to 0.125 m, the discretization error is drastically reduced, with the deviation between the two models narrowing to within a few decimals of a percentage point.

The analysis demonstrates that the *Grid* model is highly sensitive to the chosen step size and, while the 0.125 m grid provides high accuracy, it comes at a much higher computational cost compared to the *Polygon* model, which achieves superior precision without the need for a dense mesh. To achieve a level of precision comparable to the *Polygon* model, a very fine grid is required, which become extremely time consuming for large-scale utility plants.

Given its independency from the resolution and lower margin of error, the *Polygon* model is identified as the better choice for an accurate shading analysis in this thesis.

6 Results

The crop growth model and the shading model are subsequently applied to the three different agrivoltaic configurations: fixed tilted, fixed vertical, and single-axis tracking systems. Each configuration is evaluated in combination with the three crop types selected (lettuce, tomato, and fruits). For each scenario, the crop yield, electricity production, and Land Equivalent Ratio (LER) are calculated in order to identify the optimal system configurations.

6.1 Shading Model Outcomes

To further analyse the shading models, the results obtained from the *Grid* and *Polygon* methods are interpolated and benchmarked against theoretical expectations established in Paragraph 4.1. The degree of shading varies significantly based on the system type: fixed panels typically cast less shadow and their theoretical baseline is defined by Equation (28). Conversely, tracking systems cast a higher degree of shadow, necessitating the use of Equation (29) for the comparative analysis.

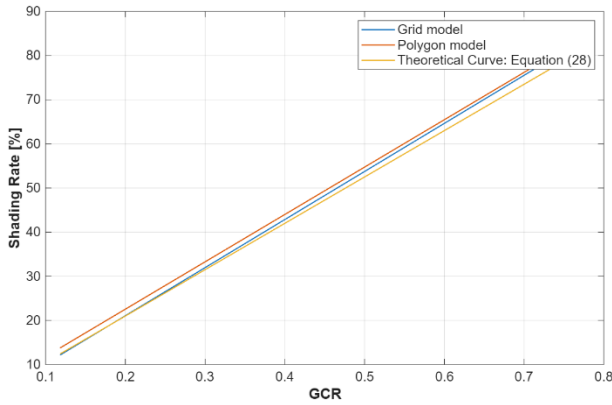
$$SR = 1.05 * GCR \quad (28)$$

$$SR = 1.10 * GCR \quad (29)$$

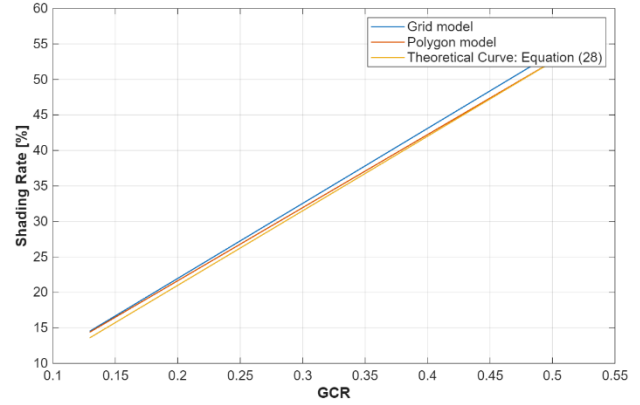
The Figure 6.1.a, Figure 6.1.b and Figure 6.1.c represent the *Grid* method results with the blue line, the *Polygon* method ones with the red line and the theoretical curve is in orange. The discrepancies between the thesis models and the theoretical baseline are expected, as the latter is derived from empirical data subject to specific site locations and different measurement and calculation methodologies.

Overall, both approaches align closely with the theoretical results, especially for fixed-panel configurations. In the tracking system scenario, the *Grid* method maintains consistent trend relatively to the theory but exhibits higher absolute values. This reduction in accuracy comes from the increased complexity of discretizing a solar field that changes its inclination hourly. On the other hand, the *Polygon* method demonstrates superior precision, overlapping with the theoretical line, but this occurs in the

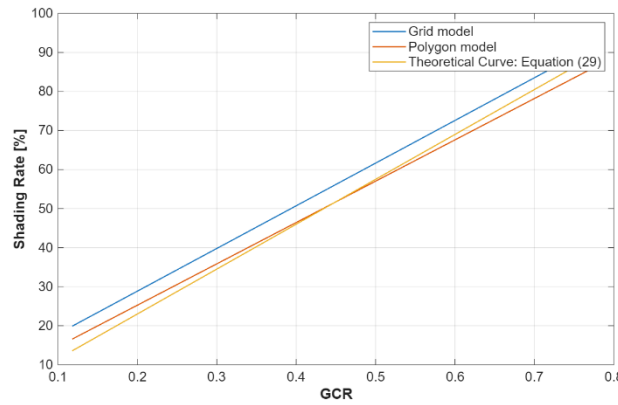
first two cases as well. This higher degree of precision across all cases confirms that the *Polygon* method is the more accurate tool for modelling shading dynamics.



f) Fixed tilted panels



b) Fixed vertical panels

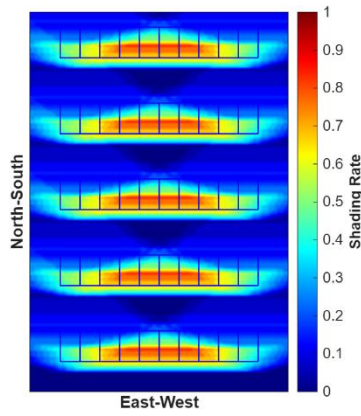


c) Tracking Panels

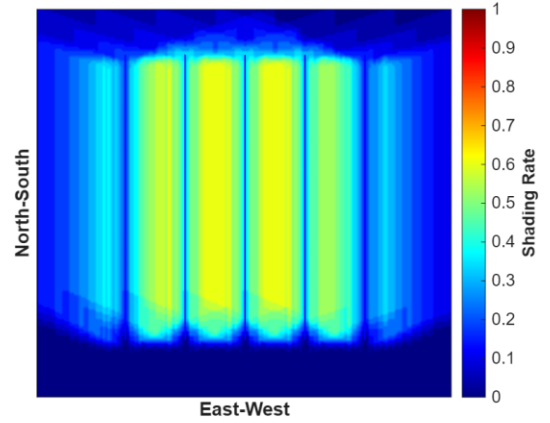
Figure 6.1: Shading model results

To visualize these shading dynamics, contour maps are generated to represent the daily shading rate trends at the fixed row distance of 5 m, specifically for the summer solstice on June 21st, for the winter solstice on December 21st and for the annual case. As illustrated in Figure 6.2.a, Figure 6.2.b and Figure 6.2.c, fixed tilted panels cast shadows mainly directly beneath the modules themselves. This results in a highly heterogeneous distribution of solar radiation, which may lead to localized variations in the crop yield. Such non-uniformity can be detrimental, as specific areas of the plot may suffer from either excessive shading or high levels of direct solar radiation, both of which can inhibit optimal plant development. While tracking technology exhibits a similar pattern of localized shading, it produces a higher overall shading intensity, consistent with the findings in the previous sections.

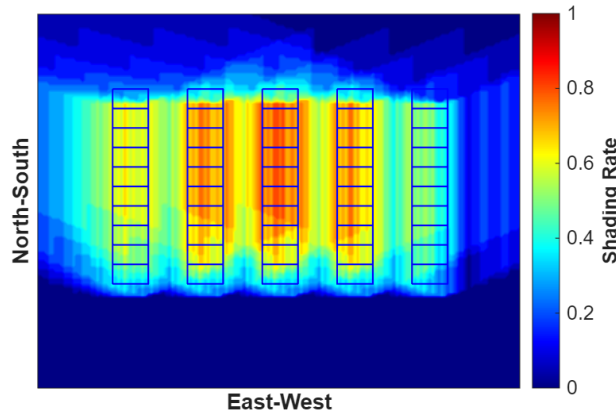
In contrast, vertical bifacial panels demonstrate average shading rates comparable to those of fixed tilted systems but offer a significantly more distributed shading profile. By spreading the shadows more broadly across the field, vertical installations ensure a more homogeneous light environment throughout the day. This uniformity is a critical advantage of vertical agrivoltaics, as it fosters more consistent crop growth and mitigates the risks associated with extreme light gradients.



g) Fixed tilted panels



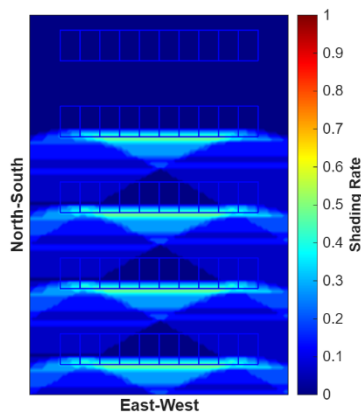
b) Fixed vertical panels



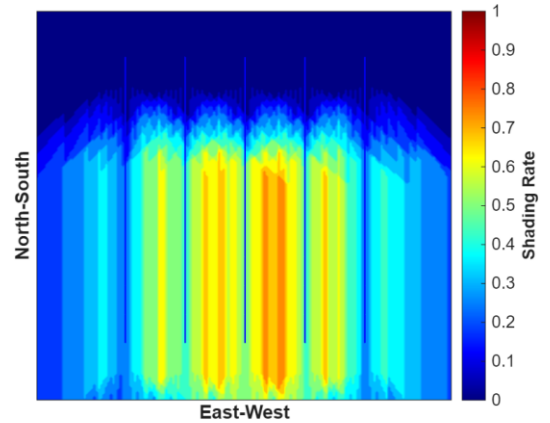
c) Tracking Panels

Figure 6.2: Contour maps of the shading level at a row distance of 5m on 21st June

As depicted in Figure 6.3.a, Figure 6.3.b and Figure 6.3.c, the shadows casted in the winter case are more pronounced and extend significantly further in the northerly direction compared to the observations recorded on June 21st, due to the lower solar elevation relative to the horizon. Consequently, the spatial distribution of shading levels appears substantially more heterogeneous, even though the magnitude of the local shading intensity may result lower compared to the summer case.



h) Fixed tilted panels



b) Fixed vertical panels

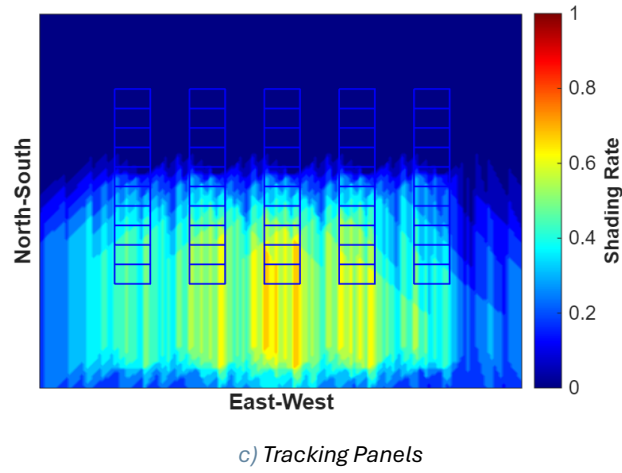


Figure 6.3: Contour maps of the shading level at a row distance of 5m on 21st December

Figure 6.4.a, Figure 6.4.b and Figure 6.4.c represent the annual shading trends. While the spatial distribution of these patterns remains largely consistent with the configurations observed during the summer case, the absolute shading values are notably attenuated.

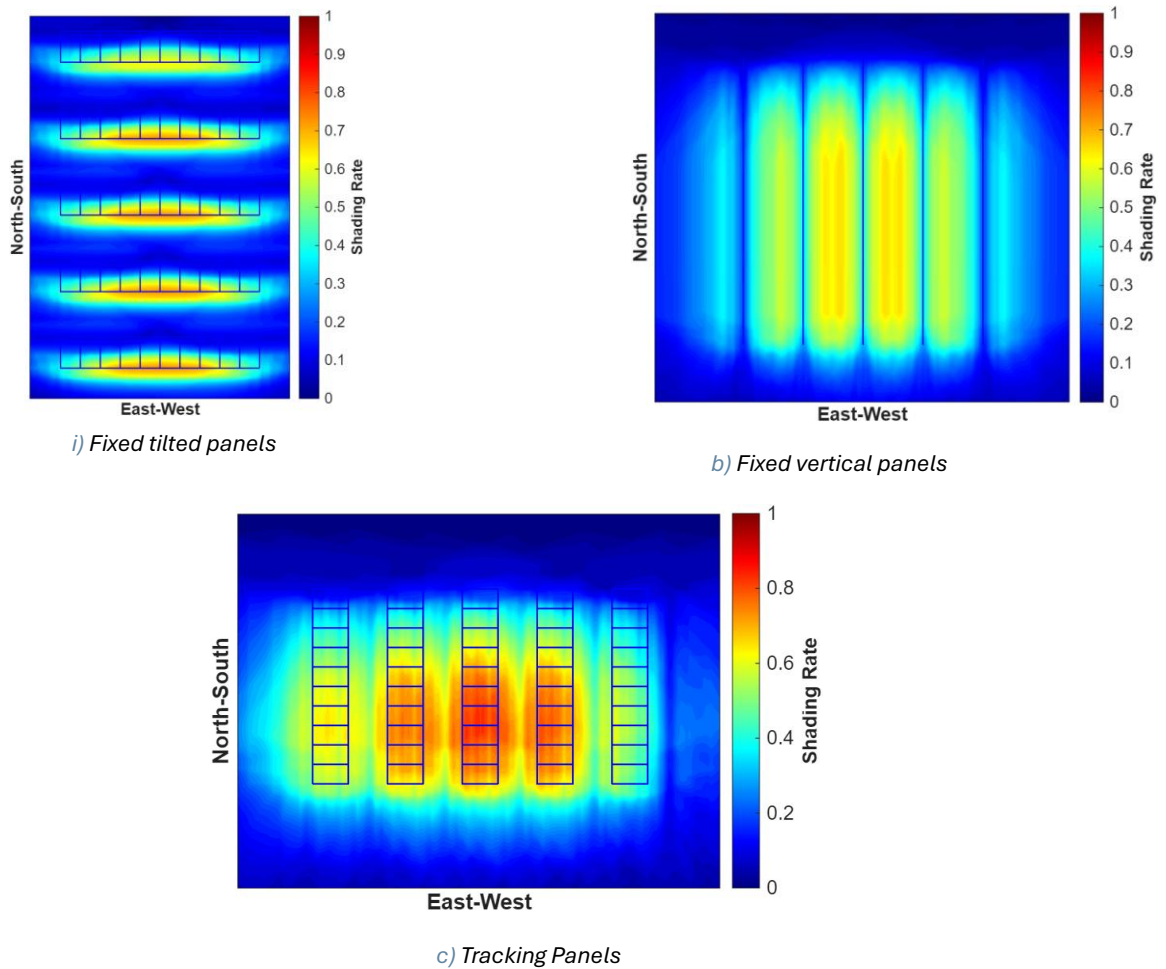


Figure 6.4: Contour maps of the shading level at a row distance of 5m on annual basis

6.2 Crop Yield

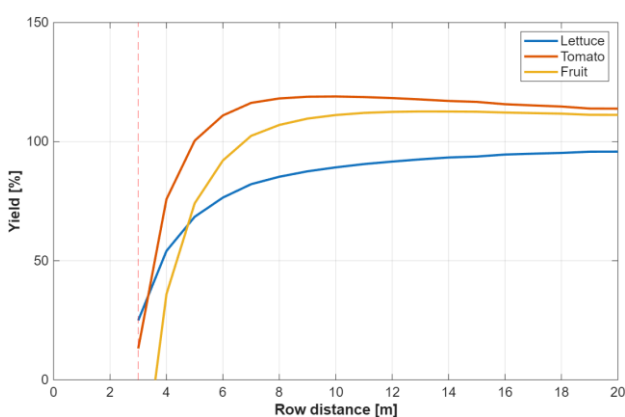
The relationship between panel row distance and the yield of the three analysed species (lettuce, tomato, and fruit) is illustrated in Figure 6.5.a, Figure 6.5.b, Figure 6.5.c. The results demonstrate a clear non-linear correlation between the spatial layout and the agricultural productivity, driven by the varying shading levels of each system.

At row distances below 5 m, the high shading rate creates an environment with insufficient light levels that severely compromises crop growth. For the fixed tilted and tracking configurations, yields for all species drop below 70% due to the persistent shadow cast by the dense array. As the row distance increases beyond 7 m, the available solar irradiance reaches a threshold that allows acceptable yield levels, even exceeding 100% for tomato and fruit cases thanks to their shade-benefitting biology. This suggests that the moderate shading provided by the PV modules protects the crops from excessive heat stress, creating a more favourable microclimate than full-sun conditions. The lettuce demonstrates its shade-tolerant nature by guaranteeing a non-zero yield for all row distances and all plant configurations.

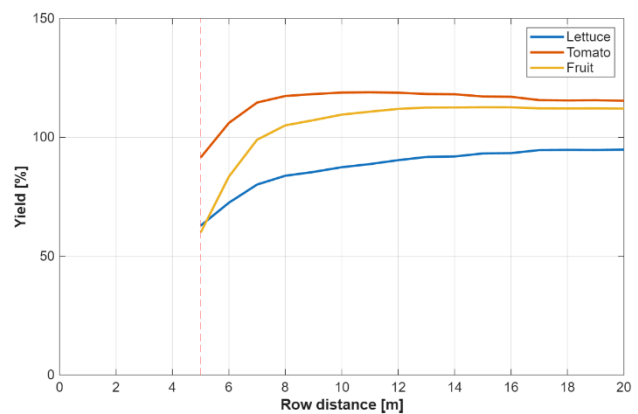
Due to the dynamic movement of the modules, the tracking system casts a more pervasive shadow throughout the day. Consequently, the yield curves increase more slowly and peak yields for fruit and tomato are shifted toward a wider inter-row distance of 10 m, compared to the fixed systems.

The vertical bifacial system presents a distinct trend. Since the minimum row distance is constrained to 5 m for technical choices, the starting yield values are significantly higher than those of the other two configurations, since the crops can benefit a higher irradiance level.

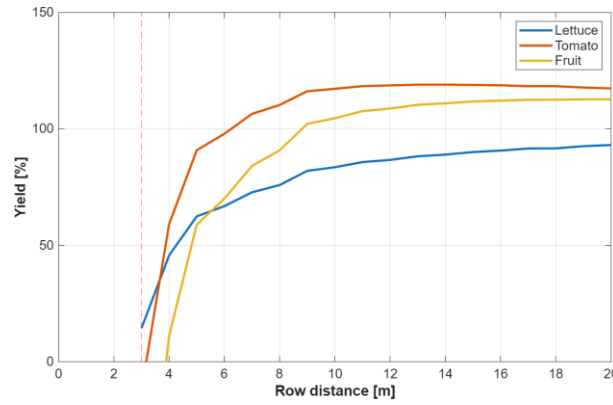
In all three configurations, as the inter-row distance approaches 20 m, the yields asymptotically converge toward 100%. This behaviour is consistent with the crop model's design: as the influence of the PV structure diminishes, the environmental conditions effectively return to a full-sun baseline.



j) Fixed tilted panels



b) Fixed vertical panels



c) Tracking panels

Figure 6.5: Yield results

6.3 Energy Production

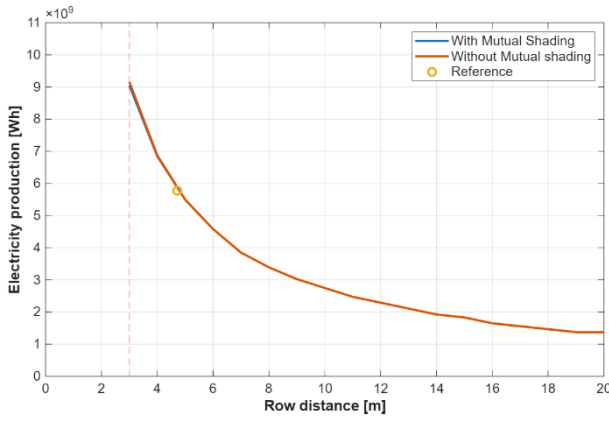
Figure 6.6.a, Figure 6.6.b, Figure 6.6.c illustrate the annual electricity production trends for the three agrivoltaics configurations as a function of the row distance, compared against a reference photovoltaic plant represented by the orange circle. As the inter-row distance increases, the total number of installed solar panels within the fixed area decreases, naturally leading to a reduction in the overall electricity yield in all configurations.

The fixed tilted panel configuration reaches a peak production close to 9 GWh/y at the minimum inter-row distance of 3 m, resembling the layout and performance of a conventional ground-mounted PV plant.

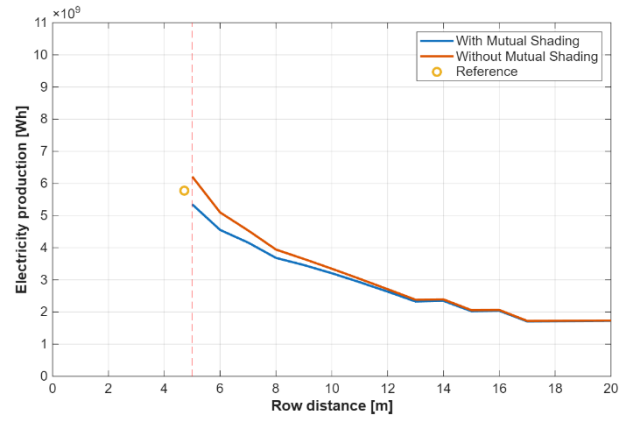
In contrast, the vertical panel AVS exhibits the lowest performance, with a production nearly half that of the other two systems. This significant disparity arises because vertical modules cannot effectively intercept solar radiation during midday, when solar irradiance is at its peak.

The tracking technology demonstrates superior performance by continuously adjusting the module orientation during the day to minimize the incidence angle of solar radiation. This optimization results in a production increase of approximately 10% over the fixed-tilt system.

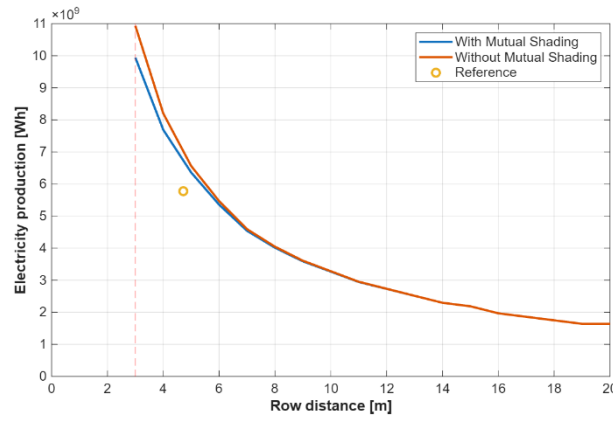
Although tracking systems are designed to maximize energy capture per individual module, they demonstrate a higher sensitivity to mutual shading compared to fixed tilted configurations. In this latter case, mutual shading influences minimally the electrical yield, affecting the performance only at low inter-row distances between 3 m and 5 m. Conversely, tracking systems remain susceptible to mutual shading at inter-row distances extending up to 13 m, with the magnitude of the negative effect intensifying as the row distance decreases, so that at the lowest inter-row distance the electricity production is reduced by 9.1%. Fixed vertical fixed panels experience the most pronounced degradation due to mutual shading across nearly all inter-row distances, exhibiting a 13% reduction in energy yield at an inter-row distance of 5 m. Lastly, the electricity production is adjusted according to the cell efficiency through Equation (18), which depends on both ambient and cell temperatures.



k) Fixed tilted panels



b) Fixed vertical panels



c) Tracking panels

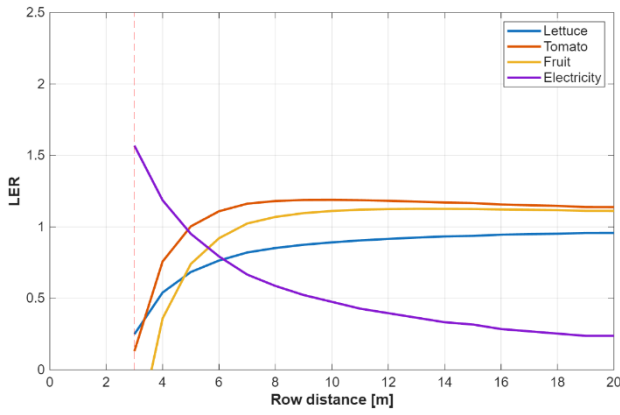
Figure 6.6: Energy production results

6.4 Land Equivalent Ratio (LER) and Optimal Configurations

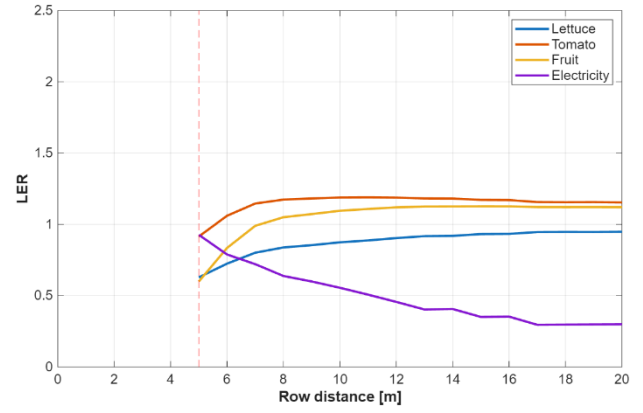
The Land Equivalent Ratio (LER), as defined by Equation (19), provides a quantitative measure of the land-use efficiency of agrivoltaic systems compared to the single land uses. The individual contributions to the LER, calculated via Equation (30) and Equation (31), are presented in Figure 6.7.a, Figure 6.7.b and Figure 6.7.c. These figures separate the crop yield component from the electrical generation component to illustrate their distinct behaviours. The observed trends align with the crop yield outcomes in Paragraph 6.2 and the electricity production data in Paragraph 6.3. In this analysis, the baseline case for electricity is a conventional monofacial PV system oriented south, while for the crop yield is the performance under full-sun conditions.

$$LER_{crop} = \frac{Y_{agri-APV}}{Y_{agri}} \quad (30)$$

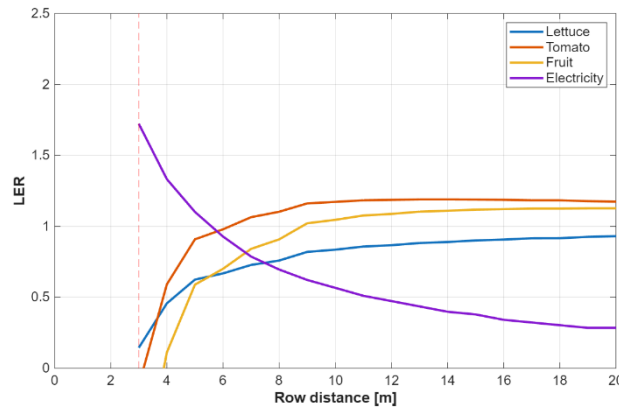
$$LER_{electricity} = \frac{Y_{energy-APV}}{Y_{PV}} \quad (31)$$



a) Fixed tilted panels



b) Fixed vertical panels

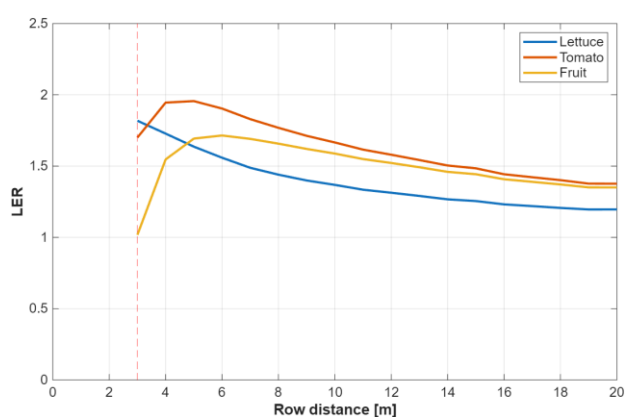


c) Tracking Panels

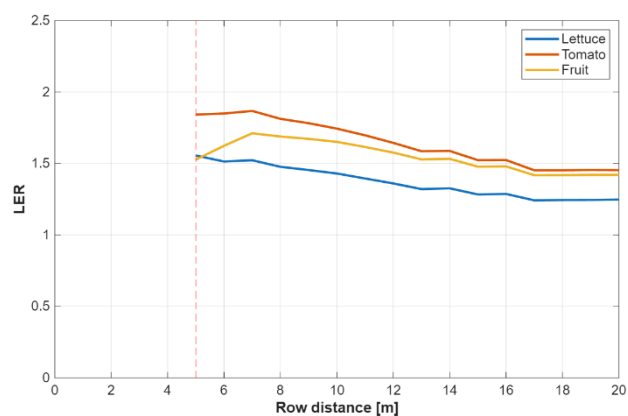
Figure 6.7: Land Equivalent Ratio separated results

The total Land Equivalent Ratio, which is given by the sum of the individual components, is displayed in Figure 6.8.a, Figure 6.8.b and Figure 6.8.c. The peaks of these curves identify the optimal configurations for the agrivoltaic installations. These maximum values are primarily concentrated within a row distance range of 4 m to 8 m, showing LER values between 1.5 and 2.0. Such results indicate that the integrated agrivoltaic system significantly outperforms the separate agricultural and energy productions in terms of land-use efficiency, effectively improving the utility of the land.

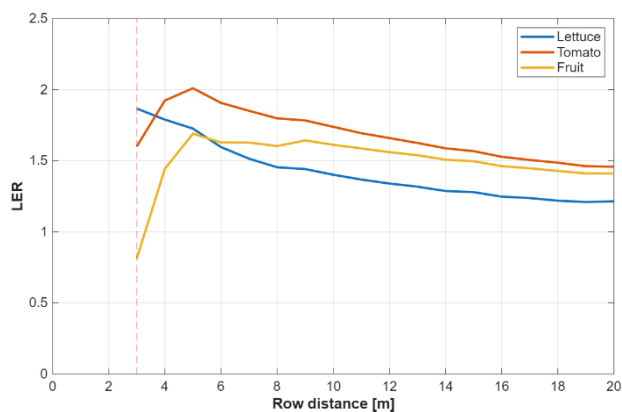
At shorter row distances, the LER remains near its maximum due to the high density of photovoltaic modules, which produces an electrical output comparable to traditional solar farms. However, at these narrow spacings, agricultural productivity is severely diminished by insufficient solar irradiance, often resulting in a LER for the crop component of less than 0.5. Conversely, as the row distance increases, the electrical contribution diminishes, while the total LER asymptotically approaches 1.0, representing the baseline of a traditional farm without solar integration.



m) Fixed tilted panels



b) Fixed vertical panels



c) Tracking Panels

Figure 6.8: Land Equivalent Ratio total results

Based on this technical evaluation, Table 6.1 summarizes the optimal configurations identified, focusing strictly on performance metrics, without considering any economic or regulatory constraints.

CROP	PHOTOVOLTAIC CONFIGURATION		
	Fixed Tilted	Fixed Vertical	Tracking
Lettuce	1.869 (4 m)	1.555 (5 m)	1.866 (3 m)
Tomato	1.966 (5 m)	1.867 (7 m)	2.000 (5 m)
Fruit	1.721 (6 m)	1.711 (7 m)	1.690 (5 m)

Table 6.1: Summary of the optimal cases, the absolute values indicates the LERs and the lengths indicate the relative inter-row distances

7 Economic Analysis

7.1 Capital Expenditure

The fundamental assumption underlying the CAPEX calculation is that the agricultural land is already available, meaning the investment analysis focuses exclusively on the installation and integration of the photovoltaic system. Following the cost frameworks established by [66], the costs specific to the installed capacity for PV modules are valued at 340 €/kW. Auxiliary electrical equipment costs are estimated at 270 €/kW for fixed configurations and 295 €/kW for tracking systems.

The primary difference in CAPEX across the three studied scenarios comes from the supporting structures and their associated installation requirements, which differ significantly by technology. For fixed tilted systems, the support structure cost is approximately 270 €/kW. In contrast, vertical panels represent the most economical option for mounting at 180 €/kW, while tracking systems require the highest investment at 340 €/kW due to their mechanical complexity. Installation costs further differentiate these technologies, requiring 180 €/kW for fixed systems and 200 €/kW for tracking systems. Lastly, Engineering, procurement, and administrative costs are scaled at 120 €/kW for fixed tilted, 140 €/kW for fixed vertical, and 160 €/kW for tracking systems.

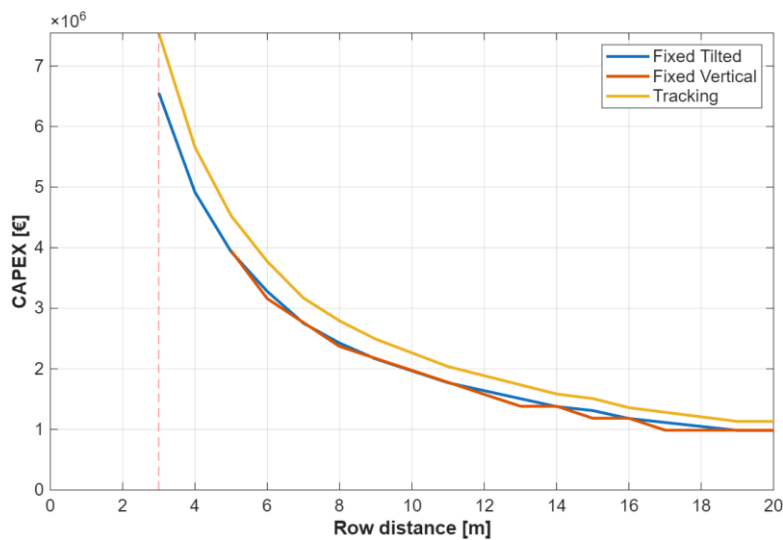


Figure 7.1: Capital Expenditure (CAPEX)

As illustrated in Figure 7.1, the total capital expenditure has a clear inverse relationship with inter-row distance. At the minimum distance, where the agrivoltaic density approximates a conventional PV plant, the CAPEX reaches its peak. The tracking system exhibits the highest initial investment at 7.5 M€, followed by the fixed tilted system at 6.5 M€ and the vertical system at 4.0 M€.

The tracking system's elevated CAPEX is a direct result of the more sophisticated technology, support structures, and labour-intensive installation processes required for dynamic orientation. While vertical panels utilize a more cost-effective mounting structure, their overall investment profile remains similar to the fixed tilted systems, because they employ a higher density of modules, specifically two panels stacked on top of each other.

COST ITEM [€/kW]	PHOTOVOLTAIC CONFIGURATION		
	Fixed Tilted	Fixed Vertical	Tracking
Photovoltaic panels	340	340	340
Auxiliary electrical equipment	270	270	295
Support structure	270	180	340
Installation	180	180	200
Engineering, Procurement and Administration	120	140	160

Table 7.1: Summary of the CAPEX [66]

7.2 Operating Expenditure

The evaluation of annual Operating Expenditure (OPEX) for the agrivoltaic system is based on the economic performance data the study [67]. For the photovoltaic component, the primary cost drivers include system maintenance and relative personnel, which are valued at 10,000 €/MW for fixed configurations and 11,000 €/MW for tracking systems. Additional overheads, including administrative fees and insurance, are estimated at 2,000 € and 5,000 € respectively, totalling 7,000 €/MW.

The agricultural management expenses, as detailed in [68], exhibit significant variability based on geographical location and crop selection. Input costs per hectare for fertilizers and seeds range from 700 € to 2,200 €, while for energy and water fluctuate between 2,000 € and 2,500 €. Labor represents the most substantial expenditure, accounting for 3,000 € to 7,000 €, followed by insurance and administrative costs of 1,300 € to 3,500 €. Yearly machinery maintenance further adds between 500 € and 1,500 € to the total. To ensure the robustness of the economic model, a conservative approach is adopted by utilizing the upper bound of these estimates. Consequently, the annual agricultural OPEX is fixed at 15,200 € per hectare, excluding the machinery costs.

SYSTEM	COST ITEM	COST
Photovoltaic system	Maintenance and Personnel	10 000 €/MW (Fixed configurations) 11 000 €/MW (Tracking configurations)
	Insurance	5000 €/MW
	Administration	2000 €/MW
Agricultural field	Fertilizers and Plant seeds	700 – 2200 €/ha
	Energy and Water	2000 – 2500 €/ha
	Labour	3000 – 7000 €/ha
	Insurance and Administration	1300 – 3500 €/ha
	Machinery Maintenance	500 – 1500 €/y

Table 7.2: Summary of the annual OPEX [67], [68]

As illustrated in Figure 7.2, the total OPEX remains relatively consistent across the three technological scenarios, though tracking systems maintain a slightly higher cost due to their increased mechanical complexity. At the minimum inter-row distance, where the installation density mirrors a conventional utility-scale PV plant, the total annual OPEX peaks at 130,000 €. This elevated cost is a direct function of the high volume of PV modules and associated maintenance requirements. As the inter-row distance increases, the total installed capacity decreases, leading to a steady reduction in operating costs. At a distance of 20 meters, the OPEX is approximately half of the initial value, reflecting the diminished infrastructure density.

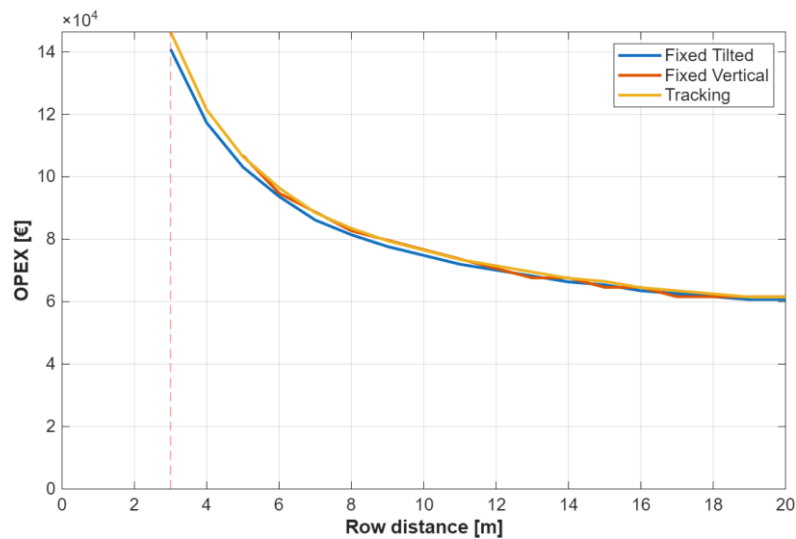


Figure 7.2: Operating Expenditure (OPEX) per year

7.3 Net Present Value

The financial attractiveness of the projects was examined by calculating the financial Net Present Value (NPV) of the investments. While the capital and operating expenditures are derived from standardized industrial and literature-based sources, estimating the agricultural productivity and the relative market revenues involves greater complexity. In fact, these variables are highly sensitive to geographical location, localized environmental conditions and specific crop characteristics.

For the revenue of the photovoltaic systems, the electricity price is fixed at 115 €/MWh that represents the 2025 average market price reported by the Gestore dei Mercati Energetici (GME). Regarding the agricultural component, the specific yields and market prices for the three selected crops are calculated as mean values from reports of the Chambers of Commerce (Camere di Commercio), regional consortia and statistical data provided by the Istituto di Servizi per il Mercato Agricolo Alimentare (ISMEA) [69], [70], [71]. The reported yield values are then adjusted to reflect the effects of shading on crop productivity, as derived in Paragraph 6.2. Given that the primary data for the fruit category in the study [57] refers viticulture, grapes are utilized as the representative crop for the NPV analysis of the fruit case. The summary of the reference values for the calculation of the NPV are summarized in Table 7.3.

PRODUCT	PRICE	YIELD
Electric energy	115 €/MWh	-
Lettuce	450 €/t	20 t/ha
Tomato	150 €/t	90 t/ha
Grape	700 €/t	30 t/ha

Table 7.3: Summary of prices and yields for the products of the AVS [69], [70], [71]

A critical distinction in the modelling concerns the harvest cycles of the selected crops. Although lettuce exhibits the lowest individual yield per cycle, its adaptability and short lifecycle of 90 to 120 days allow for multiple harvests annually [69]. To maintain a conservative approach, the NPV calculation assumes three harvest cycles per year for lettuce, despite a theoretical maximum of four. Conversely, grapes and tomatoes can have only a single harvest annually, aligned with the summer growing season.

The NPV is defined as the sum of the present values of the individual yearly cash flows. A project is financially feasible when the NPV is positive and thus the higher the NPV, the more profitable the project. The NPV is expressed by Equation (32).

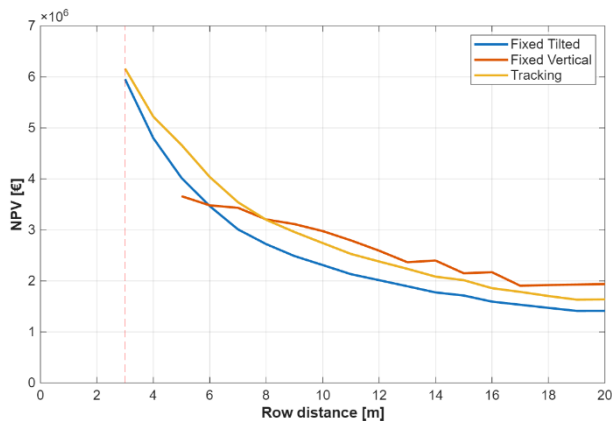
$$NPV = -I_t + \sum_{t=1}^n \frac{(R_t - M_t)}{(1 - r)^t} \quad (32)$$

In particular, I_t is the investment expenditures in year t , R_t are revenues year t , M_t represents the operations and maintenance expenditures in year t , r is the discount rate and n is the economic life of the system.

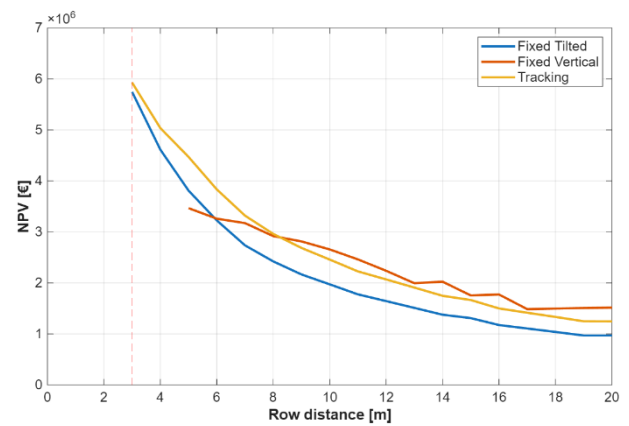
The economic performance of the agrivoltaics configurations is projected over a 30-year operational horizon, aligning with the estimated lifetime of the photovoltaic modules. To account for the opportunity cost of capital and the time value of money, a discount rate of 5% is applied, consistent with financial benchmarks for renewable energy projects [67], [72].

The Net Present Value (NPV) results, illustrated in Figure 7.3.a, Figure 7.3.b and Figure 7.3.c, reveal a consistent trend across all three crop varieties, with minor deviations arising from the influences between photovoltaic productivity, specific crop yields and market pricing.

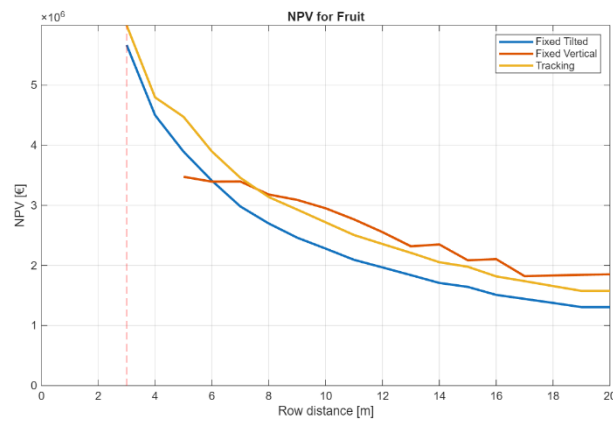
At shorter inter-row distances, the financial performance is primarily driven by electricity generation. In this high-density configuration, tracking systems achieve the highest financial returns, yielding an NPV of approximately 6 million € due to their superior energy production. Fixed tilted systems follow closely with an NPV of 5.7 million €, while the vertical configuration produces a lower initial NPV of 3.5 million €.



n) Lettuce



b) Tomato



c) Fruit

Figure 7.3: Net present value results

As the inter-row distance increases, the economic weight shifts from energy production to agricultural output. The reduction in the number of installed PV modules leads to a decline in the energy revenues, which is counterbalanced by an increase in crop yields facilitated by higher solar radiation availability.

A significant shift in economic preference occurs at an inter-row distance of 8 meters. Beyond this threshold, the vertical panel configuration emerges as the most financially advantageous option. This transition is attributed to two primary factors: the vertical disposition with two panels on top of each other allows for a higher power density compared to tilted or tracking systems and the vertical arrangement provides higher irradiance level and superior shading homogeneity. This optimized light distribution enhances crop yields more effectively than fixed tilted or tracking arrays, with similar CAPEX and OPEX, thereby maximizing the total integrated revenue of the agrivoltaic system.

8 Conclusions

This thesis utilizes a MATLAB simulation to evaluate the technical and economic performance of agrivoltaic systems across three distinct photovoltaic configurations and various crop types. The resulting model is characterized by its high degree of versatility, enabling the simulation of diverse agrivoltaic setups through the adjustment of the core parameters. This flexibility is demonstrated by the analysis of three photovoltaic configurations and the three crops varieties explored throughout the research.

A central component of the technical analysis involved the development of two distinct shading models. The first was derived from existing literature, while the second employed a more intuitive geometric approach. Comparative analysis identified the latter as the superior method for accurately capturing the light dynamics within the system.

The selection of an optimal agrivoltaic configuration is a multifaceted process that necessitates the simultaneous evaluation of technical, biological, economic, and regulatory factors. While the technical and economic findings are detailed in Paragraphs 6.4 and 7.3, these results must be integrated with the national regulatory framework for agrivoltaic systems outlined in Paragraph 2.3. Ultimately, the selection criteria prioritize systems that maintain full compliance with national legislation while maximizing the Land Equivalent Ratio, ensuring the highest possible efficiency in land use.

CROP	PHOTOVOLTAIC CONFIGURATION		
	Fixed Tilted	Fixed Vertical	Tracking
Lettuce	1.558 (6 m)	1.522 (7 m)	1.514 (7 m)
Tomato	1.904 (6 m)	1.867 (7 m)	1.851 (7 m)
Fruit	1.714 (6 m)	1.711 (7 m)	1.643 (9 m)

Table 8.1: Configurations that maximize the LER and comply with national regulations

Based on Table 8.1, the fixed tilted configuration emerges as the optimal setup across all evaluated crops when considering the Land Equivalent Ratio and broader societal impact. This configuration represents the most effective compromise between maximizing electricity generation, maintaining agricultural yield and ensuring overall economic feasibility. It is important to note, however, that the LER values remain relatively consistent across the three photovoltaic configurations. Consequently, if the primary objective shifts toward maximizing financial returns, the tracking system proves superior at an inter-row distance of 6 m, while either the tracking or vertical configurations become more attractive at greater distances due to their higher NPV.

8.1 Future Developments

Future research will focus on refining the critical parameters of the simulation framework to enhance its predictive accuracy. A primary objective is the advancement of the crop yield model; while the current models rely only on the solar radiation and geometry, future versions should incorporate the variation of the diffused component as well as complex biochemical factors such as soil quality, nutrient availability and the specific physiological growth behaviours of different crop species. An alternative methodology would involve calculating the shading rate at each discrete point within the field to determine the corresponding localized impact on agricultural productivity. The current reliance on the total shading rate presents a significant limitation to the accuracy of the model that does not consider the light distribution uniformity. Furthermore, the two models proposed do not consider the temporal distribution of shade on the crops, even though identical annual shading rates can be produced through different daily shading patterns. For instance, intermittent shading or prolonged shading throughout the day may have different effects on the crop biological processes, despite resulting in the same total shading time over the whole day.

Finally, integrating a hypothetical grid demand profile would allow for a more precise valuation of electricity production, aligning the system's output with real-world energy market dynamics and enhancing the overall utility of the model.

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