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# THE POTENTIAL OF AGRIVOLTAICS IN SOUTHEAST EUROPE: ADVANCING CLIMATE ADAPTATION AND MITIGA- TION IN AGRICULTURE



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## SUMMARY:

**Agriculture in Southeast Europe is increasingly affected by drought, heatwaves and extreme weather. Agrivoltaic systems (AV), which combine agricultural production with solar energy generation, can stabilise yields under stress conditions by improving microclimate, increasing soil moisture retention, reducing erosion and lowering irrigation demand.**

In addition to increasing resilience and optimizing land use, agrivoltaics provide farmers with diversified income, support farm competitiveness and rural development.

To unlock this potential, the study recommends establishing a clear legal framework while preserving agricultural land status; integrating AV into national climate and energy strategies; facilitating access to financing; modernising grid infrastructure and enabling on-farm energy use; and strengthening training and pilot projects.

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# 1. INTRODUCTION

Climate change and land use conflicts represent two of the most pressing global challenges. Agriculture is increasingly affected by more frequent and more intense extreme weather events, alongside rising temperatures and elevated atmospheric CO<sub>2</sub> concentrations. While phasing out fossil fuels remains the central climate mitigation strategy, adaptation measures are equally essential to ensure sustainable crop production under changing climatic conditions.

Agrivoltaics (AV) combine photovoltaic (PV) electricity generation with continued agricultural use on the same land area. This dual-use approach increases land-use efficiency while creating synergies between renewable energy production and climate-resilient farming. By protecting crops from extreme weather events and improving microclimatic conditions, AV systems support climate adaptation. At the same time, they contribute to climate mitigation through clean energy generation.

The effective utilisation of high solar irradiance and extensive agricultural areas can simultaneously enhance food and energy security. In addition to yield stability and resource-efficiency gains, agrivoltaics offer farmers income diversification, improved crop protection, and enhanced working conditions. These advantages strengthen the long-term economic viability of farms and rural areas.

Interest in agrivoltaics is expanding rapidly worldwide. By 2021, approximately 14 GW of cumulative agrivoltaic capacity had been installed globally. Although consistent global monitoring remains challenging due to differing definitions of AV across countries, more recent estimates indicate installations of approximately 18.4 GW by mid-2025. The global agrivoltaic market was valued at around USD 6.3 billion in 2024 and is projected to grow steadily in the coming decade. In Europe, agrivoltaics alone could theoretically generate up to 944 GW of installed capacity if implemented on only 1% of agricultural land — exceeding the EU's current solar energy targets for 2030.

Agrivoltaics, therefore, represent a strategic innovation at the intersection of agriculture, climate policy, and energy transition. A comprehensive scientific overview is provided in Wydra et al. (2023) [1].

## 2. AGRIVOLTAIC SYSTEMS

PV systems of various designs (elevation, module technology) are installed on arable land and grassland or sites with speciality and horticultural crops mostly in such a way that plants and soil are offered the greatest possible protection of plants against extreme weather conditions such as hail, storms, heavy rain, drought, heat, strong UV radiation and late frosts as well as sunburn and of soil against drought and erosion [1, 6, 7, 8]. In addition, solar electricity is generated in parallel for own use and grid feed-in. Benefits arise both in agriculture — through direct crop protection, wind reduction, improved soil moisture retention, reduced land loss, rainwater harvesting potential, and enhanced product quality control — and in energy production, due to improved module efficiency resulting from lower operating temperatures above vegetation.[8,9]

Different combinations of PV-technology and cultivation of crops allow, on the one hand, to optimize crop yield quantity and quality according to the light and protection requirements of the crops, depending on their development phase, or, on the other hand, to produce as much energy as possible, for example, outside the vegetation period. According to Jain et al. [9], an AV system should be distinguishable from conventional PV plants and can be classified based on the following aspects:

- application (agriculture, livestock)
- system (open, closed [greenhouse])
- construction (high, slightly elevated, vertical, and others)
- type of agricultural use (horticulture, arable crops, fruits, permanent grassland)
- flexibility (mobile, permanent system; plant/energy-optimized tracking).

Various authors defined AV and suggested classifications that find entrance into laws and regulations [10], for example, the German standard DIN SPEC 91434 (currently still a pre-standard, but in preparation for a standard DIN) [10], which provides quality criteria for constructing and operating AV systems, with two categories:

- (i) the high-mounted or overhead and
- (ii) the low-mounted or ground-level systems with crop growth underneath or between the module rows (interspace PV), respectively [11].

In Germany, governmental subsidies can be applied for when at least 85% of the area of the field is still used for agriculture, and a crop harvest of no less than 66% in comparison to a yield in a conventional field is achieved. Also, in Italy, France, and other countries, regulations on planning and construction of AV plants are being developed (s.a. below).

In the first AV systems, mainly (partly) shade-tolerant horticultural crops such as lettuces, tomatoes, kale, broccoli, eggplant, peppers, saffron, berries, apples, and pears were grown, while now also crops in arable fields such as rice, wheat, maize, potato, soybeans, and fodder crops are being cultivated with conventional farm machinery under high-elevated modules [12, 13]. In Japan, crops grown under AV modules amount to more than 120 crops, among them a high number of vegetables, fruits, and tea, but also potato, paddy rice, wheat, rape, ginger, and herbs [14]. In Europe, fruits, including grapes, prevail, but also crops such as wheat, potatoes, maize, and other field crops are planted under AV modules [8]. It is suggested that potentially almost any crop can be utilized in AV production systems [15, 16], and, based on crop models to estimate yields of various crops, on a global scale, an increase in 35–73% of land productivity could be predicted [6]. To ensure an optimal system for the desired purpose, with major emphasis on agricultural use, the following factors are important:

- (i) quality of solar radiation in the form of light intensity and photosynthetically active radiation (PAR),
- (ii) AV design options such as energy-optimized, plant-optimized and combined optimization, and
- (iii) perspective of the shareholders (especially farmers) (s.a. below, 'Business models') [17] (Table 1).

Table 1. Design options of AV plants for energy, plant, or combined optimization (modified from [17]).

|                                                          | Energy-optimized                                                               | Plant-optimized                                                                                             | Combined optimization<br>(energy + plant)                                |
|----------------------------------------------------------|--------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Pasture land,<br>unused land,<br>steppes, desert<br>land | Leave intact native vegetation (and add to it if necessary)                    |                                                                                                             |                                                                          |
|                                                          | Plant short, shade tolerant<br>crops                                           | Planting a mixture of<br>sun-loving and shade-<br>tolerant plants                                           | Planting short, shade-<br>tolerant plants                                |
|                                                          |                                                                                | Continue/introduce grazing                                                                                  |                                                                          |
|                                                          | Dense PV occupancy                                                             | High elevation of the APV construction<br>If culture is unsuitable,<br>external PV FFA may<br>be used       |                                                                          |
| Agriculture (short<br>crops)                             | Plant short, shade-tolerant<br>plants under and around the<br>PV system        | Planting a mixture of sun-loving and shade-tolerant<br>plants                                               |                                                                          |
|                                                          | Dense PV occupancy                                                             | Light/high elevation of the APV construction<br>If culture is unsuitable,<br>external PV FFA may<br>be used |                                                                          |
| Agriculture<br>(advanced<br>civilisations)               | Limited options, high<br>elevation, only suitable for<br>shade-tolerant plants | Plant mix of sun-loving<br>and shade-tolerant<br>plants                                                     | Placement of PV solar<br>systems on unused parts of<br>agricultural land |
|                                                          | Dense PV occupancy                                                             | High elevation of the APV construction<br>If culture is unsuitable,<br>external PV FFA may<br>be used       |                                                                          |

## MOUNTING SYSTEMS

The type of mounting system is therefore decisive for the categorization and use. While “inter-row PV” with vertical systems first has been established on grasslands for cultivation of hay, silage, and grazing by animals, now first projects show positive results with peas, lentils, cereals, and other field crops between vertically placed modules. Arable crops in the usual crop rotations (e.g. cereals, potatoes, and others) and specialty crops (fruits, grapes, hops, etc.) are mainly cultivated with more or less high-elevated, horizontal modules [18].

In Germany, the systems are categorized according to their technical indicators in high-mounted and ground-mounted systems. High-mounted AV systems as defined by the German DIN-SPEC91434 have a clear height of at least 2.1 m, and can be elevated more than 5 m (lower edge) [19]. A significant advantage of high-mounted systems is the covering effect of the roof-like construction, which can protect the crops from hail, heavy rain, frost, heat or sunburn [20], while rainwater can be collected and provided to the crop by smart technologies. In the ground-level systems with vertical fixed or tracking modules crop cultivation or grassland is located between the module rows, with plants below a clear height of 2.1 m according to the DIN SPEC category I in Germany [19]. In these systems, modules are not arranged above the plants and therefore do not provide the broad protective function. However, the plants receive a high incidence of light, and shading occurs in the morning and afternoon hours. The height of farming machinery is not restricted, and row spacing can be determined according to the required machine width. No rainwater collection system with water distribution is necessary, as the plants can use the precipitation without restrictions [21]. For ground-level plants, a maximum loss of area of 15% is assumed [19]. Different types of AV systems including mobile systems can provide protection and replace hail nets/foils, while tracking systems can be positioned to optimize either plant growth or energy production [22].

## TRACKING SYSTEMS

Time-specific regulation of the incoming radiation is possible via “tracking” systems. The substructure of the modules is movable and can be adjusted uniaxially (horizontally or vertically) or biaxially (horizontally and vertically), either to the position of the sun or to provide the crops with full sunlight. This allows for optimal light management and crop protection [8, 23]. When placed vertically during cultivation and harvesting, agricultural machinery can easily pass. The system is also suitable for agricultural land with very steep slopes [24]. With tracking systems, between 30% and 45% higher electricity yields are possible [25]. It is also possible to adjust the tracking algorithm according to the light demand of the plants (“anti-tracking”) [26].

# 3. AGRICULTURAL ASPECTS

The following section evaluates interactions between agrivoltaic systems, the agroecological environment, and crop growth and quality. Beyond direct benefits for plant production, AV systems contribute to improved water management and erosion control through wind reduction, reduced soil evaporation, and increased soil moisture retention. These effects help preserve fertile soils and, particularly in semi-arid and arid regions, may even enable agricultural production where it would otherwise be unfeasible. Large-scale examples in China demonstrate the successful cultivation of berries on over 1,000 hectares near the Gobi Desert and water-conserving AV systems covering more than 2,000 hectares in Heilongjiang Province [27, 28].

## SOIL, WATER, EROSION

By shading or covering the soil partly with modules, increased soil moisture and water-holding capacity, as well as reduced soil temperatures were observed [29, 30, 31-33], which contributed to increased yields of cucumbers and lettuce grown under the modules [12]. For grassland, this resulted in an increase in water use efficiency of 328% compared to grazed reference soils outside the solar system, and 90% yield increases [32]. Additionally, cooling effects of substrates were described [34,35]. The reduced evapotranspiration resulted in water savings of 70% in an AV system with apricot cultivation in France, and the need for irrigation was reduced in a vineyard in Piolenc equipped with tracking systems [23]. Innovative commercial modules with open stripes between square modules of about 10 cm ensure homogenous rain distribution. Improved soil health, increased CO<sub>2</sub> storage, water retention and infiltration, reduced run-off and reduced erosion were observed after the establishment of vegetation in solar farms [36-40].

Specific AV installations for erosion prevention are suggested for slopy areas. The modules can be elevated above crops or biodiversity stripes [8]. The protective functions can also make eroded soils usable again or enable agriculture in dry regions in the first place, as results from Namibia and China show. AV can thus make a substantial contribution to combating desertification in arid and semi-arid regions by inducing microclimatic improvements through shading and positively influencing soil quality [41]. In AV systems in disadvantaged areas in France, a yield increase of up to 17% was observed in cereals [42]. Thus, advantages of (A)PV plants are possible in all regions, but are specifically seen in semi-arid areas, and a boost of agricultural output is predicted for dry areas [43, 44].

In addition to reduced evapotranspiration under the modules, positive effects on the water balance and higher infiltration due to planting were observed under conventional PV systems and APV systems, which can lead to an increase in the groundwater level [45, 46-49]. Depending on the vegetation, temporary drying out near the surface directly under the modules may occur, but in most cases, this is offset by reduced evapotranspiration [50], while capillary forces in the soil beneath the topsoil layer restore even moisture distribution [51].

In innovative commercial modules, open strips of approximately 10 cm between square modules ensure even rain distribution. Our studies also show that AV systems can not only improve the microclimate in the field, but also protect crops and stabilise yields under stressful conditions, as well as serving to protect the soil, optimise water management, retain sediment, increase pollination efficiency and store carbon, thereby improving ecosystem services [8, 52, 53].

AV systems offer the possibility of rainwater harvesting [8, 9, 54, 55]. A rainwater harvesting system that uses the AV structure or module surfaces as a collection area can consist of simple rain gutters that collect the water, transport it to a storage and, if necessary, return it to the plants via drip irrigation during drier periods (water management system) [54, 55]. There are various options for water storage (short-term or seasonal). Drainage also offers an attractive solution, especially for special crops such as berry cultivation. The drip edge of the modules is placed in the centre between the (berry) rows. Underneath is a drainage system that returns the water to the storage tank via collection pipes [56].

## CASE STUDY ON RAINWATER HARVESTING

*In our case study of an AV system in apple cultivation in a region with 800 mm of precipitation per year (Morocco), a calculation of the possible water collection volume was carried out [55]. The AV system has an extensive overhead arrangement of 2,000 photovoltaic modules (effective area: 3,564 m<sup>2</sup>). The rainwater collected directly from the module surfaces by collection gutters is fed into a water storage tank via a sediment filter and a flow regulator. By calculating the effective collection area and the annual amount of rainwater that can be collected based on the design of the AV system, a potential of 802 m<sup>3</sup> of rainwater collection per year was determined. This volume could be used for additional irrigation of apple crops, especially in combination with efficient water management and storage techniques. The cost of this rainwater harvesting system, including gutters and piping, filtration and a storage pond with a capacity of 1,500 m<sup>3</sup>, would amount to 30-40,000 euros/ha. This investment would make it possible to collect and store a considerable portion of the annual rainfall (potential approx. 802 m<sup>3</sup>/year), providing a valuable water resource for supplementary irrigation and increasing the plantation's resilience to water shortages. Research findings by other authors also highlight the potential of combining PV systems with rainwater harvesting [57, 58, 59].*

Overall, while agrivoltaics benefits can be observed across climatic regions, their impact is particularly pronounced in semi-arid and arid zones, where water scarcity and heat stress represent major limiting factors for agricultural productivity. Under such conditions, AV systems can substantially enhance resilience and stabilise yields.

## MICROCLIMATE

Numerous studies have reported a reduction in air temperature and an increase in humidity under the modules in AV installations [60, 61]. These effects mostly reduce drought and heat stress and increase crop water productivity, with direct effects on yield; in some cases, yield increases of up to three times, as observed in tomato [61]. Increased night temperatures compared to ambient temperatures, as reported by Günnewig et al. [62], can prevent the risk of frost and damage to blossoms in orchards. Higher leaf temperatures in the early morning result in less dew formation on the leaves, which has negative effects on disease infestation, as observed in AV with berries in the Netherlands [26, 63] and with fruit trees in Austria [64].

## BIODIVERSITY

In extensively farmed AV areas growing flowering ‘pollinator’ plants and, soil-conserving cultivation can increase biodiversity. Flower strips under low-mounted modules and avoiding intense soil disturbances can have a positive effect on biodiversity, soil quality and fertility. More structurally rich habitats, a more favourable, moister microclimate and reduced temperatures under the modules increase the occurrence and diversity of insects, soil organisms and plants, as well as humus formation (C sequestration) [52, 65, 66, 67].

## CROP GROWTH AND YIELD RESPONSES

Increases in crop yields were observed by various authors, specifically in years with climatic stress for the crops, such as drought, heat, hail, frost, and storms. Generally, yields of some crops can be increased by up to 30% in combination with energy production on the same land compared to the separate production of energy and crops, and even up to 90% in the case of grassland [32, 68].

Horticultural and arable crops were subject to studies in the most recent years. In vegetable production under AV, similar yields in comparison to the reference fields were observed for kale at 55%, 62%, and 85% of PAR, and for lettuces, and chard. However, yield losses were observed for broccoli and spinach [69]. For kale and broccoli, a reduced leaf temperature was measured, which has a positive influence on photosynthetic performance and continuous growth at high ambient temperatures [70]. Additionally, broccoli can show a quality increase with greener leaves and no significant differences in yield, antioxidant capacity, some glucosinolates and hydrolysis products [71]. Also, in ornamentals and berries under AV, shadow had a positive effect on the quality and bioactive compounds, respectively [72, 72]. In other trials, spinach benefited from shading by AV [74], while Hudelson and Lieth [69] found negative effects in their systems. Cucumbers under AV increased in fresh weight [12], and tomatoes showed improved photosynthetic rates and transpiration coefficient under AV with a huge yield increase [7]. Similarly, chili even responded by tripling its productivity with the same water requirement, while only jalapenos reduced their growth under AV modules [7]. For potatoes, yield increases were observed, depending on the drought severity [43] and on the distance of module rows [75]. The latter was also true for oats [75]. Thus, crops in usual crop rotations on arable land, and horticultural or specialty crops are mostly seen as suitable for AV systems, though in some cases or in more wet years, yield reductions may occur. The performance is strongly influenced by the module type, where semi-transparent, bifacial modules provide higher PAR and thus less shading effect on plants. Nevertheless, the farmer always has an additional income from energy production.

Suitability of the main agricultural and horticultural crops in temperate climate was analyzed in depth according to their physiological properties and to literature [1], resulting in a classification in shade-tolerant crops and crops, that would profit from AV under stress conditions, which, as outlined, will be the “future normal” under climate change in most regions (Figure 1).

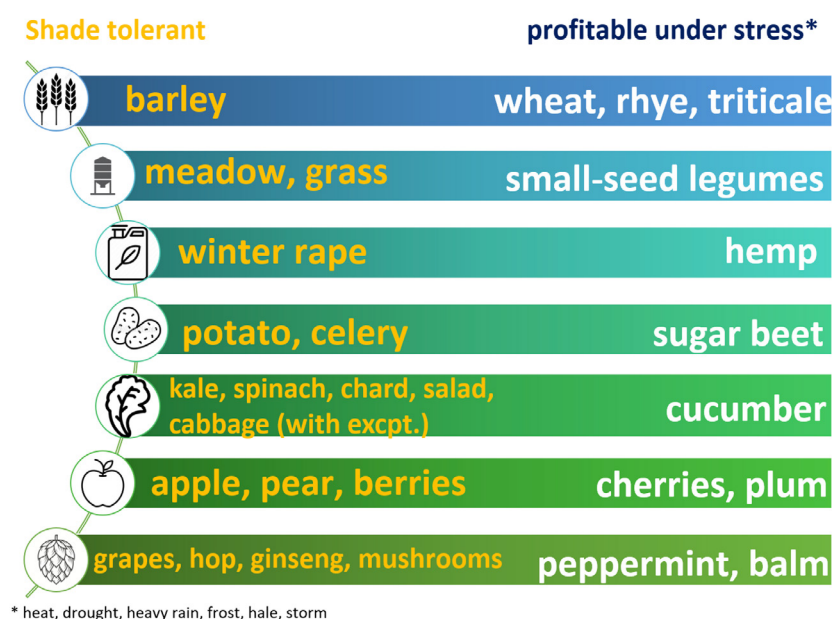


Figure 1. Classification of crops grown in temperate European regions into shade-tolerant plants and species which profit from protection in AV systems under climatic stress conditions. Based on physiological and morphological properties, light saturation point, net photosynthesis rate, stages of development, of yield formation, of assimilate distribution, leaf area index, harvest index (biomass or seed/fruit) [1]

A literature analysis of yields for major crops in arable farming revealed the range of possible yield losses and gains, mostly depending on the prevailing weather conditions in the study years (Table 2).

Table 2. Yields of major crops in arable farming under AV in comparison to reference fields (own meta-analysis)

|                                | Reference                                                        | Agri-PV<br>(partly shade net)                               |                                                              |                                                                 | Yield loss or increase |                 |
|--------------------------------|------------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------------------------------|-----------------------------------------------------------------|------------------------|-----------------|
| Crop                           | Ø yield/ha<br>(Thuringia)<br>(Erntebericht in<br>Thüringen 2023) | Yield loss<br>(worst case)                                  | Ø Yield change                                               | Yield gain<br>(best case)                                       |                        |                 |
| Winter<br>wheat                | 70 dt /ha                                                        | 42 - 49 dt/ha                                               | 65,3 - 68,1 dt/ha                                            | 70 - 83,3 dt/ha                                                 | -7% - +19%             | winter wheat    |
|                                |                                                                  | -40 bis -30 %<br>(Laub et al. 2022)                         | -6,7 to +2,7 %<br>(Wesielek et al. 2021)<br>(Li et al. 2010) | 0 to +19 %<br>(Potoczek et al. 2023)<br>(Corraliza et al. 2019) |                        |                 |
| Winter<br>rapeseed             | 32 dt /ha                                                        | 18,2 - 22,7 dt/ha                                           | 24,3 dt/ha                                                   | 28,8 dt/ha                                                      | -24% - -10%            | winter rapeseed |
|                                |                                                                  | -43 bis -29 %<br>(Bondarova et al. 2014)                    | -24%<br>(Felix Emanuel Schuck<br>2022 (Modell))              | -10%<br>(Felix Emanuel<br>Schuck 2022 (Modell))                 |                        |                 |
| Potato                         | 350 dt /ha                                                       | 227,5 - 269,5 dt/ha                                         | 287 - 304,5 dt/ha                                            | 350 - 388,5 dt/ha                                               | -18% - +16%            | potato          |
|                                |                                                                  | -30 bis -23 %<br>(Laub et al. 2022)<br>(Schulz et al. 2019) | -18 to -13 %<br>(Fraunhofer ISE 2024)<br>(Lee et al. 2022)   | 0 to +16 %<br>(Fraunhofer ISE 2024)                             |                        |                 |
| Winter<br>barley               | 79 dt /ha                                                        | 51,4 - 55,3 dt/ha                                           | 65,4 - 70,2 dt/ha                                            | 79 - 94 dt/ha                                                   | -17% - -11%            | winter barley   |
|                                |                                                                  | -35 bis -30 %<br>(Laub et al. 2022)                         | -17,2 to -11,2 %<br>(Vaccaro et al. 2022)                    | 0 to +19 %<br>(Corraliza et al. 2019)                           |                        |                 |
| Fodder-<br>alfalfa,<br>legumes | 67,5 (TM*) dt<br>/ha                                             | 50,6 - 54 (TM) dt/ha                                        | 67,5 (TM) dt/ha                                              | 94,5 dt/ha                                                      | -25% - +40%            | forage, legumes |
|                                |                                                                  | -25 bis -20 %<br>(Laub et al. 2022)<br>(Dunraz et al. 2023) | + - 0 %<br>(Dunraz et al. 2023)                              | +40 %<br>(Edouard et al. 2021)                                  |                        |                 |

Based on the analysis, the suitability of the studied crops was defined for conditions in Germany (Table 3). This may vary widely across countries, and should result in more positive yield effects under higher photosynthetically active radiation (PAR) and drought conditions.

Table 3. Suitability of the studied crops in AV systems under conditions in Germany

| Arable crop                        | Suitability                   | Source                                                                                                                                                                                          |
|------------------------------------|-------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Winter wheat                       | <u>suitable</u>               | ( <a href="#">Potaczek et al., 2023</a> ), ( <a href="#">Dupraz, 2023</a> ; <a href="#">Garrod et al., 2024</a> ; <a href="#">Yeliageti et al., 2023</a> ), <a href="#">Wydra et al. 2022</a> ) |
| Winter barley                      | <u>suitable</u>               | ( <a href="#">Yeliageti et al. 2023</a> , <a href="#">Garrod et al. 2024</a> )                                                                                                                  |
| Summer barley                      | <u>suitable</u>               | ( <a href="#">Corraliza et al., 2019</a> ; <a href="#">Wydra et al., 2022</a> ; <a href="#">Yeliageti et al., 2023</a> )                                                                        |
| Oat                                | <u>suitable</u>               | ( <a href="#">Garrod et al. 2024</a> )                                                                                                                                                          |
| Alfalfa                            | <u>suitable</u>               | ( <a href="#">Edouard et al., 2023</a> ; <a href="#">Litukienė et al., 2024</a> ; <a href="#">Towner et al., 2022</a> ; <a href="#">Varella et al., 2011</a> )                                  |
| Arable fodder / field grass        | <u>suitable</u>               | ( <a href="#">Laub et al., 2021</a> ; <a href="#">Pang et al., 2019</a> ; <a href="#">Towner et al., 2022</a> )                                                                                 |
| Rye                                | <u>suitable</u>               | ( <a href="#">Yeliageti et al. 2023</a> , <a href="#">Wydra et al. 2022</a> )                                                                                                                   |
| Spelt                              | <u>suitable</u>               | ( <a href="#">Garrod et al. 2024</a> )                                                                                                                                                          |
| Potato                             | <u>suitable</u>               | ( <a href="#">Garrod et al. 2024</a> , <a href="#">Wydra et al. 2022</a> , <a href="#">Laub et al. 2022</a> )                                                                                   |
| Winter rapeseed                    | <u>suitable</u>               | ( <a href="#">Yeliageti et al. 2023</a> , <a href="#">Garrod et al. 2024</a> , <a href="#">Wydra et al. 2022</a> )                                                                              |
| Soybean                            | <u>Conditionally suitable</u> | ( <a href="#">Yeliageti et al. 2023</a> , <a href="#">Garrod et al. 2024</a> )                                                                                                                  |
| Sugar beet                         | <u>Conditionally suitable</u> | ( <a href="#">Yeliageti et al. 2023</a> , <a href="#">Garrod et al. 2024</a> , <a href="#">Wydra et al. 2022</a> )                                                                              |
| Broad bean                         | <u>Conditionally suitable</u> | ( <a href="#">Garrod et al., 2024</a> ; <a href="#">Nasrollahzadeh et al., 2007</a> ; <a href="#">Wydra et al., 2022</a> )                                                                      |
| Corn                               | <u>Conditionally suitable</u> | ( <a href="#">Yeliageti et al. 2023</a> , <a href="#">Dupraz 2023</a> , <a href="#">Garrod et al. 2024</a> , <a href="#">Wydra et al. 2022</a> )                                                |
| White lupine                       | <u>Conditionally suitable</u> | ( <a href="#">Manting et al., 2021</a> ; <a href="#">Yeliageti et al., 2023</a> )                                                                                                               |
| Sunflower                          | <u>Conditionally suitable</u> | ( <a href="#">Lindström et al., 2006</a> ; <a href="#">Wydra et al., 2022</a> ; <a href="#">Yeliageti et al., 2023</a> )                                                                        |
| Pea                                | <u>Conditionally suitable</u> | ( <a href="#">Akhter et al., 2009</a> ; <a href="#">Blanchet et al., 2022</a> ; <a href="#">Wydra et al., 2022</a> ; <a href="#">Yeliageti et al., 2023</a> )                                   |
| Oil ( <i>Linum usitatissimum</i> ) | <u>Conditionally suitable</u> | ( <a href="#">Bazzaz &amp; Harper, 1977</a> ; <a href="#">Wydra et al., 2022</a> ; <a href="#">Yanagisawa &amp; Yanagisawa, 1964</a> )                                                          |

Examples of AV projects and the agricultural performance in various cropping systems across Europe are provided by SolarPower Europe (2025) [2].

Overall, crop performance under agrivoltaic systems depends on species-specific light requirements, prevailing climatic stress conditions, and system design parameters such as module transparency, elevation, and row spacing. While yield reductions may occur under low-stress conditions or in particularly wet years, agrivoltaics generally enhance yield stability and resilience under increasing climate variability.

## 4. ECONOMICS

For an economic analysis of AV systems, we calculated costs for six AV systems with various system designs in comparison to utility-scale ground-mounted systems considering capital expenditures (CAPEX) and operational expenditures (OPEX) (Figure 2). Cost estimations derive from pilot plants in Germany and available, minimum costs (basis: year 2023) were selected. It has to be considered that prices for mounting and special modules are not yet based on large-scale production. Therefore, these costs are due to strong future reduction, probably similar to PV modules, once industrial production has taken up. Among the AV systems, the vertical system was the most cost-effective [76, 77]. Details on the basis for the calculations are provided in Wydra et al. (2023) [1].

Among the modules with a stronger protective function, the low elevated system, for example, for horticulture, was estimated to produce electricity at an LCOE of 5.87 ct/kWh calculated over 30 years, followed by the rope systems at 6.84 ct/kWh. Costs are due to high fluctuations, specifically considering the presently low module prices. Nevertheless, the calculations can be used to compare the systems.

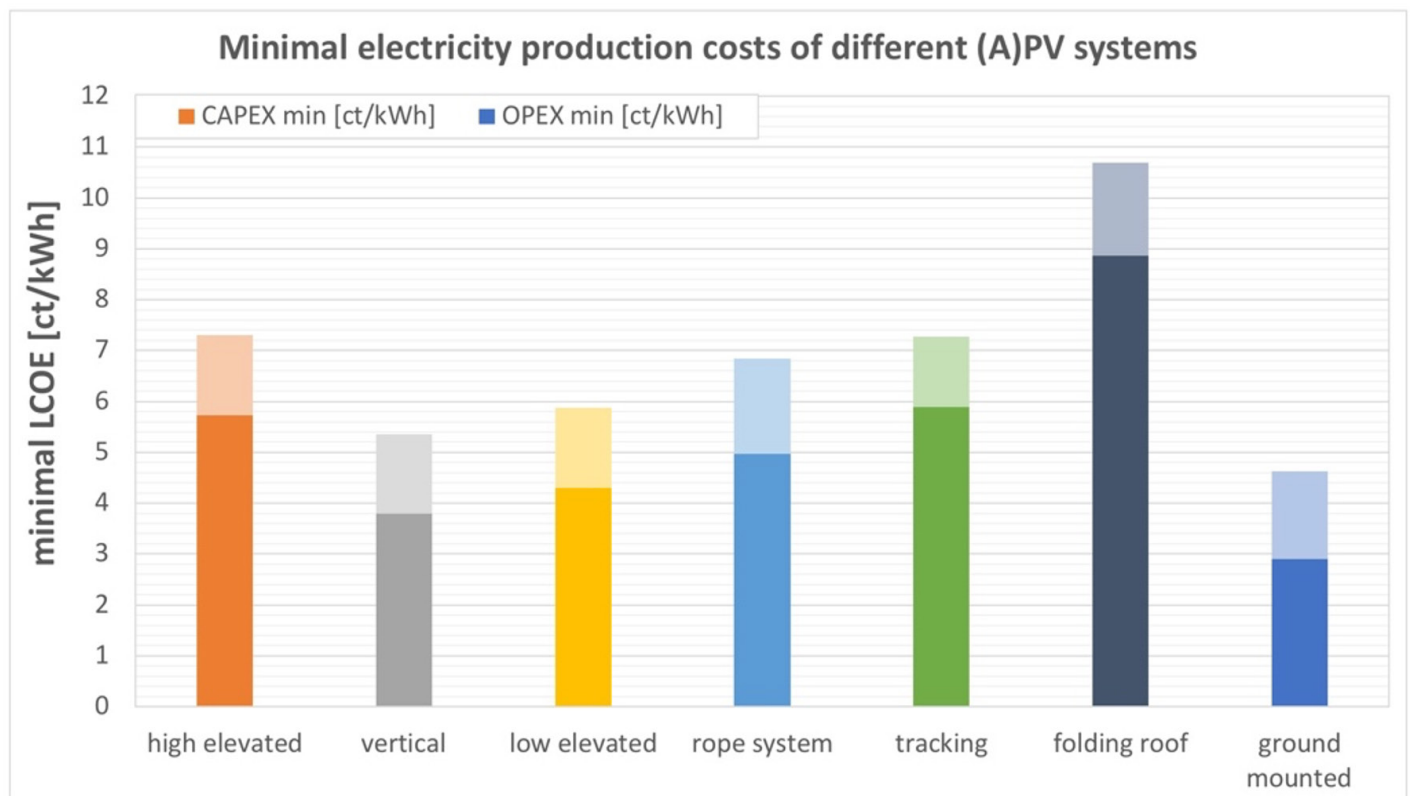


Figure 2. Comparison of the power production cost range of different (A)PV systems under German cost conditions [77].

Increasingly long periods of drought and rising temperatures and late frosts and hail in more mountainous areas are an economic challenge for farmers. Additionally, to protect crops from weather extremes and diseases, AV may provide smaller farmers with an additional income, allowing them to compete with farmers owning large areas of land. Various business models and participating parties are possible (Figure 3) and offer opportunities for additional income for smaller farmers.

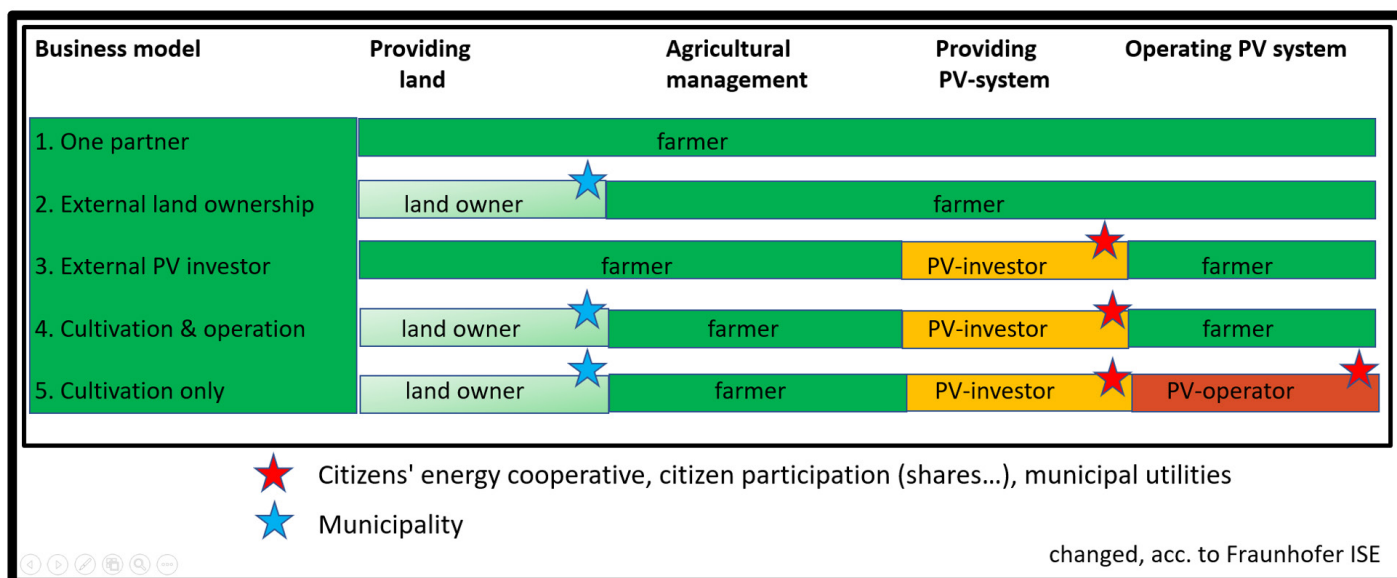


Figure 3. Typical business models and participating parties in AV systems.

Although certain agrivoltaic configurations currently involve higher initial investment costs than conventional ground-mounted PV systems, substantial cost reductions are expected through industrial scaling and technological standardisation. When accounting for avoided climate-related yield losses, diversified income streams, and long-term land-use optimisation, agrivoltaics can provide economically resilient and competitive business models for farms of different sizes.

## 5. AGRIVOLTAIC LEGISLATION

The legal and economic framework conditions for agrivoltaics, associated to the regulation of standard decentralized energy supply using PV are of crucial importance for the success and promotion of agrivoltaics.

Administrative procedures need to be simplified, whereby laws define the operational level of technologies and systems allowing the synergy between agriculture and renewable energies, and regulate how this can be controlled. Controls should ensure that the land continues to be used for agricultural purposes and that food production is maintained at a certain level.

Laws should determine the maximum area 'lost' for agriculture, e.g. up to 15% in Germany, 5% in Czechia [78]. Also, the area occupied by auxiliary components such as batteries and transformers should be fixed, e.g. 20% of the total project area (Czechia), ensuring that the land primarily remains devoted to agricultural purposes. In Italy, PV installations except AV are no longer allowed on agricultural land.

Besides batteries, other sector coupling elements should be allowed as part of the AV system, e.g. the production of hydrogen in electrolyzers, allowing the most efficient use of the produced energy. Storage systems allow for energy to be stored and used when it is needed, maximize self-consumption of the generated electricity, and ensure a stable and reliable energy supply for farms and rural communities.

Land used for AV systems should remain registered as agricultural land. This ensures that the land remains eligible for agricultural subsidies and does not need to be removed from the Common Agriculture Policy (CAP) payments. Additionally, AV systems should be classified as "buildings for agriculture." This designation allows solar installations to be set up on farms without the need for changes to local zoning plans, streamlining the process and reducing hurdles for farmers.

A legal framework for agri-solar (this may include AV and agri-thermal) should be created in energy-related legislation. AV projects should be allowed on state-owned and on private land. The spatial planning law should recognize the term agrivoltaics and define its areas of application:

AV should be allowed to be integrated in diverse farming systems, comprising plantation crops such as vineyards, orchards, nuts as well as hop yards, tree nurseries, container-grown crops, conventional, arable agriculture (cereals, legumes, potatoes, fodder, etc.), vegetable, spices and medical herbs, and grassland as well as on greenhouses. In animal husbandry, AV can enhance well-being of livestock and increase fodder quantity and quality, and in aquaculture, floating PV can reduce heat and algal growth.

Countries should develop an 'Action Plan for Power Grid Strengthening to Support the Integration of Renewable Energy Sources' [79]. Investments are needed in the construction and modernization of transmission infrastructure. Platforms and a central source of necessary information that is important to potential project holders and investors should be provided. These can guide through licensing and administrative procedures, and enhance the process. An example of a consolidated approach are the 'Studies to accelerate the development of renewable energy projects in Croatia' [78].

Legal and regulatory frameworks should enable farmers and businesses to generate their own photovoltaic energy and to feed it into the grid. Legal foundations already developed in some countries are based on the guidelines of the Energy Community, which allow surplus electricity to be sold for a fee or offset against own consumption. Regulatory authorities should be responsible for energy prices, market access to electricity grids and the setting of feed-in tariffs, and for special subsidies for agrivoltaics, such as highly elevated, more expensive forms of AV for specific cropping systems.

## 6. SKILLS AND KNOWLEDGE GENERATION

Training and knowledge generation are needed to enhance skills to further accelerate the deployment of AV. The different fields of expertise are listed in Table 4.

Table 4. Skills and expertise needed to promote AV. [80]

|                                     |                                                                                                                                                                                                                                                                                                                    |
|-------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Renewable Energy Engineering        | Engineering is a key profession in the Agri-PV sector. From the design, to the installation and maintenance of Agri-PV solutions, the understanding of the PV technology, the system sizing, and electrical design or grid integration is essential.                                                               |
| Agricultural knowledge              | A solid understanding of agricultural practices is also an essential component of an Agri-PV project. Knowledge on crop cultivation, irrigation, soil management, and livestock farming allow for optimised land use.                                                                                              |
| Project Management                  | Project Management: Effective project management skills are necessary to coordinate and oversee Agrisolar installations to ensure timely execution, resource allocation, stakeholder coordination, and adherence to quality standards and regulatory requirements.                                                 |
| Electrical Skills                   | Electricians or electrical engineers with expertise in solar PV installations are required to handle the electrical components of Agrisolar systems. Their expertise can be used to allow a proper wiring, connections, and commissioning of solar panels, inverters, and electrical systems.                      |
| Construction and Installation       | Construction workers such as technicians or installers are needed to install the Agri-PV systems.                                                                                                                                                                                                                  |
| System Monitoring and Maintenance   | Ongoing monitoring and maintenance are essential to ensure the optimal performance and longevity of Agrisolar systems. Technicians or maintenance specialists are responsible for regular inspections, cleaning of panels, troubleshooting, and repairing any technical issues.                                    |
| Environmental and Land Use Planning | Professionals with expertise in environmental impact assessment and land use planning play a crucial role in evaluating the environmental and social implications of Agri-PV projects. These professionals can ensure sustainability and regulatory requirements are adhered to.                                   |
| Research and Development            | Researchers and scientists are essential when it comes to the development of new technologies beneficial to the Agrisolar sector. Moreover, studies, data analysis and innovative solutions contribute to more productivity, and a better integration of Agri-PV solutions into agricultural lands and operations. |
| Policy and Regulatory Experts       | Professionals of the renewable energy policies, regulations, and incentives can provide guidance to better understand and navigate the policy landscape.                                                                                                                                                           |

## 7. FINANCING

Financial support through green financial products or cooperation with local banks and investors to facilitate the financing of PV systems for end consumers needs to be secured. Banks should provide low-interest loans and direct subsidies should be provided by national and international institutions. Additionally, financial grants and favourable financing models for larger systems should be available. State-subsidised programmes should be established for financing the 'start-up' of AV systems in a country, specifically the high-elevated systems with higher costs for the mounting structure, while ground-mounted systems with inter-row cropping should already be financially self-sustaining, depending on the feed-in tariff. Regulations and subsidies as well as facilitated access to financing should specifically be developed and provided for the benefit of small farmers.

## 8. AV IN: OHRID AGENDA 2025 AND THE GAWB ACTION PLAN

The Ohrid Agenda 2025 [81] emphasizes in the GAWB Action Plan [82], particularly Pillar IV – Sustainable Agriculture, the need for Climate Change Adaptation (CCAA): „...coordinated action to strengthen resilience and promote climate-smart systems...“. Furthermore, scaling investments in renewable energy and resource-efficient technologies is suggested, supporting the promotion of innovative and integrated Agri-photovoltaic (Agri-PV) systems. „A functional, non-bureaucratic regulatory framework needs to be designed to facilitate expansion of investments“.

In the Final GAWP AP, agrivoltaics can contribute to the following Pillars and specific actions:

### **Pillar 1:**

#### **Decarbonisation and Climate Resilience of the Green Agenda for the Western Balkans Action Plan 2021-2030**

Action 1 to achieving climate neutrality by 2050. AV should be part of the framework for strategic planning for implementation of climate actions related to mitigation and adaptation.

Action 4 (proposed Action 3) on preparation and implementation of climate adaptation. Strategies should list AV as measure for increasing agricultural resilience and adaptation to climate change.

Action 9 (proposed Action 5), AV should be part of the assessment of the socio-economic impact of decarbonisation, at individual and regional level and be associated to biodiversity linkages. In the Roadmap listing the economic impacts of decarbonisation, including sectoral employment effects, investment needs, and policy recommendations, AV should be considered.

Action 13 (proposed Action 8) states the increase of the share of renewable energy sources and provision of the necessary investment conditions. AV can play a decisive role and needs supportive financing opportunities. The roadmap emphasizes training programmes and certification of installers for renewable energy technologies, which should also be expanded to agrivoltaics. Grid modernisation is also a prerequisite for AV.

Action 27a (proposed: Action 18. b) suggests a plan for development of alternative fuel infrastructure deployment and building charging stations for electric vehicles. AV and sector coupling (battery storage, charging stations, hydrogen production) on farms are a growing field to avoid fluctuations in electricity prices and stabilize electricity supply.

### **Pillar 3:**

#### **Depollution of Air, Water and Soil of the Green Agenda for the Western Balkans Action Plan 2021-2030**

Action 42 (proposed Action 28). AV can contribute to soil protection, reduce soil degradation and erosion, enhance soil humidity and fertility and should be integrated in regional guidelines for soil protection. AV contributes to provision of ecosystem services, water resources management and water use efficiency and protection of biodiversity.

#### **Pillar 4:**

#### **Sustainable Agriculture of the Green Agenda for the Western Balkans Action Plan 2021-2030**

Action 46 (proposed Action 31). AV contributes to environmentally friendly (zero pollution) and organic farming and reduction of synthetic chemical products used in food production. Numerous projects showed reduced need of chemical pesticides in AV.

Action 47 (proposed Action 32). „Cooperate with scientific, education, business and agricultural holdings“. In AV there is a strong cooperation between the scientific community, business and farmers, in pilot and demonstration as well as commercial projects. Training in AV should be included to enhance the skills of advisory services in innovative and environmentally sustainable technologies and to provide farmers with relevant, up-to-date knowledge and customised advisory support.

Action 49 (proposed Action 33). LEADER should be used to support AV as part of sustainable development of rural areas, including the organisation of events for experience sharing and capacity building. Communities can be empowered to address environmental, economic, and social challenges by implementing AV in their areas.

Action 50 (proposed Action 34). „Support investments in renewable energy ...GHG emission reductions and adaptation to climate change measures in agriculture“. AV should be emphasized in policies and action plans, and form a measure to collaborate across sectors (water, environment, agriculture).

Action 57 (proposed Action 35a). „Western Balkans Six Biodiversity Information Hub“. AV was shown to enhance ecosystem services and biodiversity and should have a specific AV platform in the Hub.

#### **Pillar 5:**

#### **Protection of Nature and Biodiversity of the Green Agenda for the Western Balkans Action Plan 2021-2030**

Action 51 (proposed Action 36). „Western Balkans 2030 Biodiversity Strategic Plan“. AV enhances biodiversity and can be combined with specific biodiversity supporting measures.

Action 52 (proposed Action 37). „Prepare nature protection and restoration plans ...“. Biodiversity enhancing AV and AV in re-wetted peatland areas or river wetlands can support nature protection.

## **9. AV IN: CONCLUSIONS OF THE MINISTERS/ HEADS OF DELEGATIONS RESPONSIBLE FOR AGRICULTURE AND RURAL DEVELOPMENT IN SOUTH EAST EUROPE**

AV contributes to the statements in the „Conclusions of the Ministers/ Heads of Delegations responsible for agriculture and rural development in South East Europe Convened in Pristina, Kosovo\* from October 01st, 2025“ [83] and should be considered in the plans:

- transforming agriculture and food systems towards sustainability, resilience, and competitiveness
- integrating climate adaptation measures into agricultural investment policies and support mechanisms
- investments in climate-resilient agriculture and renewable energy
- remove non-tariff barriers for relevant inputs and technologies, harmonise regulation and ensure strict enforcement to enable regional market development
- scaling up financing for green investments in rural areas
- increase opportunities for fair income and economic perspectives for farmers supporting modernisation and sustainable farming practices, including the adoption of innovative technologies and market-oriented solutions, to improve productivity and resilience.

## 10. CONCLUSIONS

Studies and farmers' experiences demonstrate the diverse protective benefits of AV for plants, soil, biodiversity, ecosystem services and, last but not least, climate protection. Depending on the needs of the plants and the conditions and state of the soil, the systems can be technically adapted and set up and controlled to benefit agriculture and maintain and increase soil fertility. The systems offer advantages, particularly in view of the problems already being observed and expected to intensify in the future as a result of climate change, and not least also provide additional income in agriculture, which can enable farmers to operate in a more regenerative or ecological way or to maintain sustainable farming methods with fluctuating profits on the market. Supportive policies can make AV a success in climate adaptation and climate mitigation in agriculture as well as in rural development.

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