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STUDY ON THE POTENTIAL OF SOLAR ENERGY USE IN THE AGRICULTURAL AND FRESHWATER AQUACULTURE SECTORS IN CROATIA

DISCLAIMER

This report was jointly authored by the Faculty of Agriculture in Zagreb (FAZ), Faculty of Agrobiotechnical Sciences in Osijek (FASO) and Institute for Adriatic Crops and Karst Reclamation in Split (IACKRS), with funding from the European Bank for Reconstruction and Development (EBRD).

The report examines the current framework of agricultural potentials for the development of agrivoltaic (Agri – PV) projects in Croatia.

This high-level publication provides recommendations for further development of the Agri–PV system in Croatia. However, it is important to note that the information included in this report should not be regarded as legal, technical, or professional advice or services. The European Bank for Reconstruction and Development, the Renewable Energy Sources of Croatia and the authors disclaim all liability for any losses incurred by individuals or third parties who rely on this publication.

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FOREWORD

Croatia is blessed with abundant sunlight and fertile land. Now, these two natural resources need to come together to generate energy. Only two months before the publication of this study, new legislative changes allowed the installation of solar photovoltaic (PV) panels on agricultural land planted with perennial crops, such as vineyards and orchards. However, as our study shows, arable land would also benefit greatly from dual use, combining agriculture and solar power.

This EBRD-funded *Study on the Potential of Solar Energy Use in the Agriculture and Freshwater Aquaculture Sector* is the fourth study produced in cooperation with the Renewable Energy Sources Association of Croatia. The previous study, published in May 2023, identified offshore renewable energy potential of 25 GW in the low-impact areas of the North Adriatic alone.

Currently, the country imports a third of the electricity it consumes and has only a third of the solar energy production capacity of countries such as Estonia. This could change quickly if Croatia capitalised on its agri-solar potential.

If only one per cent of available agricultural land, as defined by this study, combined solar photovoltaics and agriculture, Croatia could add up to 900 MW of installed solar capacity – five times its current 182 MW. Using just five per cent of appropriate agricultural land for agri-solar installation could add up to 4.7 GW, approaching Croatia's entire electricity generation capacity (over 5 GW in 2023). Solar, the cheapest and fastest-growing source of new energy, could not only replace imported fossil fuels, but also supplement hydroelectricity, already affected by drought.

Agri-solar is not just about energy, however. As summers get hotter, farmers will increasingly need to focus on the resilience of their production methods, providing more shade and water to both crops and livestock. This study shows that many farms opting for agri-solar could increase the yields of vines, berries, soft fruit, leafy vegetables and other crops. Solar PV on farms and freshwater ponds can create shade and reduce water evaporation, which will become ever more important as the climate heats up. Growing crops or grasses beneath solar panels, in turn, reduces the need to cool down the panels, making them more efficient.

The simultaneous use of agricultural land for food and energy production is already practised in several European countries. This study details examples from Germany, France, Italy, Spain, Greece, the Netherlands and Austria.

Croatia's renewable energy potential from different sources – onshore and offshore wind, conventional and floating solar PV, and geothermal energy – is enormous. It is important to start turning this potential into reality by removing regulatory and administrative barriers to new renewable energy projects. Following the adoption of amendments to the Spatial Planning Act and related bylaws, the basic legal prerequisites for the implementation of agri-solar systems have been established, providing Croatia with a genuine opportunity to become a European solar superpower.

Victoria Zinchuk
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EXECUTIVE SUMMARY

Climate change poses a growing threat in the 21st century since it affects the frequency and intensity of extreme weather phenomena, endangering agriculture in particular by altering the growing seasons of arable crops, reducing crop yields, and increasing reliance on water.

Agriphotovoltaics (APV) could be a promising solution to increase energy production and agricultural output without increasing land use. A large number of studies have demonstrated that by combining photovoltaic systems with agricultural production it is possible to protect agricultural crops from excess solar energy and stormy weather while maintaining or even increasing crops yields. This is because agrivoltaics creates modified microclimate conditions beneath the modules by altering air temperature, relative humidity, wind speed, wind direction, and soil moisture.

The most common definition of agrivoltaics includes elements such as dual and synergetic use of agricultural land for both agricultural and energy production, where the cultivation and maintenance of agricultural production must be the main and the primary activity while installation of photovoltaics on that same agricultural land should be secondary and complementary activity that “serves” the agricultural production by protecting it from unfavourable growing conditions.

In the last couple of years, the concept of agrivoltaics has spread throughout the world (including Europe as well), with various types of agrivoltaic projects being initiated (including some pilot, scientific type of projects that have already been implemented) followed by the advanced technological development and introduction of a more sophisticated legal framework created specifically for the market of agrivoltaics.

Croatia is on track with the current trends. According to the latest legal developments, relatively solid legal foundation has been established for the preparation and development of the first agrivoltaic projects applicable to ARKOD-registered perennial agricultural crops and fishponds.

To ensure the continuation of agricultural production after the installation of APVs, the agrivoltaic market needs to be further regulated in a more systematic and comprehensive manner, including the institutional and administrative requirements. Since the agrivoltaic project should be viewed as an agrotechnical measure of partial shading, it would be necessary to ensure that all precautions have been taken to prevent soil and plant damage. Consequently, establishing technical guidelines for the design, construction, and operation of agrivoltaic systems should be a part of the process of developing agrivoltaic standards and best practices.

Based on intensive work undertaken by this study, it has been concluded that in Croatia, viticulture, fruit growing, aromatic and medicinal plants, grasslands, and fishponds would be the most suitable for application of APV, whereas vegetables, cereals, industrial and forage plants are not estimated to be suitable for application of Agri – PV projects yet, and that only small, scientific-type of projects could be initiated in that regard.

Specifically, grapevines, olives, American blueberry, blue honeysuckle, raspberry, hardy kiwi, apricot, sweet cherry, and sour cherry should be the most suitable types of plants.

It is anticipated that aromatic grapevine varieties will respond more positively to reduced temperature and UV radiation, allowing them to retain their varietal aromas. Depending on varieties, apple, pear, blackberry, kiwi, peach, nectarine, quince, and strawberry are recommended for Agri – PV. PV panels above the orchard will benefit yellow and green apple varieties such as 'Golden Delicious' or 'Granny Smith' by preventing their colour change to red.

According to the methodology created by this study, taking into account all limiting factors to the actual implementation of agrivoltaic projects, and based on the existing data of available land larger than 1 ha for all suitable crops, it is assumed that if 1% of the available land was used for APV installation, up to 900 MWp of solar power capacity could be installed, which could theoretically be increased to 4,700 MW of installed capacity if 5% of available land was used for APV application. In this regard, the important limitation will be the availability of the existing transmission network, which is presently estimated to have an installed capacity of approximately 2100 MW for all types of energy projects.

Another important challenge to the successful implementation of agrivoltaics could be obtaining the necessary support from all relevant stakeholders, such as policy makers, farmers and agriculture growers and their associations. Therefore, the communication strategy should be designed to provide all stakeholders, particularly farmers and agricultural producers, with objective information regarding the potential benefits and limitations that the implementation of agrivoltaics may bring to them. Educating the public about the advantages of APVs, organizing public events and demonstrations, and highlighting examples of successful projects can aid in building of public awareness and support for APVs.

To facilitate the development of smaller agrivoltaic projects, grants and/or feed-in tariffs can be considered as a means of providing specific financial and technical support for farmers and communities for the development of such projects.

Lastly, the relevant state institutions and scientific community should encourage ongoing scientific research of agrivoltaic projects through the establishment of relevant funding programmes and other forms of technical assistance, trainings and education of growers and other stakeholders regarding the installation, maintenance, and monitoring of agrivoltaic projects.

LIST OF ABBREVIATIONS

Abbreviation	**Full description**
ARKOD	Agricultural land use records
APV	Agriphotovoltaics
AV	Agrivoltaics
CAPEX	Capital Expenditures
CBS	Croatian Bureau of Statistics
CDPENAF	Commission départementale de préservation des espaces naturels, agricoles et forestiers
EU	European Union
FNSEA	Fédération nationale des syndicats d'exploitants agricoles
FPV	Floating Photovoltaics
GDP	Gross Domestic Product
GHG	Greenhouse gas
HOPS	Croatian Transmission System Operator
KWp	Kilowatt pick
LED	Light emitting diodes
MWh	Megawatt hour
MWp	Megawatt pick
NGEU	Next Generation EU
NGO	Non - Governmental Organization
NUTS	National classification of statistical regions
OPV	Organic solar cells
PDO	Protection Designations of Origin
PNRR	Piano Nazione di Ripresa e Resilienza
PPA	Power Purchase Agreements
PV	Photovoltaic
RES	Renewable Energy Sources

1. INTRODUCTION

Climate change poses a growing threat in the 21st century. It is a challenge for all humanity as it affects all aspects of the environment and economy, threatening the sustainable development of the society. Climate change affects the frequency and intensity of extreme weather events (extreme rainfalls, floods and flash floods, erosions, storms, drought, heat waves and fires) resulting in gradual environmental shifts (rising air, soil, and water surface temperatures, rising sea levels, acidification of the sea, and expansion of dry areas).

The agricultural sector is especially vulnerable to the pervasive effects of climate change. The expected repercussions on the agricultural sector include but are not limited to: (i) changes to the growing seasons of arable crops, with a focus on crops and oilseeds (e.g., maize, sugar beet, soybeans, etc.); (ii) lower yields from all types of crops; and (iii) increased reliance on water.

Numerous climatological studies, using both measurement analysis and climate simulations, have demonstrated that the climate of the Mediterranean region is changing. As a transition zone between Central Europe and the Mediterranean, Croatia is located in a vulnerable region of Europe, where the trend of rising average annual air temperature is evident throughout Croatia. A large variability in the measured extreme precipitation has also been observed, from severe droughts to large floods. Numerous climatological studies indicate that temperature and precipitation extremes will intensify in the future climate over Europe.

Due to its reliance on weather, the agricultural sector is particularly vulnerable to climate change. Extreme weather phenomena such as droughts and hail have cost Croatia an average of €76 million per year, or 0.6% of its GDP, from 2000 to 2007[1]. The duration/length of the vegetative period of agricultural crops is altered by climate change, resulting in reduced crop yields. Frequent droughts will increase irrigation water demand. Additionally, a longer vegetation period will also enable the cultivation of some new cultures and varieties. On the other hand, more frequent flooding and stagnation of surface water will reduce or eliminate yields.

At the same time, international and EU policy documents, strategies and implementation plans have been adopted to reduce CO_2 emissions by shifting away from fossil fuels and supporting and incentivizing the use of renewable energy sources (RES) in the production of electricity, primarily through the use of the wind and solar potentials.

The extensive use of solar energy (photovoltaics) in agriculture and freshwater aquaculture sector could have a significant impact on preventing or mitigating potential climate change damage. Such solar energy projects in the agricultural sector are typically referred as agrivoltaics (also referred to in this study as Agri – PV or APV). Agrivoltaics is an emerging approach that aims to integrate agriculture and solar energy production on the same piece of the land. This can be accomplished by elevating solar modules and increasing the space between rows, while maintaining agriculture on the ground below or between.

Through the promotion of intensive synergies between solar energy projects and the agriculture and aquaculture sectors, multiplier effects such as physical protection of certain crops (such as vineyards, olive groves, and pastures) from extreme weather events (heatwaves, extreme precipitation) can be

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[1] The World Bank Group, 2021.

achieved, which will have a positive impact on yield size and product quality. In addition to its effect on crop production, the implementation of APV increases the profitability of agriculture by generating additional income from energy production[2].

The use of agrivoltaic projects has increased significantly over the past few years in various parts of the world (primarily in the United States, Asia – i.e. Japan and South Korea, and various European countries) due to their significant potentials, which have been demonstrated through various research and pilot projects. However, as Agri – PV is a relatively new concept, significant challenges and obstacles must be addressed (legal, technical, environmental, financing etc.) to achieve the successful integration of the two sectors .This study will also address a number of these challenges pertaining to the Croatian agrivoltaic market.

Consequently, the primary objective of this document is to conduct a comprehensive analysis on the feasibility of implementing Agri – PV projects in Republic of Croatia, taking into account the experiences of Agri – PV systems and projects in some EU countries, various scientific researches and case studies on the justifiability of the Agri – PV application to various agricultural crops, as well as the overall agricultural potentials of the Republic of Croatia in terms of suitability of different crops for application of agrivoltaics. In addition, other factors, such as the existing legal framework, various financing models, possible challenges to the implementation of APV projects, and estimated investment potentials, will be discussed.

The result of this work is a bilingual study presenting the implementation potentials of Agri – PV projects in Croatia, the primary benefits and possible challenges in the application of agrivoltaic projects, as well as appropriate conclusions and recommendations for improvement

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[2] Weselek et al., 2019.

2. OVERVIEW OF RES APPLICATION IN THE AGRICULTURAL SECTOR

2.1 AGRICULTURAL PRODUCTION AND CLIMATE CHANGE

Numerous climatological studies have demonstrated that climate change has severe effects on agricultural production. According to the most recent Intergovernmental Panel on Climate Change (IPCC) report (2022), the world is set to reach the 1.5°C level within the next two decades, and only the most drastic reductions in carbon emissions from now will help prevent an environmental disaster. Regional climate model-based climatological studies indicate that temperature and precipitation extremes will intensify over Europe in the future climate. Numerous studies have demonstrated changes in the climate of the Mediterranean, both through the analysis of measurements[3] and the application of climate simulation models[4].

Croatia is located in a sensitive area of Europe where trends of increasing average temperature have been present for some time now (extreme weather events such as droughts and hail have resulted in annual average losses of €76 million per year or 0.6% of national GDP[5] from 2000 to 2007).

Under conditions of a changing climate and diminishing natural resources, agriculture faces the challenge of producing sufficient food, feed, and fibre to meet the growing demand6. Since the majority of agricultural crops are directly reliant on climatic conditions, a rise in temperature above optimal is becoming a significant concern. Growing areas shifts, growing season lengthening, winter hardening potential, frost and hail occurrence, reduced yields and food quality are some of the most evident consequences of global warming trends7. Observations show an increase in frequency and duration of warm weather extremes8. Warming tends to decrease yields because crops complete their annual development more quickly, resulting in less yield. In general, both winter and summer crops feature an advanced emergence, anthesis and maturation stages in response to higher temperatures and the duration of the crop-growth cycle is projected to decrease9. Heat stress undoubtedly negatively affects animal health and welfare. These environmental conditions can affect livestock health by causing metabolic disruptions, oxidative stress, and immune suppression, which can lead to infections and death. Indirect effects include alterations to the availability and the quality of feedstuffs and drinking water, as well as survival and redistribution of pathogens and/or their vectors10. Temperature rise will boost insect growth and development by increasing geographical distribution and overwintering11.

A large variability in the measured extreme precipitation has been observed, ranging from severe droughts to massive floods. However, rising temperatures imply water scarcity which may worsen agricultural systems, especially in semi-arid areas like Southern Europe[12]. Consequently, frequent droughts will increase the demand for irrigation water to prevent yield decline. Agricultural irrigation accounts for around 70 % of global freshwater withdrawals [13]. On the other hand, an increase in precipitation may benefit semi-arid areas by increasing soil moisture, but it may exacerbate problems in areas with an ex-

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[3] Cindrić et al., 2016.
[4] Soares et al., 2016.
[5] The World Bank Group, 2021.
[6] Anwar et al., 2013.
[7] Jones et al., 2005.
[8] Lotze-Campen and H.-J. Schellnhuber, 2009.
[9] cf. Moriondo et al., 2010.
[10] Lacetera, 2018, Bernabucci, 2019.
[11] Ziska and Runion, 2007.
[12] Agovino et al., 2018.
[13] Gitay et al., 2001.

cess of water[14]. More frequent flooding and stagnation of surface water will diminish or completely obliterate yields[15]. Climate change influences soils by increasing the rate of nutrient leaching and soil erosion[16]. Extreme rainfall and the transition from snow to rain will also accelerate erosion.

Increasing temperatures at higher latitudes in the Northern hemisphere will extend the growing season by 1.2 to 3.6 days per decade[17]. Additionally, longer vegetation period will enable the cultivation of some new cultures and varieties. Some crops that that are primarily grown in the south of Europe (such as maize, sunflowers and soybeans) will become more suitable for growing further north or at higher altitudes in the south[18]. Literature shows that crop diversification is one of the widely used *ex ante* adaptation measures in developing countries to deal with climatic shocks[19].

Also impacted by climate change are the two primary processes of desertification – erosion and salinization. The risk of soil erosion is contingent on climatic erosivity, soil erodibility, and land and crop management practices. Climate change can have an effect on all of these parameters and greatly accentuate the erosion hazard. The serious problem of soil salinization may also be aggravated by the anticipated aridification caused by an increase in potential evapotranspiration as a consequence of global warming[20]. Climate change effects diminish the capacity of most countries to meet food, energy and water demands of the growing world population.

2.2 USE OF SOLAR ENERGY IN THE AGRICULTURAL SECTOR

Climate change in turn triggered the development of project-based RES, with a particular focus on photovoltaic systems, including their use in the agriculture sector (agrivoltaics)[21].

There is no internationally standardised definition of agrivoltaics as such. In 1982, the term "agrivoltaic" was coined to describe the combination of electricity generation and crop sowing on the same agricultural land. The neologism agrivoltaics combines "*agri*" for agriculture and "*voltaics*" for photovoltaics[22]. Recent German normative act "DIN SPEC 91434:2021-05 – Agri-photovoltaics systems – Requirements for primary agricultural use"[23] provides one definition, highlighting the importance of the agricultural component:

"Agricultural photovoltaics (agrivoltaics) is the combined use of the same area of land for agricultural production as the primary use and for electricity production using a PV system as a secondary use. The dual use of land not only increases the ecological and economic efficacy of land use, but it can also result in positive synergy effects between agricultural production and the agrivoltaic system"[24].

Agrivoltaics is also known as agrophotovoltaics, solar sharing, farming photovoltaics, Agri – PV, and solar farming[25] For the purposes of this study, either "agrivoltaic" or "Agri – PV " or "APV" will be used.

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[14] Agovino et al., 2018.
[15] The World Bank Group, 2021.
[16] Lotze-Campen and H.-J. Schellnhuber, 2009.
[17] Gitay et al., 2001.
[18] Audsley et al., 2006.
[19] Macours et al., 2012.
[20] Rengasamy, 2006.
[21] IPCC, 2014.
[22] Challenges for Agrivoltaics in the International Context. Maximilian Vorast. 2022.
[23] DIN 2021.
[24] Challenges for Agrivoltaics in the International Context, Master's Thesis Maximilian Vorast. 2022.
[25] Challenges for Agrivoltaics in the International Context, Master's Thesis Maximilian Vorast. 2022.

In some countries, agrivoltaic projects also refer to projects in which farmers install the solar panels on the roofs of their farms for the purpose of energy self-consumption. Since, there is no dual use of land, which is essential to the definition of Agri – PV, these types of projects do not fall under the scope of the analysis covered by this Study.

Numerous studies have demonstrated that it is possible to integrate photovoltaic (PV) systems with agricultural production, allowing for PV development on a larger scale while protecting agricultural crops and preserving yield[26]. The first benefit of agrivoltaics is increased land productivity during the winter, when open-field agricultural production is not feasible. Many studies indicate that it is possible to increase crop yields with PV systems[27]. This is feasible because agrivoltaics creates modified microclimate conditions beneath modules by altering the air temperature, relative humidity, wind speed, wind direction and soil moisture[28]. Agrivoltaics safeguards crops against both excessive solar energy and stormy weather, such as hail[29]. Agrivoltaics also provides a more efficient use of water, which may contribute to a decrease in water consumption[30]. This is of particular interest in drylands where unfavourable growing conditions such as excessive sunlight, high temperatures and severe droughts (water shortage) are prevalent.

When attempting to describe the challenges associated with agrivoltaics, the term solar sharing is probably the most apt. Sharing the solar resource to simultaneously produce food and energy implies that the design of the photovoltaic system cannot always adhere to a standard approach in which the orientation of the panels is intended to optimize energy production, and the system design could conflict with an optimized food production[31]. Therefore, it is necessary to implement system adaptations to the local climate, crop type, and land configuration[32].

Agrivoltaics as a concept or approach encompasses a number of different technologies that are defined by a specific method of integrating agriculture and PV[33].

A closer look at the variety of agrivoltaics solutions is possible using the framework proposed by Gorjian et al (Figure 1)[34]. The first line of differentiation is defined by whether the modules are mounted in an open field or on a roof top. Fully opaque rooftops can be associated with farming buildings, including indoor farming, but there is no evidence of a direct interaction between PV systems (other than electricity use) and agricultural activity. Aquaculture and horticulture can also be integrated with both open-field PV or greenhouse systems. Open field systems can be further differentiated by growing crops between the module rows (interspace PV) or below the modules (overhead PV) with a higher vertical clearance. These systems can be fixed tilted, single- or dual-axis tracking. As compatibility with agricultural machinery is a major design criterion for agrivoltaics, it is assumed that interspace PV is primarily used for grassland farming, fodder production and grazing, whereas overhead systems can accommodate a wider range of stable food crops on arable land, as well as horticulture including perennial, permanent and specialty crops.[35]

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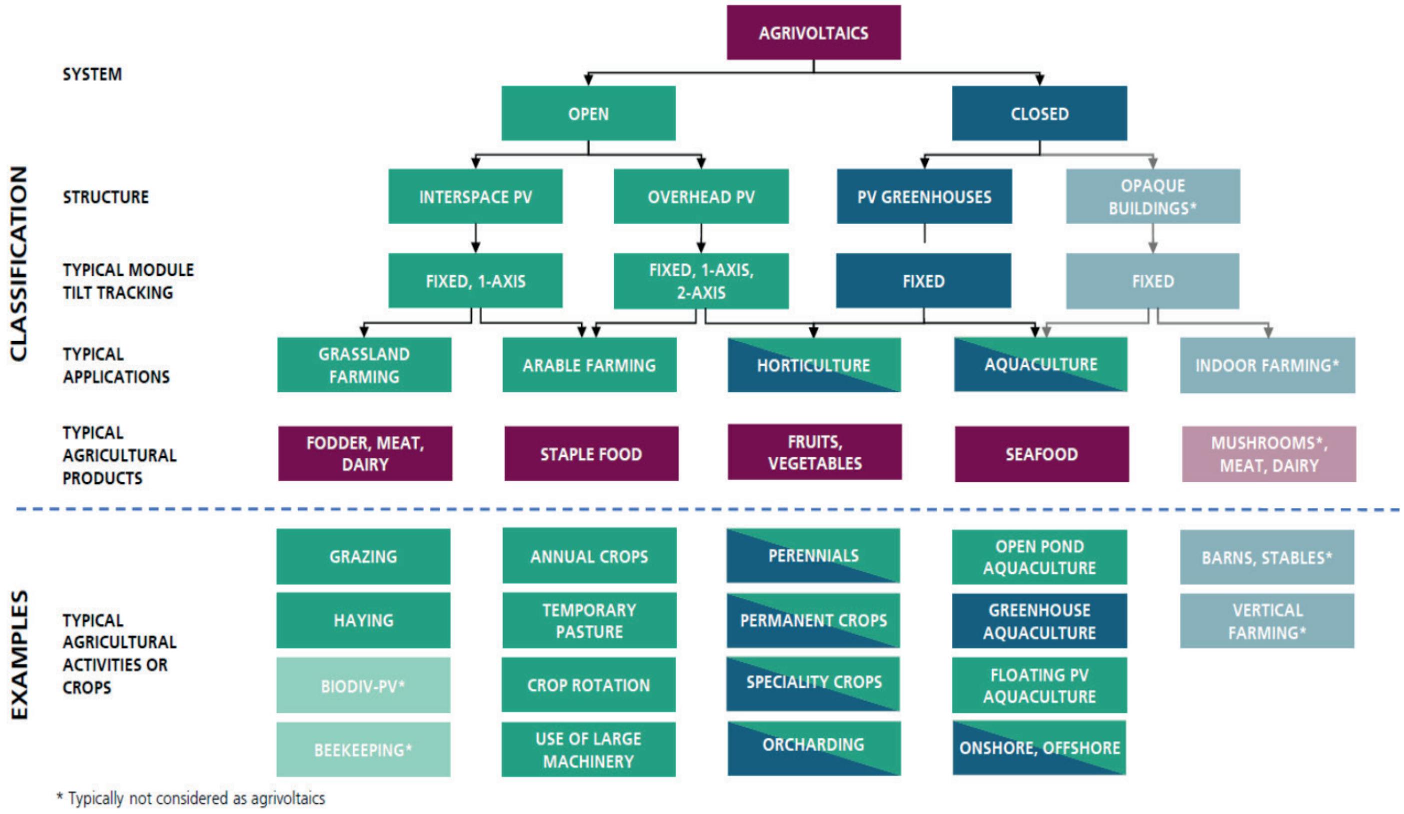
[26] Marrou et al. 2013a, Guerin et al., 2019, Pascaris et al., 2020, Pascaris et al., 2021.
[27] Hudelson et al., 2021, Trommsdorff et al., 2021.
[28] Adeh et al., 2018.
[29] Dupraz et al., 2011.
[30] Marrou et al., 2013b, Elamri et al., 2018.
[31] Toledo and Scognamiglio, 2021; Trommsdorff et al., 2021.
[32] Padilla et al., 2022.
[33] Challenges for Agrivoltaics in the International Context, Master's Thesis Maximilian Vorast. 2022.
[34] Gorjian et al. 2021.
[35] Challenges for Agrivoltaics in the International Context,

Figure 1 Proposal of agrivoltaics systems' categorization



Source: Gorjian et al. 2021.

2.3 AGRIVOLTAICS IN THE CONTEXT OF THE EU INITIATIVES AND POLICIES

At the EU level, various strategic and legislative documents have been enacted in recent years with the goal of reducing CO2 emissions and, consequently, boosting the application of different RES projects[36]. This was particularly the case in 2022, when the European Commission unveiled the REPowerEU Plan in response to the global energy market disruption precipitated by Russia's invasion of Ukraine. The REPowerEU Plan's measures respond to this ambition, through energy savings, diversification of energy supplies, and accelerated roll-out of renewable energy to replace fossil fuels in homes, industry, and power generation[37].

The EU Commission adopted the EU Solar Energy Strategy[38] as part of the Plan, and it proposes the multiple use of space as one of the innovative forms of additional deployments of solar (photovoltaics) projects. According to this document, multiple use of space can contribute to mitigating land constraints caused by competition for space, including for environmental protection, agriculture, and food security.

Master's Thesis Maximilian Vorast. 2022.

[36] European Commission, A policy framework for climate and energy in the period from 2020 to 2030, COM/2014/015; European Commission, Clean Energy for All Europeans, COM/2016/0860); European Commission, A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy, COM/2015/080; European Commission, The European Green Deal, COM (2019) 640; The Renewable Energy Directive, Directive (EU) 2018/2001, (RED II).

[37] https://ec.europa.eu/commission/presscorner/detail/en/ip_22_3131

[38] COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS (COM (2022) 221 final.

In particular, under certain conditions, agricultural land use can be combined with solar energy generation in so-called agrivoltaics (or Agri – PV). According to this document, the two activities can establish synergies in which PV systems can contribute to crop protection and yield stabilization while agriculture continues to be the predominant use of the land area. Member States should consider incentives for the development of Agri – PVs when designing their National Strategic Plans for the Common Agricultural Policy, as well as their solar energy support frameworks (e.g., by integrating Agri – PV into renewable energy tenders). It is also worth noting that, in the agricultural sector, State aid regulations permit investment subsidies for sustainable energy.

Furthermore, thanks to floating PV solutions, the water surface can be used for solar generation. Floating PV panels reduce water evaporation and can be connected to the dam's electric systems to increase total output, although the effect on aquatic biomass is still being studied.

In conclusion, the Commission will devise guidelines for Member States to promote the development of innovative forms of solar energy deployment outlined in this strategy[39]. To follow up on this commitment, the Commission has commissioned a study that will investigate the potential and specific obstacles to these innovative forms of deployment and identify best practices among Member States. The study will be conducted by a consortium comprised of Trinomics, Enerdata, Schoenherr, Fraunhofer ISE, and DNV. This will serve as the basis for the guidelines, which are expected to be published in the first quarter of 2024.

The EU intends to support agrivoltaic projects in the future in the form of a dual use of agricultural land, and concrete guidance on how to approach these types of projects can be anticipated in the near future.

Regarding the Agri - PV experiences in EU countries, there is different practice in terms of legal framework, project type and size, financing models, and similar factors, as will be illustrated in greater detail in the following chapters by case studies and examples from Germany, Italy, France, Spain, Greece, the Netherlands, and Austria.

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[39] EU Solar Energy Strategy.

3. TECHNICAL ASPECTS OF AGRI – PV PROJECT INSTALLATION

Technical approaches of integrating photovoltaics into agriculture are as diverse as agriculture itself. APVs can be placed over “arable land”, “grassland,” and “greenhouses” (Figure 2). Agrivoltaics with field crops, such as permanent crops or annual and perennial crops, usually requires special support systems for crop-adapted PV modules, whereas agrivoltaics on grassland typically employs conventional mounting structures for ground-mounted photovoltaic systems, sometimes with minor adaptations[40].

When it comes to designing farms with photovoltaics, there are various technical options for maximizing land use while enhancing crop and energy yields. Rows of elevated PV panels are typically coupled with underlying rows of crops on the same site. Another alternative is to install PV panels and plant crops or fruit trees in between[41]. Many changes and modifications can be made to optimize APV integration, such as optimizing the spacing between rows of modules, adjusting the height of mounted modules, configuring the density of solar modules, and adjusting the tilt angle; however, all of this work is dependent on the type of APV developed, geographical conditions, and the growing season[42].

Figure 2 PV modules above a foil tunnel

Source: BayWa r.e.

Agrivoltaic systems are compatible with every form of solar module. Structural modifications in solar modules used to focus primarily on solid structuring. However, there are now advances in the use of vertical bifa-

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[40] Fraunhofer ISE, 2022c.

[41] Astydama, 2022.

[42] Zainol Abidin et al., 2021.

cial photovoltaics, semi-transparent photovoltaics, and solar tracking systems. The goal is to minimize competition between PV and agriculture for solar radiation while maximizing energy production and agricultural yield[43]. Modules with wafer-based silicon solar cells account for about 95 % of the global PV market. The typical construction consists of a glass panel on the front and a white protective film on the back. With a transparent back cover (glass, foil), the spaces between the cells allow most of the light to pass through and reach the plants below. In conventional modules, the spaces between the cells account for four to five percent of the surface area. To enhance light transmission, the spaces can be widened, and the module frames can be replaced. Modules with a greater ratio of transparent to total surface area can shield plants from environmental conditions without diminishing light availability.

Bifacial modules can also use ambient light incident on the back side to generate electricity. Depending on the intensity of backside radiation, the electricity yield can be increased by up to 25 % (typically between 5 and 15%). Due to the larger spacing between rows and the typically taller supports, the quantity of light falling on the back of the modules is particularly high. Consequently, bifacial modules are well suited for Agri – PVs. Another advantage of modules with a bifacial glass structure is their residual strength in the event of glass fracturing. Thin-film modules are approximately 500 g/m2 (grammes per square metre) lighter per unit area than modules with wafer-based silicon solar cells of an otherwise identical structure. However, the efficiency is somewhat diminished. Thin-film modules have a somewhat lower cost per unit area[44].

The semi-transparent organic solar cells (OPV) have proved to be efficient due to their ability to filter out specific wavelengths of light[45]. In principle, selective spectral adjustment of the active layers of OPV is possible, meaning that a portion of the solar spectrum can be transmitted and utilized by plants growing beneath. However, OPV is still in the phase of market introduction, with low efficiency and durability being among the main challenges. There are currently very few providers of OPV and Concretator PV modules for agrophotovoltaics[46].

The application of the most appropriate technical solutions for agrivoltaic projects in Croatia will depend on the types of crops, their requirements for light/shade intensity, the characteristics of the terrain, and other factors.

In the following text, case studies will be presented on research-type projects testing various technical solutions for different crop types in agrivoltaic projects.

a. APV RESOLA (GERMANY)

The project APV RESOLA (Agrophotovoltaics – Resource Efficient Land Use), which lasted from 2015 to 2021[47], was one of the most extensive in terms of various aspects of research conducted in Germany. The Fraunhofer ISE conducted preliminary simulations regarding technical optimization of APV systems. From it emerged numerous research papers, publi-

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[43] Zainol Abidin et al., 2021

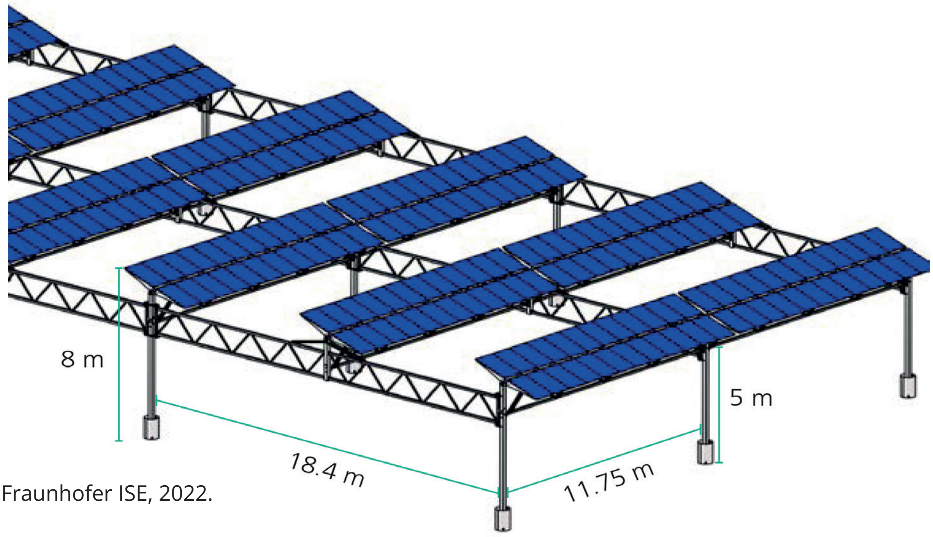
[44] Fraunhofer ISE, 2022c)

[45] Gauffin (2022)

[46] Fraunhofer ISE, 2022c.

[47] The project APV-RESOLA was funded by the German Federal Ministry for Education and Research (BMBF). The project leader was Fraunhofer Institute for Solar Energy Systems ISE and several partners. The main objective of the project was to research the basic principles of the agrivoltaic technology and demonstrate its viability (Fraunhofer ISE 2022).

Figure 3 Illustration of the agrivoltaic system in Heggelbach. © AGRISOLAR Europe GmbH



Source Fraunhofer ISE, 2022.

cations, and two APV-Guidelines published by Fraunhofer, which were also used for the purpose of this Study. This project examined not only the technical and environmental aspects of agrivoltaic technology, but also the economic and social aspects. Energy production, agricultural production, technological design, economic viability and social acceptance were discussed [48].

A pilot Agri - PV system was erected on the organic farm *Hofgemeinschaft Heggelbach* in the Lake Constance region in 2016. Total test field area, including APV system and reference area, was approximately 2.5 ha, while the APV system with dimensions of 25 m x 136 m was set up on about 0.3 ha. A total of 720 bifacial double-glass PV modules with a 5 m vertical clearance (total height of PV array: 8 m) and a width clearance of up to 19 m were set up (Figure 3). Figure 4 presents fundamental technical parameters of APV. Bifacial PV modules use both the front and back surfaces to convert solar energy into electricity, resulting in a higher electri-

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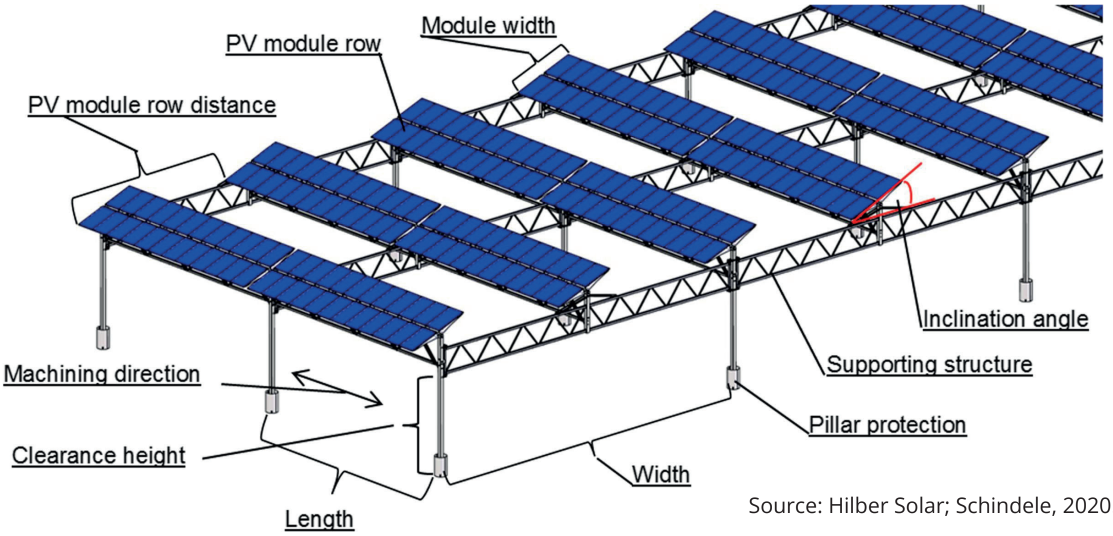
[48] Weselek, 2019.

Figure 4 Fundamental technical parameters of the APV system technology



Source: Hilber Solar; Schindele, 2020.

Figure 5 Wheat harvesting under the APV-pilot plant in 2018

Source: Farm community Heggelbach; Schindele, 2020.

Figure 6 Potato harvesting under APV panels in 2017

Source: Farm community Heggelbach; Schindele, 2020.

cal yield per unit area, while also allowing for uniform light distribution beneath the PV array[49].

The specific features of this system, including its height, greater distance between the PV module rows, and south-west orientation enabled not only sunlight homogeneity for crops but also allowed for the use of large agricultural machinery, such as combine harvesters (Figures 5 and 6). This German design differs from the majority of other agrivoltaic approaches[50]. The installed capacity of this pilot system was 194 KWp, sufficient to power 62 four-person households annually. As test crops for the APV systems, winter wheat, potatoes, celery, and clover-grass mixture were cultivated in a crop rotation[51]. To analyse the impact of APV on crop growth, fields adjacent to a system were used as a reference (without solar panels). In 2017 and 2018, microclimatic parameters, crop growth and development, and yields were observed.

Diverse weather conditions during the growing season were found to be a significant factor in crop yields. For instance, the yield of potatoes cultivated with an agrivoltaic system ranged from -20% in 2017 to +11% in the dry and hot year of 2018. Yield ranges of other crops cultivated under AV systems relative to the reference field were -19 to +3% for winter wheat, -8 to -5% for grass-clover and -18 to +12% for celery. Monitoring of crop development revealed an increase in plant height and aboveground biomass in both years. The investigation continued throughout the subsequent years. Results from 2019 indicate that APV systems can reduce crop yields by up to 33% for celery, 28% for wheat, and 19% for clover grass. Wheat yield in 2020 was marginally higher by 2% [52] .

It demonstrated that crops growing under APV may experience a decrease in productivity, but that during unfavourable hot and dry growing seasons, crop's performance and yield improve. During hot and dry periods, it is believed that crops benefited from partial shade provided by PV modules.

In the APV-RESOLA project, close attention was paid to the microclimate beneath PV modules, as it was anticipated that shading would result in a change. Modified microclimatic conditions affected the maturation and yield of crops. Under the APV, photosynthetically active solar radiation was approximately 30% lower than at the reference site. Also, in the spring and summer of both years, soil temperatures were lower under the APV system, while air temperatures remained constant[53]. Mean annual air humidity was greater under the APV in both years, but average soil moisture increased only in 2017[54]. Nonetheless, during the hot and dry summer of 2018, the wheat plot had greater soil moisture than the reference plot [55].

This pilot project's findings suggest that APV systems may have greater potential in hot and dry regions, where favourable effects on crop production are anticipated. However, due to the combined land use, the land use efficiency under the APV system in 2017 was 160%, and in 2018 it was 186%.

In Germany, there is a significant concern about land-use conflicts between agriculture and energy production. In order to ascertain

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[49] Fraunhofer ISE, 2016.

[50] Trommsdorf et al., 2021.

[51] This case study can also be observed in regard to paragraphs 7.5.3 (case studies for vegetable growing) and 7.6.3 (case studies for cereals growing).

[52] Fraunhofer ISE, 2022.

[53] Fraunhofer ISE, 2020; 2022.

[54] Weselek, 2021.

[55] Fraunhofer ISE, 2022.

the community's perspective, the APV-RESOLA project included a local survey and workshops for citizens and stakeholder groups.

There must be widespread public support for agrivoltaic technology[56]. Regarding acceptance by the agricultural sector and the general public, up to 20% yield reduction may be acceptable. The project results indicate that is necessary to achieve suitable light management for important arable crops in Germany, which is possible with a reduction in module density and modification of module alignment. In addition, the use of mobile agrivoltaic systems can increase light availability during critical growth stages, thereby reducing yield losses.

b. VERTICAL AGRIVOLTAIC SYSTEMS IN COMMUNITY SOLAR PARKS (GERMANY)

Vertical agrivoltaic system with bifacial, double-glass PV modules vertically aligned east to west and with approximately 10 m areas between the rows was commissioned in 2018 in Saarland (*Eppelborn-Dirmingen* solar park), as one of the Europe's first bifacial agrivoltaic systems of larger sizes.

In 2020, following the same pattern, a 14-hectare agrivoltaic system was installed in Baden-Württemberg (*Donaueschingen-Aasen* solar park), with the annual energy yield of 4,850 MWh/year (Figure 7). The system's capacity power of 4.1 MW_p is sufficient to supply 1,400 households. Arable land was converted into extensively farmed grassland. The share of land taken up by the PV installation is minimal, and the 10 m spacing between rows al-

Figure 7 Vertical APV System in Donaueschingen-Aasen Solarpark, Baden-Württemberg

Source: ©Next2Sun GmbH.

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[56] Ketzer et al., 2019.

Figure 8 Tractor while mowing through module rows

Source: ©Next2Sun GmbH.

lows farming with agricultural machinery (Figure 8). Both solar parks are used for fodder production i.e., hay and silage[57],[58]. It is anticipated that this new vertical installation method will be particularly favourable for plants in windy regions, as the modules can serve as windbreaks and reduce wind erosion[59]

c. H2ARVESTER (THE NETHERLANDS)

Two prototypes of a mobile solar system are currently being tested by a farmer and a research institute in the Netherlands. The first prototype mobile agrivoltaic system, called H2arvester, was deployed in 2022 on sugar beet fields in Oude-Tonge, South Holland, and the second on the research farm of Wageningen College in Lelystad. Both systems will be in operation for one year to test the impact on yield and soils and to demonstrate that there is no loss of agricultural production. This mobile system is designed to be self-propelled (Figure 9). Unlike static agrivoltaics systems, this system is designed to migrate across the field. There will thus be no constant shading of the same area. If there is no consistent shading of the same area, plant production and soil quality should not be affected. This solar-powered vehicle traverses a maximum of 10% of the land at a speed of 10 m/hour. In addition, they will test a combination with an on-farm electrolyser to generate hydrogen that can be used as a green fuel in agricultural applications. This electrolysis and hydrogen production produce residual heat that can be used to dry various crops such as oats, grass, and alfalfa. [60]

d. AGRIVOLTAICS IN BADEN-WÜRTTEMBERG (GERMANY)

The agrivoltaics pilot project in Baden-Württemberg region began in 2022 and will last

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[57] Next2Sun, 2022.

[58] This case study can also be observed in regard to Chapter 7.6.3 (the case studies for cereals, industrial and forage plants).

[59] Fraunhofer ISE, 2022.

[60] pv Magazine, 2022.

Figure 9 The mobile agrivoltaic system

Source: pv magazine, 2022.

Figure 10 Agrivoltaics in 'Gala' apple orchard in Kressbronn

Source: *https://www.ise.fraunhofer.de/en/research-projects/agri-pv-bawue.html* nearly 3 years (34 months). The initial phase entails installing five PV systems for pome and soft fruit orchards (in Ravensburg, Weinsberg, Karlsruhe, Kressbronn and Nußbach) with a total power output of 1.7 MWp. Two of these PV systems will be installed in the existing orchards (Kressbronn and Nußbach). The project's objective is to study different PV systems (standard, bifacial and semi-transparent modules with varying light transmittances; static and tracking PV panels) that are each adapted to the crop (Figure 10).

This project is also used to test the German normative act “DIN SPEC 91434:2021-05” as part of the process to introduce agrivoltaic standards in Germany.

4. OVERVIEW OF AGRI – PV LEGAL FRAMEWORKS IN OTHER EU COUNTRIES

Since the topic of Agri-PV projects is relatively new and complex, one of the primary concerns is how to define them legally, how to regulate their development and the various technical and procedural requirements for their establishment, implementation, and potential monitoring. Considering the present state of the agrivoltaic market in Croatia, as described in Chapter 6, this issue should be of particular significance for Croatia.

In the following text, the strategic and legal models for agrivoltaics in some of EU countries with the most advanced Agri – PV systems will be presented.

1. Italy

Italy is the only European country that provided significant funding for the construction of new agrivoltaics under the National Recovery and Resilience Plan (PNRR - *Piano Nazione di Ripresa e Resilienza*), which was adopted following the EU Next Generation (NGEU)-Recovery Plan for Europe. A 1.1-billion-euro investment in the technological development of agrivoltaics is planned as one of the Plan's components by 2026.

Planned for the field of agrivoltaics is the agri – solar park (*Parco agrisolare*). The primary objective of this project is to increase the production of electricity from agrivoltaics by 5% until 2026, in addition to other benefits derived from the planned activities.

The Ministry of the Environment and Energy Security (*Ministero dell'ambiente e della sicurezza energetica*) is responsible for the implementation of this project, and in June 2022 it published **Guidelines in the field of Agrivoltaic systems** (*Linee Guida in materia di Impianti Agrivoltaici*).

Guidelines are a result of the fact that on April 28, 2022, the decree-law designating suitable areas for the installation of photovoltaic plants and streamlined authorization procedures for plants located in suitable areas was converted into law.

Regional authorities in Italy are responsible for the formulation of spatial plans and the approval of energy projects, and the conditions for the installation of agrivoltaic plants may vary from region to region.

According to the Guidelines, plants are categorized by their suitability for agrivoltaic use in different type of plantations (Table 1).

In addition, the Guidelines provide various definitions of agrivoltaics based on the complexity of such projects:

Table 1 Suitability of crops for agrivoltaic use

Suitability	Crop
Very suitable crops	potato, hops, spinach, lettuce, broad beans
Average suitable crops	onions, beans, cucumbers, zucchini
Suitable crops	rye, barley, oats, green cabbage, rapeseed, peas, asparagus, carrot, radish, leek, celery, fennel, tobacco
Barely suitable crops	cauliflower, sugar beet, beetroot
Unsuitable crops	wheat, spelled, corn, fruit trees, sunflowers, etc.

Source: Linee Guida in materia di Impianti Agrivoltaici (2022)

1) Agrivoltaic system (or agrivoltaic, or agrophotovoltaic): photovoltaic system that employs solutions designed to maintain the continuity of agricultural and pastoral cultivation activities at the installation site;

2) Advanced agrivoltaic plant: agrivoltaic plant that

   - adopts innovative integrative solutions with elevated module assembly, as well as module rotation, so as not to jeopardise the continuity of agricultural and pastoral cultivation activities, also possibly allowing the application of digital and precision agriculture tools;

   - provides for the simultaneous creation of monitoring systems that allow for the verification of the impact of the photovoltaic installation on the crops, water savings, agricultural productivity for various types of crops, the continuity of the activities of the concerned farms, the recovery of soil's fertility, microclimate, and resilience to climate changes;

3) Advanced agrivoltaic system: complex system composed of the works necessary for carrying out agricultural activities in a given area and of an agrivoltaic system installed on that area, which, through a spatial configuration and appropriate technological choices, integrates agricultural activity and electricity production, and aims to enhance the production potential of both subsystems, while ensuring the continuity of agricultural activities in the area;

The Guidelines state that agrivoltaic systems must meet the five requirements listed below:

A. the agrivoltaic system shall be designed and implemented so as to employ spatial configuration and appropriate technological solutions that permit the integration of agricultural activity and electrical production while enhancing the productive potential of both subsystems;

B. the agrivoltaic system shall ensure the synergistic production of electricity and agricultural products and shall not compromise the continuity of agricultural and pastoral activity;

C. the agrivoltaic system employs innovative integrated solutions with modules elevated from the ground, with the aim of optimizing the energy and agricultural performance of the agrivoltaic system;

D. the agrivoltaic system is equipped with a monitoring system to verify the impact on cultivations, water savings, agricultural productivity for various types of cultivations, and the continuity of agricultural activities carried out by the relevant farms;

E. in addition to meeting requirement D, the agrivoltaic system is equipped with a monitoring system that allows for the verification of the recovery of soil fertility, microclimate, and resilience to climate change.

Requirements A and B are necessary to qualify a photovoltaic plant erected in an agricultural area as an “agrivoltaic plant” while requirements A, B, C, and D are necessary to meet the definition of an “advanced agrivoltaic plant”. All prerequisites must be met to qualify for PNRR incentives.

Also, in requirement A, at least 70% of the surface area must be used for agricultural activity, while less than 40% of the total area must be covered by the modules.

2. GERMANY

The concept of agrivoltaics has only recently received significant scientific attention. In 2012, a group of researchers from the Fraunhofer Institute for Solar Energy Systems ISE conducted a preliminary research regarding the applicability of APV in Germany[61]. In order to select suitable crops for Central Europe, they investigated the applicability of Agri – PV in Germany from a variety of perspectives, including plant growth under existing PV installations.

Agrivoltaic systems are not explicitly embedded in the legal framework[62]. The amendment to the EEG that went into effect on January 1, 2021 (The Renewable Energy Sources Act; *Erneuerbare Energien-Gesetz*) introduced a separate innovation tender segment for "special solar power systems, which include not only PV systems above parking lots and floating solar power systems, but also solar power systems on arable or horticultural land - i.e., permanent and perennial crops - if the land is also used for crop cultivation".

In short, the agrivoltaic systems must specifically adhere to the requirements of DIN SPEC 91434. According to section 3 (1) of this act, agrivoltaic systems are systems for the generation of electricity from renewable energy[63]. The most recent revision to the EEG 2023 predicts further development of photovoltaics and possibilities that additional land can be developed through new classifications for photovoltaic systems such as Agri – PV and other PV systems. From now on, agrivoltaics falls under the category of free-standing installations rather than innovation tenders.

Finally, on the basis of DIN SPEC 91434:2021-05, Section 12 (5) of Common Agricultural Policy (CAP) Direct Payments Ordinance defines an agrivoltaic system as a system for the use of solar radiation energy that is constructed on agricultural land, does not prevent the land from being cultivated using conventional agricultural methods, machinery and equipment, and does not reduce the amount of usable agricultural land by more than 15 percent. According to the Ordinance, this leaves 85 percent of agricultural land eligible for funding[64].

Technical rule DIN SPEC 91434:2021-05 Agri-photovoltaic systems - Requirements for primary agricultural use[65]

In 2021, a consortium of 15 agricultural and solar enterprises, research entities, and certification bodies in Germany developed the preliminary standard DIN SPEC 91434 for agrivoltaics. The purpose of DIN SPEC 91434 is to distinguish agrivoltaic systems from conventional ground-mounted PV systems **and to ensure that the land used for agrivoltaics continues to be used for crop production.**

It determines the requirements for primary agricultural use in agrivoltaic projects and includes standards for planning, operation, documentation, and operational monitoring, as well as measurement indicators for the test procedure to ensure the quality of agricultural PV systems. The requirements of the primary agricultural use include, for example, the adaptation of light intensity and light distribution under the Agri – PV system to the demands of the respective crop.

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[61] Beck at al. 2012.
[62] Vollprecht et al., 2021.
[63] Fraunhofer ISE, 2022.
[64] Fraunhofer ISE, 2022.
[65] Agri-Photovoltaik-Anlagen - Anforderungen an die landwirtschaftliche Hauptnutzung.

This standard classifies agrivoltaic systems based on vertical clearance and land use types:

- Category I includes overhead PVs with vertical clearance > 2.1 m implying farming under the agrivoltaic system;
- Category II refers to interspace PV with vertical clearance < 2.1 m and farming between the rows of agrivoltaic systems.

In both categories, land can used for permanent and perennial crops (viticulture, fruits, berries), single-year and long-term crops (arable crops, vegetables, fodder, alternating grassland), and permanent grassland with mowing or pasture. Interspace PVs are commonly used in permanent grasslands because they are less expensive and have less of an impact on the landscape. Overhead PVs use land more efficiently and provide greater protection from adverse weather conditions. They are better suited for horticulture production (fruit, viticulture, vegetables) or arable farming. For all specified categories, the agricultural process must be maintained below and between the PV modules[66].

The criteria and key requirements for the agricultural cultivation proposal are as follows:

- the previous agricultural usability of the area must be maintained, and the proposed form of land use must be outlined in an agricultural usage proposal;
- land loss after installation of the PV system must not exceed 10 percent of the total project area for Category I and 15 percent of the total project area for Category II;
- light availability, light homogeneity, and water availability must be checked and adapted to meet the needs of agricultural products;
- precautions must be taken to prevent soil erosion and damage caused by PV system design, anchoring in the soil and water runoff from PV modules;
- it must be ensured that the agricultural yield after the installation of the agrivoltaic system is at least 66 percent of the reference yield. The reference yield is calculated using the three-year average of yields from the same agricultural land or comparable data extracted from the pertinent publications.

3. FRANCE

The development of agrivoltaic projects in France began in the early 2000s with small greenhouses projects. In the meantime, agrivoltaic projects have expanded substantially. In June 2021, French solar companies Sun'Agri, REM Tec, Kilowattsol, and Altergie Développement et Râcines announced the formation of *France Agrivoltaisme*, the world's first trade body for the agrivoltaics sector.

In 2018, the "*Ministère de la Transition Ecologique et Solidaire*", in collaboration with the "*Bureau des énergies renouvables*" and the "*Direction générale de l'énérgie et du climat*" presented the agrivoltaics legal framework and preliminary conclusions. Agrivoltaic projects were evaluated according to a technical report on synergy with agricultural use. Technical report had to be endorsed by an agricultural authority, such as the local "*Chambre d'Agriculture*" (agricultural body).

Recently, the French environmental agency Ademe released a new set of guidelines that define agrivoltaics in detail. According to ADEME et al. (2021), a solar PV system can

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[66] Trommsdorff et al., 2022; Fraunhofer ISE, 2022.

be considered agrivoltaic when the solar PV modules are located on the same area of plot as the agricultural production, and when they impact the agricultural production by providing, without any intermediary, one of the services as listed below, without inducing any significant degradation of the agricultural production (both qualitatively and quantitatively), or any farm income loss:

- Climate change adaptation
- Hazard protection
- Animal welfare
- Specific agronomic services

In addition to the above stated, agrivoltaic projects must always allow the presence of an active farmer and prevent any potential change in farm ownership. Such installations must also be reversible and adapted to local conditions, without damage to the environment.

In February 2023, the Senate passed the Acceleration of Renewable Energies Act, which establishes the regulations for coexistence between agriculture and photovoltaic installations.

Depending on the form of solar installation, the text of the Act provides for two monitoring regimes.

On the one hand, power plants that do not provide a service to agriculture, also referred to as “ground photovoltaic” by the FNSEA (*Fédération nationale des syndicats d’exploitants agricoles*), should be permitted on land that has been uncultivated or has not been exploited for at least ten years. Second option refers to “agrivoltaic” installations which are defined as “electricity production installations using the radiative energy of the sun and whose modules are located on an agricultural plot where they contribute durably to the installation, maintenance or development of agricultural production”. To qualify as agrivoltaic, the installation must guarantee significant[67] agricultural production and sustainable income, allow agricultural activity to be the primary activity of the plot, and be reversible.

To be considered as an “agrivoltaic”, the project must satisfy at least one of the following four conditions:

- increase the agronomic potential of crops;
- constitute a lever allowing farmers to fight against the effects of climate change;
- help cope with various hazards such as drought or water stress;
- contribute to improving animal welfare.

In both instances, the *Commission départementale de préservation des espaces naturels, agricoles et forestiers* (CDPENAF) will be consulted.

The text of the Act also provides for sanctions against projects that would substantially degrade agricultural production.

4. Austria

The basic legislation of Austria that defines and directs the development of the renewable energy system, including agrivoltaics, is the Federal Act on the Expansion of Energy from Renewable Sources[68]. This Act also refers to the PV plants that are to be integrated into existing agricultural systems, thereby

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[67] What it will mean in practice for an installation to “guarantee significant agricultural production and sustainable income” will be defined in greater detail by a decree to be adopted in the following months.

[68] Bundesgesetzblatt für die Republik Österreich. 2022. Bundesgesetz über den Ausbau von Energie aus erneuerbaren Quellen, BGBl. I Nr. 150/2021.

creating agrivoltaic areas, that is, areas used for both photovoltaics and agriculture.

In addition to the Act, the implementation and handling of investment support for the construction and expansion of PV plants and the associated new construction of electricity storage facilities are governed by the Ordinance of the Federal Minister for Climate Protection on the Granting of Investment Grants for the Construction, Revitalization, and Expansion of Plants for the Generation and Storage of Electricity from Renewable Sources for the Year 2022 (*Bundesgesetzblatt für die Republik Österreich, 2022*).[69].

This regulation states that the 25% reduction in subsidy does not apply if the APV system is installed **on agricultural land whose primary use is the production of plant or animal products and whose secondary use is the generation of electricity,** the PV modules are evenly distributed over the total area, and agriculture uses at least 75% of the total area for the production of plant or animal products.

This Ordinance defines the prerequisites for granting of investment subsidies to APVs:

a) every system must be able to be disassembled without leaving any residue, including the system infrastructure, especially the foundation and anchoring. If the soil structure deteriorates during assembly or disassembly of the system, appropriate measures must then be taken to restore the soil structure as closely as possible to its original condition.
b) the distance between the lower edge of the module table and the ground must be at least 80 cm, and the row spacing must be at least two metres, measured between the opposite module areas. These regulations do not apply to innovative photovoltaic systems.

In addition, it stipulates that at least five of the following measures must be observed when installing PV systems on agricultural land or grassland:

a) preservation of existing biotope structures;
b) in the case of a fence, greening of the fence with site-appropriate plants of local origin;
c) creation of site-appropriate hedges or bushes of local origin;
d) establishment of nesting aids for birds, bats, and insects;
e) creation of flower strips using site-specific seed mixtures;
f) cultivation of the area by alternate mowing with a mowing height of at least ten centimetres;
g) management of the area with a mowing frequency of no more than twice per year and a mowing height of at least ten centimetres; grazing of the area without mechanical mowing;
h) greening of the area with regional seed mixtures with at least 15 plant species and wild herbs.

5. SUMMARY OF DIFFERENT AGRI – PV LEGAL SYSTEMS

Following this analysis of legal systems covering the field of agrivoltaics in various EU countries, it can be concluded that in the majority of countries there is a unified definition of agrivoltaics, emphasizing the need for dual and synergetic use of agricultural land

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[69] Bundesgesetzblatt für die Republik Österreich. 2022. EAG-Investitionszuschüsseverordnung-Strom, CELEX-Nr.: 32018L2001.

in which agricultural production must remain the primary activity..

The definition of agrivoltaics is usually part of legislation covering energy issues, while specific details (maximum area that can be covered by APV, maximum yield reduction, possible models, and technical solutions, etc.) are then covered either by specific guidelines (Italy, Germany), or by secondary legislation (Austria, France). Therefore, the APV is identified a special model of PV plants, having its specific rules, procedures of application, etc.

Regarding the applicability of these models to the Croatian market, it can be concluded that a similar definition should be included in the Croatian legislation (most likely in one of the energy laws), that legally binding specifics in terms of possible legal limitations and administrative requirements for the application of APVs should be part of a specific type of secondary legislation, while all other specifics in terms of possible models, technical conditions and specifications (that require more flexible approach) should be part of relevant guidelines and manuals (more information on this can be found in Section 6).

5. FINANCING MODELS FOR IMPLEMENTATION OF AGRI – PV PROJECTS

Identifying and employing suitable financing models is a key component of a successful agrivoltaic implementation. Each model presents stakeholders, including farmers, landowners, investors, and governments, with unique opportunities and challenges. This chapter discusses the various agrivoltaic financing models that have already been implemented in some countries, as well as how these models can promote the growth and adoption of agrivoltaic systems. In this Study, the following models are considered: direct ownership, land leasing, PPA contracting, public-private participation in energy co-operatives, and EU funding programmes and grants.

a) Direct Ownership

In the direct ownership model, the landowner or farmer makes their own investment in the agrivoltaic system. They are responsible for financing the initial costs of the system, including installation, operation, and maintenance. By owning the system, the landowner or farmer can reap the complete benefits of energy savings, revenue from selling excess energy, and potential crop yield enhancements. This model allows the landowner or farmer to have complete control over the agrivoltaic system, but it also requires a substantial upfront investment and ongoing maintenance responsibilities.

This model could be implemented for the very large and/or largest agricultural producers in Croatia, with significant financial strength and energy consumption requirements. Also, it is anticipated that lessees of state-owned land that cannot be subleased to potential developers will employ this model.

b) Land Leasing

Leasing in the context of agrivoltaics refers to land leasing, in which the farmer or landowner leases their land to a third-party RES developer for the installation of an agrivoltaic system. The developer then operates and maintains the system, selling the generated electricity to the energy grid or other customers. The farmer or landowner receives lease payments for the use of their land and may also benefit from the favourable effects of the agrivoltaic system on crop yields and microclimate.

In the initial phase, it is likely that this model will be most prevalent in Croatia, as farmers lack the technical, financial, and administrative resources to develop and implement those projects on their own. However, they may be interested in such projects because it will safeguard their crops from the adverse effects of climate change and provide them with additional income from the land lease. It is important to note that this option will primarily apply to privately owned agricultural land, as the lessee of state-owned land cannot sublease it to third parties.

c) PPA Contracting

This model typically refers to the use of Power Purchase Agreements (PPAs) between the system developer and the farmer or landowner. Under a PPA, the developer installs, owns, and maintains the agrivoltaic system on the farmer's land, and the farmer, landowner, or third-party agrees to purchase the generated electricity at a predetermined rate. This model enables farmers to benefit from the agrivoltaic system without having to bear the initial investment costs or be responsible for operation and maintenance. In exchange, the developer can secure a stable, long-term revenue stream.

Inasmuch as the PPA market for “ordinary” types of RES energy projects in Croatia is not yet fully developed, it is not anticipated that this model will be dominant for Agri – PVs, at least not during the initial phases of market opening.

d) Public-private partnerships (PPPs)

Public participation in agrivoltaic financing entails involving citizens or communities in the investment, ownership, and decision-making processes of agrivoltaic projects with governments collaborating with private investors to share the risks, responsibilities, and benefits of implementing agrivoltaic systems. Typically, PPPs involve contractual agreements between public authorities and private entities, outlining each party’s duties and responsibilities in the design, construction, operation, and maintenance of the agrivoltaic project.

As this model includes a large number of stakeholders, which entails that they possess necessary information and knowledge regarding the specifics of APV projects, a wider implementation of this model cannot be expected until the Agri-PV market enters a more mature phase.

e) EU R&D programmes and grants

EU research and development programmes constitute an additional source of funding for agrivoltaic projects, particularly research and pilot plants. The EU provides funding opportunities on a regular basis for innovative technologies and projects that contribute to the European Green Deal’s objectives, including renewable energy, climate change mitigation, and sustainable agriculture. Programmes such as Horizon Europe, the LIFE programme, and the European Regional Development Fund (ERDF) can offer grants or subsidies for the development, testing, and deployment of agrivoltaic systems. These funding opportunities can considerably alleviate the financial burden of researchers, farmers, and landowners, and facilitate collaboration between academia, industry, and public institutions.

As this was the case in other countries, it is likely that a significant number of research-based Agri – PV projects will be initiated in Croatia, supported, and funded by the EU or from a similar source.

In addition to this type of funding, farmers and communities that develop smaller agrivoltaic projects may require specialized financial and technical assistance in the form of grants and feed-in tariffs.

6. CURRENT STATE OF THE AGRI – PV MARKET IN CROATIA

6.1 LEGAL FRAMEWORK FOR AGRI – PV PROJECTS

a) Strategic framework for the implementation of Agri – PV projects

There are currently no provisions for agrivoltaic projects in any relevant strategy pertaining to the development of the agricultural sector in Croatia (such as the Agriculture Strategy until 2030, Official Gazette, 26/2022) or the production of energy from renewable energy sources in Croatia (such as the Energy Development Strategy of the Republic of Croatia until 2030 with a view to 2050, Official Gazette, 25/2020).

b) Legal framework for the implementation of Agri – PV projects (agricultural legislation)

The most important agricultural regulation is the Agricultural Land Act (Official Gazette, numbers: 20/18, 115/18, 98/19, 57/22).

Agricultural land is defined in Article 3, paragraph 1 of the Act as agricultural land that is described in the cadastre according to the method of use as: arable land, gardens, meadows, pastures, orchards, olive groves, vineyards, ponds, reeds and wetlands, as well as other land that can be used for agricultural production in accordance with the spatial plan. All cultivated agricultural land is registered in ARKOD[70].

Regarding the topic of Agri – PVs, the mentioned term is not explicitly defined in this Act.

However, with the most recent revisions from 2022, paragraphs 30, 31, and 32 were added to Article 31 of the Act, allowing for the application of renewable energy projects on state-owned agricultural land, i.e., allowing for the application of agrivoltaics.

The following is said in the aforementioned paragraphs:

(30) The lessee[71] may, in accordance with the applicable spatial plan and with the consent of the Ministry, establish infrastructure for the production of green energy on a portion of the leased state agricultural land in order to increase profitability.

(31) When building the infrastructure referred to in paragraph 30 of this Article, the lessee shall:
- keep the purpose of agricultural land in accordance with the accepted Economic Programme from the contract.
- carry out the design, construction, and management of infrastructure in compliance with legal requirements, particularly in the part related to spatial planning, environmental protection, and regulations in the field of energy.

(32) Upon the expiration of the lease agreement, the lessee shall transfer the existing infrastructure referred to in paragraph 30 of this Article to the ownership of the Republic of Croatia or remove it within 90 days of the expiration of the lease agreement.

Nonetheless, it can be deduced from the text of the cited article that only a lessee on state agricultural land (private land is excluded from the application of this Article[72]), with the mandatory approval from the Ministry of Agriculture may install “green energy infrastruc-

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[70] https://arkod.apprrr.hr/

[71] According to the Agricultural Land Act (Article 41) lessees on state–owned land are not permitted to sublet that land to third parties, which is a significant limitation in the adoption of the „land leasing“ model in APV projects.

[72] This is important information considering that only about 25% of all used agricultural land is state owned.

ture" for the purpose of "increasing the profitability of agricultural production" if this is in accordance with the spatial plan that refers to a specific location. However, it is unclear what the term "green energy infrastructure" explicitly refers to, what "increasing the profitability of agricultural production" would entail in each specific instance, and how to monitor the fulfilment of the stated condition.

As a necessary precondition for the realization of such projects, the following paragraph emphasizes the need for preservation of the purpose of agricultural land (which must be in accordance with the Economic Programme) but without specifying any limitations in terms of how much of the surface of agricultural land can/or cannot be covered by "green energy infrastructure", or similar requirements. Furthermore, it is only outlined that the provisions of regulations pertaining to spatial planning, environmental protection, and energy must be applied in regard to design, construction and management of such infrastructure, without specifying any details or particulars for these types of "green energy" projects.

The further legal coverage of Agri – PV projects in terms of agricultural legislation should also consider the fact that these types of projects should be viewed as an agrotechnical measure, in accordance with Article 2, paragraph 1, of the Regulation on Agrotechnical Measures (Official Gazette 22/2019), which states:

"Agrotechnical measures represent a set of mechanical, physical, chemical, and biological interventions in and on agricultural land aimed at increasing or maintaining the current fertility of the soil and ensuring appropriate management of organic carbon content in order to prevent or reduce soil and land degradation, ensuring food security, adapting to and mitigating climate change, improving soil quality, reducing erosion, increasing water retention capacity, and increasing resistance to drought, whereas the land capability value should be maintained or increased through the implementation of agrotechnical measures".

c) LEGAL FRAMEWORK FOR THE IMPLEMENTATION OF AGRI – PV PROJECTS (ENERGY LEGISLATION)

Energy-related laws, such as the Energy Act (Official Gazette, Nos. 120/12, 14/14, 95/15, 102/15 and 68/18), the Electricity Market Act (Official Gazette, No. 111/21, 83/23) and the Act on Renewable Energy Sources and High-Efficiency Cogeneration (Official Gazette, No. 138/21, 83/23) do not define agrivoltaics either.

Regarding the potential alignment of agrivoltaic projects with the energy type regulation, there are no appropriate provisions on how the entire procedure will look like. For the time being, it can be presumed that Agri – PV projects will be pursued in the same manner as any other RES projects with respect to the requirements to be met and licenses and permits to be obtained. This would necessitate that these projects be aligned with spatial plans, obtaining the necessary environmental permits, which in some instance (such as for photovoltaic on the fishpond that is part of Natura 2000) will mean conducting time consuming procedures. If not designed for self – consumption, one of the challenges will be connecting such facilities to the power grid, particularly in the southern part of Croatia where the transmission network is already overburdened with existing and announced projects.

Nevertheless, significant progress has been made in establishing the legal framework for agrivoltaics through various types of legislation.

The procedure to obtain an energy approval as the fundamental act in the development of renewable energy projects (as defined by the Electricity Market Act) needed to be addressed for all RES projects in general. This issue was finally regulated by the Regulation on the criteria for conducting the public tender for the issuance of the energy approval and the conditions for issuing the energy approval (hereinafter referred to as: "Regulation on the Issuance of the Energy Approval") adopted by the Government on 28 of June (Official Gazette, 70/2023). In accordance with this Regulation and following a similar formulation from the amendments to the Spatial Planning Act, Agri – PV plants (*"agrosunčane/agrosolarne elektrane"*) are defined as photovoltaic plants constructed on land designated as agricultural land in spatial plans of any level. According to this definition, Agri – PV plants should be explicitly constructed on land planted with perennial agricultural crops[73] and, as such, registered in records of the agricultural land (ARKOD) or constructed on land in addition to the existing area of farms and greenhouses. With the exception of national park and nature park activities, the installation of Agri – PV plants should support achieving the development objectives of agricultural activity, while at the same time preserving the primary purpose of agricultural land.

Article 18 of the Regulation explicitly states that the energy approval for Agri – PV plants will be issued without a public tender. This option is generally allowed by the Energy Market Act for PV plant construction projects where land property rights have been already resolved. In paragraph 6 of this Article, it is stated that an application for the energy approval for the construction of Agri – PV plants must be submitted to the Ministry, along with evidence of the establishment of perennial agricultural plantations entered in the records of agricultural land use (ARKOD) or by providing the location information about the area of farms, greenhouses, as well as the delivery of all other documentation required for all other types of energy projects as defined in Article 3 of the Regulation (feasibility study, preliminary design, preliminary opinion on the viability of grid connection, etc.).

The Regulation on Incentivizing the Production of Electricity from Renewable Energy Sources and High-Efficiency Cogeneration (Official Gazette, 70/2023) uses the same definition of Agri-PV projects, allowing them to be financed through a market premium or a guaranteed purchase price model.

d) LEGAL FRAMEWORK FOR THE IMPLEMENTATION OF AGRI – PV PROJECTS (OTHER LEGISLATION)

The enactment of the Act on Amendments to the Spatial Planning Act (Official Gazette, 67/2023) marked a significant step forward in the regulation of Agri-PV projects in relation to other aspects of the legal framework that are generally essential for the application of renewable energy projects. In accordance with the Act, the following new subparagraph 35 is added to paragraph 1 of Article 3 (*Definitions*) :

"Areas for the construction of agrivoltaics power plants *("agrosunčane elektrane")* are areas that are designated as agricultural land by the spatial plan of any level, that are planted with perennial agricultural crops and are registered in the records of agricultural land (ARKOD) or

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[73] Permanent crops refer to vineyards, reclaimed vineyards, olive groves, perennial crops of aromatic and medicinal plants, short rotation coppice, nurseries, grapevine rootstock and graft nurseries, and mixed perennial crops, as defined by the Ordinance on the Implementation of Direct Support to Agriculture and IACS Rural Development Measures for 2023 (Official Gazette, No. 25/2023).

on which the agrivoltaic power plants are installed in addition to the existing area of farms and greenhouses, with the goals of both being to achieve the development of agricultural activity and maintain the primary purpose of agricultural land, with the exemption of national park and nature park activities".

Also, subparagraph 34 has been added, stating that areas on which it is possible to build infrastructural buildings of solar power plants, in accordance with the provisions of this Act, also include areas of water surfaces - lakes created by the extraction of mineral raw materials - as well as **fishponds** and other aquaculture farms on land, with the consent of the concession grantor or lessor if the land is subject to a concession or lease.

This is the first adopted legislative act in which the term agri – PV ("*agrosunčana*" in Croatian) was explicitly used (and then repeated by the Regulation on the Issuance of the Energy Approval), and which stipulates that, under certain conditions, spatial plans on already existing agricultural land (also including fishponds) will be deemed suitable for the construction of Agri – PV plants. This piece of legislation is very important for the overall development of the agrivoltaic market in Croatia since it resolves the issue of the Agri – PV projects' alignment with the spatial plans, which is one of main preconditions for obtaining the energy approval, which, in turn, is the key point in energy projects' development.

e) CONCLUSIONS REGARDING THE EXISTING AND FUTURE LEGAL FRAMEWORK FOR AGRI – PV PROJECTS

This cross-section of the current legislation pertaining to agrivoltaics, despite being quite fragmented, provides a relatively solid initial framework suitable for the preparation of first agrivoltaic (pilot) projects in Croatia. According to the existing legislation, particularly the recently adopted amendments to the Act on Spatial Planning and the Regulation on the Issuance of Energy Approval, it is possible to initiate agrivoltaic projects on agricultural land if perennial agricultural crops have been planted on that land and the plantation has been registered with ARKOD. Article 18 of the Regulation on the Issuance of the Energy Approval states that, if all other conditions specified in the Regulation are met, it is possible to obtain energy approval for such projects as the key document for pursuing all other steps in the typical development process (obtaining approval for the grid connection agreement , applying for a location permit). If an agrivoltaic project is to be planned on state-owned land, the relevant provisions of the Agricultural Land Act must be considered, particularly those pertaining to the necessary approvals from the Ministry of Agriculture.

However, as evidenced by the examples of other countries provided in Chapter 4, this topic should be regulated in a more systematic manner. In addition to the lessons learned from the first pilot projects, relevant regulations/sub regulations should address at least some of the following issues:

1) full definition of agrivoltaic projects as projects with dual use of agricultural land that represent the agrotechnical measure in terms of the relevant Regulation on Agrotechnical Measures, including a clear definition of all preconditions that must be met in order for a project to be considered an agrivoltaic one (in addition to those elements already defined in the existing legislation);
2) definition of necessary prerequisites and criteria for maintaining and/or improving

existing agricultural production or initiating new agricultural production for agrivoltaic projects, as defined in the existing legislation;

3) definition of requirements for any acceptable spatial and/or yield limitations for different types of crops in the application of agrivoltaic projects on agricultural land in terms of defining the maximum surface of agricultural land to be covered by PV panels / allowed yield reductions of different crops in relation to the reference levels, and similar requirements;
4) definition of who can be entitled to initiate and develop such projects (other than farmer lessees/owners of the land), introducing the possibility of different investment models for the implementation of such projects on state-owned land in particular;
5) definition of potential specific permit procedures for preparation and development of agrivoltaic projects;
6) improving the necessary institutional structure for the approval and monitoring of Agri – PV projects' implementation, according to pre-defined conditions and criteria, in which case scientific institutions may play a role in the entire process (similar to France's experience);
7) dedicating specific programmes and funds to support scientific research for the implementation of APV to various types of crops in various regions of Croatia;
8) considering the creation of grant and feed-in tariff programmes for farmers and communities that develop smaller agrivoltaic projects.

In addition, specific technical regulations or guidelines should be adopted for the application of agrivoltaics for different models of technical solutions applicable to different types of agricultural crops, as was the case in some of the countries examined by this Study (such as Germany or Italy).

Finally, the concept of agrivoltaics should be appropriately incorporated into strategic documents related to promoting the production of energy from renewable sources and reducing the effects of greenhouse gas emissions, as well as those strategic documents aiming to improve agricultural production in the Republic of Croatia.

6.2 EXPECTED CHALLENGES IN AGRI – PV PROJECTS' IMPLEMENTATION

Due to the fact that the definition of agrivoltaics typically refers to the dual use of agricultural land and that the concept can be seen as something new and innovative, the establishment of a successful photovoltaic system may be met with a variety of challenges and obstacles.

From the experiences of many countries that have already established these systems to some extent, it is possible to classify these challenges and obstacles in several main categories (technological, infrastructure-related, financial, legal, cultural, etc.).

Regarding the development of the agrivoltaic market in Croatia, there are a few challenges to consider:

a) LACK OF AVAILABLE DISTRIBUTION/ TRANSMISSION GRID

The first important challenge will be the issue of connecting and integrating agrivoltaic projects in the electricity distribution and transmission infrastructure.

Table 2 Possibility of connection to transmission network

County	Region	A	B	C	Total
Osijek-Baranja County	Slavonia	300	100	300	700
Sisak - Moslavina County	Central Croatia	350	0	0	350
Istra County	Istria	200	100	0	300
Zagreb County	Central Croatia	200	0	0	200
The City of Zagreb	Central Croatia	150	0	0	150
Brod-Posavina County	Slavonia	100	0	0	100
Primorje-Gorski Kotar County	Kvarner	50	0	0	50
Virovitica-Podravina County	Slavonia	50	0	0	50
Vukovar-Srijem County	Slavonia	50	0	0	50
Bjelovar-Bilogora County	Central Croatia	50	0	0	50
Karlovac County	Central Croatia	50	0	0	50
Požega-Slavonia County	Slavonia	50	0	0	50
TOTAL		**1600**	**200**	**300**	**2100**

Legenda: Transformer station with the connection capacity A ≤ 50 MW, B ≤ 100 MW and C >100 MW.

Source: Informacija o mogućnosti priključenja no prijenosnu mrežu za 2023, HOPS December 2022.

According to the HOPS's Report from December 2022[74] (Croatian Transmission System Operator; *Hrvatski operator prijenosnog sustava*) the current potential of the grid network in Croatia is over 2100 MW for new RES production facilities to be connected to the transmission network (Table 2). When divided into regions, Slavonia accounts for 45% of the total available capacity, with the minimum of 950 MW of connection power.

In light of the vast renewable energy development potential in the Slavonia region, it is essential to prioritize investments and policies that foster the growth of RES projects in this area. Given Slavonia's predominantly agricultural nature, the integration of solar energy production into agriculture is ideally suited to the region. Implementing agrivoltaics in Slavonia can also help combat rising emigration by encouraging economic growth and diversification. By harnessing renewable energy and revitalizing agriculture, the region will become more attractive for investments and innovation.

The foregoing does not imply that APV projects cannot be implemented in the southern part of Croatia; however, the application of these projects (if not delivered for self-consumption) will be limited by the anticipated network upgrade in the next decade.

b) UNCLEAR LEGAL FRAMEWORK

As previously explained, the lack of a coherent legal framework for agrivoltaics will also pose a challenge to the successful application of agrivoltaic projects. However, as men-

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[74] https://www.hops.hr/post-file/35w5GaQFeKUAaQyym3UXM1/informacija-o-mogucnosti-prikljucenja-na-prijenosnu-mrezu-za-2023-godinu/Informacija%20o%20mogu%C4%87nosti%20priklju%C4%8Denja%20na%20prijenosnu%20mre%C5%BEu%20za%202023.%20godinu.pdf

tioned in the preceding chapter, the existing legal framework has been substantially strengthened, providing a solid foundation for the implementation of first agrivoltaic projects. Following the lessons gained from these first projects, relevant authorities (Ministry of Agriculture, Ministry of Economy and Sustainable Development) should initiate the process of overall and systematic regulation of agrivoltaics.

c) Inadequate communication and lack of public support

Possible opposition to the idea of agrivoltaics from some of the key stakeholders (farmers, NGOs, farmers' associations, local political authorities, and the general public) is yet another significant challenge that can be anticipated. Any such opposition may be brought on by a lack of relevant and objective information about the model, its advantages and disadvantages, unclear legal framework, the fear that agricultural land would be lost or significantly degraded by the installation of energy facilities, etc. It will be crucial that relevant organisations, including relevant ministries, the academic community, chambers, and associations of various interest groups share factual information about the advantages and disadvantages of agrivoltaics, provide specific guidelines and examples of best practices, and finally create an institutional and legal framework that will guarantee that any agrivoltaic project will primarily mean maintaining agricultural production while recognizing solar energy production as secondary and supplemental activity to agricultural production on agricultural land.

d) Demand overwhelms the Agri – PV projects potentials

A further issue could be an overabundance of requests for agrivoltaic projects, particularly in Croatia's northern and central regions, where grid connections are still free and readily available. In that situation, the system as a whole could be blocked by acquiring required permits (energy approvals, connection to the grid contracts), which could freeze the development of such projects for years. Determining quotas on the amount of agrivoltaic projects that can be established and approved annually or during a specified period in Croatia (or in some parts of Croatia) is one possible solution to this potential problem.

e) Other risks and obstacles

Other issues that might arise could be technical (such as how to implement APV in in karst and/or on hilly terrain), financial (such as how to make APV a financially viable project, especially for smaller solar power projects), agricultural (such as what agricultural crops should be used for agrivoltaic application), or similar. Innovative technical solutions, further scientific research, and the transfer of know-how from other countries with similar, already implemented projects can be of help in dealing with these challenges.

7. AGRICULTURAL POTENTIALS OF CROATIA FOR APPLICATIONS OF AGRI – PV PROJECTS

This chapter provides a comprehensive analysis of agricultural potentials of Agri - PV projects in Croatia. It will primarily include the analyses of the benefits and constrains for the application of Agri – PV projects for specific types of crops considering different types of research, applicable case studies, and examples of similar corresponding projects as well as authors' conclusions on the applicability of Agri – PV projects for specific types of crops in Croatia.

No matter the current or future legal definitions of agrivoltaic plants and what would legally be considered as APVs, the purpose of this chapter is to investigate the potentials of various crop types / agricultural areas for the application of APVs in Croatia.

Based on the definition of agricultural land from the Agricultural Land Act, the following types of crops / agricultural areas will be the focus of this Study:

1. viticulture;
2. fruit growing (both continent and Mediterranean type);
3. aromatic and medical plants;
4. vegetable growing;
5. cereals, industrial and forage plants production;
6. grassland and animal husbandry;
7. fishponds/floating PVs.

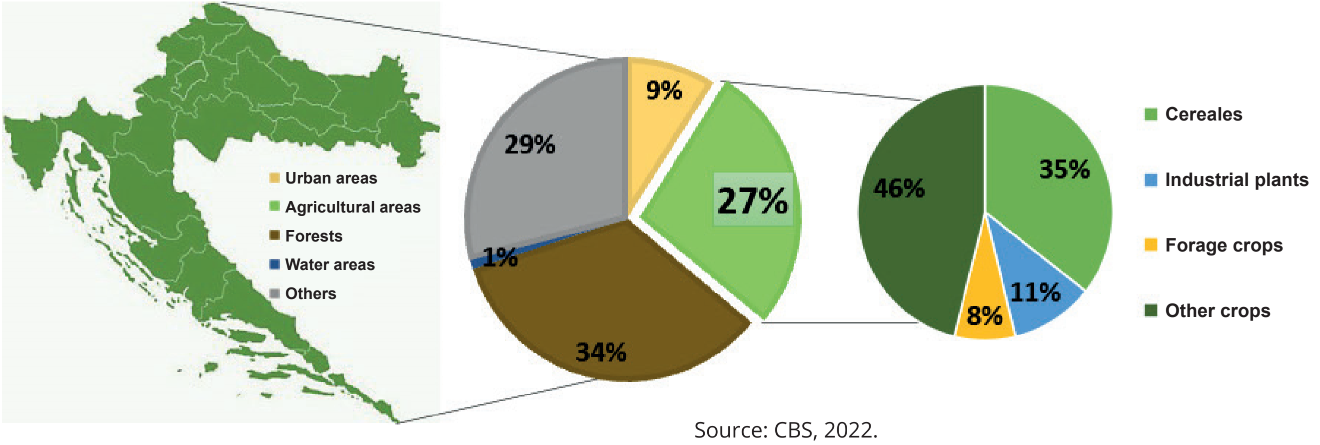
7.1 INTRODUCTION

Commonly, the Republic of Croatia is divided into the Continental Croatia and Adriatic Region. However, since 2021 there has been a new National Classification of Statistical Regions (NUTS) that defines four regions: Pannonian Croatia, North Croatia, the City of Zagreb (which all represent Continental Croatia) and Adriatic Croatia.

Continental Croatia is comprised of central Croatia, Slavonia and Baranja. Central Croatia is a slightly hilly region covered with vineyards, meadows, and forests, and traversed by rivers. Slavonia is located in the east of Croatia and is known as the "Green Treasury" because of its vast plains and abundance of arable crops. The territory of Adriatic Croatia consists of the North Adriatic i.e., Kvarner, Istria and the Mountain Region, Central Adriatic which comprises northern Dalmatia and Lika, and the central and southern Dalmatia regions. In the Adriatic region, permanent grassland prevail, and plant production is dominated by viticulture and olive growing, but also includes the cultivation of citrus fruits and vegetables.

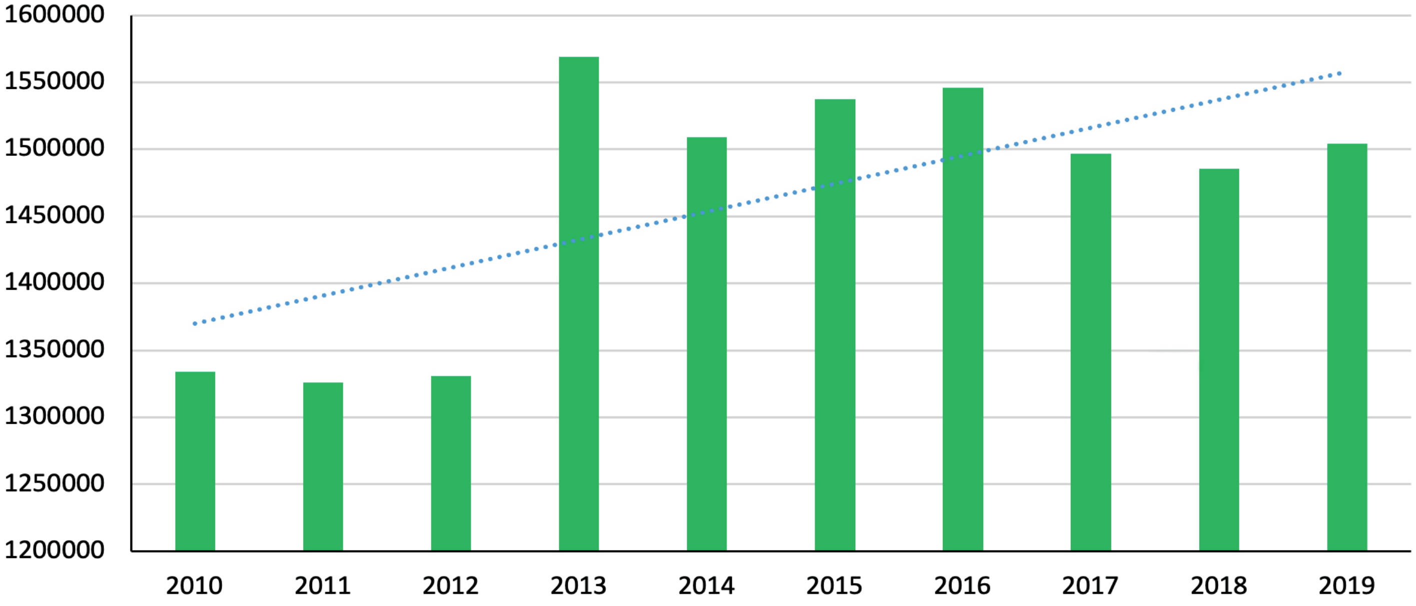
The surface area of the Republic of Croatia is 56,590 km^2, of which approximately 35% is covered by forests and vegetation, 27% by agricultural land, 9% by urban areas, 1% by

Figure 11 Land use in the Republic of Croatia



Source: CBS, 2022.

Figure 12 Used agricultural area in the Republic of Croatia from 2010 to 2019



Source: CBS, 2022.

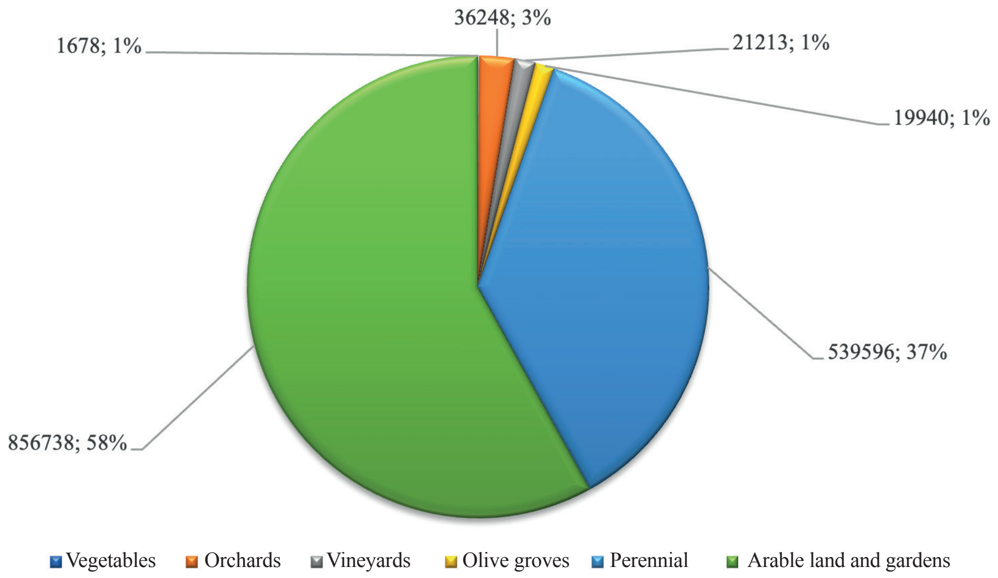
inland waters, and 29% by other land uses (Figure 11).

According to the Croatian Bureau of Statistics (CBS, 2022), the average number of hectares of used agricultural land from 2010 to 2019 on the average was approximately 1,477,000 ha (Figure 12).

About 55 to 60% of used agricultural land belongs to the category of arable land and gardens, which covers more than 850,000 ha (Figure 13), followed by perennial grass areas (approximately 540,000 ha). Other crops such as vegetables, fruits, olives, and grapevines cover about 6% of agricultural land (approximately 80,000 ha).

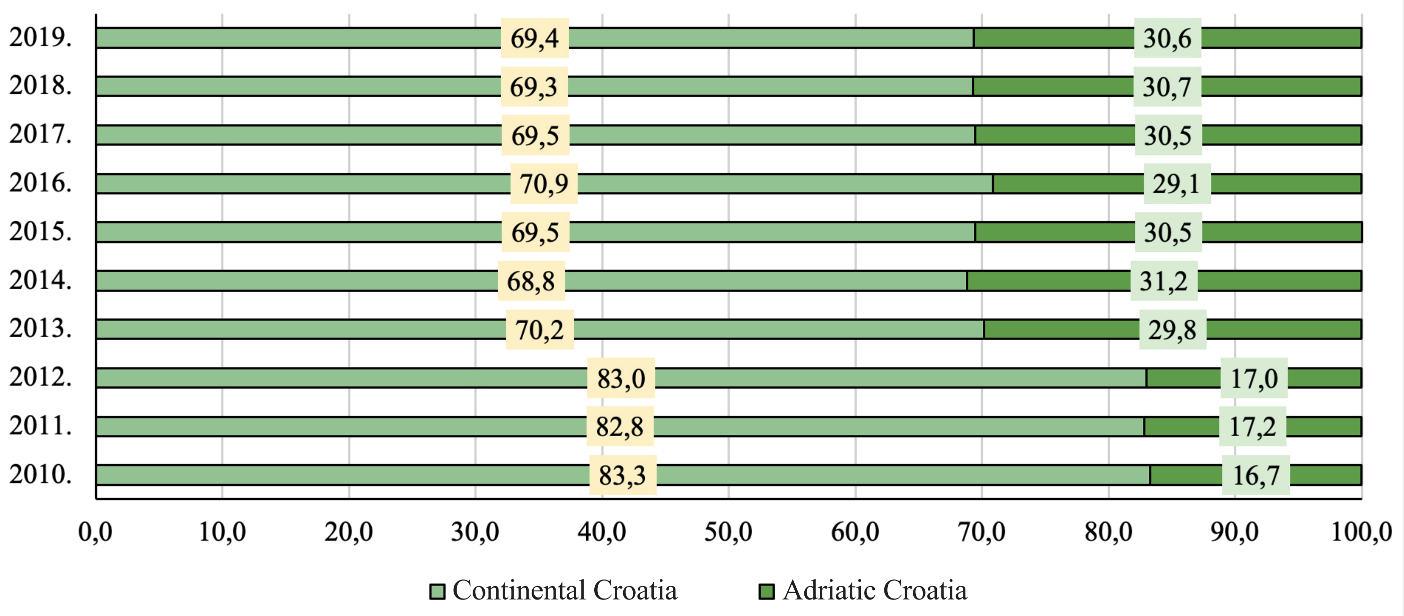
In the last decade, approximately 70% of the total agricultural land in use in Croatia is lo-

Figure 13 Area (ha) and share (%) of agricultural land by categories in 2021



Source: CBS, 2022.

Figure 14 Share of used agricultural area for Continental and Adriatic Croatia from 2010 to 2019



Source: CBS, 2022.

cated in Continental Croatia, while the Adriatic Croatia accounts for the remaining 30%. (Figure 14).

According to the research conducted by the authors of this Study, when using the most recent data managed by ARKOD, approximately 25% of the total agricultural land in use is state-owned, while the remaining 75% is privately owned (exact data for each category of agricultural land are unavailable).

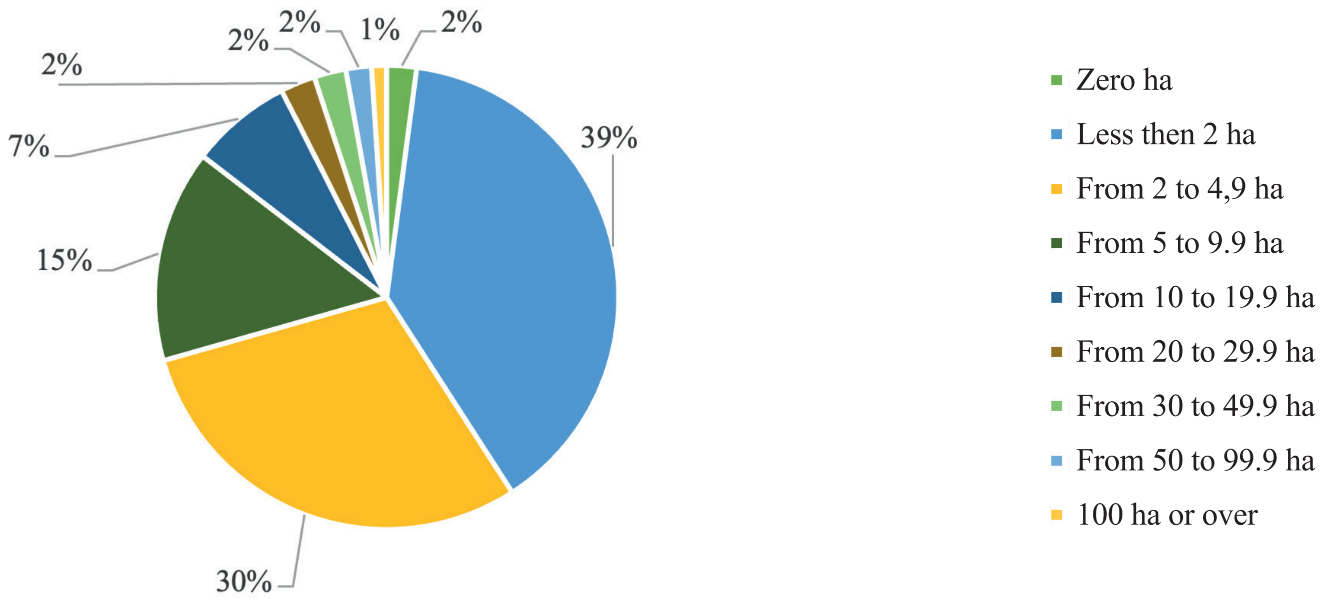
SIZE OF FARMS IN CROATIA

Agricultural farms of the Republic of Croatia are characterized by a large number of different production and economic entities.

According to the Eurostat's (2022) statistics on agriculture, forestry, and fishery, of the total number of agricultural holdings (143,927), 39% have less than 2 ha, 30% have between 2 and 4.9 ha, and 15% have between 5 and 9.9 ha. Only 1% of agricultural holdings exceed 100 ha (Figure 15). This is indicative of a great fragmentation of farms in Croatia. The average size of commercial farms is approximately 8.5 ha, while the average size of all farms is only 2.9 ha, which can be a limiting factor in the broader application of Agri – PV projects.

For the purposes of this Study, agricultural holdings larger than 1 ha on which agricultural crops that may be suitable for application of agrivoltaic systems are grown will be considered, because, according to international practice, this is the minimum area required to be able to implement financially sustainable agrivoltaic projects (which does not mean that the projects mentioned cannot be developed on smaller areas in some specific cases, especially if the owners/lessees of agricultural land use the energy thus obtained for their own consumption).

Figure 15 Agricultural land of family farms in Croatia in 2020



Source: Eurostat, 2022.

7.2 VITICULTURE

7.2.1. Background

Vineyards could be considered for agrivoltaic farms in general. One of the main reasons is the high economic value of grapevines as an agricultural crop. Vineyards are usually planted in areas with moderate temperatures and long hours of sunlight. Grapes can be grown in partial shade, despite the fact that grapevines are typically regarded as full-sun plants[75]. Possible solutions should strike a balance between energy production and tolerable shade that does not inhibit the growth and development of grapevines. Coexistence of crop vegetation and agrivoltaics still raises significant research concerns, particularly regarding soil characteristics, microclimate modifications, as well as installation and maintenance cost and performance of agrivoltaics.

Generally, vineyards are planted in a row-based layout. Typically, solar panels attached to fixed support structures are elevated above crops in order to maximise solar utilisation. This enables unimpeded access for vineyard machinery to the vines. Some authors[76] have proposed installing PV panels between vineyard rows. On the other hand, a vertical integration of photovoltaic surfaces over the vines using the same trellis structure is proposed[77], thereby minimising cost and land construction. The proposed symbiotic integration of photovoltaic modules into a vineyard trellis structure was termed *Enovoltaics*. Placed above the vineyard, APV modules can serve not only as a sunlight barrier but also as protection against hail and/or intense rainfall.

Typically, vineyards with optimal surface area for APV installations are larger than 1 hectare in size. In such large vineyards, grapevines are usually managed with machinery. Thus, APV architecture must not only adhere to re-

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[75] Rodriguez, 2022

[76] Malu et al., 2017; Cho et al., 2020.

[77] Padilla et al. (2022).

gional climatic conditions and grapevine varieties, but also canopy management in the vineyard. Elevation of APV modules, distance between modules, density and sloping angle of solar panels continue to be the subject of much research[78].

7.2.2 THE RESULTS OF PREVIOUS RESEARCH - BENEFITS AND CHALLENGES

The majority of research on Agri – PV systems has focused on very few crops, with almost no data on grapevine. Only in recent years have some studies been conducted on fruit trees such as grapevine[79], but data are extremely limited. The importance of table grapes, wine, and raisins production is well known, and in the EU, there are over 3 million ha devoted to grape cultivation, in different climatic conditions[80]. The main benefit of agrivoltaics is shading, which can be extremely beneficial for vineyards flourishing in hot and arid climates by preventing excess thermal stress during the harsh summer months[81]. Researchers have found that APV can create a cooler environment, thereby enhancing the performance of solar panels, while the increased shade can boost water-use efficiency, soil moisture content, and crop yields.

The vine is underrepresented among the agricultural crops examined in terms of the possibility of employing agrivoltaics. There are only a few scientific publications on this topic. In one of them[82], a minor decrease in sugar content and cluster weight was observed, leading to the conclusion that a 10-day harvest delay could restore normal quality. The shading rate of the solar panel was designed to be 30% of the investigated total roof area. Horizontally mounted PV panels in the interspace between vineyard rows have been studied[83], but without any biological considerations. They found economic benefits in a trellis-based vineyard.

Sun Agri reported first conclusive results of an agrivoltaic pilot project in Piolenc, Vaucluse, Rhone Valley. Vines shielded by the dynamic agrivoltaic system showed better resistance to high summer temperatures than the others: growth stunting was observed 6 to 13 days later on the shaded vines compared to the unprotected control vines. Water stress, measured with the help of sensors, was lower in the shaded vines - the reduction in water requirements varied from 12 to 34% depending on the system. Shading also had a positive effect on berry weight, which was 17% higher on the protected vines. Similarly, it had a positive impact on the organoleptic quality of the wines. Anthocyanin content was higher (+13%), as was total acidity (+9 to +14% depending on the method). Conversely, alcohol strength remained at the same level in the shaded plots and the control vineyard [84]. The same company declared a 20% reduction in plot water consumption in Domaine de Nidolères vineyard in Tressere. They claim a 13% increase in anthocyanins and a 9% to 14% increase in acidity, but it is unclear if this applies to grapes or wine. They also observed reduced stunted growth and leaf scorch during the heatwaves in the summer of 2019[85].

According to very recent research[86], photovoltaic panels reduced both air and soil maximum temperatures by 1–2 °C in a vineyard

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[78] Zaniol Abidin et al., 2021.
[79] Sun'Agri, 2022.
[80] Ferrara et al., 2023.
[81] Turan, 2021.
[82] Cho et al. (2020).
[83] Malu et al. (2017).
[84] Vitisphere, 2020.
[85] Sun Agri, 2022.
[86] Ferrara et al. (2023).

in Northern Italy's Veneto region, with the Corvina (*Vitis vinifera* L.) grape variety. Shading of the panels both in the morning and at midday significantly reduced the stem water potential (making it less negative) by approximately 1 to 6 MPa, indicating less stressful conditions for APV vines. Throughout the tree seasons, the photovoltaic panels affected the microclimate of the vineyard (lower air and soil temperature, higher soil matric potential). Vine productivity parameters (yield, cluster number and weight) were affected to a limited extent; anthocyanins, TSS, and polyphenols were reduced in grape must from APV vines. These findings reveal that the panels alter the microclimate and physiology of the vines, and that yield reductions under APV are found; nonetheless, under hot and dry weather conditions, the results could be very interesting for either energy or fruit production. Further experiments in similar environmental conditions are required in the context of the climate change.

7.2.3 THE CASE STUDIES OF REFERENT PROJECTS

a. DOMAINE DE NIDOLÈRES VINEYARD IN TRESSERE (FRANCE)

In 2018, the world's first agrivoltaic farm with remotely piloted panels was established in France, stretching over 4,5 hectares in the Domaine de Nidolères vineyard in Tressere, Aspres region, Pyrénées-Orientales department (Figure 16). Since 2017, the Aspres wine-growing region has enjoyed dedicated Protection Designations of Origin (PDO). Despite a modest yield of <40hl/ha, the region produces exceptional wines. Climate change and increasingly severe draughts directly threaten the vineyards, causing agricultural

Figure 16 Domaine de Nidolères

Source: https://sunagri.fr/en/project/nidoleres-estate/

degradation to be the highest in the region. Photovoltaic panels are installed 4.5 m above ground and cover 28.600 young grapevines (Grenache Blanc, Chardonnay, Marselan rouge). They are automatically controlled by using algorithms. The agrivoltaic farm was established by Sun'R and Bouygues Energies et Services, and set up with the support of the Occitanie Pyrénées Méditerranée region. The generated electricity is fed back into the power grid. The total installed power for the general installation is 2.1MWp. It generates enough energy to power 650 households and saves almost 3.000 tonnes of CO_2.

b. WINESOLAR SMART AGRIVOLTAIC PLANT, GUADAMUR, TOLEDO (SPAIN)

In 2022, Iberdrola company commissioned the first smart agrivoltaic plant in Spain at the González Byass and Grupo Emperador vineyards located in the town of Guadamur, Toledo. This innovative installation allows the layout of the modules to be adapted to the needs of the grapevines in order to regulate the incidence of the sun and the vineyard temperature by means of the shade of the panels.

The trackers in the system will be managed by an artificial intelligence algorithm capable of determining the optimal position of the solar panels placed above the vines at any given moment. The degree of inclination is determined based on the information collected by sensors installed in the vineyards, which record data such as solar radiation, soil humidity, wind conditions and vine trunk thickness, among other things.

The goal is to improve grape quality, minimise irrigation water use and increase crop

Figure 17 First smart agrivoltaic plant in Spain (Guadamur, Toledo)

Source: https://www.infolibre.es/contenidos-publicitarios/iberdrola-pone-marcha-primera-planta-agrovoltaica-inteligente-espana_1_1341728.html resistance to climatic conditions in the face of rising temperatures and increasingly frequent heat waves.

The output of this pilot plant, with a capacity of 40 kW, will be used entirely for self-consumption by the González Byass and Grupo Emperador wineries, allowing them to reduce emissions, make progress in the decarbonization of their activity and reduce their energy costs (Figure 17).

7.2.4 STRUCTURE OF VINEYARD AREAS IN CROATIA

Climate, along with soil and variety, is an important factor in regionalization. Republic of Croatia has a unique geographical location since it is at the crossroads of two climate types: continental (eastern and central parts of the country) and Mediterranean (southern and costal parts). As a result of the climate, temperature is one of the limiting factors for grapevine cultivation. A mean daily temperature of 10°C represents a biological zero for grapevine, whereas all temperatures above that are considered active. Active tempera-

Table 3 Structure of vineyard plots in Republic of Croatia

Viticulture plots (ha)	**Area/no of producers**	**Total**	**Share in total area (%)**
< 0,1	Area (ha)	837.50	4.73
	No. of producers	13,075.00	39.09
0,1 - 1	Area (ha)	4,851.63	27.39
	No. of producers	17,848.00	53.35
1 - 5	Area (ha)	4,257.83	24.03
	No. of producers	2,191.00	6.55
5 - 10	Area (ha)	1,351.11	7.63
	No. of producers	197.00	0.59
10 - 50	Area (ha)	2,143.14	12.10
	No. of producers	117.00	0.35
50 - 100	Area (ha)	700.68	3.96
	No. of producers	11.00	0.03
100 - 200	Area (ha)	973.91	5.50
	No. of producers	7.00	0.02
> 200	Area (ha)	2,599.50	14.67
	No. of producers	6.00	0.02
Total Republic of Croatia	**Area (ha)**	**1,7715.31**	**100**
	No. of producers	**33,452.00**	**100**
Avg. slope of the vineyard [°]		**6,38**	

Source: Paying Agency for Agriculture, Fisheries and Rural Development 2022.

tures typically extend from April until the end of October (vegetative season). The effective temperature is obtained by subtracting biological zero from the active temperature. Republic of Croatia is divided into four wine regions[87]: Croatian Uplands, Istria and Kvarner, Slavonia and Danube Area, and Dalmatia. These regions are further subdivided into 12 subregions.

According to the viticulture database data on November 24, 2022,[88], the total winegrowing area in the Republic of Croatia was 17,715.31 ha.

The structure of Croatian vineyard regions is characterized by small production plots and a small number of large viticulture producers (Table 5). Table 3 shows that 92.44 % of producers have viticulture plots smaller than 1 ha, yet their viticulture plots account for 32.12% of the total viticulture area in Republic of Croatia. The plot size greater than 1 ha was chosen as the discriminating condition for the construction of agrivoltaics, accounting for 67.88% of the total vineyard area, **implying that 12,026.17 ha of the entire vineyard area is theoretically suitable for APV application.** The average slope of vineyards is 6.38 %, which does not pose a problem for construction of agrivoltaics.

Croatian Danube Area, Slavonia, Croatian Istria (which also have the largest available grid capacity), Central and South Dalmatia, and Dalmatian Interior have the most vineyards with an area larger than 1 ha. Pokuplje, Hrvatsko Primorje, Prigorje-Bilogora, and Northern Dalmatia have the fewest such vineyards.

7.2.5 CONCLUSIONS AND RECOMMENDATIONS

As previously shown, 92.44 % of producers have vineyard plots smaller than 1 ha but, at the same time, their plots account for 32.12% of the total viticulture area in Croatia. Therefore, 67.88%, or **12.026 ha, of the total vineyard area is suitable for APV technology application**. It is highly recommended to apply APVs only in vineyards with a surface area greater than 1 ha. The vast majority of recommended vineyard surface areas are located in five viticultural subregions (Croatian Danube Area, Slavonia, Croatian Istria, Middle and Southern Dalmatia and Dalmatian Hinterland), with total surface area of 10.402 ha.

Average slope of 6,38 % is not an obstacle for the installation of agrivoltaic systems. It was not possible to obtain the information on the exposures of vineyards but given that the grapevine is as long-day plant, it is presumed that all vineyards have exposures suitable for setting up APV systems.

Regarding specific grapevine varieties, it is likely that aromatic white varieties will exhibit strong positive response to partial shading induced by APV systems. In general, white varieties are more susceptible to sunburn from intense UV radiation, and aromatic compounds found in the berry skin tend to degrade in extremely hot weather conditions. On the other hand, severe drought can result in substantial yield loss. Therefore, installation of APV systems may be particularly advantageous in arid and semi-arid viticultural areas. Considering the potential use of APV systems in viticulture, experimental confirmation of the results of previous research, which vary depending on many different factors, is necessary.

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[87] Ordinance of viticulture (OG 81/2022).

[88] *https://www.apprrr.hr/registri/*

7.3 FRUIT GROWING

7.3.1 BACKGROUND

Mounting solar panels above orchards will for sure interfere with plant growth and fruit yield. Whether this will have a positive or negative impact, depends on various factors (fruit species, fruit varieties, location, weather conditions…). As a result of climate change, numerous problems appear when it comes to traditional orchard positions and fruit growing. This necessitates either adapting fruit-growing technologies or altering the fruit species and fruit-growing region schemes at specific locations. Including agrivoltaics in fruit growing technologies seems to be a good solution. Photovoltaic panels on top of plants will undoubtedly restrict the amount sunlight that reaches the plant, hence reducing plant growth or fruit yield. That is important as photosynthesis in plants creates nourishment for plant growth. But on the other hand, vegetative and generative growth are constantly in competition. If PV panels installed on top of an orchard reduce vegetative growth (to a certain extent), fruit yield may suffer. That is confirmed by the application of agrivoltaics in raspberry production (Babberich, Netherlands) where density of installed PV panels (60% percent coverage) reduces yield by only 5% in comparison to conventional technology. Moreover, the shading provided by PV panels installed in the orchard reduces a number of physiological disorders in plants and fruits such as sunburn, heat stress, fruit over colour etc. The installation of PV panels in orchards has its potential and benefits for fruit production, but they need to be applied and adjusted with caution.

Different fruit species require distinct cultivation methods. Moreover, the same fruits species can be grown using a variety of cultivation techniques, dependant on the grower's preferences. depending on grower's wishes and demands. However, some general guidelines can be defined.

Typically, apples and pears are grown in high density orchards with 4000 to 6000 trees per hectare. This can be accomplished with the use of low, vigorous rootstock. Usage of low, vigorous rootstock necessitates the use trellis (columns and wires) to support trees and prevent them from laying down. Frequently, this infrastructure is also utilised to support irrigation systems and anti-hail nets. Typically, the distance between rows is 3-3.5 m and the distance between columns in a row is 5 to 7 m. Depending on the height of the trees, columns are between 3.5 and 5 m high. Additionally, peaches and nectarines can be cultivated with this kind of trellis systems as well. Trellis systems can be adapted and used to support PV panels.

Raspberries, blackberries, and currants are also cultivated in trellis system but with the average height of 3 m and columns distance similar to apple growing systems. Trellis systems are also used as irrigation support structures, anti-hail structures and holders for shading nets.

Kiwi is also grown on a trellis using a slightly different technology. In apple, pear, blackberry and raspberry cultivation, the trellis system is predominantly narrow. In kiwi production, trellis are formed on pergolas and are wide at the top. This structure can also be adapted to accommodate PV panels.

Peaches, nectarines, cherries are usually grown as stand-alone trees without any support.

Small berries such strawberries, blueberries, blue honeysuckle, and others do not require any supporting system. Consequently, in these orchards, supporting architecture for PV panels can be viewed as additional investment that can increase the cost of agrivoltaic installation. But as these fruit species do not reach heights over 1.5 m, PV panels can be installed at a lower height thus reducing structure costs.

As for Mediterranean fruit species, the majority are cultivated as trees in low or medium density orchards. Olives are traditionally cultivated in low density orchards with 100-150 trees per hectare and a tree height of 5-6 m. Modern olive orchards have density of 300-350 trees per hectare and a tree height of 2-3 m. Olive orchards with a greater density are rare.

Citruses are usually cultivated in orchards with a density of 2000-2500 trees per hectare and a height of 2-2.5 m, whereas almonds and figs are typically planted in low-density orchards and are grown as more vigorous trees, with some exceptions in modern intensive plantations.

In fruit cultivation, there is no optimal method that can be used in every orchard and location. Every location, every orchard, and crop necessitates an individualised approach to determine the most suitable growing system based on the producer's objectives and preferences.

7.3.2 THE RESULTS OF PREVIOUS RESEARCH - BENEFITS AND CHALLENGES

According to extant literature, the following fruit species are generally suitable to be used with PV panels on top of orchards:

Particularly recommended: american blueberry (*Vaccinium corymbosum*), blue honeysuckle (*Lonicera caerulea*), raspberry (*Rubus idaeus*), hardy kiwi (*Actinidia arguta*), apricot (*Prunus armeniaca*), sweet cherry (*Prunus avium*), sour cherry (*Prunus cerasus*).

Raspberry is known as a crop for half-shaded areas. Too much sun and direct sunlight will cause sunburn damages on leaves. Half-shade cannot be established in a production orchard without shading nets or foil that diffuses sunlight. This shading nets and diffusion foil can be substituted with PV panels and diffusion film between PV modules (confirmed by a producer in Babberich, Netherlands, Sunbiose project). Personal experience of authors of this Study in monitoring plantations of American blueberry (8 ha in Cetingrad, Croatia) and blue honeysuckle (2 ha, Samobor, Croatia), revealed that these crops have problems during summer, particularly during hot summers, with yellowing leaves and even leaf dieback. Close to the forest, where there was less direct sunlight, the plants' leaves were more robust, entirely dark green in colour, and healthier. The hardy kiwi is a plant that can withstand winter temperatures as low as -40°C. Sadly, during the summer, direct sunlight and temperatures above 30°C induce sunburn and dieback, which exhausts the plant and results in low-quality fruit. The installation of PV panels could reduce these damages and increase the potential for cultivating this crop in Croatia. Both sweet and sour cherries struggle with fruit cracking. Fruit cracking is caused by genetic factors and water management. After flowering, plants require large quantities of water, but during ripening, moderate water availability is required. Rains that occur during the ripening stage can cause fruit to crack because plants absorb water from both the soil (via their roots) and the rain that landed directly on the fruit. Photovoltaic panels above the plants will prevent the rain from falling directly on the fruit. In addition, rainwater that reaches PV panels will either flow to inter-row space (where there are fewer roots) or be driven and collected in reservoirs for future use. Therefore, water management will be better regulated, resulting in fewer fruits with cracks. To implement PV panels in sour cherry production, however, the growing technology must be adapted, as they are typically harvested by machine. Consequently, the PV support structure could be a limiting factor for machine harvesting and *vice versa*.

Recommended (depending on variety): apple (*Malus domestica*), pear (*Pyrus communis*), blackberry (*Rubus fruticosus*), kiwi (*Actinidia chinensis*), peach (*Prunus persica*), nectarine (*Prunus persica* var. *nectarine*), quince (*Cydonia oblonga*), strawberry (*Fragaria ananansa*).

Depending on the varieties, apples and pears are recommended for Agri PV. Reduced sunlight reaching apple and pear fruit can have the positive and negative effects listed above (frost susceptibility, fruit colour, delayed ripening...). Kiwi fruit is a late ripening crop, and for some varieties, delayed ripening could pose a problem. Peaches and nectarines are known as one of the few fruit crops that accumulate aroma very late (aroma is accumulated in the fruit while it is still on the tree and exposed to sunlight). From the perspective of the consumer, it is essential that fruits have a nice colour and aroma. This may be an issue for some coloured varieties. Using PV in strawberry production is contingent upon the fruit-growing technology in use. Strawberry cultivation in soil is a low-height process, so PV panels must be installed high to avoid collisions with machinery and workers. Consequently, PV infrastructure in this growing technology can involve substantial costs that will be incurred exclusively only for PV panels. In citrus fruit, colour does not indicate the maturity stage, but consumers prefer citrus fruits with specific coloration. This coloration can be obtained through postharvest de-greening techniques that have no effect on the maturation stage. Therefore, PV panels should not have an adverse impact on citrus fruit production if they are installed.

Before installing agrivoltaics in an orchard, careful consideration should be given to the orchard's location, climate conditions, intended fruit species and varieties, and intended growing technology.

Several factors must be considered when evaluating the viability of employing agrivoltaics in Mediterranean fruit plantations. First, it is about the influence of the system itself on cultivated crops. According to the available international data, this influence can move in several directions. Ideal conditions exist when the use of agrivoltaics system accomplishes a synergistic effect with fruit culture, i.e., agricultural production is enhanced qualitatively and/or quantitatively through the optimal effect of the agrivoltaics system. It is also possible for the impact on agricultural production to be neutral or even marginally negative, but the overall effect on both sectors to be positive. Obviously, there is also the possibility that agrivoltaics could have an extremely unfavourable impact on cultivated plants, in which case pairing them on the same sites should be avoided.

Regarding olive, the most important fruit species in the Mediterranean part of Croatia, the use of PV panels in traditional olive growing regions should not have a significant negative effect on the quality of cultivation; however, in some riskier low-temperature cultivation areas, delayed harvesting could have an effect. In some areas where tree bark has cracked in recent years due to climate change, the use of PV panels could have a positive effect by reducing the amount of solar radiation without the need for adjustments in tree pruning.

7.3.3 THE CASE STUDIES OF REFERENT PROJECTS

a. SUNBIOSE (THE NETHERLANDS)

The Sunbiose project is an agrivoltaic project funded by the Dutch Innovation programme MOOI. Sunbiose will investigate the impact of PV panels on soil quality, biodiversity, and the emergence of plant maladies. As panels block a portion of sunlight, a special coating (that converts UV light to visible light) will be used and its effect on plants will be investigated. PVs will be installed on top of berry and pear orchards, as movable arches in grass/clover fields and in field crops as part of the Sunbiose project. In 2020, the first agrivoltaics in the Netherlands was installed on a 3.4 ha of raspberry in Babberich with 2.7 MWp output. Panels were installed on top of crop at the height 2,6 m. Panels encompass approximately 60 % of the area above the plants (Figure 18).

The space between panels is covered with a transparent polymer material coated with special coating to diffuse sunlight. As raspberries prefer partial shade, this shading could actually be beneficial for plants. Benefits of deploying PVs above raspberry orchards include the use of this cover for hail protection, plant shading, and air temperature modification. During sunny days (summer), the temperature under PV covers is 5 to 6 °C lower than in the uncovered portion of the orchard. Additionally, during the night, the air temperature beneath PV panels is a few degrees higher than that of the uncovered portion. Lower daytime air temperatures in the sum-

Figure 18 Agrivoltaics panels in the berry orchard

Source: Photo, G. Fruk.

Figure 19 Agrivoltaics in raspberry orchard in Babberich

Source: Photo G. Fruk.

mer reduce plant stress and water needs. PV panels can reduce water consumption by up to 25%.

Orchards without PV panels are frequently shadowed with plastic foil, preventing normal ventilation. The construction of a PV-covered orchard is such that it has superior ventilation and fewer problems than an uncovered (no panels, no plastic foil) orchard. With reduced orchard ventilation, air humidity rises and plant susceptibility to disease increases. Thus, in rainy years, PV-equipped orchards are susceptible to plant diseases. Moreover, shading reduces yield by roughly 5%.

In 2022, another test field of Sunbiose project was installed in Wadenoijen on 2 ha of red currant orchard with the output of 1,2 MWp. As hail damaged plants in the uncovered portion of the orchard, it was impossible to determine the true impact on red currant plants.

In April 2023, the plan was to plant 2 ha of pears and install PV panels atop the same orchard. Both farmers (raspberries and red currants) have noticed problems a large quantity of water between rows that slides off panels during rainfall. Thus, in pear orchards it is planned to install gutters at the end of PV panels is plan in order to drain the excessive water. The intention is to accumulate this rainwater and use it for irrigation during hot days.

b. Agrivoltaic system Haidegg (Austria)

The Experimental and Research Institute for Fruit and Wine Growing in the Austrian province of Styria has launched a pilot project for the use of agriphotovoltaics with support from the Haidegg Climate Fund and in collaboration with the private sector (Figure 18 and 19)..

Installed in July 2022, these APV systems serve as a double-benefit protective measure for fruit production. On the one hand, the physical barrier provides protection against heavy rain and hail, while, on the other hand, the carport effect provides protection against mild frosts. The aim of the project is to optimize the dual use of a site with fruit crops for agricultural production and electricity generation. Also, the prospect of total protection from rain could reduce the use of plant protection agents against fungal diseases in fruit cultivation. Consequently, Agri–PV systems would also provide substantial support for organic fruit production. Experiments were set up with apples, pears, cherries, apricots, mirabella, peaches, sour cherries, and plums.

In two test quarters, the effects of photovoltaic panel covering and the resultant changes in light conditions on plant growth, plant health, pest attack, yield, and internal and external fruit quality have been recorded. In addition, the project partner evaluates the electrical performance of the system. In a second series of experiments, the possibility of further enhancing the production of different types of fruit with individually tailored modules will be investigated.

Figure 20 Comparative aerial view of the installed system of APV system Haidegg

Source: ECOwind.

Figure 21 Differences among fruits in relation to the protection method

Apple variety „Elstar“ under Agri PV

Apple variety „Elstar“ under hail protection net

Source: ECOwind.

On a 5.000 m^2 fruit orchard, APV panels cover a total of 2,775 m^2, with an installed capacity of 340 KWp and an expected annual production of 385.000 kWh. On the APV special substructure, a total of 1,134 pieces of 49% translucent modules are used, with 9 units, each of which containing 6 strings with 21 modules.

7.3.4 STRUCTURE OF FRUIT GROWING IN CROATIA

According to ARKOD data, there were 56,180.57 ha of orchards in Croatia at the end of 2022, including 17,210.25 ha of olive groves. According to data from Table 4, the total number of orchards in Croatia is **91.172.** Taking into consideration that the minimum area required for APV application is 1 ha and based on the ARKOD data, there are **25,654.13 ha (including 4,368.26 ha of olive groves) of orchards with a surface area greater than 1 ha**.

MEDITERRANEAN FRUIT GROWING

Observing data on the cultivation of Mediterranean fruit species in the Adriatic agricultural subregion (Table 5), it is evident that by far the largest area is under olives (17,210.25 ha according to ARKOD data for 2022), and olives are the leading fruit crop in all coastal counties. Olives are followed by areas under citrus cultivation, of which only mandarins (all varieties of mandarins lead in this category, but the Satsuma mandarin dominate) are represented on larger areas (1,589.87 ha), whereas the cultivation of other species is very limited. Of the other fruit species, the largest areas are under almond crops (738.34 ha), with somewhat smaller areas under marasca sour cherries (347.09 ha) and figs (303.96 ha). Other fruit species that are maintained as a separate category (pomegranate, carob, kiwifruit, and jujube) have a very small and mostly localised cultivation. Other Mediterranean fruit species (loquat, oriental persimmon, strawberry tree...) are not managed as a separate category, but are possible in the mixed fruit cultivation group, and there is no precise information

Table 4 Number of orchards by county and by size (on 31st December 2022)

County	**Orchard size (ha)**					
	0-1	**1-5**	**5-20**	**20-100**	**>100**	**TOTAL**
Continental part						
Bjelovar-Bilogora	3,906	926	61	1	0	4,894
Brod-Posavina	5,850	656	53	13	0	6,572
City of Zagreb	1,612	30	0	0	0	1,642
Karlovac	4,314	547	33	3	0	4,897
Koprivnica-Križevci	3,859	294	13	3	0	4,169
Krapina-Zagorje	8,261	56	0	0	0	8,317
Međimurje	1,628	255	21	0	0	1,904
Osijek-Baranja	4.042	1,381	136	20	0	5,579
Požega-Slavonija	4,415	607	26	5	0	5,053
Sisak-Moslavina	4,572	589	52	6	0	5,219
Varaždin	4,694	137	5	0	0	4,836
Virovitica-Podravina	2,608	479	29	9	1	3,126
Vukovar-Srijem	1,981	465	50	12	0	2,508
Zagreb	5,995	326	42	4	0	6,367
	57,737	**6,748**	**521**	**76**	**1**	**65,083**
Highlands / Coastal part *						
Lika-Senj	4,670	42	0	0	0	4,712
Primorje-Gorski kotar	805	15	1	0	0	821
Šibenik-Knin	1,281	22	9	1	0	1,313
	6,756	**79**	**10**	**1**	**0**	**6,846**
Coastal part						
Dubrovnik-Neretva	7,929	360	3	0	0	8,292
Istria	1.931	68	5	1	0	2,005
Split-Dalmatia	3.900	28	9	1	0	3,938
Zadar	4.807	167	29	5	0	5,008
	18.567	**623**	**46**	**7**	**0**	**19,243**
TOTAL	**83.060**	**7,450**	**577**	**84**	**1**	**91,172**

* Three counties in this group are situated in both areas (highlands and coastal part)

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2023).

about their numbers. The main characteristics of all Mediterranean fruit crops, which can be seen from the table, is the small average land area (0.84 ha) they occupy. Only 292 (1.31%) of the 22,142 farms have surface areas larger than 1 ha, while only 31 farms (0.14%) have slightly larger surface areas (> 10 ha).

Table 5 Cultivation of Mediterranean fruit species in the Adriatic subregion (2021)

	Total area (ha)	**Agricultural activity**	**Average area (ha)**	**Agricultural activity > 1ha**	**Agricultural activity > 10 ha**
Olive	14,225.35	14,187	1.00	180	15
Mandarin	1,589.87	1,335	1.19	13	1
Lemon	31.92	201	0.16	1	0
Orange	14.96	92	0.16	0	0
Kumquat	0.60	10	0.06	0	0
Grapefruit	0.10	3	0.03	0	0
Almond	738.34	1,041	0.71	33	5
Marasca sour cherry	347.09	236	1.47	8	4
Fig	303.96	813	0.37	31	1
Pomegranate	55.18	172	0.32	5	0
Carob	50.61	14	3.62	1	1
Kiwifruit	15.95	14	1.14	1	1
Jujube	3.01	12	0.25	0	0
Mixed fruit Cultivation	1,273.31	3,994	0.32	16	3
Fruit nurseries	17.28	18	0.96	3	0
TOTAL	**18,667.53**	**22,142**	**0.84**	**292**	**31**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

Table 6 Olive cultivation in the Adriatic agricultural subregion (2021)

	Total area (ha)	**Agricultural activity**	**Average area (ha)**	**Agricultural activity > 1ha**	**Agricultural activity > 10 ha**
Istria County	3,171.84	2,492	1.27	68	6
Primorje-Gorski Kotar County	562.05	495	1.14	19	0
Lika-Senj County	121.93	96	1.27	1	0
Zadar County	2,625.96	3,522	0.75	23	6
Šibenik-Knin County	2,061.95	2,082	0.99	28	0
Split-Dalmatia County	3,511.11	2,728	1.29	28	1
Dubrovnik-Neretva County	2,170.51	2,772	0.78	22	2
TOTAL	**14,225.34**	**14,187**	**1.00**	**180**	**15**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

There are 180 olive orchards (Table 6) with a surface area of more than 1 ha (about 700 ha in total). Most of them are located in Istria County (37.78%), with the remainder in Split-Dalmatia County and Šibenik-Knin County (15.56% each).

Other Mediterranean fruit species include 33 almond plantations on plots larger than 1 ha (in total 281ha), 30 fig plantations on plots larger than 1 ha (in total 90 ha), 13 citrus plantations on plots larger than 1 ha (48 ha), and a smaller number of plantations of other species (marasca sour cherry[89], mixed fruit cultivation).

7.3.5 CONCLUSIONS AND RECOMMENDATIONS

In Croatia, agrivoltaics in orchards has huge potential, particularly in small to medium-sized orchards (5-15 ha), such as family farms. Photovoltaic panels installed aver a fruit crop can help to prevent physiological disorders in plants and fruits (sun burn, heat stress, overcolouring etc.). At the same time, panels can be employed as hail protection without the requirement for removal during offseason (which is time and effort consuming). Panels not only affect the microclimate conditions (lower air temperatures during the day, higher temperatures at night, diffusing sunlight, changing the solar spectrum that reaches the plants.), but also reduce damages and may even increase fruit quality. In the spring, panels could prevent excessive sun heating of plants, preventing early vegetation that could cause frost damage. Furthermore, frost protection solutions such as heating the orchard (frostbuster) may be more effective since panels act as a barrier to heat losses, allowing heat to stay in the orchard for longer.

Although, there are some positive benefits of installing PV panels in orchards, there may also be some negative effects. The most noticeable difference would be in fruit colour. Each fruit species and variety has a standard colour that consumers find acceptable, and which distinguishes it from other varieties. For example, red apples such as 'Red Delicious' must have the entire fruit coloured red. With less sunlight reaching the fruit, and less air temperature (day/night) amplitudes, the colour would not achieve its full potential by harvest maturity. Yellow and green apple varieties such as 'Golden Delicious' and 'Granny Smith', on the other hand, will benefit from PV panels installed above the orchard. Panels will prevent their colour change to red (a key concern with this 'Granny Smith' variety in the last 10 years due to climate change), preventing overcolouring and making these varieties more appealing to consumers.

According to the most recent data (Table 5) there are 292 plantations of Mediterranean fruit species greater than 1 ha in size, spanning a total of 1,400 ha of land (31 plantations larger than 10 ha in size). Based on that figure, it is estimated at least 2/3 of plantations larger than 1 ha (about 200 plantations – 950 ha), have the ability to install agrivoltaics systems, either in their current cultivation form or with minor adjustments to agrotechnical measures in the plantation.

Nearly two-thirds of all plantations greater than 1 ha, 180 in total, are under olive cultivation (15 are larger than 10 ha). If the plantations are located in relief-friendly areas with infrastructure and at least a semi-intensive degree of production, they may be considered suitable for establishing an agrivoltaic system. It is anticipated that 120-150 olive plantations (around 500 ha) are potentially interesting for establishing agrivoltaic systems.

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[89] The three biggest plantations of marasca sour cherry, totalling approximately 250 ha.

Given that Istria County has around 28% of all olive plantations with available grid capacity potential, it is reasonable to predict that the first agrivoltaic projects using olives will be launched in this county.

Aside from the large fragmentation of the plots, one of the biggest obstacles to the introduction of agrivoltaics in the agriculture of Adriatic Croatia is the location of a large portion of the fruit plantations in this area, particularly of those species that do not require the use of irrigation for their development and are frequently located on unsuitable land and in areas far away from the necessary supporting infrastructure.

Because these are usually plantations with semi-intensive or extensive agricultural production, it is difficult to assume that the essential conditions and/or the landowner's interest exist to install agrivoltaics in such conditions, especially on bigger plantations. It is advised that agrivoltaics be installed only in intensive fruit plantations, where their installation and use can be viewed as one of the agrotechnical measures that will contribute to the best possible use of land resources.

Fruit species that are generally suitable for usage with PV panels are American blueberry, blue honeysuckle, raspberry, hardy kiwi, apricot, sweet cherry, and sour cherry. Depending on the variety, apple, pear, blackberry, kiwi, peach, nectarine, quince and strawberry are recommended for Agri PV application.

In general, the successful implementation of agrivoltaic systems in orchards of Mediterranean fruit species is possible, though some constraints, such as plot fragmentation and distance from the necessary energy infrastructure, may delay the installation of agrivoltaics on larger areas in Adriatic Croatia. The removal of these constraints would expand the available areas for agrivoltaics.

7.4 AROMATIC AND MEDICAL PLANTS

7.4.1 Background

Due to the diversity of climatic and agroecological circumstances, the production of medicinal and aromatic plants varies by location in Croatia. Some plants are more common in coastal agriculture (immortelle, lavender, sage), while others are more common in continental cultivation (chamomile, fennel, milk thistle, mint, lemon balm, wormwood).

7.4.2 Results of previous research – benefits and challenges

Most of the plants in this group are grown as bushes or semi-bushes, or as herbaceous plants. In any event, the plants are small to medium in height, allowing for simpler manipulation inside the plantation, particularly in relation to woody crops.

Everything that has previously been mentioned about scientific literature information regarding the possibilities of using agrivoltaics in fruit agricultural plantations also applies to medicinal and aromatic plants. The only thing that can be added is that the floral abundance was increased, and bloom time was delayed in the partial shaded plots, which has the potential to benefit late-season foragers in water-limited ecosystems. Pollinator abundance, diversity, and richness were comparable in full sun and partially shaded plots, both of which were greater than in full shade.

7.4.3 THE CASE STUDIES OF REFERENT PROJECTS

a. FATTORIA SOLARE LA PETROSA, CASTROVILLARI, CALABRIA (ITALY)

The Fattoria solare La Petrosa project (Figure 22) is planned in Castrovillari, in the province of Cosenza (Calabria), in the immediate vicinity of the Castrovillari prison. The intended area is approximately 35 ha, with 14.4 MW photovoltaic plants divided into three independent operating sections of 4.8 MW each (Castrovillari A, Castrovillari B, Castrovillari C) and installed at a height of 3 meters above ground surface. It is planned that the steel structures be used to support irrigation and aerial fogging systems. If the panel is set parallel to the ground, there is 2.7 metres of useful vertical space beneath the module. Considering the slope, the space is higher than 2 meters and enables the performance of standard agrotechnical procedures. This layout allows for the processing of all used surfaces with soil shading index ranging from 15 to 30%. The project includes the planting of medicinal plants (lavender - 10 ha, phacelia - 12 ha, hypericum - 2 ha, echinacea - 2 ha, marigold - 2 ha, rhubarb - 2 ha). In addition to the agronomic and energy components, the project intends to encourage reintegration of prisoners through agricultural activities.

b. VAMVAKIES SOLAR FARM (GREECE)

The project was established in collaboration with the municipality of Kozani and CluBE, the Cluster of Bioeconomy and Environment of Western Macedonia, and commissioned in December 2021 (Figure 23). The project

Figure 22. Fattoria solare La Petrosa

Source: https://www.infobuildenergia.it/approfondimenti/fotovoltaico-agricoltura-agrivoltaico-progetti/

is a 6.5 MW photovoltaic plant in Agios Ioannis-Vamvakies, close to the city of Veria, in the northern part of the country [90]. It includes 16,000 bifacial panels with an approximate investment of 3.5 million euros. The Vamvakies Solar Farm, which was completed in October 2021 near the town of Veria in northern Greece, will prevent the emission of 6,500 tons of CO_2 annually and contribute to the the greater decarbonization of Western Macedonia (Enel Green Power, 2022a). Aromatic plants, such as oregano, rosemary, thyme, *Sideritis* (ironwort), *Paliurus* (also known as Jerusalem thorn), and mountain tea, will be cultivated in this photovoltaic system.

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[90] https://www.enelgreenpower.com/our-projects/operating/vamvakies-solar-farm. Accessed 26 October 2022.

Figure 23 Vamvakies Solar Farm

Source: https://www.enelgreenpower.com/countries/europe/greece/sustainable-construction-site-vamvakies-pv-plant

Table 7 Cultivation of aromatic and medicinal plants in Croatia (2021)

	Total area (ha)	**Agricultural activity**	**Average area (ha)**	**Agricultural activity > 1ha**	**Agricultural activity > 10 ha**
Chamomile (*Matricaria chamomilla L.*)	6,359.92	503	12.64	475	178
Immortelle (*Helichrysum italicum (Roth) G. Don*)	589.18	655	0.90	108	4
Lavander (*Lavandula angustifolia Mill.*)	225.32	379	0.59	55	0
Fennel (*Foeniculum vulgare Mill.*)	93.29	9	10.37	6	2
Milk thistle (*Silybum marianum* (L.) Gaertn.)	22.83	14	1.63	8	0
Pepper mint (*Mentha x piperita* L.)	16.49	25	1.63	3	0
Sage (*Salvia officinalis* L.)	15.62	23	0.68	1	1
Lemon balm (*Melissa officinalis* L.)	15.54	24	0.65	6	0
Wormwood (*Artemisia absinthium* L.)	8.54	13	0.66	4	0
Rosemary (*Salvia rosmarinus Spenn*)	8.50	18	0.46	2	0
TOTAL	**7,355.23**	**1663**	**4.42**	**668**	**185**

7.4.4 STRUCTURE OF MEDICINAL PLANT PRODUCTION IN CROATIA

A total of 16 varieties are produced in areas larger than one hectare, with the ten most prevalent shown in Table 7. In Croatia, chamomile is the most commonly cultivated medicinal plant. It is cultivated in the Slavonia and Baranja regions of Continental Croatia. Adriatic Croatia is the second greatest producer of immortelle and the third largest producer of lavender. The production of fennel, milk thistle, mint, lemon balm, sage, wormwood, and common mallow is also substantial.

Table 8 Chamomile cultivation in Croatia (2021)

	Total area (ha)	**Agricultural activity**	**Average area (ha)**	**Agricultural activity > 1ha**	**Agricultural activity > 10 ha**
Zagreb County	41.64	13	3.20	8	1
Sisak-Moslavina County	346.37	17	20.37	14	7
Karlovac County	0.23	1	0.23	0	0
Koprivnica-Križevci County	115.30	18	6.41	17	2
Bjelovar-Bilogora County	219.61	10	21.97	10	7
Primorje-Gorski Kotar County	1.06	1	1.06	1	0
Virovitica-Podravina County	4,137.89	361	11.46	351	123
Požega-Slavonia County	45.97	5	9.19	5	1
Brod-Posavina County	8.10	5	1.62	3	0
Osijek-Baranja County	1,400.21	61	22.95	58	36
Vukovar-Syrmia County	22.38	3	7.46	3	1
Istria County	1.75	1	1.75	1	0
Dubrovnik-Neretva County	0.75	1	0.75	0	0
Međimurje County	2.02	2	1.01	1	0
City of Zagreb	16.54	4	4.14	3	0
TOTAL	**6,359.92**	**503**	**12.64**	**475**	178

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

Chamomile (Table 8) is the most widely cultivated medicinal plant in Croatia, encompassing over 6,300 ha (over 86% of all areas covered with medicinal and aromatic plants). It is cultivated in nearly every county, but primarily in Virovitica-Podravina County (about 65% of the Croatian chamomile production) and Osijek-Baranja County (about 22% of the Croatian chamomile production). Large chamomile plantations can also be found in the counties of Sisak-Moslavina, Bjelovar-Bilogora and Koprivnica-Križevci. The vast majority of chamomile is grown in plots larger than 1 ha. There are 475 of these plantations with a total production area of 6,348 ha, and 178 plantations larger than 10 ha. Some plantations are even about 100 ha in size.

Table 9 Immortelle cultivation in Croatia (2021)

	Total area (ha)	**Agricultural activity**	**Average area (ha)**	**Agricultural activity > 1ha**	**Agricultural activity > 10 ha**
Zagreb County	5.50	4	1.38	3	0
Krapina-Zagorje County	0.05	1	0.05	0	0
Karlovac County	0.01	1	0.01	0	0
Varaždin County	1.01	3	0.34	0	0
Koprivnica-Križevci County	0.72	1	0.72	0	0
Primorje-Gorski Kotar County	13.56	6	2.26	6	0
Lika-Senj County	5.24	4	1.31	2	0
Zadar County	204.10	231	0.88	32	2
Osijek-Baranja County	1.81	2	0.91	1	0
Šibenik-Knin County	186.39	244	0.76	32	1
Split-Dalmatia County	93.42	90	1.04	12	1
Istria County	20.45	27	0.76	7	0
Dubrovnik-Neretva County	28.91	25	1.16	7	0
City of Zagreb	28.01	16	1.75	6	0
TOTAL	**589.18**	**655**	**0.90**	**108**	**4**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

The cultivation of immortelle is the second most prevalent (Table 9). The majority of plantations and areas are found in Zadar County (34.64%), Šibenik-Knin County (28.58%) ,and Split-Dalmatia County (15.86%), implying that Dalmatia accounts for more than 80%. This makes them unsuitable for the deployment of APVs, at least in the short future, taking into consideration the electricity grid status in Dalmatia. According to data from the Paying Agency for Agriculture, Fisheries and Rural Development, 108 plantations (480 ha in total) are greater than 1 ha (32 in Zadar County and 32 in Šibenik-Knin County), with 4 plantations larger than 10 ha.

Lavender and lavendin are classified together as one item by the Paying Agency for Agriculture, Fisheries and Rural Development data and they represent the third most cultivated aromatic plant in Croatia. They are grown on an area of 225.32 ha (Table 10), with the majority in Split-Dalmatia County (32.70%) and Istria County (26.17%). They are the only medicinal or aromatic plant that can be found in each of the counties. Although Split-Dalmatia County has more than three times as many lavender plantations as Istria County, when the number of plantations larger than 1 ha is considered, the situation is diametrically opposite, with Istria County having 22 such plantations and Split-Dalmatia County 6. There are

Table 10 Lavender and lavendin cultivation in Croatia (2021)

	Total area (ha)	**Agricultural activity**	**Average area (ha)**	**Agricultural activity > 1ha**	**Agricultural activity > 10 ha**
Zagreb County	7.51	13	0.58	2	0
Krapina-Zagorje County	4.81	16	0.30	0	0
Sisak-Moslavina County	6.70	9	0.74	4	0
Karlovac County	10.48	16	0.66	5	0
Varaždin County	2.76	10	0.28	0	0
Koprivnica-Križevci County	3.61	10	0.36	1	0
Bjelovar-Bilogora County	2.86	5	0,57	1	0
Primorje-Gorski Kotar County	4.35	12	0.36	0	0
Lika-Senj County	2.40	4	0.60	1	0
Virovitica-Podravina County	1.12	4	0.28	0	0
Požega-Slavonia County	0.85	3	0.28	0	0
Brod-Posavina County	2.20	3	0.73	1	0
Zadar County	7.67	10	0.77	2	0
Osijek-Baranja County	10.67	13	0.82	5	0
Šibenik-Knin County	3.62	13	0.28	0	0
Vukovar-Syrmia County	8.37	3	2.79	1	0
Split-Dalmatia County	73.69	163	0.45	6	0
Istria County	58.96	51	1.16	22	0
Dubrovnik-Neretva County	1.73	6	0.29	1	0
Međimurje County	5.87	3	1.96	2	0
City of Zagreb	5.09	12	0.42	1	0
TOTAL	**225.32**	**379**	**0.59**	**55**	**0**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

55 plantations larger than 1 ha, representing 170 ha of land, with none greater than 10 ha.

Of all other medicinal plant species with plantations larger than 1 ha, only 35 plantations are larger than 1 ha (168 ha of land).

7.4.5 Conclusions and recommendations

As previously stated, there are 673 plantations of medicinal and aromatic plants (7,166 ha of land) larger than 1 ha and 185 plantations larger 10 ha.

At least three-quarters of plantations larger than 1 ha (approximately 500 plantations), are estimated to have the potential for agrivoltaic system installation, either in their current cultivation form or with minor adjustments to agrotechnical measures.

Aside from the cultivation conditions, not all medicinal and aromatic plants are equally amenable to the installation of agrivoltaic systems.

By far the most significant medicinal and aromatic plant grown in Croatia is chamomile. The total surface area of plantations larger than 1 ha is 6,348 ha, with 475 plantations larger than 1 ha and 178 plantations larger than 10 ha. The assumption is that all larger production plantations are suitable for the potential introduction of agrivoltaics. While the same holds true for the majority of plantations between 1 and 10 ha in size, a more in-depth assessment should be conducted. With the selection of a suitable system, the authors of this Study believe that the implementation of agrivoltaics on approximately 400-420 plantations (approximately 5,600 ha of land) is feasible. In addition, it is essential to note that chamomile is typically grown in counties with the available grid connection capacity, making them suitable for the deployment of agrivoltaic projects in the short future.

There are 108 immortelle plantations that are larger than 1 ha (480 ha in total), and 4 that are larger than 10 ha. An estimated 70% of these plantations (approximately 336 ha of land) can be considered for the implementation of agrivoltaic systems, according to an expert assessment.

Lavender remains the only medicinal and aromatic plant with slightly more plantations larger than 1 ha (55 – on 170 ha of land), but it is interesting that none are larger than 10 ha. Some of these plantations are located in the areas without infrastructure, which should be considered when evaluating the feasibility of implementing agrivoltaic systems. According to the expert opinion by the authors of this Study, approximately half of the plantations (about 90 ha of land) can be taken into account for further consideration.

Only 35 plantations are larger than 1 ha (168 ha of land) among all plantations with other species. On the basis of field knowledge, it is estimated that one-third of these plantations (roughly 60 ha of land) have favourable production conditions and can be considered for the installation of agrophotovoltaics.

In summary, there are around 500 plantations with a **total production area of 6.086 ha dedicated to the cultivation of medicinal and aromatic plants, which present potential suitability for the implementation of agrivoltaics.** With a more comprehensive evaluation, it is highly likely that the aforementioned figure will be lower.

In conclusion, it can be asserted that there are considerable prospects for the effective integration of agrivoltaic systems in medicinal and aromatic plant plantations. However, due to the limited knowledge and experience in the field of agrivoltaics, it is essential to exercise caution when selecting particular species for implementation of the APV system.

7.5 VEGETABLE GROWING

7.5.1 Background

Conventional soil cultivation of vegetables faces many challenges as a result of significant impacts of climate change, particularly the phenomenon of global warming and the occurrence of drought. The primary objective is to generate sufficient crop yields and cultivate plant material of superior nutritional grade. Greenhouse technology, also referred to as closed agriculture, plays a crucial role in the agricultural industry by enhancing production and addressing the global demand. This technology creates a favourable microclimate for plants, facilitating optimal growth, prolonged production duration, earlier harvesting, and improved yields of superior quality[91].

Given the susceptibility of vegetable crops to external factors, protective measures such as the implementation of costly structures like hail nets or films are frequently employed to safeguard them against adverse weather conditions. One benefit of employing this cultivation method is the enhanced ease of managing and controlling various factors throughout the cultivation process, such as air temperature, relative humidity, and appropriate fertilisation practices. These measures contribute to creating optimal conditions for the growth and development of vegetables according to their needs[92]. In addition to conventional outdoor cultivation methods, hydroponic systems are widely regarded as a significant technological strategy for promoting sustainable food supply and alleviating the strain on agricultural land by relocating food production to urban settings[93].

Furthermore, the implementation of hydroponic soilless techniques in greenhouses allows for more efficient water and nutrient utilisation, thereby facilitating accelerated plant growth, earlier and multiple harvests, increased production cycles due to year-round cultivation, and elevated biomass production, ultimately leading to higher yields[94]. Nevertheless, hydroponic systems are not considered to be energy-efficient solutions due to their substantial energy consumption in several aspects such as heating, cooling, ventilation, irrigation, LED lighting etc. This high energy demand not only results in an increase in operating costs, but also contributes to significant environmental repercussions[95]. However, the majority of hydroponic systems are increasingly reliant on solar energy. In order to satisfy the high energy demand and make greenhouse agriculture more sustainable, there is considerable interest in integrating photovoltaics and, by extension, APV systems into greenhouses.[96]

7.5.2 Results of previous research – benefits and challenges

The greatest challenge for hydroponic growers is determining the type and capacity of solar panels based on the species cultivated. We anticipate temperature variations in the air, soil, and plants beneath the panels as a result of the reduced solar radiation. Consequently, the majority of research has aimed to influence the growth rate of plants by positioning the solar panels to produce shade for plants.

Tomato plants in agrivoltaic systems yielded twice as much fruit as plants in the con-

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[91] Gauffin, 2022.

[92] Opačić i sur., 2022.

[93] Xu et al., 2022.

[94] Gonnella i sur., 2004; Nicola i sur., 2007.

[95] Fraunhofer ISE, 2021c.

[96] Gauffin, 2022.

trol group, which lacked solar panels. Other plants, such as lettuce and jalapenos, produced the same quantity of fruit while requiring significantly less water.

According to some authors[97], agri-photovoltaics with additional shading produced greener broccoli with higher consumer preference than that grown in the field. The yield, antioxidant capacity, certain glucosinolates, and hydrolysis products of broccoli grown using an agro-photovoltaic system were comparable to those of broccoli grown in the field. However, the uneven distribution of precipitation at the drip edges of PV modules is a result of the partial coverage of agricultural land. In these areas, measures must be taken to counteract soil erosion due to runoff of nutrient-rich topsoil, sealing, leaching of seedlings, or nutrient discharge and eutrophication of surface waters. When selecting plant varieties for systems that provide no or only partial protection from rain, potential changes in air circulation, humidity, and the risk of fungal infection must be considered when selecting plant varieties. In addition to practical considerations, knowledge of the microclimatic effects of agri-photovoltaics provides a foundation for selecting suitable plants. The suitability of individual plants is determined by the amount of partial shade beneath the plant [98].

When growing vegetables with solar panels, it is necessary to make certain adjustments to the cultivation practices, with an emphasis on mitigating light reduction and selecting crops with maximum radiation efficiency. In comparison to the control plots without photovoltaic panels, tests conducted on the crops growing between the rows of panels revealed a 60% increase in agricultural yield and average weight of fruits of certain horticultural species, such as peppers, and an increase in the number of fruits by up to 30%. The biomass of plants such as aloe vera increased by 50 to 60%, while yields of other types of aromatic, medicinal, legume, and forage crops increased by 30% to 60% [99].

7.5.3 THE CASE STUDIES OF REFERENT PROJECTS

a. SAINT-ETIENNE-DU-GRÈS AGRIVOLTAIC SYSTEM (FRANCE)

In the French commune of Saint-Etienne-du-Grès in the Provence-Alpes-Côte-d'Azur region,

Figure 24 Saint-Etienne-du-Grès agrivoltaic system

Source: https://www.pv-magazine.fr/2021/03/18/voltalia-met-en-service-son-premier-champ-agrivoltaique/

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[97] Chae et al. 2022.

[98] Fraunhofer ISE, 2022c.

[99] Enel Green Power, 2022.

Figure 25 Example of hydroponic Agri – PV farming

Source: pv magazine, 2022.

a 3 MW solar power plant on agricultural land was commissioned (see Figure 24). Located in an open space, the 3 MW Cabanon agricultural photovoltaic plant was constructed using participatory financing, with €700,000 contributed primarily by residents and neighbouring areas. The project was constructed on an area of 4,5 hectares and features 4.5-meter-tall solar panels with dynamic tracking systems that enable the passage of agricultural machinery while shielding vegetable crops from the heat [100].

b. Q ENERGY FRANCE – AGRIVOLTAICS IN HYDROPONIC FARMING (FRANCE)

Q Energy France and Aquacosy have unveiled a pilot PV system in conjunction with a hydroponic farm in the town of Montauban, in the French department of Tarn-et-Garonne. The hydroponic farm has a surface area of approximately 250 m^2 and is connected to a PV system with an installed power of 9.3 kW, equipped with a hydraulic system with two rainwater collection gutters. In this way, the rainwater that falls over the panels is collected in a basin (Figure 25) and, thanks to the closed water circuit, the plantations can be irrigated continuously to conserve water. The system, which includes hygrometry sensors, probes, and a pump, is completely solar-powered[101].

7.5.4 STRUCTURE OF VEGETABLE GROWING IN CROATIA

The Republic of Croatia has significant advantages for vegetable production, and climatic, pedological, and hydrological conditions make open-field vegetable production practicable almost year-round [102]. Despite the favourable agroecological conditions for the production of most vegetables, the current production is insufficient to meet the needs of the Croatian market due to fragmented cultivation areas, a disorganized production infrastructure, a lack of heating and irrigation systems as well as hail and frost protection systems, and inadequate storage areas. This indicates that additional investments in modernization, such as agrivoltaic systems, are required to make vegetable production competitive and profitable.

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[100] Taiyangnews, 2021.

[101] Pv magazine, 2022.

[102] Grgić et al., 2016.

It is important to note that statistical data on vegetable production in the Republic of Croatia are insufficient and incomplete, as the majority of vegetables are annual crops that do not remain on the same growing plot for an extended period (they change over the years due to the importance of crop rotation), but also within the same year on the same plot (due to the varying length of vegetation). Additionally, various crops can be grown concurrently on certain plots. For the same reason, vegetable crops are not shown separately in statistics, but instead are grouped with other vegetable crops (even with fruits such as strawberries), making it difficult to track the statistical data over the years, particularly in

Table 11 Cultivation of vegetables in Republic of Croatia (2021)

	Area (ha)	**Production (t)**	**Yield (t/ha**
Total fresh vegetables (including kitchen gardens)	10,076	214,374	21.3
Total fresh vegetables	8,398	168,624	20.1
Cauliflower and broccoli	195	3,154	16.2
Cabbage (white and red)	1,201	28,844	24
Other brassicas	146	2,536	17.4
Leeks	97	1,697	17.5
Lettuce	195	3,586	18.4
Lettuces under glass	31	701	22.6
Other leafy or stalked vegetables	520	6,419	12.3
Tomatoes	292	18,785	64.3
Tomatoes for fresh consumption	64	1,316	20.6
Tomatoes under glass	88	11,902	135.3
Cucumbers and gherkins	98	8,549	87.2
Cucumbers and gherkins under glass	43	7,554	175.7
Melons	132	1,852	14
Watermelons	720	21,476	29.8
Red peppers, capsicum	803	13,559	16.9
Red peppers, capsicum under glass	31	1,778	57.4
Other vegetables cultivated for fruit	1,327	17,938	13.5
Carrots	306	6,403	20.9
Onions and garlic	914	19,044	20.8
Beetroot	126	3,173	25.2
Other root and tuber vegetables	289	4,107	14.2
Green peas	563	4,600	8.2
Green beans	474	2,902	6.1
Fresh vegetables (kitchen gardens)	1,678	45,750	27.3
TOTAL	**28,807**	**620,623**	**907.2**

Source: Croatian Bureau of Statistics (2022).

relation to individual crops. Statistical data on the cultivation of the most common vegetable varieties in 2021 is presented in Table 11.

Tomatoes, peppers, and watermelons (melons and cucumbers may also be considered) will be examined in greater detail in light of their cultivation areas and ecological requirements for growth (thermophilic vegetable species) as part of this Study. They are heat-loving vegetables with a lengthy growing season, making them suitable and potentially profitable for an APV system. Due to their increased sensitivity to sunburn and the occurrence of tip fruit rot, the species on the list are deemed viable for cultivation in conjunction with photovoltaic panels. Using panels will result in improved microclimatic conditions. It is recommended that these plants be grown from seedlings to obtain a longer growing season and earlier fruiting.

Tomato [(Lycopersicon esculentum Mill. syn. Lycopersicon lycopersicon L. (Karsten)]

Tomatoes require irrigation and an adequate quantity and distribution of precipitation. In the Republic of Croatia, coastal and Mediterranean karst regions where irrigation is feasible

Table 12 Tomato cultivation in Croatia in 2022

County	Total area (ha)	Number of agricultural holdings
Bjelovar-Bilogora County	4.98	33
Brod-Posavina County	2.15	18
Dubrovnik-Neretva County	6.71	51
City of Zagreb	4.16	30
Istria County	113.49	82
Karlovac County	0.42	8
Koprivnica-Križevci County	3.13	23
Krapina-Zagorje County	0.1	1
Lika Senj County	0.83	1
Međimurje County	0.26	1
Osijek-Baranja County	15.2	46
Požega-Slavonia County	0.47	8
Primorje-Gorski Kotar County	2.19	8
Sisak-Moslavina County	1.83	17
Split-Dalmatia County	5.94	39
Šibenik-Knin County	0.7	4
Varaždin County	0.89	20
Virovitica-Podravina County	24.65	115
Vukovar-Srijem County	6.19	28
Zadar County	11.18	42
Zagreb County	1.37	16
TOTAL	**206.84**	**591**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022) are preferred for fresh produce production. These climatic conditions permit greater utilization of the yield capacity of the varieties, i.e., earlier sowing and harvesting commencement and harvest completion in autumn. In the continental area, conditions are favourable for the production of tomatoes for fresh consumption on alluvial soils in river valleys, and the harvest occurs in in August and September (cultivation production is shown in Table 12)[103]

PEPPER (CAPSICUM ANNUUM L.)

Due to its small root system, pepper requires a great deal of water for its growth and development, which it absorbs from the soil's surface. The plant does not tolerate waterlogging in the soil. Consequently, it is important to choose a warm, textured and light soil with a high water and air holding capacity and to provide irrigation. As the plant is susceptible to alkaline soil, it is advised to select a neutral or slightly acidic soil containing more than 3% humus. Pepper does not tolerate cultivation as well as plants in the same family (tomatoes, potatoes, cucumbers), and it takes at least 4 years before it can be grown in the same soil again. Pepper cultivation by counties is shown in Table 13.

Table 13 Pepper cultivation in Croatia in 2022

County	Total area (ha)	Number of agricultural holdings
Bjelovar-Bilogora County	37.01	63
Brod-Posavina County	19.47	54
Dubrovnik-Neretva County	4.57	35
City of Zagreb	12.44	26
Istria County	4.44	16
Karlovac County	3.47	12
Koprivnica-Križevci County	53.51	60
Krapina-Zagorje County	0.15	2
Lika Senj County	-	-
Međimurje County	3.38	7
Osijek-Baranja County	62.97	97
Požega-Slavonia County	21.48	43
Primorje-Gorski Kotar County	0.4	1
Sisak-Moslavina County	9.2	18
Split-Dalmatia County	5.04	23
Šibenik-Knin County	0.56	4
Varaždin County	32.41	107
Virovitica-Podravina County	326.62	349
Vukovar-Srijem County	32.76	67
Zadar County	7.39	32
Zagreb County	14.59	29
TOTAL	**651,86**	**1,045**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

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[103] Lešić et al., 2016.

Watermelon [Citrullus lanatus (Thumb.) syn. Citrullus lanatus var. vulgaris (Schard.) Mansf.]

Watermelon is a xerophytic plant that prefers a warm climate and is quite sensitive to low temperatures. The main root extends deeper than 1 m, however the majority of the minor roots are found in a layer of 15 to 25 cm thick. Temperatures between 28 and 30°C are the most favourable for growth and development. Growth ceases at 15°C, and if temperatures remain below 10°C, the plant may be irreversibly damaged. Watermelon is a plant that requires intense light, so when the weather is cloudy (as in the case of melons), the quality of the fruit decreases during growth. Cultivation is possible only during frost-free periods when the sum of average daily temperatures is 3000°C.

Watermelon is not sensitive to slightly saline soils and grows well at pH levels between 5 and 7. Deep, loose, humus-rich soils are most suitable. Alluvial soils in river valleys are also suitable for cultivation without irrigation. It

Table 14 Watermelon cultivation in Croatia in 2022

County	Total area (ha)	Number of agricultural holdings
Bjelovar-Bilogora County	10.1	33
Brod-Posavina County	10.46	21
Dubrovnik-Neretva County	188.33	153
City of Zagreb	5.16	10
Istria County	23.72	51
Karlovac County	4.93	21
Koprivnica-Križevci County	20.55	14
Krapina-Zagorje County	0.24	2
Lika Senj County	0.01	1
Međimurje County	0.36	1
Osijek-Baranja County	42.54	57
Požega-Slavonia County	18.49	21
Primorje-Gorski Kotar County	1.36	4
Sisak-Moslavina County	6.79	16
Split-Dalmatia County	10.91	25
Šibenik-Knin County	14	6
Varaždin County	0.87	7
Virovitica-Podravina County	62.74	80
Vukovar-Srijem County	162.09	74
Zadar County	92.46	172
Zagreb County	3.73	9
TOTAL	**679.84**	**778**

Source: Paying Agency for Agriculture, Fisheries and Rural Development (2022).

must not be cultivated on the same land for at least 4 to 5 years [104]. Watermelon cultivation by counties ~~is~~ shown in Table 14.

7.5.5 CONCLUSIONS AND RECOMMENDATIONS

The risk of using solar panels in vegetable production in particular lies in crop rotation, as these are typically annual species that alternate in space and time. In this context, the cultivation process involves a sequence of crops throughout the year. Initially, preceding crops such as spinach, lettuce, radish, peas, early potatoes, and spring onions are cultivated during the early spring or winter season. Subsequently, the main crop with the longest growing season (tomatoes, peppers, cabbage, onions) is cultivated. Finally, the succeeding crop (lettuce, spinach, spring onions) is grown after the main crop. Such cultivation enables the optimal utilisation of a given growing plot throughout the year due to the varying biological properties and vegetation durations of different vegetable species (mesophilic and thermophilic species). The utilisation of solar panels may pose a potential challenge due to variations in temperature, light and water requirements. Additionally, the implementation of appropriate agrotechnical measures must be considered in accordance with the installed APV system while cultivating different species.

On particularly hot days, when Agri-PV panels are utilised, the soil temperature decreases, and, to a lesser extent, so does the air temperature, according to various studies. Depending on the system's orientation and design, wind speed may decrease or increase. Therefore, wind tunnel effects and their impact on plant growth should be considered when designing the system. The advantage in growing vegetables by using an agrivoltaic system is that less groundwater is lost. Species that require a great deal of light (peppers, tomatoes, melons, watermelons, and cucumbers) can be grown between the rows of panels.

Numerous impediments (fragmented cultivation areas, disorganised production infrastructure) limit the likelihood of a successful implementation of Agri–PV systems in vegetable cultivation in the Republic of Croatia. Consequently, growing vegetables with solar panels requires certain adjustments to cultivation practices aimed at mitigating light reduction (particularly when growing melons, watermelons, and peppers) and selecting and combining crops with the maximum radiation efficiency.

In summary, the aforementioned factors provide significant challenges and risks when considering the installation of solar panels in vegetable production. Consequently, it may be concluded that, currently, the utilisation of APVs may not be suitable for vegetable cultivation. However, it is advisable to initiate research-oriented pilot projects focusing on select vegetable varieties, such as tomatoes, peppers, and watermelons, to assess the potential impacts of Agri-PV implementation. These projects should aim to analyse the effects of PV installations on various aspects including production, growth, yields, resistance to microclimate changes and other relevant factors.

7.6 CEREALS, INDUSTRIAL AND FORAGE PLANTS PRODUCTION

7.6.1 BACKGROUND

Cereals have a crucial role in human nutrition since they serve as a primary source of food and energy. This is achieved through the direct intake of cereal products on a daily basis,

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[104] Lešić et al., 2016.

as well as indirectly through the consumption of animal products such as meat, milk, and eggs, which rely on cereals as a key ingredient in animal feed. The great economic importance of cereals is evident in the large areas on which they are cultivated worldwide, overall global production and their substantial contribution to international trade.

There is a limited amount of research available that specifically addresses the cultivation of most commonly grown field crops, such as cereals, industrial crops, and fodder plants in agrivoltaic systems. The cultivation beneath PV arrays differs from conventional open-field farming. The primary distinctions involve tilling techniques, crop selection, and crop management. Regarding field management and the cultivation of arable crops, it is crucial to adapt the APV systems. It is necessary to adjust the mounting structure of APV arrays to allow passing of conventional agricultural machinery. For example, a minimum clearance of 4-5 metres is required for cereal cultivation due to the use of large combine harvesters[105]. For Agri – PV systems combined with light-sensitive crops, the alignment and spacing between module rows must be designed to optimize light availability and homogeneity, in order to prevent a negative impact on plant growth. Attention must be paid to ensure the PV system does not endanger workers or machinery [106].

7.6.2 RESULT OF PREVIOUS RESEARCH – BENEFITS AND CHALLENGES

Under APV, soil moisture losses are reduced, and air moisture increased [107]. On the other hand, it is well known that the primary effect of APV systems is a reduction in solar radiation which, particularly for shade intolerant crops (such as maize or sunflower), could result in a significant yield reduction. Consequently, in "normal" years with normal precipitation quantities and distribution, yield reductions for the majority of field crops such as wheat and other cereals, maize, and various industrial crops, are highly probable. The APV RESOLA project in Germany revealed that, in common vegetation seasons, yield reductions of up to 20% may be expected for crops such as potatoes, wheat, and other grains (barley, triticale, oats, rye) grown under fixed mounting structures[108].

Despite the scientific consensus that nearly all crops are suitable for cultivation under APV systems, yield reductions are to be anticipated due to shading effects. In contrast to extremely shade-tolerant crops, only a few field forages, such as grass-clover mixture and alfalfa, seem suitable for APV implementation. In very recent research[109] on APV system with mobile panels, alfalfa biomass increased by 10% on average over the course of two years in shade ranging from 29% to 44% compared to full sunlight.

Scarce information exists regarding the effects of APV, namely the shading effect, on the yield and quality of arable crops under actual conditions. Late application (during the flowering stage) of non-uniform shade on winter wheat significantly decreased grain yield[110]. The wheat cultivated under shaded conditions in a Paulownia-wheat intercropping system in China demonstrated a yield reduction by approximately 50 % [111]. In the French agroforestry system, durum wheat yield decreased under all shading intensities, and by nearly 50 % under the most intensive shading conditions (31% light reduction). The great-

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[105] Weselek, 2019.

[106] Solar Power Europe, 2021.

[107] Fraunhofer ISE, 2020.

[108] Fraunhofer ISE, 2022.

[109] Silvain et al., 2023.

[110] Artru et al., 2017.

[111] Li et al., 2008.

est impact of shading was a reduction in the grains number per spike and grains weight[112]. It is reasonable to presume that other small grain cereals would react similarly.

However, it is worth noting that in regions with high levels of irradiance, such as the Mediterranean region, barley and wheat cultivars can benefit from partial shade and increase grain yield by adapting their physiological and morphological traits[113]. The theoretical agrivoltaic potential in Europe for various winter wheat cultivars was evaluated, and it was concluded that the Mediterranean region has the greatest potential for agrivoltaics because the PV effect is greater due to higher insolation, while protection against drought and heat stress limits the grain yield reduction[114]. However, cereal cultivation in the Mediterranean (Adriatic region) of Croatia is not common.

Industrial crops include morphologically and biologically very different plant species. It is believed that plants of lower habitus have agrivoltaic system potential. Most crops tolerate reduced solar radiation up to 15%, showing a less than proportional yield decline, so forages, leafy vegetables, root and tubers crops and C3 plants exhibited less yield loss compared to maize and grain legumes, which showed a significant yield reduction even under shade conditions.[115]

As a C4 plant type with a high demand for heat and light, maize is generally regarded as unsuitable for growing in partial shade, particularly in regions with a temperate climate. So far, the majority of studies on the effects of shading on maize growing under APV or in artificial shade indicate a negative influence on maize performance and yield. In maize, there is a substantial correlation between grain yield and radiance. In an experiment where artificial shade was uniformly applied, grain weight decreased, which decreased maize grain yield[116]. Maize leaves that are exposed to shade exhibit a notable decrease in their photosynthetic efficiency[117].

According to some authors[118], it is challenging to design an APV system that produces the maximum amount of electricity in a temperate climate due to lower solar radiation. They investigated two types of solar modules with varying shading ratios (21.3%, 25.6%, 32%) and concluded that the best APV type, in terms of total profit, for soybean growing is a bifacial module with a shading ratio of 32% and for maize, a bifacial module with a shading ratio of 21.3%. In sunflowers, shading to 20% of incident radiation during floret development, anthesis and grain setting decreased grain number across all shading regimens[119].

In Italy[120], the average grain yield and the number of pods per plant for soybeans decreased by 8% and 13%, respectively, under an APV system.

In southern Russia, there is an example [121] of a PV system with configuration of 3.4 m and 6.4 m spacing between photovoltaic arrays and 4 m height above the sugar beet and lettuce crops, which have demonstrated to be shaded-tolerant and more suitable for implementation in APV systems. It is emphasized that only plants less than 50 cm tall that can tolerate some degree of shade can be taken into consideration for APV systems in the production of field crops. It may be significant

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[112] Dufour et al., 2013.
[113] Arenas-Corraliza et al., 2019.
[114] Willockx et al., 2020.
[115] Laub et al., 2020.
[116] Jia et al., 2011.
[117] Collison et al., 2020.
[118] Kim et al. 2021.
[119] Cantagallo et al., 2004
[120] Potenza et al. 2022.
[121] Kostik et al. 2020.

that the authors concluded that this system requires a substantial investment and that, according to their calculations, these systems will last between 23 and 25 years.

7.6.3 THE CASE STUDIES OF REFERENT PROJECTS

a. MONTICELLI D'ONGINA, EMILIA-ROMAGNA (ITALY)

The agrivoltaic installation is located in Monticelli d'Ongina (Figure 26) in the province of Piacenza (Emilia Romagna). The total land area is 17.11 ha, of which 2.23 ha are equipped with PV modules (13%). The present installation has been operational since August 2021 (the first one was in 2012) and contains 11,535 polycrystalline panels with an estimated annual output of 4,842 MWh. The modules are affixed on poles at a at a height of 4.5 meters on a two-axis full sun tracking system. The agricultural area is used to cultivate soybeans, and an experiment was conducted within the plantation to investigate the effects of 4 different levels of shading. The initial findings indicate an 8% reduction in total yield, which is deemed acceptable given that soybeans are among the crops that suffer the most from shading conditions. This is well below the yield reduction limits indicated by previous research in Germany and South Korea involving agrivoltaic plants.

a. TSE – SOLAR CANOPY DEVELOPMENT (FRANCE)

The project is 3 hectares in size and was installed on agricultural land where soybeans, wheat, rye, barley, and rapeseed are cultivated (Figure 27). The pilot facility features TSE's agricultural canopy and a shaded canopy (2.4

Figure 26 Monticelli d'Ongina

Source: *https://remtec.energy/agrovoltaico*

Figure 27 TSE solar canopy development

Source: Photo, Sun Services USA, 2022.

MW) with rotating solar panels attached to cables 5 meters above the ground. The canopy is supported by a 27-by-12-metre structure with 4 columns. The canopy is compatible with all agricultural machinery, including very large machines such as harvesters, sprayers, and spreaders. This technology is particularly suitable for grain farms growing canola, corn, barley, and vegetable protein, as well as sheep and cattle farms with an average size of 5 to 10 hectares. The canopy is furnished with weather sensors that regulate the movement of trackers that align solar panels along the sun's axis from east to west and in accordance with the weather forecast. In addition, the company employs tracking algorithms via a Supervisory Control and Data Acquisition (SCADA) system to align the PV panels with the prevailing weather conditions. By optimizing this tracking algorithm, TSE hopes to increase production by 10 to 20% compared to a conventional PV system[122]. Construction on the project began in June 2020 and TSE has planned an ambitious 30-year programme to conserve and restore biodiversity through 3 types of measures: de-vegetation of soils, restoration of a mosaic of grasslands, and limitation of invasive plant species[123].

7.6.4 STRUCTURE OF CEREAL, INDUSTRIAL AND FORAGE PLANT PRODUCTION IN CROATIA

Cereals account for over 60% of all arable land area for field crops. Following cereals, approximately 20% are industrial plants and 13% are fodder crops. (Figure 28).

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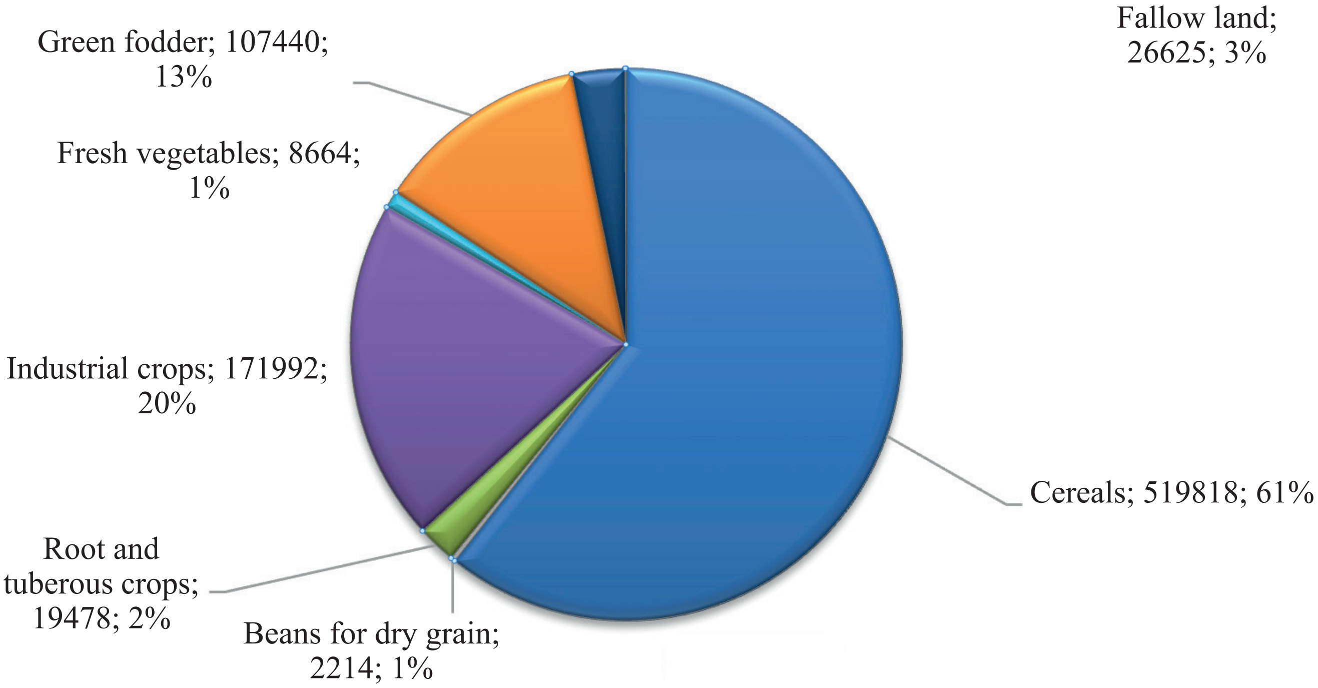
[122] Fresh Plaza, 2022; Sun Services Usa, 2022.

[123] Reglobal, 2021.

Figure 28 Area (ha) and share (%) of main field crops in 2021



Source: CBS, 2022.

The Republic of Croatia, particularly in the east, has very favourable conditions for cereal production as well as a long tradition of growing them. Croatian agricultural production is dominated by cereal, maize, and wheat production. The most common crop is maize (dry grain), followed by winter wheat (spring and durum wheat are grown on a much lower scale), winter and spring barley, oats, triticale, rye, and other cereals such as spelt, buckwheat, sorghum, etc.

Table 15 Used agricultural area of cereals, industrial plants and forage crops

	Cereals (ha)	**Industrial plants (ha)**	**Forage crops (ha)**
2010	584,663	125,209	126,297
2011	575,938	127,343	129,479
2012	611,212	112,048	122,774
2013	513,537	129,757	116,668
2014	490,811	167,140	113,674
2015	490,811	167,140	113,674
2016	529,388	178,974	107,444
2017	461,483	187,826	100,928
2018	459,703	187,033	94,864
2019	490,908	170,492	102,388
Average	**520,845**	**155,296**	**112,819**

Source: CBS, 2022.

Wheat is grown exclusively for the production of flour, which is then used in the production of other food products. Except for wheat and malting barley, other cereals, are largely used in animal feed.

Oilseeds (soybean, sunflower and rape seed, oilseed pumpkin), root crops (sugar beet and root chicory), fibre plants (industrial hemp and flax), potato and tobacco are the most important industrial plants in Croatia. The majority of overall industrial plant

Table 16 Number of agricultural holdings by type of growing crop (2020)

	Republic of Croatia	**Pannonian region**	**Adriatic region**	**City of Zagreb**	**North region**
Total number of agricultural holdings	141,211	56,546	41,987	1,897	40,781
Cereals					
Cereals	84,500	43,238	7,204	1,115	32,943
Common wheat and spelt	30,389	16,025	3,163	325	10,876
Durum wheat	430	130	80	10	210
Rye	380	130	160	10	80
Barley	34,090	16,670	4,240	520	12,660
Oat	16,320	9,360	2,270	240	4,450
Maize for grain	74,552	39,267	2,374	1,044	31,867
Other cereals (triticale, sorghum, millet, buckwheat etc.)	10,650	5,990	1,040	140	3,480
Industrial plants					
Potato	20,035	3,578	9,286	301	6,870
Sugar beet	460	400	-	-	60
Root crops for fodder and cabbages for fodder	3,106	482	1,091	104	1,429
Industrial plants - total	20,629	13,817	1,007	106	5,699
Tobacco	480	470	-	-	10
Oilseed rape	4,040	2,590	10	20	1,420
Sunflower	5,120	4,430	40	z	640
Soybean	9,610	8,510	10	30	1,060
Other oil crops	3,800	550	40	60	3,150
Fodder crops					
Dry legumes and protein crops for grain production -total	3,505	1,130	587	72	1,716
Green fodder crops - total	33,090	14,970	7,300	410	10,410
Other fodder crops in fresh state	870	440	160	z	270
Silage maize	2,170	1,150	70	z	950
Other fodder crops: legumes	18,576	8,425	5,108	209	4,834

Source: CBS, 2022

production is concentrated in continental Croatia.

Fodder crops are grown to produce voluminous fodder (hay, fresh green fodder, silage and haylage) as well as grains (legumes and cereals) for domestic animal feed.

The number of agricultural holdings producing cereals, industrial plants or fodder crops is shown in Table 16. In 2020, the most agricultural holdings produced cereals (84,500), followed by industrial plants (20,629).

7.6.5 CONCLUSIONS AND RECOMMENDATIONS

APV systems can be a good idea for expanding agricultural land area and increasing is usage efficiency. A growing number of research are now being conducted on their design and implementation on arable agricultural land. However, there is still a scarcity of information on the growth and yield responses of the most common arable crops that can be grown in APV systems in temperate climates. According to recent but limited data on arable crop yields in an actual APV system, only alfalfa appears to be suitable. Crop shade tolerance is one of the most important factors determining the economic result of APV. From that point of view, maize and sunflower are arguably the least suited crops for cultivation in an APV system.

When it comes to industrial crops, the APV system has the potential to be employed in potato and sugar beet cultivation, however it is doubtful for rapeseed and soybean.

Overall, there are still many unsolved concerns regarding the synergy of arable crops and PV production on arable land, and many Croatian farmers are unlikely to adopt this approach. As a result, it should be considered to undertake additional field experiments, provide examples of good practice, and organize specific workshops explaining the benefits and drawbacks of agrivoltaics.

The producers are surely sceptical of the rentability of this system because the inputs for its construction and adaptation can be fairly costly.

All things being considered, it would not be recommended to cultivate arable crops on a large scale in an APV system at this point particularly maize and sunflower. Nevertheless, given that some cereals (winter wheat, barley) and industrial crops (soybean, oilseed rape) occupy a significant portion of arable land, it would be prudent to conduct an APV pilot research project, i.e., a field experiment of a smaller scale in crop rotation with different arable crops over a number of years. In addition to the most commonly cultivated cereals and industrial plants, potatoes and alfalfa or clover can be included in crop rotation in such experiments.

7.7 GRASSLAND AND ANIMAL HUSBANDRY

7.7.1 BACKGROUND

The experiences of other countries (Greece, France, Austria) indicate that there are a substantial number of case studies and that the use of APV systems on grassland in conjunction with animal husbandry (primarily sheep) can have a variety of positive effects. This synergy ensures that grass and other plants at their photovoltaic arrays do not interfere with the functioning of the solar panels. This best practice also means less damage to the solar panels and lower operating costs. By keeping vegetation under control, the solar plant serves as a natural firebreak, preventing the spread of a fire, if one were to break out in a neighbouring area. It also reduces the amount of fuel required for mechanical cutting and eliminates the need for chemical herbicides, which can pollute both soil and water resources.

7.7.2 RESULTS OF PREVIOUS RESEARCH – BENEFITS AND CHALLENGES

Armstrong et al. [124] demonstrate that the PV arrays caused seasonal and diurnal air and soil microclimate variations. Specifically, during the summer they observed cooling and drying under the PV arrays compared to the gap and control areas. In contrast, during the winter, gap areas were cooler than the areas beneath the PV arrays and control areas. Moreover, during the summer, the diurnal variation in both temperature and humidity was reduced beneath the PV arrays. Under the PV arrays, microclimate and vegetation management were found to explain differences in the above ground plant biomass and species diversity, with both lower under the PV arrays. Spring and winter photosynthesis and net ecosystem exchange were also lower under the PV arrays, which was explained by microclimate, soil and vegetation metrics.

In comparison to non-shaded conditions, moderate shade increased forage yield for the majority of grasses and legumes, while dense shade had a similar effect for the majority of forages tested. Regarding forage yield [126], grasses are typically more shade-tolerant than legumes.

Separate study revealed that moderate shade had a stimulatory effect on plant mass for a variety of temperate grassland species, with a significant reduction in growth observed only when 90% of natural light was blocked [127].

Integrating livestock grazing into large-scale agrivoltaic system (>1.0 MW) has not been the subject of many studies. It creates substantial knowledge gaps because the regions around the world with the highest potential for PV power generation are typically ones where grazing is prevalent[125].

Grass has been effectively cultivated in agrivoltaic experiments. There were observable differences in mean air temperature, relative humidity, wind speed, wind direction, and soil moisture. Throughout the period of observation, areas containing PV solar panels had higher soil moisture. A significant increase in late season biomass was also observed in areas shaded by PV panels (90% more biomass), as well as a considerable improvement in water efficiency (328% improvement) in areas shaded by PV panels[126].

Water limited areas are most likely to benefit as solar management reduces potential evapotranspiration and consequently water demand. Not all crops will be amenable to solar management, and further research is required to determine the economics of active solar management with PV panels. However, semi-arid pastures with wet winters may be ideal candidates for agrivoltaic systems [127].

Increased temperatures reduce the amount of time cattle spend in zones of thermal comfort, and heat stress, and cows typically experience heat stress above 25°C[128]. Heat stress has been estimated to cost the United States

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[124] Armstrong and al. 2020.

[125] Mamun et al. 2022.

[126] Adeh et al., 2018.

[127] Adeh et al., 2018.

[128] West, 2003.

dairy industry more than $900 million per year in production losses[129]. Sharpe et al.[130] studied the effects of a solar photovoltaic system on grazing cattle in the shade. They discovered no differences in fly prevalence, milk production, fat and protein production, or drinking bouts between cattle with and without shade. Authors concluded that integrating agrivoltaics into pasture dairy systems could reduce the intensity of heats stress in dairy cows, improve the well-being of cows and increase the efficiency of land use.

SUITABILITY OF DOMESTIC ANIMAL SPECIES FOR GRAZING INSIDE PV PLANTS

Vegetation within solar power plants can grow tall enough to shade the panels themselves and interfere with electricity production. Mowing and herbicides can be used to address this issue, but they are extremely costly and potentially harmful to the environment. Sheep grazing provides a cost-free and environmentally favourable solution to this issue. During the hottest portion of the day, the solar panels provide the animals with amply shady areas to rest. Sheep are the most prevalent and most suitable animal species for grazing solar power plants, but other options are conceivable (Figure 29).

Figure 29 Sheep – most common and suitable type of animals for grazing in a PV plant

Source: *https://www.thetimes.co.uk/article/the-times-view-on-sheep-and-solar-farms-may-safely-graze-xcjc05bws*

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[129] St-Pierre et al., 2003.

[130] Sharpe et al, 2021.

Low grass is suitable for grazing, as it does not interfere with the operation of solar panels, and they themselves also short enough not to block sunlight from the majority of solar arrays. On hot, sunny days, they can seek refuge in the shade under the panels. It is unlikely that any infrastructure will be damaged. The eventual occurrence of sheep rubbing up against posts and activating emergency shut down buttons can be prevented with caps, and protective covers. If the sheep become frightened and initiate a stampede, they may damage the solar panels by jumping on them. This can be prevented by elevating the lowest portion of the structure. Sheep are also known to chew exposed wires; therefore, animals should not have access to exposed wires.

For the safety of low-mounted solar panels, goats, cows, horses and pigs are not recommended for grassland maintenance of solar power plants. While sheep have been the most common livestock used in solar pastures, new approaches indicate the possibility of harvesting the sun and providing pasture for grass-fed cattle on the same site. A new Vermont project demonstrates how on-site solar system can be used to preserve agricultural land use. Engineers designed a system with elevated panels, 244 cm above the ground at the lowest point, to allow cattle to pass underneath (Figure 30).

Agrivoltaics integrated into pasture dairy systems may reduce the intensity of heat stress in dairy cows, improve the well-being of cows and increase the efficiency of land use[131].

Figure 30 Cows grazing the grassland under the solar power plant

Source: https://www.buildinggreen.com/news-analysis/two-one-growing-food-and-solar-energy-together

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[131] Sharpe et al., 2021

7.7.3 THE CASE STUDIES OF REFERENT PROJECTS

a. Solar Park in Kozani (Greece)

The 204 MW solar park in the northern Greek town of Kozani was built by Greece's biggest oil refiner Hellenic Petroleum (Figure 31). The solar park configuration consists of 18 solar parks on 437.90 ha with an installed capacity of 204.23 MW that will generate 350 GWh of clean energy per year, equivalent to the consumption of 75,000 households[132]. According to the preliminary design, 559,526 monocrystalline silicon solar panels are installed on stable metallic bases that can sustain up to 54 solar panels (2 rows of 27 panels in vertical layout). Stationary support systems have a 25° gradient. The lower side of the panel is 75 cm above the ground, while the upper side does not exceed 2.5 m in height. The area, where the solar park is installed will primarily be used by a local shepherd who grazes approximately 800 sheep and goats (mostly sheep) and one nomadic shepherd (uses the area between spring and summer) who owns ~ 2,000 sheep[133].

b. Los Naranjos and Las Corchas plants (Spain)

The two photovoltaic plants are located in the vicinity of the Spanish towns of Carmona and La Rinconada (near Seville – Figure 32). They have a combined capacity of 100 MW and generate 202 GWh per year, which is the equivalent to Carmona's annual energy consumption.

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[132] https://www.euronews.com/green/2022/04/07/largest-double-sided-solar-farm-in-europe-opens-in-greece-supplying-power-to-75-000-househ. Accessed, 26 October 2022.

[133] 204,23 MW solar park in Kozani Greece Non-Technical Summary of Environmental and Social Assessment Report. ENVECO SA. Athens, September 2020.

Figure 31. Kozani solar park

Source: https://www.themayor.eu/en/a/view/greece-s-largest-solar-power-plant-on-its-way-to-kozani-6142

Figure 32 Sheep under a photovoltaic structure

Source: *https://www.enelgreenpower.com/our-projects/operating/los-naranjos-and-las-corchas-solar-plants*

Las Corchas and Los Naranjos consist of 258,120 bifacial photovoltaic panels that absorb solar radiation from both sides for optimal use. In addition, for their operation, 14 transformer substations, two electrical substations and 45 kilometres of underground power lines were constructed. In total, 70 million euros have been invested in the plants. The construction of the plants included the installation of a photovoltaic system to cover the energy requirements of the site, the use of tanks to capture rainwater, an efficient and low consumption lighting system, the separation of waste, and the use of an electric vehicle for transportation within the plants.

Sheep that graze beneath the solar panels and bees benefit from the installation in Los Naranjos, which is part of an innovative project that is already producing “solar honey” at the Las Corchas photovoltaic plant.

7.7.4 STRUCTURE OF GRASSLANDS AND ANIMAL HUSBANDRY IN CROATIA

According to the ARCOD database (31.12.2021), the total surface area of meadows in the Republic of Croatia was 101,633 ha,

Table 17 Types of agricultural land use

Meadow		**Pasture**		**Karst pasture**	
Total surface (ha)	Number of parcels	Total surface (ha)	Number of parcels	Total surface (ha)	Number of parcels
101,632.95	242,376	25,313.13	16,479	91,498.52	56,051

Source: ARKOD database as of 12/31/2021, *https://www.apprrr.hr/arkod/*

the total area of pastures was 25,313 ha, and the total area of karst pastures was 91.499 ha (Table 17). Therefore, the total number of grasslands registered in the ARKOD system is 218,444.

There 2.212 individual agricultural holdings larger than 1 ha, representing **22,604.75 ha of grasslands applicable for agrivoltaic application,** and 313 of these are larger than 10 ha (representing 17,391.56 ha of grasslands).

Of that number, there are 1.018 individual agricultural holdings larger than 1 ha, representing 16,394.53 ha of continental and karst pastures, and 217 of them are larger than 10 ha, representing 14,065.47 ha of continental and karst pastures.

7.7.5 CONCLUSIONS AND RECOMMENDATIONS

Grasslands are one of the top three land types with the greatest agrivoltaics potential are grasslands.

In semiarid and arid regions, agrivoltaic systems are anticipated to have the greatest potential Here, grasslands often suffer from the adverse effects of high solar radiation and resulting water losses. Grassland production under solar panels may benefit from increased water savings due to a decrease in in evapotranspiration and adverse effects of excessive radiation, while economic viability is increased, and rural electrification is made feasible.

Agrivoltaics could improve the development of grassland vegetation in response to evident climate change, which is characterized by mor frequent and longer periods of high temperatures followed by drought, due to increased soil moisture and lower temperatures under the panels. At the same time, it should be considered to sow more shade-tolerant plant species of grasses and small-grained legumes.

Water limited areas are most likely to benefit as solar management reduces potential evapotranspiration and consequently water demand. Not all species of grasses and legumes will be amenable to solar management, and additional research is required to determine the economics of active solar management with PV panels.

Warm-season grasses (C_4) exhibit no tolerance for shade, independent of season of growth. In contrast, under 50% shade, cool-season C_3 grasses (Kentucky bluegrass, orchard grass, ryegrass, tall fescue, and timothy) exhibit no significant yield reductions, making the whole thing interesting for Croatian conditions. Orchard grass and smooth bromegrass are the only cool-season grasses with reasonable shade tolerance under the 80% shade treatment (no statistical decrease in yield).

Two cool-season legumes (alfalfa and white clover) and one warm-season legume (striate lespedeza) exhibited substantial shade tolerance, notably during the summer-autumn growing season, as evidenced by no significant reductions in dry weight under 50% shade.

All types of grasslands in the Republic of Croatia would be appropriate for agrivoltaics, particularly karst pastures and continental pastures. **This is notably true for lawns larger than 1 ha, whose capacity is 22,604.75 ha** (including meadows, continental and karst pastures).

The main disadvantages of agrivoltaic energy stem from the shade cast by the panels, as this can affect crop productivity in varying degrees, requiring the selection of more resistant plants, and restricting those that are more reliant on sunlight. This also restricts the optimal latitudes for agrivoltaics, as profitability can suffer in cooler areas where the sunlight intensity levels vary throughout the year.

7.8 FISHPONDS/FLOATING PVS

7.8.1 BACKGROUND

Floating PVs (FPV) is a term coined by combining electricity production and aquaculture. The objective of Floating PVs is the efficient, dual use of water for both food production and energy generation. While solar panels above or on the water's surface generate electricity, aquatic organisms living in the water below provide a sustainable food source. Covering water can reduce water loss by up to 70-85% by preventing evaporation [134]. The floating technology enables the generation of electricity and cultivation of aquaculture species in the same area, thereby substantially increasing overall productivity per unit area in comparison to conventional land use.

These systems are designed to withstand fluctuating water levels; however, they are not commonly designed to operate while resting on the bottom if the body of water is drained[135].

The floating method seeks to maintain parameters such as water and air temperature, light availability, water pH, dissolved oxygen (DO), feeding system, and predator pressure, and to enhance the system by exploiting synergies between the aquaculture and PV systems. Cultivated species have different requirements, confirming the need for variation of essential parameters based on species type and farming systems.

The integration of photovoltaic technology with aquaculture creates synergies as aquatic farming can benefit from module shading effects when temperatures are high, while the proximity of modules to cool water environments increases their efficiency[136]. Floating systems are characterized by a very high energy input, mainly due to their need for artificial oxygen supply. The generation of electricity through the incorporation of floating, elevated, or other types of PV modules provides the opportunity to replace fossil-based energy sources without the need for additional land. To maximize the productivity of aquavoltaic systems, careful consideration must be given to the coverage of PV modules and the mounting of the whole system[137].

Common benefits of these installations were a decrease in water evaporation from the reservoir/pond [138] and a decrease in algal growth (as a result of reduced sunlight penetration within the water body)[139]. Moreover, electrical yields were marginally increased in the majority of reported cases, presumably due to the cooling benefit of the underlying water surface, as illustrated in some studies[140] involving PV panels that was in direct contact with water.

Regarding the environment and other variables, it is possible to install various types of FPV on water surfaces such as irrigation reservoirs (motivated by the rising demand for energy in modern irrigation systems and agriculture). In addition, they may be utilised in fishponds, quarry and natural lakes, wastewater tanks, oceans, etc.

However, little is known about the effects of

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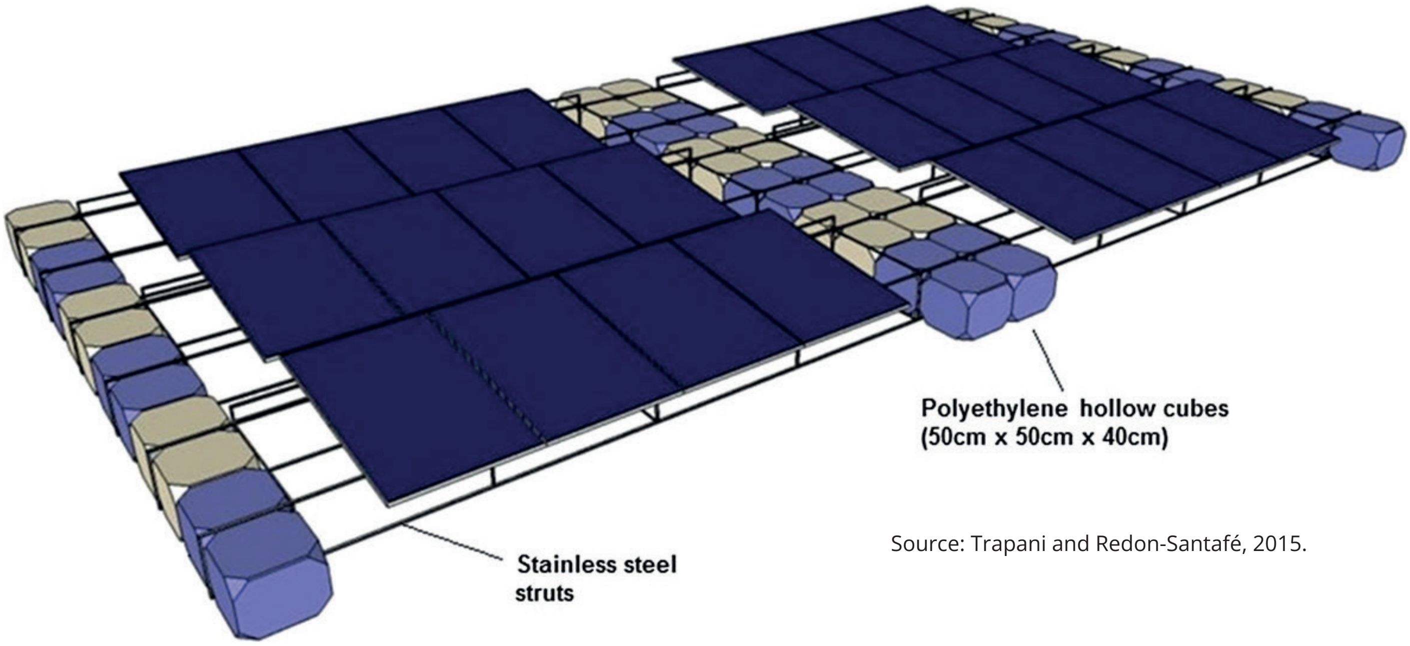
[134] Dayıoğlu & Türker, 2021.
[135] Spencer et al., 2019.
[136] Hermann et al., 2022.
[137] Hermann et al., 2022.
[138] Ferrer-Gisbert et al., 2013; Santafé et al., 2014.
[139] Alam and Ohgaki, 2001.
[140] Bahaidarah et al. 2013.

Figure 33 Schematic design of the floating PV installation in Bubano, Italy



Source: Trapani and Redon-Santafé, 2015.

FPV on the host body of water. Anticipating changes to water body processes, properties, and services as a result of FPV deployment represents a critical knowledge gap that may result in poor societal choices and water body governance [141]

Despite the availability of several commercial surface-mounted designs (Fig. 33), FPV systems typically consist of conventional solar modules mounted on floaters, which provide buoyancy to the whole arrangement while anchored to the bottom of the water body[142] .

7.8.2 RESULT OF PREVIOUS RESEARCH – BENEFITS AND CHALLENGES

Several projects and studies have been conducted out to determine the positive and negative impacts on the ecosystem, as well as the technical and economic viability of dual use under the FPV concept [143] These are the principal results:

COOLING

It is common knowledge that the efficiency of PV modules decreases as the temperature rises. In the floating approach, both water and increased wind velocities can contribute to a cooling. Thanks to the cooling effect, PV output can be increased by approximately 10 to 15% in PV output compared to fixed, ground-mounted solar systems[144]. The cooling effect of water on solar cells, which favours higher energy conversion efficiency, is regarded as one of the main advantages of FPVs [145] The magnitude of this effect is dependent on the orientation and the area of water in contact with the module.

LIGHT

Photosynthesis enables the growth of organic matter, matter, including algae, in sun-exposed waters. These algae are typically undesirable in water reservoirs due to the fact that they can obstruct pumping and filtra-

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[141] Armstrong et al., 2020.
[142] Oliveira-Pinto and Stokkermans, 2020.
[143] Pringle et al. 2017, Fraunhofer, 2021.
[144] Kamuyu et al., 2018.
[145] Skoplaki and Palyvos, 2009.

tion systems and necessitate costly chemical treatment to eradicate. Installing FPVs shades the water and inhibits photosynthesis. This reduces the formation of algal blooms and lowers chemical and operational costs.

Floating systems provide shade on the fishpond's water surface, and solar panels absorb and convert the blocked light into usable energy. An increase in shading, if unchecked, reduces algal growth, general plant life, and microbial density, affecting the entire food chain down to the fish intended for breeding[146].

Normally, fish are either more active in light and less active in darkness, or vice versa [147], but daily variations in factors such as temperature and oxygen can alter this behaviour[148]. There is a correlation between light and the growth of aquatic organisms, but it is not a universal relationship because species vary in their growth conditions. Depending on the species and stage of development, fish and larvae, for example, must be reared in specific light ranges[149].

To influence the photoperiod of aquatic life, light emitting diodes (LEDs) can be installed on the bottom of the pontoon structures in an aquavoltaic system. These LEDs are powered by the PV portion of the system. This design offers acquacultures a powerful tool for increasing and further optimizing production for specific aquatic species[150]. This requires additional testing, and the effects of energy conversion must be considered. Another option is to rotate or move the plant around the body of water in which it is situated. This action would reduce the quantity of natural light shading experienced by a given body of water[151]. A modification to the pontoon structure itself could involve increasing the distance between the modules that make up the facility. This modification would allow a controlled amount of light to penetrate the water below. This method reduces the array's efficiency per unit area due to the reduced density of solar modules, but if space is not a constraint, this is a negligible drawback[152] .

Land use and evaporation

PV systems floating on water do not occupy habitable land and can be deployed in degraded environments and reduce land-use conflicts[153], as can dual-use infrastructure, such as reservoirs, where evaporation can also be reduced [154]. Water conservation is one of the most significant synergistic effects of coupling PV systems with aquaculture. In aquaculture systems with high water discharge rates, preventing water loss is economically and environmentally advantageous. FPVs conserve water by reducing evaporation and improving water security in arid areas, while also being adaptable for use in a variety of water bodies such as fishponds, drinking water reservoirs, etc. FPVs can reduce water evaporation by up to 33% for natural lakes and ponds and by up to 50% for man-made facilities because the system functions as a protective blanket over the water[155]. Some authors noted that FPVs could reduce the loss of water from reservoirs by as much as 70-85%[156]. Especially in the context of climate change, where dry

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[146] McKay, 2013.
[147] Boeuf and Le Bail, 1998.
[148] Meseck et al., 2005; Boeuf and Le Bail, 1998.
[149] Boeuf and Le Bail, 1998.
[150] Pringle et al., 2017.
[151] McKay, 2013.
[152] Tsoutsos et al., 2005.
[153] Sahu et al., 2016; Lee et al., 2020; Pouran et al., 2022.
[154] Farfan and Breyer, 2018; Jäger-Waldau, 2020.
[155] Moradiya, 2019.
[156] Pringle et al., 2017; Dayıoğlu & Türker, 2021.

periods are becoming more frequent, evaporation reduction is a significant accomplishment [157].

MAINTENANCE

When contemplating pollution effects, a further advantage of proximity to water becomes apparent. First, particles are washed off the module surface more frequently. Other sources, such as bird droppings or biofouling, can also contribute to the soiling of PV modules' surfaces[158]. Biofouling is the colonization of PV surfaces by organisms such as algae, which can affect not only the modules but also the mounting systems and cables. According to some of authors [159], the interaction of FPVs with aquatic organisms and the potential for biofouling is one of the greatest unknows. Increased wind speeds and waves, particularly in stormy conditions, would also impose a substantial mechanical load[160]. Stable anchoring is essential to compensate for lateral forces[161], whereas flexible mounting of PV modules provides the benefit of floating with the waves and protecting the system from external forces. Depending on the location, system maintenance may be more challenging because operations must be performed from boats or from the movable pontoons. However, because access is restricted, vandalism and theft are likely to decline[162] Floating systems, on the other hand, do not require thousands of metal frames to be affixed to the ground, which expedites the construction of a panel array. In addition, decommissioning a floating system is much simpler and less expensive.

MATERIAL AVAILABILITY

To limit warming to well below 2°C , the demand for PV materials is likely to increase substantially. However, PV materials are widely available, have potential substitutes, and can be recycled [163]. Silicon, copper, glass, aluminium, and silver are the primary materials for PVs, with silicon being the most expensive and glass being the most important by mass at 70%. None of these materials are regarded as essential or potentially scarce[164].

FPVs are compatible with the existing hydropower and electric infrastructures, which contributes to the diversification and resilience of the energy supply. The lack of supporting policies and development roadmaps by the governments could hinder FPVs' sustainable growth[165]. There is scarce research on socio-environmental impacts of FPV farms. Bax et al.[166] reflected of on three key socio-environmental impacts of FPVs: job creation, non-occupation of habitable land, and the improvement of water security in water-scarce regions.

The inclusion of floating modules will most likely increase the difficulty of tending the aquaculture system, and aquatic life may slow or disrupt maintenance of the PV modules.

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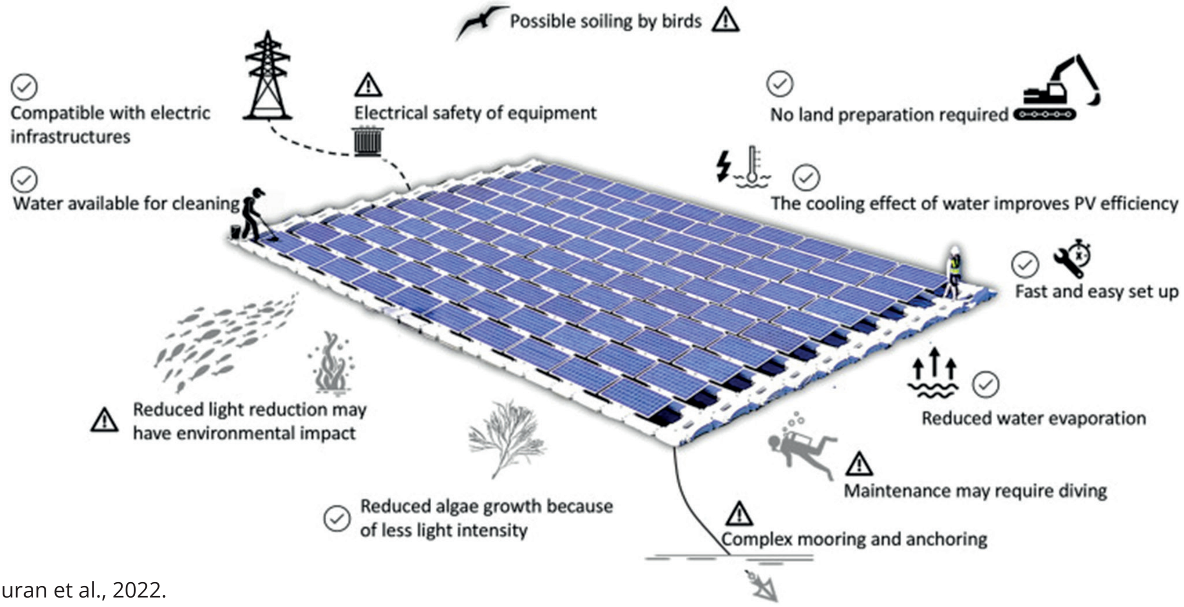
[157] Santafè et al., 2014.
[158] Pringle et al., 2017.
[159] Pringle et al. 2017.
[160] Hermann et al., 2022.
[161] Ferrer-Gisbert et al., 2013.
[162] World Bank Group, 2019.
[163] IPCC, 2022.
[164] IEA, 2020.
[165] Pouran et al., 2022.
[166] Bax et al. 2020.

Figure 34 Benefits and challenges of floating solar panels



Sources: Pouran et al., 2022.

7.8.3 THE CASE STUDIES OF SIMILAR PROJECTS

a. O'MEGA1 PROJECT (FRANCE)

The territory of France abounds in lakes from formed from former quarries as well as water reservoirs used for various purposes (drinking water, irrigation, etc.). Floating solar panels can be used to maximise the utilisation of these sites, whose geographical distribution is relatively homogenous on the national level, and which are frequently neglected or undervalued.

In 2019, Europe's largest floating solar array was installed in an abandoned quarry in Piolenc, southeast France (Figure 35). The 17 MW O'MEGA1 scheme comprises 47,000 solar panels and floating systems and is designed to reduce CO_2 emissions by 1,096 tonnes per year while providing enough electricity for 4,733 households per year.

b. SIERRA BRAVA FPV PLANT (SPAIN)

The installation is located in close proximity to the southern shore of the Sierra Brava reservoir in Zorita (Cáceres), Spain (Figure 36). Designed to span approximately 12,000 m^2, the floating solar plant occupies approximately 0.07 % of the reservoir's surface area. Five adjacent floating systems constitute the installation. Each system consists of 600 photovoltaic panels (3,000 in total) with an estimated total capacity of 1.125 MWp - clean energy equivalent to the consumption of 1.000 households. The Sierra Brava floating PV plant investigates various solar module technologies and configurations with regard to tilt, placement, and orientation, in addition to other parameters and a variety of flotation structures.

The project includes environmental measures such as the installation of signage on the natural resources in the area surrounding the reservoir, the installation of marker buoys to delineate the regulatory navigable areas, and the provision of nesting boxes and floating islands to encourage the nesting of certain bird

Figure 35 O'MEGA1 project – floating PV plant in Piolenc, Franc

Source: https://www.lechodusolaire.fr/wp-content/uploads/2019/10/Akuo-21102019

Figure 36 Sierra Brava floating photovoltaic plant

Source: https://www.acciona.com/projects/results/?solution=Energia&area=Photovoltaic&country=SPAIN&_adin=11551547647

species. Important to the project is environmental monitoring, particularly of the area's birdlife, with the dual purpose of protecting birds and studying their interaction with this type of installation. The project is supported by the Centre for Industrial and Technological Development (CDTI) of Spain.

7.8.4 STRUCTURE OF FRESHWATER (CYPRINID) AQUACULTURE IN CROATIA

In Croatia, cyprinid species are traditionally farmed in carp ponds that are typically several hundred hectares in size, with five carp ponds exceeding 1,000 ha in size. The total area of carp ponds in Croatia (Table 18) is currently 14,081.49 ha, while the production area in 2021 was 12,539 ha (Ministry of Agriculture - NADP, 2022, preliminary data).

The majority of carp ponds are situated along larger river basins in the lowlands and the continental region of the Republic of Croatia. Cultivation of cyprinids primarily entails the controlled rearing of carp (*Cyprinus carpio*) in monoculture or polyculture with other species, the most common of which are Grass carp (*Ctenopharyngodon idella*), Gray carp (*Hypophthalmichthys nobilis*), white carp (*Hypophthalmichthys molitrix*), catfish (*Silurus glanis*), perch (*Sander lucioperca*), pike (*Esox lucius*) and tench (*Tinca tinca*). The production is mostly semi-intensive, where, in addition to the natural food produced in the pond by biological processes and whose production is stimulated by agrotechnical measures (fertilization, etc.), the fish are additionally fed, typically cereals (corn, wheat, rye, barley). In carp aquaculture, the production cycle usually lasts three years. (Ministry of Agriculture, NADP, 2022, preliminary data).

According to some authors,[167] the analysis of spatial capacities and conditions for the use of the potential of renewable energy sourc-

Table 18 Register of aquaculture permits for inland waters (warmwater species only)

County	**Area**	**ha/m²**
Bjelovar-Bilogora	3,267.0347	ha
City of Zagreb *	1,273.6876	ha
Požega-Slavonia / Bjelovar-Bilogora	1,274.6526	ha
Osijek-Baranja	2,920.3078	ha
Karlovac	391.7749	ha
Virovitica-Podravina	981.224	ha
Sisak-Moslavina	742.1451	ha
Brod-Posavina	3,069.9547	ha
Zagreb / Bjelovar-Bilogora	117.9892	ha
Varaždin	4.72	ha
Međimurje	5.7454	ha
Požega-Slavonia	0.4385	ha

*Permit for cold and warmwater aquaculture

Source: Ministry of Agriculture, 2022.

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[167] Tomšić et al. 2020.

Table 19 Freshwater aquaculture production in Croatia (t)

Species	2017	2018	2019	2020	2021
Common carp	2,039	1,959	2,037	1,691	2,738
Grass carp	169	141	122	133	266
Silver carp	73	36	141	161	212
Big-head carp	477	301	344	326	414
Catfish	31	23	20	32	32
Sander	9	7	7	6	4
Pike	12	7	9	2	3
Rainbow trout	395	336	364.5	379	335.6
Brown trout		34	7.5	12.4	15
Other	67	55	48	37	22
TOTAL (t)	**3,272**	**2,899**	**3,100**	**2,779**	**4,040**

Source: (2017-2021) (Ministry of Agriculture, 2022).

es in the Republic of Croatia, as well as the considered criteria considered for determining the vulnerability of an area to the energy potential of the sun, the development of the possibility of establishing hybrid photovoltaic systems, and aquaculture are encouraged. Mainly because of their symbiotic relationships, which include increasing the efficiency of energy conversion by cooling and cleaning the surfaces of the PV modules, reducing the evaporation rate of the water surface, enhancing the growth rate of fish through integrated designs with PV-powered pumps to regulate oxygen levels, etc.[168]

Carp ponds in Croatia are located in the continental part of the country, where the climate is predominantly continental. Continental Croatia has a temperate continental climate and is in a circulation zone of mid-latitudes where atmospheric conditions are highly variable throughout the whole year. They are characterized by a diversity of weather situations with frequent and intense exchanges during the year. These are caused by moving systems of low or high air pressure, often resembling vortices with a diameter of hundreds and thousands of kilometres. The climate of continental Croatia is modified by the maritime influence of the Mediterranean, which is stronger south of the Sava River than it is in the north and diminishes eastward.

7.8.5 CONCLUSIONS AND RECOMMENDATIONS

The promise of FPV technology lies in its flexibility and adaptability to different water bodies[169]. FPV is most sustainable when combined with multiple species, such as fish, crustaceans, molluscs, and seaweed cultures. This system is a new concept that combines two areas that needs significant research. The combination between aquaculture and production of energy creates powerful synergies in terms of water conservation, more direct control of the aquatic environment in relation to photoperiod, and the possibility of ecosystem restoration.

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[168] Pringle, et al., 2017.

[169] World Bank Group et al., 2018.

In the Republic of Croatia, floating photovoltaic plants cannot be planned in areas with a high likelihood of flooding in order to safeguard naturally flooded areas and prevent the interruption of flood flows that could negatively affect other areas.

It is required, when planning a facility in the ecological network NATURA 2000, to identify, at the level of a strategic assessment, the impact of the spatial plan on the environment, the cumulative impacts with existing facilities and spatial uses, as well as possible conflicts, and to include in the assessment the connecting infrastructure, as well as all other elements and works pertinent to the functioning of the facility.

To avoid increasing land use, floating PVs offer a solution in the form of dual use of land. The concept of aquavoltaics offers many synergies, especially in countries with extended periods of drought. The significant decrease in water loss due to lower evaporation rates is particularly intriguing. Aquavoltaics can contribute to sustainable water use and fulfil the concept of the food-water-energy nexus with an appropriate system approach.

Integration of PV modules into water surfaces has been shown to be technically feasible, but robust studies on fish farming are still lacking. More research is needed to understand the effects of direct contact with pontoon structures and solar arrays on aquatic life.

Currently, the total area of carp ponds in Croatia is 14,081.49 ha, whereas the production area in 2021 was 12,539 ha (MA - NADP, 2022, preliminary data).

Due to numerous variables, it is challenging to estimate how much surface area will be actually available for the installation of floating solar panels based on this value. This is mainly due to the undefined extent and intensity of vegetation (sedges, woody vegetation, and copses) in certain parts of the registered water area and the classification of production intensity (RAS systems, rearing cages, etc.), including restrictions imposed by the ecological network EU-Natura 2000 regulations. Large carp farms are situated in the continental part of the Republic of Croatia, primarily in the vicinity of major river courses and are thus essential for the conservation of biodiversity.

8. ESTIMATED INVESTMENT POTENTIALS IN AGRI – PVS IN CROATIA

8.1 GENERAL CONSIDERATIONS

Green investments[170], such as Agri – PV investments, are intended to contribute to the expansion of renewable energy sources, create financially sustainable models that provide additional income streams for farmers or landowners through the sale of agricultural products and renewable energy, and enhance the resilience of agricultural systems to climate change. In general, their role is to transition economies that rely primarily on fossil fuels and non-renewable energy sources with significant greenhouse gas (GHG) emissions into more climate-neutral economies. Aligning investments in green energy with policy objectives presents both opportunities and challenges for governments. By transitioning towards investments in sustainable energy, economies can reduce their carbon footprint and embrace cleaner energy sources. Nonetheless, this transition requires careful planning and coordination to effectively address the associated challenges.

In reality, there is a limited number of comprehensive research studies that examine the economic, social, and environmental effects of green investments. However, a recent comprehensive study has been published recently using the MAGNET CGE[171] model that takes into consideration the mentioned impacts at the EU level has been published. The study provides insights into the impact of green investments on GDP across Member States, the cumulative impact of green energy investments on GDP growth, particularly in bioeconomy sectors, total emissions, the efficiency of emission savings in dollars per tonne, and the impacts on food and energy security, as well as wages up to 2050[172].

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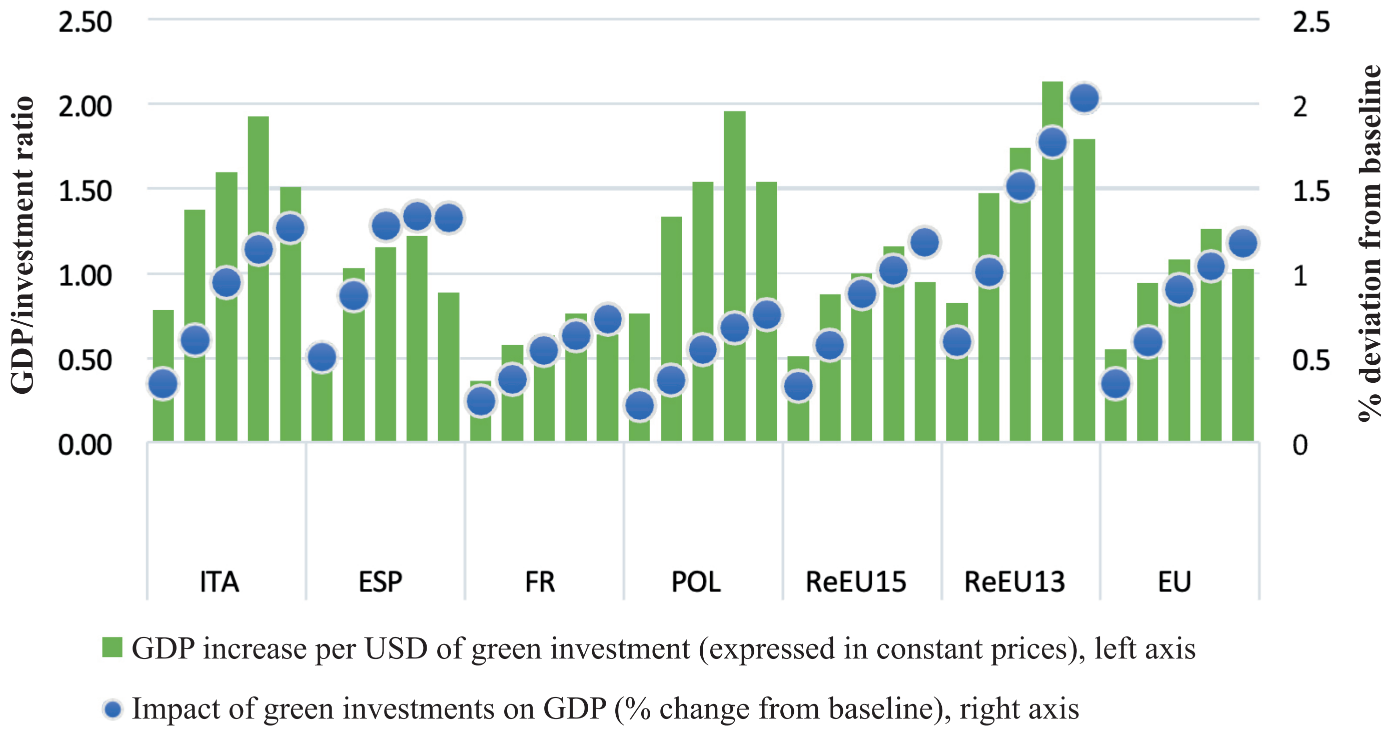
[170] Eyraud et al. 2013.

[171] Modular Applied General Equilibrium Tool.

[172] Křístková et al. 2023.

Figure 37 Impact of green energy investments on GDP



Source: MAGNET model results according to Křístková et al. 2023.

The assessment of the macroeconomic effects of additional investments in green energy (Figure 37) includes the evaluation of their impact on the GDP growth rate, expressed as a percentage deviation from the baseline (represented by the blue dot), as well as the GDP gains per dollar invested in green energy (illustrated by the green bar).

The simulation results indicate that green energy investments have a positive impact on GDP (right axis), albeit with significant variation among EU Member States. The model results reveal the highest impacts in Italy, Spain, and the remaining EU countries (EU 13 countries, including Croatia), with a projected increase in GDP of over 1.2% by 2050.

8.2 ASSUMPTIONS FOR CAPEX ESTIMATE

Considering the analysis provided in the preceding chapter, it is possible to conclude that agrivoltaics can provide benefits for various types of agriculture, but the extent and nature of these benefits depend on the specific agricultural practices and local conditions. From both an economic and physiological perspective, certain types of agriculture are more suitable for agrivoltaic integration compared to others.

Therefore, according to conclusions provided in the preceding chapter, the types of agricultural crops in Croatia where the use of agrivoltaics is generally considered beneficial are **viticulture, fruit growing, aromatic and medicinal plants, grasslands and fishponds**, while for vegetable, cereals, industrial and forage plants production, it is concluded that for various reasons it is too early to consider them suitable for application of Agri – PV projects, and that only smaller, research-based projects can be initiated for these type of crops.

In addition to this preliminary analysis of each crop's suitability for APV application, it is crucial to consider the associated capital expenditures (CAPEX) for each application, as well as the decreased production capacity resulting from the reduced spacing between modules and/or panels. Without a detailed analysis of individual projects, it is difficult to determine the precise variation in CAPEX for each specific agrivoltaic application type. However, based on general considerations, it is possible to estimate the relative variation in CAPEX for each type. The decrease in potential capacity (MWp) for each agrivoltaic application relative to non-integrated solar power plants can vary substantially based on factors such as solar panel arrangement, land use constraints, shading, and solar panel efficiency. Initial estimates place the installed capacity of the solar power plant in Croatia at 1 MWp/ha, while the estimated cost of developing such a system is 1 million €. With this information and the available surface area for individual agricultural productions in mind, the potential changes in CAPEX, installed capacity, and total potential investments are described below.

Following are some general considerations regarding the available surfaces for APV installation and the anticipated increase in CAPEX.

1. Viticulture: There are **12,026.00 ha of vineyards larger than 1 hectare** that are suitable for agrivoltaics. As vineyards typically have an open structure that permits the installation of solar panels between the rows of grapevines with minimal modifications, the increase in CAPEX

may be moderate. Incorporating agrivoltaics into large vineyards allows for the installation of solar modules and their supports on the existing pole structure, thereby reducing the quantity of material required. The percentage increase might range between 10 and 20%. In this case, the spacing between the rows of grapevines, which restricts the solar panel installation area, may reduce capacity by 10-30%. Additionally, ensuring adequate sunlight exposure for the vines may minimise solar panel density.

1. Fruit growing: There are **21,285.87 ha of orchards larger than 1 ha** that are suitable for agrivoltaics. Due to the need for more specialised mounting structures that are frequently higher off the ground and a potentially lower solar panel density, the increase in CAPEX required for orchards may be greater than for vineyards. The percentage increase could range from 15% to 30%. For fruit production orchards, a decrease in potential capacity of 20% to 40% arises from the need for specialised mounting structures and the potential reduction in solar panel density due to shading concerns and maintaining optimal sunlight exposure for the trees.

2. Aromatic and medical plants: There are a total **of 6,086 ha of the 3 most common types of aromatic and medical plantations in Croatia** (chamomile, immortelle, and lavender) that can be considered suitable for agrivoltaic application. Depending on plant species, growth requirements, and agrivoltaic design, the increase in CAPEX for agrivoltaic systems for aromatic and medicinal plants may be moderate. Some aromatic and medicinal plants may be tolerant of partial shading, allowing the incorporation of solar panels with minimal alterations to the existing cultivation system. However, for plants that require full sunlight, solar panels may need to be installed on elevated or specialised structures to minimise shading while maintaining optimal light conditions for healthy plant growth. The percentage increase in CAPEX for aromatic and medicinal plant agrivoltaic systems might range between 10% and 25%. The capacity decrease of 15% to 35% in aromatic and medical plant cultivation arises from the varying light requirements of various plant species, which may necessitate specialised solar panel arrangements or structures to maintain optimal growing conditions.

3. Grasslands: There are **22,604.75 ha of grasslands** larger than 1 ha (including 16,394.53 ha of continental and karst pastures larger than 1 ha). As solar panels can be mounted on elevated structures, allowing for continued grazing and minimal interference with the existing land use, the increase in CAPEX for agrivoltaic systems in pasture may be relatively modest. The percentage increase may range between 5% and 15%. Grasslands and pastures may experience a decrease in potential capacity of 5% to 20% as a result of the need to elevate solar panels to allow for continued grazing and minimal interference with existing land use and potentially reducing panel density. Vertical solar panels may also require less complex mounting structures compared to conventional solar panel installations. Considering these factors, the increase in CAPEX for pastures with vertical solar panels might range from 0 to 10%. This design minimises the 0-10% decrease in potential capacity because it reduces shading on the pasture and facilitates integration with the existing land use while maintaining a more uniform panel density.

4. Fishponds: As stated previously, there are a total of **12,539.00 ha of available inland water areas used for freshwater fish production**. As solar panels must be installed on floating or elevated structures above the water, fishponds may experience a greater increase in CAPEX than other categories. Floating structures can be more cost-effective in certain circumstances due to lower material and installation costs, but other factors such as anchoring, maintenance, and durability must also be considered. In general, floating solar power plants require additional engineering and materials, leading to a potential increase of 10-40%. The 20% decrease in potential capacity for aquaculture systems is a result of the need to install solar panels on floating or elevated structures above the water, which can limit panel density and increase shading concerns while ensuring minimal interference with the aquatic environment. However, if the floating solar power plant is constructed in a manner comparable to a solar power plant on land and spatial inefficiency is avoided, the water-cooling effect can increase the potential production capacity by up to 15%..

8.3 ESTIMATE OF INVESTMENT POTENTIALS IN AGRI – PV PROJECTS

For the purpose of calculating the investment potential in agrivoltaic projects in Croatia, the starting assumption is that all land plots larger than 1 ha will be, in principle, available for APV application for various types of crops identified as potentially suitable for the implementation of agrivoltaic projects.

What will be practically achievable in the next 5 to 10 years will depend on a variety of factors such as the specifics of each crop, geographical and biological limitations in terms of the level of radiation and shading, type of terrain, average farm size, legal requirements[173], environmental constraints, the availability grid connection capacity, the feasibility of each project in terms of expected capital costs, the support of landowners/lessees for APV application, etc.

Due to a large number of unknown factors, it is extremely difficult to make precise and realistic estimates of the possible APV investments. Therefore, for the purposes of this paragraph, only very provisional calculations are provided. These calculations determine what capacities could be installed (and CAPEX invested) if the level of APV application to all available surfaces larger than 1 ha for all suitable crops falls within the range of 1% to 5%, additionally diversified for three possible types of PV modules used (Table 20). This does not imply that these figures will be achieved in practice, or if they are, that they will be distributed equally across all types of crops (it is possible that the level of investments for some types of crops will exceed 5%, while for others there will be no investments at all).

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[173] For example, according to existing legislation, the Agri – PV projects can currently only be implemented for perennial type of crops that are registered in ARKOD.

Table 20 Energy production and investment potentials for agrivoltaics on 1% of available land plots larger than 1 ha

Type of crops	Total available land (ha)	Fixed mount		Bifacial		Tracking	
		Installed capacity (MWp)	Estimated investment (millions of EUR)	Installed capacity (MWp)	Estimated investment (millions of EUR)	Installed capacity (MWp)	Estimated investment (millions of EUR)
1 % of available land							
Viticulture	12,026.00	84.18 - 108.23	92.6 - 129.88	96.81- 124.47	106.49 – 149.36	109.44 – 140.70	120.38 – 168.85
Fruit growing	25,654.13	153.92 - 205.23	177.01 – 266.80	177.01 – 236.02	203.56 – 306.82	200.10 – 266.80	230.12 – 346.84
Aromatic and medical plants	6,086.00	45.64 - 54.77	50.21 - 71.21	52.05 – 62.99	57.74 – 81.89	59.34 - 71.21	65.27 – 92.57
Grasslands	22,604.75	180.84 – 214.75	180.84 - 246.96	207.96 – 246.96	207.96 – 284.00	235.09 – 279.17	235.09 – 321.04
Fishponds	12,539.00	100.31 – 144.20	110.34 - 201.88	115.36 – 165.83	126.89 – 232.16	187.46 – 130.41	143.45 – 262.44
TOTAL	78,909.88	564.89 – 727.18	611.00 – 916.73	649.19 – 836.27	702.64 – 1,054.23	791.43 – 888.29	794.31 – 1,191.74
5 % of available land							
Viticulture	12,026.00	420.91 – 541.17	463.00 – 649.40	484.05 – 622.35	532.45 – 746.81	547.18 – 703.52	601.90 – 844.22
Fruit growing	25,654.13	769.62 – 1,026.17	885.27 – 1,334.01	885.07 – 1,180.09	1,017.83 – 1,534.12	1,000.51 – 1,334.01	1,150.89 – 1,734.22
Aromatic and medical plants	6,086.00	228.23 – 273.87	251.05 – 356.03	262.46 – 314.95	288.70 – 409.44	296.69 – 356.03	326.36 – 462.84
Grasslands	22,604.75	904.19 – 1,073.73	904.19 – 1,234.78	1,039.82 – 1,234.78	1,039.75 – 1,420.00	1,175.45 – 1,395.84	1,175.45 – 1,605.22
Fishponds	12,539.00	501.56 – 720.99	551.72 – 1,009.39	576.79 – 829.14	634.47 – 1,160.80	652.03 – 937.29	717.23 – 1,312.21
TOTAL	78,909.88	2,824.51 – 3,635.93	3,055.23 – 4,583.61	3,248.19 – 4,181.31	3,513.20 – 5,271.17	3,671.86 – 4,726.69	3,971.83 – 5,958.71

Table 20 presents data on the prospective energy production and associated financial investments that can be garnered from the establishment of agrivoltaic systems. The computations herein are predicated on the average surface productivity in Croatia, which is approximately 1 MWp per hectare (fixed-mount, south orientation). This value served as the basis for subsequent calculations. As previously stated, the total capacity was determined by multiplying the total available area, the portion used for agrivoltaics, and the decrease in efficiency. The value of 1 million euros per 1MWp is used as a rough estimate of total potential investments. This price, cognizant of the projected price increase as earlier mentioned, was amplified by a certain percentage and employed in conjunction with the potential capacity. In addition, conversions for bifacial (1.15 MWp/ha) and tracking (1.30MWp/ha) modules were provided. According to this methodology, up to 900 MWp of solar power capacity could be deployed if 1% of the available land was utilised for APV installation. Similarly, if this percentage is increased to 5%, up to 4,700 MWp of solar power capacity can be installed.

As stated previously, the level of actual investments over the next 5 to 10 years will depend on all previously mentioned factors, particularly those regarding the limitations arising from the current level of available electricity distribution and transmission grid network.

9. CONCLUDING REMARKS AND RECOMMENDATIONS

The frequency and intensity of extreme weather events (extreme rainfalls, floods and flash floods, erosions, storms, drought, heat waves, and fires) are affected by climate change, which causes gradual environmental shifts (rising air, soil, and water surface temperatures, rising sea levels, acidification of the sea and expansion of dry areas).

The agricultural sector is especially susceptible to the pervasive effects of climate change. The expected repercussions in the agricultural sector include changes to the growing seasons of arable crops, lower yields from all types of crops and an increased reliance on water. The air temperature on a global scale, including Croatia, increased during the last decades of the 20th century and is intensifying in the 21st century, according to climatological data.

Agrivoltaics (APV) could be a promising solution to increase energy production and agricultural productivity without increasing land use. A large number of studies have demonstrated that it is possible to integrate photovoltaic systems with agricultural production, allowing for PV development on a larger scale while safeguarding agricultural crops and preserving yields. Numerous studies indicate that it is possible to increase crop yields under PV systems due to the fact that agrivoltaic systems create a modified microclimate beneath modules by modifying air temperature, relative humidity, wind speed, wind direction, and soil moisture. Agrivoltaic systems protect crops from both excess solar energy and stormy weather, such as hail, and enable more efficient use of water, which may contribute to a reduction water consumption.

In general, agrivoltaics refers to dual and synergistic use of agricultural land in which the cultivation and maintenance of agricultural production must be the main and primary activity and the installation of photovoltaics “serves” the agricultural production by shielding it from unfavourable growing conditions such as excessive sunlight, high temperature, and severe droughts (water shortage).

Agrivoltaics as an innovative concept has been recently accepted in many parts of the world. At the EU level, the EU Solar Energy Strategy has been adopted, which foresees agrivoltaic projects as an innovative model of combined use of agricultural land in which PV systems can contribute to crop protection and yield stabilization, while agriculture remains the primary use of the land area. As this Study also examines, the same concept has been adopted on the markets of various EU countries, where various types of agrivoltaic projects (research-type pilot projects/commercial type projects) have already been initiated for various types of crops. The growth of the agrivoltaic market has been accompanied by the development of various technical solutions that facilitate the application of APVs to different type of crops. As France, Italy, and Germany have demonstrated, some of these countries are establishing advanced legal and institutional frameworks that would regulate more precisely the conditions for further application of agrivoltaics in those countries.

In terms of the situation in Croatia, recent legislative developments have laid relatively solid legal foundations for the preparation of first agrivoltaic (pilot) projects. According to the current legislation, it would be possible to initiate the agrivoltaic projects on agricultural land if that land is planted with perennial agricultural crops and if such plantations are registered in ARKOD. If all other conditions are met, it will also be possible to obtain energy approval for such projects, which is the key document for pursuing all other steps in a typical development process. During the initial phase of the market opening, it is anticipated that the “Land Lease” model will be the prevalent one, primarily in relation to privately owned agricultural land. This is due to the restriction imposed on lessees of state-owned land, prohibiting them from subleasing that land to third parties.

Nonetheless, the agrivoltaic market would need to be further regulated in a more systematic and comprehensive manner, encompassing many issues unique to Agri-PV projects. It will be also necessary to address some other challenges to the successful implementation of APVs, such as appropriate communication with and support from various stakeholders, especially farmers and their associations.

The Study conducted a thorough analysis to determine the most suitable crops for the implementation of agrivoltaic projects in Croatia. The findings indicate that viticulture, fruit growing, aromatic and medical plants, grasslands, and fishponds are the most suitable crops for such projects. However, it is concluded that it is still premature to consider vegetable, cereal, industrial and forage plants production as suitable for agrivoltaic projects due to various reasons. In these cases, only small-scale, research-type projects may be initiated, primarily focusing on the crops identified by the Study as potentially suitable for agrivoltaic application.

For the purpose of calculating the investment potential of the prospective agrivoltaic market in the next 5 to 10 years, the starting assumption is that all land plots larger than 1 ha will be, in principle, available for APV application for various types of crops identified as potentially suitable for the implementation of agrivoltaic projects. According to very general and very illustrative calculations made by this Study, based on available data of available land larger than 1 ha for all suitable crops, it is assumed that up to 900 MWp of solar power capacity could be installed if 1% of the available land was utilised for APV installation. Similarly, increasing this percentage to 5% would allow the installation up to 4.700 MWp of solar power capacity.

What will be practically achievable will depend on a variety of factors such as the specifics of each crop, geographical and biological limitations in terms of the level of radiation and shading, type of terrain, average farm size, environmental constraints, the current available grid connection capacity, the feasibility of each project in terms of expected capital costs, the support of landowners/lessees for APV application etc.

In conclusion, taking into consideration all the aforementioned data, the recommendations for the development of the agrivoltaic market in Croatia are as follows:

1. Croatia should include agrivoltaics in the existing strategic documents pertaining to either the development of agricultural sector in Croatia (Agriculture Strategy) or the production of energy from renewable energy sources in Croatia (Strategy of Energy Development of the Republic of Croatia until 2030 with a view to 2050) in order to encourage the implementation of agrivoltaic projects by highlighting the potential positive effects for both agricultural production and production of energy from renewable resources.

2. Although the existing fragmented legal and institutional framework in principle allows

for the application of first agrivoltaic projects, the agrivoltaic market would need to be further regulated in a more systematic and detailed manner covering topics such as the binding legal definition of agrivoltaics, possible limitations of acceptable area covered by PV panels / allowed level of yield reductions, institutional and administrative requirements for approval of such projects and their monitoring, in order to ensure the continuation of agricultural production after the installation of APVs.

3. As previously mentioned in the current legislative framework, the first agrivoltaic pilot projects will involve perennials, including grapevines, olives, American blueberries, blue honeysuckle, raspberries, hardy kiwi, apricot, sweet cherries, and sour cherries. It is anticipated that grapevine aromatic varieties will have a more favourable response to decreased temperature and UV radiation, hence aiding in the preservation of their varietal aromas. Depending on the varieties, apple, pear, blackberry, kiwi, peach, nectarine, quince, and strawberry are recommended for Agri-PV. PV panels above the orchard will benefit yellow and green apple varieties such as 'Golden Delicious' and 'Granny Smith' by preventing their colour change to red. Fishponds, grasslands and aromatic plants (chamomile, immortelle, lavender) may also be deemed suitable for the implementation of first APV projects.

4. Since agrivoltaic projects should be viewed as an agrotechnical measure of partial shading, it would be necessary to ensure that all precautions have been taken to prevent negative effects on soil and plants (land loss, light availability, water availability, erosion, yield etc.). Agrivoltaic systems should be equipped with a monitoring system that measures soil performance and microclimatic conditions beneath the panels, as well as the effect of these conditions on agricultural crops and the surrounding environment. Monitoring agricultural productivity in APV systems is crucial for overcoming potential technical challenges in agricultural production. APV projects should be monitored for up to five years after installation. Developing standards and best practices for agrivoltaic projects can therefore aid in ensuring their safety and efficiency. This may involve establishing design, construction, and operation guidelines for agrivoltaic systems.

5. The communication strategy should be designed to provide all stakeholders, particularly farmers and agricultural producers, with objective information regarding the potential benefits and limitations that the implementation of agrivoltaics may have for them. Encouraging collaboration between the energy and agricultural sectors may contribute to the promotion of APV deployment.

6. State institutions and the scientific community should promote the scientific research of agrivoltaic projects by establishing pertinent funding programmes and facilitating collaboration among researchers, as well as fostering worldwide cooperation.

7. The establishment of incentive programmes through grants and/or feed in tariffs could be considered in order to provide farmers and communities with specific financial and technical support for the development of smaller agrivoltaic projects.

8. Providing producers and other stakeholders with technical assistance and training can contribute to the successful implemen-

tation and operation of APVs. This may include training on installation, maintenance, and monitoring for agrivoltaic projects.

9. Educating the general public on the advantages of APVs, organizing public events and displays, and showcasing examples of successful projects can contribute to the cultivation of public awareness and endorsement for APVs.

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