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Agrivoltaics: Opportunities for Agriculture and the Energy Transition

A Guideline for Germany | February 2024

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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.

PDF version of the agrivoltaics guideline

Third edition, February 2024

Foreword (2022)

Dear readers,

Crops need sun, and so do photovoltaic systems. We are all aware that renewable energies need to be expanded at a much faster rate if we are going to meet our climate targets. We need six to eight times more solar energy than we currently produce, both on roofs and open land. In the past, this usually meant having to choose between agriculture or renewable energies, but now we have an innovative solution to this dilemma: agrivoltaics. With this promising technology, solar cells positioned over a field can generate electricity while grain, fruit and vegetable crops grow underneath. This enables the dual use of land. Sharp technical expertise enables us to expand photovoltaics without depriving farmers of valuable land. And what's more, this special photovoltaic system offers them a new income stream, and it boosts resilience.

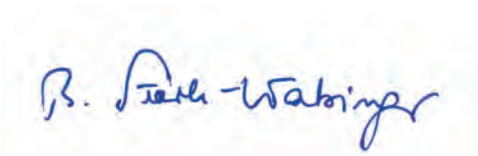
Farmers have been dealing with the effects of climate change for many years now. The uptick in extreme weather has a huge impact on agriculture more than virtually any other industry, with conditions being too dry and hot at times, while at other times unexpected hailstorms can threaten crops. This is where photovoltaic systems can help. They can slow hailstones and provide shade, saving crops from dehydration caused by overexposure to the sun. These are the benefits that one research project has documented.

This updated guideline will give you the latest insights into this technology from research and real-life operations. It outlines the opportunities for agrivoltaics and reviews current developments in this area. In doing so, we are making key progress toward standardizing these systems and thus ensuring quality.

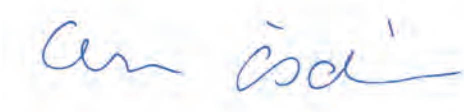
As members of the German federal government, we will be helping expand agrivoltaics with better support schemes. In April there will be an innovation tender which will establish Germany's first feed-in tariff specifically for agrivoltaic systems in accordance with the German Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG). This includes the updated implementing regulation for CAP direct payments. As a result, we are helping farms that install agrivoltaic systems to continue receiving 85 percent of the premiums 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 started in 2022.

Other countries have also identified the opportunities in agrivoltaics. Dual-use areas for agriculture and solar power generation are now an integral part of the landscapes in some Asian countries, while France is championing this technology in Europe. We are focusing on the potential of innovations like agrivoltaics in Germany, too. After all, the principle behind it is so simple and so compelling. Arable land stays arable land, and the photovoltaic system stands over it, ensuring our basic needs are covered for the future. As a result, the German federal government is creating a win-win-win situation: for climate, the environment and our farming industry. Prepare to be inspired!



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



Cem Özdemir
Member of the German Federal Parliament (Bundestag)
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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 to farming. Water scarcity, extreme weather and overall rising temperatures necessitate new measures to protect crops and soils from adverse conditions. Many farms are 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 competition in the future for space through 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

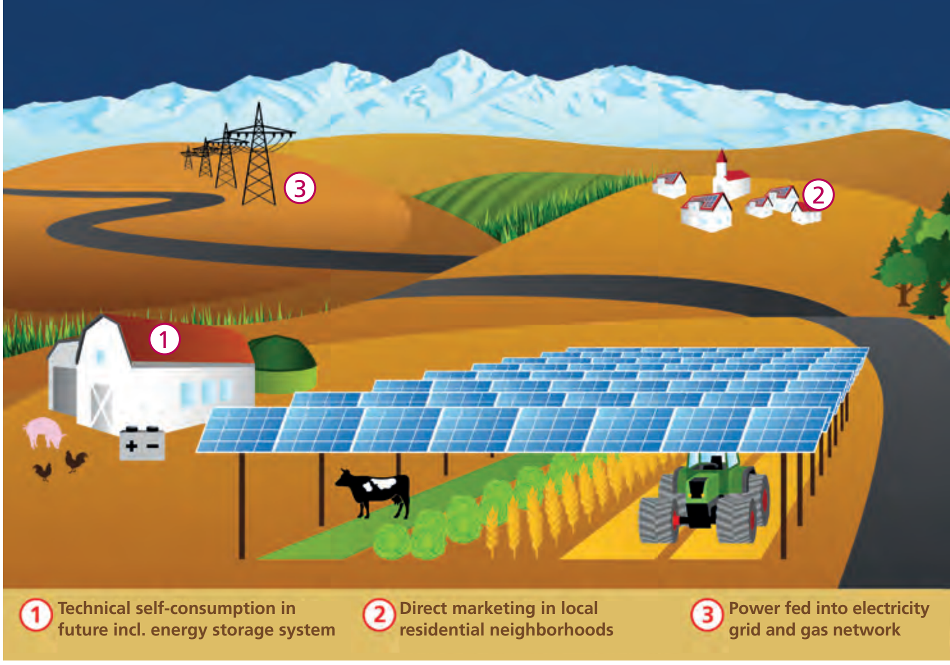


Fig. 2: Illustration of an agrivoltaic system © Fraunhofer ISE

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 third 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.

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].

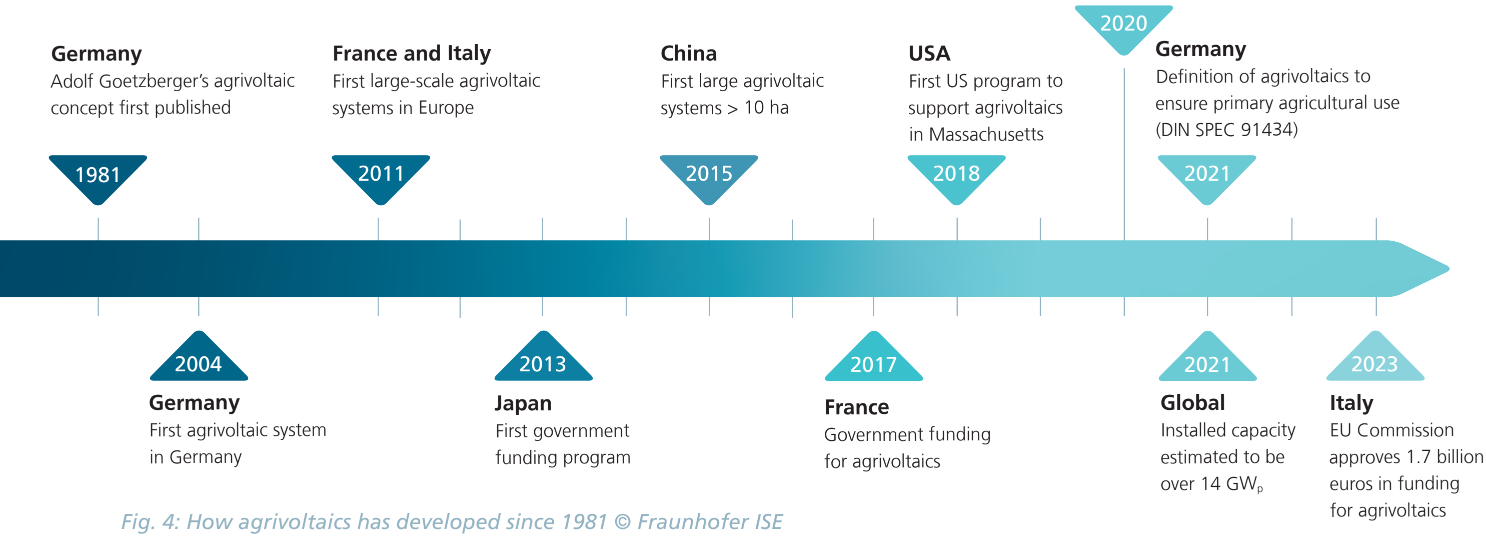


Fig. 4: How agrivoltaics has developed since 1981 © Fraunhofer ISE

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 mounting system 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 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

Funding for market development and for more research projects makes good sense, as this will allow researchers to 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 and 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 discusses possible areas for action in policymaking.

In recent years, a framework has been established in Germany that benefits agrivoltaic systems and gives them a realistic chance of being implemented. But if projects are to be realized, it is not only the German Building Code (Baugesetzbuch, BauGB) that is relevant, but also the influence of regional planning and land use policy. There are significant differences between the federal states when it comes to the responsible authorities and institutions. In addition to the construction law framework, it is also necessary to harmonize feasible instructions for authorities, regional plans and state development plans, and to support the development of solutions so that the market launch is sustainable.

Requirements

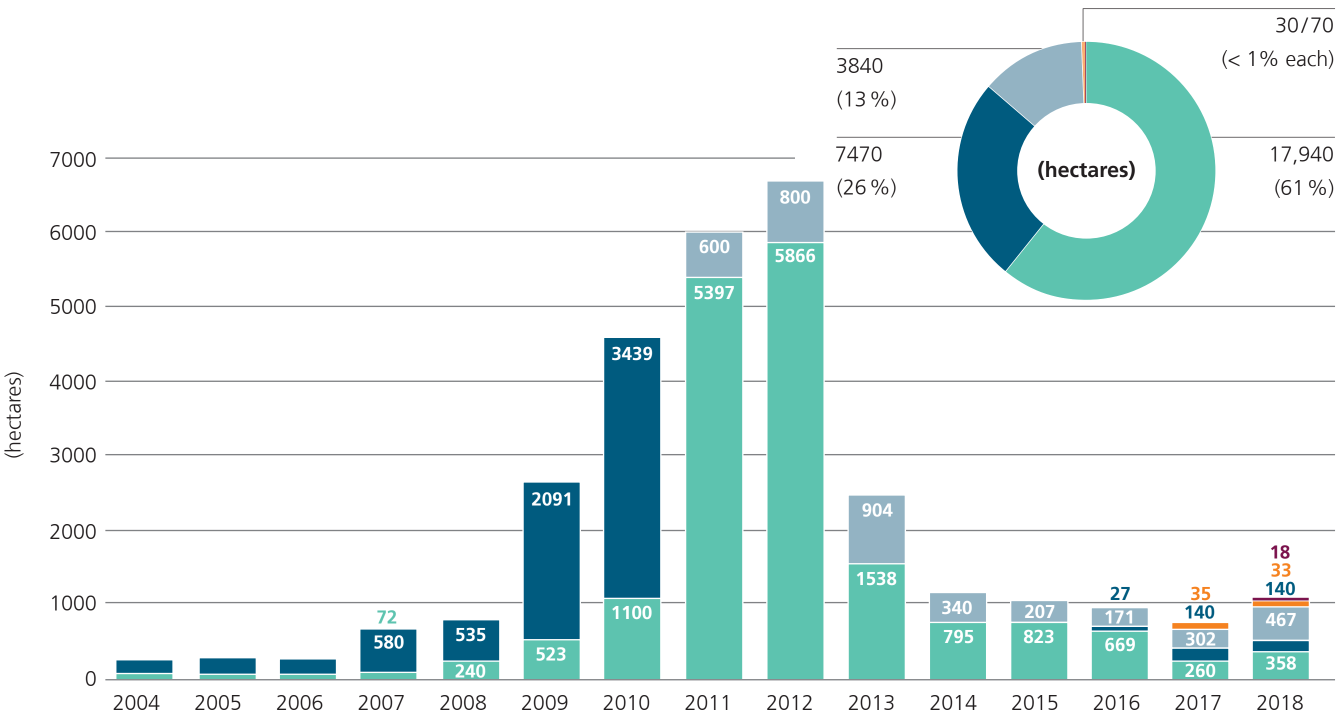
- Zoning plan: Classify agrivoltaic systems as "special area: agrivoltaics" instead of an "electrical facility/commercial area" on zoning plans to avoid them being wrongly recorded as areas covered with an impervious surface
- Extend areas that are classified for agrivoltaics use to include all agricultural land as part of the EEG
- 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

Overview of agrivoltaics

- Global installed capacity of at least 14 GW_p
- Estimated potential for stilted, overhead agrivoltaic systems in Germany is roughly 1700 GW_p

Advantages

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



- Land-use conversion, misc. physical structure
- Arable land, less-favored area as of 2016
- German Institute for Federal Real Estate (BImA)
- Area used for transportation
- Other

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

2 Agrivoltaics facts and figures

Fig. 6: Applications for integrated photovoltaics © Fraunhofer ISE

Fig. 7: Typical ground-mounted PV system © 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. Although EEG-funded ground-mounted PV systems may only be constructed on land with impervious surfaces, in conversion areas, on strips of land along highways or railroad tracks and on land in (agriculturally) constrained areas within the scope of the tender, large PV systems are also being constructed outside the scope of EEG-compliant tenders due to the enormous reduction in the LCOE for solar energy, 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).

2.2 Precipitation and global radiation

According to long-term measurements taken across Germany since 1880, there has been an average annual increase in precipitation of 8 percent. However, there has been a clear downward trend in precipitation 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.

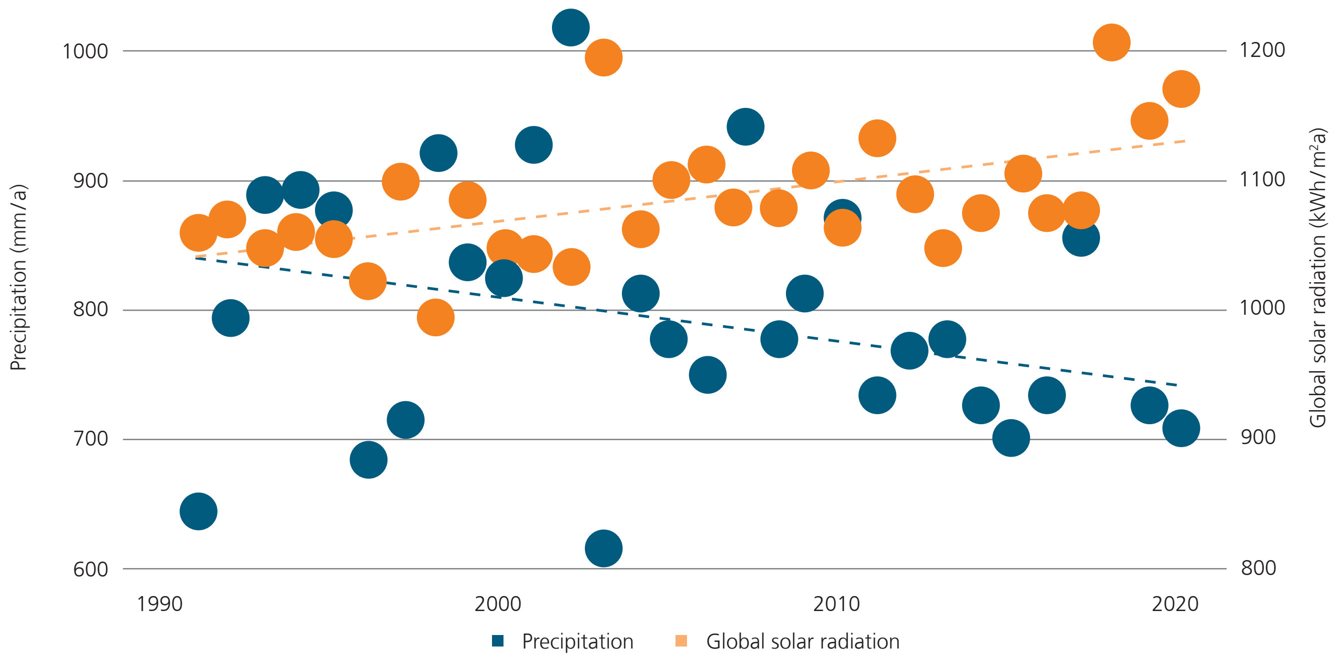


Fig. 8: Precipitation and global solar radiation in Germany since 1991
Data: German Meteorological Service. © Fraunhofer ISE

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 stilted, overhead PV. PV modules in overhead systems are mounted at least 2.1 meters above the ground (see section on DIN SPEC 91434 on next page). 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. Certain interspace system concepts can also provide protection against storm damage and excessive evaporation.

Similar to ground-mounted PV systems, agrivoltaic systems can be built either with a fixed mounting system 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 those in viticulture and fruit and vegetable growing. It discusses ground-level, interspace PV systems to a lesser extent and touches on their applications in permanent grasslands and farming. 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 provides more detailed information about the various technical solutions.

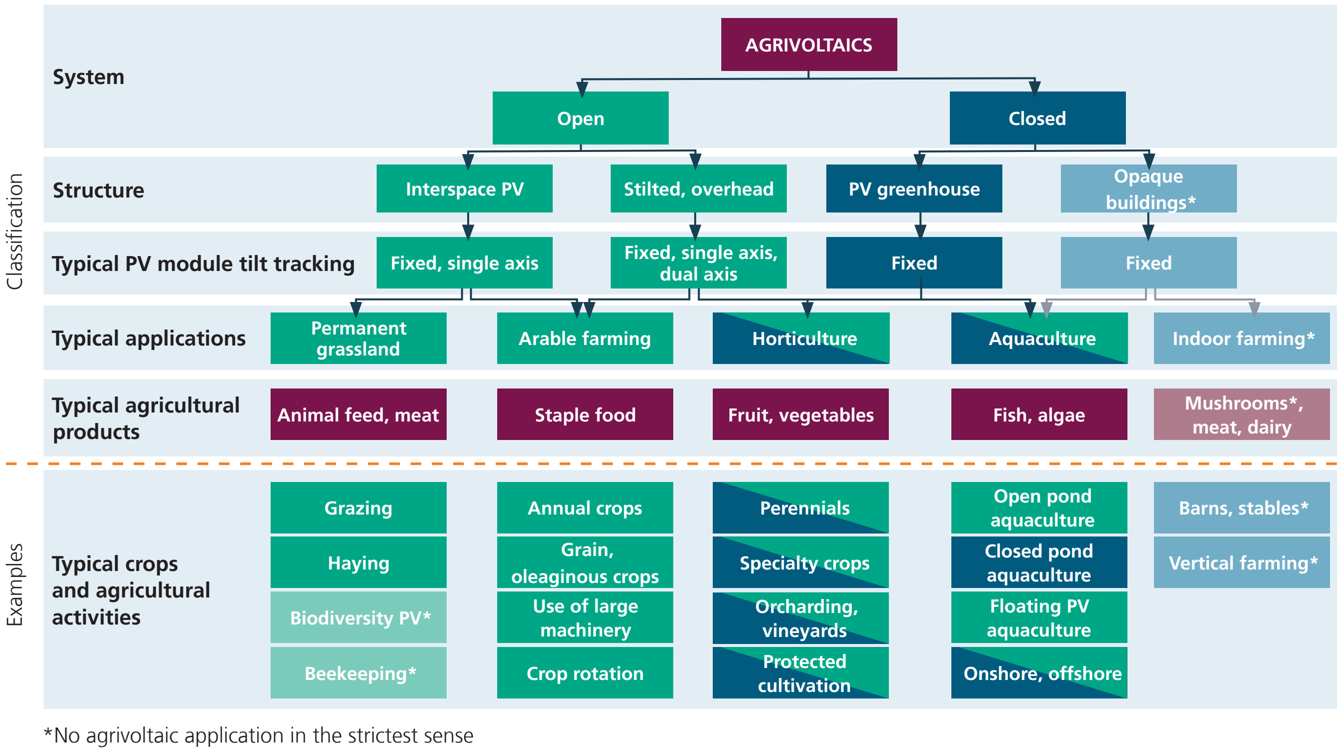


Fig. 9: Classification of agrivoltaic systems

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.

15 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:	1A: Permanent and perennial crops	Fruits, berries, viticulture, hops
Overhead PV with vertical clearance > 2.1 m	1B: Single-year and long-term crops	Arable crops, vegetables, alternating grassland, fodder
Farming under the agrivoltaic system	1C: Permanent grassland with mowing	Intensive and extensive commercial grassland
(Image A)	1D: Permanent grassland with pasture	Permanent pasture, pasture rotation (e.g., cattle, poultry, sheep, pigs and goats)
Category II:	2A: Permanent and perennial crops	Fruits, berries, viticulture, hops
Interspace PV with vertical clearance < 2.1 m	2B: Single-year and long-term crops	Arable crops, vegetables, alternating grassland, fodder
Farming between the rows of agrivoltaic systems	2C: Permanent grassland with mowing	Intensive and extensive commercial grassland
(Image B/C)	2D: Permanent grassland with pasture	Permanent pasture, pasture rotation (e.g., cattle, poultry, sheep, pigs and goats)

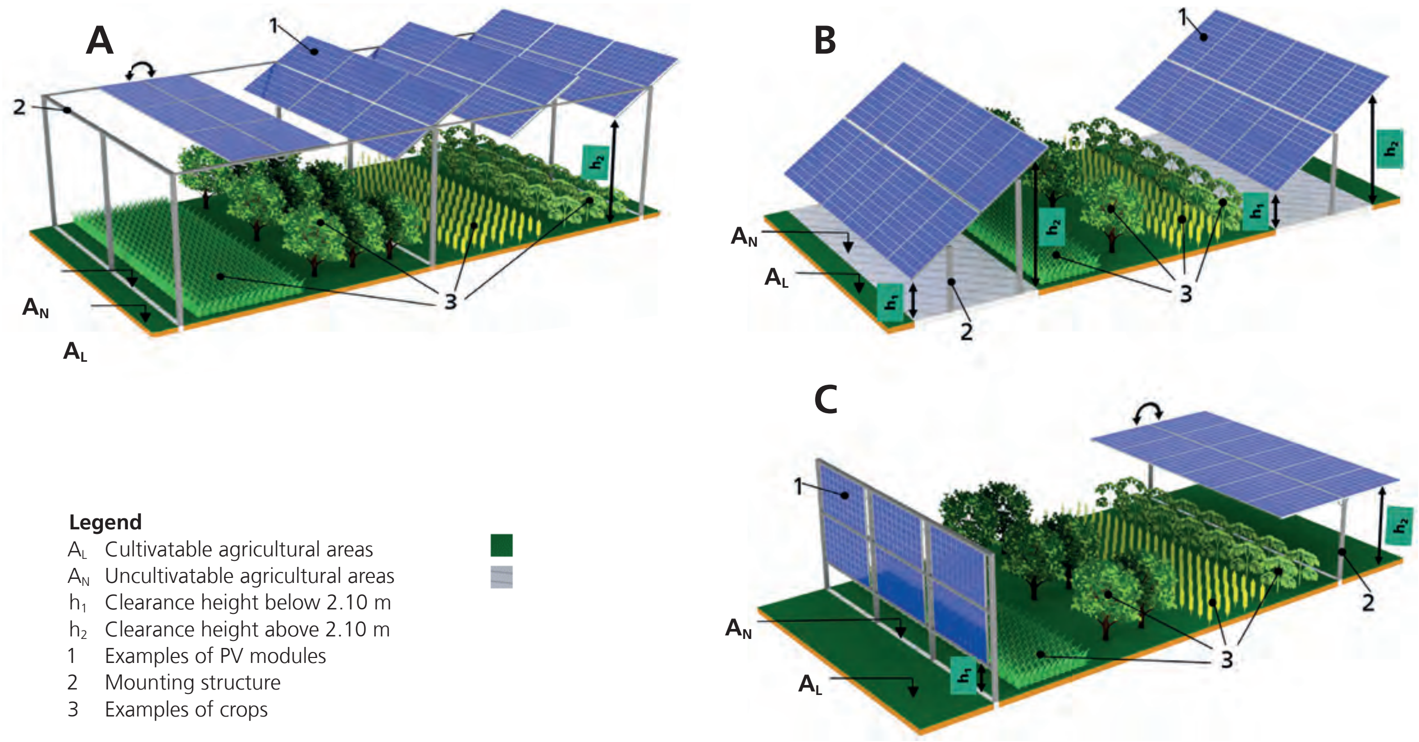


Fig. 10: Illustration of the categories and forms of land use as set out in DIN SPEC 91434 © Fraunhofer ISE
Image A: Illustration of a category I setup; Image B: Illustration of a category II setup, variant 1;
Image C: Illustration of a category II setup, variants 1 and 2.

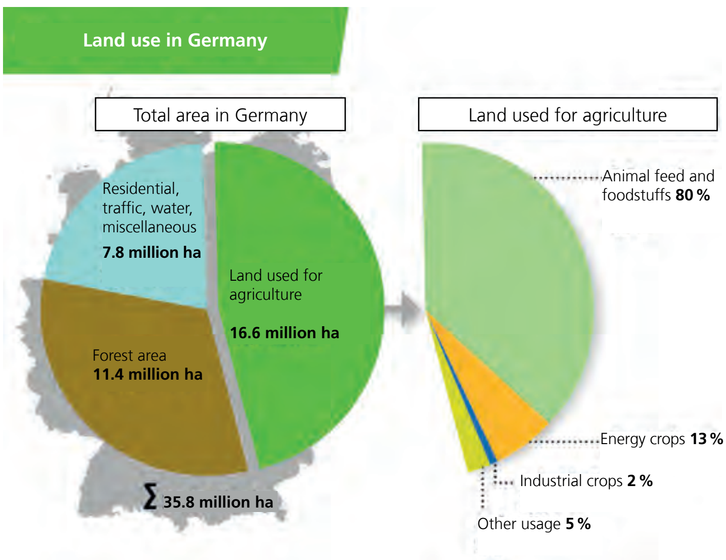


Fig. 11: Land use in Germany © Fachagentur Nachwachsende Rohstoffe e. V. (2023)[13]

High potential

Out of all the applications for integrated PV, agrivoltaics holds the greatest potential. This installed capacity would only require approximately 4 % of Germany's available farmlands to meet the country's entire current electricity demand with overhead agrivoltaic systems. Fraunhofer ISE conducted an initial assessment to estimate the potential of agrivoltaics and found that this was around 1700 GW_p in Germany. It based its estimates largely on shade-tolerant crops and those typically used in crop rotation. Even using just 10 percent of this 1700 GW_p 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 0.35 MW_p, so growing fodder on permanent grassland offers the potential to support another 1200 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 13 percent of agricultural land in Germany (see figure 11).

2.4 Research sites in Germany

There are at least eleven agrivoltaic systems in operation for research purposes in Germany. These are listed in table 2. The key data and research questions for these locations are detailed on the following pages along with summaries of other research projects.

Table 02: Overview of agrivoltaic research sites in Germany to date

Location	Type of land use	Technology	Installed capacity	Year of commissioning
Weihenstephan/Freising, Bavaria	Vegetable growing	Tracking PV array	22 kW_p	2013
Weihenstephan/Freising, Bavaria	Vegetable growing	PV tubes	14 kW_p	2015
Heggelbach, Sigmaringen district, Baden-Württemberg	Arable farming	South-west facing, fixed PV modules	194 kW_p	2016
Gelsdorf, Ahrweiler district, Rhineland-Palatinate	Fruit growing	Tracking and fixed semi-transparent PV modules	258 kW_p	2021
Alt-Morschenich, Düren district, North Rhine-Westphalia	Farming/vegetable growing	Tracking and fixed, with water management	300 kW_p	2021
Bavendorf, Baden-Württemberg	Fruit growing	Tracking and fixed PV modules	227 kW_p	2022
Dresden-Pillnitz, Saxony	Arable farming	Vertical PV modules	134 kW_p	2022
Heuchlingen, Heilbronn district, Baden-Württemberg	Fruit growing	Fixed PV modules	113 kW_p	2023
Tuniberg, Munzingen, Baden-Württemberg	Viticulture	East-west aligned, fixed PV modules	300 kW_p	2023
Blankenhornsberg, Ihringen, Baden-Württemberg	Viticulture	Single-axis tracking and fixed PV modules	200 kW_p	2023
Geisenheim, Rheingau-Taunus district, Hesse	Viticulture	Single-axis tracking PV modules	94 kW_p	2023

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 crops 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 within the system.

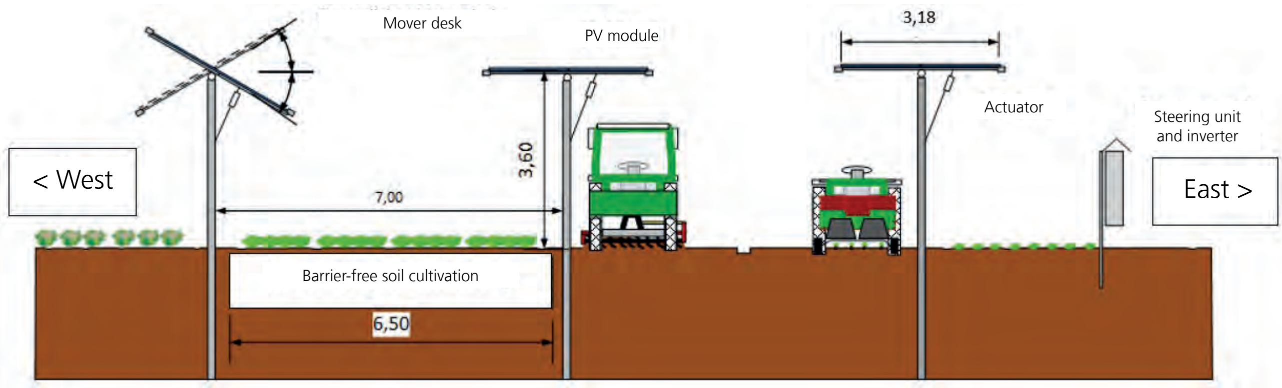


Fig. 12: Cross-section view of the agrivoltaic system in Weihenstephan
© 2020 B. Ehrmaier, M. Beck, U. Bodmer

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 with agrivoltaic system (2014)	**1348 g** Around 50 percent of the yield achieved without agrivoltaics	**1559 g** Around 56 percent of the yield achieved without agrivoltaics	**1970 g** Around 71 percent of the yield achieved without agrivoltaics	**2762 g**

Varying distances between PV modules within 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 explaining why crops in the agrivoltaic system produced reduced yields.

Technical data:

- Area: 483 m²
- Tracking: East-west; calendar controlled
- PV modules: CSG 245 W_p (90 PV modules)
- Installed capacity: 22 kW_p
- Use: Self-consumption

Weihenstephan 2015
Installing rain gutters on the drip edges of the PV modules of the agrivoltaic system 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.

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 bifacial 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.

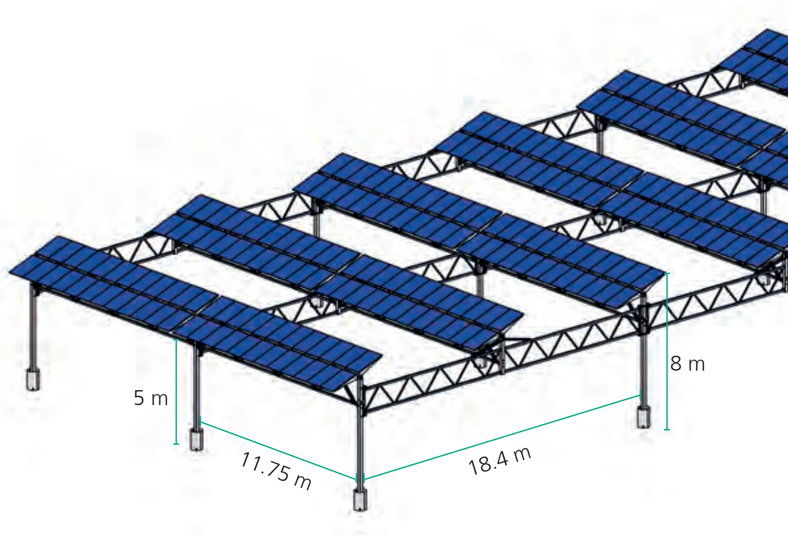


Fig. 13: Illustration of the agrivoltaic system in Heggelbach © AGRISOLAR Europe GmbH

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 1266 kWh per installed kW_p in the first 12 months (September 2016–September 2017).

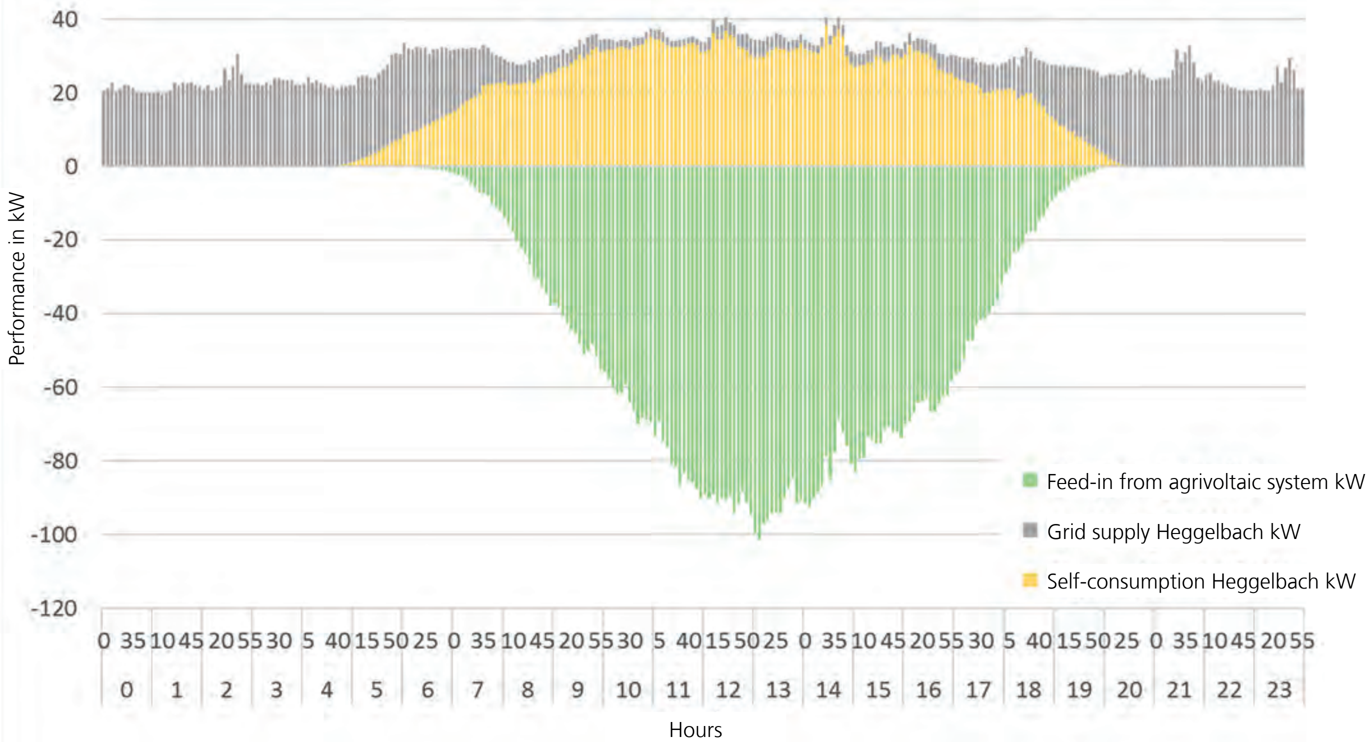


Fig. 14: The agrivoltaic system at Hofgemeinschaft Heggelbach enabled the farm to cover almost all of its energy demand in summer 2017 using the power generated with the system © BayWa r.e.

This output is a third more than the average for Germany, which is 950 kWh per kW_p. One reason for this is the high solar radiation in the region, while another is the additional yields thanks to the bifacial PV modules. 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 crops were able to compensate for the lack of rain in summer — possibly due to the additional shade from the PV modules. This observation illustrates the potential of agrivoltaics in arid regions. Further tests will need to be conducted in appropriate climate regions with additional crops. The solar irradiance was 1319.7 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 1285.3 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. The "APV-RESOLA" project was successfully completed in 2021.

Technical data:

- Area: 3400 m²
- PV modules: bifacial double-glass PV modules, 270 W_p (720 PV modules)
- Installed capacity: 194.4 kW_p
- Use: Self-consumption, feeding into grid

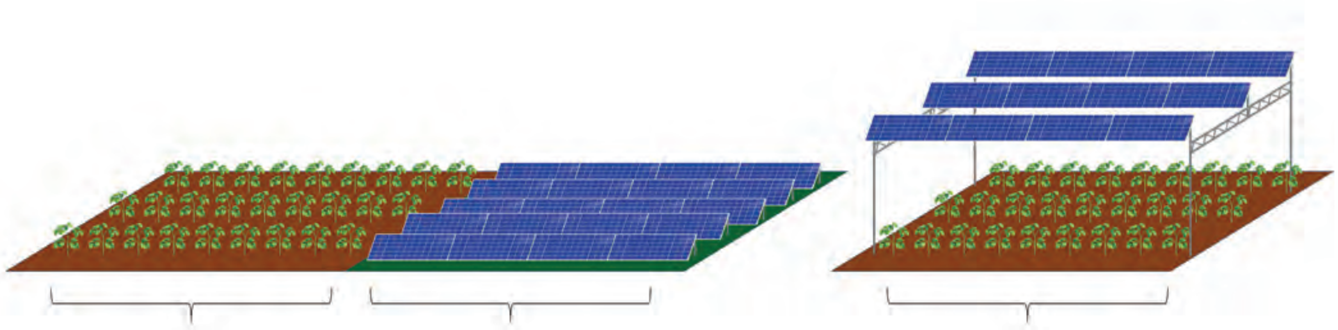


Fig. 15: The dual use of land for agrivoltaics and potato growing increased land-use efficiency on the Heggelbach test site to 186 percent © Fraunhofer ISE

Gelsdorf 2021

In the "APV-Obstbau" project, a pilot system with 258 kW_p capacity was installed 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.

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.

Technical data:

- Area: 3552 m²
- Tracking: 3 rows, single-axis
- PV modules: semi-transparent double-glass PV modules, 225 W_p (1148 PV modules)
- Installed capacity: 258 kW_p
- Use: Self-consumption, feeding into grid

Fig. 16: Agrivoltaic system at the Nachtwey organic fruit farm (2021, 2023) © Fraunhofer ISE

Alt-Morschenich 2021

The agrivoltaic system was installed as part of the "AgriFEe" project (formerly "APV 2.0"). Various solutions are implemented in this system, such as bifacial tracking and non-tracking modules and different orientations (south-facing or east-west). This allows the various effects on growth and yield of the cultivated crops to be investigated. High-value crops, fruit and vegetables are being cultivated in particular. Research is also being conducted into innovative tracking algorithms with a combined light simulation for PV and crop development and a smart irrigation system. In addition to agronomy and technical and economic considerations, issues relating to social acceptance are also being investigated.

Technical data:

- Area: 3766 m²
- Tracking: East-west for some parts of the system, test algorithms; static on two parts of the system
- PV modules: bifacial PV modules, 370 W_p (810 PV modules)
- Installed capacity: 300 kW_p
- Use: Phenotyping robots, irrigation system, buffer storage in batteries

Bavendorf 2022
At the Bavendorf site, the Kompetenzzentrum Obstbau Bodensee (Competence Center for Fruit Production in the Lake Constance Region) and Fraunhofer ISE are investigating the impact of an agrivoltaic system on organic farming using four different varieties of apple. The system comprises a static and a tracking section, as well as a reference area. Investigations are focused on the extent to which changing the microclimate under the PV modules could reduce the use of pesticides.

Technical data:

- Area: 5000 m²
- Tracking: single-axis tracking with east-west orientation (central part of system), fixed mounting structure (northern part of system)
- PV modules: semi-transparent double-glass PV modules, 300 W_p (756 PV modules)
- Installed capacity: 227 kW_p
- Use: 100 percent fed into the grid

Dresden-Pillnitz 2022
In 2022, the University of Applied Sciences Dresden constructed an agrivoltaic system with vertical modules at the Dresden-Pillnitz site using grants from the State of Saxony. The system is used for research and student education purposes. Investigations are primarily focused on issues relating to agricultural production and the environment. The topics covered include the factors influencing crop yields, the microclimate in the system, groundwater and evaporation, insect protection and the development of the agricultural technology used in agrivoltaic systems.

Technical data:

- Area: 4500 m^2
- PV modules: bifacial double-glass PV modules, 430 W_p (320 PV modules)
- Installed capacity: 134.4 kW_p
- Use: electric (autonomous) vehicles, machinery and equipment, feeding into the grid

Heuchlingen 2023
The agrivoltaic system was constructed at the experimental fruit farm of the State Education and Research Institute for Viticulture and Pomology in Heuchlingen. It is intended to cover over soft fruits and strawberries and have a positive impact on the microclimate through its closed design. Thanks to the roof structure with drainage system, it is possible to collect and store rainwater all year round and use it for irrigation purposes. In addition, a circulating water management system is intended to prevent nitrate leaching.

Technical data:

- Area: 2000 m²
- PV modules: semi-transparent double-glass PV modules, 200 W_p (384 PV modules)
- Installed capacity: 113 kW_p
- Use: partly self-consumption

Tuniberg 2023, Blankenhornsberg 2023 and Geisenheim 2023
The effects of climate change are becoming apparent in viticulture and are causing crop losses, e.g., due to heat damage, heavy rain, hail and late frosts. The PV systems (also known as viti-PV) installed directly over the vines at the sites in Tuniberg, Blankenhornsberg and Geisenheim are intended to protect the vines, delay grape ripening and provide a more consistent climate in general so that crop losses can be prevented. It is not just the crops but also the individual PV modules that benefit from the synergy, as they can be cooled by the high position and water evaporation (transpiration) of the crops. The combination of more consistent crop yields and additional income from the sale of electricity gives the farmer greater financial security, even in times of increasing extreme weather events.

Technical data for Tuniberg:

- Area: 5000 m^2
- PV modules: semi-transparent PV modules, 220 W_p (1577 PV modules)
- Installed capacity: 300 kW_p
- Use: 100 percent fed into the grid

Technical data for Blankenhornsberg 2023:

- Area: 1400 m^2
- Tracking: single-axis tracking (rows running east-west) for one part of the system
- PV modules: semi-transparent double-glass PV modules, 550 W_p (78 PV modules), 415 W_p (200 PV modules), 300 W_p (474 PV modules)
- Installed capacity: 268 kW_p
- Use: 100 percent fed into the grid

Technical data for Geisenheim 2023:

- Area: 1650 m^2
- Tracking: single-axis tracking with east-west orientation
- PV modules: semi-transparent double-glass PV modules, 170 W_p (550 PV modules)
- Installed capacity: 94 kW_p
- Use: primarily self-consumption, feeding into grid

Fig. 17: Agrivoltaic system in Blankenhornsberg, 2023
© Jona Pillatzke, WBI

Fig. 18: Agrivoltaic system in Geisenheim
© HS Geisenheim

2.5 Operational sites in Germany

In addition to the following descriptions of operational systems, there are other agrivoltaic systems in Germany that are implemented or planned.

Table 04: Overview of specified operational systems and certain other operational systems in Germany

Location	Type of land use	Technology	Installed capacity	Year of commissioning
Warmsried, Bavaria	Arable farming, vegetable growing, livestock farming	Fixed PV arrays	70 kW_p	2008
Eppelborn-Dirmingen, Saarland	Fodder	Vertical PV modules	2000 kW_p	2018
Büren-Steinbach, North Rhine-Westphalia	Berry bushes, fruits	Tracking PV modules	740 kW_p	2020
Aasen, Donaueschingen, Baden-Württemberg	Animal feed, farming	Vertical PV modules	4100 kW_p	2020
Althegnenberg, Bavaria	Corn, oats, spelt, clover	Single-axis tracking PV modules	1890 kW_p	2020
Lüptitz, Saxony	Livestock farming, vegetable growing	Single-axis tracking PV modules	1045 kW_p	2021
Kressbronn am Bodensee, Baden-Württemberg	Fruit	Fixed PV modules	239 kW_p	2022
Merzig-Wellingen, Saarland	Arable farming	Vertical PV modules	5200 kW_p	2023

Fig. 19: Module row with bifacial PV modules on the agrivoltaic system in Heggelbach
© Fraunhofer ISE

Büren-Steinbach 2020
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.

The mounting system 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 mounting system 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 forecast 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.

Technical data:

- Area: 4200 m²
- PV modules: bifacial PV modules, special production, 320 W_p (2320 PV modules)
- Installed capacity: 740 kW_p
- Use: 50 percent self-consumption, 50 percent fed into the grid

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 eG as its operator. The system has a capacity of around 4.1 MW_p and can supply power to 1400 homes [15]. As part of the project, arable land was converted into extensively farmed grassland. The overall share of land taken up by the 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 modules: bifacial double-glass PV modules, 370–380 W_p (10,960 PV modules)
- Installed capacity: 4100 kW_p
- Use: 100 percent fed into the grid

Fig. 20: Vertical agrivoltaic system in Aasen, Donaueschingen
© Solverde Bürgerkraftwerke

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
- PV modules: bifacial PV modules, 415 W_p (2520 PV modules)
- Installed capacity: 1045.80 kW_p
- Use: 100 percent fed into the grid

Kressbronn 2022

The agrivoltaic system in Kressbronn am Bodensee is the first such system to be constructed, inaugurated and connected to the grid as part of the "Model Region Agri-PV BaWü" project. It is also Germany's first electricity-generating system in the field of apple cultivation to be integrated into a plantation with a full harvest (Obsthof Bernhard). The system offers varying shading of modules with two transparency levels (51 and 40 percent); the effects of these on the ecophysiology of the apples will also be investigated, along with potential effects of pesticides on the PV modules.

Technical data:

- Area: 4000 m²
- PV modules: Type 1: semi-transparent double-glass PV modules,170 W_p (552 PV modules); type 2: semi-transparent double-glass PV modules, 260 W_p (469 PV modules)
- Installed capacity: 239 kW_p
- Use: 100 percent fed into the grid

Merzig-Wellingen 2023

The vertical agrivoltaic system in Merzig-Wellingen comprises an operational system as well as a research area, which is the focus of the "VAckerPower" and "VAckerBio" research projects. The entire area is used for farming. The purpose of the investigations is to complete a comprehensive analysis of technical issues and agronomy considerations. The use of the research area for farming purposes is supplemented by the use of the maintenance strips under the PV modules for biodiversity measures and the performance is analyzed.

Technical data:

- Area: 140,000 m², of which 17,000 m² research area
- PV modules: bifacial PV modules 420–460 W_p
- Installed capacity: 5200 kW_p, of which 500 kW_p on the research area
- Use: 100 percent fed into the grid

2.6 Research projects in Germany

Table 05: Overview of some research projects in Germany

Project	Duration	Client	Project partners	More information
APV-Obstbau (Orcharding)	April 1, 2020 to March 1, 2025	BMEL[*1], MKUEM[*2]	Nachtwey organic fruit farm, BayWa r.e. Solar Projects GmbH, DLR-RLP[*11], EWS[*12], Vertriebs GmbH, AGCO GmbH[*13], Fraunhofer ISE	https://s.fhg.de/Orcharding
Agri4Power	May 1, 2020 to June 30, 2021	BMWK[*3]	Fraunhofer IMW[*14], DBFZ[*15], Stiftung Kulturlandschaft Sachsen-Anhalt, UFZ[*16]	https://s.fhg.de/Agri4PowerGER
Landgewinn	September 1, 2021 to August 31, 2024	BMWK, Projektträger Jülich	Offenburg University of Applied Sciences, Fraunhofer ISE, KIAF[*17], IÖW[*18]	https://s.fhg.de/LandgewinnGER
AgriFEe	January 1, 2022 to December 31, 2026	BMBF[*4]	Forschungszentrum Jülich, Fraunhofer ISE	https://s.fhg.de/AgriFEe20EN
Model Region Agri-PV BaWü	January 1, 2022 to November 1, 2024	MLR[*5], UM BW[*6]	Kehl University of Applied Sciences, LVWO[*19], LTZ[*20], KOB[*21], Obsthof Bernhard, RWB[*22], Obsthof Vollmer, Fraunhofer ISE	https://s.fhg.de/ModelregionEN
SynAgri-PV	July 1, 2022 to June 1, 2025	BMBF[*4]	ZALF[*23], University of Hohenheim, Elysium Solar GmbH, BBH PartGmbB[*24], Stiftung Umweltenergierecht, Bosch und Partner GmbH, Fabian Karthaus, Hofgemeinschaft Heggelbach, Fraunhofer ISE	https://s.fhg.de/SynAgriPVEN
VAckerPower	November 1, 2022 to October 1, 2025	BMWK	Next2Sun Technology GmbH, Fraunhofer ISE	https://s.fhg.de/VAckerPowerEN
VAckerBio	October 1, 2022 to September 1, 2023	DBU[*7]	University of Hohenheim, Next2Sun Technology GmbH, Fraunhofer ISE	https://s.fhg.de/VAckerBioENG
VitiVoltaic	July 1, 2020 to June 30, 2025	ERDF[*8], ERDF-REACT[*9], HMUKLV[*10]	Hochschule Geisenheim University	https://s.fhg.de/VitvoltaicEN
VitiCult-PVmobil	January 1, 2023 to December 1, 2025	BMBF	sbp sonne GmbH[*25], Hochschule Geisenheim University, Fraunhofer ISE	https://s.fhg.de/VitvcultEN
Weinbau 4.0	May 15, 2023 to December 31, 2027	MLR, ERDF	WFG[*26], ZG Raiffeisen eG, ZG Raiffeisen Technik GmbH, Intech GmbH & Co. KG, HEG[*27], Sick AG, WBI[*28], KIAF, Fraunhofer ISE, BürgerenergieKaiserstuhl, etc.	https://s.fhg.de/Weinbau40GER

*1 German Federal Ministry for Food and Agriculture (BMEL)
*2 Ministry for Climate Protection, Environment, Energy and Mobility of the State of Rhineland-Palatinate (MKUEM)
*3 German Federal Ministry for Economic Affairs and Climate Action (BMKW)
*4 German Federal Ministry of Education and Research (BMBF)
*5 Ministry of Food, Rural Affairs and Consumer Protection Baden-Württemberg (MLR)
*6 Ministry of the Environment, Climate Protection and the Energy Sector Baden-Württemberg (MU BW)
*7 German Federal Environmental Foundation (DBU)
*8 European Regional Development Fund (ERDF)
*9 Recovery Assistance for Cohesion and the Territories of Europe (REACT)
*10 Hessian Ministry of the Environment, Climate Protection, Agriculture and Consumer Protection (HMUKLV)
*11 Center for Rural Services, Rheinpfalz Region (DLR RLP)
*12 Elektrizitätswerke Schönau (EWS)
*13 Allies-Gleaner Cooperation (AGCO GmbH)
*14 Fraunhofer Center for International Management and Knowledge Economy IMW
*15 Deutsches Biomasseforschungszentrum gGmbH (DBFZ)
*16 Helmholtz-Zentrum für Umweltforschung GmbH (UFZ)
*17 Kehl Institute for Applied Research (KIAF)
*18 Institute for Ecological Economic Research (IÖW)
*19 State Education and Research Institute for Viticulture and Pomology (LVWO)
*20 Center for Agricultural Technology Augustenberg (LTZ)
*21 Competence Center for Fruit Production in the Lake Constance Region (KOB)
*22 Regionalwerk Bodensee (RWB)
*23 Leibniz Centre for Agricultural Landscape Research (ZALF)
*24 Becker Büttner Held Rechtsanwälte Wirtschafts-prüfer Steuerberater PartGmbB
*25 Schlaich bergermann partner — sbp sonne GmbH
*26 Wirtschaftsförderung des Landkreises Emmendingen mbH (WFG)
*27 Heidelberger Energiegenossenschaft eG (HEG)
*28 State Institute of Viticulture Freiburg (WBI)

APV-Obstbau (Orcharding)
Fraunhofer ISE joined its partners in research and industry for the "APV-Obstbau" (Agrivoltaic Orcharding) 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.

Agri4Power
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]

Landgewinn
The three-year joint project "Landgewinn" is researching the agricultural sector by carrying out an energy system analysis. The team includes the Energy Systems and Energy Economy research group and the Photovoltaic Technology and Biochar research group from the Institute of Sustainable Energy Systems at Offenburg University of Applied Sciences, as well as Fraunhofer ISE, Kehl University of Applied Sciences and the Institute for Ecological Economic Research (IÖW).

As part of this research project, the team is generating a comprehensive analysis of three decarbonization technologies in order to implement an energy system analysis. This aims to highlight the available potential and the range of actions that could be taken to reduce CO_2 in agriculture. In addition to pyrolysis for producing biochar and the decarbonization of farming machinery, Fraunhofer ISE is focusing on investigating agrivoltaic technology from an economic and ecological perspective. Kehl University of Applied Sciences is also investigating the legal framework.

The motivation behind the project partners' work is to harmonize the energy supply and emissions in the agricultural sector with energy and climate goals in the medium and long term. Many agricultural businesses — as well as the German agricultural sector in general — are under increasing pressure since emissions and energy consumption in the agricultural sector have remained at the same level for many years. The purpose of an integrated assessment of the agriculture and energy sectors as part of the energy system analysis is to open up new opportunities for achieving energy and climate goals. The project will incorporate technologies such as agricultural e-mobility, the transition to flexible electricity demand or agroforestry systems.

AgriFEe
The "Coupling of photovoltaics and crop production" project ("AgriFEe," formerly "APV 2.0"), 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 in Morschenich-Alt, Germany.

Model Region Agri-PV Baden-Württemberg
The first implementation phase of the "Model Region Agri-PV Baden-Württemberg" project aims to drive the expansion of agrivoltaic technology in Baden-Württemberg. The 13 project partners, including Fraunhofer ISE, intend to focus their research on pomaceous fruits and berries in the first implementation phase. Agrivoltaic systems with a total capacity of up to 1700 kW_p are being constructed at five locations in Baden-Württemberg. Three of these systems were successfully installed in Kressbronn, Bavendorf and Heuchlingen in 2022. In order to network the projects and make use of synergies, a framework program has been established and is being jointly managed by Kehl University of Applied Sciences and Fraunhofer ISE. The program looks at a range of issues relating to the implementation potential at other sites, as well as other research topics such as crop-specific system design and a more differentiated approach to the legal framework. The agricultural investigations are being conducted by the Center for Agricultural Technology Augustenberg, the Competence Center for Fruit Production in the Lake Constance Region and the State Education and Research Institute for Viticulture and Pomology. The project is being funded by the Ministry of the Environment, Climate Protection and the Energy Sector as well as the Ministry of Food, Rural Affairs and Consumer Protection Baden-Württemberg.

Fig. 21: Agrivoltaic system in Kressbronn (2022)
© Fraunhofer ISE

SynAgri-PV

The research project "Synergetic Integration of Photovoltaics in Agriculture as a Contribution to a Successful Energy Transition — Networking and Accompanying the Market Take-off of Agrivoltaics in Germany" ("SynAgri-PV") was launched in July 2022 with a project duration of three years and is being funded by the German Federal Ministry of Education and Research (BMBF).

The overarching goal of the project is to describe and assess the central technical, legal, economic and social conditions and requirements for establishing agrivoltaics in the German market and to develop proposals relating to the widespread establishment of agrivoltaics. Under the coordination of Fraunhofer ISE and the Leibniz Centre for Agricultural Landscape Research (ZALF), the market launch of agrivoltaics in Germany is being accompanied by project partners the University of Hohenheim, Kanzlei Becker Büttner Held, Stiftung Umweltenergierecht, Elysium Solar GmbH and Bosch & Partner GmbH from an interdisciplinary and academic perspective. This involves evaluating data from existing agrivoltaic systems across Germany, with the two associated farms — Fabian Karthaus near Paderborn and Hofgemeinschaft Heggelbach by Lake Constance — gaining experience of using the prototypes in practice and incorporating this directly into the project.

The goal is to develop social objectives relating to the expansion of agrivoltaics in Germany, specify the actions required for implementation, propose some potential solutions and identify additional fields of research. This will be achieved by taking an evidence-based approach and involving as many of the relevant parties as possible. The project will involve developing participation models i.e. participation models, evaluating the findings and making them accessible to the wider public and to policymakers.

Fig. 22: Vertical agrivoltaic system in Merzig-Wellingen, 2023
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VAcker projects

The "VAckerPower" and "VAckerBio" projects involve extensive investigations into vertical, bifacial agrivoltaic systems in farming.

The combination of the two projects enables a comprehensive analysis to be made of the vertical approach in farming, both in relation to agriculture and to photovoltaic operation. The aim of the "VAckerPower" project is to investigate the impact of the vertical agrivoltaic system on land use for farming purposes. The project is accompanying the initial implementation of the vertical systems in a farming context in Germany from a technical perspective. At the same time, the project will investigate the operational reliability of the systems, including under operational conditions (soiling, use of pesticides and fertilizers, etc.), and identify potential for optimization. It will also consider social acceptance and sustainability aspects of these and other systems in a farming context. Ultimately, the project will identify appropriate locations through a potential study.

The "VAckerBio" project focuses on the influence of the agrivoltaic system on land use for farming purposes and on biodiversity. In order to investigate the development of crop cultivation, a microclimate monitoring system will be implemented and soil quality and crop growth will be observed. Usage concepts that promote biodiversity on uncultivated strips of land under the PV modules will also be developed and implemented. An important part of the investigations will take place on the testing area of the agrivoltaic system in Merzig-Wellingen.

VitiVoltaic

This project at Hochschule Geisenheim University aims to find out whether PV modules can alleviate the effects of climate change on viticulture. The agrivoltaic system for the research project was constructed in 2022 in Geisenheim. The project is being funded by the European Regional Development Fund (ERDF) ("APV-Weinbau4Real"), ERDF-REACT (equipment) and the Hessian Ministry of the Environment, Climate Protection, Agriculture and Consumer Protection ("VitiVoltaic4Future").

ViticCult-PVmobil

This project aims to develop a mobile agrivoltaic system for young vines. The project partners are sbp Sonne, Fraunhofer ISE and Hochschule Geisenheim University. The goal is to develop a flexible system that can be adapted to the needs of winegrowers. Young vines require special protection. The investigations are focused on the extent to which this system can be implemented from a technical and economic perspective and the agronomic impact. A prototype is being developed as part of the research project. The German Federal Ministry of Education and Research (BMBF) is funding the project.

Weinbau 4.0

The RegioWIN project "Weinbau 4.0" ("Viticulture 4.0") includes two sub-projects: "Agri-PV im Weinbau" ("Agrivoltaics in Viticulture") in Oberkirch and Ihringen-Blankenhornsberg and "Agri-PV im Weinbau / Bürger-Viti-PV" ("Agrivoltaics in Viticulture / Citizens' Viticulture PV) in Riegel. The State Institute of Viticulture Freiburg aims to investigate the impact of agrivoltaics on viticulture in the Southern Upper Rhine-High Rhine region. "Weinbau 4.0" is a flagship project that was awarded a prize as part of the state competition RegioWIN 2030 ("Regional Competitiveness through Innovation and Sustainability"). It is being funded by grants from Baden-Württemberg and the European Regional Development Fund (ERDF).

The project focuses on the technical implementation of agrivoltaics in viticulture as well as on investigating vines as a partner crop. The first step is to address issues relating to vine development and the extent to which agrivoltaics protect the vines, as well as to clarify the cultivation options. It is also seeking to answer questions relating to yields as well as grape and wine quality. The cooperation partners include Intech GmbH & Co. KG, HEG Heidelberger Energiegenossenschaft eG and the Wirtschaftsförderungsgesellschaft des Landkreises Emmendingen mbH as the project contact for "Weinbau 4.0." Project partners such as the State Institute of Viticulture Freiburg, the Kehl Institute for Applied Research (KIAF) and Fraunhofer ISE are also involved.

The impact of agrivoltaics on viticulture is being investigated at three sites in and around Freiburg: Blankenhornsberg, Riegel and Oberkirch. The pilot system in Riegel is still in the development phase.

2.7 International development

With over 14 GW_p of installed agrivoltaic 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 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 that have identified the opportunities offered by agrivoltaics. However, they both use smaller PV systems. At present, Japan has over 3000 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 1000 US dollars) and to 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 combination this is a very appealing prospect for 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 yield increase 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 worked with partners in Algeria on the "WATERMED 4.0" project to find out how agrivoltaics impact the 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 an appealing prospect for many countries, including parts of Germany, especially in view of the increasing frequency of dry spells [17].

2.7.1 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. Due to initial positive results, 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. 23: 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

2.7.2 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 round in 2017. In the second and third rounds, tenders for 140 MW_p 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_p 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, Occitania) 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 in France. In 2022, the French Environment and Energy Management Agency (Agence de l'environnement et de la maîtrise de l'énergie, ADEME) published a classification for agrivoltaics ("Caractériser les projets photovoltaïques sur terrains agricoles et l'agrivoltaïsme").

Fig. 24: Study with various types of lettuce at the agrivoltaics research site run by the University of Montpellier in France © INRAE / Christian Dupraz

2.7.3 USA

An agrivoltaics 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 bottom edge of the PV modules must be at least 2.4 meters high when installed in fixed rows; this must be at least 3 meters in the case of systems with module tracking. In addition, no point in the field can be more than 50 percent shaded during the main cultivation season[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).

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.

2.7.4 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.

2.7.5 Turkey

The goal of the "SusMedHouse" project is to improve the productivity, cultivation efficiency and agricultural sustainability of greenhouses in the Mediterranean region. The greenhouse is located in Ankara and comprises several areas in which the effects of innovative cultivation methods on agricultural productivity are investigated.

The project is made up of the following components: artificial intelligence to optimize processes, early detection of anomalies and economic forecasting, decision support system (DSS) that uses a mobile app to provide support when implementing the required measures, integrated pest and pathogen management (IPPM) to guarantee food safety and reduce the use of chemical fertilizers, development of biodegradable growth media from circular waste streams to increase eco-friendliness, optimization of sunlight and lighting using a special greenhouse material coating (sun protection with lower emissions), an agrivoltaic system to protect crops and generate PV energy and the development of biosensors to analyze water quality.

Fraunhofer ISE is responsible for light management in the greenhouses. The PV system has been designed so that it can be integrated into an existing greenhouse. This design puts the focus on the needs of the crops. The effects of design parameters such as PV coverage, PV arrangement and greenhouse orientation on light availability and distribution have been investigated. A pilot greenhouse was constructed and put into operation in July 2022. The PV pilot greenhouse is being used to test tomatoes, bell peppers and lettuces.

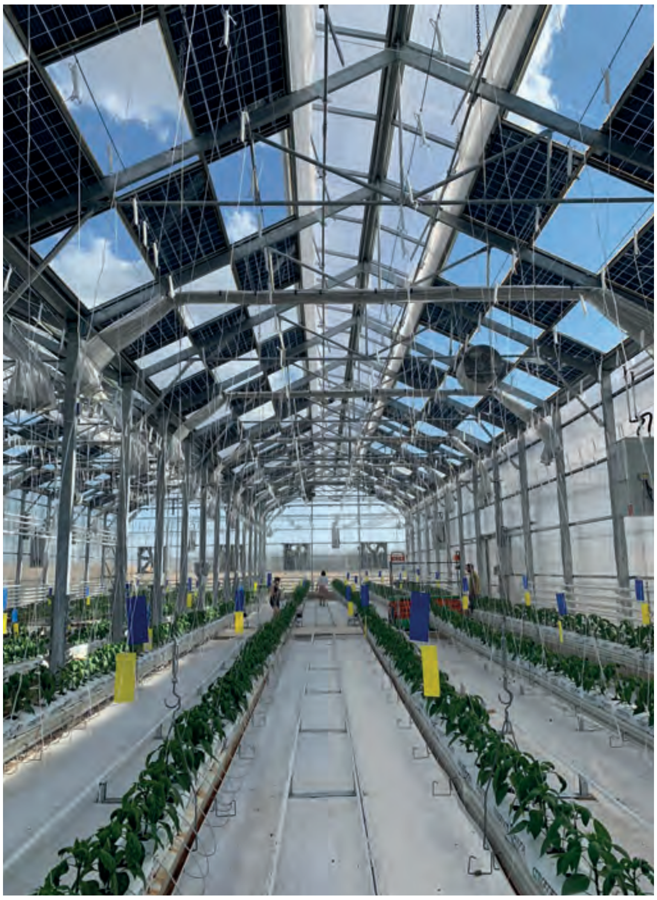


Fig. 25: PV greenhouse © Fraunhofer ISE

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. However, many places have restrictions on drawing ground and surface water, therefore more options for adaptation need to be found. Drought is not the only extreme weather event to threaten crops — hail, strong winds 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 counteract yield losses. 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. 26: 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 27). This data showed that photosynthetically active solar radiation under the agrivoltaic system was 30 percent lower on average 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. Celery benefited most from these conditions with 12 percent yield increase; potato and winter wheat crops increased their yield by 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 also need to account for the 8 percent 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.

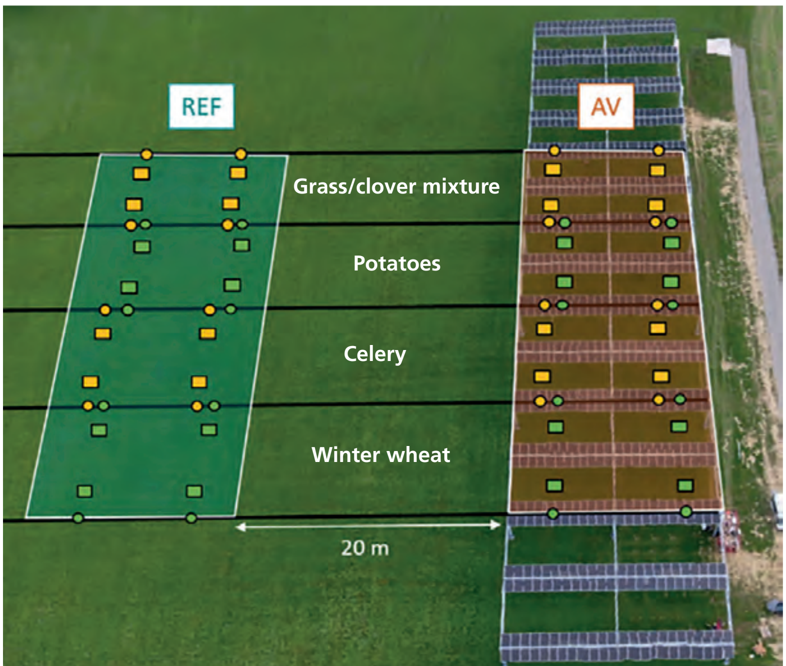


Fig. 27: Field plan for the 2017 research site, showing monitoring stations. Areas where samples were taken are shown as boxes, and the positions of the microclimate stations are shown as circles © BayWa r.e., modified by Axel Weselek/ University of Hohenheim.

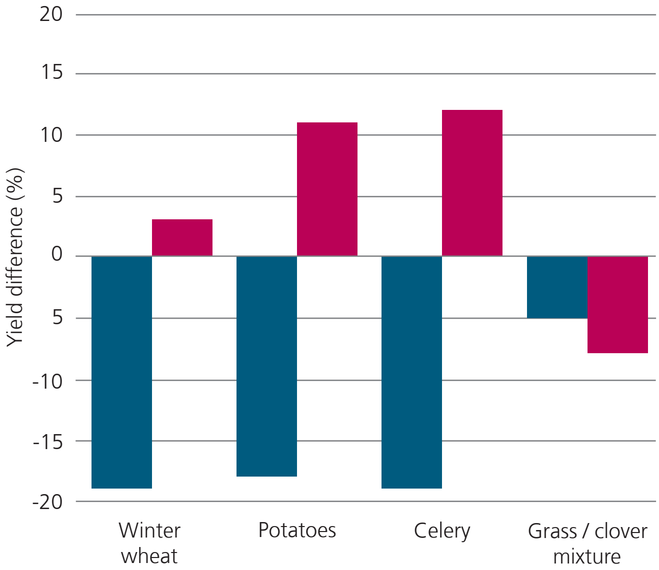


Fig. 28: Crop yield differences under agrivoltaics compared to reference plots, 2017 (blue) and 2018 (red) in Heggelbach (excluding land lost due to supports). Data: University of Hohenheim, © Fraunhofer ISE

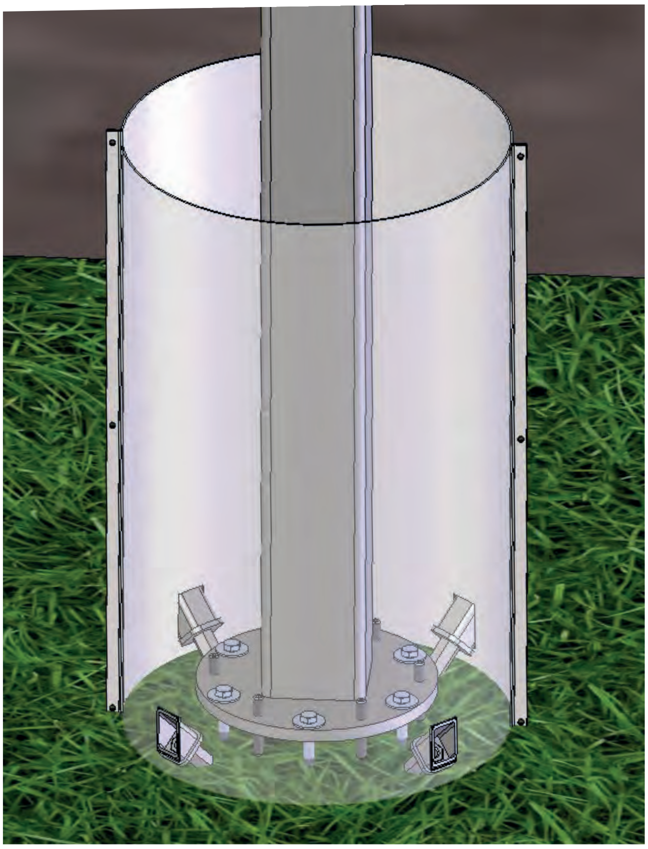


Fig. 29: Impact protection for the supports of the system in Heggelbach to protect against possible damage from farming machinery © AGROSOLAR Europe GmbH

3.2 Crop selection and cultivation

Cultivation under or between 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 mounting systems 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 mounting system 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.

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).

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. 30: Illustration of an agrivoltaic apple orchard © Fraunhofer ISE

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.

Fig. 31: Agrivoltaic system with solar tracking PV modules in France © Sun'Agri

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.

Fig. 32: Weather protection for raspberries provided by agrivoltaics. 300 kW_p test system by BayWa r.e. in the Netherlands © BayWa r.e.

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, which significantly lowers the costs of the mounting system. 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 2.7.2).

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 mounting system 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 4), societal acceptance (section 6) and regulatory feasibility (section 7).

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 stilted, overhead 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 mounting systems 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, stilted, overhead agrivoltaic systems can reduce losses in crop yields because the available light can be increased in critical growth phases.

Fig. 33: Demo project in berry cultivation shows high value creation in agriculture © BayWa r.e.

Fig. 34: Harvesting wheat with a combine harvester © Fraunhofer ISE

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 35). 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]

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 still be farmed over at least 90 percent of the area even when the stilts are close to the ground, is the installation of vertical agrivoltaic systems (see figure 36). In Germany, there are already several reference systems, such as those 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.

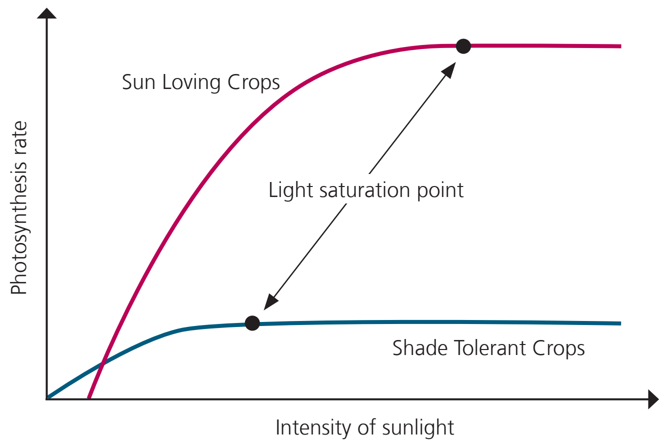


Fig. 35: Graph of the rate of photosynthesis against intensity of sunlight for sun loving and shade tolerant crops[24] © ASPS, modified by Fraunhofer ISE

Fig. 36: Vertically deployed, bifacial PV modules used within the agrivoltaic system in Eppelborn-Dirmingen, Saarland, 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."
Reyer: "We're also 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. 37: Thomas Schmid and Florian Reyer from Hofgemeinschaft Heggelbach © 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 regulations."

Why? What do you think needs to change for agrivoltaics to be used successfully in the future?
Reyer: "It's all about the regulations. Everything needs to change!"
Schmid: "The regulations 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 Energy Sources 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 regulations 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."

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

4 Profitability and business models

Note: The assumptions and calculations relating to cost-effectiveness provided in section 4 are from 2020 and do not reflect the current development in prices.

The costs of agrivoltaics are highly individually variable and depend on factors such as installed capacity, agricultural activity, system location and the PV module technology used. The acquisition cost is generally higher than that of a conventional ground-mounted PV system; in the case of stilted, overhead systems, this is mainly due to the higher, more elaborate mounting system 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 mounting system. 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 mounting system 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.

A distinction is made between interspace and stilted, overhead agrivoltaic systems below for the purposes of cost estimates. Stilted, overhead systems are further divided into systems over 2.5 meters and those with a height of 4 meters and above. Ground-mounted PV systems and small rooftop PV systems are used as references. 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.

A trend can be observed in arable farming whereby systems with a higher installed capacity are needed in order to implement agrivoltaics in an economical way. In horticulture, smaller systems can also be economical if 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 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 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 stilted, overhead agrivoltaic systems of four meters and above, and therefore a lower capacity to area ratio of 600 kW_p per hectare. The mounting system 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. In permanent grassland, a capacity of 300 kW_p per hectare is used for the calculations, as in this case the distance between rows of modules increases accordingly to enable cultivation to take place.

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

1. The module price may increase, as the size or light transmission of the 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 modules, such as semi-transparent PV modules, 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 mounting system, average costs of 372 euros per kW_p are expected in the case of stilted, overhead agrivoltaic systems (> four meters), 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 interspace systems, the cost of the mounting system is significantly lower, at 97 to 167 euros per kW_p. For stilted, overhead systems under four meters, this is between 243 and 306 euros per kW_p.
3. The site preparation and installation costs are also significantly higher, and in the case of stilted, overhead systems (> four meters) 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. In the case of interspace systems or stilted, overhead systems under four meters, 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.

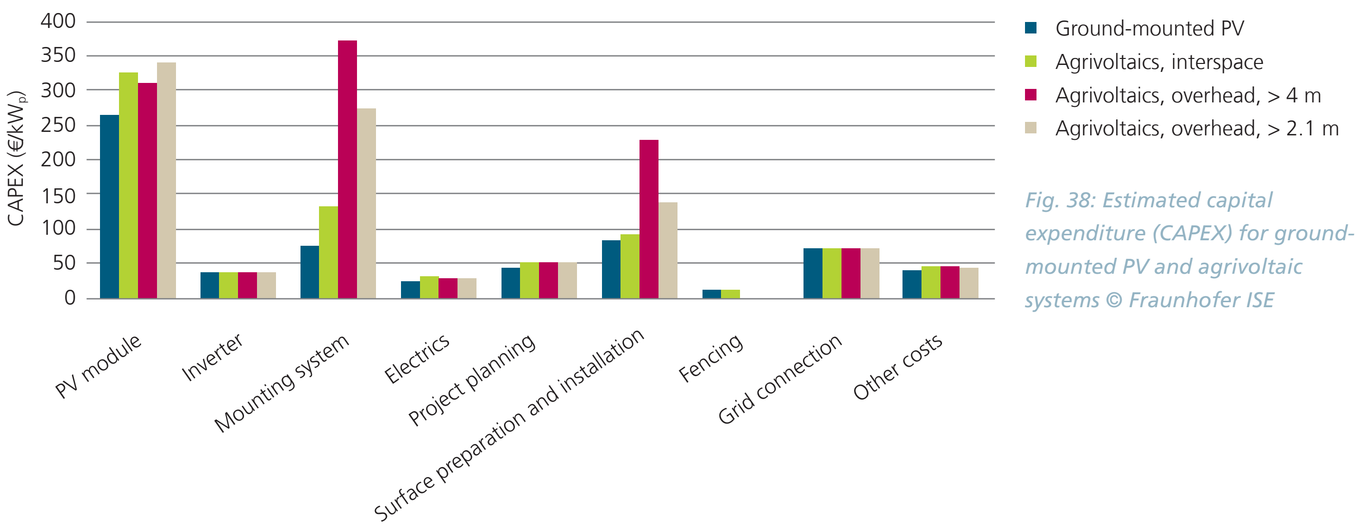


Fig. 38: Estimated capital expenditure (CAPEX) for ground-mounted PV and agrivoltaic systems © Fraunhofer ISE

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 for providing the land are reduced from around 2 euros to 1.3 to 1.6 euros per kW_p. 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 and on grassland because lower lease rates are more common than in horticulture.
2. The agricultural use eliminates the costs of maintaining the areas under the PV modules on the PV side.
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 mounting system and PV modules is currently limited.

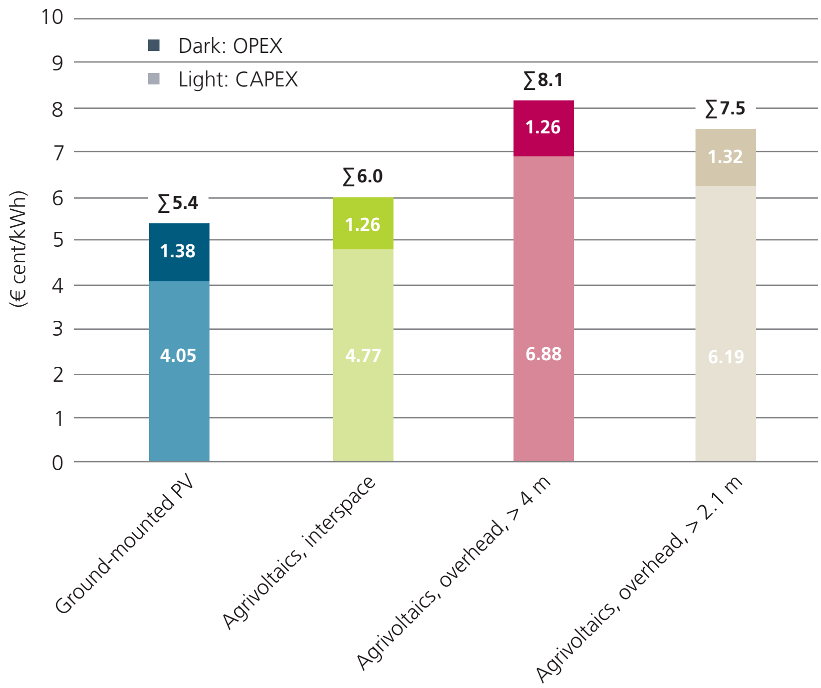
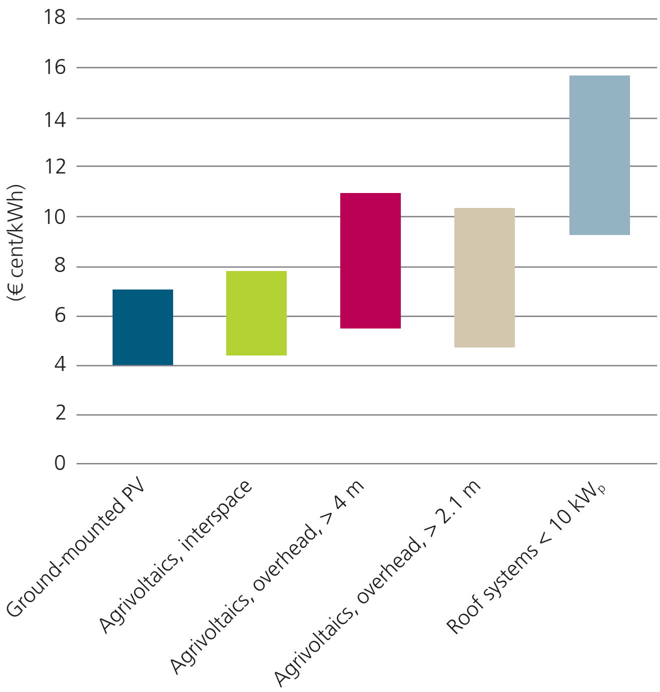


Fig. 39: A comparison of estimated levelized costs of electricity by capital expenditure (CAPEX) and operating expenses (OPEX) of ground-mounted PV systems and agrivoltaic systems © Fraunhofer ISE

4.3 Levelized cost of electricity

It can be concluded that the costs for the production of electricity in the case of stilted, overhead agrivoltaic systems (> four meters) 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 interspace agrivoltaic systems, 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 40.

The cost estimate does not take into account the fact that economies of scale in arable farming and on grassland could lead to a cost advantage because of a tendency towards larger field sizes and therefore larger agrivoltaic systems. The same advantage is also likely to apply in arable farming and on grassland 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, which will increasingly be found in horticulture due to the small field sizes, may also offer advantages in terms of cost-effectiveness, e.g., if the farms use the generated electricity for their own purposes. With an appropriately designed regulatory framework, decentralized locations close to the consumer could lead to additional incentives to build agrivoltaic systems.



4.4 Self-consumption and revenue from power generation

Power from an agrivoltaic system 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 7 euro cents per kilowatt-hour), the potential savings are 7 to 9 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 Energy Sources Act or electricity supply contracts. Section 7.4 describes the circumstances under which compensation is available under the Renewable Energy Sources Act.

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

Fig. 40: Estimated levelized cost of electricity (LCOE) for ground-mounted PV and agrivoltaic systems © Fraunhofer ISE

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: "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.

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 41 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.

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

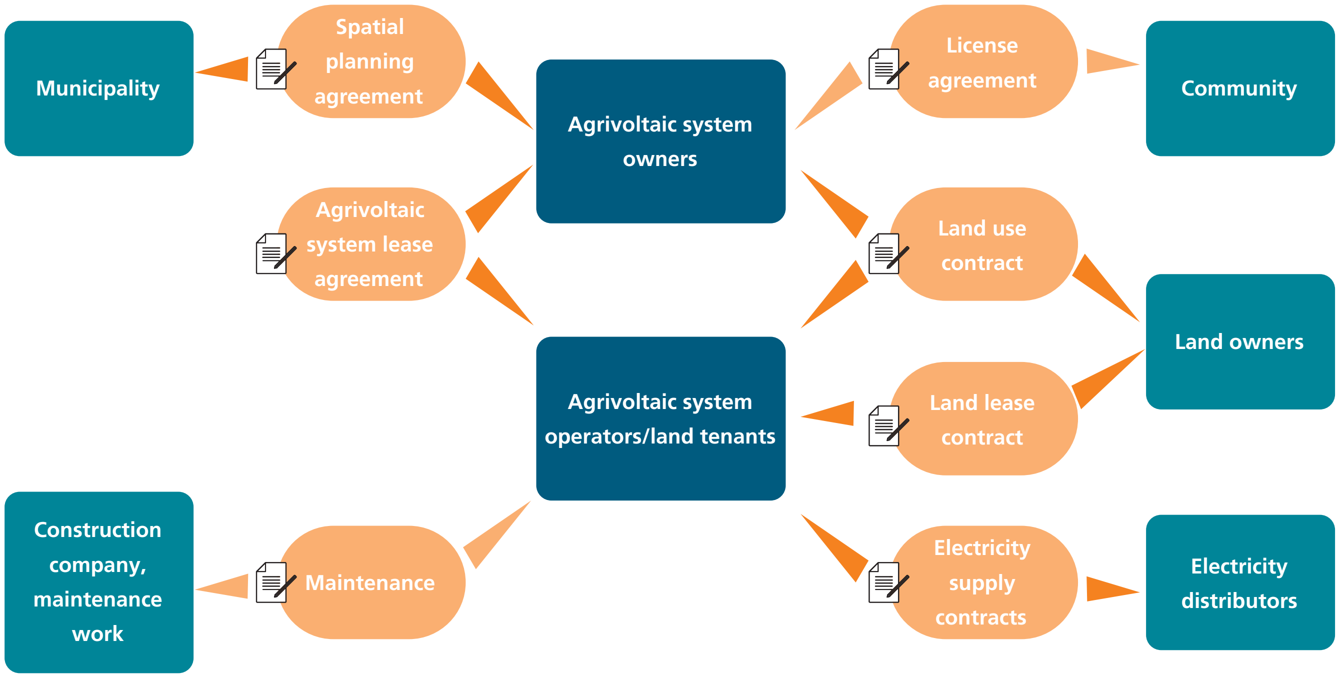


Fig. 41: Stakeholder groups and contractual model © Fraunhofer ISE

Table 06: 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 module technology, the height and alignment of the system, the mounting system 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 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]. However, at the same time there is an increase in technical expenditure as well as in the work involved in control and instrumentation.

The mounting system, 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. 42: Stilted, overhead system enabling cultivation with a potato harvester © Hofgemeinschaft Heggelbach

Fig. 43: PV modules with spatially segmented solar cells and protective function in the Netherlands © BayWa r.e.

Fig. 44: 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.

Stilted 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 stilted, overhead systems in arable farming.

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 43 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 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 mounting system, 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 and reduces the risk of wind erosion.

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 PVmodules 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. 45: PV modules above a polytunnel © BayWa r.e.

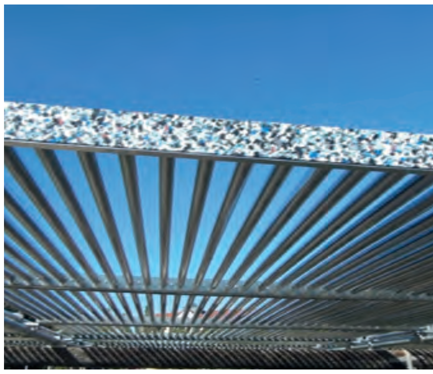


Fig. 46: Special thin-film tubular modules from TubeSolar © TubeSolar AG

Fig. 47: Semi-shade from tubular PV modules installed between tension cables by TubeSolar © sbp sonne GmbH

Fig. 48: Stilted, overhead systems with narrow PV modules in Italy © REM Tec

5.2 PV 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. 49: Stilted, overhead system with continuous rows of modules © Sun’Agri

5.3 Mounting system and foundation

5.3.1 Mounting system 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 for stilted, overhead systems 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 mounting system is lower for interspace agrivoltaic systems 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. 50: 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.

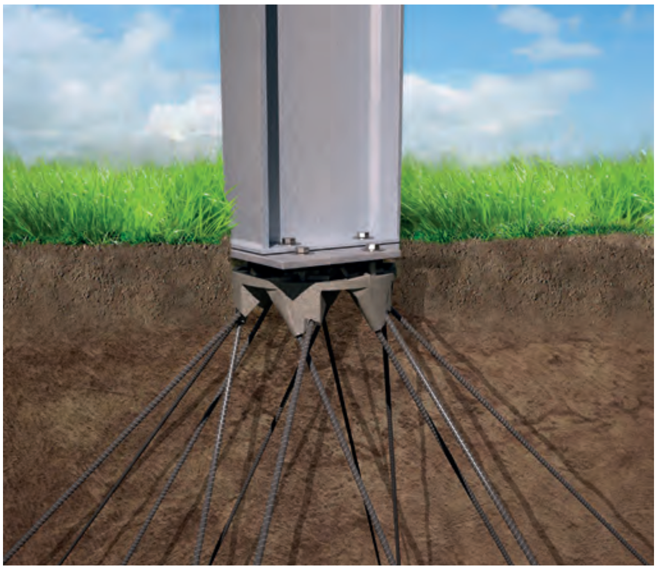


Fig. 51: Spinnanker anchor with anchor plate and threaded rods provides the foundation for the installation system © Spinnanker GmbH

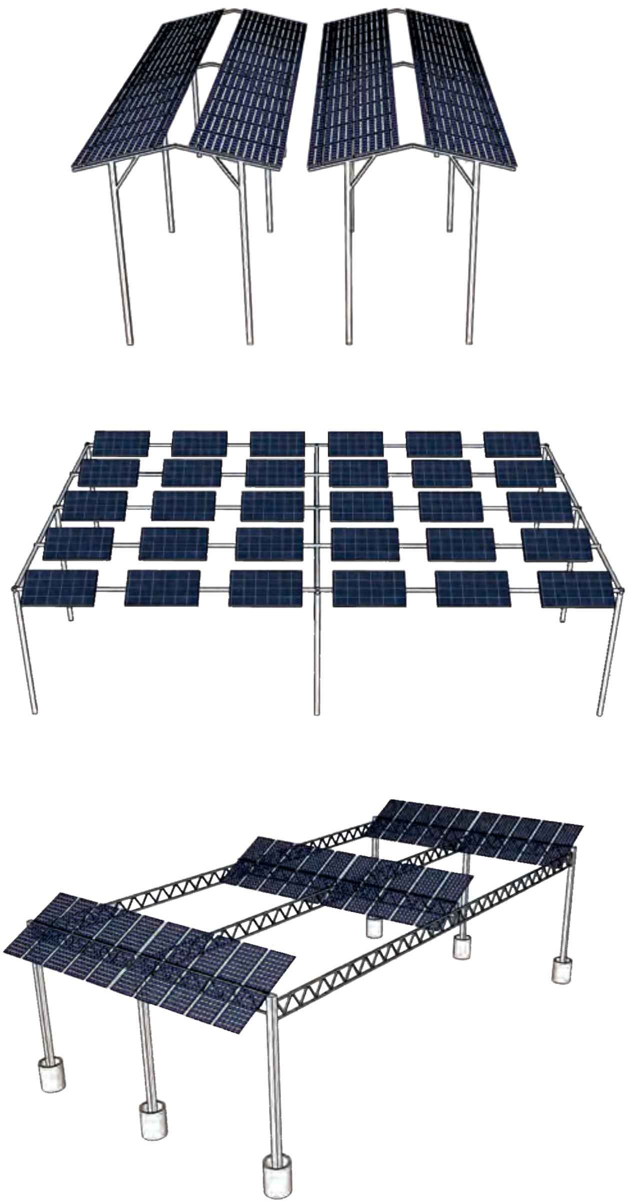


Fig. 52: Illustration of different system types oriented east-west, south and south-east © Fraunhofer ISE

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-easterly 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 southerly 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 modules 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. 53: The shaded strips underneath the PV modules move with the sun's position © University of Hohenheim

Fig. 54: Transparent PV modules casting a shadow over vines © Hochschule Geisenheim University

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. 55: Concept for a rain collection facility with storage tank © Fraunhofer ISE

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 stilted agrivoltaic systems is typically 20 to 40 percent more than that of ground-mounted PV systems. This means that stilted, 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 1100 kW_p per hectare, depending on the type of system. Interspace agrivoltaic systems, on the other hand, manage just 250 to 430 kW_p per hectare, meaning that they require around three times as much land as ground-mounted PV systems.

Fig. 56: Agrivoltaic system in Heggelbach with a capacity of 194 kW_p covering approximately a third of a hectare © Fraunhofer ISE

Fig. 57: Eppelborn-Dirmingen solar farm with 2 MW_p with vertical solar fences by Next2Sun © Next2Sun GmbH

5.7 Approval, installation and operation

Stilted 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). Stilted 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 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 mounting system 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. 58: Working 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 7 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 7.2.

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 07: 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 mounting system.

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 particularly in the case of stilted, overhead systems, 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. 59: Construction roads to avoid soil compaction © BayWa r.e

Fig. 60: 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 concrete 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 systems[32]. The building of ground-mounted PV systems may be rejected or resisted by the local population, who may criticize the form and size of the system and fear that their houses and recreational landscape will lose their value. Acceptance problems 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, even as early as the planning stage, 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 farming and leisure landscape and 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 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 made.

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 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 agrivoltaics will be affected by context factors. These are not directly related to the technology, but are to 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, and credibility of the individuals involved).

Because agrivoltaic systems used with specialized and permanent crops are usually smaller, they tend 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 lower. 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 system, such as the reduction of heat stress on crops through shading, the reduction of disease and of the 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. 61: Citizens' information workshop in the APV-RESOLA project © ITAS

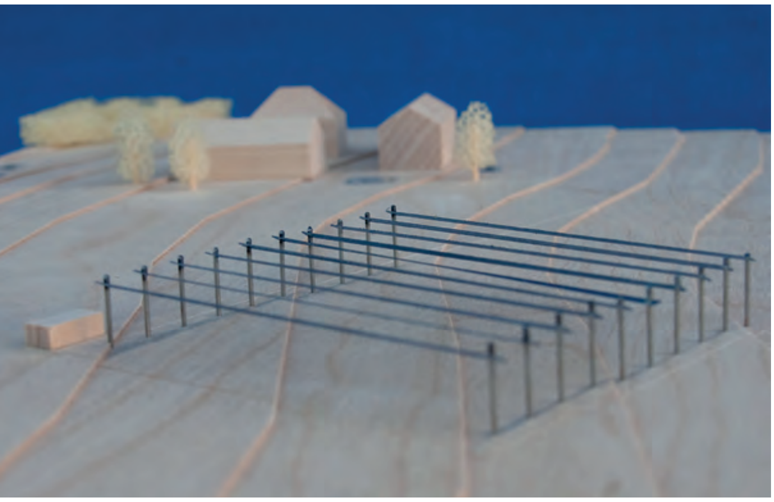


Fig. 62: Model of the agrivoltaic system in Heggelbach for information workshops © Fraunhofer ISE

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 62)[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. "Many years would be needed until clear consequences of agrivoltaics could be seen."

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 63). 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 needn't 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 citizen is 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 a 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."

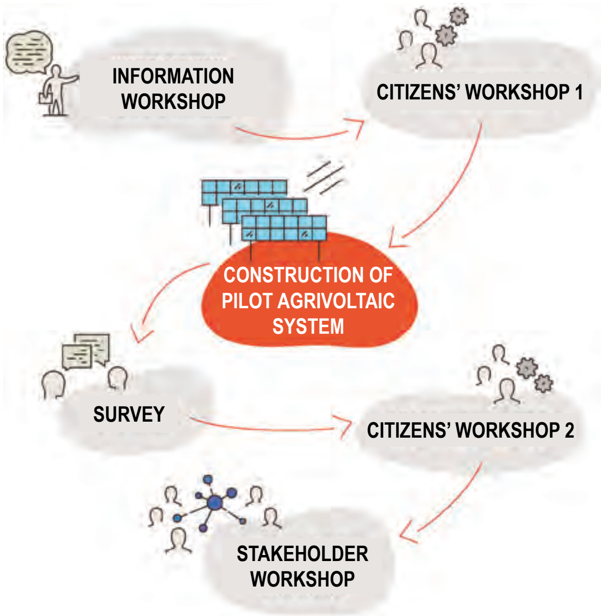


Fig. 63: Multi-stage transdisciplinary agrivoltaic research approach © ITAS

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.

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

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.

Fig. 64: Where agrivoltaic systems produce strips that cannot be farmed, these could be used to increase biodiversity on the agricultural land © Fraunhofer ISE

7 Policy and legislation

Written by Jens Vollprecht, attorney, graduate of forest management studies, Becker Büttner Held PartGmbB

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 Energy Sources 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.

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. It is also important to bear in mind that in many cases no case law has been established in relation to the issues raised, so the positions taken may be subject to legal uncertainty. It is therefore advisable to obtain legal advice when planning an agrivoltaic project.

7.1 EU direct payments

Within European agricultural policy, business owners receive direct payments for land that is primarily used for agricultural purposes, provided that the appropriate requirements are met. An important question, therefore, is whether a plot of agricultural land will lose its eligibility for financial support if it makes use of agrivoltaics.

The German CAP Direct Payments Ordinance (GAP-Direktzahlungen-Verordnung, GAPDZV) has been established as one way to implement the numerous European requirements in relation to the Common Agricultural Policy. In line with this ordinance, the loss of eligibility described above does not arise if the system is an agrivoltaic system.[2] An agrivoltaic system is defined in section 12(5) sentence 1 of the GAPDZV 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. Provided that the requirements are met, 85 percent of the land is considered eligible for financial support, broadly speaking.[3]

This new regulation is to be welcomed as it removes the uncertainty that resulted from the previous regulation. There were very good arguments that the general loss of financial support when constructing a solar PV system on the land was not compliant with European law. Rather, the financial support was to be granted if the use of the land for agricultural purposes was not severely restricted by the operation of the solar PV system.[4] It is also possible to gain this understanding when "reading into" section 12(5) sentence 1 no. 1 of the GAPDZV, meaning that sheep grazing on the land can be seen as "land being cultivated using conventional agricultural methods," for example. As the land that cannot be used for agricultural purposes is often much less than 15 percent, particularly in the case of stilted, overhead systems, the operator should be given the opportunity to obtain financial support for more than 85 percent of the land, provided that the operator can prove this to be the case. This could be achieved by adding sentence 3 below to section 12(5) of the GAPDZV: "If the operator demonstrates that the system reduces the land that can be used for agricultural purposes by less than 15 percent on the basis of DIN SPEC 91434:2021, the land that is eligible for financial support in accordance with sentence 2 increases accordingly."

7.2 Requirements of public-sector construction law

From the perspective of building regulation law, agrivoltaic systems are structural installations, so a building permit is generally required. A building permit is issued provided that the project does not conflict with any regulations under public law. If systems do not require a permit, they must still comply with regulations under public law. The regulations under public law that must be followed include those under construction planning law in particular. Permissibility under public law is based on whether the property falls within the scope of a development plan (section 30 of the German Building Code — Baugesetzbuch, BauGB), in the inner area (section 34 BauGB) or in the outlying area (section 35 BauGB).

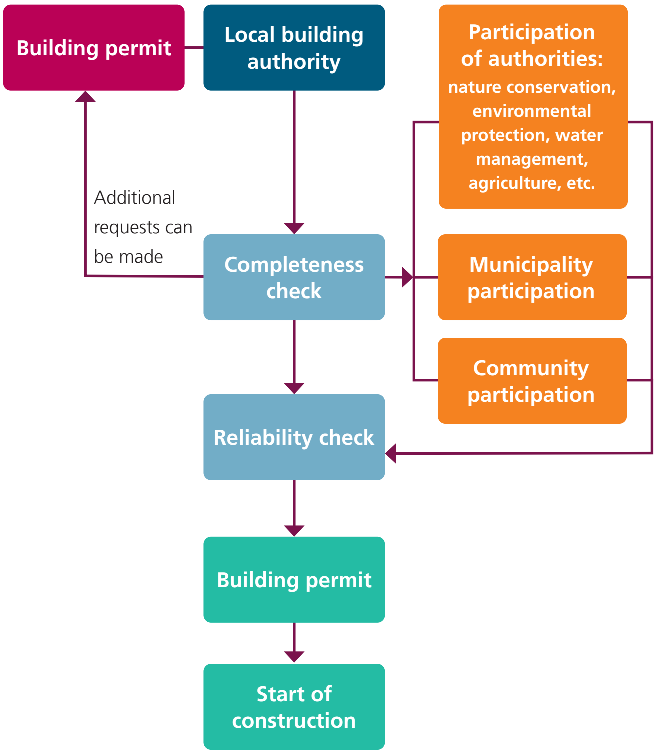


Fig. 65: Example process for a building application
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2 See section 12(4) no. 6 GAPDZV.

3 See section 12 V sentence 2 GAPDZV.

4 For more information, see Vollprecht/Kather, IR 2022, 232 (233).

7.2.1 Outside the scope of a development plan

If the property is not located within the scope of a development plan, permissibility under construction planning law depends on whether the project is in the inner area as per section 34 BauGB or in the outlying area as per section 35 BauGB. The land that comes into consideration for the implementation of agrivoltaic projects is typically located in the outlying area. For this reason, section 34 BauGB is not considered here.

Explicit privilege for agrivoltaic systems has recently been introduced in section 35(1) sentence 1 no. 9 BauGB: In this case, it must be noted that the system must meet the requirements of a special solar PV system in accordance with section 48(1) sentence 1 no. 5 (a), (b) or (c) of the German Renewable Energy Sources Act 2023 (Erneuerbare-Energien-Gesetz, EEG). As such, the requirements stipulated by the Federal Network Agency (Bundesnetzagentur, BNetzA) and the DIN SPEC mentioned above play a key role.[5] In addition, the project must have a spatial and functional relationship with a business in accordance with section 35(1) no. 1 or 2 BauGB, the area of the special solar PV system must not exceed 25,000 square meters, and only one system must be operated per business or facility.

In addition, projects have been included in section 35(1) sentence 1 no. 8(b) BauGB that are intended for the use of solar radiation energy and are constructed on land along highways or railroad tracks in the higher-level network in accordance with section 2b of the German General Railway Law (Allgemeines Eisenbahngesetz) with at least two main tracks and at a distance of up to 200 meters from these, measured from the outer edge of the road or track. Agrivoltaic systems are projects that use solar radiation energy, so these may be classified as privileged projects in the context described above.

If the agrivoltaic system is constructed on another type of land, the amount of work involved in providing justification for classification as a privileged project may be significantly increased. However, there are various other circumstances relating to privilege that may come into consideration depending on the nature of the project.

A project may be considered privileged if it serves agricultural or forestry activities and occupies only a minor proportion of the land (section 35(1) sentence 1 no. 1 BauGB). Agriculture as a term is legally defined in section 201 BauGB. Special attention should be given to the term "serving."[6] In general, the systems required to supply energy to the business's buildings meet this requirement provided that the proportion of electricity used on site primarily serves the business and has a spatial relationship with the same. The business-related proportion of the energy generation measured on the basis of the total capacity of the system must carry significant weight. If the business-related proportion does not considerably exceed the amount of energy intended for the public grid, the system may fail to meet the definition of the term "serve." The German Federal Administrative Court has deemed the use of approximately two thirds of the electricity generated in a wind farm in an agricultural business to be adequate.[7] In view of climate change and the future requirements in agriculture and forestry or horticulture (including protection against hail, heavy rain, strong solar radiation), and assuming an appropriate design of the solar PV systems, the serving function in accordance with section 35(1) sentence 1 no. 1 BauGB derives from their protective function for crops, soil and the water regime. In other words, low on-site consumption of the electricity would be no barrier to classification as a privileged project in this case.[8] The circumstances relating to privilege in accordance with section 35(1) no. 2 BauGB, which state that a project that serves a horticultural business is also considered to be a privileged project, should also be mentioned here. A critical examination would of course need to be made in individual cases with regard to section 35(1) sentence 1 no. 1 BauGB to determine whether only a minor proportion of the land is occupied. In the context of section 35(1) sentence 1 no. 2 BauGB, this additional requirement does not play a role.

5 For more information, see below in section 7.4.3.

6 For information on the term "serving," see German Federal Administrative Court, decision of November 3, 1972 — 4 C 9.70.

7 See German Federal Administrative Court, decision of November 4, 2008 — 4 B 44.08.

8 See Vollprecht/Kather, IR 2022, 232 (234); Attendorn, Klima schützen und Energiesicherheit schaffen, 2022, p. 102 f.; different interpretation Frey/Ritter/Nitsch, Neue Zeitschrift für Verwaltungsrecht (NvWZ) 2021, 1577, 1578, who express concerns under constitutional law due to their belief that privilege for ground-mounted systems in outlying areas is lacking.

7.2.2 Establishing a basis under planning law

If permissibility for a project in outlying areas not covered by a development plan is not possible, the land can be "moved" into an area covered by a development plan. This is achieved by setting up a development plan for the land. The development planning authorities are able to use several instruments for this purpose.

When it comes to issuing a simple or qualified development plan, the numerus clausus principle in accordance with section 9 BauGB must be observed. In accordance with this, the municipality is not entitled to designations that cannot be supported on the basis of section 9 BauGB or the Land Utilization Ordinance (Baunutzungsverordnung, BauNVO). For example, a basis under planning law can be established by designating a special area in accordance with section 11(1), (2) BauNVO. This stipulates that an area intended for systems that are used for research, development or use of renewable energies — such as wind and solar energy — is considered to be a miscellaneous special area. The problematic factor here is that designating it solely as a special solar area may not sufficiently take account of the agricultural use of the area. It therefore appears advisable to designate the area simultaneously as land for agriculture under section 9(1) no. 18(a) BauGB. It has been acknowledged that designations under section 9 BauGB may overlap for individual areas of land, meaning they can mutually complement one another. It is not possible to have different designations for the same area of land if these designations are mutually exclusive. However, agrivoltaic systems guarantee the implementation of different requirements on the same land, meaning these "dual" designations are possible. A further consideration is to select "special area for agrivoltaics" as the designation. These designations must be supported by appropriate written descriptions.

If a project-related development plan is issued in accordance with section 12 BauGB, it would also be possible to make use of the scope afforded under planning law, as the authority can permit the project in this case without any strict consideration of the numerus clausus principle.

7.3 Inheritance tax, gift tax, property tax and land transfer tax

If a ground-mounted system is constructed on an area of land, there is a risk that this land will be allocated to landed property, rather than agricultural and forestry activities. This means that the benefits for agricultural and forestry property in relation to inheritance tax, gift tax, property tax and land transfer tax would no longer apply — and this may even be the case retrospectively if the retention periods after the farm transfer have not yet elapsed.

According to the identical decrees of the highest tax authorities of the states regarding the assignment and assessment of agrivoltaic systems dated July 15, 2022[9], the following rule applies for the purposes of property tax, inheritance tax, gift tax and land transfer tax: Land on which solar PV systems are constructed that are category I or II agrivoltaic systems in accordance with DIN SPEC 91434 must be allocated to agricultural and forestry property. Land on which PV systems are constructed that are not category I or II agrivoltaic systems in accordance with DIN SPEC 91434 (particularly ground-mounted systems) must be allocated to landed property. This makes it clear that the benefits apply only to certain agrivoltaic systems, and not all ground-mounted systems.

However, it should be noted here that design options are available to avoid the disadvantages described above even if the system does not satisfy the requirements stipulated in DIN SPEC 91434.

It should also be noted that a special rule applies in Bavaria. According to art. 9(3) of the Bavarian Property Tax Law (Bayerisches Grundsteuergesetz, BayGrStG), taxation on the basis of the more favorable Property Tax A is possible in spite of the transfer of the land previously allocated to agricultural and forestry property for the operation of ground-mounted PV systems provided that an asset retirement obligation with subsequent continuation of the agricultural and forestry use has been contractually agreed.

9 Federal Tax Gazette (Bundessteuerblatt, BStBl) I 2022 p. 1226.12 particularly section 9 BauGB.

7.4 Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz) 2023

The following section refers to the German Renewable Energy Sources Act 2023 (EEG) in the version dated July 26, 2023 (Federal Law Gazette (BGBl.) 2023 I no. 202). Within the framework of the German government's "Solar Package I," a draft law will be ready by the end of August 2023 that provides for extensive changes in relation to the funding of agrivoltaics, including establishing a separate tender segment for stilted, overhead agrivoltaic systems[10]. Once the change in the law has passed through parliament and been published in the Federal Law Gazette, an updated version of this guideline will be drafted.

Agrivoltaic systems generate electricity from solar radiation energy and should therefore be classified as "entirely normal" systems for generating renewable energy in accordance with section 3 no. 1 EEG 2023.

7.4.1 Grid connection and allocation of costs

Operators of these systems are therefore entitled to priority grid connection from the operator of the general supply grid in accordance with section 8(1) EEG 2023. EEG 2023 also specifies the point at which the system should be connected to the grid. The priority here is to limit the economic costs: This involves identifying the grid connection option with the lowest total economic cost. Only once this option has been identified does it become clear which party has to bear which costs. Here, the following applies: The system operator must bear the grid connection costs, while the grid operator must bear the grid expansion costs.[11]

7.4.2 Purchasing of the electricity

In addition, the operator of the agrivoltaic system is entitled to claim priority purchase of the generated electricity from the grid operator in accordance with section 11(1) EEG 2023. In other words, the grid operator is only allowed to prohibit the feeding of electricity into the grid in exceptional cases. This is true in the case of Redispatch 2.0, for example; but in this case, the system operator is entitled to claim compensation for electricity not fed into the grid.[12]

However, the system operator is not obliged to feed the electricity into the grid, and can use it on-site or supply it to a third party instead "before" it is used in the grid.[13]

7.4.3 Financial support

The matter becomes more complex with regard to funding in accordance with EEG 2023 for the electricity fed into the grid. EEG 2023 has resulted in many positive changes for agrivoltaic systems in this regard.

Mandatory direct marketing, participation in tenders and funding period

Firstly, it must be noted that operators of systems with an installed capacity of more than 100 kW_p[14] are obliged to market the electricity to a third party (known as mandatory direct marketing).[15] However, this does not mean that the grid operator must make no payments in this instance: In the case of funded direct marketing, the system operator is entitled to claim a "market premium" from the grid operator in accordance with section 20 EEG 2023. This is the difference between the reference value[16] and the annual market value for solar energy.[17] Since the electricity is being sold to a third party

10 See the joint press release from three Federal Ministries (Economic Affairs and Climate Action (BMWK), Food and Agriculture (BMEL) and Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV)), available at https://www.bmwk.de/Redaktion/DE/Downloads/Gesetz/20230816-gemeinsames-pressepapier-photovoltaik.pdf?_blob=publicationFile&v=10

11 See section 16(1); section 17 EEG 2023.

12 For more information, see Lamy/Lehnert, EnWZ 2021, 208 et seq.

13 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). For example, the system operator can therefore offer the supplied party a more favorable price for the electricity than a supplier who supplies via the grid. The EEG levy will no longer apply in future as it is to be abolished on January 1, 2023. However, electricity tax still needs to be observed, though in this case the exemption conditions in accordance with section 9(1) no. 1 and 3 of the German Electricity Tax Law (Stromsteuergesetz, StromStG) can open up some potential optimizations.

14 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 2023 must usually be observed.

15 This can be deduced from section 21(2) no. 2 EEG 2023, which states that the system operator can sell electricity to the grid operator but will only receive the low fall-back feed-in tariff in this case. This low feed-in tariff is intended to encourage the system operator to switch back to direct marketing as soon as possible.

16 The reference value is an amount in cents per kilowatt-hour.

17 See no. I.2. Appendix 1, EEG 2023.

and this third party is paying the agreed price to the system operator, the operator therefore receives a total of the market premium and the price agreed with the direct marketer in the case of funded direct marketing for electricity fed back into the grid.

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 tariff" from the grid operator. The feed-in tariff is calculated on the basis of the reference value, from which 0.4 ct/kWh is deducted in the case of fluctuating renewable energies, such as agrivoltaics.[18] However, it is also possible for the operator to switch to another form of selling, such as funded direct marketing.

Operators of agrivoltaic systems with an installed capacity of more than 1000 kW_p[19] must successfully take part in a tender for first-[20] or second-segment[21] solar PV systems under section 29 et seq. in conjunction with section 37 et seq. or 38c et seq. EEG 2023. An exception to the mandatory tender may apply if the agrivoltaic system is operated by a "citizen energy community" in accordance with section 3 no. 15 EEG 2023: In this case, the level at which participation in a tender must take place is increased to 6000 kW_p.[22] It may therefore make sense to establish a citizen energy community for this reason, alongside the aim of increasing the acceptance of the agrivoltaic project. System operators 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 has been abolished.[24] This should be seen as a positive step, as integrating agrivoltaics into agriculture has highlighted the fact that it is essentially ideal in terms of meeting farms' demand for electricity. If the electricity is not used on-site "before" it is used by the grid, it can be fed into the grid and financial support can be claimed for this in the future.

For ground-mounted systems, the "20 MW_p limit" defined in section 38a (1) no. 5 EEG 2023 also needs to be taken into account: Any capacity the system may have in excess of this limit is not eligible for subsidy. As an exception, this limit is increased to 100 MW_p in the case of a bidding date in 2023.[25] For second-segment systems, the size per bid must not exceed 20 MW_p.[26]

Financial support is paid for 20 years from the time at which the system is commissioned.[27] For systems with financial support that is defined in law, payment is extended until December 31 of the twentieth year. It should be noted that entitlements to claim grid connection and purchase of the electricity are not time-limited, meaning they are perpetual rights.

Requirements for financial support

In addition to the general requirements for financial support under the EEG 2023, there are special requirements relating to solar energy that must be met. These are outlined but not described in full below.

18 See section 21(1) no. 1 in conjunction with section 53(1) no. 2 EEG 2023.
19 See section 22(3) sentence 2(a) EEG 2023.
20 Ground-mounted systems and solar PV systems installed on or in structural facilities that are neither buildings nor noise barriers; see section 3 no. 4a EEG 2023.
21 Solar power systems to be installed on or in a building or noise barrier; see section 3 no. 4b EEG 2023.
22 See section 22(3) sentence 2(b) EEG 2023.
23 See section 22(3) sentence 1 EEG 2023.
24 In principle, it was not previously possible for electricity from systems subject to the tendering procedures to be used to supply power directly to the operator. In the event of breaches, the reference value for the entire calendar year in which the breach occurred was reduced to zero; see section 52(1) no. 4 in conjunction with sentence 3 EEG 2021.
25 See section 100(13) sentence 1 EEG 2023.
26 See section 38c(2) EEG 2023
27 See section 25(1) EEG 2023; see also section 51a EEG 2023.

Systems on buildings or other structural facilities
As specified in section 48(1) no. 1 EEG 2023[28], a system is eligible for financial support if it is installed on or in a building 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").

The PV system may also be installed as a roof.[29] 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 function. There is no barrier to financial support if the building structure for supporting and operating the energy-generating systems — as well as with regard to any compensation to be obtained in accordance with the EEG — undergoes a certain amount of optimization with regard to its stability and durability, even if these measures would not otherwise have been strictly necessary in terms of achieving the primary purpose of the structural facility.[30] As a result, a close examination of the individual case is required. For non-residential buildings in outlying areas not covered by a development plan under section 35 BauGB, such as greenhouses, the restriction in section 48(3) EEG 2023 must also be observed. In the case of rooftop systems with a capacity of up to 1000 kW_p, the financial support available is increased if — in simplified terms — all of the electricity generated is fed into the grid and not simply the "surplus."[31]

In cases where the system is not installed on a building, it must be determined whether the system may be constructed on another type of structural facility. If, for example, the structure in question is a trellis for hops to which the module is merely attached, it is possible to make a good argument since the trellis is constructed to allow the hops to grow upward, i.e., for purposes other than generating solar energy. It should be possible to apply the considerations of the Federal Court of Justice (BGH) mentioned above regarding optimization of stability and durability to this configuration. In other words, a certain amount of reinforcement of the trellis would be no barrier to financial support in accordance with section 48(11) no. 1 EEG 2023. The same applies to trellises in orcharding and vineyards, but careful consideration of individual cases is required here too.

Ground-mounted system
If the requirements of a building or other structural facility are not met, eligibility for financial support may also be based on section 48(1) no. 3 EEG 2023[32]: In these cases, an agreed development plan must generally[33] be available for the land, which also — and this is a new stipulation — must not be drained, marshy soil used for agricultural purposes[34]. 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 500 meter strip measured from the outer edge of the fixed road or track[35] or in a "conversion area."

In the case of ground-mounted systems, payment entitlement in accordance with section 38a(1) no. 5(b) EEG 2023 may only be issued if the system is not located on land that was legally defined as a nature conservation area in accordance with section 23 of the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG) or as a national park in accordance with section 24 BNatSchG at the time the decision to establish or amend the development plan was made.

New additions to the EEG that are to be welcomed are the three different conditions for funding in section 37(1) no. 3(a) to (c) EEG 2023 and section 48(1) no. 5(a) to (c) EEG 2023 for certain agrivoltaic systems.[36] In each case, the following requirements (among others) must be met: According to (a) in the regulations, systems on arable land with simultaneous crop cultivation on the same land are funded[37] (arable agrivoltaics)[38].

28 In the case of systems subject to the tendering procedures, this is based on section 38c(1) EEG 2023 or section 37(1) no. 1 EEG 2023

29 Regarding the EEG, see 2004 Federal Court of Justice (BGH), verdict of November 17, 2010 — VIII ZR 277/09.

30 Regarding the EEG, see 2004 Federal Court of Justice (BGH), verdict of November 17, 2010 — VIII ZR 277/09.

31 See section 48(2), (2 a) EEG 2023.

32 In the case of systems subject to the tendering procedures, this is based on section 37(2) no. 2(c) EEG 2023.

33 This does not apply in exceptional cases in accordance with section 37(1) no. 2(c) EEG 2023 if the requirements specified in section 35(1) no. 8(b) BauGB are met (see above for more information).

34 According to section 3 no. 34a EEG 2023, marshy soil is any soil that meets the requirements of section 11(2) of the German CAP Conditionality Ordinance (GAP-Konditionalitäten-Verordnung, GAPKondV) and that can be used as the basis for the area classification in accordance with section 11(3) GAPKondV. The fact that it may not be possible to classify an area of land with legal certainty on the basis of the listed criteria is problematic. It would therefore be desirable if the BNetzA were obliged to designate these areas of land as marshy soil in a definition with legal certainty.

35 The strip was previously limited to 200 m and a corridor 15 m wide had to be kept clear within this strip; see section 37(2) no. 2 EEG 2021 or section 48(1) no. 3 EEG 2021.

36 In the case of systems subject to the tendering procedures, this is based on section 37(1) no. 3(a) to (c) EEG 2023.

To claim the funding in accordance with (b), the systems must be constructed on land with simultaneous agricultural use in the form of cultivation of permanent crops or perennials on the same land[39] (crop agrivoltaics)[40]. At the last moment, (c) was added: This provides for funding of systems on grassland with simultaneous agricultural use as permanent grassland provided the land is not located on a Natura 2000 site in accordance with section 7(1) no. 8 BNatschG and is not a habitat type listed in Annex I of Directive 92/43/EEC (grassland agrivoltaics)[41]. The land must not be classified as marshy soil. It should also be highlighted that the land does not need to be located within an agreed development plan.[42]

If these agrivoltaic systems are stilted to a total clearance height of at least 2.1 meters, the reference value is increased to include a technology bonus, which is 1.2 cents/kWh for a tender awarded in 2023 and reduces incrementally to 0.5 cents/kWh for tenders awarded in 2026 to 2028.[43]

This bonus is to be welcomed but should be increased significantly since the additional cost of the stilts is so high that they are generally not covered by the bonus amount. As a result, there are fears that these stilted, overhead systems will not be implemented. It is conceivable that the Federal Network Agency (Bundesnetzagentur, BNetzA) could be granted powers to increase this value. Similar powers are granted to the authority in section 85a EEG 2023. Another option would be to establish a separate tender segment for these stilted, overhead agrivoltaic systems with a much higher maximum value than that currently provided for first-segment solar PV systems. The additional costs would then be determined in a competitive process.

In addition, the technology bonus is only granted if the system operator has successfully participated in the tenders for first-segment solar PV systems. This is based on the reference to "special solar PV systems in accordance with section 37(1) no. 3(a), (b) or (c)" in section 38b(1) sentence 2 EEG 2023. As a result, this bonus cannot be claimed for systems with a level of financial support that is determined in law. This is not comprehensible since additional costs for stilts are incurred in this size class too. There is no obvious material reason for such unequal treatment. Sentence 3 below should therefore be added to section 48(4) EEG 2023: "Section 38b(1) sentence 2 should be applied with the stipulation that it is not the award of the tender that is used as the basis but the time at which the system is commissioned."

A further category of special solar PV systems is marsh PV in section 37(1) no. 3(e) EEG 2023.[44] In this case, the prerequisite for financial support is that the systems are constructed on marshy soil that has been drained and used for agricultural purposes, and that the land will undergo permanent rewetting following construction of the solar PV system. In this case too, the land does not need to be located within the scope of a development plan. Section 38b(2) sentence 3 EEG 2023 provides for a "marsh bonus" of 0.5 cents/kWh. However, in this case too, this bonus cannot be claimed for systems with a level of financial support that is determined in law. Once again, there is no obvious material reason for this. For this reason, in section 48(4) sentence 1 EEG 2023, "and sentence 3" should be added after "sentence 1" and the "is" should be replaced with "are."

The details regarding these special solar PV systems are specified in a definition by the BNetzA in accordance with section 85c EEG 2023. In the context of arable agrivoltaics and crop agrivoltaics, the definition by the BNetzA dated October 1, 2021 is to be applied.[45] With regard to grassland agrivoltaics and marsh agrivoltaics, the relevant definition has now been issued.[46] A positive development is that a stipulation has been made in the context of marsh PV whereby the additional paludiculture is a permissible

37 It should be noted here that when submitting the bid, the tenderer must submit a self-declaration stating that they have checked that the land is not arable land with relevance to nature conservation. (see section 37(2) no. 3 EEG 2023). It is unclear what requirements in relation to financial support can be derived from this.

38 For systems with a reference value that is determined in law, the land must not have been legally defined as a nature conservation area in accordance with section 23 of the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG) or as a national park in accordance with section 24 BNatSchG (see section 48(1) no. 5(a) EEG 2023)

39 It should be noted here that when submitting the bid, the tenderer must submit a self-declaration stating that they have checked that the land is not arable land with relevance to nature conservation. (see section 37(2) no. 3 EEG 2023). It is unclear what requirements in relation to financial support can be derived from this

40 For systems with a reference value that is determined in law, the land must not have been legally defined as a nature conservation area in accordance with section 23 of the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG) or as a national park in accordance with section 24 BNatSchG (see section 48(1) no. 5(b) EEG 2023).

41 For systems with a reference value that is determined in law, the land must not have been legally defined as a nature conservation area in accordance with section 23 of the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG) or as a national park in accordance with section 24 BNatSchG (see section 48(1) no. 5(c) EEG 2023).

42 This is a fundamental difference when compared to the requirements relating to financial support for "normal" ground-mounted systems in accordance with section 48(1) no. 3 EEG 2023 or section 37(1) no. 2(c) EEG 2023.

43 See section 38b(1) sentence 2 EEG 2023.

44 For systems with a reference value that is determined in law, this is based on section 48(1) no. 5(e) EEG 2023.

additional use. It is a good idea to exploit this potential too, but the technology bonus should be granted in addition to the "marsh bonus" for stilted, overhead marsh systems. This can be achieved by adding the following clause to section 38b(1) sentence 3 EEG 2023: "Sentence 2 applies accordingly if the additional agricultural use of the land (paludiculture) is regulated in accordance with section 85c(1) sentence 3."

This area can only be extended for systems that take part in tenders: Financial support can then also come into consideration for land with plots that were used as arable land or grassland at the time the decision to establish or amend the development plan was made. In short, we can say that the areas of land cannot be assigned to any land category other than that specified in section 37(1) no. 2 EEG 2023 and are located in a constrained area.[47] It should be noted that the definition of a constrained area in section 3 no. 7 EEG 2023 has been expanded to include the areas of land referenced in (b). However, this expansion only applies where the state government has passed a legal ordinance for tenders on land in such areas. This has so far only happened in Bavaria, Baden-Württemberg, Hesse, Lower Saxony, North Rhine-Westphalia, Saxony, Saxony-Anhalt, Saarland and Rhineland-Palatinate on the basis of EEG 2021 — and therefore with the current definition of a constrained area.

In principle, there are no exclusions or superior/subordinate relationships between the regulations regarding rooftop systems, systems on structural facilities, "conventional" ground-mounted systems and special solar PV systems. There is no basis for this in the wording of the regulation, and it is not necessary in view of the purpose of the funding. In fact, the relevant entitlement to claim payment is linked solely to the different land-related requirements and the tenderer or system operator can decide which funding category to claim if the requirements for several funding conditions have been met.[48]

Only in the case of land in constrained areas in accordance with section 37(1) no. 2(h) or (i) EEG 2023 should the land not be one of the types specified in (a) to (g) or (j) of section 37(1) no. 2 EEG 2023.

Innovation tenders[49]

Only system combinations as defined in the German Innovation Tender Ordinance (Innovationsausschreibungsverordnung, InnAusV) are entitled to participate in innovation tenders. In other words, the agrivoltaic systems must be linked to a storage system or another renewable energy system and feed in the electricity via a common grid connection point.[50] Tenderers who succeed in the tender will receive the market premium from the grid operator for the electricity fed in as per section 19(1) no. 1 EEG 2023.[51] The fixed market premium has been abolished, as have the special regulations for special solar PV systems, as these were transferred to the first-segment tenders as of January 1, 2023 in accordance with EEG 2023.[52]

It is questionable whether the technology bonus can also be claimed when a stilted, overhead agrivoltaic system is part of the system combination. The same applies to the marsh bonus in the case of marsh PV.

In section 3(3) InnAusV (old version), reference was made to section 38b EEG 2021 and the application of this was mandated accordingly. This was necessary as the reference value was used as the basis in section 38b EEG 2021 and section 38b EEG 2021 should be read with reference to this fixed market premium. The reference has been removed in the Easter amendment. This is justified on the grounds that the abolition is an amendment that follows on from the abolition of the fixed market premium, so that "the cited standards are to be applied directly."[53] The starting point for this direct application is section 3(1) InnAusV. As such, there are strong arguments that section 38b(1) sentence 2 or 3 EEG 2023 is

45 See section 85c(2) EEG 2023; definition dated October 1, 2021 — file no.: 8175-07-00-21/1, available at: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Ausschreibungen/Innovations/GezeichneteFestlegungOktober2021.pdf;jsessionid=2CCC48CFBAEEAB49D559C0D002E2107D?__blob=publicationFile&v=3

46 Available at: https://www.bundesnetzagentur.de/SharedDocs/Downloads/DE/Sachgebiete/Energie/Unternehmen_Institutionen/Ausschreibungen/Solar1/BesondereSolaranlagen/Festlegung.pdf?_blob=publicationFile&v=2

47 See section 37(1) no. 2(h) and (i) EEG 2023.

48 This is also the position of Clearingstelle EEG|KWKG on the regulations regarding conversion areas (section 37(1) no. 3(b) EEG 2017) and other structural facilities (section 37(1) no. 2 EEG 2017) in the arbitration award dated January 11, 2019 — file no. 2018/39, available at https://www.clearingstelle-eeg-kwkg.de/sites/default/files/Schiedsspruch_2018_39.pdf).

49 This document does not discuss tenders for innovative concepts with hydrogen-based storage of electricity in accordance with section 39o EEG 2023 or for systems for generating electricity from green hydrogen in accordance with section 39p EEG 2023. Agrivoltaic systems could play a role in this context but the relevant ordinances have not yet been passed, so no specific statements can currently be made on the subject.

50 See section 2(1) InnAusV.

51 See section 8(1) InnAusV.

52 For more information on the original regulations, see Vollprecht/Kather, IR 2021, 266 (268).

51 See explanatory memorandum, Bundestag document no. 20/1630, p. 261.

to be applied in the case of tenders from January 1, 2023 to electricity from a stilted, overhead agrivoltaic system or marsh PV system that is part of the system combination. If a storage system is part of this type of system combination, this ultimately also applies to electricity from the storage system that is fed into the grid. This is because — in brief — it can be taken from section 8(2) InnAusV that electricity taken out of the storage system receives financial support just as the electricity fed into the storage system would have done if it had been fed immediately into the grid. In order to avoid legal uncertainty, it would nevertheless be useful to bring appropriate clarification to InnAusV and add sentence 2 below to section 8(1) InnAusV: "The entitlement can increase pursuant to section 38b(1) sentences 2 and 3 of the Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz, EEG)."

7.4.4 Local government involvement in ground-mounted systems

With regard to acceptance, section 6 EEG 2023 is of interest: This regulation states that operators of ground-mounted solar PV systems can grant affected municipalities allowances of up to 0.2 cents per kWh fed into the grid.[49] For systems in receipt of financial support, the allowances are reimbursed by the grid operator. For other systems ("PPA systems"), the system operator must bear this cost themselves.

53 For a similar regulation for wind farms, see Baur/Lehnert/Vollprecht, EnWZ 2021, 341 et seq. The Bundesverband Neue Energiewirtschaft e. V. has developed a template contract for community participation, which is available at https://sonne-sammeln.de/mustervertrag/.

8 Promoting agrivoltaics

Society 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 its various areas of application. Aside from enabling more efficient land use, agrivoltaics can help increase climate resilience, 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. The most important amendments to the legal framework in Germany have been made in recent years, enabling agrivoltaics to be implemented in an economical way. In this process, the potential of other, similar PV concepts with dual land use has been recognized and the relevant political framework has been established, including PV systems on marshy soil with subsequent rewetting, PV systems to increase species diversity and agrivoltaic systems with extensive cultivation. While this development is very welcome in the context of climate and species protection, adequate distinction between the definitions of these PV concepts seems to be of central importance to a sustainable market launch, so that transparency and ultimately social acceptance of agrivoltaics is achieved. The following areas of action therefore appear to be particularly relevant in the context of the upcoming market launch:

- A clear definition with measurable criteria for the different PV concepts with dual land use, which are not intended primarily for intensive agricultural use of the land but for an increase in species diversity or the provision of additional ecosystem services.
- Compensation for the electricity from agrivoltaic systems in accordance with EEG at different rates that take sufficient account of the additional costs and synergies for the different interspace and stilted, overhead agrivoltaic applications.
- Scientific support for the market launch in order to establish the necessary data base to evaluate the different system types and application areas and to counteract undesirable developments effectively and in good time.

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. In addition, approval processes can be implemented in a simplified way through construction law privilege for agrivoltaic systems close to farms with a spatial and functional relationship in accordance with section 35(1) no. 2 BauGB. Typically, this is primarily the case for agrivoltaics in horticulture.

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 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. Furthermore, the momentum of the climate crisis demands the simultaneous activation of all reasonable options.

Admittedly, a slight decrease in crop yields has been observed for the bulk of the systems studied to date. However, the harvest results for the research system 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.

Some future fields of research for agrivoltaics include analyses of the potential in relation to different crops, construction types, PV module tracking and validation of models for yield forecasting. Combinations with energy storage systems, organic PV film and solar water treatment and distribution, as well as the use of electric farming machinery and intelligent and automated field cultivation, are also promising research areas in some cases. 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 mounting system 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 mounting system 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 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.

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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
BauGB	Baugesetzbuch, German Building Code
BMBF	German Federal Ministry of Education and Research
CAPEX	Capital Expenditure
CIS	Copper Indium Selenide
CdTE	Cadmium Telluride
CPV	Concentrating Photovoltaics
EE	Renewable energy resources
EEG	Erneuerbare-Energien-Gesetz, Renewable Energy Sources Act
GW	Gigawatt
GWh	Gigawatt-hour
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized Cost of Electricity
MW	Megawatt
MWh	Megawatt-hour
OPEX	Operational Expenditure
OPV	Organic Photovoltaics
PPA	Power Purchase Agreements
PV-FFA	Ground-mounted photovoltaic systems
REAP	Rural Energy Advancement Programs
STC	Standard Test Conditions
TWh	Terawatt-hour
W	Watt
Wh	Watt-hour
a-Si	Amorphous Silicon
µ-Si	Microcrystalline Silicon
ZALF	Leibniz Centre for Agricultural Landscape Research, Leibniz-Zentrum für Agrarlandschaftsforschung

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://ise.link/agri-pv

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

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PDF version of the agrivoltaics guideline