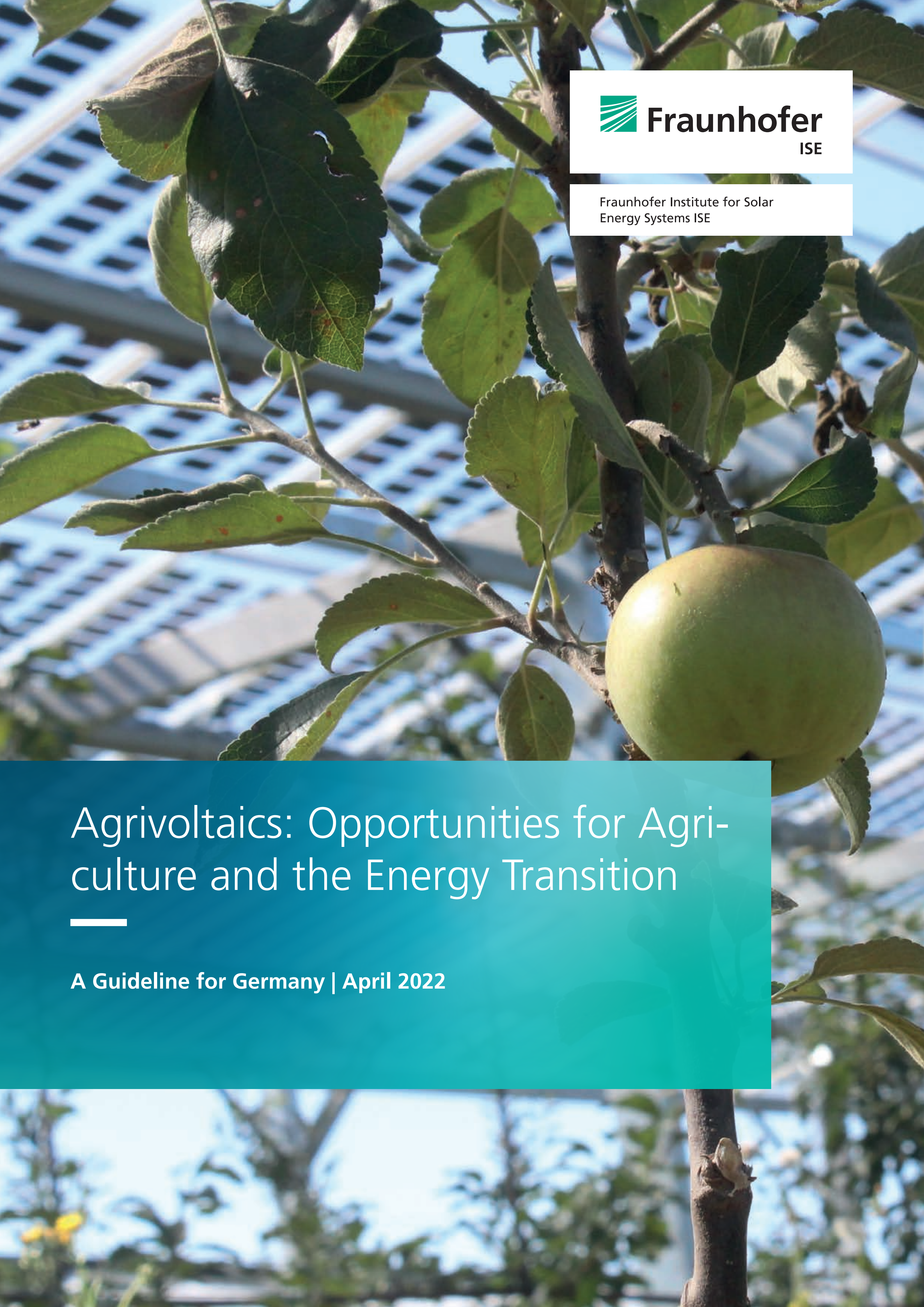

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Energy Systems ISE

Agrivoltaics: Opportunities for Agriculture and the Energy Transition

A Guideline for Germany | April 2022

Publishing notes

Published by
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Heidenhofstrasse 2
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www.ise.fraunhofer.de

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Special thanks to
Hofgemeinschaft Heggelbach
Solar Consulting GmbH
Forschungszentrum Jülich GmbH
inter 3 — Institute for Resource Management
Leibniz-Zentrum für Agrarlandschaftsforschung (ZALF) e. V.
Hilber Solar GmbH
AMA FILM GmbH

Design and typesetting
netsyn, Freiburg

Note
This guideline provides information on the potential of agrivoltaics, including the latest technologies and regulatory frameworks in this area. It also offers practical tips on how agrivoltaics can be used by farmers, municipalities and companies. This guideline is not intended to be exhaustive. All the application methods presented in this document should be taken as examples. Great care has been taken in preparing this guideline; nevertheless, those involved in its preparation assume no liability for its contents. Each agrivoltaic project must be examined on a case-by-case basis during its planning and implementation stages, with technical, economic and legal advice sought if needed.

Second edition, April 2022

Foreword

Dear readers,

Crops need the sun, and so do photovoltaic systems. We are all aware that the exploitation of renewable energies needs to be expanded at a much faster rate if we are going to meet our climate targets. We need to produce six to eight times more solar power than we do at present, both on roofs and on open land. In the past, this usually meant having to choose between agriculture and renewable energies, but now we have an innovative solution to this dilemma: agrivoltaics. With this promising approach, solar panels mounted above a field can generate electricity while grain, fruit and vegetable crops grow underneath. This eneables the dual use of land. Clever technological expertise enables us to expand photovoltaics without depriving farmers of valuable land. What's more, these special photovoltaic systems offers them an additional source of income. And they boost resilience.

Farmers have been dealing with the effects of climate change for many years now. The rise in increasingly extreme weather has a far more radical impact on agriculture than on almost any other economic sector, with conditions at times too hot and dry or at others characterized by sudden hailstorms. This is where photovoltaic systems can help. They shiled crops from too much sunand dehydration as well as from hailstones by breaking their fall. These are the benefits that one research project has already documented.

This updated guide gives you the latest insights into this technology from research and practice. It outlines the opportunities for agrivoltaics and reviews current developments. In this way, key progress has been made towards standardizing these systems and thus to ensuring quality.

As the German Federal Government, we are helping to expand agrivoltaics with improved methods of support. In April 2022 there is an innovation tender which will establish Germany's first feed-in tariff specifically for agrivoltaic systems in accordance with the German Renewable Energy Sources Act (EEG).
Our support also includes the update CAP Direct Payments Ordinance. It enables farms that install agrivoltaic systems to continue receiving 85 percent of the payments granted for agricultural land use.

Although many of the basic issues around this new technology have now been addressed, some questions remain unanswered: Can agrivoltaic systems be effectively combined with the cultivation of specialty crops, such as berries? Are there solutions for greenhouses? How do we establish broad public support for agrivoltaics? A key research project run by the Fraunhofer Institute for Solar Energy Systems ISE and its partners starts in mid-2022 and will look at these issues.

Other countries have also recognized the opportunities presented by agrivoltaics. Dual land use for agriculture and solar power generation is now an established part of the landscape in some Asian countries, while France is prominet in driving this technology in Europe. In Germany, we too are focusing on the potential of innovations like agrivoltaics. After all, the principle behind it is as simple as it is compelling. Productive arable land remains productive arable land, while the photovoltaic system is mounted above it, safeguarding our future. In this way, the German Federal Government is helpin to create a win-win-win situation: for the climate, for nature and for our farming industry. Prepare to be inspired!

B. Stark-Watzinger

Bettina Stark-Watzinger
Member of the German Federal Bundestag
Federal Minister of Education and Research
Photo: © German federal government / Guido Bergmann

Cem Özdemir
Member of the German Federal Bundestag
German Federal Minister for Food and Agriculture
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Content

1 Resource-efficient land use with agrivoltaics

The global population is growing — and demand for food is growing along with it. At the same time, land for installing more ground-mounted PV systems is urgently needed to tackle the climate crisis.[1] There is growing competition for space, especially in densely populated areas.

The demand for space to build ground-mounted PV systems is becoming an increasingly decisive factor as falling costs have now made them economically viable, even without state subsidies. The climate crisis is also presenting ever more challenges for farming water scarcity, extreme weather and overall rising temperatures necessitate new measures to protect crops and soils from adverse conditions. Many farms are already under strain from regulatory frameworks and economic uncertainty. This significantly limits the scope for protecting water and wildlife on the one hand and stabilizing or even increasing crop yields on the other.

Dual use of agricultural land

Agrivoltaics could mitigate the future competition for space with the dual use of land. It offers the possibility of installing large PV systems on open land while keeping the ground clear for food production. This dual use of land for agriculture and photovoltaics can be particularly beneficial for areas that are good for farming due to their fertile soil and temperate climate and are a suitable location for ground-mounted PV systems because they receive high levels of solar radiation.

Solar energy is becoming an integral pillar of the energy supply for the future alongside wind power, so there is seemingly an urgent need to integrate PV systems effectively into different areas of human activity with good public backing. Calculations by the Fraunhofer Institute for Solar Energy Systems ISE show that the installed PV capacity in Germany needs to be increased by a factor of six to eight by 2045 if the country's energy system is to become climate neutral[2].

Fig. 1: Agrivoltaic research site at Lake Constance.
© Fraunhofer ISE

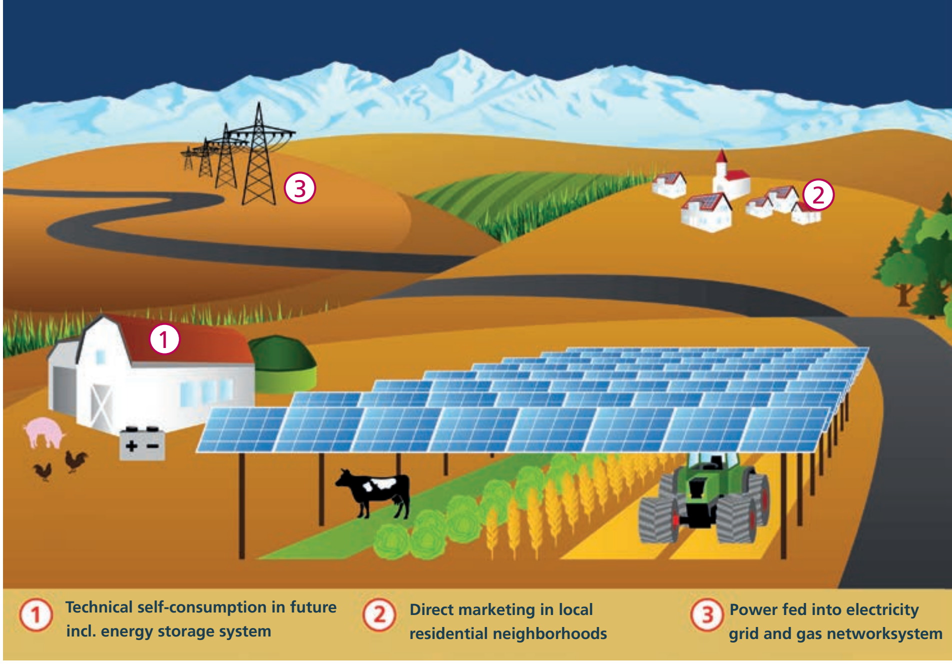


Fig. 2: Illustration of an agrivoltaic system. © Fraunhofer ISE

Prof. Adolf Goetzberger, founder of Fraunhofer ISE, and Dr. Armin Zastrow were the first to propose this kind of dual land use with their 1981 article "Kartoffeln unter dem Kollektor" (potatoes under the collector), which appeared in the "Sonnenenergie" journal[3]. In 2014, the innovation group APV-RESOLA ("Agrivoltaics: contribution to resource-efficient land use") took this idea and expanded on it with further research. The German Federal Ministry of Education and Research (BMBF) funded the project as part of the FONA research program, which looks at sustainable development. This resulted in a pilot project at Heggelbach farm near Lake Constance. The project investigated the economic, technical, social and environmental aspects of agrivoltaic technology in real-world conditions, with the aim of demonstrating its basic feasibility.

The project partners were: Fraunhofer ISE (management and coordination), the University of Hohenheim, the Institute for Technology Assessment and Systems Analysis (ITAS)[4] based at the Karlsruhe Institute of Technology (KIT), BayWa r.e. Solar Projects GmbH, Regionalverband Bodensee-Oberschwaben, Elektrizitätswerke Schönau, and Hofgemeinschaft Heggelbach.

The system on the Heggelbach site is installed on arable land covering one third of a hectare and features 720 bifacial PV modules with a 5 m clearance, providing an installed capacity of 194 kilowatt peak (kW_p). The project showed that with the PV system, land-use efficiency rose 60 to 86 percent, and crops adapted more effectively during dry spells in 2017 and 2018. Further research on the site is ongoing.

The purpose of this guideline

This guideline is based on the key outcomes from the APV-RESOLA research project, and this second edition incorporates results from other studies and research projects. It provides information on the benefits and opportunities presented by agrivoltaics, gives an overview of its potential and current state of the art, and offers practical advice for farmers, municipalities and companies on how to use the technology.

It also presents case studies from successful projects, outlines the challenges in using agrivoltaics in Germany and proposes ways to promote agrivoltaics in Germany in future.

Fraunhofer ISE
BayWa r.e. r.e.think energy
KIT Karlsruher Institut für Technologie
itas Institute for Technology Assessment and Systems Analysis
EWS ElektrizitätsWerke Schönau
UNIVERSITÄT HOHENHEIM
demeter Hofgemeinschaft Heggelbach Landwirtschaft & Käserei
Regionalverband Bodensee-Oberschwaben

Fig. 3: Partners in the APV-RESOLA project.

A brief history of agrivoltaics

Agrivoltaic technology has developed rapidly over the last few years and is now available in most parts of the world. Its installed capacity has increased exponentially from around 5 megawatt peak (MW$_p$) in 2012 to at least 14 gigawatt peak (GW$_p$) in 2021. Government funding programs in Japan (since 2013), China (around 2014), France (since 2017), the USA (since 2018) and most recently in South Korea have made these advances possible[5].

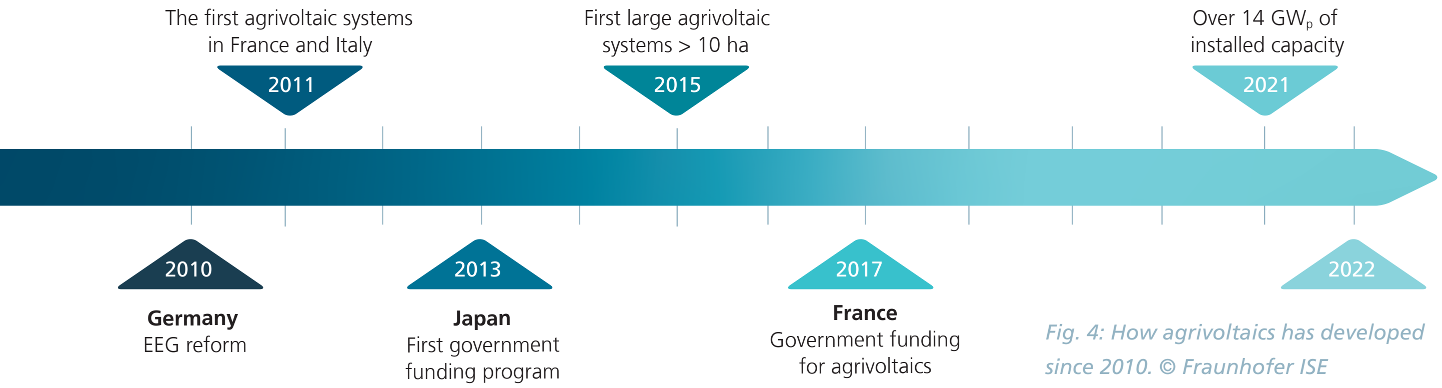


Fig. 4: How agrivoltaics has developed since 2010. © Fraunhofer ISE

Opportunities for agrivoltaics

In addition to increasing land-use efficiency, agrivoltaics can boost resilience and crop yields if the systems have the right technical design. Research has demonstrated such effects, such as in the APV-RESOLA project. Fruit and specialty crops that are being increasingly damaged by hail, frost and drought can also benefit from the protection offered by the PV modules, which partially cover the crops[6].

More potential synergies between PV and agriculture can be harnessed, including:

- Reducing irrigation demand by up to 20 percent[7];
- Collecting rainwater for irrigation;
- Reducing wind erosion;
- Using the PV system's substructure to attach protective nets or sheets;
- Optimizing the available light for crops by using solar tracking PV systems, for instance;
- Increasing PV module efficiency through improved convective cooling;
- Increasing the efficiency of bifacial PV modules, which use light from both sides to generate electricity, thanks to greater distances between the PV modules, the ground and the adjacent PV module rows.

Agrivoltaics can create added value locally and benefit rural development. It also gives farms the opportunity to produce green, solar-generated electricity for their own local consumption, reducing the need to purchase expensive electricity from the grid and cutting their overall expenditure on power. Agrivoltaics also enables farms to create another source of income if they sell the electricity that they generate.

Challenges: barriers to implementing agrivoltaics

Although many countries have demonstrated the technical and economic feasibility of agrivoltaics, there are still obstacles preventing its widespread use in Germany. For instance, current German legislation does not explicitly state which steps must be taken to gain approval for construction. The possible funding available as part of the innovation tenders, provided for by EEG 2021, is unlikely to create adequate incentives. More detailed information on the legal framework in Germany can be found in section 7.1.

Public backing for agrivoltaics is another hurdle for this technology in some regions. As a result, one of the key areas for action is engaging stakeholder groups and citizens who live in the municipalities where an agrivoltaic system is planned for construction. Section 6 discusses this aspect in more detail.

Funding and market development for more research projects are recommended so that researchers can draw firmer conclusions about the possible synergies and acceptance issues for the different approaches to agrivoltaics. This will also enable them to examine the non-technical, social success factors and the economic and ecological risks and opportunities in greater detail. At the same time, these projects can make investors more willing to invest and encourage stakeholders, citizens and commercial enterprises to develop creative solutions. Section 7.2 discusses possible areas for action in policymaking.

Overview of agrivoltaics

- Global installed capacity of at least 14 GW_p
- Estimated potential installed capacity just for overhead agrivoltaic systems in Germany is roughly 1,700 GW_p

Advantages

- Combines agriculture and ground-mounted PV systems
- Offers additional benefits for farming, including protection against hail, frost and drought damage
- Has a lower levelized cost of electricity (LCOE) compared to small rooftop PV systems
- Diversifies income for farmers

Requirements

- Zoning plan: Classify agrivoltaic systems as “special area: agrivoltaics” instead of an “electrical facility/commercial area” on zoning plans to avoid them being wrongly recorded as areas covered with an impervious surface
- Extend areas that are classified for agrivoltaics use to include all agricultural land as part of the EEG
- Establish statutory feed-in tariffs in line with the EEG for small, overhead agrivoltaic systems (< 1 MW_p) that are not subject to tendering (based on criteria)
- Establish a separate tender segment for large, overhead agrivoltaic systems (> 1 MW_p) that are subject to tendering (based on criteria)
- Partial special status in BauBG: Give projects to build small PV systems and those in a horticultural context with less than 1 MW_p capacity a special status in line with section 35 German Building Code (Baugesetzbuch, BauGB) to simplify the approvals process
- Run an agrivoltaics R&D program for Germany
- Engage as many citizens and stakeholder groups as possible at an early stage to analyze the non-technical success factors in building an agrivoltaic system, and identify suitable locations

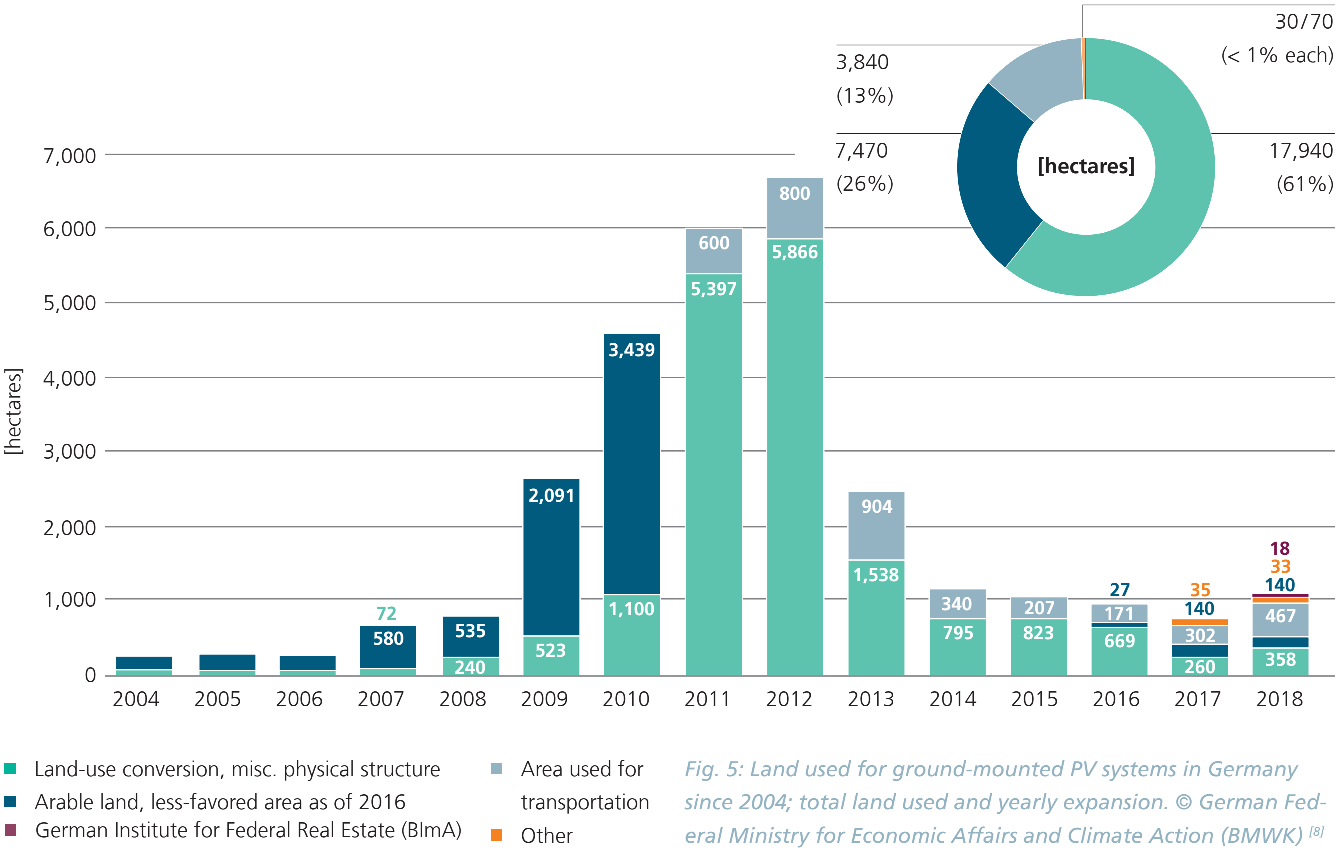


Fig. 5: Land used for ground-mounted PV systems in Germany since 2004; total land used and yearly expansion. © German Federal Ministry for Economic Affairs and Climate Action (BMWK) [8]

2 Agrivoltaics facts and figures

Fig. 6: Applications for integrated photovoltaics. © Fraunhofer ISE

Solar PV and wind power will be cornerstones of the future energy supply. Photovoltaics is now the most affordable renewable energy technology, with prices for PV modules having fallen by around 90 percent between 2009 and 2019. The levelized cost of electricity (LCOE) is currently 4–11 euro cents per kilowatt hour, depending on the size of the system.

Solar power also enjoys strong backing from the public. However, solar PV needs a relatively large amount of space compared to wind power and fossil fuels, so it is usually difficult to find the right areas to build large PV systems. One solution to this problem is integrating PV systems into different areas of human activity, such as on buildings, lakes and land with impervious surfaces, like areas for transportation. Doing so can make the areas dual purpose, and in the case of agrivoltaics, it significantly reduces land use. It does not have to be a choice between photovoltaics or photosynthesis; the two can complement each other well.

Germany had around 59 GW_p installed PV capacity by the end of 2021, 75 percent of which came from rooftop systems, with the rest from ground-mounted systems[9]. But this is not nearly enough: Fraunhofer ISE has calculated that Germany needs between 300 and 450 GW_p of installed capacity by 2045. Integrating PV technology into buildings, vehicles and transport routes and using it on agricultural land, bodies of water and in urban spaces could unlock huge yield potential.

Several factors determine how much of the technically feasible potential can be tapped from a practical and commercial point of view, including regulatory and economic contexts. The LCOE with integrated PV is likely to be higher than with simple, large-scale ground-mounted PV systems, but integrated PV eases competition for land use and can create synergies. For instance, it can be a substitute for a building facade or use the existing structure of a noise barrier. It can increase the range of electric vehicles or make agricultural land dual purpose. With all scenarios, the bigger a PV system's added value is, the more successful its integration will be.

2.1 Agrivoltaics: A new approach to mitigate competing demands for land use

Ground-mounted PV systems can create competition for the use of agricultural land. Ground-mounted PV systems supported by the EEG's innovation tenders may only be constructed on sealed surfaces, converted areas, strips along highways or railroads, and on land in (agriculturally) less-favored regions. However, the huge drop in LCOE for solar power has led to large-scale PV systems being constructed outside of EEG-compliant tenders, negating the EEG's aim to incentivize the protection of valuable agricultural land.

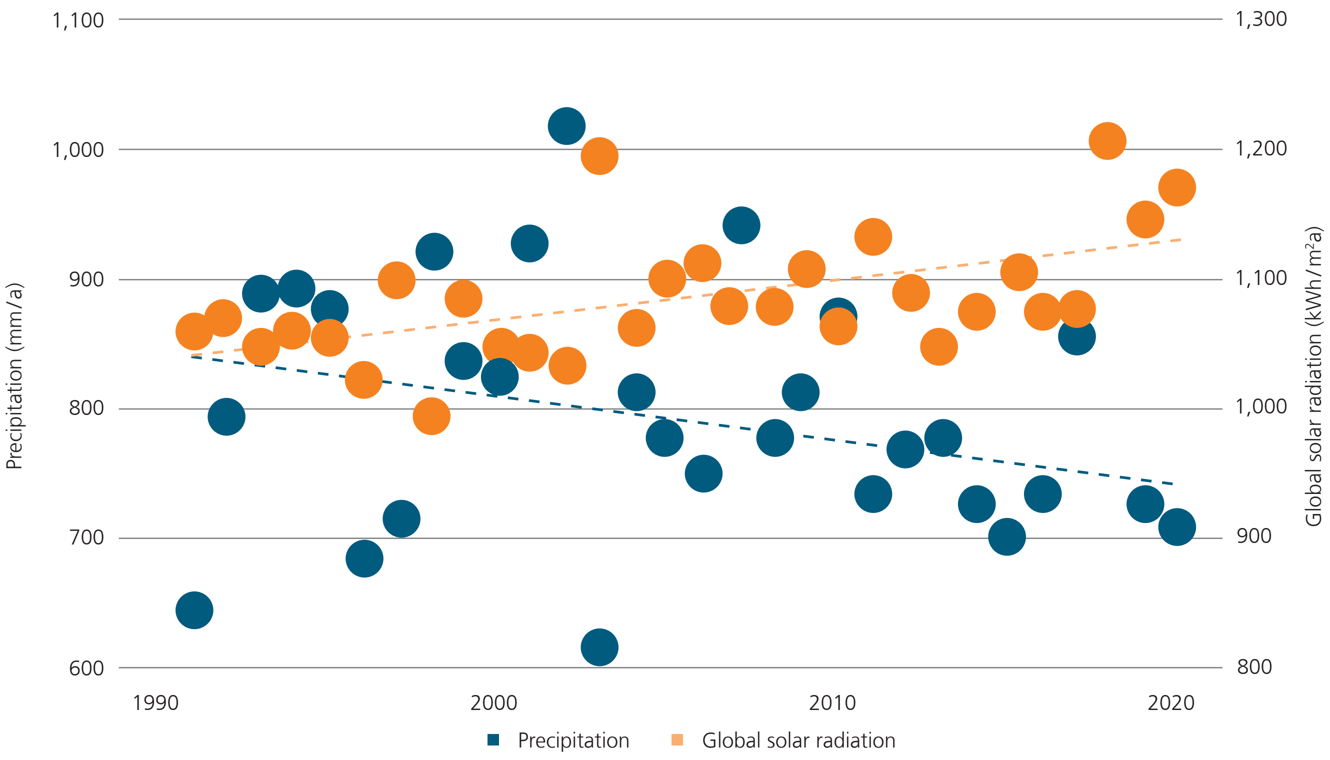
Considering the limited availability of arable land, the increasing demand for space locally may exacerbate competition for land use and trigger social, political, economic and environmental conflicts. With this in mind, it would be prudent to discuss the future importance of rural areas as sites for new technologies so as to mitigate potential competing goals and inconsistencies in valuation. Research and development in agrivoltaics is a key undertaking with respect to the requirements of the High-Tech Strategy 2025 pursued by the German Federal Ministry of Education and Research (BMBF).

Fig. 7: Typical ground-mounted PV system. © Fraunhofer ISE

2.2 Precipitation and global radiation

Although long-term precipitation records for Germany starting in 1880 show an average yearly increase of 8 percent, a clear downward trend can be observed over the last 30 years. Data from the Deutscher Wetterdienst (German meteorological service, DWD)[10] shows a yearly decline in precipitation of 0.39 percent since 1991. The average amount of rainfall has therefore fallen by almost 12 percent between then and now (see figure 8, blue trend line). Weather conditions in spring, which are key for crop growth, have fundamentally changed. Over the last 12 years, the amount of rainfall in April has sometimes been up to 70 percent less than the historical average for the month. Warm weather in spring is increasingly leading to soil moisture deficit early in the year, which cannot be rectified later in summer[11]. Data analysis also clearly shows that global solar radiation (the sum of direct and diffuse radiation) increased by 0.28 percent yearly in the same period (red trend line), which is a positive development for PV yields. The combination of decreasing precipitation levels and increasing global radiation suggests that as time passes agrivoltaics will become an increasingly ideal solution to make agricultural systems more resilient to climate change and turn climate impacts to good account.

Fig. 8: Precipitation and global solar radiation in Germany since 1991. Data: Deutscher Wetterdienst. Graph: Fraunhofer ISE



2.3 Definition and potential of agrivoltaics

Agrivoltaics is a technology that allows land to be used simultaneously for farming and generating electricity with photovoltaics[12]. This means that a field can be dual purpose: to grow crops (photosynthesis) and generate solar power (photovoltaics). Some PV modules that provide shelter to animals are counted as agrivoltaics although their features are similar to those on a conventional PV roof.

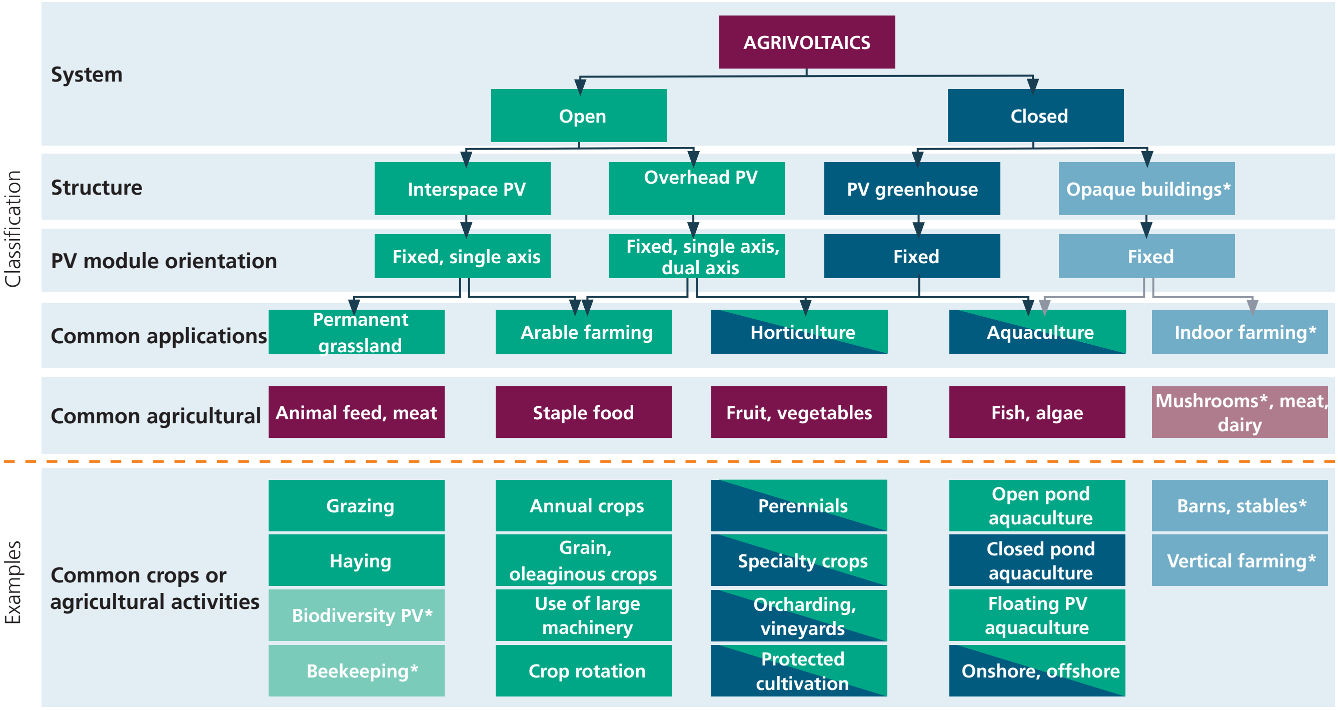
The technical solutions for integrating PV into farming are as diverse as farming itself. They can be broadly categorized into open and closed systems (see figure 9). Closed systems mainly cover PV greenhouses, while open agrivoltaic systems can be broken down into ground-level, interspace PV and overhead, overhead PV. PV modules in overhead systems are mounted at least 2.1 meters above the ground (see section on DIN SPEC 91434 below). With overhead systems, the land under the PV modules is used for farming, whereas with interspace systems, it is usually the land between PV modules that is farmed.

The main benefits of interspace systems are that they have lower costs and tend to impact the landscape less. Overhead installations, on the other hand, use the land more efficiently and can give crops greater protection against adverse environmental effects.

Similar to ground-mounted PV systems, agrivoltaic systems can be built either with a fixed substructure or a single or dual-axis tilting construction (solar trackers). Tracking systems allow for more flexible light management as their PV modules can be tilted individually.

This guideline mainly looks at overhead PV systems in farming (> 2 m) and horticulture (approx. 2.5 m), including applications for specialty crops such as fruit and vegetables and viticulture. It discusses ground-level, interspace PV systems to a lesser extent and touches on their applications in permanent grasslands. The heights given here for each of the applications should only be seen as a trend; they serve to group the use cases from a technical and economic point of view. This guideline does not cover closed systems such as PV greenhouses. Section 5.1 provides more detailed information about the various technical solutions.

Fig. 9: Classification of agrivoltaic systems. © Fraunhofer ISE



*No agrivoltaic application in the strictest sense

Summary of DIN SPEC 91434: "Agri-photovoltaic systems — Requirements for primary agricultural use"
Fraunhofer ISE and the University of Hohenheim have worked with the German Institute for Standardization (DIN) and a consortium of partners in research and industry to develop the standard DIN SPEC 91434. By outlining the requirements for the primary agricultural use of agrivoltaics, the standard aims to clearly distinguish agrivoltaic systems from conventional ground-mounted systems, which is likely to be a key prerequisite for ensuring agrivoltaic systems are successfully brought to market. The DIN SPEC provides legislators, funding bodies and regulatory authorities with a basis for testing and sets out quality criteria for constructing and operating agrivoltaic systems. The DIN SPEC also aims to lay the groundwork for the further development of a test method and the possible certification of agrivoltaic systems.

Fifteen institutions, mostly from the solar PV industry, participated in the consortium that drew up the standard. The DIN SPEC specifications mainly cover the agricultural aspects of agrivoltaics as the relevant technical standards for solar PV already exist and can therefore be adopted for this area of application. Table 1 shows the key areas covered by the DIN SPEC and how it categorizes agrivoltaic systems.

A core tenet that applies to all categories is that the land used for agrivoltaics must continue to be used for agricultural purposes. A more detailed description of the agricultural activities at each agrivoltaic area needs to be recorded in an agricultural cultivation proposal. The criteria and key requirements for the agricultural cultivation proposal are:

- The previous agricultural usability of the area shall be maintained, and the planned form of land use shall be set out in an agricultural usage proposal.
- Land loss after installing the PV system must not exceed 10 percent of the total project area for category I and 15 percent for category II.
- Light availability, light homogeneity and water availability must be checked and adapted to the needs of the agricultural products.
- Steps should be taken to avoid soil erosion and damage caused by PV system design, anchoring in the soil or the water runoff from the PV modules.
- It shall be ensured that the agricultural yield after constructing the agrivoltaic system is at least 66 percent of the reference yield. The reference yield is calculated using the three-year average of yields from the same agricultural land or using comparable data taken from the relevant publications.

In addition to these key metrics and specifications, the DIN SPEC lists further recommendations for designing and installing agrivoltaic systems effectively. The DIN SPEC can be downloaded free of charge here: https://www.din.de/en/wdc-beuth:din21:337886742

Table 01: Overview of categories and forms of land use as set out in DIN SPEC 91434

Agrivoltaic systems	Use	Examples
Category I: **Overhead PV with vertical clearance > 2.1 m** **Farming under the agrivoltaic system** **(Image A)**	1A: Permanent and perennial crops	Fruits, berries, viticulture, hops
	1B: Single-year and long-term crops	Arable crops, vegetables, alternating grassland, fodder
	1C: Permanent grassland with mowing	Intensive and extensive commercial grassland
	1D: Permanent grassland with pasture	Permanent pasture, pasture rotation (e.g., cattle, poultry, sheep, pigs and goats)
Category II: **Interspace PV with vertical clearance < 2.1 m** **Farming between the rows of agrivoltaic systems** **(Image B/C)**	2A: Permanent and perennial crops	Fruits, berries, viticulture, hops
	2B: Single-year and long-term crops	Arable crops, vegetables, alternating grassland, fodder
	2C: Permanent grassland with mowing	Intensive and extensive commercial grassland
	2D: Permanent grassland with pasture	Permanent pasture, pasture rotation (e.g., cattle, poultry, sheep, pigs and goats)

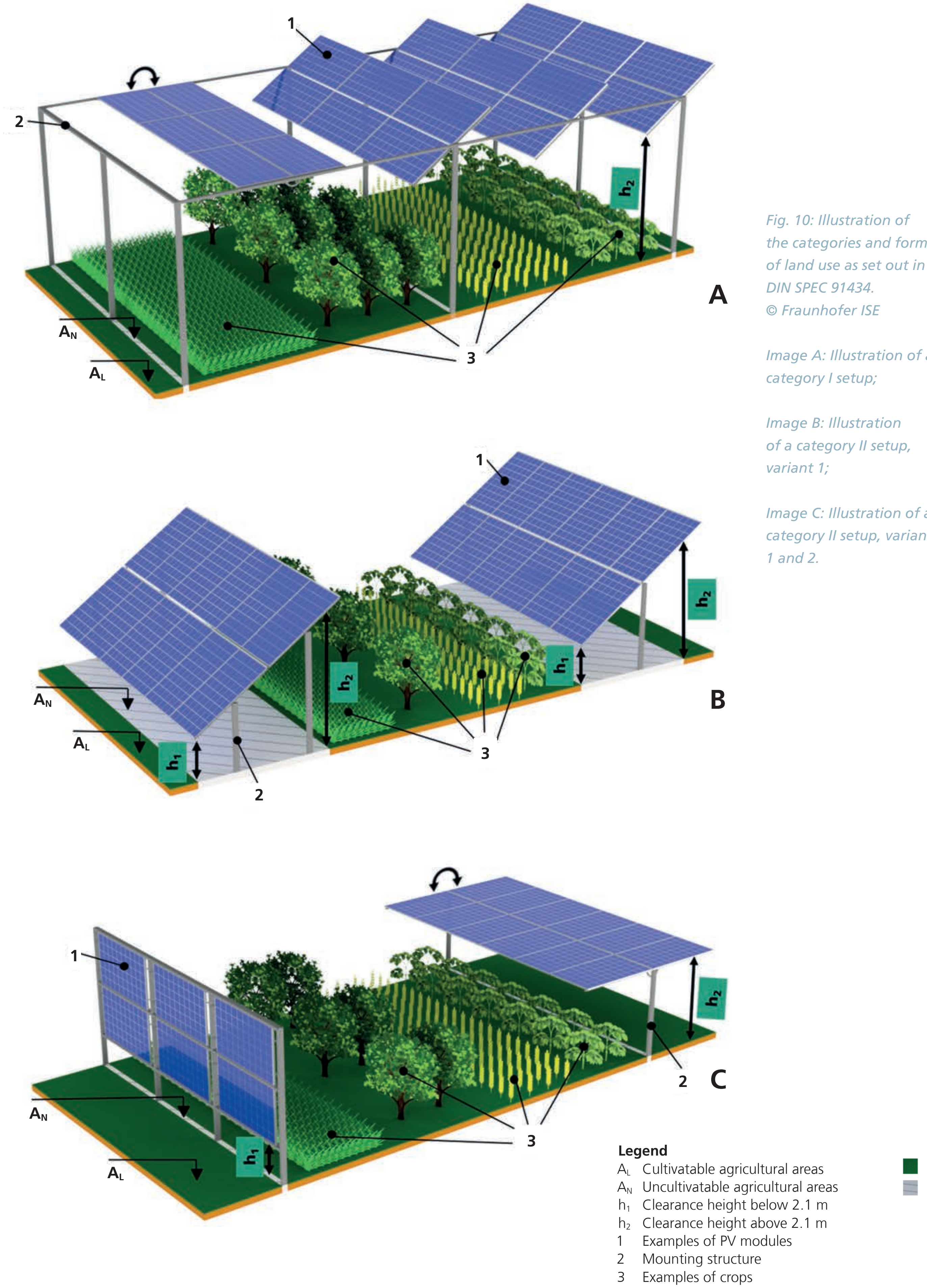


Fig. 10: Illustration of the categories and forms of land use as set out in DIN SPEC 91434.
© Fraunhofer ISE

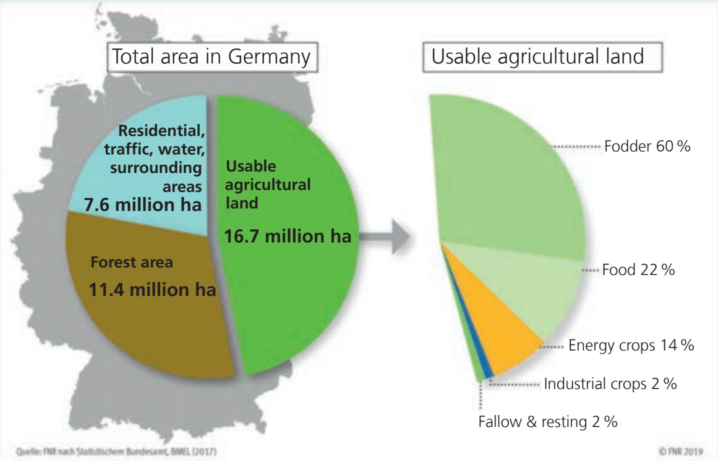
Image A: Illustration of a category I setup;

Image B: Illustration of a category II setup, variant 1;

Image C: Illustration of a category II setup, variants 1 and 2.

High potential

Out of all the applications for integrated PV, agrivoltaics holds the greatest land potential. Fraunhofer ISE conducted an initial assessment to estimate the potential of agrivoltaics and found that this was around 1,700 GW_p in Germany. This installed capacity would only require approximately 4 percent of Germany's available farmlands. It based its estimates largely on shade-tolerant crops and those typically used in crop rotation. Even using just 10 percent of this 1,700 GWp capacity would almost triple Germany’s current PV capacity. Interspace PV modules that are installed close to the ground with wide gaps between rows allow crops to be grown in the intervening strips. One hectare is needed to generate 0.25 MW, so growing fodder on permanent grassland offers the potential to support another 1,200 GW_p capacity. From the perspective of generating electricity, the dual use of agricultural land with agrivoltaics is considerably more efficient than growing energy crops (e.g., it generates 32 times more power per hectare than growing maize as a biofuel). Energy crop cultivation takes up 14 percent of agricultural land in Germany (see figure 11).



Quelle: FNR nach Statistischem Bundesamt, BMEL (2017)

© FNR 2019

Fig. 11: Land use in Germany. © Fachagentur Nachwachsende Rohstoffe e.V. (2019)[13]

2.4 Research sites in Germany

There are several agrivoltaic systems in operation in Germany as part of research projects. The key data and research questions of five German agrivoltaic systems (listed in Table 2) are detailed in the following pages along with summaries of other research projects.

Table 02: Overview of research sites in Germany to date

Agrivoltaic systems	Location	Type of Land Use	Technology	Installed Capacity	Year of Commissioning
1	Weihenstephan/Freising, Bavaria	Vegetable Growing	Tracking PV Array	22 kW_p	2013
2	Weihenstephan/Freising, Bavaria	Vegetable Growing	PV Tubes	14 kW_p	2015
3	Heggelbach, Sigmaringen district, Baden-Württemberg	Arable Farming	South-West Facing, Fixed PV Modules	194 kW_p	2016
4	Grafschaft-Gelsdorf, Ahrweiler district, Rhineland-Palatinate	Fruit Orchard	Tracking and Fixed Semi-Transparent PV Modules	258 kW_p	2021
5	Morschenich, Düren district, North Rhine-Westphalia	Arable Farming/Vegetable Growing	Tracking and Fixed, with Water Management	approx. 300 kW_p	2022

Weihenstephan 2013

Researchers at the Institute for Horticulture based in the University of Weihenstephan-Triesdorf conducted the first preliminary tests on a small, dummy ground-mounted PV system (south-facing) in 2011. They used roofing felt to simulate the shade from PV modules and grew crop such as lettuce underneath. Results showed that the differences in shade and soil moisture caused considerable disparities in crop growth between the more/less shaded areas directly under/north of the dummy PV modules, which would make it unsuitable for real-world application. The first agrivoltaic system with rows of east-west solar tracking PV modules (see figure 12) was constructed in 2013 as a way of preventing excess shading on parts of the ground under the system.

Technical data:

- Area: 21 x 23 m = 483 m^2
- PV module rows: 3 rows, 3.2 x 21 m each, with 30 PV modules of 1.6 m^2 each
- Tracking: East-west; calendar controlled
- PV modules: CSG 245 W; 200 W/m^2 (average; 245 W x 90 = 22 kW_p; 45 W/m^2)
- Yearly production: Approx. 35,000 kWh
- Installed capacity: 22 kW_p
- Use: Self-consumption, no feed-in tariff

Varying distances between PV modules in the rows aims to help determine how different amounts of shade affect the crop yield and thereby identify the optimal row density. Tests with Chinese cabbage showed 29 to 50 percent declines in yields. The results differ depending on the amount of shade and are shown in table 3.

Soil compaction from constructing the PV system and damage to crops positioned under the PV modules' drip edge were possible compounding factors why crops under the agrivoltaic system produced reduced yields.

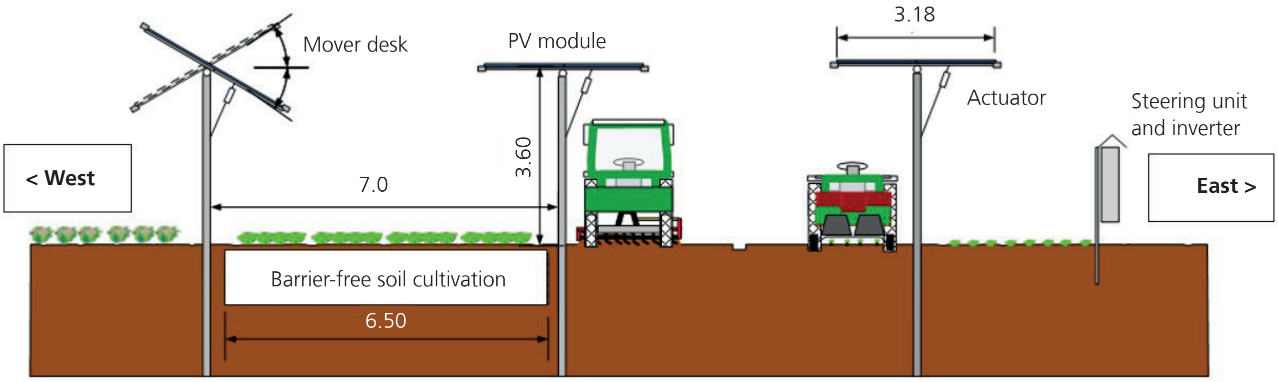


Fig. 12: Cross-section view of the agrivoltaic system in Weihenstephan.
© 2020 B. Ehrmaier, M. Beck, U. Bodmer

Table 03: Damage to cabbage crops. © 2020 B. Ehrmaier, M. Beck, U. Bodmer

	Dense Section of PV Module Rows: 0 cm between PV Modules	25 cm between PV Modules	66 cm between PV Modules	Grown without a PV System, for Comparison
Average Weight of a Head of Chinese Cabbage Grown within Agrivoltaic Aystem (2014)	**1,348 g** Around 50 Percent of the Yield Achieved without Agrivoltaics	**1.559 g** Around 56 Percent of the Yield Achieved without Agrivoltaics	**1,970 g** Around 71 Percent of the Yield Achieved without Agrivoltaics	**2,762 g**

Weihenstephan 2015

Installing rain gutters on the drip edges of the PV modules caused new problems, particularly in winter. As an alternative, researchers examined how horizontal, overhead tubular PV modules affected crop yields.

In 2015, the Weihenstephan-Triesdorf University of Applied Sciences constructed a second German research site with the company TubeSolar where researchers tested the viability of tube-shaped PV modules. This PV system has a capacity of 14 kW_p, and potatoes and varieties of lettuce are grown underneath. A test with lollo rosso lettuce showed that yields for crops under the PV tubes were no more than 15 percent lower than the yields achieved without the agrivoltaic system, meaning such PV modules offer new opportunities for agrivoltaics in horticulture, at least for shade-sensitive crops. For a comprehensive assessment, however, the LCOE needs to be examined against the contribution margin from crop production (referred to as ”by products”).

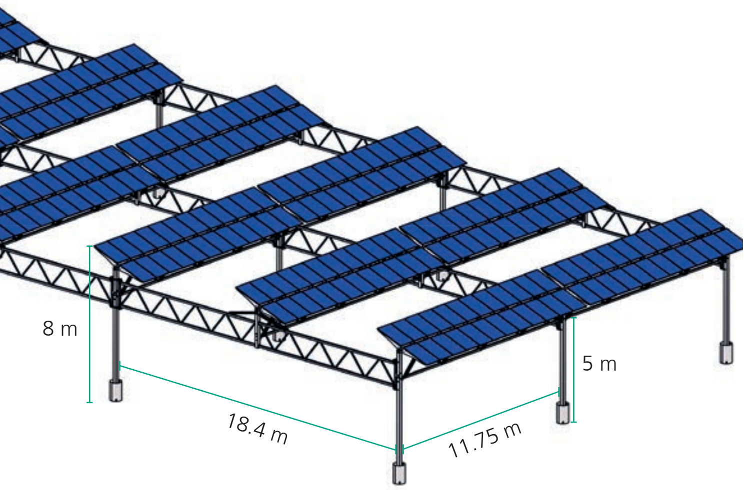


Fig. 13: Illustration of the agrivoltaic system in Heggelbach.
© AGRISOLAR Europe GmbH

Heggelbach 2016

The third agrivoltaics research site was constructed at the Hofgemeinschaft Heggelbach farm near Lake Constance (Germany) in 2016 as part of the APV-RESOLA project. This biodynamic mixed-farming business has been operating for more than 30 years with 165 hectares of agricultural land.

Winter wheat, potatoes, celery and clover grass were planted as test crops. Installing the bi-facial double-glass PV modules with five-meter ground clearance, south-west orientation and a larger gap between the rows of PV modules ensures that the crops receive consistent amounts of sunlight. The clearance height and distance between the supporting structures also enables the farmers to use large machinery, such as a combine harvester, without any major restrictions. The rows are 9.5 m apart with a row width of 3.4 m. The installed capacity of this test system is enough to supply 62 four-person households annually. Due to the increased distances between rows, this installed capacity is around 25 percent lower per hectare compared to conventional ground-mounted PV systems.

Technical data:

- Area: 25 m x 136 m = 3,400 m²
- PV module rows: 15 rows measuring 136 m in length, each with 48 PV modules of 1.7 m²
- Tracking: None
- PV modules: Bi-facial double-glass PV modules, SolarWorld, 270 W
- Yearly production: Approx. 256,000 kWh in 2020
- Installed capacity: 194.4 kW_p
- Use: Self-consumption, grid supply, no statutory feed-in tariff

Results showed that the land-use rate rose to 160 percent during the first year of the project (2017), demonstrating the practical viability of agrivoltaics. The yields of crops grown under PV modules remained over the critical 80 percent mark compared to reference areas without PV modules, allowing them to be marketed as commercially viable.

The agrivoltaic system generated 1,266 kWh per installed kW_p in the first 12 months (September 2016–September 2017). This output is a third more than the average for Germany, which is 950 kWh per kW_p. One reason for this is the relatively high solar radiation in the region, while another is the additional yields thanks to the bifacial PV modules.

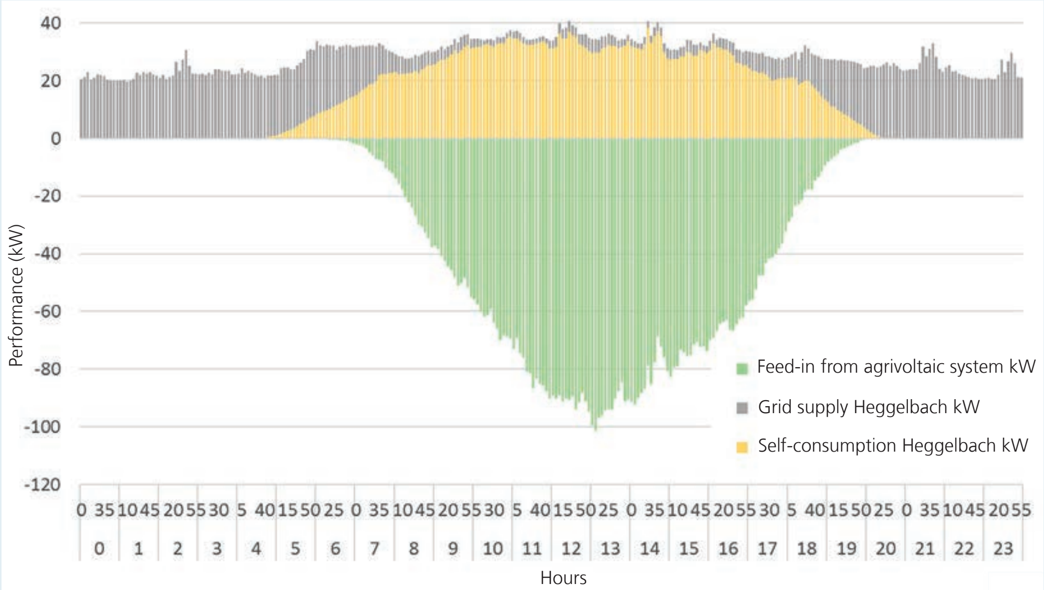


Fig. 14: The agrivoltaic system at Hofgemeinschaft Heggelbach enabled the farm to cover almost all of its energy demand in summer 2017 using the power generated with the system. © BayWa r.e.

The electricity generated over the day suits the farm's load profile, meaning that the farm consumes around 40 percent of the solar power generated on site, such as for charging electric vehicles and processing agricultural products. The agrivoltaic system almost covered the farm's entire daily load in summer. Installing a battery storage device with 150 kWh capacity boosted the level of self-consumption to around 70 percent. Project partner Elektrizitätswerke Schönau buys the surplus power.

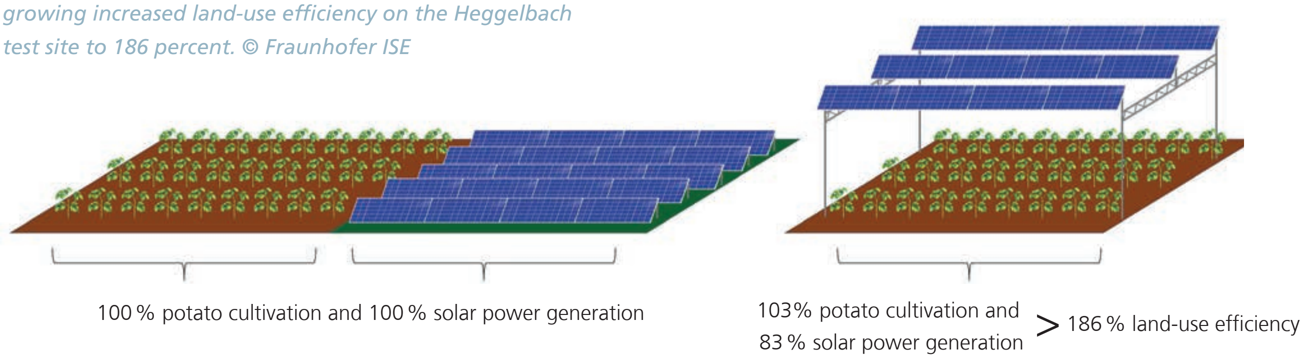
Yields during the 2018 summer heat waves significantly exceeded the previous year's results. The partial shade under the PV modules increased crop yields while the high levels of solar radiation increased solar power generation. This improved land-use efficiency by 86 percent where the potato crops were being tested.

The research group believes that the crops were better able to compensate for that summer's lack of rain thanks to the shade provided by the PV modules. This observation clearly shows the potential for agrivoltaics in arid regions and the need to conduct further testing in other climates and with more crops.

The solar irradiance was 1,319.7 kWh per square meter in 2018, an increase of 8.4 percent over the previous year. This meant that solar power generation in the 2018 harvest year rose by 2 percent to 249,857 kWh, resulting in an exceptionally high specific yield of 1,285.3 kWh per kW_p.

The outcomes of the Heggelbach pilot project suggest that agrivoltaics help stabilize yields as crops benefit from the additional shade, especially during dry spells[5]. More information about the pilot's agricultural results is detailed in section 3.1.

Fig. 15: The dual use of land for agrivoltaics and potato growing increased land-use efficiency on the Heggelbach test site to 186 percent. © Fraunhofer ISE



Research at the University of Applied Sciences Dresden

At the University of Applied Sciences Dresden (HTW Dresden), Professor Feistel's team has spent several years researching agrivoltaics and how PV systems effect the soil water regime. Their research focuses on changes in evaporation and infiltration and how these changes are classified in the context of adverse climate impacts. They have studied both large solar PV systems and small agrivoltaic systems.

Agri4Power project — Sustainably combining agriculture, biodiversity and renewable energies

Researchers at Fraunhofer IMW ran the Agri4Power project between 2020 and 2021. The project looked at how sustainable synergies could be created by combining vertical, bifacial solar PV systems with flower strips, which foster biodiversity, alongside agricultural production at the same time. They examined the economic and environmental aspects, as well as questions of social acceptance[14].

APV Obstbau 2021

Fraunhofer ISE joined its partners in research and industry for the APV Obstbau project where they examined the extent to which agrivoltaic systems can replace nets and sheets to protect apple orchards from hail, which system design would be most useful and how much the PV system affects harvest yields. For their research, they installed a pilot system with 258 kW$_{p}$ capacity at the Nachtwey organic fruit farm in Gelsdorf (Ahrweiler district, Rhineland-Palatinate) in spring 2021. The research team used the agrivoltaic system on the orchard to look at light management, system design, landscape esthetics, the system's cost-effectiveness, its social acceptability and the parameters of crop cultivation.

Technical data:

- Area: 32 m x 111 m = 3,552 m²
- PV module rows: 8 rows, fixed structure, 111 m in length with 106 PV modules of 2.1 m² each
  3 rows, tracking structure, 111 m in length with 100 PV modules of 2.1 m² each
- Tracking: Single axis
- PV modules: Semi-transparent, double-glass PV modules, 225 W
- Yearly production: Approx. 276,000 kWh (forecast)
- Installed capacity: 258 kW$_{p}$
- Use: Powering electric tractors, water pumps; feeding into the grid, no statutory feed-in tariff

The project has four different pilot systems: (1) control field with conventional hail-protection nets; (2) agrivoltaic system; (3) agrivoltaic system with reduced use of crop protection product; and (4) sheet covering. The part of the project dealing with public acceptance and social responsibility looks at different possible areas of conflict (land use, distribution, fair processes) in various stakeholder groups. The initial results from the trial are expected in fall 2022.

APV 2.0 2022

The APV 2.0 project in Morschenich (Düren district, North Rhine-Westphalia), led by Forschungszentrum Jülich, has been further developing linked radiation and simulation models, allowing both PV and crop production to be optimized together. To assess how this affects the crops, researchers are developing and deploying an in-situ phenotypic monitoring system to collect and analyze quantitative phenotypic data about the crops. They are also developing innovative tracking algorithms, rainwater collection systems and smart irrigation strategies. The test system was constructed in December 2021.

Technical data:

- Area: 2 x 25 m x 41 m; 2 x 22 m x 39 m giving a total of 2,050 m² + 1,716 m² = 3,766 m²
- Tracking: East-west for some parts of the system, test algorithms; static on two parts of the system
- PV modules: 370 W, bifacial
- Installed capacity: Approx. 300 kW$_{p}$
- Use: Self-consumption, no statutory feed-in tariff. on-site storage

Fig. 16: Agrivoltaic system at the Nachtwey organic fruit farm. © Fraunhofer ISE

2.5 Operational sites in Germany

There are a dozen private agrivoltaic systems in Germany in addition to the test ones for research purposes. One organization, Elektro Guggenmos, has been growing potatoes, wheat and leeks under its agrivoltaic system in Warmsried (Bavaria) since 2008. Some details about this system are shown below. More systems are currently being planned.

Büren 2019

Farmers Fabian Karthaus and Josef Kneer began constructing an operational agrivoltaic system at their organic soft fruit farm in Büren (North Rhine-Westphalia) in 2019. They applied for a building permit to construct the system, classifying it as a greenhouse for specialty crops, and it was approved as a special project in line with section 35 BauGB.

Technical data:

- Area: 70 x 60 m = 4,200 m²
- PV module rows: 20 rows, 3.5 x 60 m each (116 PV modules of 1.6 m² each)
- PV module orientation: East-west, 15°
- PV modules: Bifacial; manufactured by Solarfabrik, special production, 320 W (200 W/m²)
- Use: 50 percent self-consumption, 50 percent fed into the grid
- Installed capacity: 750 kW_p
- Inverter: Huawei 110 kW_p

The substructure was built in the "venlo" greenhouse style and comprises a total of 20 gabled roofs. The structure is made from steel and aluminum profiles. The substructure is embedded in the ground using driven piles. The spacing in the system (3.5 m x 4.2 m) and a clearance height of 3.2 m enable the farmers to use standard agricultural machinery to maintain their crops. The actual roof is made of the bifacial PV modules. They generate electricity and protect the crops underneath from the sun and the elements. The cabling runs only in the roof construction to ensure that the farmers can work on the land under the PV modules without any problems.

Beneath the installation, blueberries, raspberries and apples are planted in ridges around the supporting structure, with each roof apex covering a ridge. A sensor-supported drip irrigation system regulates the watering of the ridges. The watering system takes into account the current temperature, the wind, sun intensity and the forecasted rainfall. The drip edge for each roof panel is positioned between each ridge. Rainwater infiltrates the facility and is captured in drains where it is then prepared for reuse.

The farmers report that they were impressed by the high blueberry yields in the first few years. They recorded slightly lower strawberry yields in the first year. There has not been any yield information regarding the apples and grapes yet.

Table 04: Overview of some operational systems in Germany

Agrivoltaic systems	Location	Type of land use	Technology	Installed capacity	Year of commissioning
1	Warmsried, Bavaria	Arable farming, vegetable growing, livestock farming	Fixed PV arrays	70 kW_p	2008
2	Eppelborn-Dirmingen, Saarland	Fodder	Vertical PV arrays	2,000 kW_p	2018
3	Büren-Steinbach, North Rhine-Westphalia	Soft fruit production	Tracking PV array	740 kW_p	2020
4	Donaueschingen Aasen, Baden-Württemberg	Fodder	Vertical PV arrays	4,100 kW_p	2020
5	Althegnenberg, Bavaria	Specialty crops and berry shrubs	Single axis, solar tracking PV array	749 kW_p	2020
6	Lüptitz, Saxony	Livestock farming, vegetable growing, honey crops	Single axis, solar tracking PV array	1,045 kW_p	2021

Community solar park, Aasen, Donaueschingen 2020

Next2Sun constructed a vertical agrivoltaic system near Aasen, north of Donaueschingen, in partnership with the energy cooperative Solverde Bürgerkraftwerke Energiegenossenschaft as its operator. The system has a capacity of around 4.1 MW_p and can supply power to 1,400 homes[15]. As part of the project, arable land was converted into extensively farmed grassland. The overall share of land taken up by the PV module rows is minimal with a 10 m gap between rows, allowing the land in between to be farmed.

Technical data:

- Area: 140,000 m²
- PV module rows: 33 rows, up to 400 m in length; 10,960 PV modules
- PV module orientation: 90° east, 270° west
- PV modules: Bifacial, double-glass PV modules; Type: Jolywood JW-D72N, 370-380 Watt (front side) with 72 six-inch cells each
- Use: 100 percent fed into the grid
- Installed capacity: 4,100 kW_p
- Yearly production: 4,814 MWh
- Inverter: 46 x Huawei SUN2000-60KTL-M0

Community solar park, Lüptitz 2021

Solverde Bürgerkraftwerke Energiegenossenschaft eG also operates another agrivoltaic system in Lüptitz near Leipzig. This involved dismantling an existing ground-mounted PV system and replacing it with a more efficient, more advanced interspace PV system. Data from the operator shows that the Repowering Lüptitz project is profitable despite the costs to dismantle the first system. The PV system was constructed in a commercial area and put into operation in June 2021.

Technical data:

- Area: 16,500 m²
- 12 rows of PV modules of varying length (up to 190 m), totaling 2,520 PV modules
- PV module rows: Rotary axis 166° south-west
- PV modules: Bifacial, 2,520 x Jolywood JW-HD144N, 415 W each
- Use: 100 percent fed into the grid
- Installed capacity: 1,045.8 kW_p
- Yearly production: (predicted) 1,350 MWh
- Inverter: 29 x Huawei SUN2000-30KTL-M3

Fig. 17: Vertical agrivoltaic system in Aasen, Donaueschingen. © Solverde Bürgerkraftwerke

Fig. 18: PV module row with bifacial PV modules on the agrivoltaic system in Heggelbach. © Fraunhofer ISE

2.6 International development

With over 14 GW_p of installed APV capacity worldwide (as estimated by Fraunhofer ISE), China has the largest share of installed capacity with 12 GW_p (as of July 2021). The country also has the world's largest agrivoltaic facility on the edges of the Gobi Desert. Its solar PV modules have an installed capacity of 700 MW_p, and berries are grown underneath them. This facility also helps to combat desertification. Japan and South Korea are two more countries in Asia have that identified the opportunities offered by agrivoltaics. However, they both use smaller PV systems. At present, Japan has over 3,000 systems. In South Korea, where there is a huge migration away from rural areas to urban areas, the government is planning to build 100,000 agrivoltaic systems on farms as a form of retirement provision for farmers (selling electricity can earn them a monthly income of around 1,000 US dollars) and combat the decline in farming.

Agrivoltaics has multiple uses, so it can bring major benefits to (semi-) arid areas in emerging and developing countries that receive a high level of solar radiation. In addition to protecting crops and livestock from the sun, agrivoltaic systems also provide power to collect and treat water, which can stem desertification and soil degradation trends. In future, agrivoltaics could help crops to grow in areas with dry, hot climates and high levels of solar radiation, conditions in which they would otherwise not grow. Generating power locally is another benefit of agrivoltaics for villages that are usually far away from centralized grids. This technology could give people access to education, information (e.g., by allowing them to charge radio and cellphone batteries) and improved medical care (e.g., by powering refrigeration for vaccines and medicines) and enable them to tap new sources of income. This also reduces rural populations' reliance on fossil fuels, such as diesel for generators.

Electricity generated from agrivoltaics can also go straight into powering refrigeration and processing equipment for the agricultural products. This gives them a longer shelf life, makes them more marketable and allows farmers to continue selling them beyond the harvest season, which in turn brings higher revenues. Many countries still face political and economic barriers to realizing the huge potential for development cooperation. Political instability and limited capital reserves in particular make technology transfer difficult and hinder long-term investment in agrivoltaics.

A preliminary study conducted by Fraunhofer ISE at a site in the Indian state of Maharashtra suggests that shade and reduced evaporation under agrivoltaic systems can lead to up to 40 percent bigger yields of tomatoes and cotton[16]. In this particular case, Fraunhofer ISE researchers expect the land-use efficiency for this region to double.

As part of the EU's Horizon 2020 program, Fraunhofer ISE is working with partners in Algeria on the WATERMED 4.0 project to find out how agrivoltaics impact water regime. In addition to reduced evaporation and lower air and soil temperatures, using PV modules to harvest rainwater also plays a role here. This rainwater collection is a appealing prospect for many countries, including parts of Germany, especially in view of the increasing frequency of dry spells[17].

2.6.1 Research projects in Chile

An agrivoltaics project in cooperation with Fraunhofer Chile, which was completed in spring 2018, saw three systems with 13 kW_p capacity constructed in areas surrounding Santiago city, in the municipalities of El Monte, Curacaví and Lampa. This region has high annual solar radiation and low precipitation levels. An ongoing drought in what is already a dry and sunny climate has reduced precipitation by 20 to 40 percent over the last ten years. These climatic conditions have led farmers to actively seek out shade-giving installations to help stop their crops from drying out and becoming sunburned. This is where the use of agrivoltaics offers major potential for synergies.

This project was backed by the local government, and its participants researched which crops could benefit from having slightly less solar radiation. The participating farms had different profiles. One farm that grew broccoli and cauliflower used the solar power generated by the agrivoltaic system for post-harvest processes, such as cleaning, packing and refrigeration. Another pilot system was set up by a family-run business specializing in herb growing. A third PV system was constructed in a remote area with poorly developed infrastructure and an unreliable power supply, providing seven families there with a secure supply.

These three sites in Chile are the first of their kind in Latin America. The researchers looked at how agrivoltaics could be adapted to suit the climatic and economic conditions in the region and optimized overall. There were positive results from the agricultural production and solar power generation, so there are plans to build on this research by Fraunhofer Chile with the support of local government. Researchers continue to monitor the three pilot systems in field operation[18].

Fig. 19: Pilot PV systems in Curacaví and Lampa where the Fraunhofer Chile Research Institute is investigating which crops benefit from slightly less solar radiation. © Fraunhofer Chile

2.6.2 France

There have been separate tenders for agrivoltaics in France since 2017, and there are plans for 15 MW_p of installed capacity per year. Contracts are awarded partly based on the offered price and partly based on how innovative the project is. The maximum project size is 3 MW_p of installed capacity. Only greenhouse projects won tenders in the first tendering process in 2017. In the second and third rounds, tenders for 140 MW each are awarded for systems with a capacity between 100 kW_p and 3 MW_p. Successful projects are guaranteed a feed-in tariff over 20 years. In March 2020, 40 MW was secured for agrivoltaic projects, especially for systems with solar tracking PV modules. Europe's largest PV facility with solar tracking PV modules to date was constructed at a vineyard in Tresserre (Pyrénées-Orientales, Occitanie) in 2018.

However, there are problems with the acceptance of agrivoltaics in France. The first round of tendering did not clearly outline the criteria for agrivoltaics, so some projects have little to no agricultural production. This kind of bandwagon effect from the PV industry has caused some resistance to agrivoltaics, especially in the agricultural sector. The French energy and environmental agency ADEME (Agence de l'environnement et de la maîtrise de l'énergie) is currently working on a definition of agrivoltaics.

Fig. 20: Study with various types of lettuce at the agrivoltaics research site run by the University of Montpellier in France. © INRAE / Christian Dupraz

2.6.3 USA

The USA also has agrivoltaic facilities. For instance, a research site in Massachusetts has successfully demonstrated dual land use for growing crops and generating electricity. On the back of this project, the state began providing funding for dual use solutions in 2018. This financial support comes with specific requirements, stipulating that it is only awarded to PV systems that are built on agricultural land and do not exceed 2 MW. The lower edge of PV modules must be at least 2.4 m high on fixed models and at least 3 m on tracked ones. No part of the crop field can be more than 50 percent shaded during the main growing period[5].

The US Department of Agriculture also provides funding for solar PV systems in rural areas as part of the Rural Energy Advancement Program (REAP). This support could help further the expansion of agrivoltaics.

Arizona, Colorado, Indiana and Oregon are also home to agrivoltaic facilities. Systems that focus on promoting biodiversity rather than agricultural use are particularly popular. Several universities and research institutions are working on developing sustainable business models to make agrivoltaic systems with an emphasis on agricultural use more attractive.

2.6.4 Mali and The Gambia

Mali and The Gambia are two of the world's hardest hit regions when it comes to the climate crisis. Extreme weather events such as droughts will occur more frequently in future. The APV-MaGa research project aims to improve food and energy security and strengthen the stability of the agricultural sector in the two countries by examining the extent to which agrivoltaic systems with integrated rainwater collection can boost agricultural resilience.

The international consortium comprising Mali, The Gambia and Germany brings together R&D activities in agronomics, socioeconomics and solar energy. It aims to demonstrate the challenges and opportunities presented by agrivoltaics and develop a deeper understanding of the synergies and interrelationships at the water-energy-food nexus. The project also looks at the socioeconomic aspect of this technology and seeks to promote the sustainable development of rural areas in the partner countries.

3 Agriculture

Extreme weather events over the last few years have shown that global warming is not an abstract threat — it is already having a major impact on Germany's agriculture. Springtime precipitation is particularly crucial for crop growth, and it has decreased significantly over the last 30 years[19]. Extra irrigation can make up for these dry spells and protect yields. Many places have restrictions on drawing ground and surface water, however, so more options for adaptation need to be found. Drought is not the only extreme weather event to threaten crops — hail and heavy rainfall can also harm crop growth.

Farms are increasingly using crop protection measures to cope with challenges posed by climate change, water conservation and the demand to increase yields. Such measures include growing crops in greenhouses and polytunnels and using anti-hail netting in orchards. Anti-frost and anti-hail protection measures are used especially for high-value specialty crops and range from heating cables, anti-frost candles and static gas and oil burners to helicopters and cloud seeders that disperse fine particles of silver iodide under the cloud base. These technical and mechanical crop protection measures are expected to grow in importance over the next few decades as climate change impacts agriculture more and more.

The dual use of agricultural land for growing food and generating solar power gives farmers the opportunity to address many of these problems at the same time. Agrivoltaics offers farms the option to diversify their income and make their internal processes circular. Reduced evaporation rates and protection against hail and frost are also key aspects. More protection systems can be integrated in a cost-effective manner if farms harness existing structures, boosting productivity and adding value to agricultural land.

Using agrivoltaics does, however, present challenges for agricultural production, including changing light conditions and difficulty in tending crops due to the system's structures. In this case, the right crops and a suitable system design should be chosen to minimize the risks and optimize synergies.

Fig. 21: Crops from the research site in Heggelbach (celery, potatoes, wheat and clover grass). © University of Hohenheim / Andrea Bauerle.

3.1 Results from the APV-RESOLA research project

As part of the APV-RESOLA research project, a sequence of several crops comprising celery, potatoes, winter wheat and clover grass were successfully grown under the pilot system in Heggelbach using a biodynamic approach. The results showed that weather conditions are a significant factor in how the agrivoltaic system impacts the yield. For instance, differences in yields for potato crops growing under the facility compared to a reference plot varied from minus 20 percent in 2017 to plus 11 percent in 2018 when it was dry and hot.

Depending on the geographic location and local climate, growing crops under an agrivoltaic system can reduce evaporation and protect against intense solar radiation. This will become ever more important given the increasing frequency of heat waves in Central Europe and Germany[20]. Research with potatoes has also shown that using agrivoltaics can increase the proportion of sellable tubers.

Researchers at the University of Hohenheim collected data on crop development, crop yield, harvest quality and microclimatic conditions, both under the agrivoltaic system and on a reference plot without PV modules (see figure 22). This data showed that photosynthetically active solar radiation under the agrivoltaic system was around 30 percent lower than on the reference plot. Besides solar radiation, the agrivoltaic system primarily affected the soil temperature and distribution of precipitation. The temperature of the soil under the agrivoltaic system was lower than that of the reference plot in spring and summer, although the air temperature remained largely the same. During the hot, dry summer of 2018, the wheat field had more soil moisture than the reference plot.

The initial yields from the test site in 2017 were promising: The clover grass yield was only slightly below that on the reference plot, producing 5.3 percent less, but the reduced yields of potatoes, wheat and celery caused by shading were slightly more pronounced at 18 to 19 percent.

During 2018, which was a dry year, the winter wheat, potato and celery crops produced higher yields than the reference plot with no PV modules. The celery benefited most from these conditions with its yield increasing 12 percent; the yields for the potato and winter wheat crops rose 11 and 3 percent respectively. The clover grass yield was 8 percent lower than the yield on the reference plot. Calculations for the total yield loss need to account for the 8 percent reduction loss as a result of not being able to use the strips of land between the supporting pillars for growing crops.

Results from 2019 showed reductions in yields for crops growing under agrivoltaic systems amounting to 19 percent for clover grass, 28 percent for wheat and 33 percent for celeriac. Wheat grown with agrivoltaics produced 2 percent more in yields in 2020.

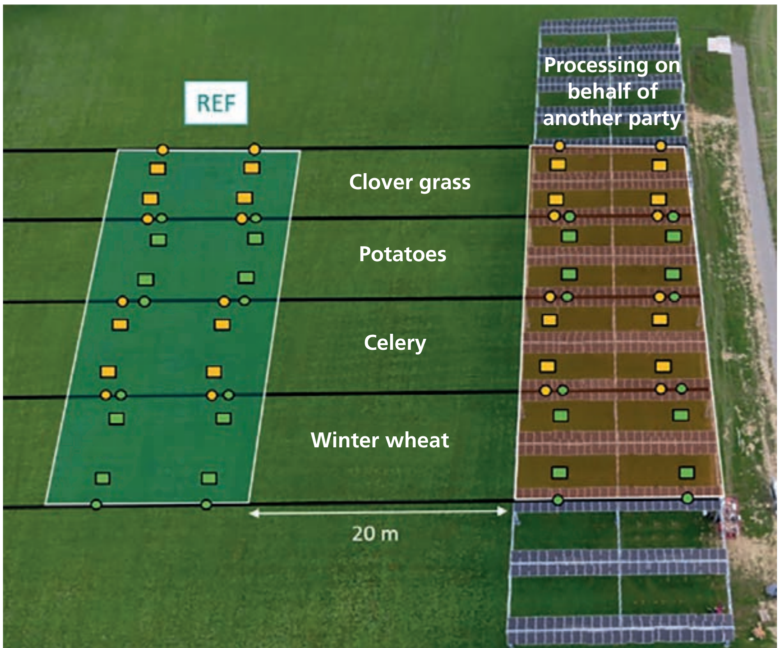


Fig. 22: Field plan for the 2017 research site, showing monitoring stations. Areas where samples were taken are shown as boxes, and the positions of the microclimate stations are shown as circles. © BayWa r.e., modified by Axel Weselek/University of Hohenheim.

3.2 Crop selection and cultivation

Cultivation under PV modules is not the same as farming on "open fields." There are differences in tilling (3.2.1), crop management (3.2.2) and crop selection (3.2.3).

3.2.1 Reconciling substructures and farming machinery

When planning a system, practical requirements need to be taken into account before cultivation takes place. One important requirement is that the system needs to be aligned with the direction of tilling, and the distances between the substructure supports need to be suitable for the widths and heights of the machines used. The machine operator needs to get used to maneuvering between the pillars, especially at the outset. In the APV-RESOLA project, the pillars are equipped with impact protection to prevent damage to the system. The actual land lost due to the pillars and impact protection in Heggelbach was less than one percent of arable land. Because it is often not practical to cultivate the strips between the supports using machinery, around eight percent of the arable land was not usable in the case of the research system in Heggelbach. With manual cultivation or cultivation in rows, the area lost is reduced to cover only the area that is actually sealed. Innovative cabling techniques can also help to reduce the number of supports to allow the largest possible area to be cultivated (section 5.3). The use of precision farming and automated track guidance systems makes cultivation easier.

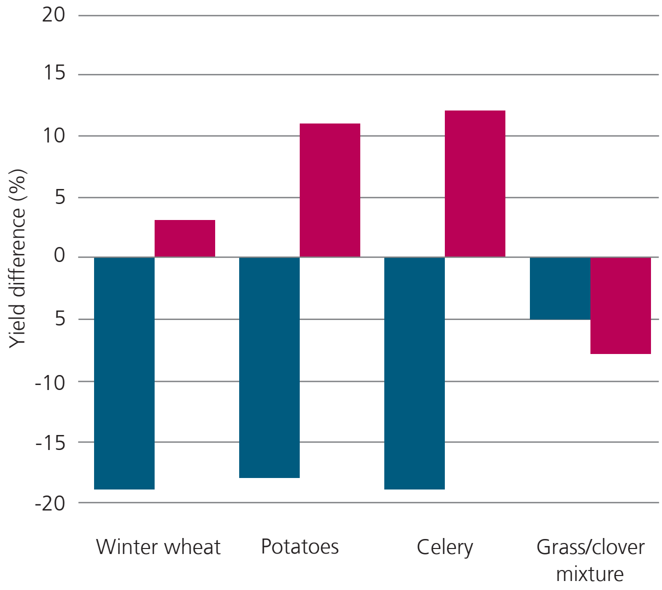


Fig. 23: Crop yield differences under agrivoltaics compared to reference plots, 2017 (blue) and 2018 (red) in Heggelbach (excluding land lost due to supports). Data: University of Hohenheim, graph: Fraunhofer ISE

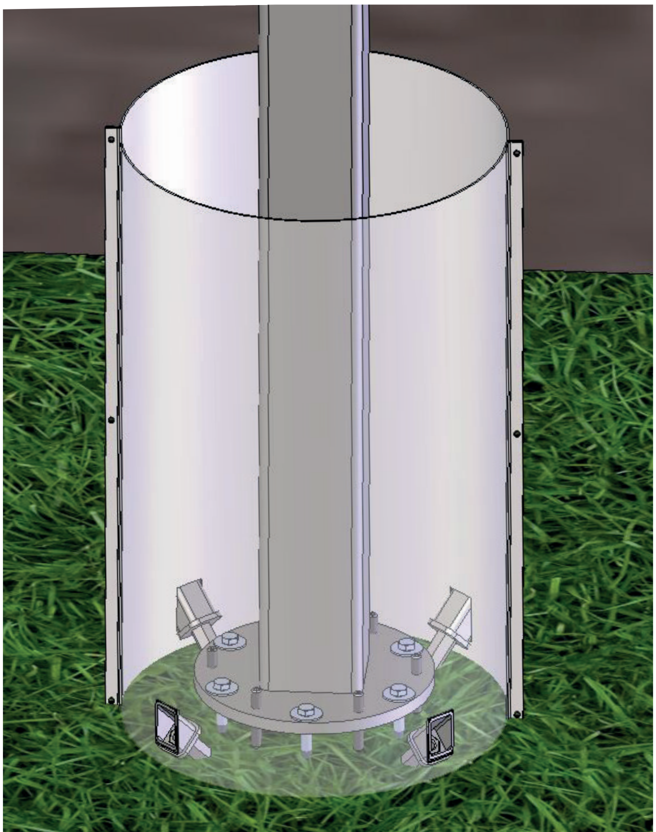


Fig. 24: Impact protection for the supports of the system in Heggelbach to protect against possible damage from farming machinery. © AGROSOLAR Europe GmbH

3.2.2 Changes to the microclimate

Shading of the agricultural land changes the microclimate below the PV modules. As well as the investigations in Heggelbach described above, research has also been done into possible effects on the microclimate at sites in the United States[21] and France[7]. Depending on the location and design of the system, the researchers were able to identify various changes in the microclimate.

In combination with the findings from APV-RESOLA, the findings can essentially be summarized as follows:

1. The solar radiation available to the crops can vary depending on the technical design (e.g. the distance and orientation of the PV modules). As a guideline, a reduction in radiation of around a third can be considered acceptable for arable farming in Germany.
2. The lower the height of the supports, the greater the microclimatic changes.
3. On particularly hot days, the ground temperature decreases, as does the air temperature to a lesser extent.
4. The wind speed can decrease or increase depending on the orientation and design of the system. Wind channel effects and their impact on crop growth should therefore be taken into account when planning the system.
5. Less groundwater is lost under an agrivoltaic system. The hotter and drier the climate, the stronger the tendency for soil moisture to increase compared to reference plots without agrivoltaics.

Partial covering of the agricultural land leads to an uneven distribution of precipitation on the drip edges of the PV modules. Measures should be taken in these areas to counteract soil erosion due to run-off of nutrient-rich topsoil, capping, washing out of seedlings or nutrient discharge and eutrophication of surface water. Some possible options can be found in the technology section (section 5.4).

These findings play an important role in agricultural practice. For example, with systems that offer no protection or only partial protection from rain, it is necessary to take into account possible changes in air circulation, humidity and risks of fungal infections when choosing crop varieties. It is also important to keep in mind that the decrease in solar radiation and canopy temperature can prolong development time.

Aside from practical considerations, knowledge of the microclimatic effects of agrivoltaics also serves as a basis for selecting suitable crops. The partial shade underneath the system determines the suitability of individual crops.

Fig. 25: Illustration of an agrivoltaic apple orchard. © Fraunhofer ISE

Fig. 26: Agrivoltaic system with solar tracking PV modules in France. © Sun'Agri

Fig. 27: Weather protection for raspberries provided by agrivoltaics. 300 kW$_p$ test system by BayWa r.e. in the Netherlands. © BayWa r.e.

3.2.3 Suitable crops

Based on current knowledge, all types of crops are generally suitable for cultivation under an agrivoltaic system, with different effects on yields to be expected as a result of the shade provided. Highly shade-tolerant crops such as leafy vegetable species (e.g. lettuce), field forage species (grass/clover mixture), various pomaceous and stone fruit and berry species and other specialized crops (e.g. wild garlic, asparagus, hops) appear to be particularly suitable.

Permanent and specialized crops
Agrivoltaics is likely to offer the greatest potential for synergy effects in the case of specialized crops from viticulture and fruit and vegetable growing. This is because the high added value to area ratio and the often relatively sensitive crops entail a greater need for protective measures. A sensibly designed agrivoltaic structure can ensure direct protection from environmental influences such as rain, hail and wind. The supports can also be used to integrate additional protective elements such as hail protection nets and polytunnels. Agrivoltaics can help to reduce the amount of plastic used so that less of it leaches into the soil. It also lowers the costs of conventional protective measures and the yield risk at the same time.

Leafy vegetable cultivation with lettuce produced positive results under an agrivoltaic system. The crops responded to the reduction in light of approximately 30 percent with increased leaf surface area growth[22], in a similar way to the celery in Heggelbach.

In viticulture, on some types of vine the increased solar radiation and temperature change caused by the climate crisis have had a marked effect on yields, leading to sunburn as well as water shortage. Greater solar radiation increases the sugar content of the grapes, which in turn increases the alcohol content of the wine and can impair its quality. A shifting of cultivation regions and changes in harvest times can already be clearly observed in many regions. In high temperatures, the partial shade therefore has a positive effect on growth while also preventing early ripening[23]. Compared to other types of agriculture, in viticulture the agrivoltaic system only needs to be two to three meters high (see figure 26), which significantly lowers the substructure costs. There are also potential cost reductions to be achieved from integrating the agrivoltaic system into existing protective structures. In France, agrivoltaic systems are being increasingly promoted and implemented in viticulture (section 2.6.2).

Systems associated with pomaceous fruits such as apples are also showing promise. Reducing the effects of the climate crisis on the quality of the apples and harvest yields in Germany often requires costly protective systems. Agrivoltaics can reduce these costs. For many types of apple, just 60 to 70 percent of the available light is sufficient for optimum apple yields[24]. In Rhineland-Palatinate, Fraunhofer ISE has set up a pilot system on an organic orchard to investigate the effects of the PV modules on pest infestations and yields compared to those of conventional protective measures. Synergy effects are expected in hop production as well: The substructure can be used both as a climbing aid for the hops and as a fitting for the PV modules. This can substantially lower the costs of a hop yard. On the other hand, crops and cultivation systems that are susceptible to moisture-related fungal infestations that cannot be reduced with accompanying cultivation techniques appear to be less suitable.

Another area of application among specialized crops is the protected cultivation of berry bushes. Here, PV modules could take on part of the function performed by polytunnels, providing protection against rain and hail. Other advantages of systems installed above permanent and specialized crops relate to cost-effectiveness (section 3.3), societal acceptance (section 5) and regulatory feasibility (section 6).

Arable farming

The results from Heggelbach with various agriculturally relevant crops show that, especially in dry areas, these crops can clearly benefit from the shade of agrivoltaic systems. The positive effect on yields in hot and dry years is particularly worth emphasizing. In years of high precipitation, on the other hand, crops such as potatoes, wheat and other grains (barley, rye or triticale) under fixed substructures should be expected, as in the case of Heggelbach, to suffer yield losses of up to 20 percent. In temperate latitudes, corn is not well suited to cultivation in partial shade because of its characteristics as a C4 crop (higher heat and light demand). There is little experience so far with other popular crops such as canola, turnips and legumes. It is recommended — including in view of achieving broad acceptance among the population and in farming — that total yield losses should not exceed 20 percent. The findings from Heggelbach show that this is achievable for some relevant arable crops in Germany through suitable light management, which involves having a lower density of PV modules and adjusting the orientation of the PV modules. Movable agrivoltaic systems can reduce losses in crop yields because the available light can be increased in critical growth phases.

Fig. 28: Demo project in berry cultivation shows high value creation in agriculture. © BayWa r.e.

Fig. 29: Wheat harvest with combine harvester. © Fraunhofer ISE

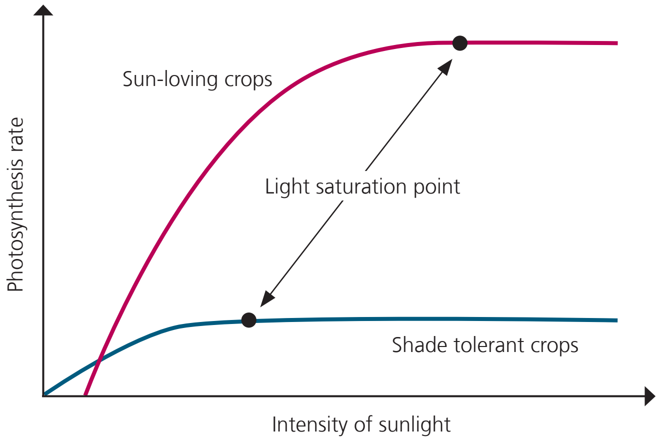


Fig. 30: Graph of the rate of photosynthesis against intensity of sunlight for sun-loving and shade tolerant crops[24]*.*
© ASPS, modified by Fraunhofer ISE

Grassland

Dual agricultural use for ground-mounted PV systems and sheep farming is common practice in Germany. These systems are typically optimized purely on the PV side. The expected synergy effects and the agricultural added value to area ratio are relatively low compared to other agrivoltaic applications. However, concrete research findings are still needed in this area.

A new approach, which allows the land to be farmed to a large extent even when the stilts are close to the ground, is the installation of vertical agrivoltaic systems (see figure 31). In Germany, there are already two reference systems in Donaueschingen (Baden-Württemberg) and Eppelborn-Dirmingen (Saarland). The main advantages for crop growth are expected to be in windy areas such as those close to coastlines, where the PV modules can act as wind barriers to prevent wind erosion.

Light saturation point

Crops need light for photosynthesis. The ability to make use of incident light differs from crop to crop. The rate of photosynthesis stagnates after a certain level of light intensity depending on the species of crop (see figure 30). An important criterion in determining the suitability of crops for agrivoltaics is the light saturation point. After this point, crops cannot convert any more light into photosynthesis output, and can even become damaged. The lower the point at which a crop reaches light saturation, the better suited that crop is for cultivation under an agrivoltaic system.[21]

Fig. 31:Vertically deployed, bifacial PV modules used within the agrivoltaic system in Eppelborn-Dirmingen, with 2 MW$_p$ of capacity, built by Next2Sun. © Next2Sun GmbH

3.3 Reports from farmers

The farmers in Heggelbach report chiefly positive effects, but also clearly note the limitations due to the existing regulatory framework in Germany. In an interview, Thomas Schmid and Florian Reyer explain why they have chosen an agrivoltaic system, how practically feasible it is and how they think the legal regulations should be changed. Thomas Schmid is a co-founder of the farming community Demeter-Hofgemeinschaft Heggelbach, founded in 1986. Since then, he has withdrawn from active farming and now works on the supervisory board of the Demeter association and as a consultant in Baden-Württemberg. Florian Reyer has been a partner in Hofgemeinschaft Heggelbach since 2008 with responsibility for the areas of renewable energy, technology, agriculture and vegetable farming.

Interview with Thomas Schmid and Florian Reyer

What drove you as an agricultural practice partner to take part in the pilot project and make your land available for a pilot system?
Schmid: "For 15 years, we have had the ideal of achieving not just a closed operational cycle but also a closed energy cycle on the farm. Because of that, we have invested in various sources of energy in the past (note: wood gas power, roof PV systems). When Fraunhofer ISE approached us in 2011, the energy transition was already a major topic. Agrivoltaics seemed to be an opportunity for us to play our part in a successful energy transition and also, through dual land use, to showcase an alternative to biogas production on agricultural land."
Florian: "We're also very interested in innovative developments in renewable energies in general."

How did the planning and construction go? Were all your requirements taken into account, like maintenance of soil functions for example?
Schmid and Reyer: "As a full practice partner, we were involved in the entire planning process and we had a say in the decisions made in every area, so our agricultural needs and our high demands for maintaining soil fertility were considered from the start. For example, a temporary construction road was laid to build the system, and a special anchoring system was used to eliminate the need for concrete foundations."

Fig. 32: Thomas Schmid and Florian Reyer. © AMA Film GmbH

How practical is it for you to farm under the system?
Reyer: "In terms of the benefits of dual use, it's totally practical. That also means that some of the constraints on cultivation aren't relevant. If you want to do it, you can."

What benefits do you get from generating power using the system?
Schmid: "Our aim is to use as much of the energy produced ourselves as possible so we can reduce energy costs. That's why we're trying to further increase consumption of our own energy and, with the help of our practice partner, Schönau power station, to adapt storage, management and consumption to the power that is generated."

Given what you know now, would you choose to build this system again?
Reyer: "As a research system, yes, but not under the current conditions."

Why? What do you think needs to change for agrivoltaics to be used successfully in the future?
Reyer: "It's all about the conditions. Everything needs to change!"
Schmid: "The conditions in Germany* are not right at the moment. Building the system means we don't get an agricultural subsidy for the land any more. At the same time, we don't get compensation under the Renewable Energies Act for feeding the power that's generated into the grid."
Reyer: "New technology needs funding to incentivize people to use it in practice. It also requires political will to adapt the underlying conditions accordingly."
Schmid: "More research is also needed to test the technology in other areas of use, such as hop production, fruit growing and even conventional agriculture."

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* The statements refer to the regulatory conditions in 2019. Some conditions have since been adapted, see also section 6.

4 Profitability and business models

The costs of agrivoltaics are highly individually variable and depend on factors such as installed capacity, agricultural activity, position and the PV module technology used. The acquisition cost is generally higher than that of a conventional ground-mounted PV system, mainly due to the higher, more elaborate substructure and the need to produce the PV modules specially. The clearance height and the spacing between the posts have a significant effect on the cost of the substructure. Using smaller farming machinery or performing as many operations as possible manually can have a positive effect on cost-effectiveness. Perennial row crops also provide cost advantages, because the substructure posts can be integrated into the rows with no appreciable loss of acreage. Especially when the crops on the agricultural land need to be protected in any case, investing in an agrivoltaic system can be lucrative from the point of view of an agricultural business, as there are potential savings to be made here. Unlike conventional ground-mounted PV systems, overhead agrivoltaic systems do not usually need to be fenced in, which eliminates this as a cost factor.

When in operation, slight cost savings are expected with agrivoltaic systems compared to ground-mounted PV systems, as steps such as pruning the vegetation under the PV modules are already carried out as part of agricultural operations. Only the non-tillable rows should be maintained to prevent unwanted weeds from spreading. Dual use can also be expected to enable cost reallocations or savings on leased land. This is addressed in section 4.1.2.

Below, applications on permanent grassland and in arable farming and horticulture are considered separately and compared to the costs of ground-mounted PV systems and small PV roof systems so that the costs can be estimated. Horticulture here includes both permanent crops, such as fruits and wine, and specialized crops. Because of the high economic complexity of the overall system, the following considerations are limited to the PV level. Income and expenditure from farming activities have not been taken into account in this estimate. For the purpose of simplification, it has been assumed in the calculations that applications on permanent grassland are interspace systems and applications in arable farming and horticulture are overhead systems.

The results show a tendency for systems with a higher installed capacity to be necessary in arable farming in order to put agrivoltaics into practice cost-effectively, while smaller systems appear to be possible options in horticulture when conditions are favorable. Crop rotations in arable farming mean that the design of the agrivoltaic system needs to be adapted to the needs or tilling methods used for all of the crops in the rotation. For permanent crops, on the other hand, the design of the system can technically be adapted entirely to the needs and cultivation of the single crop. The most cost-effective systems are interspace systems on permanent grassland.

The underlying figures used here represent estimated medium-term costs and income. Cost fluctuations and supply bottlenecks, such as those due to the coronavirus crisis or the war in Ukraine in the case of steel and PV module prices, have not been taken into account in the calculations.

4.1 Capital expenditure

The capital expenditure estimates are based on an area of two hectares and, for the roof system, an installed capacity of 10 kW_p. Because arable crops that are typical in Germany, such as wheat, barley or canola, tend to need more light than horticultural crops, larger spaces between the PV modules have been assumed for arable farming, and therefore a lower capacity to area ratio of 600 kW_p per hectare. The substructure clearance height and spacing between posts correspond to the dimensions of the system in Heggelbach. For low permanent crops such as berries, a capacity of 700 kW_p per hectare and a clearance height of three meters have been assumed. On permanent grassland, a capacity of 300 kW_p per hectare has been calculated.

For ground-mounted PV systems, a capacity of 1 MW_p per hectare has been used. An optimistic and a conservative scenario reflect the expected range of costs. For the agrivoltaic scenarios, any possible risk premiums or additional costs to comply with legal conditions have not been taken into account. The values therefore correspond to the estimated medium-term costs in the event of an agrivoltaic market launch. The differences between the capital expenditure expected for ground-mounted PV and that for agrivoltaic systems are shown in figure 33.

The differences in capital expenditure are largely attributable to three cost points:

1. The PV module price may increase, as the size or light transmission of low-level PV modules can be adjusted to the crop's growth needs (section 5.2). When using bifacial double-glass PV modules, an average increase of 326 euros per kW_p has therefore been assumed in the example calculation. In the case of special PV modules that can be used in horticulture, the assumed price is between 240 and 440 euros per kW_p. These additional expenses associated with bifacial PV modules can be offset in part by the increased power generation to installed capacity ratio.
2. For the substructure, average costs of 372 euros per kW_p are expected in arable farming, compared to 76 euros per kW_p for ground-mounted PV systems. However, this estimate (still) contains many uncertain elements, and fluctuates between 243 and 500 euros per kW_p depending on the design as well as on possible learning effects and economies of scale. For permanent grassland, the cost of the substructure is significantly lower, at 97 to 167 euros per kW_p. In horticulture, this is between 243 and 306 euros per kW_p.
3. The site preparation and installation costs are also significantly higher, and in arable farming are estimated to be 190 to 266 euros per kW_p (ground-mounted PV systems: 67 to 100 euros per kW_p). Cost-driving factors include soil protection measures such as the use of construction roads and less flexibility with regard to installation, because cultivation times for agriculture and the trafficability of the soil need to be taken into account. On permanent grassland and in horticulture, lower average costs of 93 and 137 euros per kW_p respectively may be expected.

Aside from the aspects mentioned, the costs of power inverters, electrical components, grid connection and project planning are, according to current information, comparable to those of ground-mounted PV systems in most cases. Some small savings can be made by not fencing off the system.

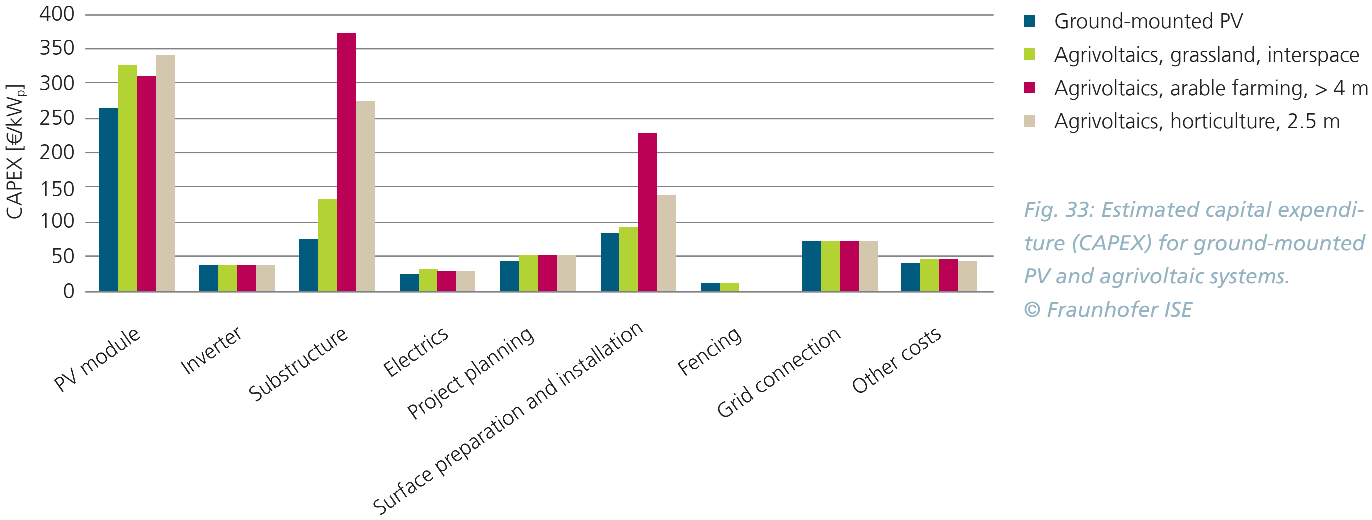


Fig. 33: Estimated capital expenditure (CAPEX) for ground-mounted PV and agrivoltaic systems. © Fraunhofer ISE

4.2 Operating costs

The costs of agrivoltaic systems are individually variable, and there is a tendency for there to be potential savings on operating expenses, unlike on capital expenditure, compared to ground-mounted PV systems. For the most part, the savings are accounted for by the following:

1. The costs of providing the land fall from around 2 to 1.3 euros per kW_p in arable farming or on permanent grassland, and to 1.6 euros per kW_p in horticulture. For this estimate, it was assumed that the area costs for agrivoltaic systems are based on agricultural lease rates and are divided equally between the farm and the operator of the agrivoltaic system. This figure may vary depending on the ownership structure and business model. The potential savings may be higher in arable farming because lower lease rates are more common there than in horticulture.
2. Land management costs that are traditionally carried by a PV system operator are eliminated by regular agricultural use.
3. However, the costs of cleaning the PV modules or repairing the system are likely to be higher if this work needs to be done at a greater height, for example using lifting platforms. Because the regular rainfall in Germany means that the costs of cleaning PV modules are only minor, this additional cost is likely to be manageable. In regions with a higher probability of soiling, the additional costs of cleaning may be far more significant depending on the cleaning technique used. Experience regarding the long-term effects of fertilizers and crop protection products on the substructure and PV modules is currently limited.

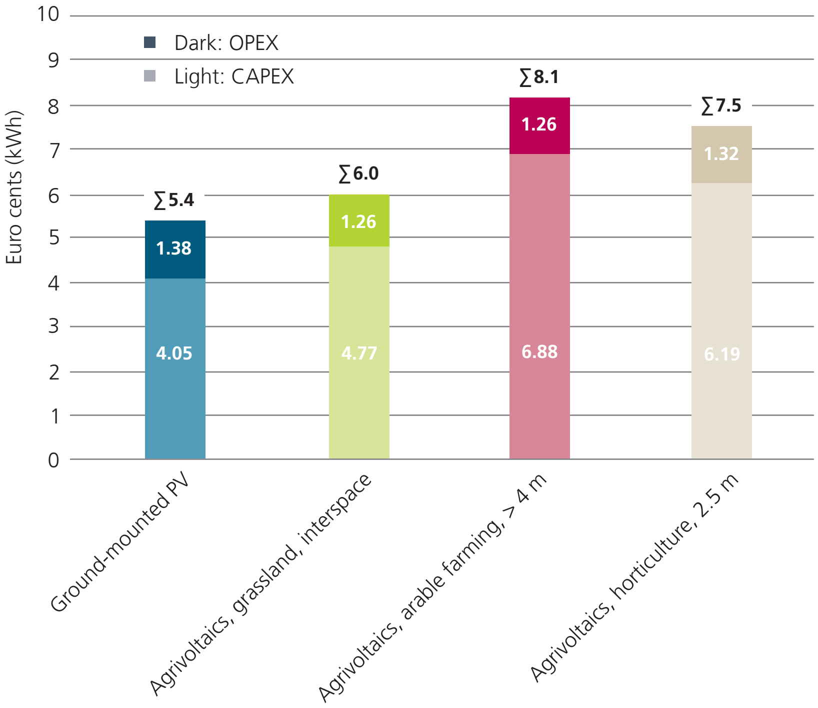


Fig. 34: A comparison of estimated levelized costs of electricity by capital expenditure (CAPEX) and operating expenses (OPEX) of ground-mounted PV systems and agrivoltaic systems.
© Fraunhofer ISE

4.3 Levelized cost of electricity

It can be concluded that the costs for the production of electricity in arable farming over a period of 20 years with average electricity generation costs of 8.15 euro cents per kWh are around 50 percent higher than those for the average ground-mounted PV system, and more cost-effective on average than small roof systems. For permanent grassland, on the other hand, electricity generation costs amount to 6.03 euro cents on average, only slightly higher than those of a ground-mounted PV system. The range of electricity generation costs of agrivoltaic systems compared to ground-mounted PV systems and small roof systems is shown in figure 35.

The cost estimate does not take into account the fact that economies of scale in arable farming could lead to a cost advantage of applications in arable farming over those in horticulture because of a tendency towards larger field sizes and therefore larger agrivoltaic systems. The same advantage is also likely to apply in arable farming with regard to fixed costs (such as project planning and grid connection) because a larger system means that these costs are lower relative to the system's size, thereby potentially improving overall cost-effectiveness. On the other hand, small systems could also offer advantages in terms of cost-effectiveness, for example if farms use the generated electricity themselves. With an appropriately designed regulatory framework, decentralized locations close to the consumer could lead to additional incentives to build agrivoltaic systems.

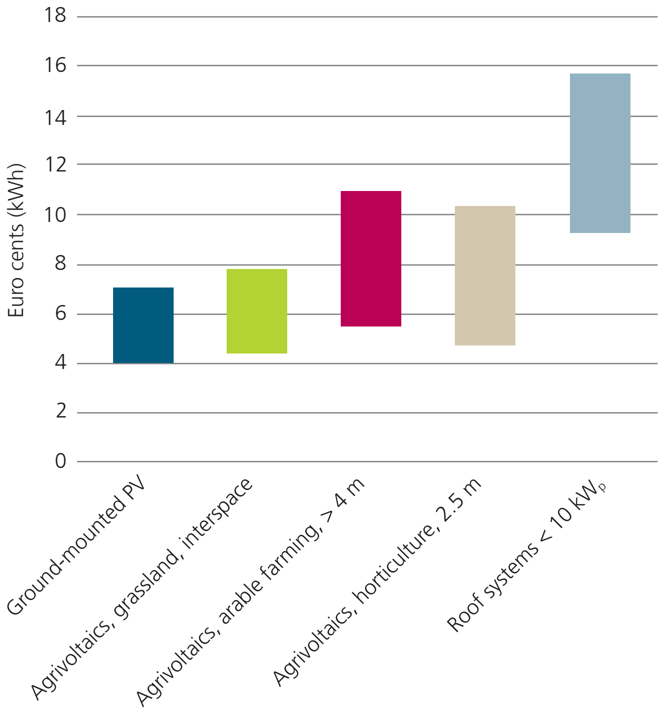


Fig. 35: Estimated levelized costs of electricity (LCOE) for ground-mounted PV and agrivoltaic systems. © Fraunhofer ISE

4.4 Self-consumption and revenue from power generation

Power from an agrivoltaic crop is usually most lucrative when it is used for the producer's own consumption, thereby reducing the need to purchase electricity externally. For example, if the cost of purchasing electricity commercially is 14 to 16 euro cents per kilowatt-hour[25] (and the cost of generating electricity is seven euro cents per kilowatt-hour), the potential savings are seven to nine euro cents per kilowatt-hour. To achieve high direct consumption, it is beneficial to have a consumption profile that is similar to the generation profile, with peaks in the middle of the day and in the summer. These generation peaks can be shifted depending on the orientation of the agrivoltaic system.

For applications such as cooling, where energy can be stored, thermal storage allows the consumption profile to be adapted to the generation of electricity. Charging vehicle batteries is another way in which the generation profile can be taken into account and producer consumption can be increased.

Given the falling costs of stationary energy storage, this could also be a cost-effective way to ensure a favorable consumption profile, and should be considered on a case-by-case basis. For PV energy that cannot be consumed immediately or stored, a buyer needs to be found. This usually relies on models based on the German Renewable Energies Act or electricity supply contracts. Section 7.1.3 describes the circumstances under which compensation is available under the Renewable Energies Act.

Some energy suppliers will buy energy from operators of PV systems through electricity supply contracts. Umweltbank, for example, has drawn up an electricity supply contract template for ground-mounted PV projects.

4.5 Business models

Because agrivoltaic systems incorporate agricultural land, the business models are often more complex than for ground-mounted PV. Depending on the parties involved in the project, its implementation can often involve different players or areas of responsibility with different functions.

There are at least four different areas:

1. Provision of land (ownership)
2. Agricultural use of the land
3. Supply of the PV system (ownership/investment)
4. Operation of the PV system

Basic case: “everything from a single-entity model”
In the simplest business model, all four areas may be dealt with by a single party — typically a farming business. This model is mainly used for smaller agrivoltaic systems close to farms in western Germany. This is because those who farm the land on these farms are often also the owners, and the capital expenditure could be manageable. This business model has a number of advantages: Firstly, the costs of project planning and the complexity of contract negotiations are lower. Secondly, the advantages and disadvantages of an agrivoltaic system are easier to estimate if the income from the agricultural and the photovoltaic activity goes to the same economic entity. This is particularly relevant in the case of agrivoltaic systems because of possible interactions between the two areas of activity. For example, bifacial PV modules can increase albedo values, and therefore electricity yields, depending on the choice of crop and the agricultural operations. The producer’s ability to use the energy generated and the fact that many farms have already installed roof systems, and therefore have experience operating PV systems, are also points in favor of this business model.

What should a farm ideally bring to the table?

Beneficial factors for the economical implementation of agrivoltaics:

- A good connection to the grid in terms of proximity and capacity
- Row cultivation
- Permanent crops
- Protected cultivation
- Low employment of machines/low clearance height
- A large, contiguous area (> 1 hectare)
- A low slope
- High and flexible energy consumption (e.g. cooling, drying, processing)
- A willingness to invest

External land ownership
In many cases, however, the land is not owned by the farming business itself. This can be seen from the high proportion of leases in Germany, particularly eastern Germany[26]. If the other three responsibilities at least are all in the hands of the farming business, it can still benefit from the synergy effects described above. As in the case of ground-mounted PV projects, this requires long-term land lease and use contracts, usually with a term of more than 20 years.

External PV investment
For large agrivoltaic systems, it is also likely to be more unusual for the farming business to own the PV system, and the likelihood of external investment is likely to increase. Part-ownership could help to create an incentive structure for synergetic dual land use. The larger the proportion of borrowed capital, however, the more difficult it will be to maintain an overview of the use of both production levels during ongoing operations. This business model nonetheless has the potential for economies of scale and optimization thanks to greater division of labor.

Shared responsibilities
In the example of the pilot system in Heggelbach, the mix of players involved is relatively complex. The ownership of the land, the ownership of the PV system and the operation of the farm and PV system are all in the hands of other parties. Figure 36 shows the basic structure of the required network of contracts. It remains to be seen what configurations will become established in Germany; this will depend significantly on the future regulatory framework. Cooperative models, with multiple farmers working together, are also a possibility.

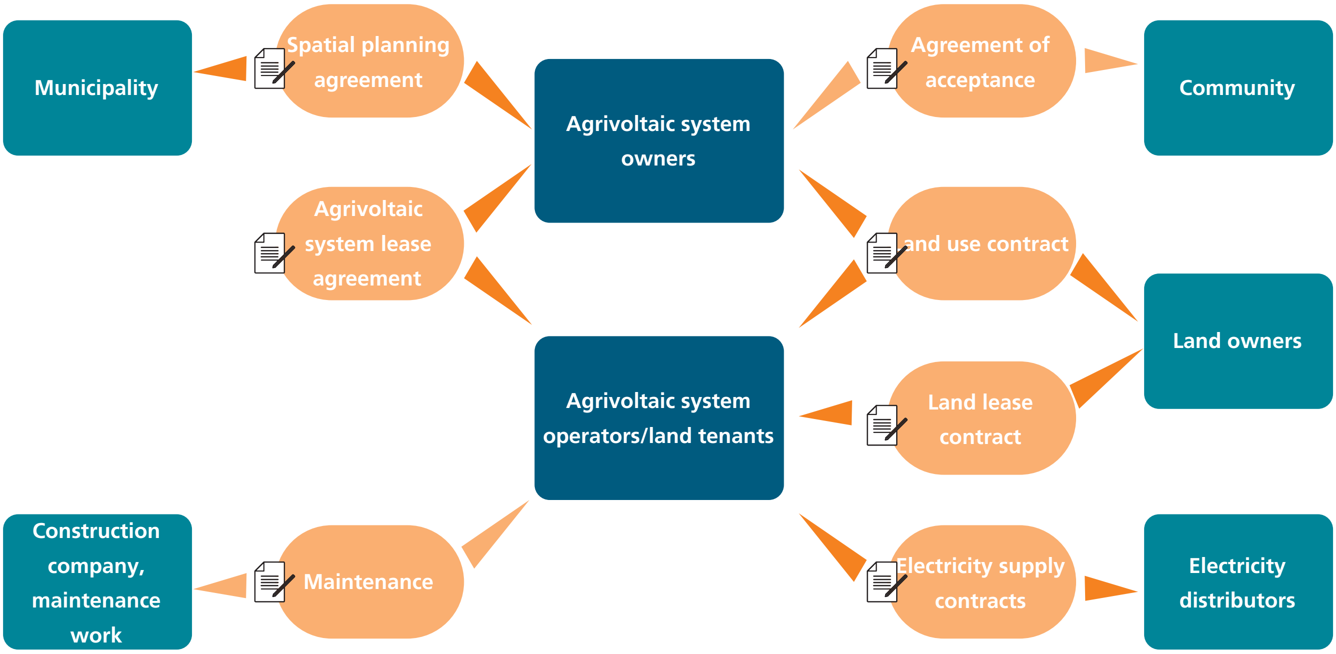


Fig. 36: Stakeholders and contract model.

Table 05: Configurations of different agrivoltaic business models (based on Schindele et al. 2019[5])

Business model	Function			
	Providing land	Agricultural management	Providing the PV system	Operating the PV system
1. Base case	Farm			
2. External land ownership	Land owners	Farm		
3. External PV investment	Farm		PV investors	Farm
4. Cultivation and operation only	Land owners	Farm	PV investors	Farm
5. Cultivation only	Land owners	Farm	PV investors	PV operators

5 Technology

The way that power generation works is the same for agrivoltaic systems as for ground-mounted PV systems. However, the requirements of agrivoltaic systems in terms of technical components and supports for the system are different because the land used is also being cultivated at the same time: The PV module technology, the height and alignment of the system, the substructure and the foundation all need to be adapted to farming using agricultural machines and the needs of the crops. Sophisticated light and water management is also important in order to ensure that yields are sufficiently high and consistent.

To enable dual use of the land for agricultural production and power generation, the solar PV modules are installed with elevated supports three to five (or, in the case of hop growing, more than seven) meters above the field, depending on the use case. This allows even large agricultural machines, such as combine harvesters, to work the land underneath the agrivoltaic system. To ensure that the crops get enough light and precipitation, the spacing between the PV module rows is often wider than in conventional ground-mounted PV systems. This typically reduces the degree of surface coverage to around one third. In combination with the high supports, this process ensures that there is enough available light. When using solar tracking PV modules, the light management can be adapted specifically to the development stage and the needs of the individual crops[27].

The substructure, and in some cases also the PV modules, are often different from those used in ground-mounted PV systems. There are different technologies and designs to choose from, adapted to site-specific requirements and farming conditions. In general, agrivoltaic systems should be state-of-the-art and comply with commonly accepted regulations and standards (see section 2.3 on DIN SPEC).

Fig. 37: Overhead system enabling cultivation with a potato harvester. © Hofgemeinschaft Heggelbach

Fig. 38: PV modules with spatially segmented solar cells and protective function in the Netherlands. © BayWa r.e.

Fig. 39: Bifacial, vertically installed PV modules by Next2Sun, Eppelborn-Dirmingen. © Next2Sun GmbH

5.1 Approaches to agrivoltaic system construction

Agrivoltaic systems, as already in use in countries such as France and Japan, are often mounted on elevated supports. The clearance height describes the unobstructed vertical space between the ground and the lowest structural element. Various possible system structures are described below.

Overhead systems offer significant potential for synergy effects (see section 3). Ensuring that cultivation under the PV modules remains possible poses particular structural and economic challenges, particularly for overhead systems in arable farming (see figure 37).

If, as well as generating power, PV modules also perform the function of protecting against hail, rain, night frost and other extreme weather events, the use of special PV modules is a natural choice. Figure 38 shows a research system by BayWa r.e. above a fruit orchard. This system in the Netherlands was built using PV modules with wider cell spacing, which increases the sunlight available to crops and can also enhance the roofing and protective function by means of transparent PV module parts.

There may also be synergy effects with PV modules installed close to ground level. Next2Sun accomplishes this by using bifacial PV modules that are installed vertically. While this type of system is more cost-effective due to the lower substructure, it also offers fewer light management options. One advantage of interspace systems could be a reduction in wind speed, which in turn has a positive effect on evaporation.

Another possible design is provided by TubeSolar AG in the form of tubular PV modules installed horizontally on supports. This innovative approach promises spatially uniform light and water permeability, which is particularly important in agricultural production with no artificial irrigation. Agratio GmbH combines these novel PV modules with a low-cost cable structure used as a support.

In Japan, narrow PV modules are installed above agricultural land in a concept called “solar sharing” to adjust the availability and distribution of light. There are many other possible technical solutions, each with its own advantages and disadvantages.

Fig. 40: PV modules above a polytunnel. © BayWa r.e.

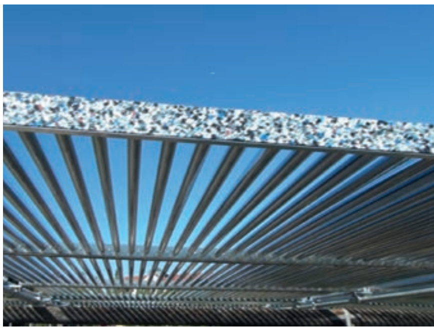


Fig. 41: Special thin-film tubular PV modules from TubeSolar. © TubeSolar AG

Fig. 42: Semi-shade from tubular PV modules installed between tension cables, by TubeSolar. © sbp sonne GmbH

Fig. 43: Overhead systems with narrow PV modules in Italy. © REM Tec

5.2 Module technologies

All types of PV modules can in principle be used for agrivoltaics. PV modules using wafer-based silicon solar cells account for around 95 percent of the global PV market. The usual design calls for a glass pane on the front and a white covering film on the back. Opaque solar cells are connected and laminated between these in series at a distance of 2–3 mm. A metal frame is used for mounting and stabilization.

Where there is a transparent back covering (glass, film), the spaces between the cells allow most of the light to pass through and, in the case of agrivoltaic systems, to reach the crops below. With the PV modules that are currently most common, the spaces between the cells make up four to five percent of the surface area. To increase light transmission, however, the spaces can be widened and the PV module frames replaced by clamp mountings. PV modules with a larger ratio of transparent to total area protect crops against environmental influences without limiting the available light to the same extent.

Bifacial PV modules can also use the light that hits the reverse side to generate electricity. Depending on the level of radiation on the reverse side, this can increase electricity yields by up to 25 percent. Because agrivoltaic systems tend to have a larger distance between rows and taller supports, the reverse sides of the PV modules tend to receive more light than conventional ground-mounted PV systems. Bifacial PV modules are therefore often well suited to agrivoltaics. Another advantage of PV modules with a double glass structure is the increased residual load-bearing capacity if the glass shatters, which benefits road safety as well as occupational health and safety.

Thin-film PV modules (CIS, CdTe, a-Si/µ-Si) can be installed on flexible structures, making cylindrical bending possible. While their structure is otherwise identical, their weight is approximately 500 grams per square meter of surface area less than that of PV modules with wafer-based silicon solar cells. Their efficiency is somewhat lower, however. The cost to surface area ratio of thin-film PV modules is somewhat lower than that of silicon solar cells.

The same applies to organic photovoltaics (OPV). In contrast to silicone-based crystalline PV modules, they are composed of organic carbon compounds. Selective spectral adjustment of the active layers of OPV systems is in principle also possible, which means that those layers can be incorporated into flexible base films. For example, part of the solar spectrum can be transmitted into PV polytunnels and used by the crops growing below. The current challenges of OPV films include low efficiency and durability.

In concentrator photovoltaics (CPV), lenses or mirrors focus the light onto small photoactive surfaces. CPV modules need to have solar tracking, with the exception of systems with low concentration. Diffuse light is largely transmitted. Spectrally selective approaches can also be carried out using CPV if the reflective layers reflect only part of the solar spectrum. There are currently only few commercial suppliers of CPV modules for use in agrivoltaics. One example is the Swiss company Insolight.

Fig. 44: Overhead system with continuous rows of PV modules. © Sun'Agri

5.3 Substructure and foundation

5.3.1 Substructure construction

As well as the clearance height and working width, the headland for the agricultural machines to be used also needs to be taken into account with agrivoltaic systems. The distance between the ground and the bottom of the structure (clearance height) is typically at least five meters in arable farming. The advantages of such clearance heights include not only making the land more easily trafficable, but also producing a more even distribution of light underneath the PV modules. On the other hand, the capital expenditure for the substructure is lower for interspace agrivoltaic systems with low clearance heights because they use less steel and have lower structural demands. As row spacing becomes significantly larger, the area of land required by an agrivoltaic system increases, as does its cost, relative to the electricity yield.

5.3.2 Single and dual-axis solar tracking

There are systems, for instance in France, that work with single- or dual-axis tracking. This means that the direction in which the PV modules are facing is adjusted by a mechanism to track the position of the sun. With single-axis tracking, the PV module field either follows the sun horizontally according to its angle of incidence (elevation) or vertically according to its orbit (azimuth). Dual-axis trackers do both, and therefore produce the highest solar power yield. However, dual-axis systems with large PV module tables can create an umbra under the PV modules, while other parts of the land receive no shade at all. Notwithstanding the higher acquisition and maintenance costs, however, tracking can optimize energy yields and light management for crop farming[27] (section 5.4). The flexible angle of inclination allows tracking systems to optimize their constructive protection against hail or extreme sun by adjusting their orientation as appropriate.

Fig. 45: Single-axis tracker system on a demonstration system in France. © Sun'Agri

5.3.3 Anchoring and foundation

The anchoring or foundation needs to ensure the statics and stability of the agrivoltaic system. Proof of fulfillment of these safety requirements must be provided when building a system (see section 5.7.2). Concrete foundations are not recommended in view of protecting valuable farmland. Alternative options include piled or screw foundations, which allow the system to be removed without leaving any traces.

Mobile agrivoltaic concepts make it possible to assemble the system, disassemble it again and install it in another location without using large machinery. One possible benefit is that, because this is not a structural alteration, a building permit may not be necessary. This means that mobile agrivoltaics can be flexibly adapted to farming, and even deployed spontaneously in crisis regions.

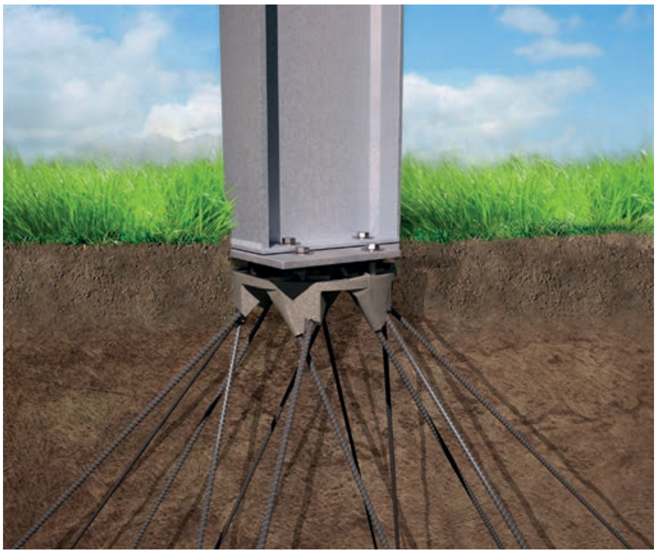


Fig. 46: Spinnanker anchor with anchor plate and threaded rods provides the foundation for the installation system. © Spinnanker GmbH

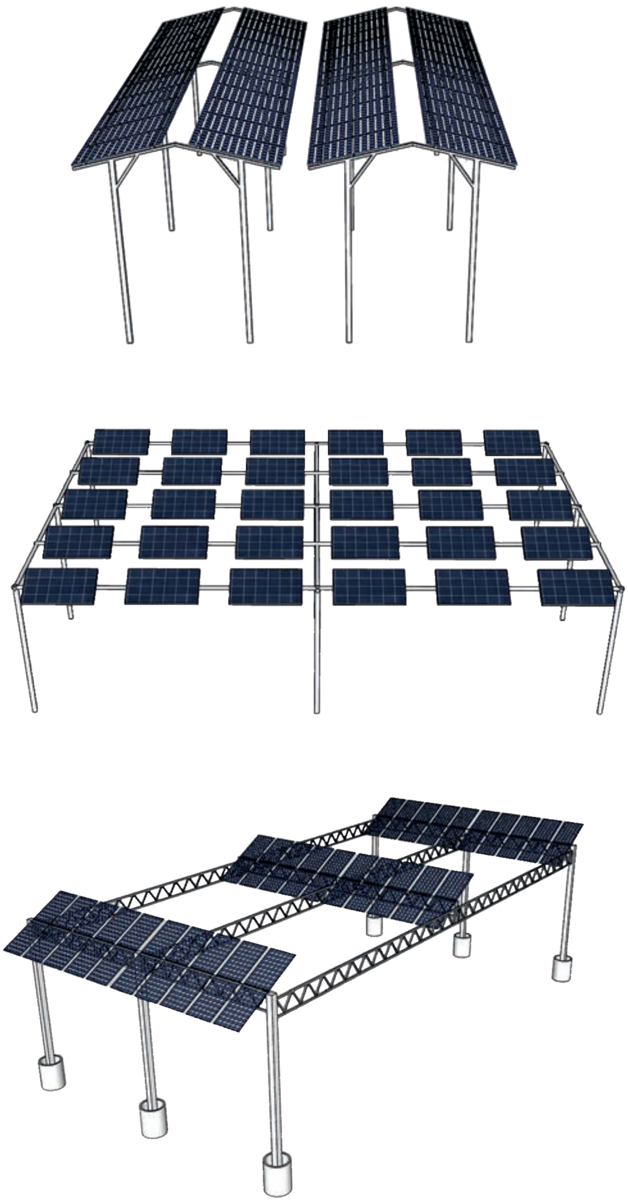


Fig. 47: Illustration of different system types oriented east-west, south and south-east. © Fraunhofer ISE

5.4 Light management

The sun's path over the course of the day and its changing position over the year mean that the shadow cast over the farmland changes constantly. In most cases, light should ideally be as homogeneous as possible for healthy crop growth, uniform ripening and maximizing potential synergy effects. This can be achieved in various ways:

1. Simulations and measurements show that a south-east or south-west orientation at an angle of 30 to 50 degrees to due south results in even shading. For the Heggelbach site, an angle of 45 degrees to due south was used. A power generation loss of around five percent was built into the calculation. The actual alignment may differ depending on local conditions.
2. Another option is to maintain the south-facing orientation and use narrower PV modules. This approach is frequently used in Japan, where it is referred to as "solar sharing."
3. Uniform light conditions can also be achieved by aligning the PV modules east-west. This alignment maximizes the movement of shadow over the course of the day. To avoid the creation of an umbra under the fixed and completely opaque PV modules, the width of the PV module rows should be considerably less than the height of the system. As a rule of thumb, the clearance height should be at least 1.5 times as great as the width of the PV module rows, or at least twice as great for tracking PV modules. For transparent PV modules, on the other hand, this factor is reduced in both cases depending on the degree of transparency.
4. Another option for achieving targeted light management and higher electricity yields is the use of single- or dual-axis tracking PV modules. As described in section 5.3.2, however, this type of PV module entails higher capital expenditure and maintenance costs. Dual-axis tracking systems that use large PV module tables tend to be less suitable for the cultivation of crops because an umbra usually forms underneath the PV modules, while other parts of the land are permanently exposed to full sunlight.

Fig. 48: The shaded strips underneath the PV modules move with the sun's position. © University of Hohenheim.

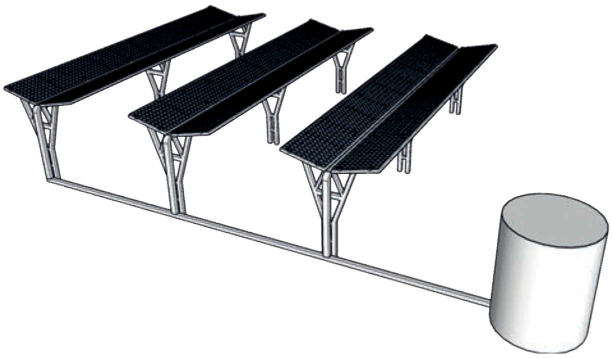


Fig. 49: Concept design for a rainwater harvesting system with storage tank. © Fraunhofer ISE

5.5 Water management

When it rains, rainwater running off the edges of the PV modules can cause soil erosion and wash away the soil. There are various approaches that can be taken to avoid negative consequences for crop growth and soil quality: For example, as with light management, narrow PV modules or PV tubes can prevent large quantities of water from collecting on the edges of the PV modules. However, if the PV modules are intended to provide constructive protection for the crops, it is preferable to prevent run-off by using tracking PV modules[28] or by channeling away the rainwater. If using the latter option, it is important in most cases to ensure that sufficient water is provided through irrigation. Collecting and storing rainwater can help to conserve groundwater resources, or even make it possible to farm in the first place, especially in arid regions.

Fig. 50: Agrivoltaic system in Heggelbach with a capacity of 194 kW$_p$ covering approximately a third of a hectare. © Fraunhofer ISE

Fig. 51: Eppelborn-Dirmingen solar farm with 2 MW$_p$ with vertical solar fences by Next2Sun. © Next2Sun GmbH

5.6 Size of the PV system

The size of agrivoltaic systems can vary considerably from country to country. While Japan has an increasing number of smaller systems ranging from 30 to 120 kW$_p$, in China there are already agrivoltaic systems with capacities of several hundred MW$_p$. The key criteria include not only cost-effectiveness, decentralization of energy generation and social aspects, but also the impact on the farming landscape, which in turn affects social acceptance. The path that Germany will take remains to be seen and may also differ from region to region. The regions of southern Germany, which mostly have smaller land parcels and sensitive landscapes, are better suited to smaller systems, typically installed above specialized crops. In northern and eastern German regions, on the other hand, larger systems may be more practical given the larger land parcels there, not least because the economies of scale could compensate financially for the lower annual solar radiation.

The amount of land required by overhead agrivoltaic systems is typically 20 to 40 percent more than that of ground-mounted PV systems. This means that overhead agrivoltaic systems have a capacity of 500 to 800 kW$_p$ per hectare, while a conventional ground-mounted PV system can achieve 700 to 1,100 kW$_p$ per hectare, depending on the type of system. Interspace agrivoltaic systems, on the other hand, manage just 250 to 400 kW$_p$ per hectare, meaning that they require around three times as much land as ground-mounted PV systems.

5.7 Approval, installation and operation

Overhead agrivoltaic systems, which are classified as structural facilities by definition, generally use glass/glass PV modules. In Europe, the PV modules are subject to electrical requirements through their certification under the "Low Voltage Directive 2014/35/EU" (IEC certification for approval as an electrical component), as well as requirements for construction products regarding the use of glass in the construction industry under the "Construction Products Regulation (EU) 305/2011."

Unlike conventional ground-mounted PV systems, agrivoltaic systems are expected to be navigated by machinery. To ensure that it is safe to work under the glass/glass PV modules, the planning, measurement and design of the PV modules is subject to particular requirements. These are set out in the Administrative Provisions of the Technical Building Regulations (Verwaltungsvorschriften der Technischen Baubestimmungen, VwV TB) of each of the federal states. In addition, the requirements regarding the usability of construction products set out in the building code of each state (Landesbauordnung, LBO) must be observed.

Glass used in the construction industry is subject to certain design and construction rules to ensure the necessary level of safety and protection. These rules make it mandatory to use glass with safe shattering behavior (see "DIN 18008 Glass in building — design and construction rules" series of standards). Overhead agrivoltaic systems use a structure that can be classified as overhead glazing, because it is normally necessary to carry out work underneath the PV modules. If so, the residual load-bearing capacity of the structure if the glass shatters must be ensured without any appreciable consequences in terms of damage or injury. This can be achieved by selecting appropriate products, such as laminated glass and suitable modular frame structures. Some manufacturers sell glass/glass solar PV modules that are IEC certified under the Low Voltage Directive for use within the regulatory scope of DIN 18008 through a general building approval (Allgemeine bauaufsichtliche Zulassung, AbZ) and general type approval (allgemeine Bauartgenehmigung, aBG).

If an agrivoltaic system deviates from European and German electrical regulations or building regulation law, a separate permit from the building authorities is required to build the PV module, or appropriate proof of usability is required to use it in this special construction context. Aside from this, proof of load-bearing capacity and serviceability is required for each agrivoltaic system, including PV module coverage. This is dependent on geometry, location, net weight and possible meteorological effects such as wind, snow or thermal loads. It is also necessary to ensure that the potentially extreme stress from external influences is always less than or equal to the stress resistance of the components. Furthermore, a guarantee is required that the loads from the agrivoltaic system, made up of its net weight and external influences, can be transferred safely by the substructure into the subsoil.

Additional information can be found in the brochure: "Allianz-BIPV_Techn-Baubestimmungen.pdf" available for download free of charge from https://allianz-bipv.org/.

It should be noted that the descriptions given here are generally applicable throughout Germany. Consultation with the competent legal board of construction for the federal state of the construction project is recommended for each agrivoltaic system. The requirements and regulations applicable to the specific project (project-specific type approval) must be checked or evaluated. Specific cases may be resolved on a case-by-case basis taking into account the local conditions and construction framework, even within the regulatory area or with a special verification concept and special measures, possibly with an application to deviate from regulations.

In the future, some exceptions may even be introduced for agrivoltaic systems at the state or federal level as part of the government's energy transition policy, which could then in turn be implemented in state law (construction law) by the individual federal states. It is worth keeping an eye on developments in this area.

Fig. 52: Work in an agrivoltaic system under the PV modules. © Fabian Karthaus.

5.7.1 Approvals process for agrivoltaic systems

Some specifics must be considered in the approval process for the construction of an agrivoltaic system. The required documentation should be prepared in close coordination with the technical side. Table 6 provides an overview of the necessary approvals, expert opinions and documents.

In the case of the research system in Heggelbach, the land underneath the agrivoltaic system was designated a special use area. The application for agricultural land subsidies was rejected even though farming was still being carried out. Further information on approval processes can be found in section 7.1.

Fraunhofer ISE, together with project partners, has drawn up a DIN specification to define quality standards that could serve as criteria for tenders, funding or simplified planning processes (see section 2.3). These include the definition of agrivoltaic indexes and corresponding test processes that can be used by certifying bodies such as the VDE (Association for Electrical, Electronic and Information Technologies) or TÜV.

Table 06: Overview of approval steps for agrivoltaics

Process steps	Institution	Comments
Building permit	Municipality	Zoning map and development plan
Required expert opinions	Certified experts	Environmental, soil and glare protection report. Wind load testing
Recording of the easements (optional)	Notary	Right of way and ownership structure, for example Applications submitted through notaries
Insurance	Insurance company	In the APV-RESOLA project, the pilot system in Heggelbach was insured under the same conditions as a conventional ground-level PV system.

5.7.2 Installing an agrivoltaic system following the Heggelbach example

Project planning and land use planning are generally handled by a firm from the solar industry. However, in principle, the farm can install the system, either on its own or in cooperation with the local machinery ring.

The technical partners are responsible for all planning and processes relating to the construction, installation and operation of the system. This includes:

- Finding partners to purchase the excess electricity and feed it into the grid
- Material procurement and logistics planning
- Construction site setup and soil protection
- System setup
- Concept for connection, lightning protection and monitoring
- Grid connection
- Technical maintenance and removal

In the case of the research system in Heggelbach, the building application was submitted just six months after the hearing in the Herdwangen-Schönach municipal council. The building permit was granted one month later. However, building approval was linked to a verification of the statics by an independent test engineering firm. A soil report was also prepared to document the actual retention force of the anchoring. The results of this report and the feedback from the test engineering firm were incorporated into the revision of the agrivoltaic substructure.

The various contracts for the installation of the research system were awarded to various firms in accordance with the procurement regulations, and the construction process was coordinated in close consultation with the farming community Hofgemeinschaft Heggelbach. The power electronics and wiring of the system were installed so that the research system could be quickly connected to the grid upon completion.

5.7.3 Agrivoltaics in operation

Because of the crop cultivation and the height of the supports, the PV modules are not fully accessible at all times. Maintenance and repair work should therefore be carried out when fields are fallow and the land is not being used for farming. Not all maintenance vehicles are suitable for working on agricultural land. Workers must be secured when working at clearance height.

Soil can be churned up while land is being cultivated, leading to soiling of the PV modules. This is especially true in high winds and when the soil is particularly dry. Tilling in these conditions should therefore be avoided as far as possible.

Fig. 53: Construction roads to avoid soil compaction. © BayWa r.e.

Fig. 54: Maintenance work on the agrivoltaic system in Heggelbach. © Fraunhofer ISE

6 Society

If the energy transition is to succeed, it must be anchored in society through social acceptance[29]. There are two aspects to this: the fundamental approval or rejection of political goals and concrete measures and the willingness, or lack thereof, of citizens to accept specific local infrastructural measures, such as the building of ground-mounted PV or agrivoltaic systems. The German federal government's target for increasing the share of electricity generated from renewable energy sources has the broad approval of the population across technologies. This is shown by scientific, representative opinion polls carried out in recent years[30]. The most encouraging response was to the building of additional solar power systems on the roofs of houses, which is supported by 92 percent of respondents[31]. The approval rate for the political target of expanding ground-mounted PV systems is 74 percent, which is significantly lower than in previous years when it was at 80 percent[30].

However, even where the specifications of planning law and local policy have been met, the expansion of renewable energy supply remains controversial and faltering when it comes to finding suitable sites for building new solar parks[32]. The building of ground-mounted PV systems may be rejected or resisted by the local society, who may criticize the location, form and size of the system and fear that their houses and recreational landscape will lose their value. Acceptance challenges at the local level arise when decisions are made at particular political or economic levels to build new systems in a certain form or in a certain way without adequately taking into account the interests of the population or the concerns of the community or giving local people the opportunity to voice their opinions or be involved. It is therefore no wonder when societal groups do not accept such decisions, even if they were made following the proper planning or local policy procedures.

There are indications that agrivoltaic systems are generally viewed in a more positive light than ground-mounted PV systems because of the dual use of agricultural land. However, even in the case of agrivoltaic systems, it is nonetheless crucially important already in the planning phase, to involve the various stakeholder groups and the local population with a connection to the planned system. Developing a shared understanding of the sustainability targets to be achieved in regional food production, species conservation, preservation of the arable and leisure landscape as well as the decentralized generation, storage and use of renewable energy is of particular importance in this context[29]. A transdisciplinary approach helps to take into account the different interests and expectations, but also the different preferences and concerns, to understand and reduce acceptance problems and to drive the energy transition forward on site with local stakeholder groups[33]. This makes it possible to increase regional willingness to invest and local value creation and to take into account the interests of the population even before the decision to build a system is taken.

The role of subjective risk-benefit evaluations by the various stakeholder groups is particularly significant: They lead to concerns about potential financial, health or aesthetic problems associated with local changes to the environment, and particularly to land use and the visual landscape[34]. It is therefore the job of investors and project planners to employ appropriate communication strategies to approach the stakeholder groups in the community at an early stage in order to keep them informed in a transparent manner and allow them to contribute and have their say.

6.1 Engaging citizens and stakeholder groups

Because an agrivoltaic system is a cross-sector enterprise between the agriculture and energy supply sectors, communication and dialogue with all those involved, both directly and indirectly, is absolutely key. When establishing infrastructure projects, it is important to avoid conflicts of interest by involving the (local) population and stakeholder groups at an early stage. Bringing citizens and stakeholder groups into the approval process requires a clear framework, and should be based on a shared understanding of the problems and lead to the joint development of an idea to solve those problems. The project's goals should be communicated clearly and openly to prevent misunderstandings about the role and process of involving stakeholder groups and citizens[32]. The communication process should allow those involved to gain a new perspective on individual structures in their actions, values and preferences: on the one hand the citizens and stakeholder groups that are in many cases interested in changing the responsibility and decision-making structures and in getting involved both politically and financially, and on the other hand the investors and project planners who are looking for tailored, easy-to-implement, effective and marketable solutions[32]. An important trust-building measure is the proactive, timely and comprehensive communication of information about the planned system, the approval process and the opportunities that exist to speak to investors and operators in order to get involved in shaping outcomes. The decisions as to how stakeholder groups and citizens are addressed and involved and what forms of participation are used need to be tailored to the specific context. This depends on the combination of players involved and their individual concerns. The following general rules apply: The earlier communication begins and dialog is proactively created, the sooner the conditions for success and questions of involvement can be discussed, examined and resolved.

6.2 Context-specific acceptance

The acceptance of agrivoltaic systems will be affected by context factors. These are not directly related to the technology, but are related to aspects that shape the context in which the process of creating acceptance takes place and that influence the perception of the issue from the outside by those who are being asked to accept it. These aspects include the use of technology, social, legal and environmental contexts and circumstances (physical, cultural, social, economic and agricultural) and sociopolitical and normative conditions (such as guidelines, participation culture and experience as well as credibility of the individuals involved).

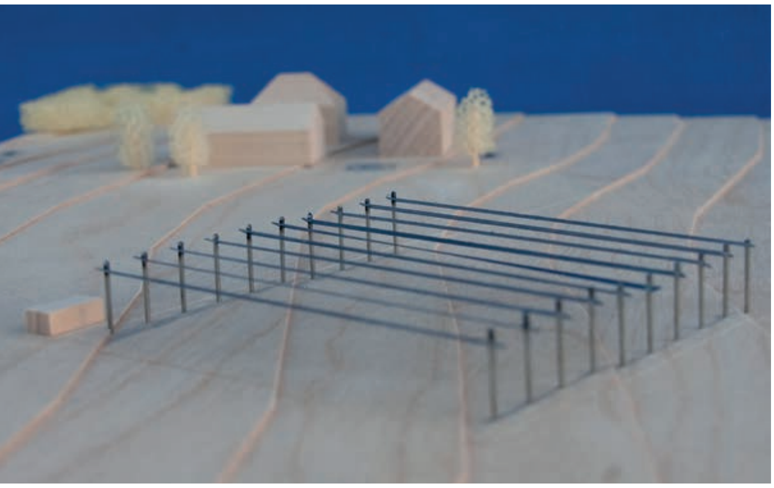
Because agrivoltaic systems used above specialized and permanent crops are usually smaller, they are expected to be more readily accepted by society than systems used in arable farming. The smaller size and generally lower clearance heights mean that the negative visual impact is usually less disturbing. Furthermore, the visual landscape is already impaired in these cases by polytunnels or hail protection nets. The potential additional benefit gained from using agrivoltaics above specialized and permanent crops is the most important driver of potential greater acceptance in the general population. The added agricultural value could come from various benefits of the agrivoltaic systems, such as the reduction of heat stress on crops through shading, the reduction of diseases and need for chemical pesticides, erosion protection, irrigation using renewable electricity, greater biodiversity or more stable yields, even in extreme weather conditions such as heatwaves or hail. The concrete manifestation and visualization of these benefits is likely to play a crucial role in increasing the likelihood of acceptance of agrivoltaic systems among stakeholder groups and the public.

6.3 Two examples for dialogue and engagement

6.3.1 APV-RESOLA research project

Fig. 55: Citizens' information workshop in the APV-RESOLA project. © ITAS

Fig. 56: Model of the agrivoltaic system in Heggelbach for information workshops. © Fraunhofer ISE



The APV-RESOLA project, run by the Institute for Technology Assessment and Systems Analysis (ITAS) at the Karlsruhe Institute of Technology (KIT), aimed to gather an early impression of opinions within society and normative value systems on agrivoltaics in order to identify potential obstacles, but also conditions for the successful establishment of agrivoltaics. These conditions served to answer questions within society about the future of sustainable, decentralized energy supply and to produce a design for an agrivoltaic system that would be accepted by society. Bringing the different citizens and stakeholder groups together at an early stage to exchange their ideas strengthened the mutual understanding of interests, values and preferences.

In concrete terms, the APV-RESOLA project was a multi-stage transdisciplinary process, conducted on the site of the pilot system in the Lake Constance region on arable land cultivated biodynamically in accordance with the Demeter guidelines, to involve citizens and stakeholder groups using different formats and at various times. Following an information workshop for all stakeholders, all citizens aged 18 to 80 in the immediate vicinity of the planned agrivoltaic pilot system were asked to indicate whether they wanted to take part in the process. An open brainstorming session with the stakeholders on the opportunities and challenges of agrivoltaics then took place before the system was built, using a model as a basis (see figure 56)[33]. The participants agreed that the effect of agrivoltaics on regional food production and the leisure and farming landscape needed to be taken into account, and that decisions about the locations of systems needed to be made at the municipal level so that particular local conditions and region-specific size and concentration criteria could be considered[34]. This first citizens' workshop was followed by a tour of the pilot system and a survey when the system was opened. One year after the system was put into operation, those who had participated in the first workshop were invited back. The aim of the second citizens' workshop was to analyze possible changes in opinions and approval patterns. Some participants confirmed their rejection of the system, which they found obtrusive. "I don't like it at all. I don't think an enormous structure belongs in the middle of the countryside. As a pilot system of this size, I don't have a problem with it. You can imagine that. But when I imagine it on a large scale somewhere, I just can't get my head around that." On the other hand, some other participants were positively surprised and their initial concerns had been put into perspective. "Well, standing underneath it, it doesn't seem so massive to me, more light and airy. It doesn't feel like an industrial system to me now." However, the time frame for assessing the system was seen as too short. "The consequences, either negative or positive, of agrivoltaics would take many years to materialise in a clear way."

In the second citizens' workshop, selection criteria for choosing a site for an agrivoltaic system were also developed. These include restrictions — factors that restrict or prevent use — as well as preferential aspects in favor of or enabling the use of a system. These criteria were applied by participants to identify suitable sites for agrivoltaics in the Herdwangen-Schönach municipality in the Lake Constance region, for example. This planning exercise allowed participants to work out the context-specific and complex interdependencies for themselves and to verify the practicality of the criteria that had been developed in a realistic setting (see figure 57). This resulted in recommendations for action on political management of land use for ground-mounted PV and agrivoltaics. "Regulations need to be adopted to stop land from being leased to energy suppliers at higher prices so that farming can actually continue to be practiced under these systems." Some aspects were identified as key success factors and implemented at the trial stage. One prominent example is the increased resource efficiency gained through local storage and use of the power generated (see more in section 6.4). "If I don't have a storage concept, then I don't need to bother setting up solar systems. That's the biggest problem. Storage. If we had storage, it would be fine right away."

The results and recommendations for action from the second citizens' workshop have been discussed in a workshop with stakeholder representatives. The participants included representatives from technological development companies, the energy sector and energy cooperatives, municipal, regional and state administrations, agriculture, conservation and tourism, as well as representatives of the general public. A criteria-oriented and open process to identify potential sites is seen as crucial for regional land use for solar farms or agrivoltaics. "The land and rural areas should not just be viewed as cheap energy suppliers for urban areas. It should be clear where it's necessary and where it isn't. Are sloping sites or biotopes an issue? We don't want to have the same uncontrolled growth as we do with biogas systems." It is important to have proactive, timely and open communication on planned projects and to involve citizens locally. "If the citizens are involved in the project, not just a little bit, but if it's a citizens' project, then the project has a greater chance of becoming reality." There is a lot of concern and "fear that enormous areas will be built over" and the familiar and beloved natural and leisure landscape in people's backyards will be changed for the worse. "I find it paradoxical that people say that wind bothers people and disrupts tourism and then they might authorize a ten-hectare stretch of agrivoltaics."

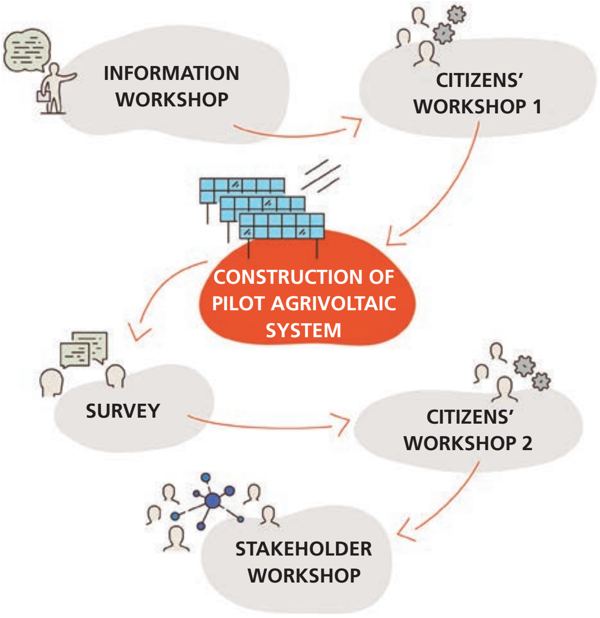


Fig. 57: Multi-stage transdisciplinary agrivoltaic research approach. © ITAS.

6.3.2 APV Obstbau research project

Another example of early involvement of stakeholder groups is the APV Obstbau (Agrivoltaic Orcharding) research project in the district of Ahrweiler in Rhineland-Palatinate. For a technological innovation like agrivoltaics to succeed, it requires the support not only of the population, but also of all stakeholders involved in the implementation of a system. The aim of the qualitative analysis was therefore to obtain a subjective picture of the sentiments surrounding the factors that helped or hindered support for agrivoltaics. To achieve this, a survey was conducted alongside the implementation of the agrivoltaic research system to interview representatives from administration, the energy sector, environmental and species conservation associations, the agriculture sector, farmers' associations, local politics and science. The content of the interview questions addressed knowledge of the APV Obstbau project, perceptions of agrivoltaics and estimations of the opportunities, challenges and future prospects of agrivoltaics.

As a result, there was a predominantly positive attitude across all stakeholder groups toward agrivoltaics for the orcharding region, its future and the research project. The responses to the interview showed that the acceptance of agrivoltaics (as is generally the case with renewable energies) is highly dependent on regional conditions[5]. In the region of the APV Obstbau research project, plastic films and hail protection nets in orcharding have been in use across large areas in orcharding for many years. The familiar view of a farming landscape with structures built over it favors the aesthetic perception of technical structures like agrivoltaics, particularly if they have additional synergy effects. These include, in particular, dual land use for food and energy production, financial profits for farmers and positive environmental effects. The crop protection factor of agrivoltaics is also important for farmers. The main factors hindering acceptance are uncertainties surrounding the economic viability of agrivoltaic systems, integrating them into modern agricultural work management and the current legal framework for constructing them. For species and environmental conservationists, any negative environmental impacts that may arise must also be viewed with criticism where possible. Based on the estimation of the local stakeholders involved, concrete communication concepts specific to the various stakeholder groups can then be developed for the circumstances in the Ahrweiler district. Although the results of such studies are tied to the region and the context, the resulting findings and communication concepts can serve as a template for future projects.

6.4 Success factors

The transdisciplinary research carried out in the APV-RESOLA project has the following key success factors for social acceptance of the use of agrivoltaics, confirmed from the viewpoint of the current status of the APV Obstbau project:

Expansion strategy

1. Using the existing potential of PV on rooftops, industrial buildings and parking lots should take priority over identifying sites for agrivoltaic systems.
2. The systems should be set up on sites where the dual use of the land will give rise to synergies, for example from using the resulting shade to reduce heat stress on crops or the supply of power for irrigation or digital land management with electrified and, in the future, autonomous systems.

Production of food and energy

3. Agricultural use of the land to produce food underneath agrivoltaic systems should be mandatory in order to prevent the unilateral optimization of power generation and "pseudo-farming" underneath the PV modules.
4. The systems should be integrated into a decentralized energy supply in order to use the solar power on site or for processes with higher value creation such as irrigation, cooling or processing agricultural products.
5. The systems should be combined with an energy storage system to increase resource efficiency so that the available electricity can be used to meet local demand.

Integration into the leisure and farming landscape

6. The size and concentration of the systems should be limited and, as with wind farms, minimum distances from residential areas should be defined in view of local site characteristics and societal preferences. In order to manage the number of systems in regions that are used for agriculture, regional land use policy should manage the approval of agrivoltaics, for example by limiting site coverage levels[1].
7. Agrivoltaic systems must not negatively alter the quality of local and regional recreation or the visual landscape. Sites that are naturally shielded from view (on the edges of forests, for example) or flat sites should be given preference in order to integrate the systems into the landscape in the best way possible.

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[1] Standard for the building site types in the Land Utilization Ordinance (Baunutzungsverordnung, BauNVO).

Fig. 58: Where agrivoltaic systems produce strips that cannot be farmed, these could be used to increase biodiversity on the agricultural land. © Fraunhofer ISE

Ecological contribution

8. Where the systems have strips of land that cannot be farmed, these should be used as erosion protection strips or corridor biotopes to maintain or increase biodiversity in agriculture.

7 Policy and legislation

According to the provisions of the German Federal Climate Change Act (Klimaschutzgesetz, KSG), greenhouse gas emissions need to be reduced to the point of net greenhouse gas neutrality by 2045. After 2050, greenhouse gas emissions should be negative. The coalition agreement between the Social Democratic Party (SPD), the Greens (Bündnis 90/Die Grünen) and the Free Democratic Party (FDP) states that 80 percent of gross energy needs will be met using renewable energies in 2030. The scenarios for achieving these goals assume that PV needs to be expanded to up to 500 GW_p[2]. This is approximately ten times the currently available PV capacity. A considerable share of PV expansion is expected to be ground-mounted, since this is where PV is currently most cost-effective.

However, the expansion of ground-mounted PV systems goes against the political goal of reducing the amount of land used, which stipulates that new land used for settlements and traffic needs to be reduced to 30 hectares per day by 2030 and to net zero by 2050. This is intended in part to conserve fertile soil for food production. At present, around 56 hectares of land per day is allocated for settlements and traffic in Germany. This is equivalent to around 79 soccer pitches. As well as PV systems on roofs, facades, sealed areas, lakes created in former mining areas and parking lots, agrivoltaics could also help to generate energy in a space-neutral and environmentally friendly way.

Unless a suitable legal framework is created, however, it will be difficult to establish agrivoltaics in Germany in an economically viable way for the foreseeable future. Agricultural subsidies, regulatory approval aspects and financial support under the Renewable Energies Act (EEG) are crucially important in the heavily regulated agricultural and energy sectors. This is particularly the case because agrivoltaics is a new technology that has had little time to accumulate learning effects and economies of scale, but that nonetheless has to compete with established technologies.

To study agrivoltaics further and increase its potential, it therefore appears prudent, in addition to further research projects, to implement operational sites close to the market. This will allow insights into the acceptance, economic viability and diverse areas of use of the technology to be gained hand in hand with agriculture and solar power companies. Germany has the opportunity to learn from the experience of France and other countries and to pave the way for further development of the technology with suitable funding instruments.

The innovation tender for April 2022 earmarked in the EEG for special solar power systems is highly unlikely to provide targeted funding for agrivoltaics. Instead, because of pricing competition among different applications, the obligation to combine systems and the lack of consideration for the interests of the agricultural sector, the tender risks delaying the market launch of agrivoltaics and the acceptance of the technology by the general population. One possible way to provide targeted and systematic funding for agrivoltaics could be to create a dedicated market premium and tendering segment for overhead systems and to implement a “1000-field agrivoltaic program” (see section 7.2.4).

7.1 Regulatory framework

Below is an overview of the key aspects of the legal framework. It is not possible to examine all the legal aspects and possible combinations of cases here. Ultimately, each case needs to be examined and evaluated individually.

7.1.1 EU direct payments

As part of its agricultural policy, the EU provides direct payments for land that is used primarily for agriculture. An important question, therefore, is whether a plot of agricultural land will lose its eligibility for financial support if it makes use of agrivoltaics. Of interest in this context is a verdict by the German Federal Administrative Court (Bundesverwaltungsgericht, BVerwG) on a so-called corn maze[2]. In the view of the German Federal Administrative Court, corn mazes do not affect eligibility for financial support because, in brief, they do not severely limit the agricultural use of the land. What does this verdict imply for agrivoltaics?

Agrivoltaic systems enable mixed use of the same land for both solar power generation and farming. The crucial question is whether the predominant purpose for which the land is used is clearly agricultural. Section 12 (3) no. 6 of the Direct Payment Implementation Ordinance (DirektZahlDurchfV) stipulates that areas of land on which there are systems for generating energy through solar radiation are primarily used for non-agricultural activity. However, following the verdict of the German Federal Administrative Court, this regulation must be seen through the lens of European law: The crucial criterion is that the intensity, nature, duration or timing of agrivoltaics must not limit agricultural activity too severely. This view was also adopted by the Higher Administrative Court of Bavaria in a case of sheep grazing underneath a ground-mounted PV system[3]. A severe limitation of agricultural activity would exist if there were any real, significant difficulties or obstacles to the performance of the agricultural activity for the farms concerned resulting from the performance of another simultaneous activity. This did not apply in the case in question, and the court therefore ruled that the financial support should be granted[4].

If an agrivoltaic system is properly planned and installed, it does not limit the agricultural use of a plot of land, or at most only limits it to a small extent (as a result of the anchoring for the PV mounting system, for example). There are therefore good arguments to support the case that farms cultivating a plot of land on which there is an agrivoltaic system installed are acting in line with EU law requirements for direct payments and should be eligible to receive such payments for cultivating the land. Enshrining this in concrete terms in the Direct Payment Implementation Ordinance could create planning certainty for farmers. Compliance with the requirements of DIN SPEC 91434 could be a suitable condition for receiving the direct payments. As long as regulatory uncertainties remain, consulting the competent authorities at an early stage is recommended. A draft bill by the German Federal Ministry for Food and Agriculture stipulates that, from 2023, farmers will be entitled to 85 percent of the direct payments provided that at least 85 percent of the usable agricultural land can be cultivated[5].

The related provisions in the DirektZahlDurchfV have since been amended, and the amendments were published in the Federal Law Gazette (Bundesgesetzblatt) on January 31, 2022: Section 12 (4) no. 6 of the Common Agricultural Policy Direct Payments Ordinance (GAPDZV) now stipulates that the exclusion does not apply to agrivoltaic systems. Section 12 (5) GAPDZV defines an agrivoltaic system as a system for the use of solar radiation energy that is constructed on agricultural land and does not prevent the land from being cultivated using conventional agricultural methods, machinery and equipment and does not reduce the usable agricultural land by more than 15 percent on the basis of DIN SPEC 91434:2021-05. According to the ordinance, this leaves 85 percent of the agricultural land eligible for funding. This regulation takes effect on the day on which the Common Agricultural Policy Direct Payments Act (GAP-Direktzahlungen-Gesetz) takes effect, according to section 28 (2) GAPDZV.

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[2] German Federal Administrative Court, verdict of July 4, 2019, file no. 3 C 11.17.

[3] See verdict of June 1, 2021, file no. BV 19.98; also ECJ, verdict of July 2, 2015, file no. C-684/13 (also known as the Demmer verdict); Munich Higher Administrative Court, verdict of April 19, 2016, file no. 21 B 15-2391; Regensburg Administrative Court, verdict of November 15, 2018, file no. RO 5 K 17.1331

[4] See verdict of June 1, 2021, file no. BV 19.98;

[5] https://www.bmel.de/SharedDocs/Downloads/DE/Glaeserne-Gesetze/Referentenentwuerfe/gapdzg.pdf?__blob=publicationFile&v=2

7.1.2 Public law

Agrivoltaics usually consists of structural installations for the purposes of building regulation law. A building permit[6] is usually needed to construct installations of this type. It is granted as long as the project does not conflict with public law regulations. Public law regulations include provisions of building regulation law (as set out in the building codes of the German state governments) and building design law (as set out in the Federal Building Code, BauGB).

Whether a project is permissible under building design law depends on the location of the plot of land: If the land is in an area covered by a development plan, the requirements of the development plan must be taken into account (see sections 30, 31, 33 BauGB). On land that is not covered by a development plan, whether the installation is permissible under building design law depends on whether the project is inside an urban area (see section 34 BauGB) or outside an urban area (see section 35 BauGB)[7].

The areas under consideration are typically located outside urban areas. In such cases, the Federal Building Code draws a distinction between special status projects and other projects: Special status projects are inadmissible under section 35 (1) BauGB only in exceptional cases where they conflict with public interests. Other projects, on the other hand, are generally inadmissible outside urban areas under section 35 (2) BauGB except in exceptional cases where they do not conflict with public interests. Some public interests are explicitly listed in section 35 (3) BauGB. These include depictions in zoning maps or requirements in spatial development plans.

A complete list of special status projects is provided in section 35 (1) BauGB. These special status projects include, for example, projects that:

- Serve an agricultural or forestry enterprise and make up only a minor proportion of the enterprise's land (no. 1),
- Serve a horticultural production enterprise (no. 2) or
- Serve to make use of solar radiation energy on roof and exterior wall surfaces of buildings that are used permissibly if the system is structurally subordinate to the building (no. 8).

Agrivoltaic systems are therefore not explicitly specified as special status projects. This can considerably increase the effort required to justify the classification of agrivoltaics as special status projects. This is clear from the use of the term "serve" (no. 1): According to the Federal Administrative Court, this requirement is only met "if a reasonable farmer would construct this project with approximately the same intended purpose and approximately the same design and configuration for an equivalent enterprise, even and especially when taking into account the requirement to conserve the non-urban area to the greatest extent possible, and if the project is shaped by this allocation to the specific enterprise in a way that is visible even externally[8]." What does this mean for agrivoltaic systems? The systems necessary for the supply of energy to the building and enterprise fundamentally meet this requirement. The crucial factor is whether the energy supplied to the enterprise is significant compared to the total capacity of the system: If it does not considerably exceed the amount of energy intended for the public grid, the system will fail to meet the definition of the term "serve."

The Federal Administrative Court considers the use of approximately two thirds of the electricity generated by a wind farm in an agricultural enterprise to be sufficient[9]. The aforementioned shaping of the enterprise by the project is likely to require the agrivoltaic system to be located relatively close to the focal points of the enterprise's processes.

In view of the climate crisis and the associated demands on farming, forestry or horticulture (including protection from hail, heavy rain and high solar radiation) it is likely to strengthen the fulfillment the definition of the term "serve" in section 35 (1) no. 1 or no. 2 BauGB if future systems are conceptualized as performing a protective function for the crops, soil and water management. As a result, the proportion of the electricity from the systems that is used in the enterprises themselves would be irrelevant. In other words, using less energy on site would not prevent the project from being classified as a special status project in this case[10].

The term "agriculture" used in section 35 (1) no. 1 BauGB is defined separately in section 201 BauGB, which also mentions

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[6] The Federal Immission Control Act (BImSchG) does not apply because agrivoltaic systems are not listed in the annexes to the fourth ordinance for the Implementation of the Federal Immission Control Act (4th Federal Immission Control Ordinance, 4. BImSchV).

[7] See also Vollprecht/Trommsdorff/Hermann, Legal Framework of Agrivoltaics in Germany, AIP Conference Proceedings 2361, 020002 (2021).

[8] German Federal Administrative Court, verdict of November 3, 1972, file no. 4 C 9.70.

[9] German Federal Administrative Court, decision of November 4, 2008, file no. 4 B 44.08.

[10] According to Vollprecht/Kather, Der Rechtsrahmen für Agri-PV: Aktuelle Herausforderungen und Lösungsansätze (The legal framework for agrivoltaics: current challenges and approaches to solutions), IR 2021, pp. 266 et seq. 12

horticultural production. Special status under section 35 (1) no. 2 is therefore also likely to apply to enterprises that grow crops in pots, containers and other receptacles, especially in greenhouses.

If the project is not permissible outside an urban area under section 35 BauGB, the preparation of a development plan — possibly with a partial amendment of the zoning map — should be considered. In that case, "only" the requirements of the development plan would need to be met. A problem in this respect, however, is what is known as the "standardization requirement," because the municipality is bound by the stipulations of section 9 BauGB and the Land Utilization Ordinance (Baunutzungsverordnung, BauNVO). A solution could be to establish "photovoltaics" as a special area under section 11 BauNVO. However, this raises the question of whether agricultural use can be stipulated at the same time. A possible solution could be to designate the area simultaneously as land for agriculture under section 9 no. 18 a) BauGB[11].

Another possibility is to pass what is known as a project-specific development plan. This would enable the leeway provided by planning law to be utilized, because the municipality would then be able to approve the project without having to consider section 9 BauGB[12] or the BauNVO. However, the stipulations of the BauGB and the BauNVO always have a guiding function. Orderly urban development must therefore be taken into consideration even within the scope of a project-specific development plan[13].

With agrivoltaics, the question of whether it constitutes an interference in the natural environment is often posed. Avoiding interferences is a priority, and unavoidable significant damage must be compensated[14]. However, land use according to the rules of good agricultural practice is privileged in the fact that it does not constitute an interference[15]. If an area is used to generate electricity, this currently constitutes an interference for the purposes of section 14 (1) of the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG). For example, the APV-RESOLA research project was considered an interference, and eco-points had to be utilized in accordance with the Eco-Account Ordinance (Ökokonto-Verordnung, ÖKVO). This ordinance defines requirements for Baden-Württemberg for the recognition and assessment of advance nature conservation and landscape care measures (eco-account measures) that are to be assigned to an interference project as compensation measures at a later date.

Because agrivoltaics, when appropriately designed, can be beneficial for the agricultural use of land, including in view of the climate crisis, projects should be examined on a case-by-case basis to determine whether the use of the land follows the rules of good agricultural practice and therefore does not constitute an intervention for the purposes of the BNatSchG. Continuing this line of thought also raises the question of whether an agrivoltaic system could even generate eco-points under the ÖKVO.

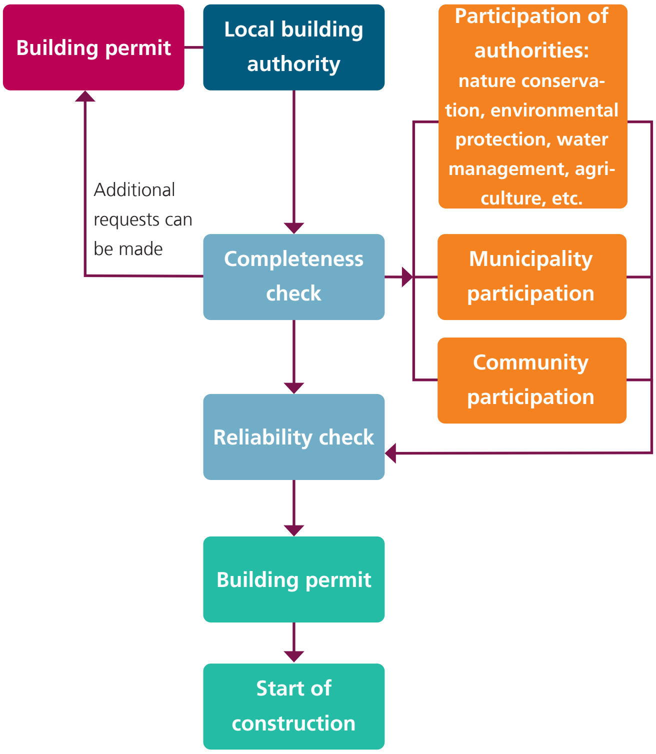

Fig. 59: Example process for a building application. © Fraunhofer ISE

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[11] According to Vollprecht/Kather, Der Rechtsrahmen für Agri-PV: Aktuelle Herausforderungen und Lösungsansätze (The legal framework for agrivoltaics: current challenges and approaches to solutions), IR 2021, pp. 266 et seq.

[12] Notably section 9 BauGB.

[13] German Federal Administrative Court, NVwZ 2003, 98.

[14] See section 13 (1) BNatSchG

[15] See section 13 (2) BNatSchG

7.1.3 German Renewable Energy Sources Act (EEG)

Agrivoltaic systems are systems for the generation of electricity from renewable energy according to section 3 (1) of the Renewable Energies Act (EEG). The operator of an agrivoltaic system is therefore entitled to priority connection to the grid from the grid operator under section 8 (1) EEG. This involves identifying the grid connection option with the lowest total financial cost. Only once this option has been identified does it become clear which party has to bear which costs. In principle, the grid operator bears the grid expansion costs and the system operator bears the grid connection costs[16].

In addition, the operator of an agrivoltaic system is entitled under section 11 (1) EEG to first refusal of the electricity generated. However, the system operator is not required to feed the electricity into the grid, but instead can use it directly[17] or supply it to a third party "upstream of" the grid[18].

Financial support for the electricity fed into the grid is more complicated. First of all, operators of systems with an installed capacity of more than 100 kW_p[19] are obliged to sell the electricity through a third party. The grid operator is only available as a purchaser of the electricity in exceptional cases[20]. In cases of subsidized direct sale, however, the system operator is entitled under section 20 EEG to a "market premium" from the grid operator, as well as receiving the agreed price from the direct seller for the electricity supplied. If the system's capacity is below the 100 kW_p threshold, the grid operator is obliged to purchase the electricity. The operator then receives the "feed-in payment" from the grid operator.

Operators of systems with an installed capacity of more than 750 kW_p must successfully take part in a tender for first-[21] or second-segment[22] solar systems under section 29 et seq. in conjunction with section 37 et seq. or 38c et seq. EEG. They cannot claim financial support from the grid operator under the EEG unless they have a surcharge or, in the case of first-segment systems, a "payment entitlement"[23]. Section 27a EEG is also relevant: In principle, electricity from systems subject to the tendering procedures cannot be used to supply power directly to the operator. For systems with a capacity of up to 750 kW_p, the values stipulated in section 48 EEG apply (degression must also always be taken into account in such cases).

For ground-mounted PV systems, the "20 MW limit" defined in section 38a (1) no. 5 EEG and elsewhere also needs to be taken into account: Any capacity the system may have in excess of this limit is not eligible for subsidy. For second-segment systems, each bid must not exceed 20 MW[24].

The financial support is paid for a period of 20 years starting on the date the system is put into operation. For systems whose financial support is determined by law, the payment is extended until December 31 of the twentieth year.

In addition to the general requirements for financial support under the EEG, solar energy is also subject to further special requirements. These are outlined but not described in full below:

As specified in section 48 EEG, a system is eligible for financial support if it is installed on or in a building (rooftop system) or other structural facility that was built primarily for purposes other than the generation of solar power. Essentially, this means that the solar power system should be installed on a surface that is being used "anyway" ("dual use"). This means that the PV system can also be installed as a roof[25]. In the case of PV systems on greenhouses, for example, it must be ensured that the use of the greenhouse focuses mainly on its actual

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16 See section 16 (1), section 17 EEG.

17 The EEG levy may be reduced in such cases.

18 Because the general supply grid is not used under this arrangement, grid charges are not incurred. The same applies to grid charges and levies (such as the cogeneration levy, the levy under section 19 (2) of the Grid Charges Ordinance (StromNEV), the offshore grid levy or the concession fee). This allows the system operator to offer the electricity to the customer at a more favorable price, for example.

19 When determining the size of the system in this case and also thereafter, the "system combination rules" under section 24 (1) and to some extent (2) EEG must usually be observed.

20 See section 21 (1) no. 2 EEG.

21 Ground-mounted systems and solar systems installed on or in structural facilities that are neither buildings nor noise barriers; see section 3 no. 4a EEG.

22 Solar power systems to be installed on or in a building or noise barrier; see section 3 no. 4b EEG.

23 See section 22 (3) EEG; when determining the "750 kW limit," the "system combination rules" contained in section 24 (1) and (2) EEG must also be observed.

24 See section 38c (2) EEG.

function. In situations such as the cultivation of crops that do not need to be grown in a greenhouse, this would not be the case. This means that a detailed examination of each individual case is necessary. For non-residential buildings in rural areas not covered by a development plan under section 35 BauGB, such as greenhouses, the restriction in section 48 (3) EEG must nonetheless be observed.

In the case of rooftop systems (although presumably not systems on other structural facilities), the following must also be observed: According to section 48 (5) EEG, systems with a capacity of between 300 and 750 kW_p are eligible for financial support for just 50 percent of the power generated. To prevent this, the system operator must take part in the tenders, in which case the ban on self-supply under section 27a EEG applies.

If these requirements are not met, the system may still be eligible for support, for example under section 48 (1) no. 3 EEG: An agreed development plan is always required in such cases. If that development plan was established or amended after September 1, 2003 for the purpose of constructing a solar power system, the agrivoltaic systems must be located in particular areas, for example along highways or railroad tracks within a 200 meter corridor measured from the outer edge of the fixed road or track — with a clear corridor 15 meters wide — or in a "conversion area."

This area can only be extended for systems that are required to take part in tenders. Financial support is also considered for these systems in areas whose plots of land were used as arable land or grassland at the time of the decision to establish or amend the development plan, cannot (to put it briefly) be allocated to any land category other than that mentioned in section 37 (1) EEG and are located in disadvantaged areas[26]. However, this only applies where the state government has passed a legal ordinance for tenders on land in such areas (known as a "state opening clause"). So far, this has only been done in Bavaria, Baden-Württemberg, Hesse, Lower Saxony, Saxony, Saarland and Rhineland-Palatinate.

With regard to acceptance, section 6 EEG, which was added to the EEG in the summer amendment, is of interest: This regulation stipulates that operators of ground-mounted solar power systems can grant affected municipalities allowances of up to 0.2 euro cents per kilowatt-hour fed in. This requires a written contract between the system operator and the affected municipality[27]. For systems receiving financial support, the allowances are reimbursed by the grid operator. For other systems ("PPA systems"), system operators must bear this cost themselves.

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25 Regarding the EEG, see 2004 Federal Court of Justice (BGH), verdict of November 17, 2010, file no. VIII ZR 277/09.

26 See section 37 (1) sentence 1 h.) and i.) EEG.

27 The Association of Energy Market Innovators (bne) has a sample contract for municipal participation, a supplementary sheet with useful clarifications of the content of the contract and additional information, all available free of charge from https://sonne-sammeln.de/mustervertrag/.

7.1.4 Including agrivoltaics as part of innovation tenders as provided for in the EEG

The amendment to the EEG that entered into force on January 1, 2021 introduced a separate innovation tender segment for "special solar power systems" with 50 MW_p of installed capacity. The German Federal Parliament (Bundestag) approved an increase to 150 megawatts in June 2021. Special solar power systems include not only PV systems above parking lots and floating solar power systems, but also solar power systems on arable or horticultural land — i.e. permanent and perennial crops — if the land is also being used for crop cultivation at the same time. The requirements for special solar power systemss were set out in more detail by the Federal Network Agency (BNetzA) in a regulation issued on October 1, 2021[28]. In brief, the agrivoltaic systems must fulfill the requirements of DIN SPEC 91434 in particular. This segment will initially only exist as part of the call for tenders on April 1, 2022. Bids must be submitted to the Federal Network Agency before that time.

However, only system combinations as defined in section 2 of the Innovation Tenders Ordinance (Innovationsausschreibungsverordnung, InnAusV) are eligible to participate. This means that agrivoltaic systems must be connected to a storage system or to another green electricity system and feed the electricity in via a shared grid connection point. A bid for a system combination including a special solar power systems must have a minimum capacity of 100 kW_p and must not exceed a two megawatts-peak.

Section 37 EEG is not applicable, meaning that the requirements for financial support set out in the EEG regarding areas to be utilized and development plans[29] do not need to be observed. Operators of agrivoltaic systems who win a tender will receive a fixed amount from the grid operator per kilowatt-hour of electricity fed in ("fixed market premium"). The maximum value of the bid permitted in the tender is expected to be around 7.43 euro cents per kilowatt-hour. Another source of income could be revenue generated from selling the electricity — this is likely to be around four to six euro cents per kilowatt-hour depending on the time of the sale. Furthermore, as with all systems subject to tendering procedures under the EEG, the electricity must not be used by the operator under section 27a EEG, but instead must either be supplied to a third party upstream of the grid, or be fed into the grid.

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[28] https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Ausschreibungen/Innovations/GezeichneteFestlegungOktober2021.pdf?__blob=publicationFile&v=3

[29] Important: This relates to the requirement for financial support under the EEG. The requirement for a development plan may well still apply under public law (see above).

7.2 Recommendations for policy-related action

7.2.1 Possibilities for improvements with the innovation tenders

While including agrivoltaics as part of the innovation tenders under the EEG basically marks a step in the right direction, the regulation for providing targeted funding for agrivoltaics does not seem to be suitable for various reasons. There is a need for improvement, especially in the following areas.

No obligation to have system combinations
Only system combinations can participate in EEG innovation tenders. However, the obligation to be coupled with a storage system or one or more renewable energy systems imposes a restriction in terms of content that can hardly be justified for the agrivoltaic systems to be funded. The grid efficiency target specified in the innovation tenders should therefore be considered independently of any possible financial support for agrivoltaics. After all, the innovative approach to the agrivoltaic sector lies in the coexistence of energy production and agricultural use on the land, meaning that the issue of whether the agrivoltaic system offers any particular market or grid convenience should be irrelevant in the context of the innovation tender process in April 2022.

Realistic chance of funding
The tendering process involving agrivoltaic systems is being planned together with floating PV systems and PV parking lot canopies. By establishing direct competition between the three types of system, it will be clear as to which technology will ultimately come out on top in the joint tender. The cost structures for the three area-neutral PV technologies may differ in such a way that contracts cannot be awarded to all three system types. Therefore, if the other system types offer a more affordable option, agrivoltaic systems will not be given a chance. In addition, interspace agrivoltaic systems allowing crops to be grown between the PV module rows (Category II, DIN SPEC 91434) have a less complex substructure, which gives them a clear competitive edge that is likely to have a strong influence on the composition of the projects awarded. As a result, overhead systems allowing crops to be grown between the PV module rows (Category I, DIN SPEC 91434) are not likely to be awarded funding. In fact, it is precisely these systems that are conducive to a more efficient use of land and offer crops protection against the consequences of climate change.

Facilitating own consumption of energy produced for farms
One requirement imposed by the EEG on systems participating in the tendering process is that they should generally not consume the electricity generated themselves, but deliver it to a third party before it is supplied to the electricity grid, or feed it all into the electricity grid. In the case of conventional ground-mounted PV systems, this applies from the power output that makes the tendering process compulsory, which is currently 750 kW_p. As the innovation tender process in April 2022 will also support funding for smaller agrivoltaic system combinations from 100 kW_p, the ban on self-supply will also apply to these agrivoltaic systems under 750 kW_p. Integrating agrivoltaics into agricultural has highlighted the fact that it is essentially ideal in terms of meeting farms' demand for electricity. The fact that this is excluded under current conditions reduces the economic viability of agrivoltaic systems. This is especially true for smaller systems where self-consumption tends to account for a larger share of the electricity produced and which could therefore benefit the most from savings on grid charges.

Realistic chance of funding for smaller systems too
When there is direct competition, larger systems typically have an advantage over smaller systems thanks to economies of scale. Due to the cost pressure involved in tenders, this means that larger agrivoltaic systems will tend to be awarded contracts in the 2022 innovation tender process. However, this contradicts the idea that a large range of different applications can be supported in the early years of funding, with a view to gathering knowledge about their potential synergy effects. This trend could also be detrimental to the public acceptance of agrivoltaic systems as smaller, local systems close to farmyards would presumably enjoy greater support among the public.

Planning certainty and long-term investment incentives through multiannual funding
The one-off implementation of an innovation tender process with the "special solar power system" segment in April 2022 will offer German solar power companies and farms variable prospects in terms of investing in the development of agrivoltaic systems and relevant product strategies or projects. On the other hand, consistent and transparent multiannual funding conditions could provide planning certainty and investment incentives, and set the course for sustainable generation of energy in the future.

7.2.2 Explicit special status for agrivoltaics

An explicit special status for agrivoltaic systems according to section 35 (1) BauGB appears reasonable in principle, since they are a natural part of the outdoors due to their agricultural use. Agrivoltaic systems crop rarely have any impact on public sentiment, as they are used for climate protection purposes, improve climate resilience, and reduce water consumption. However, the landscape is affected by these systems. Preference should therefore be given to sites not located in fragile landscapes, such as areas along the edge of a forest or sites where protective structures for agriculture are widespread.

Practical example, raspberry plantation
To protect raspberries against hail and strong solar radiation, a row of PV modules above the trellis forming fruit can achieve a twofold benefit. Usually, raspberry cultivation takes precedence over generation of solar power in terms of value creation.

7.2.3 Addition of agrivoltaics as a “special area” in the BauNVO

Due to the uncertainties described above regarding the regulatory options in terms of building planning, a new “settlement component” should be added to the BauNVO in the form of a “special agrivoltaic area”.

7.2.4 Possible funding criteria and scenarios

In the “Easter Package”, the German federal government tabled draft legislation early April 2022, which proposed extensive funding for agrivoltaic systems under the EEG. Some of the measures envisaged include an expansion of the area to cover arable and horticultural land, and a technology payment for overhead agrivoltaic systems. The exact wording of the EEG 2023 amendment will only be discussed in the next edition of this guide.

In addition to a general expansion of the area used, a statutory feed-in payment appears to have an important role in the EEG, especially for overhead agrivoltaic systems that are not subject to the tendering process. A separate tender segment would be effective for major agrivoltaic systems that are subject to the tendering process, especially for overhead agrivoltaic systems.

In order to simplify approval procedures, granting partial special status would allow those agrivoltaic systems to be classified as special status projects according to section 35 of the Federal Building Code, which enjoy a particularly high level of public acceptance. This could include systems in the horticultural sector and small systems with a power output of less than one MW_p.

Agrivoltaics combined with cultivation of paludiculture crops is a future-oriented application that makes it possible to leverage the vital climate protection potential. Therefore, when drafting the legal framework, it should also allow for systems on rewetted bogs.

Since agrivoltaics means dual use — for agriculture and energy — the circumstances are similar to those for the dual use of buildings and other physical structures[30]. This is an argument in favor of treating both scenarios equally in the legal drafting of the regulation. In view of the EEG, a development plan would then be just as dispensable as the existence of a specific land category. Agricultural use must be able to continue largely unrestricted. This is important for reasons of acceptance alone and avoids contradictory values within the EEG. The prerequisites for EU direct payments should be applied in order to ensure this. That increases legal certainty as well. The applicable jurisprudence[31] could then be transferred to the “new” provision in the EEG. How might that be implemented?

For one thing, a new point 2 could be added after point 1 in sentence 1 of section 48 (1) EEG. The regulation would then be worded as follows:

“For electricity from solar installations, where the applicable value is determined by law, this is [...] euro cents per kilowatt-hour if the system […]

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[30] Also see above regarding no. 1 in sentence 1, section 48 (1) EEG.

[31] Also see above regarding DirektZahlDurchfV.

has been constructed on farmland and the agricultural activity on this area is carried out without being severely limited by the intensity, type, duration, or timing of the operation of the system, […]"

With regard to proof of the prerequisites, the following sentence 2 could be added after sentence 1:

"Proof of the prerequisites of sentence 1, no. 2 can, in particular, take the form of submitting a notice for this area about the allocation of a single payment in terms of Regulation (EU) No 1307/2013 of the European Parliament and of the Council of December 17, 2013 establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009 (Official Journal L 347 of December 20, 2013, p. 608) in the respective current version."

Corresponding amendments would be required in section 37 (1) EEG among others.

Currently, the investment costs for agrivoltaic systems and other land-use-neutral PV generating systems are somewhat higher compared to conventional ground-mounted PV systems. A technology payment (euro cents per kWh) could be implemented in the EEG to provide the market boost required for these innovative systems. The legally established payment (see section 48 EEG) would be increased accordingly and would then be adequate. This payment would be reduced year by year and reach zero as soon as the new PV generating system technologies are competitive, thus making a market boost no longer necessary. With the current tenders (see sections 37 et seq. EEG), land-use-neutral solar generating system technologies hardly stand a chance at present due to the cost structure described above. The technology payment could compensate for these competitive disadvantages. The idea is that it would increase the award value accordingly, meaning that it would only be taken into account after the conclusion of the tendering process. Bidders could therefore take part in the tenders with a lower bid, making them more competitive using conventional ground-mounted PV systems.

In order to ensure that the benefits for agriculture are achieved, the regulations should also define in precise terms the requirements for an agrivoltaic system. The performance figures and test procedures of the DIN specification 91434 could serve as a starting point.

A 1000-field program is another possible funding scenario: Similar to the 1000-roof program for PV systems in the 1990s, a targeted and systematic funding program could be launched that gives due consideration to the specific challenges posed by and the funding requirements for both interspace and overhead agrivoltaic systems in the application areas of horticulture/ permanent crops, arable farming, and PV greenhouses. An accompanying scientific measurement and evaluation program could provide the necessary data establishing a basis for designing future legal frameworks.

8 Promoting agrivoltaics

Humanity is faced with challenges of previously unknown magnitude due to the climate crisis, water scarcity, and the steadily increasing demand for energy and foodstuffs. Whether and how humanity will overcome these global challenges will be decided in the coming years. To maintain quality of life in industrialized countries and improve it in the countries of the Global South, we need to find ways to achieve seemingly conflicting goals: maintaining prosperity, facilitating development and a livable future, and simultaneously reducing the consumption of natural resources and the emission of climate-damaging substances. Agrivoltaics can make a relevant contribution to all this.

This guideline describes the current state of agrivoltaic technology, its potential, and various areas of application. Aside from enabling more efficient land use, agrivoltaics can help reduce water consumption in agriculture, generate stable additional sources of income for farms, and make many farms more resilient against crop losses. Involving local citizens at an early stage is a key success factor in the specific implementation of agrivoltaics. With a levelized cost of electricity between six and ten euro cents per kWh, agrivoltaics is already competitive with other renewable energy sources. However, in Germany, agrivoltaics can only be implemented in an economically viable manner in rare cases due to the lack of a suitable legal and regulatory framework. Adapting the regulatory framework to the technical advancements in agrivoltaics could encompass, for example:

- A special status for agrivoltaic systems according to section 35 (1) BauGB to make approval procedures easier
- Remuneration for electricity generated from agrivoltaic systems according to the EEG, falling in between that for ground-mounted PV systems and roof systems, for instance in the form of special tenders for agrivoltaic systems
- Implementation of a 1000-field program to fund and further develop agrivoltaics

Horticultural applications appear especially well suited for launching agrivoltaics on the market. Reasons for this include the frequent close physical proximity of the growing area to the farmyard, the high synergy potential of the cultivated crops, the lower cost of supports, and the comparatively simple process of integrating them into the farming methods used for permanent crops. Benefits in terms of approval can also be expected in horticulture. In addition, it may be easier to achieve classification for agrivoltaics in horticulture as a special status building project as stipulated in section 35 (1), no. 2 BauGB.

A general increase in agricultural value creation could be another benefit in horticulture. This is because many horticultural applications are highly productive: Accounting for only about 1.3 percent of farmland, horticulture contributes more than 10 percent of the value created in agriculture[35]. Creating incentives for agricultural operations to become more active in this sector by funding agrivoltaics in horticulture could therefore serve as leverage for the entire agricultural production sector in Germany, even with a small proportion of land being used for agrivoltaics. This applies in particular to fruit and berry production.

In discussions about agrivoltaics, the argument is often made that the potential of roof surfaces in Germany should be better utilized first. There is no doubt that roof systems will continue to be instrumental in PV expansion going forward, and not only because of their local proximity and land use neutrality. Nevertheless, there are good reasons for also deploying agrivoltaics as a supplement to the existing renewable power generation technologies. For one thing, agrivoltaics — especially in the case of larger systems — can be implemented more cost effectively on average than roof systems due to economies of scale, which helps keep renewable power affordable. In addition, the PV modules can, in the best case scenario, offer added benefits for crop growth while roof systems are ”just” land-use-neutral.

Admittedly, a decrease in crop yields has been observed for the bulk of the systems studied to date. However, the harvest results for the research project in Heggelbach in 2018 indicated that agrivoltaics, even at this early stage of the technological journey, could provide a possible answer to the various challenges faced by farmers. One of them is the increasing periods of drought in Germany. The fact that the average temperature, extreme weather events and, in the case of Central Europe, solar radiation will increase due to the climate crisis suggests that a possible protective function provided by PV modules for crops will grow in importance going forward.

Future fields of research involving agrivoltaics could include combinations with energy storage systems, organic PV films, and solar water treatment and distribution. The use of electrical agricultural machines and smart, automated field cultivation are also, to some extent, promising fields of research. One future vision is “swarm farming”, using smaller, automated, solar electrified agricultural machines, which are operating under the agrivoltaic system and generating the required energy directly in the field. This could result in a significant reduction in clearance height requirements. The substructure and power generation of an agrivoltaic system offer conditions that are conducive to the integration of such smart farming elements. Automated field cultivation is currently being integrated into the substructure of an agrivoltaic system at Fraunhofer ISE for testing on a 1.2 x 3 meter area of land.

Over the long term, PV will become the cornerstone of energy supply, alongside wind power. The climate crisis and increasing water scarcity require new approaches in agriculture, partly to make farms more economically and ecologically resilient. To mitigate land use competition, agrivoltaic technology offers a way to expand PV capacity while conserving fertile soil as a resource for food production. This dual use of the areas considerably increases land use efficiency. Soils exposed to increasing and more frequent severe weather events such as heat, heavy rain, or drought can be protected at the same time. Agrivoltaics can also provide more climate-friendly energy to cover the energy consumption of farms.

The first agrivoltaic systems in Germany have shown that the technology works. However, to fully realize the potential offered by this technology, the measures adopted in Germany thus far are nowhere near sufficient. This is because conventional tenders are unable to handle the wide range of different application areas and synergy effects that are partially still unknown if contracts are awarded only to systems with the lowest current levelized cost of electricity.

The specific challenges and funding requirements for agrivoltaic systems can only be identified as part of a cross-sectoral exchange. Therefore, an important, central step is to establish a working dialog between the agricultural and energy sectors. Only then can a framework be created that gives due consideration to the needs of the agricultural sector, on the one hand, and to the technical and economic opportunities of the PV sector, on the other. Only then can agrivoltaics be successfully promoted with targeted and systematic funding. Only then can the opportunities offered by agrivoltaics for agriculture and the energy transition be fully seized.

9 Bibliography and sources

9.1 Sources

[1] D. Ketzer: Land Use Conflicts between Agriculture and Energy Production. Systems Approaches to Allocate Potentials for Bioenergy and Agrophotovoltaics. Dissertation,. 2020

[2] P. Sterchele, J. Brandes, J. Heilig, D. Wrede, C. Kost, T. Schlegl, A. Bett, and H.-M. Henning: Wege zu einem klimaneutralen Energiesystem. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen, Freiburg 2020. https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/wege-zu-einem-klimaneutralen-energiesystem.html, accessed on: June 8, 2020

[3] A. Goetzberger and A. Zastrow: Kartoffeln unter dem Kollektor. Sonnenenergie 3/81 (1981), p. 19 – 22

[4] Institute for Technology Assessment and Systems Analysis: APV-RESOLA — Agrivoltaics innovation group: contribution to resource-efficient land use. Project description, year not specified https://www.itas.kit.edu/projekte_roes15_apvres.php

[5] S. Schindele, M. Trommsdorff, A. Schlaak, T. Obergfell, G. Bopp, C. Reise, C. Braun, A. Weselek, A. Bauerle, P. Högy, A. Goetzberger, and E. Weber: Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications. Applied Energy 265 (2020), p. 114737

[6] Stellungnahme zur BMWK-Konsultation »Eckpunkte für ein Ausschreibungsdesign für Photovoltaik-Freiflächenanlagen. «. Agrophotovoltaik (APV) als ressourceneffiziente Landnutzung, D. H.-J. Luhmann, P. D. M. Fischedick, and S. Schindele, 2014

[7] Y. Elamri, B. Cheviron, J.-M. Lopez, C. Dejean, and G. Belaud: Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. Agricultural Water Management 208 (2018), p. 440 – 453

[8] T. Kelm, J. Metzger, H. Jachmann, D. Günnewig, P. Michael, S. Schicketanz, K. Pascal, T. Miron, and N. Venus: Vorbereitung und Begleitung bei der Erstellung eines Erfahrungsberichts gemäß § 97 Erneuerbare-Energien-Gesetz. Teilvorhaben II c: Solare Strahlungsenergie. Final report, 2019. https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/bmwi_de/zsv-boschundpartner-vorbereitung-begleitung-eeg.pdf?__blob=publicationFile&v=7

[9] Bundesverband Solarwirtschaft e.V.: Entwicklung des deutschen PV-Marktes. Auswertung und grafische Darstellung der Meldedaten der Bundesnetzagentur. As of: Mid-February 2020, 2020

[10] DWD — German Meteorological Service: Zeitreihen und Trends. https://www.dwd.de/DE/leistungen/zeitreihen/zeitreihen.html?nn=344886#buehneTop, accessed on: December 21, 2021

[11] M. Ionita, V. Nagavciuc, R. Kumar, and O. Rakovec: On the curious case of the recent decade, mid-spring precipitation deficit in central Europe. npj Climate and Atmospheric Science 3 (2020) 1

[12] A. Weselek, A. Ehmann, S. Zikeli, I. Lewandowski, S. Schindele, and P. Högy: Agrophotovoltaic systems: applications, challenges, and opportunities. A review. Agronomy for Sustainable Development 39 (2019) 4, p. 35

[13] Fachagentur Nachwachsende Rohstoffe e. V.: Anbau und Verwendung nachwachsender Rohstoffe in Deutschland. As of: March 2019, 2019

[14] Fraunhofer Center for International Management and Knowledge Economy IMW: Nachhaltige Kombination von bifacialen Solarmodulen, Windenergie und Biomasse bei gleichzeitiger landwirtschaftlicher Flächennutzung und Steigerung der Artenvielfalt, year not specified https://www.imw.fraunhofer.de/de/forschung/projekteinheit-center-for-economics-of-materials/forschungsprojekte/BiWiBi.html

[15] Next2Sun GmbH: References. https://www.next2sun.de/referenzen/

[16] Feasibility and Economic Viability of Horticulture Photovoltaics in Paras, Maharashtra, India, M. Trommsdorff, S. Schindele, M. Vorast, N. Durga, S. M. Patwardhan, K. Baltins, A. Söthe-Garnier, and G. Grifi, 2019

[17] K. Schneider: Agrophotovoltaik: hohe Ernteerträge im Hitzesommer. Freiburg 2019

[18] K. Schneider: Agrophotovoltaik goes global: von Chile bis Vietnam. Freiburg 2018

[19] G. P. Brasseur, D. Jacob, and S. Schuck-Zöller: Klimawandel in Deutschland. Berlin, Heidelberg: Springer Berlin Heidelberg 2017

[20] J. Ballester, X. Rodó, and F. Giorgi: Future changes in Central Europe heat waves expected to mostly follow summer mean warming. Climate Dynamics 35 (2010) 7 – 8, p. 1191 – 1205

[21] G. A. Barron-Gafford, M. A. Pavao-Zuckerman, R. L. Minor, L. F. Sutter, I. Barnett-Moreno, D. T. Blackett, M. Thompson, K. Dimond, A. K. Gerlak, G. P. Nabhan, and J. E. Macknick: Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nature Sustainability 2 (2019) 9, p. 848 – 855

[22] H. Marrou, J. Wery, L. Dufour, and C. Dupraz: Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. European Journal of Agronomy 44 (2013), p. 54 – 66

[23] S. K. Abeysinghe, D. H. Greer, and S. Y. Rogiers: The effect of light intensity and temperature on berry growth and sugar accumulation in Vitis vinifera "Shiraz" under vineyard conditions. VITIS - Journal of Grapevine Research 58/1 (2019), p. 7 – 16

[24] M. Büchele: Lucas' Anleitung zum Obstbau. Libreka GmbH; Verlag Eugen Ulmer 2018

[25] The Power to Change: Solar and Wind Cost Reduction Potential to 2025, International Renewable Energy Agency, 2016

[26] Solaranlage Ratgeber: Anschaffungskosten für Photovoltaik-Anlagen, year not specified https://www.solaranlage-ratgeber.de/photovoltaik/photovoltaik-wirtschaftlichkeit/photovoltaik-anschaffungskosten, accessed on: August 7, 2020

[27] E.ON Energie Deutschland GmbH: Solaranlage Kosten: Was kostet Photovoltaik 2020?, year not specified https://www.eon.de/de/pk/solar/photovoltaik-kosten.html, accessed on: August 7, 2020

[28] K. Grave, M. Hazart, S. Boeve, F. von Blücher, C. Bourgault, N. Bader, B. Breitschopf, N. Friedrichsen, M. Arens, A. Aydemir, M. Pudlik, V. Duscha, and J. Ordonez: Stromkosten der energieintensiven Industrie. Ein internationaler Vergleich. Zusammenfassung der Ergebnisse, 2015

[29] A. Tietz: Der landwirtschaftliche Bodenmarkt — Entwicklung, Ursachen, Problemfelder. Wertermittlungsforum 36(2) (2018), p. 54 – 58

[30] B. Valle, T. Simonneau, F. Sourd, P. Pechier, P. Hamard, T. Frisson, M. Ryckewaert, and A. Christophe: Increasing the total productivity of a land by combining mobile photovoltaic panels and food crops. Applied Energy 206 (2017), p. 1495 – 1507

[31] Y. Elamri, B. Cheviron, A. Mange, C. Dejean, F. Liron, and G. Belaud: Rain concentration and sheltering effect of solar panels on cultivated plots. Hydrology and Earth System Sciences 22 (2018) 2, p. 1285 – 1298

[32] C. Rösch: Agrophotovoltaik — die Energiewende in der Landwirtschaft. GAIA - Ecological Perspectives for Science and Society 25 (2016) 4, p. 242 – 246

[33] Soziales Nachhaltigkeitsbarometer der Energiewende 2019. Kernaussagen und Zusammenfassung der wesentlichen Ergebnisse, I. Wolf, Potsdam 2020

[34] Soziales Nachhaltigkeitsbarometer der Energie- und Verkehrswende 2021. Kernaussagen und Zusammenfassung der wesentlichen Ergebnisse, I. Wolf, A.-K. F. Fischer, and J.-H. Huttarsch, Potsdam 2021

[35] C. Rösch, S. Gölz, J. Hildebrand, S. Venghaus, and K. Witte: Transdisziplinäre Ansätze zur Erforschung gesellschaftlicher Akzeptanz. Energy Research for Future — Forschung für die Herausforderungen der Energiewende (2019)

[36] D. Ketzer, N. Weinberger, C. Rösch, and S. B. Seitz: Land use conflicts between biomass and power production — Citizens' participation in the technology development of agrophotovoltaics. Journal of Responsible Innovation (2020) 7 (2), p. 193–216

[37] D. Ketzer, P. Schlyter, N. Weinberger, and C. Rösch: Driving and restraining forces for the implementation of the Agrophotovoltaics system technology A system dynamics analysis. Journal of environmental management 270 (2020), p. 110864

[38] BMEL German Federal Ministry for Food and Agriculture: Der Gartenbau in Deutschland Auswertung des Gartenbaumoduls der Agrarstukturerhebung 2016. https://www.bmel.de/SharedDocs/Downloads/DE/Broschueren/Gartenbauerhebung.pdf?__blob=publicationFile&v=7

9.2 List of figures

9.3 List of tables

9.4 Acronyms

Agri-PV	Agrivoltaics
APV-RESOLA	Agrophotovoltaik-Ressourceneffiziente — Landnutzung, Resource-efficient land use with agrivoltaics
BMBF	German Federal Ministry of Education and Research
W	Watt
kW	Kilowatt
kWh	Kilowatt-hour
Wh	Watt-hour
GW	Gigawatt
GWh	Gigawatt-hour
TWh	Terawatt-hour
MW	Megawatt
MWh	Megawatt-hour
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
LCOE	Levelized Cost of Electricity
STC	Standard Test Conditions
EEG	Erneuerbare-Energien-Gesetz, Renewable Energy Sources Act
EE	Renewable energy resources
REAP	Rural Energy Advancement Programs
PV-FFA	Ground-mounted photovoltaic systems
PPA	Power Purchase Agreements
CIS	Copper Indium Selenide
CdTE	Cadmium Telluride
a-Si	Amorphous Silicon
µ-Si	Microcrystalline Silicon
OPV	Organic Photovoltaics
CPV	Concentrating Photovoltaics

9.5 Links to further information

Agrivoltaics website of Fraunhofer ISE:
https://www.agri-pv.org

Short film about the agrivoltaic research site in Heggelbach:
https://www.youtube.com/watch?v=BlXPf-e1a0U

Guidelines for ground-mounted solar power systems from the Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg:
https://um.baden-wuerttemberg.de/de/service/publikation/did/handlungsleitfaden-freiflaechensolaranlagen/

R&D for agrivoltaics at Fraunhofer ISE:
https://www.ise.fraunhofer.de/de/geschaeftsfelder/photovoltaik/photovoltaische-module-und-kraftwerke/integrierte-pv/agrar-photovoltaik.html

APV Obstbau project website:
https://www.ise.fraunhofer.de/de/forschungsprojekte/apv-obstbau.html

Agrivoltaics sector directory of the LandSchafftEnergie consultancy network:
https://www.landschafftenergie.bayern/beratung/branchenverzeichnis/

DIN SPEC 91434:2021-05, »Agri-Photovoltaik-Anlagen - Anforderungen an die landwirtschaftliche Hauptnutzung« [“Agri-photovoltaic systems - Requirements for primary agricultural use”]:
https://www.beuth.de/de/technische-regel/din-spec-91434/337886742

Status report on agrivoltaics from the Technology and Support Centre, Straubing:
https://www.tfz.bayern.de/service/presse/268709/index.php

Funded by

Federal Ministry
of Education
and Research

Federal Ministry
of Food
and Agriculture

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