Ref. Ares(2025)207355 - 12/01/2025

Definitions and KPIs for agri-PV plants

Funded by
the European Union

Symbiosyst

Horizon Europe EU project
Grant Agreement No. 101096352

Document control sheet

Project	**SYMBIOSYST – Create a Symbiosis where PV and agriculture can have a mutually beneficial relationship**
Topic identifier	HORIZON-CL5-2022-D3-01-06
Grant Agreement N°	101096352
Coordinator	ACCADEMIA EUROPEA DI BOLZANO (EURAC)
Duration	01/01/2023 – 31/12/2026
Work package N°	WP5
Work package title	Demonstration of novel agri-PV solutions
Work package leader	EF SOLARE ITALIA
Task n°	7.3
Task leader	EF SOLARE ITALIA
Document title	LCOE & LCA – First Analysis & Plan
Lead Beneficiary	EF SOLARE ITALIA
Dissemination level	PUBLIC
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Issue date	10/01/2025

History of versions

Version	Date	Author - Beneficiary	Comments
V1.0	15.12.2024	Angelo Pignatelli – EF Solare Italia	First Draft
V1.1	23.12.2024	David Moser - Eurac	Revision and editing
V2.0	10.01.2025	David Moser – Eurac	Final draft and review

Acknowledgements

The work described in this publication has received funding from the European Union Horizon Europe research and innovation programme under grant agreement Nº 101096352.

Disclaimer

Executive Summary

The SYMBIOSYST project, supported by the EC Horizon Europe Programme, aims to bridge the gap between solar energy production and agriculture by developing tailored photovoltaic (PV) solutions for both greenhouse and open-field agriculture across diverse climatic conditions in three nations. The initiative includes the creation of several agri-PV demonstrators, encompassing scenarios from vegetable farming to fruit cultivation with traditional and other training systems under adjustable tracking systems or into greenhouses with roof partially covered by PV modules. In particular the agri-PV demonstrators are:

- Bolzano (Italy) demonstrator is an open apple orchard combined with a PV tracking system that partially cover the apple trees
- Barcelona (Spain) demonstrator is an open cultivation of short-stature and trellised seasonal vegetables such as tomatoes, onions, lettuce, and fava beans.
- Schipluiden (Netherlands) demonstrator is a greenhouse in which tomatoes are cultivated.
- Scalea (Italy) demonstrator is an open citrus fruit production, with existing PV systems (this is also a demo driver).

This deliverable deals with the technical/economical design of agri-PV plants where specific criteria for the evaluation of LCA and LCOE indexes are developed for the specific agri-PV scenarios under study.

Table of Contents

1. INTRODUCTION

1.1. DESCRIPTION OF THE DELIVERABLE CONTENTS

SYMBIOSYST covers both open and closed agri-PV. The focus of the project is on specific archetypes depending on the level of integration.

For open agri-PV, solutions are developed to bring an increase in PV-crop synergies and optimise yield with a targeted electricity production. The selected demo sites are designed to demonstrate the difference between working on new (where the design of PV and crops can be fully integrated together with auxiliary systems such as irrigation, water catchment, crop protection, etc) or existing crops (where compromises and adaptation will be needed).

For closed agri-PV, similarly, solutions are studied to be fully integrated in new greenhouses (the greenhouses structure can be modified to accommodate standard size PV modules) or adapted for existing greenhouses. For the latter, the aim is to drive the development towards nearly zero energy greenhouses.

In SYMBIOSYST, the envisioned analysed scenarios for demonstration are:

Open agri-PV Scenario, for:

Production of vegetables or horticultural crops characterized by a limited vertical development. The height of the tracking system in horizontal configuration needs to consider optimised crop yield, prevent human injury, and ensure free movement of semi-automatic agricultural devices. The ideal height is 3.5 m for tall herbaceous crops (e.g., trellised tomatoes) and tall equipment. A lower height of 2-2.5 m will allow for low herbaceous crops (e.g., lettuce, beans, etc.) and low height equipment. The minimum height of 2.1 m is typically required in emerging national and international standards for the agri-PV field to be classified as "Innovative Agri-Photovoltaic".

Production of fruit trees (apples, pears, citrons, lemons, ...) in a "Classic" configuration: tree growth in a 3D configuration, maximum height < 4 m, inter-row spacing of about 3.00 - 3.50 m.

Apple production according to a different training system: tree growth in a 2D configuration, maximum height < 3.5 m, inter-row spacing < 2.5 m. This system is also of interest for grape production.

Closed agri-PV Scenario, for:

Production of vegetables or horticultural crops in Venlo type greenhouses which are used for crops like tomatoes, cucumbers, peppers, but also for cut flowers like roses and many others and pot plants. These are characterized by glass spans of 3.2 m and gutter heights about 4-6 m to accommodate for high wire planting system, thermal screens, and supplementary lighting**.**

The previous deliverables, D5.1, D5.2, D5.3 and D5.4 reported on the various steps that led from the conceptual design to the final project specifications (D5.1 and D5.2), described the executive design (D5.3) and the execution schedule (D5.4) for the demonstrators.

The scope of this deliverable is to describe key performance indicators (KPI) from an economic, environmental and sustainability viewpoint and address which of these KPIs will be measured in SYMBIOSYST.

1.2. ABBREVIATION LIST

Table 1: Abbreviation list.

Abbreviation	**Meaning**
1P	PV layout with 1 row of PV modules installed in Portrait mode
1L	PV layout with 1 row of PV modules installed in Landscape mode
2L	PV layout with 2 rows of PV modules installed in Landscape mode
Agri-PV	Agrivoltaics
BEG	Bifacial energy gain
CAPEX	Capital Expenditures
CoO	Cost of Ownership
GCR	Ground cover ratio
GHG	Greenhouse Gas Emissions
GTI	Global Tilted Irradiance
GWP	Global Warming Potential
HSAT	Horizontal Single-Axis Tracker
IRR	Internal Rate of Return
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
LCOE	Levelised Cost of Electricity
LER	Land Equivalent Ratio
NDVI	Normalized Difference Vegetation Index
NPV	Net Present Value
OPEX	Operational Expenditures
PAR	Photosynthetically active radiation
POA	Plane of array
PV	Photovoltaics
T_a	Air temperature
WACC	Weighted Average Cost of Capital

2. Literature review on agri-PV economic KPIs

Agrivoltaics (Agri-PV) integrates photovoltaic (PV) systems with agricultural practices, optimizing land use to generate renewable energy while maintaining or enhancing agricultural productivity. Evaluating the economic viability of such systems requires robust key performance indicators (KPIs). This review synthesizes findings from the literature to outline critical economic KPIs used in assessing Agri-PV systems [1], [2].

2.1. Levelised Cost of Electricity

The levelised cost of Electricity (LCOE) is a primary KPI in renewable energy projects, representing the average cost per unit of energy generated over a system's lifetime [3] including technical parameters (for e.g., lifetime, yield, degradation), cost parameters (capital and operational expenditures, CAPEX and OPEX) and financial parameters (weighted average cost of capital, WACC). In Agri-PV systems, LCOE calculations are more complex due to additional factors like shading impacts on crops and dual land use and various authors have studied how the LCOE can be considered in Agri-PV systems [4], [5]. LCOE for agri-PV is typically competitive with free standing PV systems when agricultural productivity losses are minimal, supported by optimized system design.

2.2. Crop yield and revenue compensation

A unique aspect of Agri-PV economics is the interplay between energy generation and agricultural output. The revenue from crops may decrease or increase depending on system design and crop types. Reduction in crop yield might be due to negative shading effects, land allocation and economic trade-offs, and operational challenges. However, agrivoltaics aims to balance this by enabling co-production, where electricity generation is combined with sustainable agricultural practices to optimize both outputs. Studies by Dupraz et al. (2011) [6] demonstrated that specific crops, such as lettuce and tomatoes, can achieve yield reductions below 20% under partial shading, while the energy revenue compensates for any losses. Weselek et al [7] also reported on early results on crop yield.

2.3. Land equivalent ratio

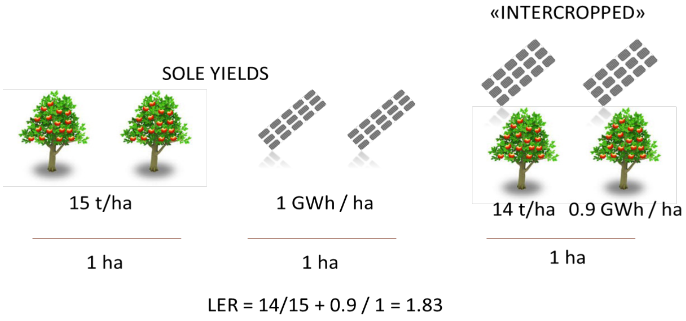

Figure 1: exemplary illustration of LER

Land Equivalent Ratio (LER) [4], [8] is a parameter that can evaluate the impact of intercropped strategies compared to sole yields. Using the same concept in Agri-PV, values greater than 1 would indicate that by combining agriculture and photovoltaic modules, a greater overall efficiency is obtained than the two individual activities carried out separately, both from the point of view of agricultural and electricity production. However, this approach does not allow to evaluate the minimum required performance of the two integrated subsystems (agricultural and energy), allowing for example to obtain a LER value greater than 1 in the presence of a subsystem that is very efficient compared to the standard and a subsystem that is particularly inefficient.

2.4. Payback period and Internal Rate of Return

Standard KPIs like payback period, Internal Rate of Return (IRR) and Net Present Value (NPV) measure the profitability of Agri-PV investments. The presence of dual revenue streams—agricultural and energy—often shortens payback periods compared to standalone PV. Schindele et al. (2020) reported IRRs above 10% for Agri-PV systems in Europe under favorable policy frameworks [9].

2.5. Incentives and Policy impacts

Economic viability heavily depends on incentives such as feed-in tariffs, subsidies, and tax breaks. A meta-analysis by The work of Pascaris et al [10], [11] underscores the role of policies in reducing upfront capital costs, enhancing the financial attractiveness of Agri-PV projects and emphasize the importance of policy support, community engagement, and economic incentives in advancing agrivoltaic systems. Incentives and policy support can have an impact in economic KPIs such as reduced LCOE, increased IRR or NPV. They could also have an impact in increase farmer income, secure limited acceptable reduction in crop yield, improve biodiversity, etc. Notably, Italy have dedicated incentives for innovation Agri-PV system in terms of CAPEX and feed-in tariff[1].

3. Literature review on agri-PV Life environmental KPIs

3.1. Greenhouse Gas Emission and Carbon Footprint

Modern agriculture is responsible of a large share of a country's total emissions, its impact ranging from 12% of total GHG emissions for industrialised countries to 35% for developing countries [12]. A photovoltaic system has lower emissions, from 14 to 73 gCO2-eq/kWh, respect to fossil fuels (607 g CO2-eq/kWh) oil (742 g CO2-eq/kWh), and coal-fired power plants (975 g CO2-eq/kWh).

Agri-PV systems contribute to reducing GHG emissions by displacing fossil-fuel-based energy production. However, the production and installation of PV modules also generate emissions. Life-cycle assessments (LCAs) are often employed to evaluate net emissions. Studies by Schindele et al. (2020) estimated a reduction in lifecycle emissions of up to 50% compared to separate agricultural and PV land uses, emphasizing the system's potential for climate change mitigation. [9]

3.2. Water use efficiency

Agri-PV systems can influence water use in agriculture. The partial shading from PV panels reduces evapotranspiration, conserving water in arid and semi-arid regions. Adeh et al. (2018) [13] demonstrated that Agri-PV systems reduced water demand for crops like tomatoes and lettuce by 10-30%, making water use efficiency a critical KPI for evaluating their environmental sustainability.

3.3. Biodiversity Impacts

Biodiversity conservation is a key environmental objective for Agri-PV systems [14]. Metrics such as "species richness" and "habitat quality index" are used to evaluate biodiversity impacts. Various authors have found that Agri-PV systems designed with vegetation corridors and pollinator-friendly plants can enhance local biodiversity compared to monoculture farming or conventional PV systems. [15]

3.4. Microclimatic effects and crop productivity

The microclimatic conditions under PV panels, such as temperature, humidity, and light intensity, are critical environmental KPIs that affect both agricultural and ecological outcomes. Shading from PV panels moderates extreme temperatures, which benefits crop resilience during heatwaves. These moderated microclimatic conditions also

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[1] https://www.gse.it/servizi-per-te/attuazione-misure-pnrr/sviluppo-agrivoltaico (accessed on 15.12.2024)

promote soil health by reducing temperature fluctuations and retaining soil moisture [16]. Recent data reported by the company Sun Agri showed that Agri-PV can have benefit results in terms of protection against frost, heatwaves, reduce water stress and thus limit the reduction or even enhance crop yield and quality of crops[2].

3.5. Soil quality metrics

Agri-PV systems can impact soil quality through changes in moisture retention, erosion, and organic matter content. Metrics like "soil organic carbon" and "erosion prevention index" are used to assess these changes. Reduced wind and water erosion under PV arrays can improve soil quality, promoting long-term agricultural productivity [17].

3.6. Circularity and End-of-Life management

The environmental footprint of agri-PV systems also depends on the circularity of materials used in PV panels and the system's end-of-life management. KPIs such as "material recovery rate" and "recycling efficiency" are critical in ensuring that the system remains environmentally sustainable over its lifecycle. Fraunhofer ISE (2021) [18] emphasized the importance of integrating recyclable materials and robust decommissioning practices into Agri-PV systems. Life cycle assessment (LCA) studies have been presented for the case of Agri-PV [19].

4. Economic KPIs for SYMBIOSYST

The experience in cost analysis for Agri-PV systems is growing but is still rather limited as various companies are proposing a range of diversified solutions. CAPEX, OPEX and LCOE should not be directly compared with free field PV systems in terms of competitiveness as the results would be misleading. In some countries Agri-PV will be the only option for multi-MW installations and therefore new benchmarks must be defined for the sector. In addition to this, the benefits must be calculated with an integrated approach where energy and crop yields should be considered as a whole. Focusing on the energy yield and cost for open Agri-PV, a broad differentiation for a preliminary cost analysis can be done by defining two macro scenarios:

- Arable crops/farming characterised by high structures (> 5 m) for the use of large machinery;
- Horticulture, fruit and vegetables characterised by lower structures (< 5 m).

The main differences in cost items are related to:

- The use of special structures: the higher the structure, the costly and challenging it gets. Cost can increase from 50 €/kW (for fixed structure at low height) to up to 300 €/kWp for horticulture&fruits and 600 €/kWp for arable crops (for e.g., wheat).
- Site preparation. Cost can double from 150 €/kWp to 300 €/kWp.
- PV modules with increasing cost due to the use of double glass / bifacial cells / frames / optimised cell distancing to increased semitransparency (with lower power density as a result). The cost can increase from 150 €/kWp to 750 €/kWp.

Overall, starting from around 650 €/kWp for traditional type PV plants (800 €/kWp with single-axis tracking, single tracker), we arrive at around 1500 €/kWp for arable crops systems (with variability of around 425 €/kWp) and 1100 €/kWp for permanent crop systems (with variability of about 375 €/kWp). On average, it is expected that an Agri-PV plant compared to a traditional plant, will present an increase in CAPEX of around 130% for a system with arable crops, and of 70% in the case of a system with permanent crops (see Figure 2).

In SYMBIOSYST we will start with a target CAPEX cost of 1450 €/kWp. Thanks to the innovations, the aim is to achieve

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[2] https://www.bifipv-workshop.com/welcome-chambery-2024

an overall cost decrease of 15%, leading to a target value of 1230 €/kWp.[3]

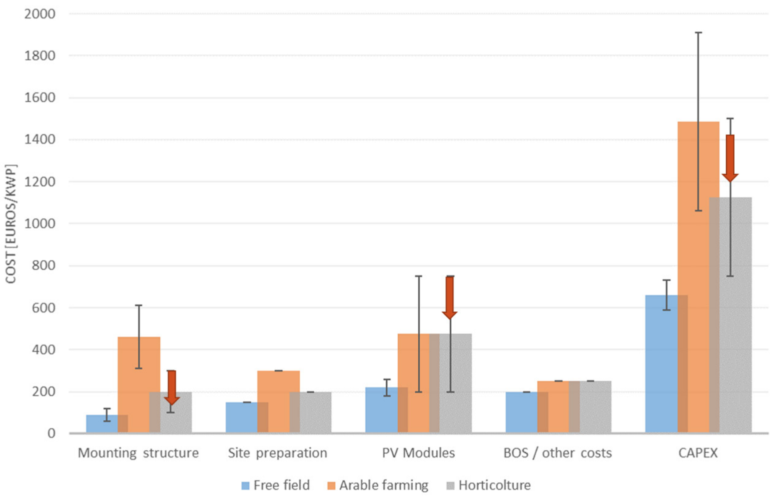

Figure 2: CAPEX analysis of agri-PV compared to free field and SYMBIOSYST targets. Red arrows show the ambition of SYMBIOSYST

The LCOE calculated of a system located in the north of Italy would show values as indicated in Figure 3. SYMBIOSYST improvements (-30%) (indicated with the red arrow) derive from longer lifetime (25 years instead of 20) thanks to longer trackers durability, higher performance ratio (0.9 instead of 0.85) and 10% reduction in O&M cost for an agrivoltaic system compared to a traditional system [9] thanks to the digital platforms, drone services, advanced monitoring, and better tracking algorithms developed in the project. While the implications in terms of the investment and electricity cost of PV can be directly evaluated, more complex is the estimation of the effect on the crop yield. Experience in Bolzano with the Demo Driver (existing Agri-PV system installed in 2007 at 8 m height with Ground Cover Ratio, GCR, of 0.3) is that no impact was measured on apples in terms of plant phenotyping and quality traits. In SYMBIOSYST's systems we aim at increasing the GCR to 0.4-0.5 and keeping the maximum height of the trackers around 4.5 m while maintaining a very low impact on the continuity of the agricultural activity.

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[3] Note that to keep costs acceptable, in SYMBIOSYST we will focus on 2 m^2 PV modules with already standardized dimensions. For example: 1722±2 mm length and 1134±2 mm width for 108 HC modules with M10 cells. Al Frame mounting holes are also standardized at 400/1500±1 mm. As for Al frame thickness, we will use standard dimensions (either 30 mm, 35 mm or 40 mm depending on mechanical resistance required by tracker and greenhouse) to again keep costs down. Customisation of PV modules in terms of size, colors, etc, can lead to an increase of the PV module cost of up to 100%.

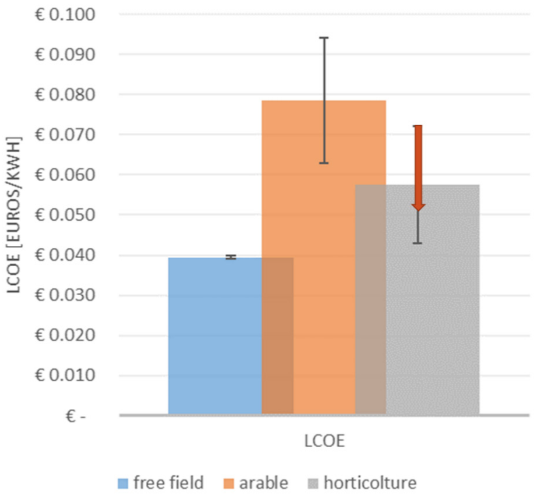

Figure 3: LCOE for location Bolzano

In Symbiosyst, we have developed a comprehensive LCOE and economic KPIs calculator to include the impact of Symbiosyst solutions. In the following sections we provide an explanation on key assumptions. Details about technology cost is not provided at this stage as it is considered as confidential information.

4.1. CAPEX

For the Capital Expenditure we have included the following categories:

- Inverters (values from the market)
- Electrical BOS (cables, connectors, etc) (from the market)
- Mounting structure (detailed analysis below)
- Site preparation (based on EFSOLARE experience)
- PV modules (detailed analysis below)
- Installation cost (based on EFSOLARE experience)
- Agriculture related extra costs (detailed analysis below)

4.1.1.PV modules

For the calculation of the cost of PV modules we have used a simplified Cost of Ownership (CoO) model. The model includes the following parameters:

Tempered low-Fe front glass (with AR coating)
Transparent backsheet
Al frame (35 or 40mm)
Encapsulant
Cells
String ribbons
Bussing ribbons
Split junction boxes

Details are not included for confidentiality reasons. The partner Aleo has developed various options with different level of transparencies.

4.1.2.Mounting structures

For the calculation of the cost of mounting structures we have differentiated between various PV modules layout and whether the PV modules are mounted on fixed or tracking systems.
To calculate the cost in Euros/kWp of the mounting structure we have followed these steps:

1) Number of modules per linear m of mounting structure (configurations 1P, 1L or 2L)

1P: Number of modules per linear m = 1/width
1L: Number of modules per linear m = 1/height
2L: Number of modules per linear m = 1/height *2

Configuration 2P was not considered due to self-shading.

2) kW installed for each linear m of mounting structure

power per linear m = number of modules per linear m * PV module efficiency * module area

3) cost of mounting structure per linear m (provided by CONVERT)

here we have considered the impact of the final height of the mounting structure and PV module brackets for 1P, 1L, 2L configurations.

4) cost of mounting structure per kWp

cost of mounting structure per kWp = cost of mounting structure per linear m / power per linear m

4.1.3. Extra costs related to new or existing agricultural activities

The differentiation here is between the installation of the Agri-PV plant in an existing cultivated area or the installation together with new crops. This is highly relevant for the apple tree orchard (as studied in the demo case of Ora) as the agricultural system comes with irrigation, hail and frost protection, structure for plant training and stability. The inclusion of a water catchment system will also have a cost. An indication about the costs were provided by LAIMBURG.

4.2. Input data for yield calculation

Global tilted irradiance (GTI) with or without tracking can be calculated using available satellite data for example by accessing PVGIS or using other professional software for yield assessment.
Performance Ratio will depend on various factors, but the main differences can derive from the ease of maintenance (impacting downtime and availability).
Bifaciality enhancement or bifacial gain will vary depending on the type of mounting structure, the height, the distance between PV module and crops, albedo, etc.
Degradation of performance per year could be different depending on temperature profiles, soiling, UV exposure, etc.

For the agricultural yield, this will vary depending on the distance between PV modules and crops, shading, microclimatic conditions below the mounting structure.

4.2.1.OPEX costs

Operational Expenditure costs will vary depending on the maintenance needed by the different system configurations, the ease of access to the PV modules and mounting structure, the height of the system, etc.

4.3. Results

Using the excel tool developed by EURAC together with the input provided by the partners, we provide here an example of outputs deriving from the LCOE calculation shown in Figure 4 where:

SCENARIO 1: 6 m TRACKED with modules in 1P
SCENARIO 2A: 4.5 m TRACKED with modules in 1L with new apple trees
SCENARIO 2B: 4.5 m TRACKED with modules in 1L with existing apple orchard
SCENARIO 3A: 4.5 m TRACKED with modules in 2L with new apple trees
SCENARIO 3B: 4.5 m TRACKED with modules in 2L with existing apple orchard
SCENARIO 4A: 4.5 m TRACKED with modules in 1P with new apple trees
SCENARIO 4B: 4.5 m TRACKED with modules in 1P with existing apple orchard
SCENARIO 5: 4.5 m FIXED with modules in 1P

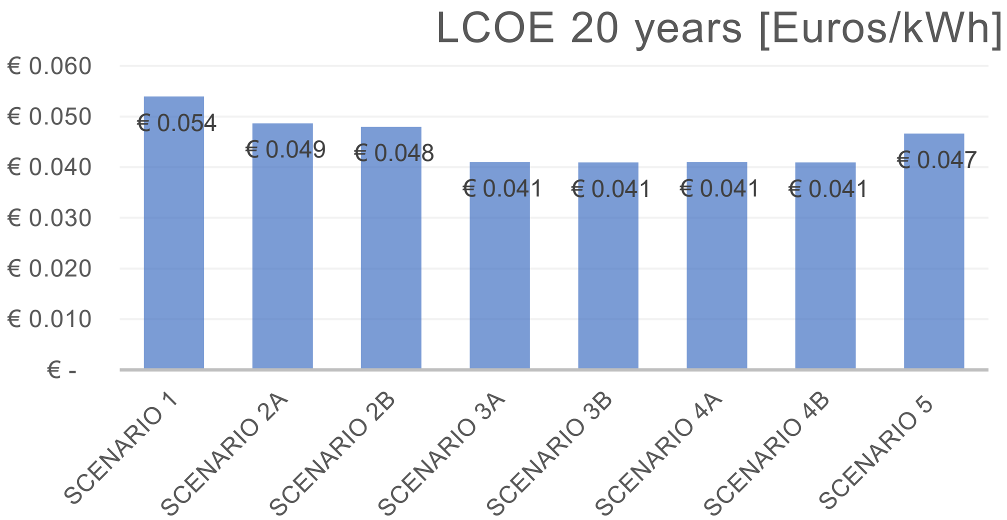

Figure 4: Preliminary results of the LCOE analysis for various SYMBIOSYST scenarios for PV module layout and mounting structures

5. Environmental and sustainability related KPIs introduced by SYMBIOSYST

Table 2: Environmental and sustainability KPIs monitored in Symbiosyst

KPI	Description
Carbon footprint	Measurement of the amount of carbon emitted during the entire life cycle of the entire system, PV modules, trackers, inverters and sensors, from production to end-of-life treatment
Human health	Measurement of lifecycle emissions that are toxic for humans
Ecosystem health	Measurement of the lifecycle emissions that are responsible for damages on the natural ecosystem
Water footprint	Quantity of water used during the production of the entire system

Resource use	Mineral, metal and fossil resources depletion, along the agri-PV system lifecycle
Energy efficiency	Amount of energy produced compared to that consumed during manufacture, installation and maintenance of the system
GHG emission reduction	GHG emission reduction due to the energy produced by the Agri-PV system
Water saving	Amount of water saved considering both the water saved through the shadow effect of the modules and the water potentially collected
Biodiversity	This KPI is measured by assessing the number of different species in an area.
Use of machinery	Total number of working hours of agricultural machinery. This figure is used to assess possible differences in GHG emitted by machinery. This KPI is important from the point of view of both sustainability and the agricultural part of the project.
Soil phenology	Measurement of the microclimatic conditions (acidity and temperature) of the crops under the PV panels. This KPI is important from the point of view of both sustainability and the agricultural part of the project.

Table 2 summarises the lifecycle-based environmental sustainability KIPs that are taken into account within the Symbiosyst project. Some of them are discussed in more detail below, with some sub-parameters being measured.
Part of the activities of the Symbiosyst project were dedicated to the selection of ad-hoc sustainability KPIs, including environmental aspects, but also social and economic ones, while considering all the lifecycle stages of an Agri-PV system.
The economic KPIs were explained in the previous chapter of this report, while the pure environmental lifecycle indicators are described in Deliverable 4.2. These indicators are based on the Environmental Footprint[4] methodology, that was selected since it is among the most recognized at European level. They allow the evaluation of several impact categories, analysing all the lifecycle stages, from the raw material extraction to the production of the required component and operation activity, until the end-of-life treatments. Sixteen impact categories are included in the Environmental Footprint, which can be clustered in: impact on climate change, by the measurement of the carbon footprint, impact on human health, by the measurement of emissions that are toxic for humans, impact on the environment by the measurement of emissions that are toxic for the natural ecosystem, and finally impact on the water use, land use and resources use, including energetic, water and materials resources.

In addition to these indicators, a stakeholder-based approach was applied as well, to select other relevant indicators that are more specific to the agri-PV system. These second set of KPIs are presented in Deliverable 4.1, divided into the three categories of social, photovoltaic and agricultural KPIs.
These indicators include aspects related to energy efficiency of the agri-PV system, an evaluation of the GHG emissions reduction of the farm thanks to the use of solar energy, on water savings, biodiversity aspects, change in machinery operations and soil quality. The selected KPIs that are more specific to measure the agricultural quality are included in the next chapter.
The selected KPIs are measured on the Symbiosyst demo-drivers, and the results of these measurements will be explained in further detail in Deliverable 4.4, both for the LCA-based Environmental Footprint indicators, and the rest of sustainability KPIs selected based on a stakeholder engagement process.

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[4] https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html

5.1. Carbon footprint

According to the selected Environmental Footprint methodology, the carbon footprint might have an impact both on humans and ecosystem health, and it is measured via the Global Warming Potential (GWP). The GWP is a well-known method to measure the impact of different greenhouse gases on the global warming, based on the capability of each gas to trap the heat over a certain period, generally in LCA analysis a 100-year period is used[5].

The carbon footprint was here evaluated via LCA, by measuring the CO_2-equivalent emissions that occurs from the raw materials extraction to the production of the system components, including PV modules, trackers, mounting structures, inverters and other electrical components. The agricultural operations and end-of-life procedures are included as well in the assessment.

5.2. Human health

The indicators related to the human health that are measured within the LCA assessment, considering the same lifecycle stages as the carbon footprint evaluation, and based on the Environmental Footprint method. The human health related indicators can be summarized in the Table 3.

Table 3 Description of human health related Environmental Footprint indicators used in the LCA assessment

INDICATOR	UNIT	DESCRIPTION
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	Potential for chemicals to cause cancer in humans
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	Potential for chemicals to cause non-cancer health effect (e.g., respiratory issues, neurological damage, etc.)
Particulate matter	Disease incidences	Human health effects associated with exposure to PM2.5.
Ionising radiation, human health	kBq U235	Human exposure efficiency relative to U235
Photochemical ozone formation, human health	kg NMVOC-eq	Tropospheric ozone concentration increase

5.3. Ecosystem health

Similarly to the human health indicators, other KPIs can be used to measure the ecosystem health, along the entire Agri-PV system lifecycle. They consider several aspects of the earth ecosystem health, from ozone layer depletion to damages on water and soil ecosystems.

Those indicators are explained in Table 4 and are again based on the Environmental Footprint impact categories.

Table 4 Description of ecosystem health related Environmental Footprint indicators used in the LCA assessment

INDICATOR	UNIT	DESCRIPTION
Ozone depletion	kg CFC-11-eq	Ozone Depletion Potential
Acidification	mol H+-eq	Accumulated Exceedance of emissions causing acid rain (e.g., SO2 and NOx)
Eutrophication, terrestrial	mol N-eq	Accumulated Exceedance of nutrients reaching the land ecosystem (mainly nitrogen) causing ecosystem imbalance

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[5] Understanding Global Warming Potentials | US EPA

Eutrophication, freshwater	kg P-eq	Fraction of nutrients reaching freshwater end compartment (mainly phosphorous) causing ecosystem imbalance
Eutrophication, marine	kg N-eq	Fraction of nutrients reaching marine end compartment (mainly nitrogen) causing ecosystem imbalance
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	Potential harm of chemical emissions on freshwater organisms

5.4. Water footprint

The LCA impact on water use is measured according to the Environmental Footprint impact methodology, by the evaluation of water scarcity, expressed in cubic meter of world equivalent deprived water, considering the same lifecycle stages of the previous indicators. The indicator measures the remaining water available in a region after accounting for human and ecosystem demands, following the Available WAter REmaining (AWARE) model.[6]

5.5. Resource use

The lifecycle-based resource use was evaluated considering the depletion of minerals, metals and energy fossil fuels resources, following the same Environmental Footprint methodology. The two indicators are described in Table 5.

Table 5 Description of resource use related Environmental Footprint indicators used in the LCA assessment

INDICATOR	UNIT	DESCRIPTION
Resource use, minerals and metals	kg Sb-eq	Abiotic resource depletion of ultimate reserves
Resource use, fossil	MJ	Abiotic resource depletion – fossil fuels

5.6. Energy efficiency

The energy efficiency is measured as the amount of energy required by the Agri-PV system lifecycle - for its production, operation and end-of-life treatments - compared to the amount of energy that is produced by the PV system during its lifetime. This measurement allows to evaluate the Energy Payback Time, meaning the number of years that the PV plant needs to operate, to payback the energy required for its lifecycle.

5.7. GHG emission reduction

The LCA results are also used to measure the GHG emission reduction thanks to the use of solar electricity from the Agri-PV system, compared to the use of electricity from the national grid. This parameter can be used to evaluate the GHG payback time (GHGPBT), in a similar way to the EPBT previously described. The GHGPBT measures here the number of years that an Agri-PV system needs to operate in a certain installation location, in order to payback the GHG emissions of the system lifecycle. This indicator is based on the concept of GHG avoided emissions, with respect to the emissions coming from the national grid electricity, or other energy sources, depending on the desired assumptions and the goal of the analysis.

5.8. Water saving

Within the project, an attempt will be made to exploit the dynamic measurement of soil humidity to reduce irrigation on days and hours when it is not necessary. The placement of the PV on top of the crops might maintain the humidity of the plant and soil, leading to less usage of water for irrigation, and maintaining the humidity of the plants, especially in arid climatic conditions. Additionally, the Agri-PV system might be integrated with a rainwater recovery system, allowing to further reduce the water consumption.

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[6] https://wulca-waterlca.org/aware/what-is-aware/

5.9. Biodiversity

The interaction between agriculture and biodiversity is monitored on open-field crops, by asking the Agri-PV filed owners if there are in place or in program activities dedicated to the protection of biodiversity. More in detail, the agrobiodiversity is monitored by asking if there is a differentiation of agricultural species cultivated, a periodic rotation of cultures, a use of companion plants, or other measurements. In addition to that, the biodiversity is also measured by asking the Agri-PV owner if the flora and fauna on the field is monitored and compared with a non-agrivoltaics field, to verify if there is effect of the Agri-PV system on the local biodiversity. The most important indicators that can be monitored are the amount and diversity of flowering, wild bees pollinators, butterflies and insects, birds, among others. The indicators also are meant to monitor if there are areas dedicated to the preservation and increase of biodiversity, such as hedges, small ponds, or other non-cultivated areas inside the Agri-PV field.

5.10. Use of machinery

The use of machinery can be monitored both as an environmental sustainability and agricultural KPI. In fact, the machinery operations can be hindered by the introduction of the PV system in the field, leading to an increase of passages required for the machines to perform the necessary agricultural activities such as harvesting, irrigating or fertilizing. The increase in the time of machinery usage can lead to an increase in cost and GHG emissions, therefore, this indicator is monitored by comparing the machinery hours required in an Agri-PV field with respect to the machinery hours of a traditional field of the same crop type.

5.11. Soil phenology

The soil microclimatic conditions can be affected by the presence of PV modules, since they introduce an heterogenous moisture distribution due to a different water supply, when compared to a traditional agricultural field without PV. This change can lead in turn to a variation of the soil acidity level. In fact, by reducing the evaporation rate of the moisture, the soil pH level can be consequently less subject to fluctuations, creating a more stable environment. For this reason, the soil phenology is monitored by measuring the average soil pH level and the average soil temperature of the crops under the Agri-PV systems, in comparison with a cultivated area of the same crops, without PV systems.
The soil nitrogen content, soil organic matter and microbial activity evaluation would be other relevant indicators for the soil quality measurement. Although, those parameters are more affected by agricultural practices itself, rather than by the presence of PV panels on the crops, which primarily has an influence on microclimatic conditions. For this reason, only the acidity and temperature parameters were included as relevant KPIs.

6. Agricultural KPIs in Symbiosyst

Probably the most interesting aspect of an Agri-PV project such as Symbiosyst is the study of the impact of the structures, trackers and PV modules, on the biological part of the entire system. it is clear that such a system only makes sense when it succeeds in safeguarding agricultural production, both in terms of output and in terms of the quality of the harvested fruit. In addition to this, it is also important to analyse the reaction of the biological system to the presence of the PV system, thus the well-being of the plants and the entire ecosystem.
Table 6 summarises the KPIs that have been identified and measured to assess this impact.

Table 6: Agricultural KPIs

KPI	Description
Water Efficiency	in the agriculture of the coming years the use of water and its saving will be increasingly important. Symbiosyst seeks to assess the use of water for irrigation.
Crop yield	the agricultural production of the field with the presence of the agrivoltaics system is measured.
Plant Vigour	this KPI puts together a list of parameters that help assess the health of the plant and its growth.
Postharvest quality tests	In the postharvest period, tests will be carried out on samples of fruit harvested from the field in the control area and in the AgriPV system to assess any differences
Soil phenology	This KPI is important from the point of view of both sustainability and the agricultural part of the project. Soil temperature, moisture and pH are measured.
PAR (photosynthetically active radiation)	The irradiance on plants of PAR radiation is measured. This data is very important for verifying the impact of shading on plant growth and health.
Microclimate	Parameters related to the microclimate generated in the presence of an agrivoltaic system are measured.
LAOR	Land area occupation ratio
Agricultural activity continuity	This condition occurs where the area subject to intervention is used for agricultural crops, floriculture, or livestock grazing.
Production vocation	The maintenance of the crop type, or if possibly, the transition to a new crop type with a higher economic and/or biodiversity value, measured in terms of standard company production value, should be guaranteed.

6.1. Water Efficiency

In the agriculture of the future, at any latitude, the use of water and its saving will be increasingly important. One of the objectives of the Symbiosyst project is to measure and evaluate the amount of water used for irrigation. This is to quantify how much the shading given by the presence of the Agri-PV plant's structures, succeeds in limiting the evaporation of water from the soil and the plants themselves and thus optimise its use. Strategies for rainwater recovering will also be evaluated to further optimise its utilisation.

6.2. Crop Yield

During the second part of the project, the agricultural production of areas with agrivoltaic facilities will be measured and compared with control areas.

6.3. Plant Vigour

To assess the vigour of the plants there are certain parameters that are analysed. First of all, vegetative growth of the plants is measured, through parameters such as the sprouts height, the stem diameter, the number of fruits they produce, and the dimension and the size of the leafs. NDVI, the Normalized Difference Vegetation Index, is also measured. This is a measure of the reflectance of light in the red and near-infrared bands. The principle on which this kind of analysis is based is that a healthy plant absorbs much more light in the red band for photosynthesis than a plant with some kind of stress, be it water, heat or due to some infection.

6.4. Postharvest quality test

As far as postharvest quality tests are concerned, there are some analyses and measurements on the fruit in Symbiosyst. Shape, average size, weight and colour of agricultural products will be monitored. The sugar content and acidity of the products will also be monitored.

6.5. Soil Phenology

The parameters measured to study soil phenology within the project are temperature, humidity and pH. These parameters affect the plant's ability to absorb nutrients from the soil.

6.6. PAR (Photosynthetically Active Radiation)

The amount of PAR reaching the various zones of the plant is an important parameter in understanding how an Agri-PV plant affects its growth and well-being. PAR will therefore be measured at different heights and in different zones of the plant.

6.7. Microclimate

To assess any changes in the microclimate in which the plants grow, temperature and air humidity are measured.

6.8. Laor

Laor is a parameter that measures the percentage of land occupied by the photovoltaic system. it is important for optimising land use as well as the economic viability of the system as a whole.

7. Photovoltaics KPIs monitored by Symbiosyst

The electricity yield is for sure one of the important parameters that can be assessed during the design phase to verify the correct integration of the energy production activity with the agricultural one. PV yield can be measured and compared with initial assessment during the operation of the agrivoltaic system through monitoring, to ensure the optimization of the performance of agricultural activity in synergy with the production of renewable energy. On the basis of the characteristics of the agricultural plants analysed, it is clear that the expected electricity yield of an agricultural plant (in GWh/ha-year), compared to the reference area related electricity production of a standard photovoltaic plant (standard PV), will depend on the Ground Cover Ratio. As typical GCR for utility scale PV is around 0.5, the area related energy yield from Agri-PV should not be less than 50% of the energy yield of a utility scale plant. In SYMBIOSYST we aim at achieving values of electricity yield similar to those that can be found in utility scale PV with a low bound of -10%.

In the light of these considerations, a number of parameters will be monitored in the project. Table 6 summarises the KPIs that are monitored in Symbiosyst. In the light of these considerations, a number of parameters will be monitored in the project. Table 7 summarises the KPIs related to PV production that are monitored in Symbiosyst.

Table 7: PV KPIs measures in Symbiosyst

KPI	Unit
PV modules temperature	$^\circ C$
Global irradiance	W/m^2
GTI irradiance (front and back)	W/m^2
Air temperature	$^\circ C$
Air relative umidity	%
Wind direction	
Wind speed	m/s
Albedo	W/m^2
Ground Coverage Ratio (GCR)	%

8. CONCLUSIONS

An Agri-PV plant presents the need to introduce KPIs which can clearly capture the synergy between energy and crop production. In Symbiosyst we will use the data coming from the 3 demonstrators (2 open Agri-PV plant and 1 greenhouse) together with the data coming from the demo drivers (so far we have secured 10 demo drivers) to calculate economic and environmental/sustainability KPIs. In summary in the next tables we present the parameters and KPIs which will be monitored by the project.

Parameter	KPI	Means of verification
Combined yield		
Land Equivalent Ratio	Land Equivalent Ratio	sum of area related yields
Optimisation of electricity yield		
Highest possible efficiency with semitransparency	Power density [MWp/ha]	Direct measurement
Increase in electricity yield thanks to optimized tracking algorithm	Energy Yield [kWh/kWp or GWh/ha]	Direct measurement
Cost reduction in operation and maintenance	Cost per year [Euros/kWp]	Use of Cost Priority Number (CPN) methodology[7]
Optimisation of crop yield		
Use of semitransparent modules	PV module active area [m/m]	Direct measurement
Use of functional coating to shift solar spectra	PAR measurement [mmol/m^2 or W/m^2]	Direct measurement
Use of precision farming	Number of sensors connected to external devices for optimized crop yield	List of sensors
Adoption of water resource optimization measures	Amount of water collected compared to reference area	Directly measured / comparison with control area
Plant phenotyping and Postharvest Quality traits	Growth (height, diameter, etc.), chlorophylls, PAR, cycle tracking. total yield, commercial yield, Colour, Size, Texture, Sugar content, Acidity.	biomass, total n. of fruits or pods produced, n. of fruits per plant / n. of pods per plant / n. of seeds per pod, average fruit/pot weight
Improvement of site ecological value		
Improvement of biodiversity	Reduction in use of pesticide and fertilisers. Flowering. Presence of pollinators.	Comparison with control area
Soil improvement and preservation	Soil improvement	Qualitative

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[7] Developed by EURAC https://doi.org/10.1002/pip.2857

Landscape integration	Aesthetic impact	Qualitative / quantitative via the use of modelling tools
Environmental parameters		
Environmental footprint	Carbon footprint, Human health, Ecosystem health, Water footprint, Resource use, Energy efficiency, GHG emission reduction	Environmental footprint methodology

A fundamental parameter for the qualification of an agrivoltaic system is the continuity of agricultural activity. This condition occurs where the area subject to intervention is used for agricultural crops, floriculture, or livestock grazing. Finally, each demonstrator in SYMBIOSYST will be categorised by also using the following Parameters.

Parameter / Index	Description / Unit
Installed nominal power and power density	MW, MW/ha
LAOR: *Land area occupation ratio*	%
Power and area normalised Yield	(GWh/MW-year) (GWh/ha-year)
PV module efficiency	%
Min. and max height of PV modules from ground	m
Azimuth / orientation / tilt angle	Fixed / Variable, …
Covered area	m^2
Agri-PV volume (area x structure height)	m^3
System type	Fixed/ tracked (single or double axis)
PV module type	Opaque / transparent / bifacial
Foundations type	Shallow, deep
Field consumption	Permanent / not permanent
Distance between mounting structure	m
Width of cultivated land	m
Ratio between cultivated land and the agri-PV system	%
Culture type	Vegetables, horticulture, fruits, etc
Possibility to rotate the culture type	%
Precision farming typology	Active linked / Passive not linked to productive cycle
Presence of total or partial water catchment	%

REFERENCES

[1] M. A. A. Mamun, P. Dargusch, D. Wadley, N. A. Zulkarnain, and A. A. Aziz, “A review of research on agrivoltaic systems,” *Renewable and Sustainable Energy Reviews*, vol. 161, p. 112351, Jun. 2022, doi: 10.1016/j.rser.2022.112351.

[2] S. Asa’a *et al.*, “A multidisciplinary view on agrivoltaics: Future of energy and agriculture,” *Renewable and Sustainable Energy Reviews*, vol. 200, p. 114515, Aug. 2024, doi: 10.1016/j.rser.2024.114515.

[3] E. Vartiainen, G. Masson, C. Breyer, D. Moser, and E. R. Medina, “Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity,” *Progress in Photovoltaics: Research and Applications*, vol. 28, no. 6, pp. 439–453, 2020, doi: 10.1002/pip.3189.

[4] B. Willockx, C. Lavaert, and J. Cappelle, "Performance evaluation of vertical bifacial and single-axis tracked agrivoltaic systems on arable land," *Renewable Energy*, vol. 217, p. 119181, Nov. 2023, doi: 10.1016/j.renene.2023.119181.

[5] M. Trommsdorff, M. Hopf, O. Hörnle, M. Berwind, S. Schindele, and K. Wydra, "Can synergies in agriculture through an integration of solar energy reduce the cost of agrivoltaics? An economic analysis in apple farming," *Applied Energy*, vol. 350, p. 121619, Nov. 2023, doi: 10.1016/j.apenergy.2023.121619.

[6] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, and Y. Ferard, "Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes," *Renewable Energy*, vol. 36, no. 10, pp. 2725–2732, Oct. 2011, doi: 10.1016/j.renene.2011.03.005.

[7] A. Weselek, A. Ehmann, S. Zikeli, I. Lewandowski, S. Schindele, and P. Högy, "Agrophotovoltaic systems: applications, challenges, and opportunities. A review," *Agron. Sustain. Dev.*, vol. 39, no. 4, p. 35, Jun. 2019, doi: 10.1007/s13593-019-0581-3.

[8] H. Sánchez Ortiz, S. Dittmann, C. Meza, and R. Gottschalg, "Comparison of Different AgriPV Layouts in Terms of Photovoltaic Energy Yield Output," *40th European Photovoltaic Solar Energy Conference and Exhibition*, pp. 020428-001-020428–004, 2023, doi: 10.4229/EUPVSEC2023/4DO.2.2.

[9] S. Schindele *et al.*, "Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications," *Applied Energy*, vol. 265, p. 114737, May 2020, doi: 10.1016/j.apenergy.2020.114737.

[10] A. S. Pascaris, C. Schelly, L. Burnham, and J. M. Pearce, "Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio-political dimensions of agrivoltaics," *Energy Research & Social Science*, vol. 75, p. 102023, May 2021, doi: 10.1016/j.erss.2021.102023.

[11] A. S. Pascaris, C. Schelly, and J. M. Pearce, "A First Investigation of Agriculture Sector Perspectives on the Opportunities and Barriers for Agrivoltaics," *Agronomy*, vol. 10, no. 12, Art. no. 12, Dec. 2020, doi: 10.3390/agronomy10121885.

[12] A. A. Zahrawi and A. M. Aly, "A Review of Agrivoltaic Systems: Addressing Challenges and Enhancing Sustainability," *Sustainability*, vol. 16, no. 18, Art. no. 18, Jan. 2024, doi: 10.3390/su16188271.

[13] E. H. Adeh, J. S. Selker, and C. W. Higgins, "Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency," *PLOS ONE*, vol. 13, no. 11, p. e0203256, Nov. 2018, doi: 10.1371/journal.pone.0203256.

[14] N. Gomez-Casanovas *et al.*, "Knowns, uncertainties, and challenges in agrivoltaics to sustainably intensify energy and food production," *Cell Reports Physical Science*, vol. 4, no. 8, p. 101518, Aug. 2023, doi: 10.1016/j.xcrp.2023.101518.

[15] F. Ascensão, S. Chozas, H. Serrano, and C. Branquinho, "Mapping potential conflicts between photovoltaic installations and biodiversity conservation," *Biological Conservation*, vol. 287, p. 110331, Nov. 2023, doi: 10.1016/j.biocon.2023.110331.

[16] A. Weselek, A. Bauerle, J. Hartung, S. Zikeli, I. Lewandowski, and P. Högy, "Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate," *Agron. Sustain. Dev.*, vol. 41, no. 5, p. 59, Aug. 2021, doi: 10.1007/s13593-021-00714-y.

[17] J. Luo, Z. Luo, W. Li, W. Shi, and X. Sui, "The Early Effects of an Agrivoltaic System within a Different Crop Cultivation on Soil Quality in Dry–Hot Valley Eco-Fragile Areas," *Agronomy*, vol. 14, no. 3, Art. no. 3, Mar. 2024, doi: 10.3390/agronomy14030584.

[18] "Agrivoltaics: Opportunities for Agriculture and the Energy Transition - Fraunhofer ISE," Fraunhofer Institute for Solar Energy Systems ISE. Accessed: Jan. 09, 2025. [Online]. Available: https://www.ise.fraunhofer.de/en/publications/studies/agrivoltaics-opportunities-for-agriculture-and-the-energy-transition.html

[19] M. Wagner *et al.*, "Agrivoltaics: The Environmental Impacts of Combining Food Crop Cultivation and Solar Energy Generation," *Agronomy*, vol. 13, no. 2, Art. no. 2, Feb. 2023, doi: 10.3390/agronomy13020299.