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International Energy Agency
Photovoltaic Power Systems Programme

Task 13 Reliability and Performance of Photovoltaic Systems

PVPS

Dual Land Use for Agriculture and Solar Power Production: Overview and Performance of Agrivoltaic Systems

2025

Report IEA-PVPS T13-29:2025

What is IEA PVPS TCP?

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). The Technology Collaboration Programmes (TCP) were created with a belief that the future of energy security and sustainability starts with global collaboration. The programmes are made up of 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies.

The IEA Photovoltaic Power Systems Programme (IEA PVPS) is one of the TCPs within the IEA and was established in 1993. The mission of the programme is to "enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition to sustainable energy systems." To achieve this, the programme's participants have undertaken a variety of joint research projects in PV power systems applications. The overall programme is headed by an Executive Committee, comprised of one delegate from each country or organisation member, which designates distinct 'Tasks,' that may be research projects or activity areas.

The IEA PVPS participating members are Australia, Austria, Belgium, Canada, China, Denmark, Enercity SA, European Union, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, Solar Energy Research Institute of Singapore (SERIS), SolarPower Europe, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, United States.

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What is IEA PVPS Task 13?

Within the framework of IEA PVPS, Task 13 aims to provide support to market actors working to improve the operation, reliability, and quality of PV components and systems. Performance data from PV systems in different climate zones compiled within the project will help provide the basis for estimates of the current situation regarding PV reliability and performance.

The general setting of Task 13 provides a common platform to summarize and report on technical aspects affecting the quality, performance, reliability, and lifetime of PV systems in a wide variety of environments and applications. By working together across national boundaries, we can all take advantage of research and experience from each member country and combine and integrate this knowledge into valuable summaries of best practices and methods for ensuring PV systems perform at their optimum and continue to provide competitive return on investment.

IEA PVPS Task 13 has so far managed to create a framework for the calculations of various parameters that can indicate the quality of PV components, systems, and applications. The framework is available and can be used by the PV industry which has expressed appreciation towards the results included in the high-quality reports.

The IEA PVPS participating members are Australia, Austria, Belgium, Canada, China, Denmark, Enercity SA, European Union, Finland, France, Germany, India, Israel, Italy, Japan, Korea, Malaysia, Morocco, the Netherlands, Norway, Portugal, Solar Energy Research Institute of Singapore (SERIS), SolarPower Europe, South Africa, Spain, Sweden, Switzerland, Thailand, Türkiye, United States.

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COVER PICTURE

Agrivoltaics system on apple farming in Gelsdorf/ Rhineland-Palatinate, Germany. © Fraunhofer ISE

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Inclusion and Diversity Statement: One or more of the authors of this report self-identifies as an underrepresented ethnic minority in science.

LIST OF ABBREVIATIONS

ADEME	Agence de la Transition Écologique (French agency for ecological transition)
AFNOR	Association Française de Normalization (French norming organization)
APER	Accélération de la Production des Énergies Renouvelables (French acceleration law)
APSIM	Agricultural production systems simulator
APV	Agrivoltaics
AC	Alternating current
BauGB	Baugesetzbuch (German Building Act)
BiPV	Building integrated photovoltaics
BOS	Balance of system
CAP	Common agricultural policy
CAPEX	Capital expenditure
CEI	Comitato Elettrotecnico Italiano (Italian norming organization)
CERES	Crop environment resource synthesis (crop model)
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
CROPGRO	Crop growth (crop model)
CWSI	Crop water stress index
DC	Direct current
DHI	Diffuse horizontal irradiance
DLI	Daily light integral
DNI	Direct normal irradiance
DSSAT	Decision support system for agrotechnology transfer (crop model)
EDF	Électricité de France (French multinational electric utility company)
EEG	Erneuerbare-Energien-Gesetz (German renewable energy sources Act)
ENEL	Ente nazionale per l'energia elettrica (Italy’s national electricity board)
EPC	Engineering, procurement, and construction
EPIC	Environmental policy integrated climate (crop model)
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Statistics Office
FEM	Finite element method
FMEA	Failure modes and effects analysis
GCR	Ground cover ratio
GECROS	Genotype-by-environment interaction on crop growth simulation (crop model)

GHI	Global horizontal irradiance
GMPV	Ground-mounted photovoltaic systems
GW	Gigawatt
IEA	International Energy Agency
IRR	Internal rate of return
kg	Kilogram
kg/m³	Kilograms per cubic meter
KPI	Key performance indicator
kW	Kilowatt
kWh	Kilowatt-hour
LAI	Leaf area index
LCOE	Levelized cost of electricity
LED	Light-emitting diode
LER	Land equivalent ratio
LPF	Land productivity factor
MASE	Ministero dell'Ambiente e della Sicurezza Energetica (Italian Ministry of Environment and Energy Transition)
MOFA	Ministry of Agriculture, Forestry and Fisheries (Japan)
MWh	Megawatt-hour
NDVI	Normalized difference vegetation index
NPV	Net present value
NREL	National Renewable Energy Laboratory (U.S.)
O&M	Operations and maintenance
OECD	Organization for Economic Cooperation and Development
OPEX	Operating expenses
OSCs	Organic solar cells
PAR	Photosynthetically active radiation
PR	Performance ratio
PV	Photovoltaics
PVPS	Photovoltaic Power Systems Programme
R&D	Research and development
ROI	Return on Investment
SAM	System advisor model
SIMPLE	Simple generic crop model (crop model)
STICS	Multidisciplinary simulator for standard crops (crop model)
TCP	Technology Collaboration Programme
UNI	Ente Nazionale Italiano di Unificazione (Italian national standardization body)
USA	United States of America

WP	Water productivity
WUE	Water use efficiency

EXECUTIVE SUMMARY

Our food and water systems are highly vulnerable to the impacts of projected climate change. At the same time, there is an urgent need to decarbonize the energy sector by rapidly and sustainably expanding photovoltaic (PV) systems. Given the alarming rate of species extinction caused by human activities and the subsequent loss of biodiversity, these challenges underscore the necessity for innovative land use concepts to tackle these interconnected crises.

Ground-mounted PV (GMPV) systems are one of the most cost-competitive solutions among renewable energy conversion technologies, but with the disadvantage of typically requiring more land per produced kWh compared to other technologies like wind power, hydropower, or geothermal power [1, 2]. Moreover, the typically high land lease prices for GMPV systems can be beneficial to single farmers while reducing the available area for agricultural production, leading to societal challenges threatening the acceptance towards the deployment of GMPV and potentially leading to restrictive legislations to prevent losses of fertile farmland.

Agrivoltaics offers the possibility to simultaneously use land for agriculture production and solar power generation and provides opportunities to think beyond the way we have installed GMPV over the last two decades. The shading produced by the PV modules can increase the resilience of agriculture by protecting crops or animals against the rising number of severe weather events or, in agricultural applications with low intensity, can provide habitats for flora and fauna to mitigate biodiversity losses. Additionally, agrivoltaics can reduce water consumption and provide attractive business models enabling a more sustainable expansion of PV in accordance with local stakeholders and the farming sector. Driven by the great diversity of agricultural practices and applications, the ongoing market launch has led to a vast variety of different technological approaches ranging from open systems on permanent and horticulture crops, arable farming, or permanent grassland, to closed systems like PV greenhouses.

This report provides a comprehensive overview of the definition of agrivoltaics, its current state of global research and development activities, with a focus on open questions regarding technical performance. The presented research activities aim to optimize design through integrated modelling and simulation approaches.

Creating a common understanding of agrivoltaics seems key at this early stage of the market uptake. Though, the diversity of agricultural applications represents a challenge for the definition of agrivoltaics which varies globally, influenced by legislative, historical, and societal factors. More narrow definitions typically focus on productive agriculture (e.g., food, fiber, dairy), while wider definitions also include non-productive agriculture (e.g., ecosystem services). Countries with a narrower definition like Japan, Germany, and France have also set minimum agricultural production requirements to ensure the agricultural relevance of agrivoltaic systems. In the United States of America, in contrast, there is no clear definition of federal level resulting in a rather wide definition that also includes non-productive agriculture activities. While broader definitions encompass a wider variety of technological approaches by also considering systems that are technically and economically like GMPV, this may diminish the agricultural relevance, potentially undermining the concept of dual land use. In contrast, narrower definitions often demand more technical adjustments, resulting in higher costs compared to GMPV. For example, overhead systems used in horticulture, which generally offer higher agricultural value, tend to have greater investment costs than interspace systems designed for arable or grassland farming.

To meet some countries' legal definitions of agrivoltaics, predicting the agricultural performance based on different agrivoltaics designs represents a crucial task before the installation of a system. While several modelling and simulation approaches have been discussed, only very few software or a combination of software is available to clearly address the market's needs. One main challenge is to enable comprehensive models of agrivoltaics that analyse crop relevant factors like light and water availability and the energy performance of the systems.

Unlike traditional agriculture or PV systems, monitoring of agrivoltaic systems requires the assessment of a much broader range of parameters. This task is especially complex due to the interactions between agricultural and PV-related factors. While a standardized monitoring can help to reduce this complexity, varying research questions and individual local conditions often demand for adjusted monitoring concepts. This report includes a guide to monitoring parameters commonly used to evaluate the overall performance of agrivoltaics systems and their respective relevance. Additionally, it provides an overview of existing regional databases of agrivoltaic facilities and proposes a framework for the global expansion of these databases to include installations worldwide.

Regarding operation and maintenance, this report provides an overview of common practices and challenges focusing on the PV components of agrivoltaic systems. Main identified aspects are soiling and increased damages or corrosivity of PV components due to farming activities and plant protection agents. Due to the few performed R&D works on existing projects and the resulting thin database, many questions remain still open. Future research could explore custom-designed farm equipment that can successfully operate within agrivoltaic facility configurations, anti-soiling technologies, integrated irrigation and PV module cleaning technologies, and novel tracking algorithms to reduce O&M costs.

The report also addresses legal and socio-economic aspects by summarizing the legal framework of six pioneer countries in Asia, Europe, and North America, highlighting main findings of factors influencing societal acceptance among different stakeholder groups, and providing an overview of the economic performance of agrivoltaic systems. Key drivers identified for successful project implementation are stakeholder involvement in an early stage, a supportive policy environment and incentive programs, and transparent performance standards. Also, the increasing importance of societal acceptance underpins the need to address existing limitations, gaps, and future opportunities of socio-economic and legal frameworks. Earlier works on agrivoltaics of the IEA PVPS addressed performance indicators and presented a showcase from Germany[1].

To reach our climate goals, there are strong arguments in favour of using both GMPV systems and agrivoltaics. A primary challenge for policymakers is choosing the appropriate technologies by aligning local land use goals with national and global PV development goals. In areas where agrivoltaics provides agricultural benefits high enough to justify higher cost, agrivoltaics should generally be preferred. However, regional factors may shift the balance, influencing the value of each approach. Given the wide variety of agrivoltaic technologies and the current limitations in accurately assessing key factors, an interdisciplinary collaboration through existing and future IEA PVPS Tasks would be valuable to address the diverse aspects of agrivoltaics technology.

[1] See IEA-PVPS Report T13-15:2021

1 INTRODUCTION AND MARKET OVERVIEW

Since the early 1960s, the world population has doubled and is projected to reach 9.8 billion people by 2050. This rapid growth is expected to intensify the global challenge of food security, one of the most critical sustainable development goals [3]. Food security is additionally challenged by climate change with its increasing frequency of droughts and severe weather posing significant risks to agriculture production [4]. At the same time, areas for the installation of GMPV are urgently needed to reduce greenhouse gas emissions and enable the transition to a decarbonized economy [5]. While GMPV systems are economically highly competitive with other energy conversion technologies, they take up significantly larger areas of land compared to other renewable energy technologies like wind turbines or fossil energy sources [1, 2]. This issue is especially relevant in densely populated countries with low availability of fertile agricultural regions where compromising on agricultural production represents an increasing obstacle for PV developers. Effective conservation strategies must be implemented to protect and restore natural habitats, promote sustainable land use, and reduce human-induced pressures on ecosystems. Such actions are critical for preserving biodiversity and maintaining ecosystem services that are vital for human well-being and the planet's health [6].

One solution to these challenges is integrating PV into multifunctional land use concepts that allow for agricultural or nature conservation actions while generating electricity [7, 8]. This way, land can be used more efficiently for several purposes while societal acceptance of the expansion of PV can be maintained.

The idea of agrivoltaics to enable the co-production of agriculture and PV electricity on the same land was first introduced in 1981 by Goetzberger and Zastrow [9]. After several years of research and development, the global market for agrivoltaics has experienced significant growth from around 5 Megawatt peak (MW_p) in 2012 to an estimated 14 Gigawatt peak (GW_p) in 2021[2] [10, 11]. This progress has been made possible mainly by government support initiatives, e.g., in Japan (since 2013), China (around 2014), France (since 2017), the USA (since 2018), Germany (since 2019), and Italy (since 2023, see Figure 1).

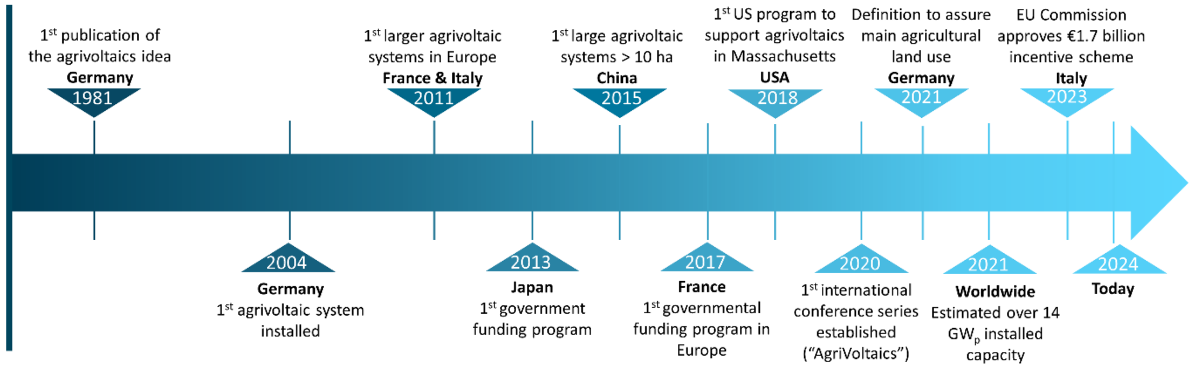

Figure 1: Timeline of the development of agrivoltaics [22].

Agricultural applications and the associated technical approaches differ significantly from country to country. Subsidy programs in Japan have led to more than 4000 small overhead systems tailored for horticulture and arable farming with an average system size of less than 0.1 hectares and often using special thin PV modules to achieve homogeneous light distribution at the crop level [12, 13]. In contrast, the USA market is mainly driven by large interspace

[2] These figures follow a narrow definition of agrivoltaics only considering systems with a significantly different design than GMPV.

systems on permanent grassland, focussing on pollinator-friendly grass mixtures, beekeeping, or sheep grazing as extensive agricultural activities [14]. This integration allows the systems to be configured as conventional GMPV systems, making them cost-competitive and independent from government subsidies [15–17]. An earlier IEA PVPS report already addressed performance indicators and presented a showcase from Germany, see Chapter 4.5 "Performance indices for parallel agricultural and PV usage" and Chapter 5.3 "Performance of agrivoltaics systems: a showcase from Germany" of report IEA-PVPS T13-15:2021.

Figure 2: Some of the different agrivoltaics approaches. a) Top left: Large scale facility in China with moderate higher vertical clearance compared to GMPV, © Fraunhofer ISE; b) top right: Agrivoltaics in French viticulture; © Sun'Agri; c) bottom left: Apple farming in Germany, © Fraunhofer ISE; d) bottom right: Agrivoltaics with sheep grazing in USA, © Lindsay France, Cornell University. A more comprehensive classification of agrivoltaics can be found in Chapter 2.

Due to the wide range of agricultural practices and the resulting variety of integrating PV into agricultural activities or vice versa (see Figure 2), there is no "one-fits-all" approach, and defining uniform requirements for agrivoltaics remains challenging. To provide a better overview of the diversity of agrivoltaics, Chapter 2 of this report sheds light on definitions, classifications, and where to draw the line between agrivoltaics and GMPV.

Governmental support initiatives typically include legal definitions that set minimum requirements for the intensity of agricultural land use involved, e.g., a certain threshold of agricultural yield or a minimum share of land dedicated to farming. To meet such requirements, modelling and simulating the impact of PV systems on agricultural performance represents a central exercise when designing an agrivoltaic system. To address the rising number of tools and the need to predict agricultural yields in agrivoltaic systems, Chapter 3 provides a comprehensive overview of modelling and simulation approaches for optimizing agrivoltaic system designs.

Since agrivoltaics is still in its infancy and most of the existing facilities have only been operating for a few years, Chapter 4 and Chapter 5 address first experiences and open questions of monitoring, operation, and maintenance issues. Both chapters also address first experiences and open questions of monitoring and control schemes as well as operation and maintenance issues. Chapter 4 and Chapter 5 also include a summary of monitoring parameters, a framework for agrivoltaics databases, optimized tracking algorithms, and failure modes and effects analysis.

Challenges in the market uptake for agrivoltaics include higher levelized cost of electricity (LCOE) compared to GMPV, higher communication efforts for intersectoral collaboration, acceptance losses in case of insufficient level of agricultural activities, and regulatory barriers that may arise due to an unclear land status. Chapter 6 provides an overview of legal frameworks in pioneer countries and how they tackle those challenges. It also addresses socio-economic aspects highlighting opportunities of stakeholder involvement as well as gaps, limitations, and emerging trends of socio-economic and legal frameworks. In summary, the global market for agrivoltaics is poised for continued growth as players recognize the economic, environmental, and social benefits of integrating agriculture and solar power conversion. As technology advances and awareness increases, agrivoltaics will likely play an increasingly important role in the transition to more sustainable and resilient energy and agricultural systems worldwide.

2 TERMINOLOGY, CLASSIFICATION, AND KEY PERFORMANCE INDICATORS

2.1 Terminology, definition, and classification

Given the growing interest and the various open questions and challenges in agrivoltaics, consistent and precise terminology is a prerequisite for efficient and transparent communication. Various terms have been introduced to describe the concept of agrivoltaics. Promoted by pioneer Akira Nagashima, since 2003, Japan has used the term "solar sharing" to refer to agrivoltaics [18]. In 2011, the term "agrivoltaics" was introduced by Christian Dupraz et al. in their paper "Combining solar photovoltaic panels and food crops for optimizing land use: Towards new agrivoltaic schemes [7]." It was the first time a terminology for agrivoltaics was suggested in a peer-review paper. The term "agrivoltaics" represents a fusion of "agriculture" and "photovoltaics," symbolizing the combination of agricultural activities with the conversion of solar energy. Since 2011, China's regulatory framework has supported agrivoltaics, sometimes referring to it as "PV+" [19]. In Germany, the term "agrophotovoltaics" was introduced by Fraunhofer ISE, drawing parallels with established agricultural practices such as agroforestry, agrofuels, and agroecology [20]. Today, the standard term in the German language is “Agri-Photovoltaik (Agri-PV)” [21, 22]. In Italy, variants such as "agrofotovoltaico" or "agrivoltaico" are used [23–25], while in France, the standard term is “agrivoltaïsme” [26].

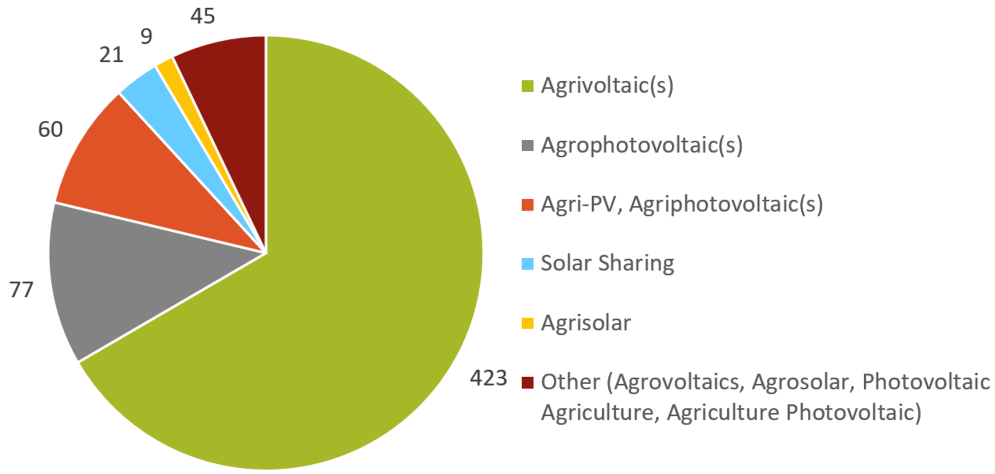

Figure 3: Terminologies used in publications until May 2024 (n=635).

While beside "agrivoltaics" also other terms describe the same concept in the English language, e.g., "agriphotovoltaic(s)" or "agrovoltaics," a review of 635 peer-reviewed papers shows a consensus in science to use the term agrivoltaics (see Figure 3). Looking at the development of the terms used over time, as shown in Figure 4, before 2020, it was not clear whether "agrophotovoltaics" or "agrivoltaics" were used more often. Since then, though, the growing scientific community has aligned increasingly with a clear majority of 85% of papers published in the first five months of 2024 using the term "agrivoltaics" (n=68). Regarding spelling and grammar, agrivoltaics is generally not regarded as a proper noun and is therefore not capitalized. Analogous to "photovoltaics," agrivoltaics is a singular term, and the adjective form is "agrivoltaic." Standard abbreviations are AV, AVS (for agrivoltaic systems), APV, or agriPV (both for agriphotovoltaics), with the latter appearing in different spelling variants (Agri-PV, agri-PV, AgriPV), see for instance Chatzipanagi et al. [27]. In this report, we use agrivoltaics in the text and—where needed—the abbreviation APV in graphs or tables.

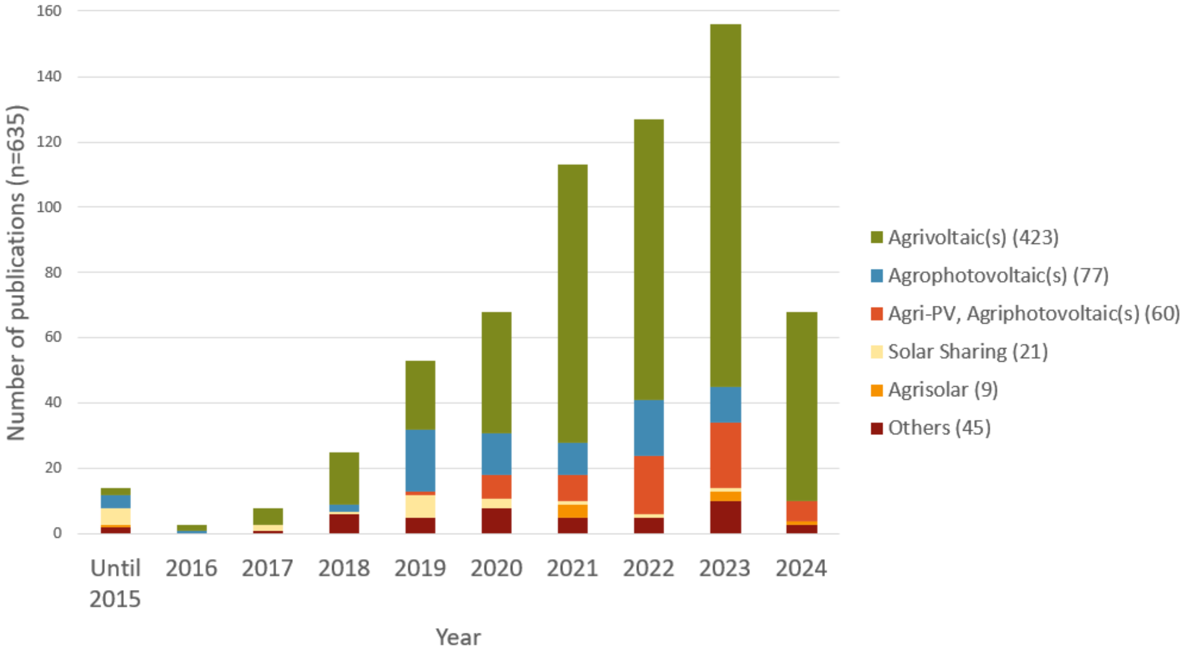

Figure 4: Terminology used in scientific publications per year. The number of publications mirrors the growing interest in the technology and the trend to use agrivoltaics as the standard term.

While all these terms and abbreviations can be considered synonyms, their respective regional backgrounds might indicate slightly different concepts.

Regarding the definition of agrivoltaics, next to clear terminology, creating a shared understanding of agrivoltaics represents a crucial task in harnessing its full potential. This necessity is particularly underpinned by the high number of involved stakeholders, the novelty of the technology, and the great diversity of agriculture that results in a wide range of agrivoltaics concepts and applications. Also, the need to adjust the legal framework to overcome legal barriers identified in several countries [20] highlights the importance of setting criteria defining agrivoltaics in its different variants. Such criteria, which should be at least partially measurable and verifiable, reduce ambiguities and pave the way for implementing agrivoltaics policy frameworks by guiding policymakers on differentiating agrivoltaics from GMPV and implementing control and sanctioning mechanisms. Similarly, for farmers, industry stakeholders, and researchers, a common understanding supports the adoption of agrivoltaics on a broader scale by increasing transparency, improving communication, facilitating cross-study comparisons, and identifying and promoting best practices.

The baseline of an agrivoltaics definition is the colocation of agriculture and PV power production [7, 9, 22, 28]. While earlier concepts of agrivoltaics understood colocation as a dual land use on two layers, i.e., high elevated PV modules with agriculture activity below, for some years, a more comprehensive definition also considers concepts that use the space between PV modules installed on ground level from [29] (see Figure 5).

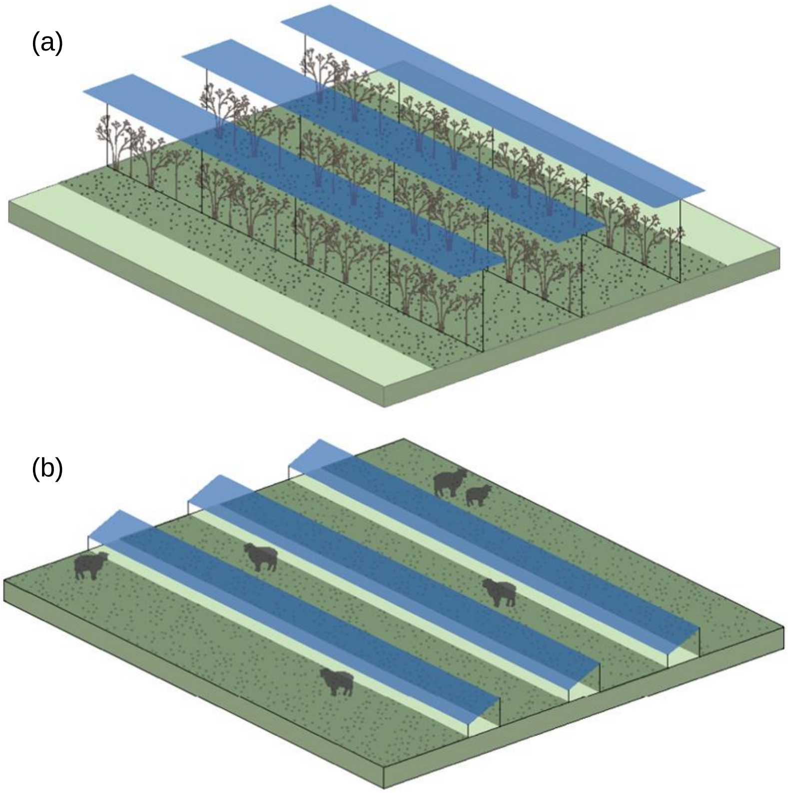

Figure 5: (a) Overhead agrivoltaic system with fixed modules. (b) Interspace agrivoltaic system with fixed modules and sheep grazing. Illustrations from Biró-Varga et al. [29].

This distinction between overhead and interspace systems suggests that a common understanding of agrivoltaics should include both narrower and broader definitions. This would facilitate the identification of trends in cost, land use efficiency, technical designs, or other aspects related to the different system approaches or application areas.

To ensure the co-locating character, it may be useful to set a limit in the spatial distribution of the land parcels for interspace systems. One possible requirement could be significant interactions between the agricultural and the PV areas [14]. If the agricultural and the PV land parcels are too far from each other so that no significant interactions exist, it seems not plausible to consider such systems as agrivoltaics.

However, a concrete quantification of the allowed spatial distribution depends on several factors, e.g., the kind of agricultural activity and the local land structure. This example already indicates that whether a project can be considered agrivoltaics or not is ultimately decided on the project level.

Beyond the colocating character of a project, the two involved land use activities, agriculture, and PV power production, must be clarified and specified. While the definition of PV power generation is generally less challenging than that of agriculture activities, the fusion of "agriculture" and "photovoltaics" represented in the term "agrivoltaics" implies that solar energy projects only qualify as agrivoltaics if they include PV technologies. However, solar energy projects such as solar thermal or concentrated solar power exhibit several aspects that could justify considering them as agrivoltaics. Notably, the constructive design and the general visual appearance of larger solar thermal projects can be very similar to agrivoltaic systems. Even though the relevance of those projects is still minor, not considering them might restrict their access to existing legal frameworks for agrivoltaics, hence curtailing their future potential of combining them with agricultural land uses. This example might support a broader understanding of agrivoltaics concerning the solar energy technologies employed.

Regarding agriculture, the wide range of land use forms suggests specifying in more detail which agricultural activities qualify as such in the light of agrivoltaics. One definition criterion frequently used for defining agrivoltaics is the solar sharing character, implying a simultaneous involvement of photosynthesis and PV [14, 22]. Following this criterion, PV rooftops on barns or staples cannot be considered agrivoltaics. The same holds for the indoor cultivation of mushrooms. Despite the Japanese origin of the term solar sharing, the Japanese regulation considers mushroom cultivation an agrivoltaic activity [13].

This criterion needs to be further clarified in animal husbandry. Marketable products like meat, milk, or eggs are only indirectly the result of photosynthetic processes. Even more ambiguous, supplementary fodder sources can reduce the relevance of the involved photosynthesis in the area to a neglectable level, e.g., in the case of poultry raising. In intensive livestock farming, no feed can grow on the land due to the animals' high stocking density.

In aquaculture applications, the situation is similar. Although the cultivation of aquatic plants, such as algae or lotus, directly involves photosynthesis, the production of aquatic animals like fish, crustaceans, and molluscs relies on photosynthetic processes only indirectly and only when algae contribute to their feed composition [30]. In animal husbandry—both on land and in water bodies—though, complying with the solar sharing character might not only be limited to photosynthetic processes since, arguably, sunlight is also relevant for the animals for orientation, well-being, and health.

Similarly, agrivoltaic systems that focus on biodiversity enhancement or beekeeping directly or indirectly depend on photosynthetic processes. Some biodiversity-enhancing measures, like the establishment of stone walls or wetland habitats, might even reduce the overall level of photosynthetic processes in the area compared to a GMPV on permanent grassland. On the other hand, the ultraviolet light spectra could be important for pollinators to orient themselves and identify flowers. While showing several differences to open agrivoltaic systems, PV greenhouses clearly meet the solar sharing criterion. Other indoor farming methods with opaque building envelopes that involve photosynthetic processes powered by artificial lighting, such as vertical farming, represent another ambiguous application as the sunlight is not instantly shared. Here, an additional requirement for qualifying as an agrivoltaic could be that on-site electricity powers artificial lighting.

Accordingly, the solar sharing criterion, which involves photosynthesis and PV, is fully met only in plant cultivation, while applications of animal husbandry, aquaculture, biodiversity-promoting measures, or vertical farming comply with it only partially or not at all.

Another definition criterion for agrivoltaics is primarily agricultural land use [21]. However, determining whether the land is used primarily for agriculture or PV is not easy. Indicators for primary land use can be the respective political land use goals, the administrative and actual status of the land, the intensity of agricultural land use, and the degree of involvement of agricultural stakeholders [14, 20, 31, 32].

While the administrative and the actual land status should ideally reflect the respective political land use goals of an area, in practice, there is often a gap between both, e.g., when political goals change more swiftly than the administrative status adjusts. In agrivoltaics, political land use goals seem particularly relevant concerning conflicting environmental protection goals and agricultural productivity. Following the definition criteria of the simultaneous involvement of photosynthesis and PV, agrivoltaics, in a narrow understanding, focuses on productive agricultural activities, e.g., food, fibre, or feed production. If an agricultural area's political goal or administrative status focuses on environmental protection, non-productive agricultural activities, e.g., the increase of soil organic matter, biodiversity, and other ecosystem services, might arguably represent a primary agricultural land use. If land use goals are not sufficiently defined by policy or administrative status, they might be derived from previous land use activities. Suppose the area is not officially classified as agricultural land from a legal point of view, it seems impossible to fulfil the definition criterion of primary agricultural land use even if the land is used for agriculture. In this case, the first step is to acknowledge the agricultural status of the land formally.

If an area is classified as agricultural land, the most common method to ensure its primary agricultural use is to verify whether the agricultural activity is sufficiently intense [24, 31–33]. There are generally two approaches to verifying the level of agricultural activity: first, setting criteria for the intensity of the agricultural activity; second, restricting the intensity of PV land use. The reasoning for disregarding PV intensity is that as long as the integration of PV systems does not significantly impede the primary agricultural use of the land, the original character of the land use remains unchanged. Additionally, this approach ensures that technical innovations are not curbed, allowing for both high agricultural and high PV intensity [20]. Typical parameters for ensuring a sufficient intensity of agriculture are the level of agricultural yield, the share of the area under agricultural cultivation, or the economic value of the agricultural activity [31, 32, 34, 35]. Within open applications on plant cultivation, overhead systems on permanent and horticulture crops typically show the highest intensity of agriculture measured by those parameters [36, 37]. To quantify the intensity of agricultural activity, the former land use or comparable agricultural cultivation can serve as a reference.

However, determining the primary land use out of two collocating activities might also consider the relation of both activities. The definition of primary land use is implicit in several legislations that additionally restrict the intensity of PV land use [25, 31, 32, 38] A potential reason for limiting PV intensity, especially in applications on arable land, is the competition for sunlight and space, which creates a trade-off between agricultural and PV land use. This competition occurs when the shading from PV modules restricts plant growth [36], or when the installation of PV components hinders the use of machinery. Another argument is that—especially in ecovoltaics or applications with animal husbandry—the respective revenue shares incentivize favouring a higher installed PV capacity over agricultural performance, marginalizing the agricultural activity in the design phase [20]. An overview of revenue shares of different agrivoltaics applications is illustrated in Figure 17 in Section 6.4.2. Typical parameters to restrict the intensity of the PV land use are the level of shading or the PV module ground cover ratio (GCR), which is discussed in Table 3 of Section 2.2.2 [20, 39]. While compliance with such parameters is relatively easy to control, they might lead to higher costs without considering the specific needs of the respective agricultural applications [20, 40]. Finally, the involvement of agricultural stakeholders can also contribute to the primary agricultural land use character of agrivoltaic projects. One example of how this can be specified comes from the French Agency for Ecological Transition (ADEME), which suggests the participation of an active farmer to ensure that agricultural perspectives are sufficiently considered, e.g. in terms of financial decision-making [32].

Further definition criteria are increased land use efficiency, synergies, and interactions between agriculture and PV power production [14, 20, 31, 32]. Closely related to the collocating character discussed above, land use efficiency is typically measured by the land equivalent ratio (LER). Unlike the primary agricultural land use criterion, the LER always considers electrical yield. For non-productive agrivoltaics, the calculation of the LER is challenging and seems only meaningful when considering the efficiency of a land area in providing ecosystem services. Notably, a minimum intensity level of the PV land use plays no or only a minor role in defining agrivoltaics in most legislations[1]. Table 1 of Section 2.2.2 presents more details of the LER.

The degree of synergies and interactions reflects the level of integration between the two land use activities. While interactions can include adverse effects, synergies refer to interactions where at least one of the activities benefits. Accordingly, synergies are a subset of interactions. Although synergies and interactions often contribute directly to land use efficiency, quantifying them can be challenging. This challenge is due to the need to account for and compare a potentially high number of parameters and site-specific effects that manifest in various areas or dimensions.

Dual land use applications that do not sufficiently meet the definition criteria of agrivoltaics can be summarized under the term agrisolar [28]. This term is sometimes used to refer to a broader range of solar power technologies within an agricultural context. It represents a broad definition of agrivoltaics, encompassing, for example, PV installations on opaque buildings and solar energy projects that do not involve PV technologies.

Figure 6 illustrates a hierarchy of narrower and broader definitions of agrivoltaics, summarizing the discussion above. Systems and applications are ranked based on the extent to which they meet the four main criteria: (i) land use efficiency, (ii) photosynthetic processes, (iii) intensity of agricultural activity, and (iv) the synergies and interactions involved. Another ranking could happen by using other criteria or considering local factors like climate or soil quality.

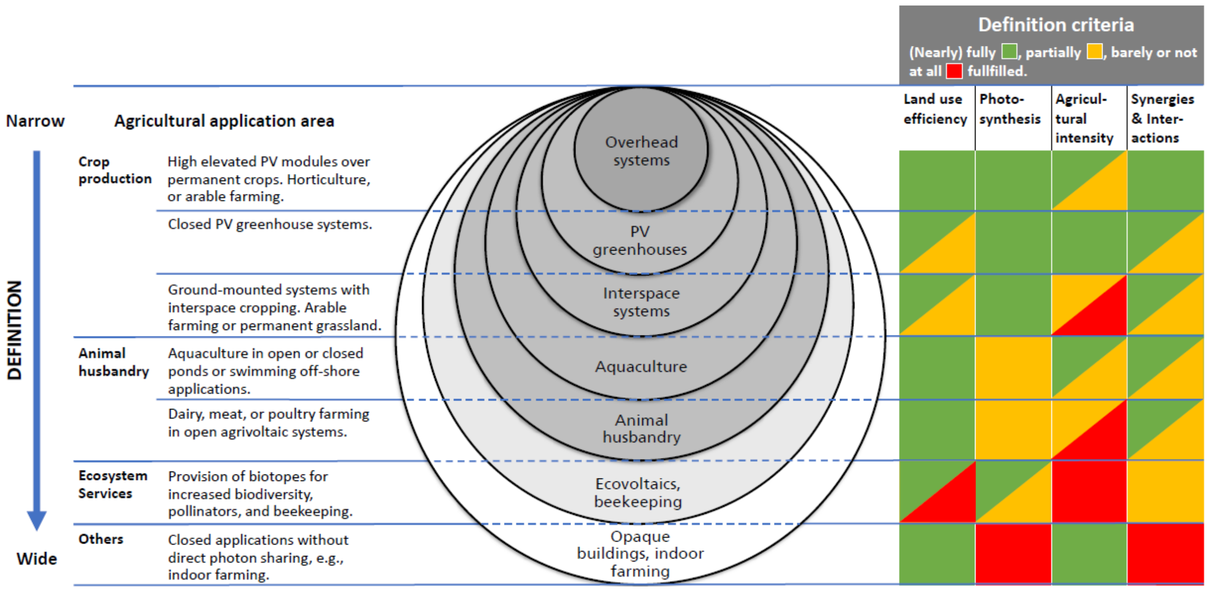

Figure 6: Definition hierarchy of agrivoltaics. Systems and applications are ranked after their level of fulfilling the four main definition criteria. The level of fulfillment can vary depending on the specific crops or other factors of the respective systems and applications. This is represented by triangles of distinct colors. © Fraunhofer ISE

To structure the manifold variants of narrower or broader definitions for agrivoltaics, a classification of the respective technical approaches and agricultural applications helps to gain a better overview of the diversity of agrivoltaics. The first attempt to classify different agrivoltaic systems dates to a work by Lasta and Konrad in 2018 [41]. Later revisions of this work, carried

[1] Italy represents an exception with a required installed PV capacity of at least 70% compared to average GMPV [35].

out by Willockx et al. [42] also consider common approaches with tracked or non-tracked installed PV modules. Figure 7 illustrates a revised version of a more recent classification in Trommsdorff et al. [43] and Gorjian et al. [97] that distinguishes between open and closed systems and identifying hybrid forms also considering extensive agriculture and indoor farming as broader definitions of agrivoltaic systems. The authors classified agrivoltaics by system type (closed or open), structure type (overhead PV, interspace PV), module tilt (non-tracking, single-axis tracking, dual-axis tracking) and application type (permanent grassland, arable, horticulture, aquaculture). Ma Lu et al. [44] added a further layer to the classification to reflect the transparency of the PV modules deployed in agrivoltaic applications with three subcategories: opaque, semi-transparent, and transparent.

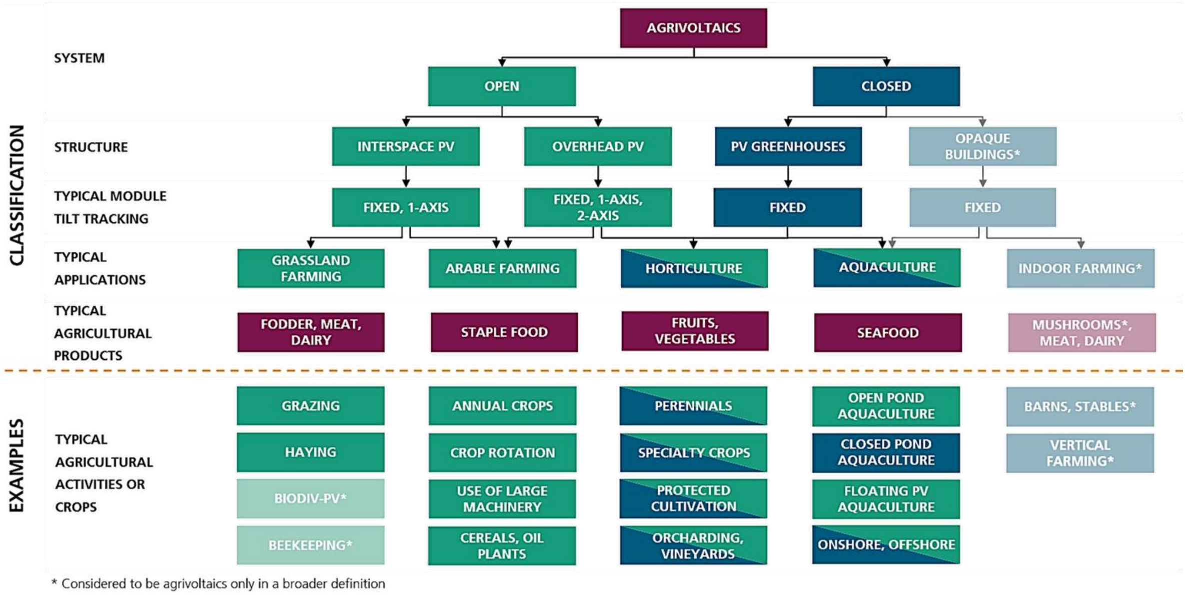

Figure 7: Classification of agrivoltaic systems according to Trommsdorff et al. [43] based on the original version of Gorjian et al. [97]. Green boxes represent open agrivoltaic systems, blue boxes represent closed systems, and green-blue boxes indicate that these applications can be either open or closed systems.

GMPV projects sited on land that is typically unsuited for agricultural production—such as contaminated land or areas with low fertility—are likely to be more readily accepted by local stakeholders. These sites are particularly suitable for low-intensive agrivoltaic systems that aim to enhance biodiversity and improve the ecological value of the land. If low soil fertility is the result of degraded soils suffering from low water availability, agrivoltaics could enable soil fertility to be restored by reducing evapotranspiration, increasing soil moisture, and thus increasing carbon fixation. While previously tilled and intensively used agricultural land is usually well suited for overhead or interspace agrivoltaics projects focusing on agricultural production, from an ecological point of view, those areas represent a remarkably high potential for improving local biodiversity. In contrast, greenfield sites that have not been used in the past for human use and that show a high ecological value should instead not be considered for the development of either agrivoltaics or GMPV to not exacerbate the ongoing anthropogenic biodiversity crisis.

Several terms were introduced to specify agrivoltaics applications in more detail, e.g., cropvoltaics, fruitvoltaics, cowvoltaics, chickenvoltaics, or ecovoltaics. Such specifications are challenged when agricultural activity might change during the operation of the systems. To a lower extent, this might however also be the case for the general classes illustrated in Figure 7.

2.2 Key performance indicators of agrivoltaics

To ensure high quality in agrivoltaics project development, minimize risks for both farmers and PV developers, and provide a comprehensive report on the agricultural concept within the project, it is essential to establish clear key performance indicators (KPIs). These KPIs serve as critical benchmarks to guide project success, streamline processes, and provide transparency throughout the project's lifecycle. Furthermore, policymakers also need guidance on how agrivoltaics projects can be differentiated from GMPV, not only legally, but also by control mechanisms that can be evaluated and benchmarked. A reduction in ambiguity increases the probability of the introduction of a holistic agrivoltaics policy framework on a national level. Key metrics of agrivoltaic systems could be classified into yield, cost, and design metrics.

2.2.1 Yield and cost KPIs

Table 1 lists yield KPIs distinguishing electrical, agricultural, and combined yields. Table 2 presents cost KPIs also considering environmental impact.

Table 1: Yield KPIs of agrivoltaic systems.

Electrical yield KPIs

Parameter	Explanation
Performance Ratio (PR)	The PR is given by the ratio between the actual annual electrical energy yield and the theoretical annual energy yield.
Specific yield	The electrical yield as electricity produced per nominal power is key in several financial analyses typically indicated as kWh/kW_p.
Energy yield per area	Represents the ratio between the energy conversion and the total land area of the system over a period. It provides insights into the final electrical yield of different agrivoltaic configurations by allowing direct comparison between distinct systems [42].

Agricultural yield KPIs

Parameter	Explanation
Agricultural yield per area	Represents the ratio between the agricultural output and the total land area of the system over a period. The typical agricultural outputs are fresh biomass and dry biomass [42]. The amount of biomass can be measured through different approaches: (i) using hand-collected samples across various small plots, (ii) employing remote sensing techniques like Normalized Difference Vegetation Index (NDVI) from drones, and (iii) using harvesting machines that record harvest yields over extensive areas. The agricultural yield is typically averaged over multiple seasons.

Environmental yield KPIs

Parameter	Explanation
CO_2 capturing	CO_2 captured due to the growth of the crops.

Financial yield KPIs

Parameter	Explanation
Annual financial return	Measures the percentage change in an investment's value over a year, reflecting income and capital gains or losses. It shows the profit or loss earned relative to the initial investment. For agrivoltaics, the annual return typically includes income from selling electricity and agricultural products.
Return on investment (ROI)	Ratio between net income and investment. In agrivoltaics, this typically refers to the income generated by electricity and agricultural sales over the operation period of the facility divided by agricultural and electrical investments.

Combined yield KPIs

Parameter	Explanation
Land Equivalent Ratio (LER)	Indicator that can be used to calculate the land use efficiency in agrivoltaic systems. It represents the sum of the relative agricultural yield and the relative PV energy conversion. The relative agricultural yield is the ratio between the yield of the agrivoltaic system and the yield of a traditional monocropping system. The relative PV energy production is calculated as the ratio between the energy converted per area in the agrivoltaic system and the energy converted per area in a traditional GMPV. An LER>1 indicates that the agrivoltaic system provides a gain versus separate PV and agricultural activities occupying the same land area [7].
Land Productivity Factor (LPF)	Evaluates the productivity of agrivoltaic systems by considering the sum of the relative yields of energy conversion and the accumulated PAR reaching the crops [45].
Water Productivity (WP)	Represents the ratio between the agricultural plant/biomass production and the total amount of water consumed by the crops (actual evapotranspiration), expressed in kg/m³ [46]. Plant transpiration is the process that allows crops to regulate their temperature and is strongly linked to the photosynthesis process. The combination of both soil evaporation and plant transpiration is called evapotranspiration. The higher the value of WP, the more effective water is used for agricultural production. At the plant production system level, a decrease in consumed water can be directly translated to water savings, and an increase in productivity can be attributed to improved management practices that address the specific plant physiology of the crops [47].

Water Use Efficiency (WUE)	Unlike other efficiency indicators, WUE is not a dimensionless ratio but represents the product/gross water available or applied (rain + irrigation). It should only be used on plot or field level as a measure of localized efficiency. However, it does not allow allocation of what the water is used for or where it went. The methodology is easier to use than those of WP as it is not required to calculate actual evapotranspiration [48, 49].

Table 2: Cost KPIs of agrivoltaic systems.

Environmental costs KPIs

Parameter	Explanation
Relative material consumption	Materials used (e.g., metal, concrete) for the mounting structure, per kW_p PV nominal power.
Carbon footprint of the mounting structure	Represents the carbon emissions associated with the production of electricity from agrivoltaic systems from the point of view of the mounting structure. Typically, in agrivoltaic facilities, the mounting structure needs to be adapted to the crops and the agricultural management. In some cases, this implies the use of more kg of steel per kW_p, which can increase the carbon footprint when compared against traditional GMPV [50].

Financial cost and levelized costs KPIs

Parameter	Explanation
Levelized Cost of Electricity (LCOE)	Index used to quantify the cost of producing a kWh of electricity through an agrivoltaic installation [51]. It is typically employed to compare different energy conversion technologies. Also, it can be utilized to economically assess various agrivoltaic configurations and technologies [52]. The LCOE does not consider agricultural production.
Net Present Value (NPV)	Expresses the profitability of an investment and is calculated as the difference between the net present value of cash inflows and cash outflows. Its value is positive if the investment returns a profit over a defined period [53].
Capital expenditure (CAPEX)	Refers to the initial costs associated with establishing an agrivoltaic system. This type of CAPEX involves a wide range of investments that are necessary for both the energy and agricultural aspects of the system, often requiring more complex infrastructure than either sector alone.
Operating expenses (OPEX)	Refer to the ongoing costs required to run and maintain an agrivoltaic system. Unlike CAPEX, which covers initial investments in long-term assets, OPEX focuses on the day-to-day operational expenses necessary to keep the system functioning efficiently.

2.2.2 Key design metrics

Local environmental and climatic conditions, crops, farming systems, and socioeconomics influence the design of an agrivoltaic system. In general, the layout of the system configuration needs to be optimized to allow sufficient sunlight to reach the underlying crops. The layout depends on the amount of solar irradiation at the location and the shade tolerance of the target crops. In an area receiving high solar irradiation (and PAR), a denser PV module layout would be possible when growing shade-tolerant crops compared to an agrivoltaic system at higher latitudes and with less shade-tolerant crops underneath [21]. The same applies to water-stressed regions where the limiting factor for plant growth is water instead of sunlight. For interspace PV, the pitch distance (row-to-row spacing) needs to be set at a distance that allows agricultural activity to be adequately conducted. The system design should ensure that any machinery used can pass unobstructed through the rows, avoiding damage to the PV infrastructure. For overhead systems, the height of the PV modules that will facilitate farming underneath depends on the planned crops and cultivation methods. Taller crops and mechanized farming will need a taller PV module mounting structure than shorter, hand-picked crops. Even where large agricultural machinery is not used, PV modules might need to be placed high enough to avoid a negative impact on plant growth [30]. Besides the agricultural considerations, the vertical clearance of overhead systems are crucial economic and technical factors (i.e., wind load) also affecting social acceptance (i.e., system aesthetics) and environmental impacts.

The orientation of PV modules affects how much sunlight they receive, as well as how dust and dirt accumulate on them (see Chapter 5.2.1). Also, the orientation can influence the balance between solar energy conversion and agricultural production throughout the day or year. For example, vertically installed bifacial PV modules facing east and west primarily generate electricity in the morning and evening. This design leaves midday sunlight fully available for crop photosynthesis. Generally, fixed tilt PV systems are oriented towards the equator to optimize sun exposure, facing south in the northern hemisphere and north in the southern hemisphere. However, this equator-facing orientation results in an uneven distribution of sunlight to the crops below the PV modules. Adjusting the orientation to either northwest, northeast, or east-west further improves light distribution below the PV modules and enhance homogeneity [57]. Regarding shifts of the production focus within a year, higher tilt angles in an equator-facing fixed-tilt PV system can increase electricity production during winter while providing more sunlight for crops during summer.

Different PV module technologies can be used for agrivoltaics. Higher efficiency and lower weight must be balanced with the PV module price, as is the case for all PV installations. The competitive price of bifacial PV modules, combined with the higher energy yield through increased height and higher rate of reflection of sunlight make the application in overhead agrivoltaics more attractive. In vertical agrivoltaics systems, using bifacial PV modules with high rear side efficiencies is key to maintain the overall efficiency of the system. Semi-transparent PV modules with a higher rate of transparency than conventional opaque PV modules can provide more sunlight for the crops. From an economic perspective, high market value crops can rather justify the use of more expensive semi-transparent PV modules to increase the light distribution to the area below. However, this needs to be assessed on a case-by-case basis, with the overall site economics determining the eventual selection of module technologies.

Table 3 presents the main design metrics used for agrivoltaic systems.

Table 3: Key design metrics of agrivoltaic systems.

Agrivoltaic system design metrics	
Parameter	**Explanation**
Nominal power	Power of PV modules at standard test conditions with additional information of alternating current (AC) nominal power of the inverter or batteries capacity used.
Irradiation	Annual global horizontal solar irradiation.
Orientation	Including tilt and surface azimuth angles of the PV modules for fixed tilt systems or tracker torque tube azimuth for tracked systems. The orientation of PV modules influences the balance between solar energy conversion and agricultural production throughout the day or year.
Ground Cover Ratio (GCR)	The GCR is usually defined as the ratio of the PV module area to the total land area utilized by the agrivoltaic system [42, 55]. The definition of both the PV module area and the total land area can be specified in different ways, e.g., with or without considering the headland. The GCR is a central parameter to consider as it influences the level of total irradiation on the crops. However, as the orientation and, accordingly, also the area sheltered by PV modules are not considered in the standard definition of the GCR, the actual implication parameter might be somewhat misleading. Alternatively, hence, the GCR can be calculated by the projected covered area from above–this way really indicating the share of the covered area. For tilted PV modules, accordingly, the projected GRC is always smaller than the GCR calculated in the usual way [205].
Pitch distance	The distance between PV module rows. The larger the pitch distance, the higher the irradiation (i.e., the lower the shading) at crop and ground level. Usually, also light heterogeneity on ground level increases with larger pitch distances which can be challenging particularly in industrialized arable farming systems where homogeneous ripening of crops is key [42, 55, 56]. Furthermore, the planting distance of crops and the planned machine employment play an important role in determining a suitable pitch distance [56].
Vertical clearance	The vertical clearance indicates the distance between ground level and the lowest point of PV module rows mainly used for overhead systems. Crop height and size of agricultural machinery are primary factors in determining the vertical clearance. The vertical clearance of the system influences the material requirement of the racking and, hence, the CAPEX of a system and is directly correlated with light homogeneity [56–58].
PV module technology	Various PV module technologies can be used, each with trade-offs in efficiency, weight, and cost. Bifacial PV modules become the standard being particularly attractive for overhead or vertical systems due to their higher energy yield from increased height and sunlight reflection. Semi-transparent PV modules, which allow more sunlight to reach crops, are rather used for high-value crops, though their higher cost must be justified by the specific economics of the site.

System technology	In the literature, distinct PV systems have been explored: the mechanical tracker system and the fixed system. In the mechanical tracker system, PV modules are installed on a single or dual-axis rotational mechanical system, allowing for the adjustment of PV module positions. This adaptability ensures that the sunlight requirements of plants can be promptly met with appropriate tracking strategies. The tracker system offers significant flexibility, effectively mitigating the detrimental effects of shading on crops, particularly in unfavourable weather conditions when irradiation levels are low. More details on bifacial tracking systems can be found in the report of Subtask 2.3 [59].
Mounting structure	Concrete foundations in agrivoltaics pose challenges by creating permanent structures that affect crop growth and reduce cultivable land [56]. Alternatives like screw piles are preferable, as they minimize soil disturbance, preserve soil health, and allow easier removal, while the choice of mounting structure also depends on local wind conditions [57, 60].
Water distribution	Indicates the uniformity of water, particularly rainfall, distributed across the ground level of an agrivoltaic system. The configuration of the PV system plays a pivotal role in determining how rain is redistributed on the soil surface [61].

Widespread acceptance of agrivoltaics may be jeopardized if too much metal and concrete encroach on agricultural land to construct the PV systems. The ecological claim of reducing greenhouse gases through PV electricity can be diminished if the CO_2 footprint of the mounting structure is of the same order of magnitude as that of typical PV modules. At the same time, it is evident that the costs of the PV module structure, especially for the overhead systems, are proportional to the amount of metal and are typically higher than the classic PV module. It is therefore recommended to use the simple KPI kg metal per kW_p PV nominal power as a comparative aid for comparing various agrivoltaics concepts. In the still very young agrivoltaics sector, not many such system comparisons are currently possible. Nevertheless, the first vertical agrivoltaic systems could be compared with the overhead system from Heggelbach for illustration purposes and placed in relation to the technically related PV carport systems in terms of the supporting structure, as shown in Table 4.

Table 4: Amount of steel used in the PV mounting structure could exceed the CO_2 footprint of a regular PV module of about 30g CO_2/kWh [206].

PV Configuration	APV System	Annual MWh/ha	Steel intensity kg/kW_p	Carbon emissions per energy converted gCO_2/kWh
Height at top edge~2.8 m	 4100 kW_p system by Next2Sun in Donaueschingen, Aasen, Baden-Württemberg, Germany	343	40-70	5-9
Overhead height ~2-4 m	 System by Insolight in Conthey, Switzerland (http://insolight.ch)		60-80	8-10
Overhead height >5 m	 System of Fraunhofer ISE, Heggelbach, Germany	248	284	36

*Estimate: 2.5kg CO_2 per kg of galvanized steel

In a future circular economy, recycled steel, which some PV module suppliers already offer as green steel, will be used with a CO_2 footprint reduced by about a third. However, even then, the total costs of such green steel agrivoltaics facilities could only be cost-effective if the amount of metal per kW_p of PV power is again minimized.

3 MODELLING AND SIMULATION

Before installation, the fundamental steps for evaluating the profitability and projected performance of an agrivoltaic system are the simulation and optimization of the system design. Agrivoltaic systems are unique in their challenge to assess how the microclimate produced by the PV modules affects crop growth and, to a lesser extent, how the microclimate and crop growth affect PV production. Several software platforms or algorithms exist for modelling PV system yield, crop yield, and microclimate. However, the combination of these modelling needs makes agrivoltaic modelling unique. The lack of an end-to-end agrivoltaics modelling tool simultaneously simulating PV power output and crop yield highlights a significant area where further research and development are needed. Moreover, with the development of the agrivoltaics sector, many governments have found it necessary to revise or develop laws, standards, and guidelines for the PV and agricultural sectors. Some regulatory frameworks set specific design parameters which might include: (i) ratio of agricultural areas reserved for conventional agriculture [25]; (ii) ratio of the total land area occupied by the agrivoltaic system [25]; (iii) maximal reduction in irradiance received by the crops [62], and (iv) required minimum crop yield relative to conventional agriculture. Thus, it is imperative to consider both the PV production and crop yield in a holistic manner to ensure that a proposed agrivoltaic system is both cost-effective and in line with regulations.

Modelling of agrivoltaic systems is a scientific challenge. A diagram of the workflow for simulating agrivoltaic systems is depicted in Figure 8. Scientific challenges arise because crop production under shading conditions (i.e., shading cast by the PV modules and related supporting structures on the crops) is a relatively new area of research, both for experimentalists and modelers. Few research studies have been conducted on the effects of shadings produced by PV systems while the literature is more comprehensive on the effects of shading nets—materials used to cover crops and provide partial shade—on crop yield but for a relatively small set of crops [63, 64]. From a PV perspective, the scientific challenge is to understand how the microclimate produced by the agrivoltaic system affects (i) the albedo underneath the PV system, (ii) the shading scene, and (iii) the temperature conditions of the solar cells and thus their efficiency. Given the market trend for bifacial PV modules, estimating solar irradiance distribution at ground level becomes fundamental for assessing the irradiance incident on the rear side of the PV modules and, thus, the overall PV electricity production. In this context, crop selection becomes important because the rear irradiance depends on the albedo, which depends on the crop type and phenological phases. Standard PV system modelling procedures using fixed or limited albedo variation over time and space can thus miscalculate the rear irradiance and, thus, PV yield. Crop management practices can also affect soiling and thus PV yield performances. These are also market challenges because profitability is a fundamental issue independent of the business models adopted for the specific agrivoltaic project [39, 43] Actors involved in the project are advised to carefully assess the profitability of the project prior to installation. Additionally, an unconvincing report on the crop yield performance could result in the project failing to secure the benefits and privileges outlined in the legal framework summarized in Section 6.2.

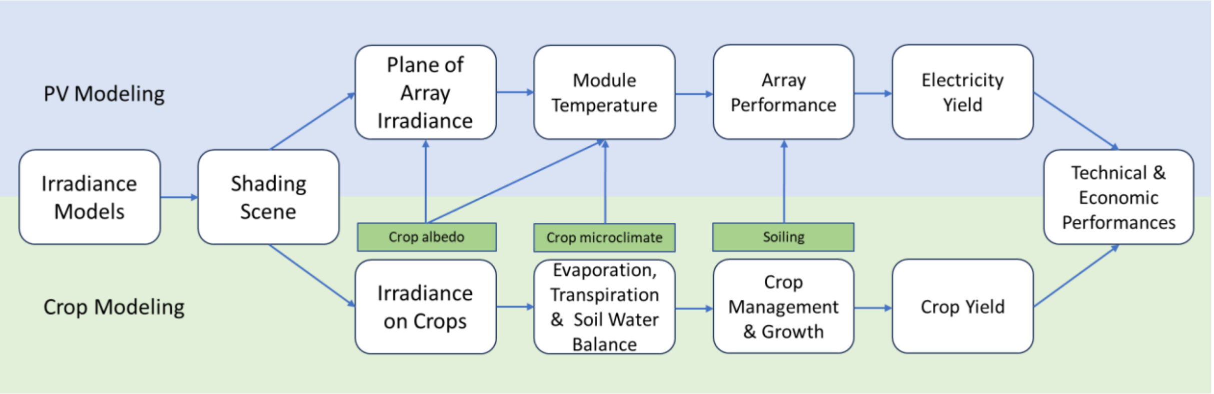

Figure 8: Simplified workflow for agrivoltaic systems simulation.

3.1 Meteorological data for agrivoltaic system modelling

Modelling agrivoltaic installations at various stages of development and operation demands information on the meteorological conditions at the site of interest for estimating crop growth and PV yield. For example, long-term historical data are necessary for site selection during feasibility studies. Similarly, in the project design phase, meteorological data is used to predict PV power output and crop yield for facility design and financing. Moreover, comparison between model output and performance indicators measured in real-time can enable performance evaluation and enhanced operation of the agrivoltaic system.

However, onsite measurements are often unavailable in the design phase of agrivoltaic systems. Typical meteorological year data is sometimes used for prospecting sites for conventional PV systems. Such data files contain 8760 hourly irradiance values, wind speed and direction, temperature, relative humidity, and barometric pressure, representing the typical conditions at a particular location over an extended period. Accurate datasets are essential for optimizing the design of the PV system in terms of power output. For agrivoltaic systems, multi-year datasets are advantageous since they also capture interannual variability. Considering more data is imperative to ensure a safe design, such as accounting for high wind loads.

Further, higher temporally resolved data should be used because it is crucial for studying the effects of shading on crops. Satellite or reanalysis data are valuable alternatives when ground measurements are unavailable. However, it is crucial to utilize datasets validated through ground measurements conducted on or near the site to reduce yield uncertainty.

The "Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Fourth Edition" [65] of the IEA PVPS Task 16 gives a comprehensive overview of all aspects of solar irradiance as well as other meteorological parameters relevant for PV applications. The handbook also includes agrivoltaics relevant parameters related to crops, such as photosynthetically active radiation (PAR), soil moisture, and humidity.

3.2 Software and methods for irradiance modelling

Irradiance modelling is a crucial aspect of agrivoltaic systems design and optimization, as it directly impacts both crop growth and PV module energy yields. In conventional PV systems, solar irradiation on the PV array is maximized to achieve the highest energy output while ensuring a safe system design and allowing for efficient O&M of the PV system. However, in agrivoltaic systems, the irradiance distribution must also be optimized to promote crop growth and allow efficient maintenance and harvest of the crops. To study the distribution of irradiance between crops and PV modules, research has focused on aspects such as decomposition models that decompose global horizontal irradiance (GHI) or PAR into beam horizontal irradiance (BHI) and diffuse horizontal irradiance (DHI) or relative PAR components [61, 62], transposition models that transpose GHI, BHI, and DHI into irradiance received to the plane of array [66, 67], and how the shading scene affects the irradiance reaching the PV modules and crops through view-factor analysis or ray-tracing techniques [68]. Most decomposition and transposition models were originally developed for conventional PV systems applications [66–68]. However, it is important to revisit these models from an agrivoltaic perspective since the crops influence available irradiance in terms of ground albedo that depends on the state and type of the crop [69]. Some decomposition models have been modified to estimate the PAR and the photosynthetic photon flux density (PPFD) in agrivoltaic installations [69–71]. Ma Lu et al. [69] assessed the performance of seven stand-alone models to predict the PAR with measurements recorded in three different Swedish locations. The best-performing models were Yang2 and Starke, showing a normalized root mean square error of 25.1% (Yang2) and 28.6% (Starke). Yajima et al. [70] developed a mathematical model for assessing PPFD under PV modules by relying on an all-climate solar spectrum model able to simulate the solar spectrum both in clear-sky conditions and in overcast conditions. The model was validated with PPFD measurements for various days with different weather conditions and under different PV tilt angles and in general showed rather good performances with most of the standard residuals comprised between -6 and -3.

Building on such models, various approaches and tools have been developed to specifically calculate the irradiance reaching the ground in agrivoltaic systems. Amaducci et al. [72] developed a software platform in Scilab to investigate the solar irradiation distribution at crop level by discretizing the ground with a mesh and calculating shading by PV modules using a Boolean approach, where unshaded areas receive GHI, and shaded areas receive only DHI. Similar methods were implemented by Campana et al. [67] with Agri-OptiCE® in Matlab®, Trommsdorff et al. [57] for overhead agrivoltaic systems, and Zainali et al. [73] for benchmarking three different agrivoltaic configurations. Zainali et al. [73] compared the results against two commercial software tools (PVsyst® and SketchUp®). Campana et al. [74] improved the shading analysis of Agri-OptiCE® by using a view factor approach considering PV module reflections on the ground. Katsikogiannis et al. [75] used the Radiance-based daylighting simulation tool Daysim to calculate ground-level irradiance for a fixed bifacial agrivoltaic array, while Prakash et al. [76] analyzed PAR distribution using Autodesk® Revit®. Wang et al. [77] developed an in-house tool to model the different irradiance components. They validated the tool against measurements from an agrivoltaic installation in the USA and found that their tool overestimated the global irradiance but underestimated the diffuse component. Bruhwyler et l. [78] deployed the ray casting algorithm from PyVista library to compute irradiation on ground in a vertical agrivoltaic system.

Spatial, and computational fluid dynamics (CFD) models customized to simulate the irradiance and the PAR distribution in agrivoltaic systems have been developed and validated. Tahir et al. [79] explored the spatial PAR heterogeneity under different agrivoltaic configurations and validated the model's results by using field measurements from an agrivoltaic system in the USA [80]. Zainali et al. [55] used a CFD model to map the global irradiance at ground level. They validated the results against actual field measurements taken in an agrivoltaic system in Sweden. They found that the model slightly underestimated the irradiance. Bruhwyler et al. [81] developed the Python Agrivoltaic Simulation Environment (PASE 1.0), where irradiance on the ground for a vertical agrivoltaic system was simulated and validated.

When assessing irradiance for plant growth, several key questions arise regarding how to best represent plants in 3D modelling and define ground-level crop growth zones. Plant shapes can be modelled using either simple shapes, which approximate the outer boundaries of the crops, or more intricate shapes, which attempt to replicate the geometry of plant organs faithfully and leaves in detail. Complex geometries attempt to realistically represent the shape of crops, facilitating the utilization of more intricate models used to evaluate crop photosynthesis and providing reasonable estimates of the 3D optical porosity. However, such approaches demand significantly higher computational resources due to the required spatial resolution and the number of points where irradiance must be assessed. It also restricts the use of simpler agronomic models developed based on a preliminary evaluation of the irradiance incident on the external canopy envelope.

In contrast, using basic shapes that depict the external envelope of crops reduces computational complexity, facilitating the direct utilization of parametric models that assess photosynthesis in the canopy based on the solar irradiation reaching its outer envelope. When employing these straightforward models, optical properties, including optical porosity, cannot be directly modeled and must be incorporated through a parametric model attached to the object's texture. In some agrivoltaic modelling tools such as LuSim, experience has favored the use of basic geometric shapes alongside parameterized optical properties [82]. The right trade-offs between model complexity and accuracy remain to be evaluated and validated. So far, only Willockx et al. [83] have validated their in-house developed 3D light simulation tool, capable of evaluating the light distribution below PV canopies at the crop level of an agrivoltaic system in Belgium. They validated the simulations against field PAR measurements with a ± 8% agreement between monthly measured and modelled shading levels.

Similarly, irradiance modelling for PV modules in agrivoltaic systems requires specialized tools and methods to account for the unique factors present in these systems. A few different tools exist that account for some of the irradiation-specific changes. The tool bifacial_radiance is a peer-reviewed open-source Python wrapper based on the ray-tracing software Radiance developed and maintained by the National Renewable Energy Laboratory (NREL) [84]. The program enables sub-hourly simulations with customized tracking algorithms, and modelling of detailed 3D scenes for the PV and plant systems. Another example is the commercial SPADE tool that estimates irradiation on PV modules and crops [85].

3.3 Tools and approaches for microclimate modelling

The presence of the PV modules in an agrivoltaic system affects crops' microclimate and growing conditions [86]. Plant development is closely connected to the crop temperature, resulting from the energy balance at the ground and the plant itself. The energy budget at the ground is described by the following equation [87]:

Equation 1: $R_n - H - \lambda E - G = 0$

where R_n is the net irradiance (W/m^2), H and λE are the sensible and latent heat fluxes (W/m^2), and G is the rate of heat storage in the vegetation and soil (W/m^2), respectively. The contribution of the incoming and reflected shortwave irradiance and the incoming and outgoing longwave irradiance give the net irradiance R_n. The sensible heat flux H corresponds to the convective heat exchanges between the air and the crop. The latent heat flux λE corresponds to the energy released through soil evaporation and plant transpiration.

Equation 1 can be used to show how changes induced in the microclimate by the presence of the agrivoltaic system might affect how the crops grow underneath the system. For example, shading caused by PV modules directly affects the incoming shortwave and longwave irradiance, R_n. Shading might cause a reduction in the canopy and ground temperatures, and thus, the sensible H, latent λE, and rate of heat storage in the vegetation and soil G. Moreover, if the PV modules and supporting structure induce a significant change in the ambient temperature or wind speed, the agrivoltaic systems can also affect the aerodynamic resistance of the crop. This will, in turn, affect the latent heat flux, λE, which can also be affected through changes in the stomatal resistance (plant breathing resistance) caused by shading. The main critical physical phenomena and their interaction with an agrivoltaic system are highlighted in Figure 9.

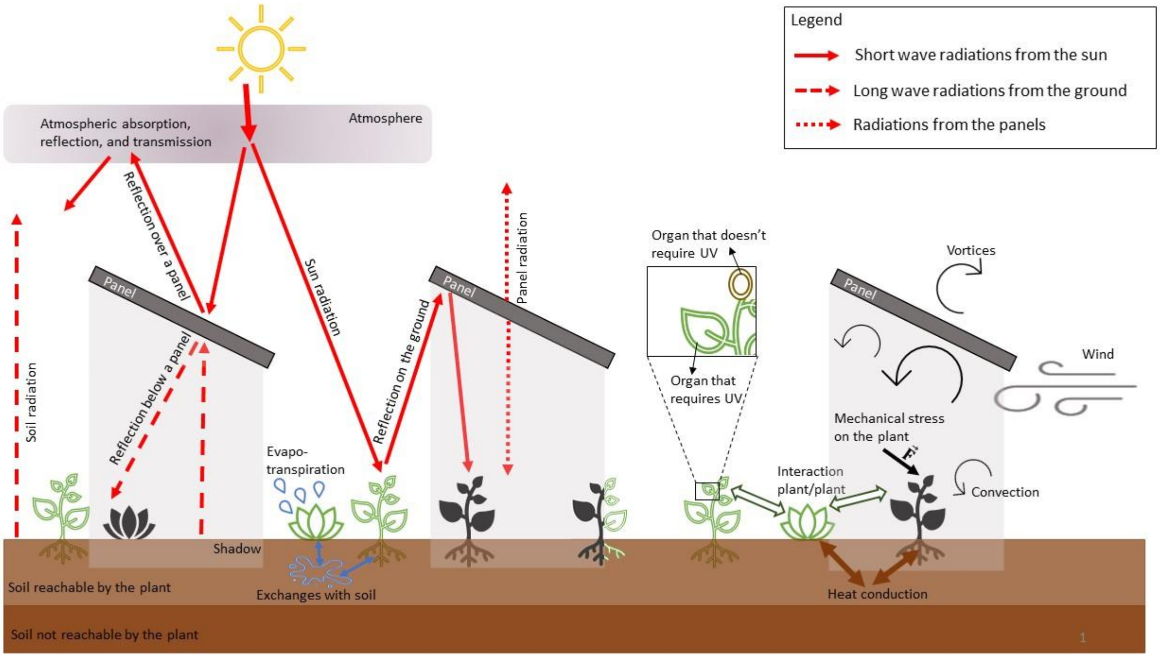

Figure 9: Diagram of the main physical phenomena within an agrivoltaic system and how they interact [88]. Colour code: red (irradiance); blue (evapotranspiration); black (displacement of air, sensible heat); brown (heat conduction in the soil). Note that relevant weather phenomena, like rain, or energy removal by electric cables, are not shown here.

The presence of the PV modules might also change the distribution of rainwater, affecting soil moisture and its distribution and, in extreme cases, leading to soil erosion when rain concentrates [61]. On the other hand, agrivoltaic systems, especially those equipped with water harvesting techniques and solar trackers, can mitigate soil erosion and protect crops during extreme rainfall or hailing. The microclimate produced by these systems can enhance growing conditions for crops, depending on their shade tolerance and the surrounding weather and climate. In hot and dry climates, the shading provided by agrivoltaic systems can reduce stress related to high temperatures and water scarcity [72, 89]. In areas exposed to strong winds, these systems can protect against the adverse effects of wind on crops, such as enhanced evapotranspiration and soil erosion. Agrivoltaic systems also enable the deployment of water harvesting techniques to redirect rainwater, reducing the risk of aeration stress in the crops. With the ongoing climate change, it is expected that the frequency and intensity of extreme weather phenomena, e.g., drought and floods, will increase. Thus, the microclimate generated by agrivoltaic systems might provide security against crop failures. Moreover, research studies have shown that the microclimate produced by agrivoltaic systems can lead to lower interannual variation in crop yield [72]. One of the research and market gaps in the agrivoltaics sector is the lack of specialized microclimate modelling tools for agrivoltaic systems, despite several tools developed in research studies being available for microclimate simulations in different applications [90–94].

Several works are available in literature on microclimate modelling and control under PV greenhouses [95, 96], defined as closed agrivoltaic systems [97]. However, only some studies are available for microclimate modelling under open agrivoltaic systems. Although open and closed agrivoltaic systems can share methodologies, approaches, and tools for the estimation of microclimate, microclimate modelling under a greenhouse is a relatively more straightforward task for two main reasons: (i) greenhouses are a closed environment, and (ii) in most of the cases the microclimate is a controlled parameter [98].

While solar irradiance is one of the main parameters affecting the microclimate underneath agrivoltaic systems, as presented in Section 3.2, other key parameters need to be modelled. Elamri et al. [61] developed a 2D model, AVrain, written in the R programming language to depict rain distribution under agrivoltaic systems. The program considers the effect of wind speed and direction, the speed and size of the raindrops, and agrivoltaic system geometry on the rain distribution. Rain distribution is essential for accurately simulating soil moisture distribution and how this affects crop water-related stresses. Zainali et al. [55] used a computational fluid dynamic (CFD) approach to calculate solar irradiance, wind speed, soil, and air temperature in an experimental agrivoltaic system in Sweden. The 3D model of the agrivoltaic system was built in Solidworks® CAD, whereas the CFD simulations were performed in Solidworks Flow Simulation®. CFD tools are key modelling tools that enable investigations into how the presence of the agrivoltaic system's structure influences the wind speed and direction. Similarly, Williams et al. [99] adopted a CFD approach to assess the effects of agrivoltaic system configurations on the cooling of the PV modules considering albedo, evapotranspiration, and module height. The authors calculated that an overhead agrivoltaic system with soybeans could lead to an operating temperature of the PV modules of 10 °C lower than GMPV 0.5 m elevated from the bare soil. Simulations were carried out in ANSYS Fluent®.

Despite the growing number of models dedicated to simulating various microclimatic parameters within agrivoltaic systems in recent years, there remains a significant need for validation studies to assess their accuracy. Only a limited number of studies have validated simulations of air temperature and relative humidity against actual measurements in either open or closed agrivoltaic installations [100–102]. Table 5 summarizes some of the approaches deployed to simulate microclimatic parameters in agrivoltaic systems.

Table 5: Approaches for microclimate modelling in agrivoltaic systems.

Software	Microclimate variable					Reference
	GHI/ PAR	ST	ET	WS/WD	P	
Scilab	✓	✓	✓			[72]
Matlab	✓	✓	✓			[74]
Autodesk Autodesk ® Revit ® Analysis	✓					[76]
Solidworks® CAD and Solidworks Flow Simulation®	✓	✓	✓	✓		[73]

Code_saturne		✓	✓	✓		[103]
ANSYS Fluent®		✓	✓	✓		[99]
R software					✓	[61]
Python	✓		✓	✓		[81]

GHI: global horizontal irradiance; PAR: photosynthetically active radiation; ST: soil temperature; ET: evapotranspiration; WS: wind speed; WD: wind direction; P: precipitation.

3.4 Approaches for crop modelling

The growth of a crop is a very complex phenomenon that depends on the interaction of many factors. Crop models are mathematical equations representing the processes occurring within the plant and the interactions between the plant and its environment. Crop models can provide quantitative information about the major processes involved in plant growth and development and are essential for estimating the final state of total biomass or harvestable yield.

The importance of applying crop modelling to agrivoltaics research is clearly demonstrated by the fact that, among the first scientific publications regarding crop production in agrivoltaic systems, most were entirely, or at least partly, based on the results of crop modelling [7, 72, 104, 105]. Crop modelling provides scientists and researchers with practical operational tools and methods to understand how the complex system of weather-soil-plant interactions is affected by conditions imposed by the agrivoltaic system on the microclimate and growing conditions of the crops.

First, it is essential to distinguish between empirical and mechanistic crop models [106]. While a mechanistic growth model describes the performance of a crop based on the knowledge of the processes that are taking place in its growth and development, an empirical model describes the plant's behavior based directly on observations at the plant level. So far, most of the models used in agrivoltaics adopt an empirical approach for the processes that are most affected by shading, i.e., photosynthesis, leaf structure, and especially the specific leaf area. Using a model based on daily irradiation use efficiency for photosynthesis might not lead to sufficiently accurate results [107]. Because photosynthesis and transpiration responses to environmental variables are strongly nonlinear, photosynthesis and transpiration should be first evaluated at the leaf level on a short time scale and then extended to the canopy level daily. This modelling approach requires a mechanistic approach. However, it should be clear that, at certain stages, all models adopt empirical solutions.

A variety of different crop models have been used in agrivoltaics research. The SIMPLE crop model [108] was adopted in a simulation study to find optimal solutions for different configurations of agrivoltaic systems [49]. The SIMPLE crop model is designed to simplify crop modelling to basic components. The model is well-validated and uses simple parameters, enabling straightforward and fast implementation. Biomass accumulation is based on a radiation use efficiency approach and implements empirical solutions to consider water and temperature effects [107]. Within the SIMPLE simulation framework, irradiation values are computed with a light-based simulation. The irradiation values are then passed to the crop model that calculates crop yield outputs in both reference full light and agrivoltaics conditions.

Another study on a simple modelling approach to crop growth was conducted by Campana et al. [67], who used the Environmental Policy Integrated Climate (EPIC) model. The validation of the EPIC model simulations against actual seasonal potato and oats crop yield data from an agrivoltaic system in Sweden showed that the model tended to overestimate the measurements if a previous calibration was not conducted. Although EPIC also uses empirical relationships to simulate potential growth, it contains several modules to account for different thermal and nutritional stresses.

The solution of optimized configurations of agrivoltaic facilities may include the need to ensure, in the long term, agronomic and economic value using multiple crops and management options. For this kind of multi-objective requirement, platforms that can simulate different crops with different crop models are very effective. An example of this is given in the work of Ko et al. [109], who simulated rice, barley, and soybean using three crop models (CERES-rice, CERES-barley, CROPGRO-soybean) implemented in the DSSAT package. The level of process details varies greatly, and, in many cases, users may select among model options, allowing the user to assess how different assumptions affect the simulations. The authors utilized field trial data to calibrate and validate the models. Subsequently, a geospatial crop simulation modelling system incorporating these crop models was employed to simulate regional variations in crop yield under different solar irradiation reduction scenarios.

Another crop model used for agrivoltaics studies is STICS, which relies on well-known relationships and simplifications of existing models. Using STICS, Dinesh and Pearce [110] estimated the effect of shading on lettuce yield with two densities of PV modules. They showed that the model output can be used to support predictions for the economic evaluation of an agrivoltaic system. Under severe shading conditions, the STICS model overestimates wheat production [7, 111]. In both studies, the authors concluded that the overestimation of wheat production was related to an incorrect estimation of the leaf area index (LAI).

One crop model that offers interesting possibilities for simulating cropping systems in agrivoltaics conditions is the Agricultural Production Systems Simulator (APSIM). This is a comprehensive model developed to simulate biophysical processes in agricultural systems, particularly as it relates to the economic and ecological outcomes of management practices in the face of climate risk. To date, it has been used for agrivoltaics simulations in two different studies. First, Mamum et al. [112] employed it to simulate pasture production under three different agrivoltaic configurations, i.e., fixed-tilt, single-axis tracking, and dual-axis tracking. However, not many details were provided by the authors, as they only reported that there is a module in APSIM to adjust irradiation with respect to full light. Second, Hau [113] directly employed the APSIM-Oryza model to estimate rice's grain yield and total biomass under an agrivoltaic installation in Japan. The comparison against actual measurements demonstrated the adequate performance of the model with almost perfect matches between the modelled and the observed values (coefficient of determination values higher than 0.95). An interesting feature of APSIM for agrivoltaics studies is the simulation of crop phenology considering the effect of photoperiod. The model includes a so-called "photoperiod sensitivity" parameter, which determines the rate at which crop development progresses in response to changes in daylength. The manipulation of this parameter could—even at the empirical level—be exploited to simulate genetic differences to daylength of different cultivars of the same crop when grown in agrivoltaic systems [109].

A crop model with a high level of mechanistic relations is GECROS, which was adopted by Amaducci et al. [72] in a simulation study on maize grown under different agrivoltaic systems and water management strategies. The model is particularly suitable for agrivoltaics modelling for the capability of hourly simulations to capture temporal radiative patterns of intermittent shade. The GECROS model [114] was developed to overcome the inherent weakness of the approach based on dividing crop production into potential, water-limited or N-limited levels. GECROS can capture elementary traits of genotype-specific responses to the environment based on quantitative descriptions of complex traits related to crop phenology, root system development, photosynthesis and stomatal conductance, and stay-green traits. Therefore, the model is suitable for analyzing several physiological processes in response to environmental stresses, including stressors caused by limited irradiation, which is the most important aspect in agrivoltaics modelling. Using a modified version of GECROS, Potenza et al. [115] estimated the grain yield of soybeans under different shading levels in an open agrivoltaic system in Italy. After validating the results against actual measurements, they found that the model tended to underestimate yield with increasing shade, with a maximum root mean square error of 16.5% for a 27% shading level.

A way to improve the simulation of crop growth in agrivoltaic systems is to use modelling solutions to capture the reciprocal influences of the factors: available irradiation, canopy development, biomass accumulation, and available soil water. The interdependence of these factors indicates that the lower the energy the system receives, the lower the biomass accumulated, but there is a decrease in water demand due to lower evapotranspiration. The capacity to simulate the effect of irradiation on canopy development, particularly the changes caused by shade on leaf morphology, would be a desirable feature. At present, this is only available in sophisticated crop models, e.g., GECROS.

In agrivoltaics studies, the overall scope of the work must guide the implementation of a new model or the choice of an existing one. Empirically based models can comprehensively estimate crop yield in an agrivoltaic system. By contrast, mechanistic crop models are needed to study how different assumptions affect the soil-plant-atmosphere or ontogenetic effects caused by the shading scene.

3.5 PV yield modelling

PV yield modelling in agrivoltaic systems builds upon the modelling of irradiance and microclimatic factors discussed in previous subchapters to predict the electrical energy output. So far, commercial actors have broadly used conventional PV modelling tools such as PVsyst or the System Advisor Model (SAM) with minor adaptations to model energy yields in agrivoltaic systems [113]. However, these tools have limitations in addressing the additional effects on energy yields caused by the agrivoltaic design and the presence of crops.

To model the conversion of irradiation on PV modules to electrical energy output in research, many approaches with varying complexity are used. Simpler efficiency models, like PVWatts [116], have been employed. Amaducci et al. [72] assumed a fixed system conversion efficiency of 14%, while Riaz et al. [45] implemented system conversion efficiencies of 19% for the front side and 16% for the rear side of bifacial PV surfaces. Willockx et al. [83] employed the PVWatts model to simulate the energy conversion in an agrivoltaic system within a pear orchard in Belgium, and the results were validated against actual power measurements.

Researchers have used diode equivalent-circuit models for a more detailed analysis of electricity output, with the single-diode model being a prevalent choice. This approach has been adopted for different system configurations, including vertical bifacial systems [67], as well as systems employing tracking mechanisms both on greenhouses [117] and on the ground [118]. These models can more precisely simulate the behaviours of agrivoltaic systems than simple efficiency models but are more complex and require more data. Additionally, validation against actual power measurements and energy yield data from diverse agrivoltaic systems is essential. The model utilized by Campana et al. [67] has been validated, and this was done against PVsyst simulations, which may not fully address concerns regarding accuracy.

Some researchers have taken novel approaches to model PV yield from modules with spectral properties tailored for agrivoltaic systems. Ravishankar et al. [119] developed a detailed energy balance model for greenhouses integrating semi-transparent organic solar cells (OSCs). They calculated the short-circuit current from the external quantum efficiency and incident irradiance on the OSCs and then estimated power output using assumed values for open-circuit voltage and fill factor based on the literature.

PV cell conversion efficiency is directly affected by operating temperature, and this is an important area of research for agrivoltaic systems, as they may experience different temperature profiles than conventional PV systems [120]. Agrivoltaics energy yield modelling is increasingly building upon dedicated thermal modelling through methods such as CFD [67, 109] and finite element methods (FEM) [110], analytical frameworks [111, 112], and empirical relationships [114] that relate cell temperature from ambient conditions. Due to their adaptability, traditional PV modelling frameworks like SAM have also been used for thermal analysis of green roof systems [121].

To refine the precision of PV yield modelling and optimize the performance of agrivoltaic systems, it is important to consider factors such as unique PV technologies, the agricultural effect on the PV system's O&M, the influence of crops, and microclimatic variations that may not be present in traditional PV systems. The problem is truly multidisciplinary since developing a holistic modelling framework must combine insights from modelling microclimate, crop growth, and PV systems.

3.6 Integrated platforms for irradiance, crop, and energy simulations

Integrated platforms for the simulation and optimization of agrivoltaic systems are software or a combination of software that enable comprehensive modelling of agrivoltaic systems to depict energy, water, and crop performances from a technical point of view. The technical aspects obtained from the modelling can then be used as a starting point for modelling economic or environmental aspects. Optimization algorithms are combined with simulation models to find the optimal design concerning one KPI or a set of KPIs in the case of multi-objective optimization. Alternatively, sensitivity analyses can be performed to study how the agrivoltaic systems' key design parameters affect the crop and energy yields. One of the first integrated simulation studies of agrivoltaic systems was performed by Dupraz et al. [7] by combining (i) a solar irradiance model developed inhouse in the R programming language to depict irradiation distribution on the ground cast by a stilt-mounted PV system and (ii) the STICS crop model. The integrated tool was deployed to study the effects of shading on durum wheat. The land equivalent ratio (LER) was used to assess the overall performances of the agrivoltaic systems. Dinesh and Pearce [110] also studied the effects of different PV system configurations on the yield of lettuce using the STICS crop model combined with PVsyst® to simulate PV production. Amaducci et al. [72] used an irradiation distribution model developed in Scilab® and combined it with GECROS v3.0 to study the effects of shadings on maize grown under stilt mounted two-axis tracking agrivoltaic system in Italy. The electricity production from PV modules was estimated using a static efficiency. The LER was used as a KPI to compare different agrivoltaic configurations to solely agriculture and reference optimized GMPV. The efficiency of agrivoltaic systems was also compared to biogas systems, highlighting the significantly higher land productivity of agrivoltaic systems.

Campana et al. [67] integrated the EPIC crop model in the open-source package OptiCE for clean energy conversion systems simulation and optimization. The integrated platform, Agri-OptiCE®, simulates irradiation on ground, microclimate, crop yield, and PV production. The model was used to study the effects of shadings on oats and potatoes. The simulation platform was coupled with a genetic algorithm to optimize the system design based on three KPIs: the LER, the annual electricity production, and the power fluctuation. The optimization model applied to vertically mounted agrivoltaic systems in Sweden highlighted that the LER is probably not the best KPIs to be optimized for agrivoltaic systems since it might lead to unwanted system configurations that maximize land use efficiency at the expense of both crop and energy performances. Isied et al. [122] developed a computational framework to trace light rays through closed agrivoltaic systems, i.e., greenhouses. The framework was used to estimate PV power production and the power absorbed by the crops. Zohdi [123] proposed a mathematical framework for constructing a digital twin of an agrivoltaic greenhouse. A genetic algorithm is coupled with the digital twin to optimize the greenhouse's geometry, transparency, and material characteristics while targeting specific PV power production and crop-absorbed irradiance. Mengi et al. [49] improved the integrated platform proposed by Zohdi [108] by combining the ray-tracing framework with the SIMPLE crop model. This enabled the authors to analyse the effects of shadings on biomass accumulation and compare the results to open-field conditions. Katsikogiannis et al. [75] combined several commercial and open-source software to perform simulations of solar irradiation distribution on the ground, PV system electricity production, and crop productivity. The effects of agrivoltaic systems on crop productivity were assessed by deploying a photosynthesis light response curve, which was used as a proxy for crop yield. Sensitivity analyses were performed to investigate the effect of some design parameters, such as the row-to-row distance, on the PV electricity production and PAR received on crops for the three main agrivoltaics topologies. An integrated and open-source modelling platform for agrivoltaic systems has been developed by Bruhwyler et al. with the capability of selecting different crop models and performing crop yield and energy conversion simulations [81].

Despite the agrivoltaics sector being exponentially expanding, very few studies and platforms are available to clearly address the market’s needs, especially for simulating crop yields under shading conditions, and optimize agrivoltaic systems layouts to meet yield targets and optimize electricity production.

4 MONITORING

Analysing the performance of agrivoltaic systems is essential to understand better the impact of PV components on crop growth and the practicality of agricultural cultivation, to ensure that PV performance is within specification (capacity testing) right after commissioning, and to identify potential measures to improve the performance of both existing and future systems. Differently from traditional agriculture or PV systems, the performance assessment of agrivoltaic systems involves evaluating a much wider range of parameters, which is particularly challenged by the interactions between agriculture and PV parameters. In addition, monitoring and control systems can be crucial to ensure that agrivoltaic systems comply with legal requirements, which is particularly important with respect to minimum agricultural yields. From a governmental perspective, it appears recommendable to check whether existing agricultural control schemes can be used before implementing new ones to monitor and control agricultural yields efficiently. Examples of existing control schemes are, for example, those implemented in EU member states to control the eligibility of direct payments. Also, control and monitoring methods, which address data collection and analysis approaches interact and complement the governmental control schemes in ensuring effective management of agrivoltaic installations. For instance, control algorithms may provide updated data on the operation of the systems, thus simplifying governmental control and decision-making.

This chapter provides a guide with all the parameters that should be monitored within an agrivoltaic installation. Also, it details the indexes that are commonly used to evaluate the overall performance of agrivoltaics installations. The chapter also describes a framework for creating a database of agrivoltaic facilities already deployed worldwide. The Task 13 report on the performance of new PV system designs already provides the initial performance results of the agrivoltaic installation in Heggelbach, Germany [124].

4.1 Overview of monitoring parameters for agrivoltaic systems

After designing and implementing an agrivoltaic system, it is essential to monitor the different parameters that can impact its overall performance. The importance of taking field measurements within agrivoltaic systems is justified by the current need to improve the understanding of the synergies and trade-offs between agriculture and PV power generation. Also, an appropriate monitoring system can provide valuable information to validate the different simulation models that are being specifically developed to assess the performance of these systems (see Chapter 3).

Table 76 and Table 7 summarize the main parameters relevant to monitoring crop growth and micro-climate. The "Guide to Agricultural Meteorological Practices" [125] provides a comprehensive summary of measurement guidelines for all the parameters relevant to agricultural activities, encompassing meteorological station classifications and instrumentation. Regarding PV performance, a more detailed explanation and summary can be found in the IEA PVPS Task 16 report “Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Fourth Edition” in Chapter 5 “Further Relevant Meteorological Parameters” [65]. The IEA PVPS Task 13 report “Analytical Monitoring of Grid-connected Photovoltaic Systems. Good Practices for Monitoring and Performance Analysis” describes in detail the variables of interest for monitoring PV performance [126].

Table 6: Parameters related to crop growth and yield.

Parameter	Required equipment	Why relevant?
Morphological measurements	A ruler, image-based devices.	The control of different morphological measurements, such as the stem length, the number of leaves per plant, and the internodal length, throughout the different stages of the crop development, can provide valuable knowledge about the impact of the shading cast by PV modules on the crop growth [60].
Dry or fresh biomass	Weighing scale	These parameters determine the total mass of the plant after its complete development [60]. The measurements can also include fruits.
Stem water potential	Pressure chamber	It represents the plant water status by measuring the water tension within the plant [127].
Crop water stress index (CWSI)	Soil moisture probe and air relative humidity sensors	It represents the relative transpiration rate occurring from a plant at the time of measurement. For its calculation, it considers the canopy temperature of a plant and the vapor pressure deficit, which indicates the dryness level in the air [46].
Soil temperature	Soil temperature probe	Found to fall significantly beneath the PV systems as compared with full sun exposure [87].
Soil moisture	Soil moisture probe	Affects root growth and plant water requirements. Change in soil moisture resulting from agrivoltaic installation has been detected [128].
Soil nutrients	Soil nitrogen, phosphorus, and potassium (NPK) Sensor	A correct level of phosphorus, iron, calcium or even nitrate (nitrogen) in soil is essential for good soil quality [60].
Soil pH and electrical conductivity	pH and conductivity meter	Agrivoltaic systems can alter soil physicochemical and biochemical characteristics including pH and electrical conductivity [129].
Photosynthetic rate	Specific photosynthesis measurement systems	By measuring the photosynthetic response curves, it is possible to obtain valuable information about the light response of crops in different environmental conditions and at distinct phenological stages [130].
Grain yield	Weighing scale	A measure to estimate the yield of certain crop species, such as wheat or corn, by counting the number of grains per pod and by considering the grain weight [113].

Metabolizable energy and crude protein	Near-Infrared spectrophotometers	These two parameters provide information about the nutritional content of the plants [131].

Table 7: Meteorological parameters to monitor the micro-climate conditions.

Parameter	**Required equipment**	**Why relevant?**
Global horizontal irradiance (GHI)	Pyranometer or reference PV cells	Broadband solar irradiance in a horizontal plane. Impact on plant growth and yield as well as PV production.
Photosynthetically Active Radiation (PAR)	PAR sensor	Solar irradiance in wavelength range 400-700 nm. Chlorophyll a and b, and carotenoids mainly absorb this range of wavelengths [97, 132].
Daily light integral (DLI)	PAR sensor	PAR integrated over 24 h. Plants can be roughly divided into high light, medium light and low light demanding crops. Some studies present thresholds on optimal and sufficient DLI levels for each plant type [97, 133].
Light homogeneity	PAR / Irradiance sensors	An accurate knowledge of the irradiation/PAR distribution in agrivoltaic systems is crucial to analyse the crop development and its final yield [73].
Light quality	Spectrometer	They are usually indicated by the red/far-red light spectra and/or blue/far-red ratios. Low red/far-red light ratios can cause, for example, the "shade avoidance syndrome," which plants compensate for, for example, by stem elongation [134, 135].
Ground surface albedo	Albedometer or reference PV cells	It indicates the percentage of incident sunlight (rays and diffuse sky light) that a surface reflects. It is especially important for bifacial PV facilities.
Ambient temperature	Temperature probe with irradiation shield	One of the major factors that impacts crop development. The relationship between temperature and crop growth rate depends on plant type and development stage [136]. Between minimum and optimum temperatures, specific crops increase their growth rate. In contrast, temperatures above the optimum lower the plant growth rate, and no crop growth is possible at temperatures above the maximum. The optimum temperature is usually higher during the vegetative development than during the reproductive period of the crop [137].
Relative humidity	Relative humidity probe with irradiation shield	It affects evaporation and transpiration of crops and, thus, it has an impact on growth and water requirements. It also influences the crop health, as high relative humidity induces a decrease in transpiration and increases the risk for fungal diseases [138].

CO_2 concentration	CO_2 concentration sensor	Relevant factor to optimize crop growth [139] as the photosynthetic activity of crops is less efficient with a lack of CO_2 [140]. Note that this is not a common measurement in traditional weather stations.
Precipitation	Precipitation sensor	It has a major impact on plant growth and yields, especially factors such as precipitation distribution over time and area, angle of incidence, and type of precipitation [46, 61, 141]. For example, hail events can damage not only the PV system, but also the corresponding crops. Rainwater harvesting together with electricity production could enable a self-watering and self-powering approach [142].
Evapotranspiration	Soil moisture probe or lysimeter	Defined as evaporation at soil–air interface, plus transpiration of plants, under the existing conditions of soil moisture [60].
Wind speed Wind direction	Anemometer	Agrivoltaic systems can interact with wind conditions by changing wind speed profiles. Crop growth under agrivoltaic systems can cause differences in wind direction. Wind speed affects plant evaporation and thus can increase water demand. Strong wind can cause plant damage [128].

4.2 Framework for agrivoltaics databases

Commercial deployments and research projects are rapidly growing in line with growing interest in agrivoltaics worldwide. Many agrivoltaic research projects focus on understanding the system's impact on crop growth across diverse climates and on different crop varieties and system designs. Then, they inform policymakers and stakeholders about decisions, ranging from recommended crops for given climates to best practices for O&M activities of agrivoltaic systems.

With both research and commercial agrivoltaic projects, there needs to be more standardized reporting and documentation of key project features, which would assist in database aggregating. This is due to a variety of factors, including national and regional-level publicly available data, commercial sensitivities, the large number of influencing factors for agricultural practices, and a lack of agreed-upon metrics, e.g., absolute yields [83] versus relative yields [60]. The available data and documentation differences can hamper comparisons over multiple sites and agrivoltaic configurations or require additional processing or calculation steps.

Nevertheless, this situation presents a compelling opportunity to gather and analyse data over multiple sites, enabling a more profound and faster understanding of agrivoltaic systems across geographies, agricultural applications, and configurations. A collaborative initiative to establish a global agrivoltaics database is envisaged by active stakeholder organizations within the Agrivoltaics field, such as the IEA Task 13 Agrivoltaics Subtask, SolarPower Europe, NREL, and Fraunhofer ISE. These latter two organizations have already ongoing projects to develop national databases of agrivoltaic facilities (InSPIRE project and SynAgri-PV project) [14, 143–145]. Such databases facilitate monitoring and comparisons across sites and learnings from successful projects, thereby expediting the progress of agrivoltaics development. Recognizing that creating such a database is beyond the scope of the current task, a roadmap is proposed for its development to aid future initiatives.

The roadmap includes identifying relevant data to be collected, methods for data collection and validation, platform hosting and data display considerations, and eventual public dissemination strategies, which are discussed below in this section.

4.2.1. Essential data to be collected

The data to be collected for inclusion in agrivoltaic databases should contain the necessary information to allow comparison, aggregation, and filtering according to user needs. By necessity, a database often contains a subset or high-level view of the information of each agrivoltaic site or system, yet it serves as a starting point for subsequent analyses. Additional data could be collected that provides greater insight into the system and its surrounding conditions, but this data might only sometimes be readily available. A preliminary list is provided in Table 8.

Table 8: Main parameters that should be collected for each agrivoltaic installation.

Parameter	Description
Owner	Name of the company/institution that is the proprietor of the agrivoltaic system
Developer	Company/institution that oversees the development of the system
Operator	Company/institution that is dedicated to the control and maintenance of the system
Project type (commercial / research)	Identifying the project type would help to classify the agrivoltaic installations
Project/installation name	Identification of the project name in case of agrivoltaic research sites, or commercial name in case of agrivoltaic commercial systems.
Start of operation	Commissioning date of the agrivoltaic system
Location	Specific details of the location of the system. These can include: • Country • Region/Province • City/Town • Coordinates (latitude, longitude)
Land surface [ha]	Area occupied by the agrivoltaic system. In open-field installations, its value is linked to the purpose of the system
Land use activities	Agricultural applications or activities that take place in the agrivoltaic system like orcharding, arable farming, or grazing
Crop	Crop cultivar(s) being grown within the agrivoltaic system
Ground Coverage Ratio (GCR)	Ratio between the area occupied by the PV modules to the total area of the agrivoltaic system (projected GCR or absolute GCR)
System configuration	Different information regarding the configuration/specifications of the PV modules. Table 3 in Chapter 2 introduces the different parameters that should be collected

Performance metrics	Indexes that assess the performance of an agrivoltaic system (more details can be found in Chapter 2, Tables 1-3)

4.2.2. Data collection methods

Developing and implementing efficient approaches for gathering data from agrivoltaic systems is crucial to generating and effectively maintaining complete databases. Below, some possible techniques are detailed:

Surveys

Surveys can be distributed to various relevant stakeholders, including solar industry representatives, agricultural organizations, national and regional government agencies, and/or non-profit organizations working in the field. Surveys must be designed to be administered regularly and not place undue burden on participants. This issue was underpinned by experiences with an 80-question Fraunhofer ISE survey, which led to incomplete responses from the contacted facility owners due to its length and detailed nature [207]. The focus should be on essential parameters, keeping the survey brief (e.g., around 10-15 minutes), and ensuring user-friendly design for comprehensive submissions.

Research literature review

The use of scientific search systems, such as Scopus, Web of Science, and Google Scholar, can help identify research agrivoltaic facilities whose results have been published in journals or presented in conferences.

Publicly available news articles

Local, regional, and national news outlets and other public sources of information (e.g., social media) could help identify agrivoltaic site locations. However, further engagement would be required to fully complete essential data requirements.

Formal requests to national governmental organizations

In countries where there is already a legal framework for agrivoltaics, a register that contains general information about all agrivoltaic installations may have been implemented. This record book is usually generated and protected by national ministries or other governmental institutions, so a formal request may be required to access the data.

Open-access contributions

An open-access portal could facilitate the addition of new agrivoltaic projects into the database, given sufficient motivation and incentive for user-driven contributions.

4.2.3. Data validation

In all cases of data collection, data validation will be needed to ensure the database accurately represents the conditions at the agrivoltaic sites. Specific validation approaches will vary based on data collection approaches, but ideally, validation activities should occur regularly, such as every year. Agricultural land management practices can change yearly, and ownership and personnel changes can affect certain activities. Because of these issues, regular validation of project sites can help ensure updated characterization of agrivoltaic projects.

Any data collection and validation activities will require clear guidance and definitions on eligible agrivoltaic projects that could be considered in the database. As most countries have differing definitions of agrivoltaics, and some countries have sub-national differences in definitions, establishing criteria will be necessary for ensuring accurate representation. In some cases, the definitions of agrivoltaics could differ in the database from those in a host country.

4.2.4. Database creation (data analysis and visualization)

The generation of shared databases, which can be accessed by investors, developers, researchers, and other stakeholders, will help optimize the design and deployment decisions of agrivoltaic systems. Also, these platforms can provide a better understanding of agrivoltaics synergies while facilitating the validation of specific agrivoltaics models. Furthermore, a global agrivoltaics book record could allow researchers to explore the geographic restrictions of agrivoltaics, thus leading to relevant insights about climate change adaptation and how agrivoltaic systems could assist in that issue. Figure 10 shows the USA Agrivoltaics Map created by NREL within the context of the InSPIRE project [14].

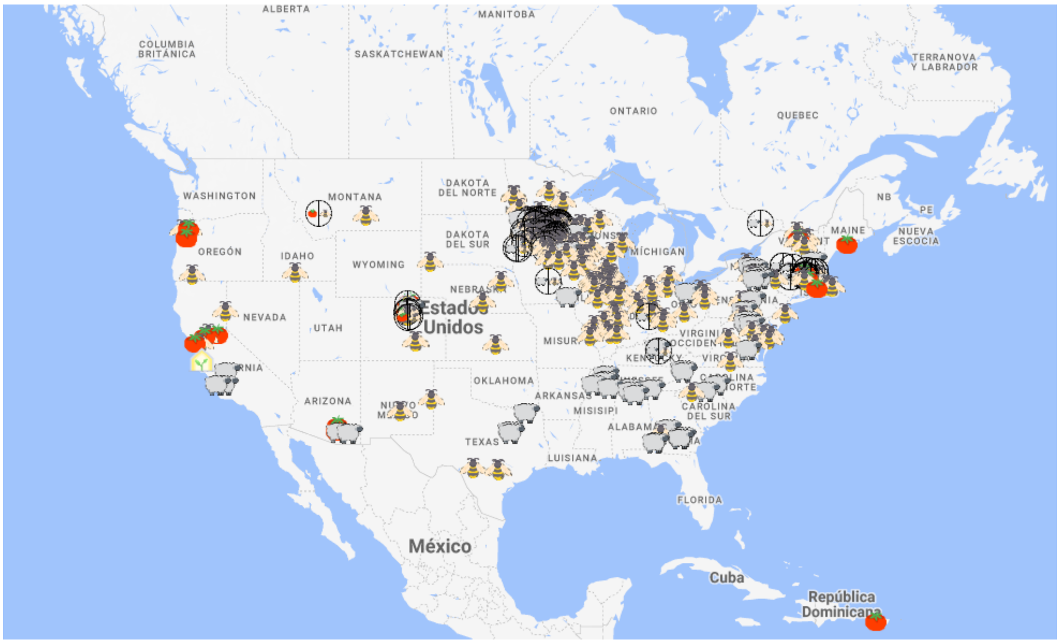

Figure 10: Dynamic map that represents a census of agrivoltaic installations located across the United States. On 13th December 2023, it showed a total of 515 installations, adding up to 7.3 GW_p. Available online (US Department of Energy and NREL, 2024) [146].

The generation of an open-source global database of agrivoltaic facilities will allow stakeholders to analyse the distribution of this kind of installation worldwide easily. A wide variety of graphs can be created. Figure 11 shows three examples of visualizations using data from the German database of Fraunhofer ISE. Similar metrics are available for the USA.

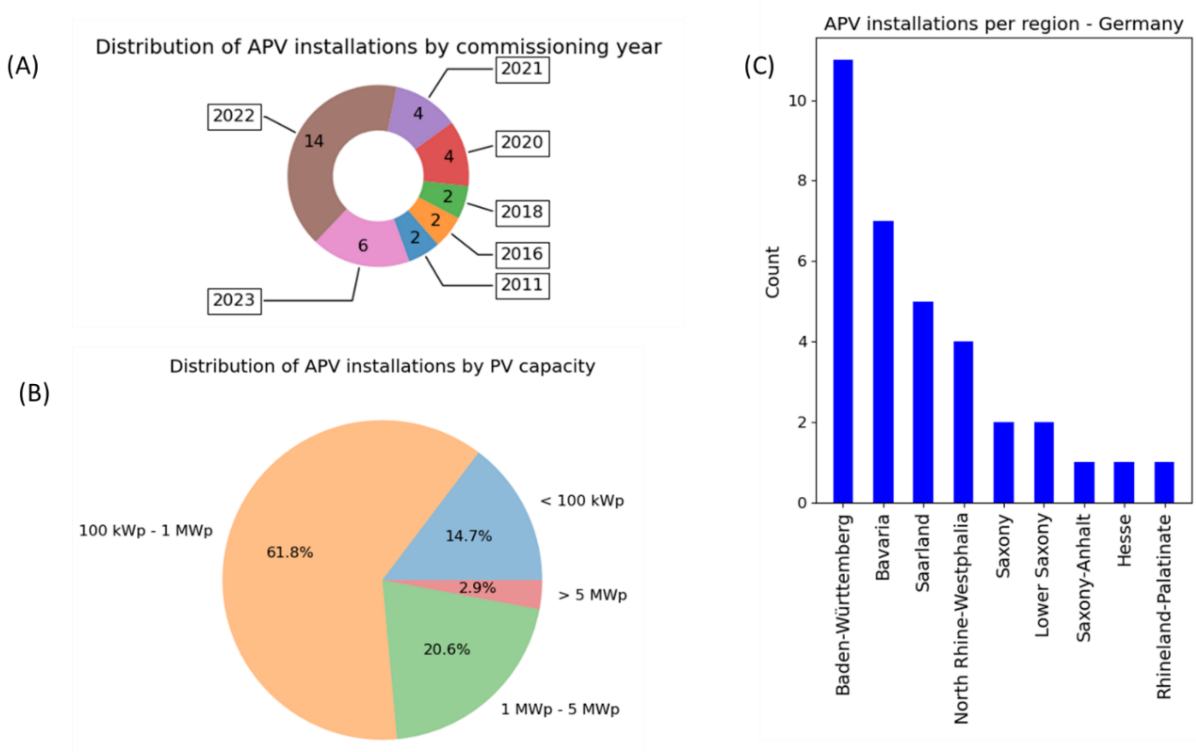

Figure 11: Examples of data visualization using the German agrivoltaics database. (A) Distribution of agrivoltaic installations by commissioning year. (B) Pie chart with the distribution of agrivoltaic facilities according to the installed PV capacity. (C) Number of agrivoltaic installations per region in Germany [207].

An approval process based on a set of standards will need to be established to include a project in the public database. Guidelines will need to be straightforward to ensure fairness and reduce complexity. The database will also need to manage access to raw data and access for moderators to make decisions on whether projects are eligible for inclusion. A publicly available database will also require resources to keep it updated in the long term and other necessary ongoing and periodic data validation activities.

Future activities to support a global database include further establishing essential data to collect, identifying, and evaluating various data collection and validation approaches, examining multiple data hosting platforms, and developing a long-term management plan for the database.

5 OPERATION AND MAINTENANCE

5.1 Agrivoltaic facilities maintenance practices

In many circumstances, standard PV systems' current O&M best practices, requirements, and regulations (electrotechnical, health, safety, environment, design) are also applicable and relevant for agrivoltaic installations. High-quality O&M in PV is meant to enable mitigation of potential technical risks (hence, downtime), with a positive impact on long-term PV energy yield and eventually on the Levelized Cost of Electricity (LCOE) and the return on investment (ROI). Some key factors relevant to agrivoltaic systems should be considered in the design and construction of an agrivoltaic system that will affect O&M activities, namely wire management, site preparation, and operator access.

Wire management includes both belowground and aboveground considerations. Belowground cabling must be buried deep enough not to create a risk for agrivoltaics operators who could be tilling or digging in the land or for animals that may be digging or rooting. Belowground cabling should also be marked for agrivoltaics operators to be aware of to avoid. The presence of underground cabling may affect the type of agricultural activities possible on an agrivoltaics site. Similarly, the presence of aboveground cabling could limit the types of agricultural activities that could be suitable on-site, the type of agricultural equipment that could be used, and the types of access certain livestock could have. Loose or unsecured aboveground cabling could pose a safety risk for agrivoltaics operators or livestock on site. Site preparation considerations are also slightly different for agrivoltaics sites and, if not executed properly, could affect agrivoltaics operations substantially. Minimizing soil compaction during construction of the agrivoltaics site will be essential to maintain soil fertility, as well as to reduce the need for agricultural operators to undertake de-compaction, tilling, or other activities involving substantial ground disturbance, which could lead to additional soiling, carbon emissions, or other health and safety concerns.

Creating access spaces during the design phase for PV O&M and agricultural vehicles and equipment can minimize the potential disturbance to soil and disruption to agricultural activities during agrivoltaics operation. Access points can potentially reduce land allocated to agricultural activities, but they could reduce potential negative impacts on agricultural yields and productivity for areas that are under cultivation or being managed with livestock. O&M in agrivoltaics systems involves a combination of actions to ensure the optimal performance of both the agriculture and PV components. Such a framework of actions is summarized in the following table.

Table 9: Overview of actions and their importance in the general O&M framework for agrivoltaics.

Action	Importance / Rationale
Regular PV Module Cleaning	
Periodical cleaning of PV arrays to remove built-up soiling (e.g., dust, dirt, pollen, debris). More details are discussed in following Section 5.2.	Minimize soiling losses, boost light absorption, prevent follow-up failures (hot spots due to severe soiling and consequent mismatch effects). More details are discussed in Section 5.2.
Vegetation Management	

Periodical vegetation management under and around the PV arrays and their mounting structures to avoid interference with infrastructure.	Prevent seasonal shading (partial or full) and consequent mismatch losses of the PV arrays. Also ensures proper light exposure for crops beneath/nearby.
Inspection of Mounting Structures	
Regular inspection of the structural integrity of the mounting structure.	Identify and address any signs of wear, corrosion, or structural/static issues that may compromise the stability of the PV arrays and indirectly the safety of personnel.
Preventive Maintenance / Checks of Balance of Systems (BOS, inverters, cabling)	
Routine checks on inverters for proper functioning; inspections and testing of other electrical components (e.g., cabling and combiner boxes).	Ensure normal (safe and efficient) operation of the inverters according to the manufacturers' specifications. Identify and address issues related to wiring, connectors, and other electrical components to prevent downtime and ensure safety.
Weather-Related Resilience and Preparedness	
Development and deployment of multi-level contingency plans for extreme weather events.	Minimize potential damage to the crops and PV system (e.g., modules, structures, BOS) from storms, hail, heavy snowfalls, or other severe weather conditions.
Irrigation System Maintenance	
Maintenance and inspection checks of the irrigation system for proper functioning. Action that may be considered with soiling mitigation/cleaning interventions, see Section 5.2.	Ensure that crops receive adequate water, especially in periods of prolonged drought, to support healthy growth.
Fertilization and Pest / Disease Control	
Implementation of integrated pest management strategies. Action that may be considered with soiling mitigation/cleaning interventions, see Section 5.2.	Boost crops growth and safeguard crops from pests and diseases without compromising the efficiency of PV system, with appropriate mitigation measures against pesticides-induced soiling. Integrated pest management should be employed to strike a balance between agricultural productivity and PV system reliability.
Data Management, Monitoring, and Analysis	
Continuous data management (e.g., acquisition, storage, and quality control),	Enable early detection of anomalies (e.g., PV and/or crop level underperformance). Inform decision-making/ticketing for maintenance

monitoring, and actionable analysis of agrivoltaics performance data.	interventions. Support data-driven inspections, maintenance, and optimization of PV system and crop performance. Detect and correct or isolate cases of abnormal performance degradation and ensure long-term reliability.
Agronomic Practices	
Development and application of agronomic best practices (e.g., crop selection, planting patterns, and irrigation strategies), in coordination with agronomic experts.	Maximize land use efficiency and maintain a harmonious coexistence between land/crops and PV systems.
Regulatory Compliance and Safety Measures	
Review, application, and update of standardized O&M actions and health, safety, and environment procedures. Prioritize safety protocols for both PV and agricultural activities.	Ensure adherence to all relevant, effective and future/changing, regulations and standards governing both PV and agronomic practices.
Training and Education	
Provision of training for O&M personnel, farmers, and, in certain cases community members. Regular safety training for personnel working in agrivoltaic installations.	Continuous improvement and knowledge-sharing to enhance O&M practices and eventually overall system performance and operation. Prevent/address risks related to electrical and agricultural interventions.
Community Engagement and Communication	
Engage in open communication with local communities and stakeholders.	Foster positive relationships, address concerns, and ensure community support for the agrivoltaics project. Ensure that the community is informed about the benefits, risks, and ongoing maintenance activities associated with agrivoltaic systems.
Documentation and KPIs Follow-up	
Safekeeping and organization of detailed records of maintenance activities, monitored data/KPIs and observed trends in performance and reliability of the agrivoltaic system.	Facilitate tracking of system history. Aid in troubleshooting. Support compliance with regulatory framework and KPI targets.

The facility installer must generally document the essential maintenance tasks in the operational manual, and the operator should adhere to these instructions. Documenting the confirmed parameters in a specialized operational protocol for the facility is advisable. Proper on-site crops and pasture maintenance are crucial to mitigate the fire risk. In severe weather conditions like ice accumulation, extreme wind, and heavy snow loads, it is recommended that work be avoided beneath the facility for safety reasons. The implementation of rainwater distribution systems can help prevent the formation of icicles [147]. Caution is essential when conducting maintenance on agrivoltaic systems due to human activity on the site and the potential for intensive agricultural operations, which can elevate the likelihood of damage and contamination. It is crucial to communicate any maintenance requirements or risks related to the PV systems to farmers and workers [28]. Although the potential risk of damages from agricultural machineries to the agrivoltaic systems is often mentioned in literature [148–150], these aspects have not yet been well investigated and reported.

5.2 Soiling mitigation and vegetation management

5.2.1 Soiling

As agrivoltaic systems are in direct proximity (i.e., above, or adjacent) to agricultural activities, their PV arrays are expected to face relatively higher levels of soiling (i.e., buildup of dust and dirt) compared to GMPV systems. In addition to dust and dirt particles, other sources of increased soiling on PV arrays may include excrement from local fauna (especially birds and large insects) and contamination from crop management products, e.g., insecticides and fertilizers.

Soiled PV arrays experience optical losses and, consequently, PV power output deficits that vary depending on the site characteristics (i.e., microclimate, cleaning intervals, inclination), see Figure 12. The soiling losses can reach from 10% in standard cases [147], up to over 30% in severe cases of non-homogeneous soiling (e.g., hot spots due to bird droppings) [151]. As for any PV system prone to significant buildups of dust/dirt particles and contamination, soiling losses can substantially negatively impact the ROI and overall economic viability of agrivoltaic systems.

To monitor and minimize soiling losses, a time- and cost-efficient soiling assessment and mitigation plan should be adopted for each agrivoltaic system, involving regular cleanliness inspections and periodic cleaning interventions. Cleanliness inspections typically include on-site and/or remote measurements (e.g., IV tracing, imagery), in order to determine standard relevant metrics such as: (a) soiling ratio: ratio of the maximum power of a soiled PV module (or array) to the maximum power of the clean PV module (or array) under the same conditions (dimensionless); (b) soiling rate: daily derate of soiling ratio, when no cleaning occurs on the PV module/array (fraction per day) [118].

For systems with heavy soiling and/or contamination, cleaning measures should be carried out appropriately depending on the assessed cleanliness. An optimal cleaning schedule requires an accurate prediction of the seasonality of soiling accumulation and restorative rainfall to maximize the effect of cleaning on the PV energy yield while limiting its cost and environmental impact [114, 119].

Figure 12: Examples of different sources of soiling buildup in PV arrays [152].

In most conventional PV systems, cleaning interventions (water-based or waterless, e.g., brushing) are carried out manually. The use of automatic soiling management equipment (e.g., cleaning robots) has been limited to date, given high added costs and complexities in their deployment, which are hard to justify and counterweigh in most cases [117]. Yet, in agrivoltaic systems, where soiling losses can be relatively higher, automated PV array cleaning solutions are expected to be highly relevant. Besides, low-water or no-water cleaning solutions, such as fully automated dry brushing, receive growing attention for ecological and economic reasons. The reasons are the increasing water scarcity, costs of water resources, and, in some cases, high mineral content. The latter can result in mineral deposits on the module glass, such as calcified film. One opportunity of water-based cleaning solutions is to use the water for irrigation, or vice versa. However, this may require additional efforts for water treatment, as the quality of water for cleaning and irrigation can differ significantly.

Preventive soiling mitigation solutions in the design phase of an agrivoltaic system include i) the use of anti-soiling and hydrophobic coatings on the PV modules' front (glass) cover and ii) opting for higher tilt angles of the PV arrays. Higher tilt angles reduce the buildup of soiling on the PV modules and can increase the "self-cleaning" effect caused by precipitation or snow events. More factors for defining the optimal tilt angle are discussed under Section 2.2.2.

As a best practice, it is recommended that cleanliness inspections and cleaning interventions be applied in agrivoltaic systems as a function of crop- and soil-specific characteristics. Attention should also be drawn to the use of detergents, if applicable. The latter should fully comply with relevant food, feed, pharmaceutical and environmental legislation in the EU or similar regulatory frameworks at the (inter)national level [28]. Cleaning interventions in agrivoltaic installations should be data-driven and only initiated whenever necessary. Such an approach can minimize unnecessary loads or accidental damage to the agrivoltaic system and save resources (e.g., electricity, water, and labor).

From a research perspective, conclusive studies, and insights into the impact of soiling in agrivoltaics applications are very scarce, and only a few have been reported in the literature so far. Among these few, in [201], the authors presented a soiling assessment study of a pilot agrivoltaic installation in Chile, where the impact of the specific agricultural context was elaborated, see Figure 13. The study showed that particular attention should be paid to soiling when deploying agrivoltaic systems in arid regions, i.e., with prolonged dry periods, such as the studied case of central and northern Chile. In these regions, self-cleaning events, notably rainfall, are rare, and fieldwork on dry soils results in high dust levels. This conclusion is especially relevant since the highest potential for agrivoltaics applications is in dry and sunny regions, where PV arrays provide shading to protect crops against excessive thermal stresses and efficiently reduce water evaporation, thus lowering irrigation needs.

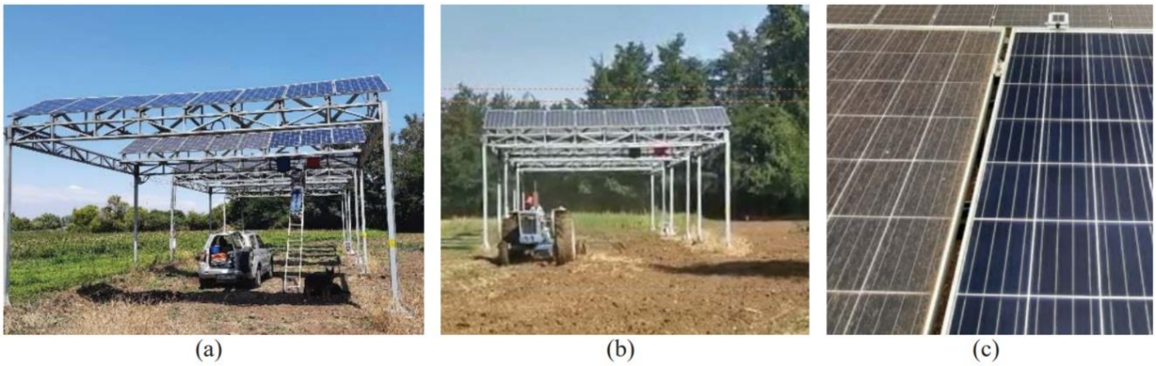

Figure 13: (a) Agrivoltaic pilot installation under soling study (b) Use of plow and disk ripper to prepare the field underneath the PV arrays, (c) Cleaned PV module next to uncleaned PV module, in the same pilot installation. Reproduced from [201] with the permission of AIP Publishing.

5.2.2 Pasture and vegetation management

Vegetation management strategies have gained popularity in recent years, including pasture management in collaboration with local farmers deploying specific grazing animal species, see Figure 14. For relevant agrivoltaic projects, an adequate pasture (grazing) management strategy must be adopted to ensure that permanent grassland has sufficient time to regenerate [152, 202]. Vegetative ground cover under and around the PV arrays should be maintained to minimize soil erosion and stormwater runoff [202]. Vegetative conditions and growth rate will fluctuate naturally during the grazing season, from a spring “flush” of new growth early in the season to a slower regrowth rate or even dormancy during summer heat and/or periods of low precipitation or drought. In these situations, stocking rates or grazing frequency should be adjusted as necessary [202]. The division of the project site into several sections, in addition to a pasture rotation cycle, is advised [152]. From an agricultural point of view, the grazing activity represents a service to the PV operator instead of a primary agricultural land use.

Figure 14: Sheep grazing between PV module rows. © Lindsay France/Cornell University.

5.3 Research and innovation outlook in operation and maintenance

Innovative research and technology deployment could improve O&M efficiencies and lower O&M costs [153]. Innovations could be adapted from new technologies and approaches developed in the agricultural sector, the PV industry, or an emerging agrivoltaic technology field. Within the agricultural sector, automation of agricultural activities (e.g., planting, pest management, harvesting) could substantially reduce labor costs associated with crop production. Precision agricultural practices combined with automation could also reduce agricultural input costs and potentially lead to higher yields and improved environmental performance. In some cases, existing automated agricultural solutions must be adapted or modified to be compatible with agrivoltaic infrastructure. However, agrivoltaic systems offer new opportunities to integrate automated solutions better. Specifically, the agrivoltaic mounting structure could be directly integrated with smart farming equipment, including cameras, sensors, artificial lighting, irrigation components, and other instrumentation to facilitate precision and automated agricultural activities.

Further field research is necessary to measure microclimate, module temperatures, and solar electricity generation. This, combined with model validation, will help clarify the potential magnitude of the operational benefit. Solar PV O&M technology innovations could also be applied to agrivoltaic systems for cost savings. Technologies to rapidly assess soiling, clean PV modules, detect inadvertent shading, and/or isolate PV module damage could significantly impact agrivoltaic facilities, where these occurrences occur more frequently. Using drones for fault detection could also be combined with other agricultural monitoring techniques.

Particularly about soiling in agrivoltaic systems, future research should also investigate i) agrivoltaics designs and layouts that passively minimize soiling buildup, ii) streamlined and automated cleaning solutions that enable dual use of water for PV module cleaning and irrigation, as well as iii) cleaning procedures for agrivoltaic systems with elevated PV arrays (which, today, comprise a challenge for cleaning interventions, in terms of safety and efficiency).

Lastly, novel technology and controls could be developed specifically for agrivoltaics projects. These could include custom-designed farm equipment that can successfully operate within agrivoltaic facility configurations, anti-soiling technologies, integrated irrigation and module cleaning technologies, and novel tracking algorithm control processes that reduce O&M costs.

6 LEGAL AND SOCIO-ECONOMIC ASPECTS

6.1 Introduction and overview of agrivoltaic scope

The novel and collaborative use of land across energy and agricultural sectors can lead to differences in how these projects are treated in national and sub-national policy. Involved systems differ likewise in community perception compared to traditional utility-scale solar projects. Policy frameworks and social perspectives of agrivoltaic represent a critical enabling factor helping to determine which systems ought to be implemented. While most of the research in the field to date has been focused on physical and biological sciences related to crop and technology performance, social science research related to policies and social perspectives is essential to assess better the potential future deployment of agrivoltaics, its impact on the energy and agricultural sectors, and various co-benefits and tradeoffs.

Policy, regulatory, and legal frameworks within a country can impact on the size, configuration, performance, rentability, and compatibility of agrivoltaic systems. Regarding regional planning, dual land use applications might need to clearly fit within traditionally defined zoning and policy definitions [38]. In some countries, specific legal frameworks, and policies address agrivoltaics. In contrast, in other countries, various aspects of the energy sector, agricultural sector, and land-use frameworks can all directly or inadvertently affect project development. However, in contexts without dedicated legislation for these systems, the intersection of energy, agriculture, and land-use regulations can complicate the permitting and construction processes.

For example, a conventional GMPV system may have different regulations compared to a dual use agrivoltaic project. These differences can include yield requirements for agricultural production, suitable locations for installation, eligibility for financial incentives, and designations as either industrial or agricultural projects. Additionally, there may be specific height restrictions and other on-site requirements that can impact both the design and financial viability of the project [38, 154–157]. While sub-national definitions and frameworks within countries, as well as variations in definitions across different countries, can be justified to better meet local needs and preferences, they can also complicate the deployment of agrivoltaics [14].

Social and community perspectives on solar and agrivoltaics can also play a significant role in determining whether an agrivoltaics project can be built and its final design. As has been demonstrated, agricultural lands are often promising locations for solar development due to their large, contiguous areas, access to existing transmission lines, strong solar resource, stable soil, and minimal slope [158, 159]. However, for various reasons across countries, there can be public opposition to solar development on active agricultural lands [160, 161].

This chapter provides an overview of the legal and socio-economic aspects of agrivoltaics by highlighting various legal frameworks and policies from a select group of countries, assessing the state of research on social perspectives, and summarizing key economic and financial considerations.

6.2 Legal frameworks and policies addressing agrivoltaics

Legal frameworks and policies operate on multiple jurisdictional levels (e.g., international, national, sub-national, and local) and are aligned with individual countries' existing political infrastructure. This section overviews a few select countries that have implemented agrivoltaic policy mechanisms.

6.2.1 Japan

Japan was the first country to support a broad implementation of agrivoltaic, with over 4000 farms as of 2021. The main instrument for this development was a feed-in tariff provided by the central government. The feed-in tariff was contingent on annual yield reports, ensuring that yield reductions did not exceed 20% compared to the pre-agrivoltaic installation baseline [13]. However, the central government did not significantly change the relevant laws. Instead, the Ministry of Agriculture, Forestry and Fisheries (MOFA) issued a series of directives or notifications to allow agrivoltaics with conditions under the current regulations [162–166], which were consolidated in a ministerial ordinance enforced on April 1, 2024 [167].

As a result, the conditions stipulated in these directives, e.g., yield reduction limits or the system's minimum height, became a loose "definition" of agrivoltaics. Advantages of this approach are (1) swiftness—no leading time to wait for adaptation of a new law or clause, and (2) preservation of farmland—only a fraction of the land, the structural base, is temporally converted to non-agricultural use so that the land remains as farmland and farmers can enjoy relevant subsidies as before. The downside is the lack of definite standards, which makes the land conversion procedure controversial. The first screening is governed by the local agricultural committee, which almost all municipalities have. The screening results are somewhat arbitrary as decision criteria differ with the respective local administrations due to the lack of detailed standards and instructions from the central level.

The duration of the permitting process varies widely by location, ranging from three months to three years. Besides feed-in tariffs and certain exemptions in the conditions to obtain those, little incentives exist for agrivoltaics. Consequently, many people find agrivoltaics less attractive since even the feed-in tariffs cannot offset the higher LCOE compared to conventional GMPV systems. Complying with structural regulations is essential as well. In Japan, many utility-scale facilities were built on mountain slopes due to easier land conversion than flat farmlands. Some poorly constructed facilities were destroyed by disasters, leading to the government tightening the structural standards for solar PV facilities, including agrivoltaics [168].

6.2.2 France

Agrivoltaics was first explicitly introduced in the French legislation by the vote of the "Acceleration law" (Accélération de la production des énergies renouvelables, APER) that was passed on 10 March 2023 with an unusual majority of Members of Parliament (the left and greens helped the government to pass this law). This law defines agrivoltaics in France and proscribes any GMPV on agricultural or forest land, with few exemptions for long-term fallows (10 years minimum) in specific areas identified by the Chambers of Agriculture. The law insists on the reversible character of the installation and demands the constitution of financial guarantees for dismantling. Agrivoltaics is defined in France as a tool to improve agriculture production. At least one of the following services must be provided directly to the agricultural parcel: (i) improvement of the agronomic potential, (ii) adaptation to climate change, (iii) protection against hazards, (iv) improvement of animal welfare. The law states that agriculture should remain the "main" production, which is challenged by the fact that the revenues from electricity tend to be 5 to 20 times the revenues of agriculture in most agrivoltaic systems. An application decree of the APER law was published in 2024, defining criteria to be considered to qualify as an agrivoltaics project [169]. The decree includes a limit of 10% maximum reduction of the agricultural production, which makes French law more demanding than most other countries. The decree also states that the area of land that cannot be cropped due to the system should be limited to 10% of the parcel. Assuming a loss of 10% area, achieving the 10% yield reduction implies that the cropped area should have a 100% yield compared to a control without PV modules. A synthesis of all published yields in agrivoltaic systems [39] evidenced that this could only be achieved with very low Ground Coverage Ratios (GCRs ≤20%), which is creating a heated debate in France on the profitability of agrivoltaics schemes with low GCRs.

The French Agency for Ecological Transition (Agence de la transition écologique, ADEME) will define "approved" technologies qualified as sustainable agrivoltaics. Other technologies will have to prove that they comply with the criteria by installing control areas for crop production. Fewer constraints are considered for agrivoltaics with greenhouses or grazing animals. However, the decree indicates that the farm revenue should not decrease, which would, for example, prevent the replacement of profitable crops by low-intesive sheep grazing. The permit process will require a favourable decision by a local instance (CDPENAF), with project developers fearing that this instance may block many projects, which could lead to numerous trials before the administrative courts. This risk is underpinned by controversial positions of farmer trade unions: major unions support unregulated agrivoltaics while other trade unions ask for more regulations or oppose it. No decision has been made so far on the limits of size for agrivoltaics projects, but sharing the agrivoltaics rent among all territories and farmers is a concern. The minimum height of PV modules in agrivoltaic systems with grazing is also debated. The AFNOR company has designed an agrivoltaics label. The crop version is available, but the grazing version is still expected. This norm must be adjusted to the final dispositions of the decree. Labelled projects may be favoured by the French Departmental Commission for the Preservation of Natural, Agricultural and Forest Areas (Commission Départementale de Préservation des Espaces Naturels, Agricoles et Forestiers) in the permitting process. Since adopting the Acceleration Law, agrivoltaic installations may be subject to specific calls for future tenders. Also, the presence of agrivoltaic facilities on agricultural land does not prevent the same land from being eligible for the EU's Common Agricultural Policy (CAP) aid. However, no decision has been made on reducing the CAP payment if the cropped area is reduced.

6.2.3 USA

The USA legal framework is generally characterized by three tiers of government (Federal and Tribal, State, and Local), each with its own set of rights and restrictions. Within these tiers, various departments or agencies are operating to oversee the respective sector. Relevant to agrivoltaics, authority over solar energy permitting and agricultural land use is within the jurisdiction of state and local governments. In most cases, statewide energy programs direct solar development, while local governments manage the zoning and land use considerations associated with project siting. These varied processes and authorities result in a complex landscape for agrivoltaics in the United States, with no comprehensive legal framework to standardize development across the country [16, 170]. At the federal level, effort to drive R&D is reflected in funding opportunities provided by the U.S. Department of Energy (e.g., DE-FOA-002697) and the U.S. Department of Agriculture (e.g., ILLU-470-620).

However, state governments exhibit the most significant innovation in administering agrivoltaic programs. Most notably, the state of Massachusetts (MA) offers a feed-in tariff (6¢ per kWh) through the Solar Massachusetts Renewable Target (SMART) program to incentivize projects that meet agrivoltaic standards. Jointly developed and administered by the MA Department of Energy Resources and MA Department of Agricultural Resources, this program defines an agrivoltaics project as “a solar tariff generation unit located on land in agricultural use or important agricultural farmland that allows the continued use of the land for agriculture.” Key program eligibility criteria include: 1) the use of the Department’s Shading Analysis Tool to demonstrate a maximum 50% sunlight reduction throughout the farmer area under consideration; 2) coordination with the University of Massachusetts Amherst extension services to ensure compatibility of solar design with agricultural plans; 3) annual reporting of the agricultural productivity that validates ongoing commercial agricultural activity and achievement of projected yield originally stated in the approved agricultural plan. Other system design parameters include panel height requirements of a minimum height of 8 feet (fixed tilt) or 10 feet (i.e., for single-axis tracking) of the lowest panel edge and a maximum AC capacity of 5 MW_p. Illinois and New York also encourage agrivoltaics by maintaining bid preferences for projects that meet agricultural and environmental standards [171]. Other policy approaches have emerged, including voluntary programs and mandates for ecovoltaics in Minnesota and Michigan, while other states, such as New Jersey and California, are in the process of defining programs for agrivoltaics [203]. While these state initiatives provide the supportive structure for the solar industry to engage in agrivoltaic development, local governments arguably possess the most power over project realization [38, 172]. More time is needed to evaluate the efficacy of these early initiatives properly. However, they serve as an essential testing ground for policy learning for the continued development of robust programs that balance solar development with farmland preservation in a just, cost-effective manner. Early learning lessons related to the existing legal framework in the United States and initial programs show that developing supportive legal conditions for agrivoltaic development will require horizontal and vertical alignment across federal funding efforts, state energy programs, and local land use policies.

6.2.4 Germany

In Germany, the preliminary standard DIN SPEC 91434 [21] is the legal framework's foundation. According to this standard, the main prerequisite for categorization as an agrivoltaic system is that the area is mainly used for agricultural purposes after the system has been installed. Depending on the category, the loss of usable agricultural land must not exceed 10% or 15%, and the agricultural yield must be at least 66% compared to a reference area without a PV system. This standard itself is not legally binding. However, requirements from DIN SPEC 91434 have been referred to fully or partially in various laws, ordinances, regulations, or decrees establishing the legally binding nature of DIN SPEC 91434.

With the Innovation Tender Ordinance, in 2021, the legislator created special regulations for agrivoltaic systems for the first time. Since then, the legal framework for agrivoltaic systems has continued to evolve. Instead of a particular law, the regulations have been anchored in the respective specialized laws (for an overview, see [173]).

As the regulations are set on a national level, the requirements are equally valid in all of Germany. It should be noted, however, that the federal states and the local municipalities play an essential role in tax law or the preparation of development plans.

The Renewable Energy Sources Act (EEG) is the central law for promoting electricity generation from renewable energies – and therefore also for agrivoltaics [157]. According to the EEG, the facility operator is entitled to immediate and priority connection to the grid and feed-in of the electricity. Finally, the facility operator is entitled to financial support from the grid operator for the electricity fed into the grid if the requirements for this are met. Since January 2023, the EEG has included special financial incentives for solar installations on arable land, permanent and perennial crops, and grassland. The Federal Network Agency defined the requirements in two specifications, in which comprehensive reference is made to DIN SPEC 91434. A recent amendment to the EEG from May 2024 established further improvements for implementing agrivoltaics [174].

Main adjustments target small facilities with a system size of up to 1 MW_p and overhead systems with a vertical clearance higher than 2.1 meters and vertically installed PV modules.

If the municipalities have yet to issue a development plan, no project may be realized in the so-called outdoor area. So-called privileged projects are exempt from this. As agrivoltaic systems are often built on such areas, categorizing the project as a privileged project plays an important role. Since 2023, the German Building Act (Baugesetzbuch, BauGB) has included privileges for certain agrivoltaic concepts in § 35 (1) BauGB. Hereby, reference is made to the special requirements for agrivoltaic systems in the EEG and the requirements of the DIN SPEC 91434.

A special regulation for agrivoltaic systems can also be found in the EU CAP subsidies. Here, however, reference is only made to parts of the DIN SPEC 91434 with additional requirements for the compatibility of the agrivoltaic system with standard machine employment [175].

In the field of inheritance, gift, and land and real estate transfer tax law, the supreme tax authorities of the federal states have determined in identical decrees from 15th of July 2022 (BStBl. 2022, p. 1226) that land with agrivoltaic systems within the meaning of DIN SPEC 91434 is to be assigned to agricultural and forestry assets, which is very advantageous in terms of tax law.

6.2.5 Italy

Agrivoltaics is experiencing significant growth in Italy. The development of agrivoltaics started several years ago, mainly because of the goal of decarbonization, the need to support agriculture and control agricultural soil consumption and, more recently, the goals of the Italian National Recovery and Resilience Plan (Piano Nazionale di Ripresa e Resilienza), made the competent authorities to become keener to authorize agrivoltaics instead of regular PV facilities. Still, the main requirements necessary for classifying a facility as “agrivoltaics” were identified only in 2022 with the guidelines issued by the Italian Ministry of Environment and Energy Transition (“MASE”). In the guidelines, agrivoltaics is defined as PV systems that adopt solutions to preserve the continuity of agricultural and pastoral cultivation activities at the installation site. The guidelines distinguish between “basic” and “advanced” agrivoltaics (i.e., compliance with the requirements of minimum height from the ground and the presence of a monitoring system [25]. Not legally binding technical rules define the best practices for agrivoltaics (UNI PdR 148:2023 and CEI PAS82-93).

The Government is supporting the growth of agrivoltaics both in terms of accelerating and simplifying the permitting procedures and providing economic support. Under the permitting profile, a municipal fast-track procedure (PAS) is envisaged, irrespective of project-related power capacity, in case the agrivoltaic facility is in the so-called agro-belt (within a 3 km buffer from industrial areas). At the same time, the environmental impact assessment thresholds increase up to 25 MW_p when the project involves “suitable areas”.

In July 2024, the Government adopted a decree that forbids the installation of GMPV on agricultural land to address agricultural soil consumption [35, 204].

Regarding the incentives, advanced agrivoltaics developed by agricultural companies, entrepreneurs or temporary associations between electricity producers, investors and agricultural companies or entrepreneurs are entitled to (i) capital contribution of up to 40% of the investment costs; (ii) benefit from an incentive tariff granted for 20 years (MASE Decree n. 436 of 22.12.2023, effective from 14.02.2024) [24].

The Italian Government is currently working on a further incentive decree that provides an incentive tariff but not capital contribution, which is dedicated, among other things, to PV systems of all kinds, including agrivoltaics.

However, the expansion of this technology is still slowed by several factors: (i) the process of identification of suitable areas is still pending at national level, and this influences the correct individuation of the authorization procedure; (ii) some Regions (Emilia-Romagna, Lombardia, Piemonte, Marche), pending the completion of the identification of the suitable areas at national level, have adopted some restrictions to the development of PV facilities on agricultural areas, including agrivoltaics; (iii) the access to the incentives dedicated to advances agrivoltaics is subject to subjective requisites [25] that are not easily digested by investors, especially considering the joint liability with the agricultural companies or entrepreneurs.

6.2.6 Israel

As all land in Israel is defined for specific purposes, land zoned for agriculture cannot be used to generate electricity unless the purpose is changed by the Israel Planning Administration, an independent unit within the Israel Ministry of Interior with its 12 internal divisions of the six regional planning bureaus.

Solar PV energy is expected to be the main source of energy by 2050, as other renewable energy sources are not sufficiently abundant. Electrical regulation is developing quickly to enable an energy market based on open market principles, enabling the sale of distributed solar energy and storage from the residential level up.

As a country, the state must carefully balance agricultural land use. Inherent to the reality that energy produces more money for less effort, it is seen as a danger that farmers may allow the energy use to harm the agricultural use of the land. The reluctance of regional planning offices to reclassify dual-use areas for agrivoltaics led to a long delay in the implementation of the numerous pilot projects approved by the Ministries of Energy and Agriculture. The national level of the Planning Administration has put together an inter-ministerial task force to develop a single set of criteria and regulations for agrivoltaics to apply across the country.

A small example of some of the expected elements to enter the regulation include [176]:

- The land classification of the Planning Administration will not restrict farmers from cultivating the land beyond the covered area of the agrivoltaic facility.
- Farmers can use additional land for the development of PV systems in addition to the land they use for pure agriculture.
- Unlike many PV projects, which are put out to tender by the government, agrivoltaics projects do not require a call for tenders.
- In contrast to the current zoning paradigm, agrivoltaic projects can be developed in the country's center in specific cases.
- The design and implementation of the supporting energy infrastructure – including energy storage – is permitted without additional cost implications in the approval process.
- Once zoned for agrivoltaics, the proposed land usage cannot be changed from agricultural without incurring a penalty.
- Agrivoltaics projects will carry high penalties if the agricultural activity of the agrivoltaic system is no longer carried out. An enforcement unit will be set up to enforce the ongoing agriculture activities in the agrivoltaic facilities.

The land legislative agreement between the farmer and the Land Administration will include a minimum yield clause of at least 70% of the annual average yield for land of a similar type. The developer must report the agricultural yield and install a monitoring device. The joint agrivoltaics pilot project initiative was formed in August 2021, including members from the ministries of agriculture, energy, finance, and interior, as well as the Public Utilities Authority and the Land Administration. Under the lead of the Ministry of Agriculture, the initiative published its suggestions in November 2022, enabling the authorization of 183 separate projects to 26 companies embarking on projects encompassing fruit groves, vineyards, vegetables, flowers, and spice crops. These research projects were awarded through a joint call by the ministries of energy and agriculture in January 2022. The studies involve 10 PV technologies and include the effect of joint land usage on irrigation, crop shading, pests, and disease.

6.3 Social impacts and perspectives of agrivoltaics

A growing research agenda is dedicated to exploring the diversity of stakeholder perspectives on agrivoltaics and understanding how interactions across social, economic, and regulatory contexts impact technology diffusion. By combining theoretical foundations in Diffusion of Innovations theory [177], Socio-technical Transitions theory [178], and Social Acceptance of Renewable Energy theory [179] with empirical findings derived from mixed social science methods (e.g., interviews, surveys, policy analysis, and content analysis), researchers have developed rich insight into the complex challenges and opportunities for stakeholder adoption, social acceptance, and diffusion of agrivoltaics. This research advances a central thesis: broad adoption and acceptance of agrivoltaics across stakeholder groups primarily depend on improved technological readiness and proof of concept for farmers and developers, just and inclusive participatory processes, and favorable economic conditions created by supportive legal frameworks. As research in this space is, in many cases, just beginning and is also dependent upon local agrivoltaic deployment trends, there is not a fully comprehensive body of literature, and insights here are drawn from a few select regions that serve as case studies. As agrivoltaics grows and more studies on social impacts in other jurisdictions are conducted, insights will likely evolve.

This chapter is organized into four primary sections: 1) solar industry perspectives; 2) agricultural sector perspectives; 3) community perspectives; and 4) crosscutting topics highlighting the importance of social issues for the agrivoltaics field.

6.3.1 Case study: USA solar industry

Recognizing the significant role of the solar industry in the diffusion of agrivoltaics, researchers have leveraged semi-structured interviews and conducted policy analyses to determine challenges and opportunities for USA industry uptake. The core factors hindering industry adoption identified are consistent across geographies and operating scales: gaps in knowledge, cost-benefit uncertainties, and regulatory barriers [16, 170, 180–184]. Underlying these challenges is a perceived “liability of newness” – from a solar developer's perspective, the novelty of agrivoltaics and associated underdeveloped knowledge, business models, and best practices renders the technology risky and immature [170, 181–184]. Pending broader proof of concept from a business case standpoint and reduced gaps in knowledge, industry actors are strained in their ability to perform cost-benefit analyses and develop reliable investment plans and system designs for agrivoltaics [170, 181, 183]. The challenge of uncertainty and complexity is further emphasized in the regulatory arena in which solar developers partake; in a targeted engagement with developers in the Northeast USA, study participants stressed how a lack of cohesion across state departments severely encumbers agrivoltaic development [184]. The lived experience of regulatory complexity is validated through a set of policy analyses that highlight how a lack of legislative action, program clarity, development standards, and formal definitions, as well as zoning restrictions for solar on farmland, effectively discourage industry actors from pursuing agrivoltaic projects [16, 17, 38, 180, 182].

Equally important, this body of literature discusses solar industry interests in agrivoltaics and identifies drivers of adoption in the USA. Perceived as a unique development strategy, industry actors consider agrivoltaics a meaningful approach for reducing opposition to solar on farmland

and securing continued access to rural markets [170, 183, 184]. The potential for agrivoltaics to increase rural community acceptance of solar has been underscored as the most attractive opportunity for the industry; study participants elaborated how agrivoltaics provides a means to retain agricultural interests and maximize ecosystem services in solar projects, which they anticipate will earn them better community relations and public reputation, ultimately leading to reduced friction in the permitting process, greater project acceptance, and the sustainable long-term deployment of solar [170, 183, 185]. Beyond maximizing project co-benefits and the resultant community acceptance, further economic benefits for developers, such as potential savings in operations and maintenance costs through solar-integrated grazing practices or ecovoltaics, as well as state-level financial incentives, are currently driving industry adoption in the USA [183, 184]. Experiences from Fraunhofer ISE on the adaptiveness of different stakeholders in Europe show a clear tendency of solar industry players to favor agrivoltaics applications with large area potentials that can be implemented on a utility scale and require rather low technical adaptations compared to GMPV [191]. Accordingly, system designs that enjoy a high expected acceptance of project developers are interspace systems focusing on permanent grassland followed by arable farming applications. In contrast, small-scale overhead systems on horticulture or permanent crops with complex integration approaches trying to address the agricultural requirements in the most synergetic way appear less attractive for a typical solar industry player. This preference to avoid technological complexity and associated higher costs by adapting standard large-scale solar designs for agrivoltaics is shared by solar professionals across the United States and European markets, emphasizing the need for future research to focus on optimizing agricultural compatibility at scale with standard solar designs to support broader industry adoption.

Various policy analyses maintain the key role of incentives in increasing the affordability of agrivoltaics and suggest that preferential solar land assessments and taxation programs, among other market mechanisms, could improve the value of agrivoltaics for the industry [16, 38, 182, 186, 187]. The combined implications of these identified challenges and drivers of industry adoption are helpful for informing future research and policy agendas.

6.3.2 Agricultural sector

Another stream of literature emphasizes the importance of agricultural voices, concerns, and interests in agrivoltaic development. Foremost, the diverse farmers engaged in the study were concerned about potential system impacts on soil, crop and forage productivity, and long-term farmland preservation; they also discussed operational challenges with navigating within fixed solar infrastructure and flagged how implications on crop rotation and evolving farming practices could create technical and financial uncertainty [181, 184, 188]. Like solar professionals, agriculturalists stressed a need for broader proof of concept to validate technical feasibility, prove economic viability, and ultimately reduce adoption uncertainties [188]. A survey study aimed at Connecticut farmers in the United States found that despite willingness to engage in agrivoltaic projects, existing farmland preservation policy does not allow for solar on their land, effectively barring adoption [189]. Other studies forewarn of related socio-political challenges, having identified concern about just outcomes and the potential negative effects on tenant farmers who could be displaced by the technology if land agreements do not proactively address this sensitivity [17, 181, 184, 188, 190].

Despite the complexity of farmer concerns and adoption challenges, agricultural sector interest in agrivoltaics persists. Perceived as an effective way to enhance farm viability, farmers value the potential for economic diversification and security provided by engagement with a solar project [17, 181, 184, 188, 191]. From their perspective, agrivoltaics can contribute to improved climate resilience from solar infrastructure shade for livestock and crops, intergenerational succession opportunities, on-farm energy cost savings, and rural energy security advancements [181, 184, 188]. The various farmer adoption challenges and interests in agrivoltaics identified in this research suggest the technology's unique role in retaining rural values in solar development and emphasize the importance of designing projects to generate legitimate economic and ecological benefits and mitigate unintended consequences in the agricultural sector.

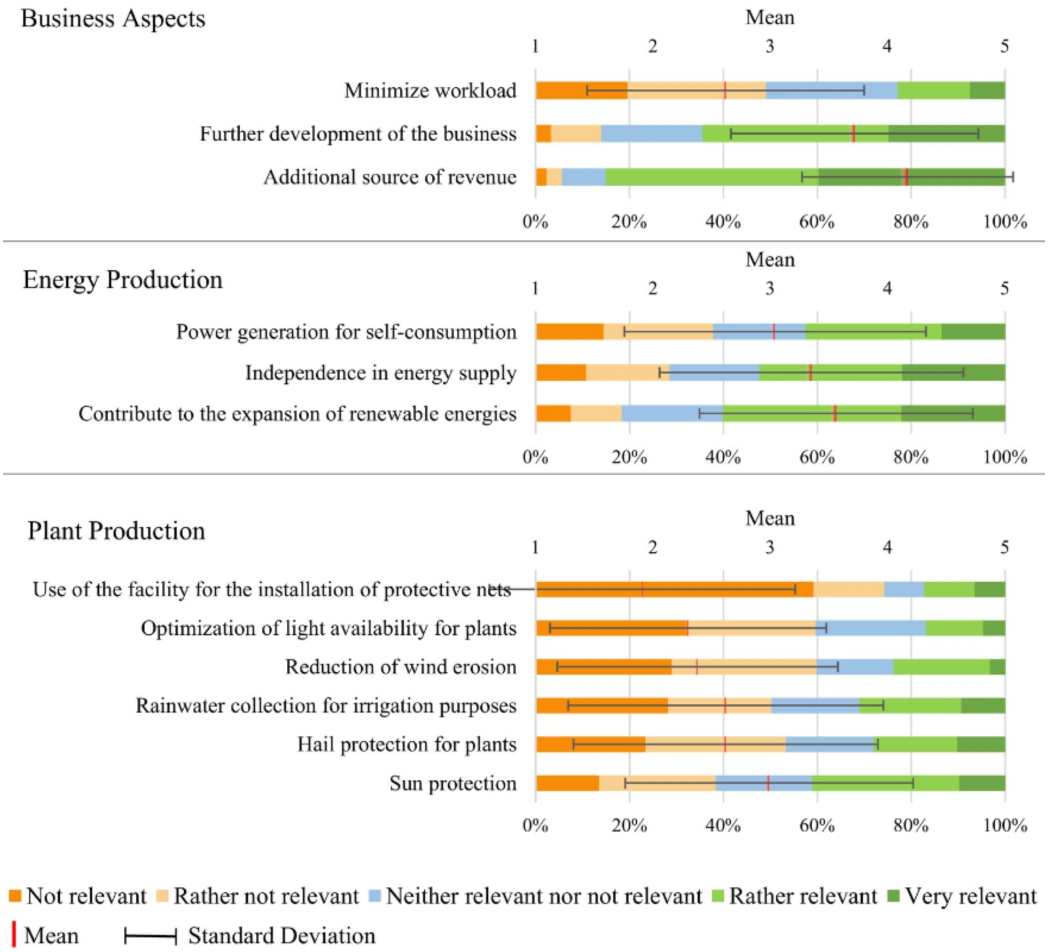

Figure 15: Results from an online survey among 214 German farmers to assess their perceived willingness to use agrivoltaics on their farm and to identify driving factors [191].

Recent research conducted through an online survey in Germany in February 2023 indicates a positive response towards agrivoltaics, with 72.4% of farmers showing a willingness to adopt this technology [191]. The survey results highlight that the strongest motivator for adopting agrivoltaics is its "perceived usefulness," followed by the "subjective norm" and the farmer's own "innovativeness," see Figure 15. For many farmers, the primary benefits of agrivoltaics include generating additional income and supporting the long-term development of their farms. Notably, distrust of technology is not a significant deterrent. However, bureaucratic processes, an unclear regulatory environment, and the complexities of managing agricultural operations under solar installations pose significant challenges.

6.3.3 Local communities

Because integrating solar energy into agricultural landscapes requires farmers' willingness to adopt it and community acceptance, researchers have begun exploring public concerns and interests in agrivoltaics. Although limited in number and scope, research concerned with community stakeholders and acceptance provides early insight into preferences and priorities to be included in developing agrivoltaic projects in the United States and Europe. Through a series of citizen workshops to understand how participatory planning for agrivoltaics impacts community perspectives, Ketzer et al. found higher acceptance of projects emphasizing citizen participation in the development process [192, 193]. This team of researchers stresses that framing agrivoltaics for high acceptance and successful market introduction requires proactive community engagement to define site selection and aesthetic criteria, local regulatory frameworks, performance standards, and business models. Citizens involved in this pre- and post-development workshop identified system design factors (specifically size) and impact on landscapes and local economies as the main negative factors that reduce acceptance of agrivoltaics [192, 193]. Community influence over solar project design and perceived economic and environmental impacts were also found to be concerning to USA residents, yet study findings indicate that increased in-person engagements and collaborative development of local economic benefit agreements improve community perceptions and project acceptance [185].

Survey and interview studies conducted in the United States further demonstrate how place-based economic and agricultural factors and community involvement in the development process shape attitudes towards solar on farmland [185, 194]. Survey study participants noted the most significant concern, as well as opportunity, around distributive justice – directing economic benefits to the farmer and the host community, was identified as the primary driver of community acceptance of agrivoltaics, whereas the unfair distribution of benefits was cause for opposition [194]. Distributive justice was also found to be of primary concern to citizens in Denmark [195] and Germany [193]. Similar to citizens in Germany [193], potential effects on rural landscapes were identified as concerning; survey participants specified preferences for siting agrivoltaics on private property rather than public property yet indicated a greater willingness to accept solar in their community if the project included agricultural production [194]. While the survey study found protecting local interests and maintaining rural landscapes in development were key community concerns, content analysis performed by McLennan [181] showed that common public discourse on agrivoltaics in the United States emphasizes how the practice can help maintain farming lifestyles for rural communities through economic benefits. Potential local economic gains, such as tax benefits for the host community, were cited in the news media as key opportunities relevant to community acceptance of agrivoltaics. These initial community-engaged research studies suggest that proactive and inclusive multi-stakeholder engagements that prioritize participatory planning processes to incorporate local values and preferences in the development of agrivoltaic projects will be critical for improving community acceptance of solar on farmland and continued diffusion of agrivoltaics.

6.3.4 The importance of social aspects

As agrivoltaics involves reconciling agriculture and energy sectors to realize common, localized goals, research and development efforts must be built on extensive cross-sector collaboration and participatory processes. Initial social science on agrivoltaics reveals how this disruptive innovation prompts change in solar development practice, farming operations, and agricultural heritage, and suggests that proactive consideration of these social aspects of technical transitions will be critical in sustained technology adoption, acceptance, and diffusion. Moreover, preliminary research across geographies indicates some variations and commonalities of perceptions of different stakeholders, implying generalizations in one region might only apply to some regions. This subchapter emphasized commonalities across regions to present a shared global perspective on the key social aspects of importance for agrivoltaics research and development. Applying the lessons learned from this scholarship to real-world deployment efforts will require improving technological readiness and proof of concept, participatory processes, and developing legal frameworks that improve economic conditions – all of which can be driven by diverse partnerships aimed at making agrivoltaics operational through shared best practices [28, 196], innovative business models, and supportive policy environments.

6.4 Economic performance

The economic performance of agrivoltaic systems largely depends on the agricultural application, the system design, the respective business model, and the local conditions. An economic viability assessment typically considers capital and operating costs, revenue streams, financing plans, and sensitivity- and risk analysis. To comply with government mandates on maintaining minimum agricultural productivity for primary land use, market players often prioritize PV production over agricultural yield, especially in applications with low agricultural revenue, such as arable farming and permanent grassland. Economies of scale are crucial for reducing the cost of agrivoltaics, likely resulting in large-scale implementations primarily in these low-revenue areas. For a practical and sustainable market introduction of agrivoltaics, it is essential to have a well-crafted and differentiated regulatory framework that addresses each application area's specific externalities and challenges. The significance of this overview is limited by the early stage of the technology and the resulting sparse database.

6.4.1 CAPEX, OPEX, and LCOE

Depending on the system design, the CAPEX of agrivoltaics can be significantly higher than that of GMPV. The lowest costs are associated with low intensity agriculture with interspace agrivoltaic systems in permanent grasslands. In contrast, the highest costs are found in systems with high PV integration, such as overhead systems [37]. Key drivers are high PV module elevation and non-conventional technologies like semi-transparent PV modules. As for GMPV, the CAPEX of agrivoltaic systems is also strongly location-driven and depends, e.g., on the distance to the grid connection point, slope and geotechnical characteristics of the area, conditions for self-consumption of electricity, and the involved business case.

Trommsdorff et al. [43] note that the CAPEX PV component of overhead agrivoltaics is higher than that for GMPV systems. This is due to the need for an elevated mounting structure that provides sufficient vertical clearance for agricultural activities. They also point out that a greater proportion of farm labour, combined with less reliance on farm machinery, is more conducive to generating higher financial returns. Additionally, they explain that maintenance and weed management of the PV system can be done as part of the farming activities, which typically leads to lower operational expenses (OPEX).

A critical factor in the viability of agrivoltaics relates to O&M costs. As noted in section 5.1, O&M activities can differ for the solar PV system operator and the agricultural provider in an agrivoltaic project compared to GMPV. These different activities can lead to differences in the costs of individual O&M activities. Agrivoltaic O&M costs can be organized into three categories: O&M costs for the agricultural provider, impacts on electricity generation, and O&M costs for the solar system operator.

Under certain climate conditions and land management practices, vegetation can lead to cooler microclimates, which can lead to higher PV module efficiency and greater electricity output, thus increasing revenue for the system owner [197]. However, microclimate and PV module temperature changes can vary significantly by location and ground cover, with potentially more significant benefits in more arid regions [198–200].

Agrivoltaic activities can reduce vegetation management O&M costs for PV system operators compared to GMPV, as agricultural activities are replacing traditional land management costs. However, the magnitude of the cost savings (or increase) will depend on the nature of the PV system operator's agreements with agricultural providers. For example, the PV system operator might pay a sheep grazer to manage the vegetation or a crop producer to manage the vegetation underneath the modules. These agreements could be more or less than traditional vegetation management practices from the PV system operator's perspective. Agreements with agricultural producers could include a multitude of different costs that PV system operators are responsible for, including water, irrigation equipment, soil amendments, auxiliary electric loads for food preservation, fuel for equipment and machinery, labour costs, non-agricultural vegetation management, or other items agreed upon between parties. McCall et al. [198] highlighted considerable variability in vegetation management costs for PV system operators, with no significant differences between agrivoltaic (sheep grazing) and non-agrivoltaic (turf-grass) vegetation management practices at utility-scale solar projects in the United States. The presence of agrivoltaic activities within a PV array could also affect PV technology O&M access, maintenance schedules, and maintenance protocols, leading to higher labour and/or equipment costs to avoid damage to agricultural components.

Operating costs can also change for the agricultural producer in an agrivoltaic project compared to a traditional full-sun farm. PV modules under specific configurations could limit equipment, machinery, and/or labor access. Changes in these practices could lead to differences in labor, fuel, equipment rental, and other costs for the agricultural producer. The potential reduction in arable land suitable for planting in an agrivoltaic array could also change agricultural input quantities and costs, and irrigation water quantities are likely to be lower than in full-sun conditions.

Across all types of O&M costs, we anticipate multiple opportunities for cost reductions through industry experience, new technologies and management approaches, and greater standardization of practices. An improved understanding of specific changes in O&M activities, documented through deployed agrivoltaics projects across geographies, agricultural types, and management practices, would aid in the evaluation of O&M costs and the overall economic performance of agrivoltaic systems.

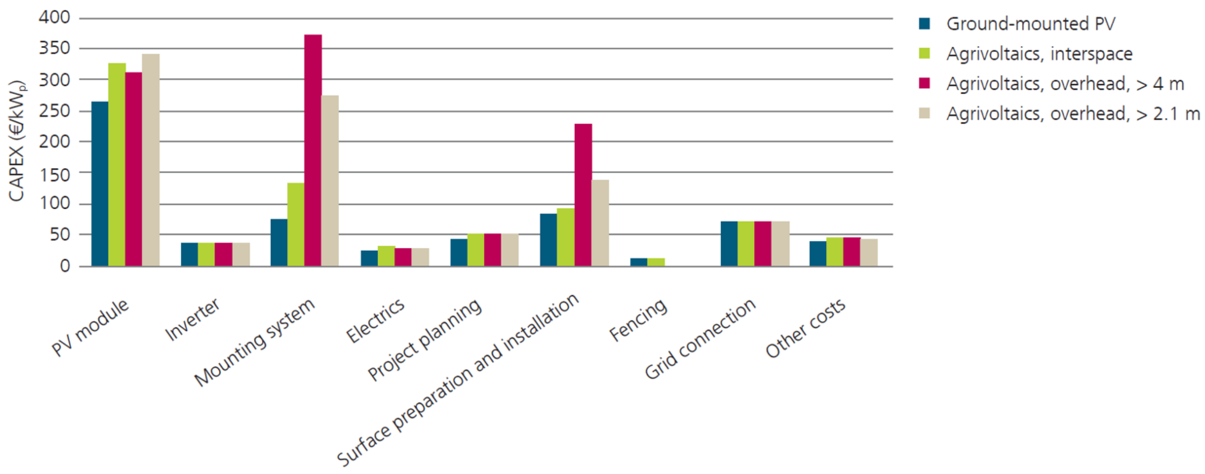

Figure 16: Estimated CAPEX for GMPV and three different agrivoltaic systems. © Fraunhofer ISE [196].

Figure 16 shows an overview of estimated CAPEX for three different agrivoltaics applications compared to GMPV in Germany. Main driver of higher CAPEX is cost on PV modules, mounting systems, and surface preparation and installation. In a 2020 report by NREL [23], a bottom-up investigation of capital costs for a range of reference models for PV systems was published. The results compared GMPV systems with agrivoltaics. To simulate the cost of installing PV systems, the researchers examined a range of scenarios, including PV + grazing, PV + pollinator habitat and PV + cropping. A 500 kW_p (direct current, DC) baseline system was compared for each scenario. This methodology included each stage of the installation process and the labor, materials, and equipment costs. The results showed that the capital cost premium ranged from US$0.07/$W_p$ DC to US$0.80/$W_p$ DC, depending on the scenario. In addition, higher capital costs were expected for all scenarios compared to standard GMPV systems. The lowest price premium was found for PV with grazing, while the largest premium was found for the systems with expensive high-efficiency materials. It was also found that the lifetime economics of the system are strongly influenced by the total cost of ownership, which increases with decreasing energy conversion. A more comprehensive overview of the economic performance of agrivoltaics is provided by Trommsdorff et al. [37].

6.4.2 Assessment of profitability and revenue estimates

ROI is typically used to measure rates of return on money invested to assess the profitability of agrivoltaic systems and decide whether to undertake an investment. The ROI can also be used as an indicator to compare agrivoltaics investments with other investment opportunities (see also the definition of ROI in Table 2).

To calculate the ROI, revenues from both the sale of electricity and agricultural products must be considered. Agricultural variables include the type of crops grown, growing season, tillage techniques, crop size relative to farm size, agricultural processing activities, post-harvest management, local produce market, and anticipated market prices for the sale of produce and purchase of non-agricultural inputs [8].

While relevant parameters should generally be considered for both electricity and agriculture, agricultural production is also neglected, with the argument that its value is low compared to the revenue generated by electricity. While this might be true for most permanent grassland or arable farming applications, agricultural revenues from cash crops like vegetables, fruit growing, or vineyards can contribute a significant share of the overall economic performance.

Figure 17 provides an estimation of Trommsdorff et al. on the revenue streams stemming from agricultural and electricity production in different agrivoltaic systems across nine crops in six countries, indicating average agricultural revenue shares below 4% in sheep grazing and rice and wheat production [37]. In contrast, average revenues for tomato and strawberry cultivation amount to more than 55%, exceeding revenues from electricity production. Accordingly, neglecting the agricultural yield seems to be an appropriate approach only for applications in permanent grassland or arable farming and should better be assessed on a case-by-case basis.

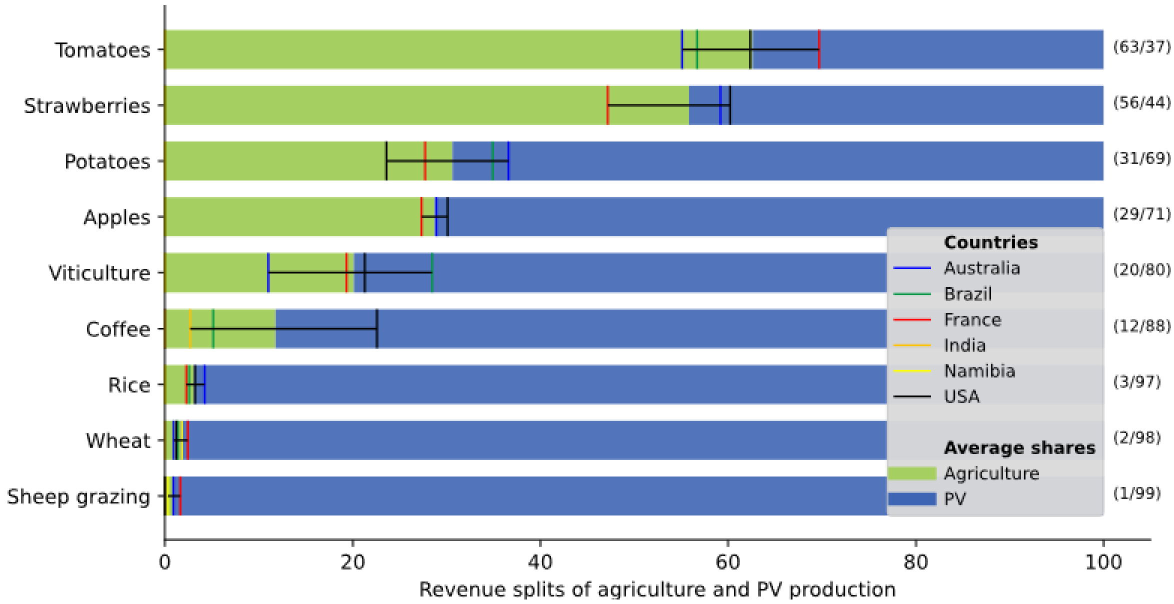

Figure 17: Revenue splits of agriculture and PV production according to Trommsdorff et al. [37]. Coloured lines indicate the variations of considered countries. Agriculture data: FAO Stat.; PV data: Solar GIS.

6.4.3 Business case and financial modelling

A business model is required to determine whether an agrivoltaic system is feasible and to ensure that the higher investment costs compared to GMPV are acceptable. The business model for an agrivoltaic project can be quite complex as the number of stakeholders is typically higher than for GMPV projects (e.g., landowner, farmer, PV facility owner, bank, and electricity off-taker). This complexity poses additional risks to the overall project. In addition, there are a few examples of such commercial arrangements from which lessons can be learned about best practices and potential challenges.

From a business perspective, the critical question is whether the income generated can offset all expenses and generate an appropriate return for the investor. Although national legislation may determine details of the legal structure between the partners (e.g., when a farming education may be required to receive financial support for farming activities and when self-consumption of electricity is only allowed with a single enterprise entity), it is still possible from an analytical perspective to bundle all financial activities into a single business case representing all involved stakeholders to assess the combined financial aspects of the business opportunity. It does not necessarily mean that all partners must bring their activities into such a single particular purpose company, as the financial and activity-related responsibilities and revenues alternatively can be described in a separate contractual framework.

To assess whether a business case is viable, the following elements of the financial model should be considered:

1. CAPEX, covering all expenses to develop the project and obtain all permits to construct and operate the plant ("soft" cost), as well as EPC (engineering, procurement, and construction), grid connection and other development/adaptation cost ("hard" cost) and cost for advisors and financing the project.

2. Operation and maintenance (O&M) costs, which, in addition to traditional technical tasks, also include additional costs of cleaning and increased insurance costs for the PV facility due to the agricultural activities at the site, as well as asset management costs covering commercial and technical management on behalf of the investor, such as accounting, auditing, decommissioning guarantee, inverter replacement, grid balancing costs, transformer service, supervision, and monitoring. O&M cost also needs to consider land rent, the total amount of capital paid by the agrivoltaics consortium to the landowner. If the landowner is a partner in the consortium, this payment may reflect the market value of such lease less the value of the management rights for the area if the landowner retains this right.

3. Revenue calculations are based on expectations for energy sold and electricity sales prices. Here, the forecasted electricity generation gives the amount of energy to be sold, excluding energy losses up to the point of connection due to system degradation, inverter-, plant- and grid downtime, and curtailment due to grid limitation and farming activities imposed operating restrictions. The electricity price to be adapted is based on the forecasted future electricity price as applicable to the technology-specific generation profile. Details on revenue from agricultural activities are further described below.

4. Subsidies in the form of per-hectare support, agricultural subsidies linked to, e.g., eco-schemes, guarantees of origin for renewable energy and a potential agrivoltaics-specific subsidy based on the amount of PV electricity sold.

5. Depreciation of assets (hard CAPEX), project development costs (soft costs), and corporate tax.

6. Financing costs will differ for various cost categories, such as land (if land purchase or ownership is included), external EPC/turnkey installation (total CAPEX costs), soft costs, and working capital. Since the early 2020s, financing costs have shown quite strong temporal and national fluctuations as global economic development, interest rates, and global economic conditions have strongly impacted the interest rate offered by lenders.

After carefully assessing the business model, including associated sensitivity- and risk analysis, a final investment decision may be made, and construction can be initiated. This decision considers the expected ROI as seen by the investor, given by the absolute and relative return on equity, characterized by parameters like expected equity value or Internal Rate of Return (IRR). The investor may have other strategic visions related to the investment and the financial return. This could be an intention to obtain a leading role in this business segment or a formulated strategy to divest the project to specific institutional investors. For such reasons, providing a single quantified criterion for a favourable investment decision is impossible. It should be emphasized, however, that investment decisions can only be made based on complete financial modelling and not based on a simple LCOE calculation.

6.5 Emerging trends in socio-economic and legal frameworks

Trends in the socio-economic and legal frameworks for agrivoltaics will be closely tied to general trends in agrivoltaics deployment. As noted above, legal frameworks, social perspectives, and economic factors can drive the magnitude of and type of agrivoltaic systems deployed. In addition, the continued rapid expansion of utility-scale solar projects and agrivoltaics projects can lead to varied responses from governments and communities. Some overarching general trends in agrivoltaics deployment include:

1. Continued rapid expansion of agrivoltaics: agrivoltaics, spurred by local policies and regulations, land-use restrictions, and project economics, are poised to continue growth and expansion, just as utility-scale solar development growth is projected to continue. In some areas, agrivoltaics might be an essential enabling factor for continued solar development growth. This growth will also create opportunities for new agrivoltaic system developers to compete.
2. More standardization of agrivoltaics designs: as agrivoltaics developers identify promising and successful configurations that work across geographies and agricultural applications, standard agrivoltaics design packages are likely to emerge, which can help to lower costs.
3. Emergence of novel technologies and customized solutions: although standardization of agrivoltaics designs will continue, continued reduction in PV costs and a greater demand for agrivoltaics solutions will lead to an increase in experimental and customized agrivoltaics designs for specific crops, geographies, and other needs. This could include novel PV technologies and other agricultural support equipment for planting, harvesting, and maintaining agricultural lands.
4. Regional and locally tailored agrivoltaics: just as agricultural practices, equipment, techniques, and approaches can vary dramatically within and across countries, agrivoltaics designs and configurations will reflect local agricultural conditions and needs, which could lead to substantially different forms of agrivoltaics in different regions.
5. Scaling up agrivoltaic system sizes: with more significant agrivoltaics expansion to meet national solar energy deployment goals and reductions in agrivoltaic system costs, agrivoltaics projects are poised to increase. Legal frameworks and policies, social perspectives, and costs will impact and influence the following trends.
6. Legal frameworks and policies: there will likely be an increase in countries and subnational governing bodies developing specific agrivoltaics policies, frameworks, and definitions to foster the development of agrivoltaics. Regardless of whether these policies include financial incentives, the result will likely lead to greater standardization of agrivoltaics designs to ensure projects meet stated definitions of agrivoltaics. Reflecting current differences in agrivoltaics definitions and policies across countries, these frameworks and policies could vary dramatically from one region to another. With the emergence of more novel agrivoltaics solutions that meet agricultural and energy sector needs, strict definitions could imply more challenges for innovators than flexible definitions and policy structures, highlighting the importance of balancing innovation potentials and securing a minimum of agricultural intensity.
7. Social perspectives: with the rapid expansion of utility-scale solar projects and agrivoltaics, there are likely to be more conflicts and confrontations from community members resisting using agricultural land for solar development. However, the continued expansion and demonstration of successful agrivoltaics installations could help reduce the impact of this resistance, especially if there are locally tailored solutions and novel approaches that address key agricultural concerns. The prominence and persistence of this resistance will also likely lead to solar developers prioritizing community engagement more and potentially offering more agrivoltaics options that could be pursued on a given site.

8. Economics: the trends of greater standardization, efficiencies from completing an increasing number of projects, and greater competition among agrivoltaics developers will lead to lower costs for deployed agrivoltaic systems. Moreover, there are likely to be more creative financial arrangements among developers and agricultural producers (e.g., sharing of agricultural and/or solar revenues, tax credits, and financial risks) that meet the various stakeholders' needs. These innovative partnerships will spur greater certainty in development costs, agricultural production, and potential risks.

6.6 Limitations, gaps, and future opportunities of socio-economic and legal frameworks

Research on the legal frameworks, social perspectives, and economic factors related to agrivoltaics is relatively limited, which constrains the potential impact of the research summarized in this chapter. Given the early stage of agrivoltaic implementation, particularly at the commercial scale, it is not surprising that gaps exist in the research. There are significantly fewer case studies to draw conclusions as compared to other areas of study, such as utility-scale GMPV systems or agriculture. Insights gained from early adopters of agrivoltaics may not fully represent the future of research in this field as both the agrivoltaic industry and the body of related research continue to grow. For countries and sub-national bodies that have developed agrivoltaic policy frameworks, it is likely too early to assess the impact of various policy measures fully or to understand the full implications of various agrivoltaic definitions and eligibility criteria that are represented in different countries' policies. Moreover, as the industry matures and more agrivoltaic projects are built in diverse conditions, the efficacy of existing policy and legal frameworks could shift. There are multiple opportunities to expand upon existing research, including i) closely evaluating and comparing the potential impacts of different policy approaches established in multiple countries, ii) conducting multi-sector modelling studies of different policy frameworks and policies to better understand their impacts on both agricultural and solar industry adoption, and iii) facilitating discussions among policymakers, agrivoltaic developers, and agrivoltaic practitioners to better understand trade-offs among different stakeholders and what potential implications could be of different policy frameworks.

The first generation of social science research on agrivoltaics provides a valuable foundation for further exploration of how the interactions between social, economic, and regulatory contexts affect the diffusion of technologies. Although insightful, much of what has been done to capture stakeholder perspectives has been speculative – more research with experienced stakeholders will be vital in overcoming the limitations of understanding the development process of agrivoltaics, the impacts on the actors involved, and identifying factors that have contributed to the success or failure of projects. There are still knowledge gaps regarding other critical stakeholder perspectives on agrivoltaics, including regulators, spatial planners, insurance, and financial experts. These stakeholders have not yet been formally included in the study but play an essential role in shaping the landscape for agrivoltaic development. More systematic assessments across different regions and applications (e.g., arable versus livestock) could also contribute to our understanding of the different uptake potentials among solar companies, farmers, and communities. Exploring how to deal with social, economic, and environmental trade-offs is an essential opportunity for the future. Assessing the nuances of project size, application type, location, and business models in relation to the adoption and acceptance of agrivoltaics among different stakeholder groups will be critical to further deployment efforts.

Our understanding of the economic implications of agrivoltaic installations is inherently limited by the public availability of cost and performance data. Given the dynamic and rapidly expanding nature of agrivoltaics, studies on current cost data often need to be updated by the time they are published. In addition, costs can vary dramatically from site to site based on local conditions, agricultural needs, and other site-specific factors. Compared to traditional utility-scale solar projects, the relatively small number of agrivoltaic installations, combined with a lack of a standard design used across sites, can be challenging, and imbued with considerable uncertainty.

There are critical research gaps in understanding specific capital and O&M costs of various agrivoltaic system designs, marginal cost implications of various design modifications (e.g., elevating modules, incorporating novel tracking algorithms), costs associated with retrofitting existing utility-scale solar projects to incorporate agrivoltaics, which business models best support industry adoption of agrivoltaics, and what pathways might be to support more extensive and scalable deployment of agrivoltaic systems. Future research could be improved through more significant partnerships with agrivoltaic developers to understand cost trade-offs, more projects built with standardized designs and approaches, establishment of design and management best practices for agrivoltaic systems, and more exploration of various business models that could support solar developer and agricultural interests better.

CONCLUSIONS

Climate change and increasing water scarcity necessitate mitigation and adaptation measures in agriculture, which are increasingly vulnerable to extreme weather events and a major contributor to greenhouse gas emissions. In the coming decades, PV technology is expected to become a key player in meeting global energy demands. The land used by GMPV leads to increased competition between agriculture and the PV sector, threatening societal acceptance towards GMPV and potentially slowing down PV expansion.

Agrivoltaics addresses land use competition by expanding PV capacity while preserving farmland for food production. PV modules can protect soil and crops from severe weather events like heat, heavy rain, and drought, providing climate-friendly energy for agricultural operations, diversifying farmers' income, and strengthening rural economies. In a wider definition of agrivoltaics, applications with low-intensity agricultural uses, like animal husbandry or biodiversity services, can facilitate measures for environmental conservation to tackle the ongoing anthropogenic biodiversity crisis.

In recent years, agrivoltaics has seen rapid development worldwide, with installed capacity growing from approximately 5 MW_p in 2012 to an estimated 14 GW_p in 2021 (only agrivoltaics in a narrow definition, see Section 2), supported by government subsidies in countries like Japan, China, France, the USA, Korea, Israel, Italy, and Germany. Given trends in land scarcity, renewable energy expansion, PV system costs, and the need for agricultural resilience against weather extremes and water scarcity, agrivoltaic capacity is expected to continue expanding. For instance, high solar irradiance and extreme temperatures in wine growing can damage grapes, but partial shading from agrivoltaics can protect them, preventing premature ripening. Consequently, agrivoltaics has been increasingly funded and implemented in southern France.

Pioneer countries set different definitions of agrivoltaics, with most of them setting minimum requirements for the intensity of agricultural production, such as a threshold for agricultural yield or maximal coverage rations of PV modules. While agrivoltaic systems can generally be classified into open and closed systems, most market developments and legal frameworks focus on open systems.

Agricultural applications of open agrivoltaics include grassland farming, arable farming, and horticulture. Each activity shows different trends in integrating PV systems. Grassland farming typically uses interspace systems with low added value for agriculture, while horticulture benefits from overhead systems with semitransparent PV modules, offering protection and enhancing crop quality. Horticulture, with its typically closer proximity to farmyards, high synergy potential, and more straightforward integration, seems well-suited for the initial market launch of agrivoltaics. Additionally, horticulture areas face fewer challenges regarding landscape aspects due to existing structures like foil tunnels or hail protection nets. Arable and grassland farming, however, usually offers much larger surfaces for agrivoltaic installations.

Modelling and simulating agrivoltaic systems are crucial for evaluating expected profitability and performance and ensuring that they align with the legal requirement, e.g., minimum required agricultural yields. While several software platforms or algorithms exist for modelling PV system yield, crop yield, and microclimate separately, more modelling tools must be developed to predict PV output and agricultural yields simultaneously. In this regard, despite the exponential growth of the agrivoltaics sector, very few studies still address the market's needs.

Since agrivoltaics is still in its infancy and most existing facilities only have a few years of operation, there are few experiences with monitoring results and operation and maintenance issues. Open questions include ensuring access to agrivoltaics monitoring data, optimizing tracking algorithms, assessing the impact of pesticides and agricultural chemicals on PV components, and addressing insurance risks. These risks may arise from damage to mounting structures or non-compliance with minimum agricultural cultivation or yield requirements.

Involving local citizens early in the planning process is crucial for successfully implementing agrivoltaics. Landscape impact is a common concern but can be mitigated through site-specific planning and stakeholder involvement. Highlighting local benefits and providing platforms for stakeholders such as neighbors, decision-makers, farmers, and investors can enhance societal acceptance of agrivoltaics projects.

Regarding future trends, agrivoltaics is expected to continue its rapid expansion, driven by local policies, land-use restrictions, and project economics, creating opportunities for developers and farmers. Standardized agrivoltaic design systems will likely emerge, helping to lower costs as developers find successful configurations. Despite this standardization, there will be a rise in experimental and customized designs to meet specific needs, leveraging novel PV technologies and agricultural support equipment. Agrivoltaic designs will vary regionally, tailored to local agricultural conditions and practices. As the sector grows and costs decrease, agrivoltaic projects are expected to scale to meet national solar energy deployment goals.

To address climate change effectively, advancing our energy and climate policy goals and enhancing food production resilience is crucial. Agrivoltaics, with its potential for climate mitigation and adaptation, stands out as one promising tool for achieving these objectives.

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