FRAUNHOFER INSTITUTE FOR SOLAR ENERGY SYSTEMS ISE

AGRIVOLTAICS: OPPORTUNITIES FOR AGRICULTURE AND THE ENERGY TRANSITION

OCTOBER 2020

A GUIDELINE FOR GERMANY

EDITORIAL NOTES

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Federal Minister of Education and Research
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Minister Julia Klöckner
Federal Minister of Food and Agriculture
Photo: © CDU Rheinland-Pfalz

Dear Readers,

Climate change is making itself felt around the world and the agricultural sector in particular is feeling its immediate effects. This is why we need to take action now, realize the opportunities of research, and design climate protection measures so that food security and a sustainable supply of energy go hand in hand.

Germany is not the only country set to become climate-neutral by 2050. With the European Climate Law that is being developed under Germany's Presidency of the Council of the EU, we intend to make a joint commitment for the first time in the European Union towards achieving this ambitious goal. We need to continue expanding renewable energy sources in order to reach this goal. Land requirements and efficient land use are two aspects that also need to be considered in this context.

As the Federal Ministers for Education and Research and for Food and Agriculture, we are working together closely to support the scientific investigation and practical testing of approaches to balancing the competing interests of land use for food and animal feed production on the one hand and renewable power generation on the other. This task is becoming more and more difficult as the use of renewable energy continues to rise, therefore also increasing land requirements.

Agriphotovoltaics (APV) is a promising concept for combining both types of use. This intelligent dual use of land for agriculture and solar power generation has the potential to counteract the scarcity of usable space and to contribute to the sustainable development of rural areas. Farmers have the opportunity to develop new sources of income without losing the productivity of their land.

This technology could also make agricultural businesses more resilient in the face of climate change. The APV modules offer protection against excessive solar radiation, heat, drought, and hail. In very hot and dry summers, this can mean above-average crop yields in addition to the proceeds of solar power generation. This would result in a clear win-win effect.

A recent study carried out as part of the APV-RESOLA research project verified precisely this effect during the hot summer of 2018. Furthermore, even for less extreme summers, the results still showed that the proceeds from power generation more than compensate for possible minor reductions in crop yield. These results clearly prove the suitability of the APV pilot plant for practical use.

The German Federal Ministry of Education and Research (BMBF) and the German Federal Ministry of Food and Agriculture (BMEL) have already given their support to two further agriphotovoltaics research projects. We are thus increasing the number of field-tested use cases and are able to further optimize plant technology. Practical experience with agriphotovoltaics and its use in combination with various forms of cultivation and production methods is essential. Only then can we answer questions that still remain open and use this to set the direction for the future.

This handbook provides comprehensive information about agriphotovoltaics and the results and experiences to date. We expressly welcome the involvement of Fraunhofer ISE, its partners, and other players in the APV field. The BMEL and BMBF will continue to pursue the research and testing of this technology.

The COVID-19 pandemic has clearly shown us that speedy, concerted preventive action helps us provide a more targeted response to the challenges we face.

As climate change progresses, speed is of the essence here as well. The effects are clearly noticeable. Taking the right steps to reach our energy and climate policy goals – which the agricultural sector is also committed to – is becoming increasingly demanding. We are convinced that this can only succeed by employing a wide variety of tools. Agriphotovoltaics could be one of them.

1. RESOURCE-EFFICIENT LAND USE WITH AGRIVOLTAICS

Agriculture in Germany faces the challenge of increasingly scarce arable land resources. One reason for this is the growing development of new settlements and roads. However, the energy transition also demands more area for the solar power generation. Due to the rising demand for land, the lease rates for farmland are increasing. Agrivoltaics has the potential to reduce land competition through the dual use of the land. The agrivoltaic technology generates renewable electricity without taking away arable farmland resources for food production.

Agriculture is increasingly facing major problems due to climate change. Water shortages, extreme weather and increasing global temperatures require new measures to protect plants and the soil against negative environmental influences. Farms in many regions of Germany are under pressure due to legal framework conditions and economic uncertainties. There is little scope for action between species and water protection on the one hand and increasing or stabilizing crop yields on the other hand.

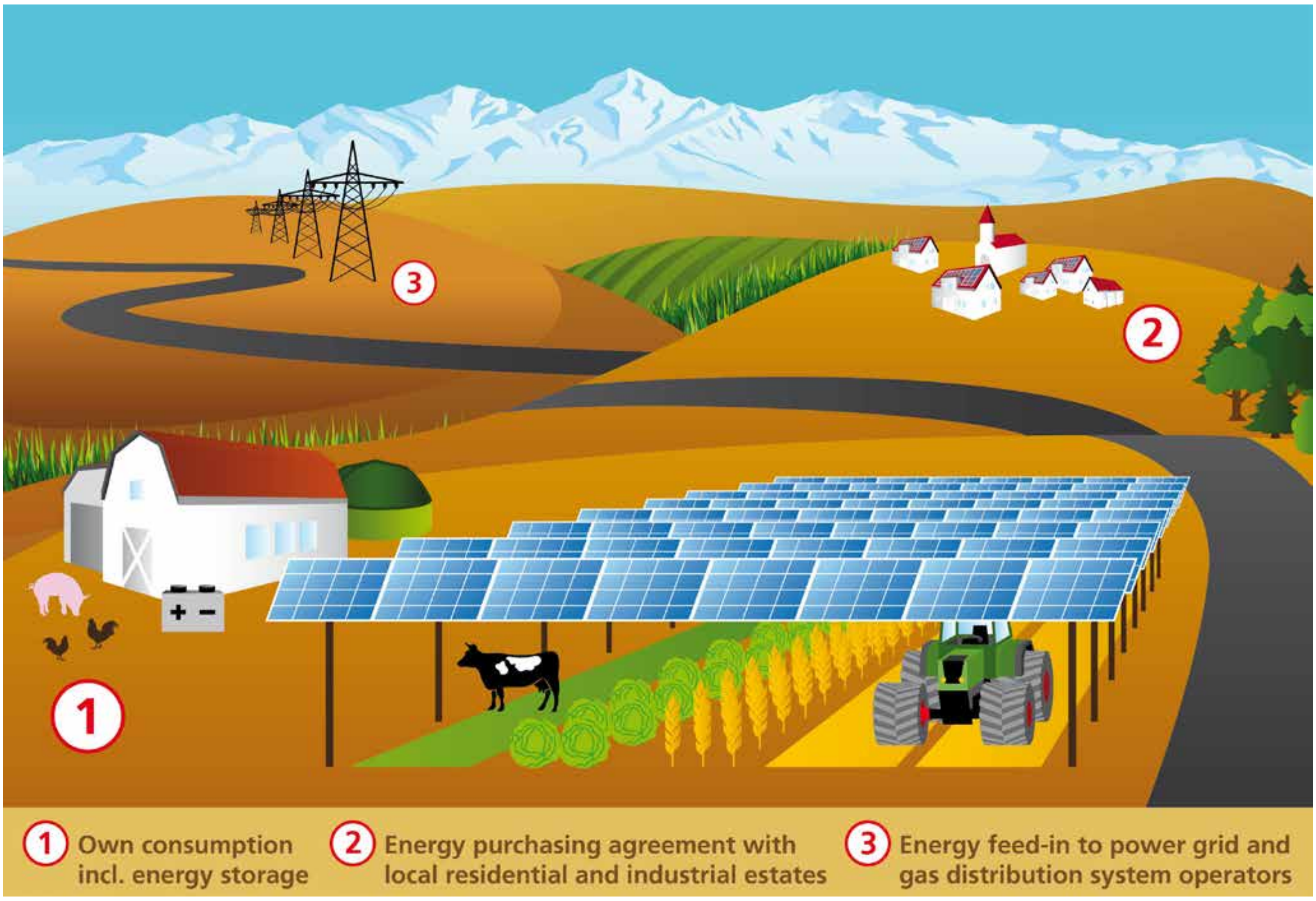


Figure 1: Illustration of an agrivoltaic system. © Fraunhofer ISE

Another problem is that land is becoming an increasingly scarce resource in Germany and worldwide. In addition to the demand for land for residential and commercial space and roads, the energy transition is also claiming farmland. As a result, land use competition is resulting in higher lease rates in agriculture. Regions which are attractive for agriculture thanks to their fertile soil and mild climate and are suitable for ground-mounted photovoltaic systems thanks to high solar radiation are particularly affected by this. The demand for land for ground-mounted photovoltaic systems plays an increasing role. In the meanwhile thanks to continuously falling costs, these systems have become economically profitable even without government subsidies.

The agricultural sector is moving more into the focus as one of the largest emitters of greenhouse gases, especially the gases methane and nitrous oxide (laughing gas). The question thus arises how these challenges can be met in the context of the resolutions of the Paris climate conference in 2015 and the German government's ambitious climate targets.

Dual Use of Arable Land

The dual use of arable land is one possible approach: With agrivoltaics, large ground-mounted photovoltaic systems are installed on farmland which is simultaneously used for food production. Increasing photovoltaic capacity is essential as it is seen as an important pillar of the future energy supply over the long term. According to calculations of the Fraunhofer Institute for Solar Energy Systems ISE, the installed photovoltaic capacity in Germany has to be increased by a factor of eight to ten by the year 2050 for a climate-neutral energy system.[1] At the same time, the efficient integration of a photovoltaics offered by an agrivoltaic system can protect plants and soil against negative environmental impacts, contribute to climate protection and resilience.

Prof. Dr. Adolf Goetzberger, founder of Fraunhofer ISE, and Dr. Armin Zastrow were the first to point out this dual form of land use back in 1981 in the "Sonnenenergie" magazine ("Kartoffeln unter dem Kollektor" (Potatoes under the Collector).[2] In 2014 the APV-RESOLA innovation group ("Agrivoltaics: Contribution to resource efficient land use") picked up this concept from the 1980s, expanding the research to address further questions. The Federal Ministry of Education and Research (BMBF) funded the project within the scope of the FONA research program (research for sustainable development). In this project, the economic, technical, social, and ecological aspects of the agrivoltaic technology were examined in a pilot plant under realistic conditions until 2020.

The project partners were Fraunhofer ISE (management and coordination), the University of Hohenheim, the Institute for Technology Assessment and Systems Analysis (ITAS) [3] of the Karlsruhe Institute of Technology (KIT), BayWa r.e. Solar Projects GmbH, Regionalverband Bodensee-Oberschwaben, Elektrizitätswerke Schönau , and Hofgemeinschaft Heggelbach. The objective of the project was to research the basic fundamentals of the agrivoltaic technology and demonstrate its feasibility.

With the installation of the pilot plant in Heggelbach in the Lake Constance region in 2016, the project partners investigated the combination of solar electricity production and plant harvesting on the same piece of land. 720 bifacial photovoltaic modules with an installed capacity of 194 kilowatt peak (kW_p) were installed with a clearance height of five meters on one third of a hectare of arable land. In 2017 and 2018, the results showed an increase in land use efficiency between 60 and 84 percent as well as improved adaptability during dry periods. The system is currently being used for further research.

Figure 2: APV-RESOLA project partners.

Purpose of Guideline

This guideline presents the key research results of the APV-RESOLA project. It provides information on the possibilities and advantages of the technology and use, gives an overview of the current state of the technology as well its potential, and offers practical advice on the use of the technology for farmers, municipalities, and companies.

Figure 3: The Fraunhofer ISE agrivoltaic research plant at Lake Constance. © Fraunhofer ISE

In addition, the guideline shows successful application examples and points out obstacles and challenges in the use of agrivoltaics in Germany. It also presents proposals on how agrivoltaics can be promoted.

Historical Development

The development of the agrivoltaic technology in recent years has been highly dynamic. Today it is prevalent in almost all regions throughout the globe. The installed capacity has increased exponentially, from around 5 megawatts peak (MW_p) in 2012 to at least 2.8 gigawatts peak (GW_p) in 2020. This was possible thanks to government funding programs in Japan (since 2013), China (around 2014), France (since 2017), the USA (since 2018), and most recently Korea.[4]

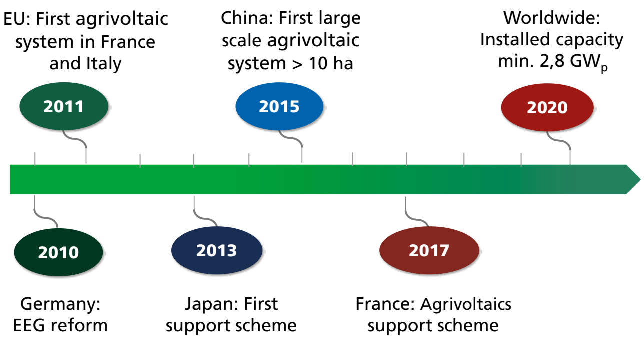


Figure 4: Development of agrivoltaics form 2010 up to today.
© Fraunhofer ISE

Opportunities

The agrivoltaic technology could defuse a current conflict in highly populated countries: Should the already scarce arable land be used to produce food or solar power? As the world population continues to grow, so does the demand for food. At the same time, land is needed for green electricity generation [6] in order to overcome the climate crisis. The combination of agriculture and photovoltaics in the form of agrivoltaics offers benefits for both the energy and the agricultural sector. It may represent an adequate, resource-efficient solution to the problem of land use competition.

Beyond improving land use efficiency, agrivoltaics can also increase resilience and agricultural yields, provided it has a suitable technical design. This was demonstrated in the APV-RESOLA project. Fruit and special crops that are increasingly affected by hail, frost, and drought damage may benefit from the protection provided by the partial roofing with PV modules.[7]

AGRIVOLTAICS AT A GLANCE

- At least 2.8 GW_p installed capacity worldwide
- Estimated technical potential in Germany: ca. 1700 GW_p installed capacity

ADVANTAGES

- Harmonious combination of ground-mounted PV systems with agriculture
- Potential additional benefits for agriculture e.g., protection against damage from hail, frost and drought
- Lower levelized cost of electricity (LCOE) compared to small rooftop PV systems
- Diversification of source of income on farms

CHALLENGES

- Avoid declaration as a "sealed area" on zoning maps, identify agrivoltaic systems as a "special area: agrivoltaics" instead of a "electrical facility/commercial area"
- Establish feed-in tariffs according to the EEG for small agrivoltaic systems (< 750 kW_p), based on criteria
- Establish EEG innovation tenders for large agrivoltaic systems (> 750 kW_p), based on criteria
- BauGB privilege: In order to simplify the approval procedure, classify agrivoltaic systems as privileged projects according to §35 of the German Building Code (BauGB) based on their land-use neutrality and typical outdoor installation.
- Implement a R&D program for agrivoltaics in Germany
- Encourage early and broad involvement of citizens and the different interest groups in order to analyze the non-technical success factors for constructing an agrivoltaic system and to indentify suitable sites

Agrivoltaics offers further potential for synergies between photovoltaics and agriculture such as:

- reducing the need for irrigation by up to 20 percent [8]
- possibilities of rainwater collection for irrigation purposes
- reduction in wind erosion
- use of the PV mounting structure for protective nets or foils
- optimizing light availability for arable crops, e.g. PV tracking systems
- higher module efficiency through better convective cooling
- higher efficiency of bifacial modules due to larger distances to the ground and adjacent module rows

The use of agrivoltaics can create additional value in the region, benefiting rural development. Furthermore, agrivoltaics offers the chance to generate renewable electricity for self-consumption on farms. Solar electricity used directly on site lowers electricity costs by reducing the need to purchase expensive power from the grid and allows farms to establish an second financial base.

Challenges: Barriers to Implementation

While the technical and economic feasibility of agrivoltaics has been proven in many countries, the current regulatory framework is probably the greatest hurdle to exploiting its potential. In Germany, for example, the dual use of land for photovoltaics and agriculture is currently not defined in law and the Renewable Energy Sources Act (EEG) does not provide adequate compensation. Detailed information on the legal framework in Germany can be found in Section 6.1.

Social acceptance certainly poses a further challenge for the use of agrivoltaic systems in some regions. The early involvement of stakeholders and the citizens of municipalities on whose territory the planned agrivoltaic system is to be built is therefore one of the important fields of action of this guideline. This topic is presented in Chapter 5.

In order to be able to make more reliable statements about the different approaches, possible synergy effects and questions of acceptance, it is necessary to install the first larger pilot plants as well as carry out more research projects. In this way, not only the ecological and economic opportunities and risks but also the non-technical, social success factors can be examined in greater detail. At the same time, approaches can be developed to promote the willingness to invest; and players, citizens, and economic enterprises can be encouraged to develop creative solutions. Section 6.2 provides a guide to possible fields of political action.

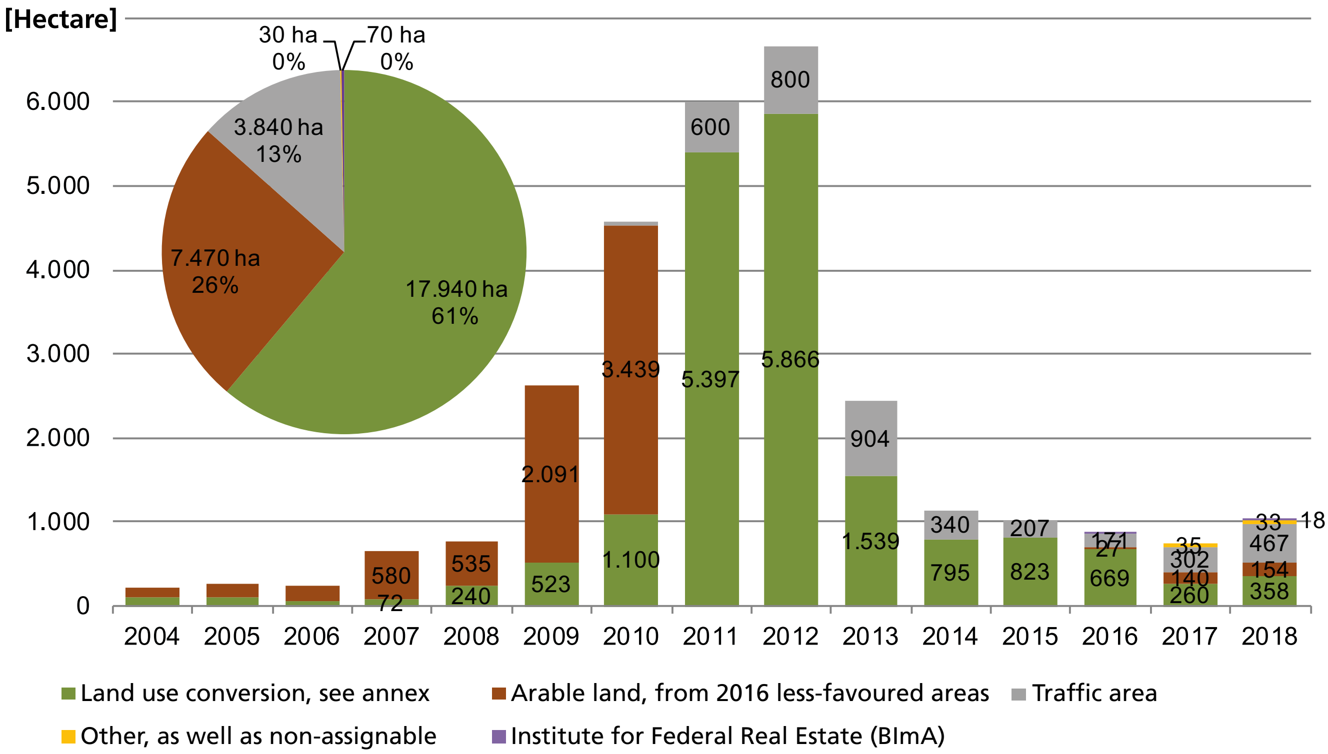


Figure 5: Land use for ground-mounted photovoltaic systems since 2004 in Germany, total portfolio and annual growth.[5] © BMWi

2. DATA AND FACTS

The use of renewable energy sources needs to be considerably expanded in order to meet Germany's climate protection goals. In the last few years, photovoltaics has become one of the most attractive and economical renewable energy technologies available in many regions of the world. Furthermore, solar power shows strong public acceptance compared to other methods of power generation. That said, solar power generation requires comparatively more land than wind or fossil energy sources. Difficulties in finding sufficiently sized land tracts are frequently encountered, especially for large PV systems. The integration of PV into various parts of the human environment – in buildings, lakes or traffic routes for example – is one solution, which allows the land to be used more efficiently for multiple purposes. Agrivoltaics, on the other hand, reduces land consumption. Land use conflicts resulting from the competing interests of energy or food can be potentially alleviated through agrivoltaics, which becomes especially significant in regions with limited available space.

PV and wind power are considered the most important pillars of the future energy supply. The EEG feed-in tariff for solar power in Germany has been decreasing steadily since the year 2000. Meanwhile, prices for PV modules have consistently fallen by about 90 percent from 2009 to 2019. New photovoltaic plants have thus become one of the most attractive sources of electricity in Germany in the meantime. Currently the levelized cost of electricity is in the range of four to nine cents per kilowatt hour (kWh), depending on the size of the system.

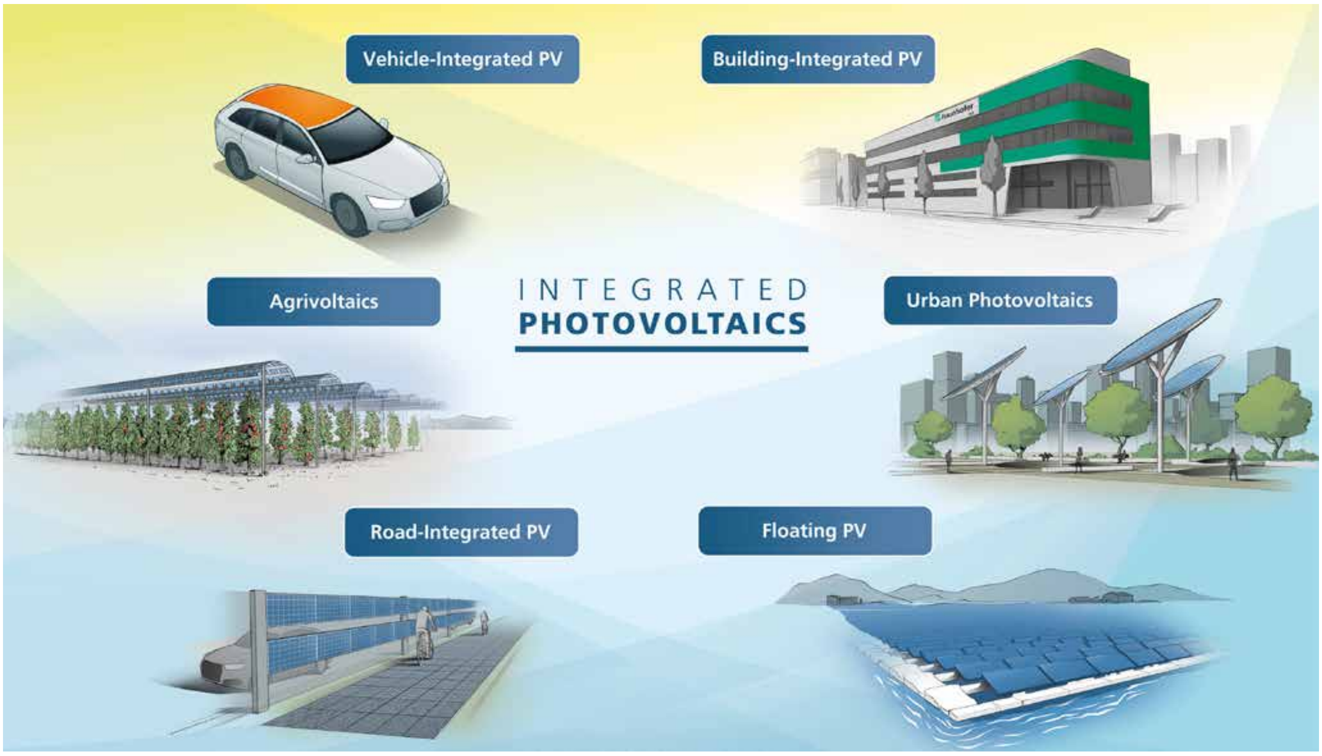


Figure 6: Applications for the integration of photovoltaics. © Fraunhofer ISE

As of mid-2020, around 52 GW_p of PV capacity was installed in Germany. Rooftop installations accounted for some 75 percent and ground-mounted systems for the rest.[9] Considerably more PV installations are needed, however. Calculations by Fraunhofer ISE call for an installed capacity of 500 GW_p by 2050. Large areas with high potential for PV generation can be opened up by integrating PV on buildings, vehicles, and roadways as well as agricultural land, bodies of water and also in urban public spaces.

Just how much of the technically feasible potential can be practically and economically used depends on complex combination of economic, regulatory, and technical constraints. Societal acceptance also plays a role. In general, the levelized cost of electricity is expected to be higher for integrated PV than for simple, large-scale ground mounted plants. On the other hand, integrated PV avoids competition of interests. Synergies can be realized: For example, the PV array can also serve as a building façade or a noise protection wall. Integrated photovoltaics increases the driving range of electric vehicles, or enables the dual use of arable land. Here the following principle applies: the larger the added benefits of PV, the more successful the integration.

2.1 A New Approach to Alleviate Land-Use Competition

Rising numbers of ground-mounted photovoltaic systems will lead to increased land use competition. It is true that ground-mounted photovoltaic systems receiving EEG-subsidies and tenders are only allowed to be constructed only on sealed areas, conversion areas, on strips along highways or railroads, and on areas in (agriculturally) disadvantaged regions. Because the levelized cost of electricity of photovoltaics has decreased enormously over the past years, large PV plants are already being constructed outside of EEG tenders. As a result, the steering effect of the EEG to protect valuable farmland is eliminated.

Figure 7: Ground-mounted PV system. © Fraunhofer ISE

In view of the limited availability of arable land, it is possible that the increasing demand for land will lead to new dimensions of land-use competition, creating new constellations of economic, ecological, political, and social conflicts. Against this background, discussions about the future importance of rural areas as sites for new technologies are in order to defuse looming conflicts of aims and values – also under the aspect of Germany's pioneering role in resolving these global challenges (High-Tech Strategy 2025).

2.2 Definition and Potential

Agrivoltaics allows the simultaneous use of land for both agriculture and photovoltaic power generation. Food crops and electricity can be harvested on the same plot of land. PV modules offering shelter to animals are partly included in the agrivoltaic concept, however, suitable design concepts for modifying a conventional PV roof are still lacking here.

Similar to the case of ground-mounted PV systems, an agrivoltaic system can be realized with either a rigid mounting structure or a one or two-axis solar tracking capabilities. Such tracking systems offer more flexibility in the light management for both agriculture and power generation. Together with the German Institute for Standardization DIN and partners in science and industry, Fraunhofer ISE is currently working on a standard definition of agrivoltaics. A publication of the standard is expected by March 2021.

The technical approaches for the integration of PV in agriculture are as varied as agriculture itself. A rough classification as "cropland", "grassland", and "greenhouses" is possible. Agrivoltaics with cultivated plants, such as permanent or annual and perennial crops, typically requires specialized support systems for the PV modules that are adapted to cultivation, while conventional mounting structures for ground mount photovoltaic systems – sometimes with minor adaptations – are generally used for agrivoltaics on grassland. This guideline mainly examines the "cropland" category (category I), encompassing applications with special crops such as vegetables, fruit, wine growing, or arable farming (Table 1). Applications on permanent grassland are also examined to a lesser extent (category II). Enclosed systems such as greenhouses are not covered (category III).

Table 1: Various categories of agrivoltaics and examples of applications.

#	Agrivoltaic Categories	Examples
I	Cropland (annual, perennial, and permanent crops)	Orchards, berries, grapevines, vegetables and other types of arable farming
II	Grassland (permanent grassland)	Pastures and hayfields
II	Greenhouses (plant growing in closed systems)	Greenhouse, plastic tunnel

In category I, parts of the guideline differentiate arable farming further between permanent and special crops. While applications are highly diverse even within these subcategories, this allows the most important differences between the crops to be identified in a simplified form. Further information on the various technical approaches in categories I and II are found in Section 4.1.

High Potential Evident

Among all approaches of integrated PV, agrivoltaics harbors the greatest potential. Only around four percent of arable land is needed to cover Germany's current total electricity demand (final energy) on the balance sheet (ca. 500 GW_p installed capacity). According to an initial assessment by Fraunhofer ISE, the technical potential of agrivoltaics in Germany alone is around 1700 GW_p, based on shade-tolerant crops in category I for the most part. If only ten percent of these 1700 GW_p were to be utilized, the current PV capacity in Germany would more than triple. From an energy perspective, the dual use of arable land for crop and energy harvesting is considerably more efficient than just growing plants for energy alone, which presently amounts to 14 percent of the agricultural land in Germany (Figure 8).

2.3 Research Sites in Germany

Three agrivoltaic systems for research purposes are presently in operation in Germany. Preliminary tests on a small, dummy ground-mounted system (south-facing) were first conducted in 2011 at the Institute for Horticulture of the University of Weihenstephan-Triesdorf. Roofing paper was used to simulate the shading of the PV modules and lettuce was grown, among other crops. Differences in the amount of shade and variations in the soil moisture caused significant differences in plant growth in the shaded areas directly under and north of the dummy module rows. Results that would be unsuitable in the practice.

An actual agrivoltaic system (see schematic below) with east-west tracked rows of modules was later constructed in 2013. The tracking system mitigated the problem of excess shade caused by the agrivoltaic system.

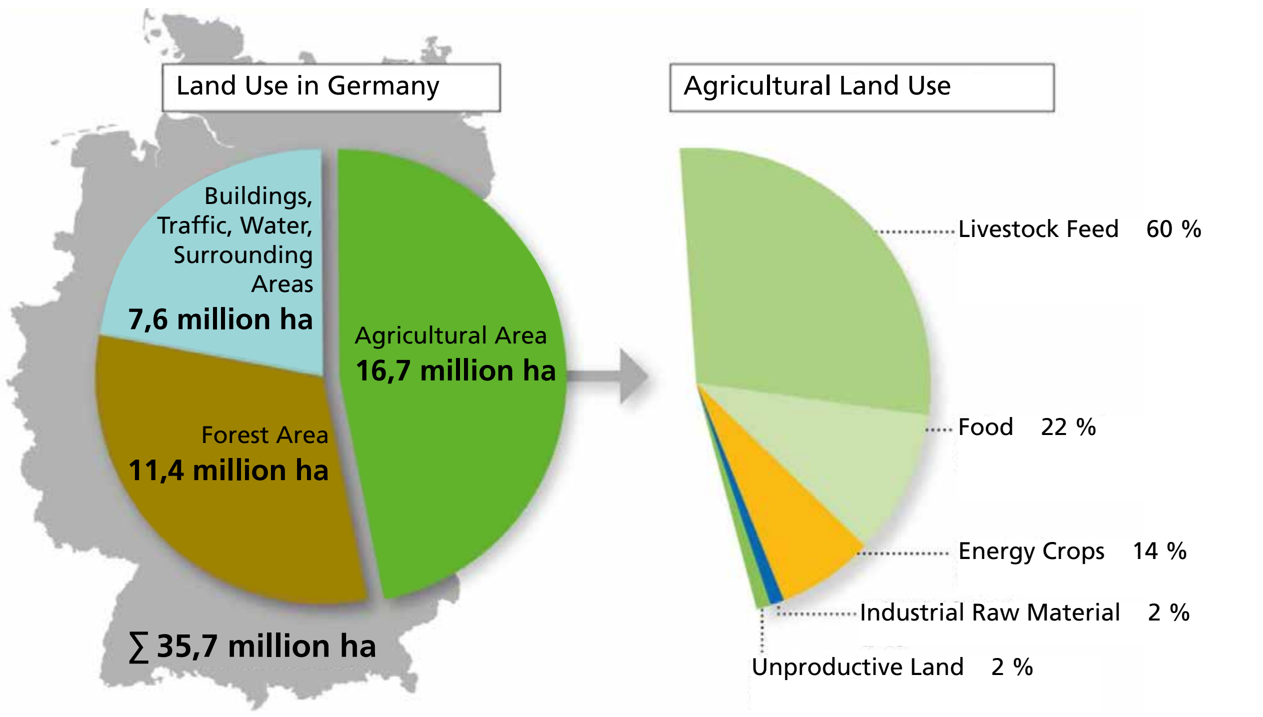


Figure 8: Land allocation in Germany. © Fachagentur Nachwachsende Rohstoffe e.V. according to Federal Statistical Office, BMEL (2017) [11]

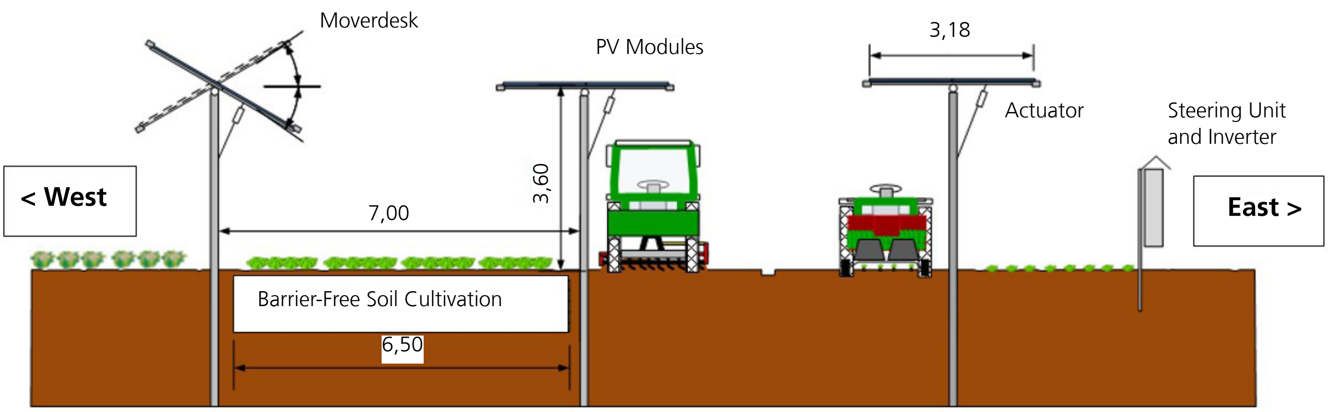


Figure 9: Cross-section of the agrivoltaic plant in Weihenstephan. © 2020 B. Ehrmaier, M. Beck, U. Bodmer

Technical Data of the System:

Area:	21 x 23 m = 483 m²
Moverdesk:	3 pieces per 3,2 x 21 m per 30 modules per 1,6 m²
Tracking:	east-west, calendar controlled
PV module:	CSG 245 W_p; 200 W_p/m² (average value); 245 W_p x 90 = 22 kW_p; 45 W_p/m²
Production/a:	about 35.000 kWh
Use:	own consumption, no subsidy

Investigations considering different distances between the modules in the module row are carried out to determine the influence of various amounts of shade on plant yields and to identify the optimal distance giving the best yield. Tests with Chinese cabbage showed yield reductions due to shading between 29 and 50 percent. The results depend on the varying levels of shade and are shown in the following table:

Causes for the reduced crop yields with agrivoltaic systems include soil compaction during the construction of the system and damage to the plants under the eaves of the modules (Figure 9). Installing rain gutters on the eaves of the modules caused new problems, especially in winter, so that the effects of horizontally arranged, elevated tubular PV modules on the plant yield were investigated as an alternative. In a test with lettuce (Lollo Rosso), for example, the yield underneath the PV tubes was less than 15 percent lower than the reference plant yield without the agrivoltaic installation. Thus, new prospects for agrivoltaic use are possible with such modules, at least for shade sensitive plants. For a complete assessment, the levelized cost of electricity (LCOE) has to be examined with consideration to the profit margins from plant production (referred to as co-products).

Figure 10: Damage on cabbage plants. © 2020 B. Ehrmaier, M. Beck, U. Bodmer.

Table 2: Plant yield comparison between agrivoltaics and open land. © 2020 B. Ehrmaier, M. Beck, U. Bodme

	Dense installation, rows of modules; 0 cm distance between the modules	**25 cm module distance**	**66 cm module distance**	**Cultivation outside the system for comparison**
Average weight of head of Chinese cabbage with agrivoltaics (2014)	1348 g Around 50% of the yield on adjacent open field	1559 g Around 56% of the yield on adjacent open field	1970 g Around 71% of the yield on adjacent open field	2762 g

In 2015, the University of Weihenstephan constructed the second German research plant together with the TubeSolar company. Here the researchers tested the suitability of tube-shaped PV modules for daily use. The installed capacity of this system is 14 kW_p. Potatoes and lettuce varieties were grown.

The third agrivoltaic research plant in Germany was constructed at Lake Constance in 2016 as part of the APV-RESOLA project (Section 2.4).

A team in the vicinity of Dresden led by Prof. Dr. Ulrike Feistel investigated the effects of an agrivoltaic system on the soil's water supply. The crops investigated were spinach, beans, peas, chard and radishes.

In 2020, Fraunhofer IMW launched the BiWiBi project in which the sustainable synergies between vertical, bifacial solar systems and wildflower strips for species conservation and simultaneous agriculture were investigated with consideration to economic, ecological and acceptance issues.[12]

Aside from these research plants, private agrivoltaic systems also exist in Germany. Elektro Guggenmos among others has been growing potatoes, wheat and leeks under an agrivoltaic system in Warmsried, Bavaria since 2008.

2.4 Heggelbach Research Plant: Background and Results

A Demeter farm in Heggelbach, in the Bodensee-Oberschwaben region, was chosen as the site for the research plant. Hofgemeinschaft Heggelbach GbR has been engaged in the organic-dynamic management of the mixed farm, in total approximately 165 hectares (ha), since more than 30 years. The holistic concept behind the Demeter farm includes viewing the operation as a whole. The farm community has been closely examining the topic of energy since 2003. Aside from various PV systems, including one for its own use, it operates one of the first wood gas plants from the company Spanner. It converts wood chips into heat energy for heating the buildings and supplies electrical energy to the grid as a byproduct. In 2009 the farm community received the German solar prize in recognition of its innovative energy concept.

2.4.1 Background Information on the Site

The Lake Constance (Bodensee) district is one of three districts in the region. The proportion of renewable energy sources in this district is far below the German average and now faces the challenge of increasing the target share of renewable energy from ten percent (as of 2013) to 26 percent in 2022. PV with 15 percent is to account for the largest share of that. However, this cannot be accomplished with rooftop systems alone.[6] The supply of farmland and conversion areas in the Lake Constance district is very limited. New approaches are therefore needed. Agrivoltaic technology could be an important component, especially if citizens are included in the decision-making process early on, as in the project APV-RESOLA. The potential for the alternative – wind power plants – in the region is very limited. Wind power plants currently cover only one percent of the electricity demand in the region. This is due to low societal acceptance, driven by efforts to protect the landscape and panorama view of the Alps. By 2022, wind power plants could potentially cover at most six percent of the region's electricity demand. Expanding the use of biomass for power generation, with a contribution of two percent predicted by 2022, is also limited by the low space efficiency (electricity yield lower by a factor of about 40 compared to a conventional ground-mounted photovoltaic system), higher emission factors (CO_2 equivalents higher by a factor of about 2-3 per generated kWh using biogas or biomethane), and falling acceptance by the local population.

Winter wheat, potatoes, celery, and a grass/clover mixture were grown as test crops under the agrivoltaic system in Heggelbach. A larger row distance between the bifacial glass-glass solar modules at a height of more than seven meters and the south-west alignment ensure that the crop

INFO BOX

- Further information on the APV-RESOLA research project is available on the website https://agri-pv.org/en. Please subscribe to the agrivoltaics newsletter, if interested.

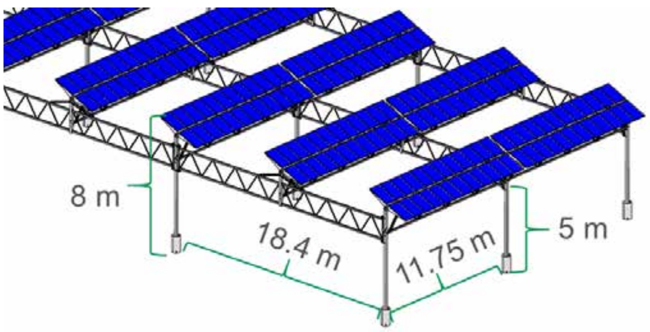


Figure 11: Sketch of the agrivoltaic reference plant in Heggelbach. © Hilber Solar

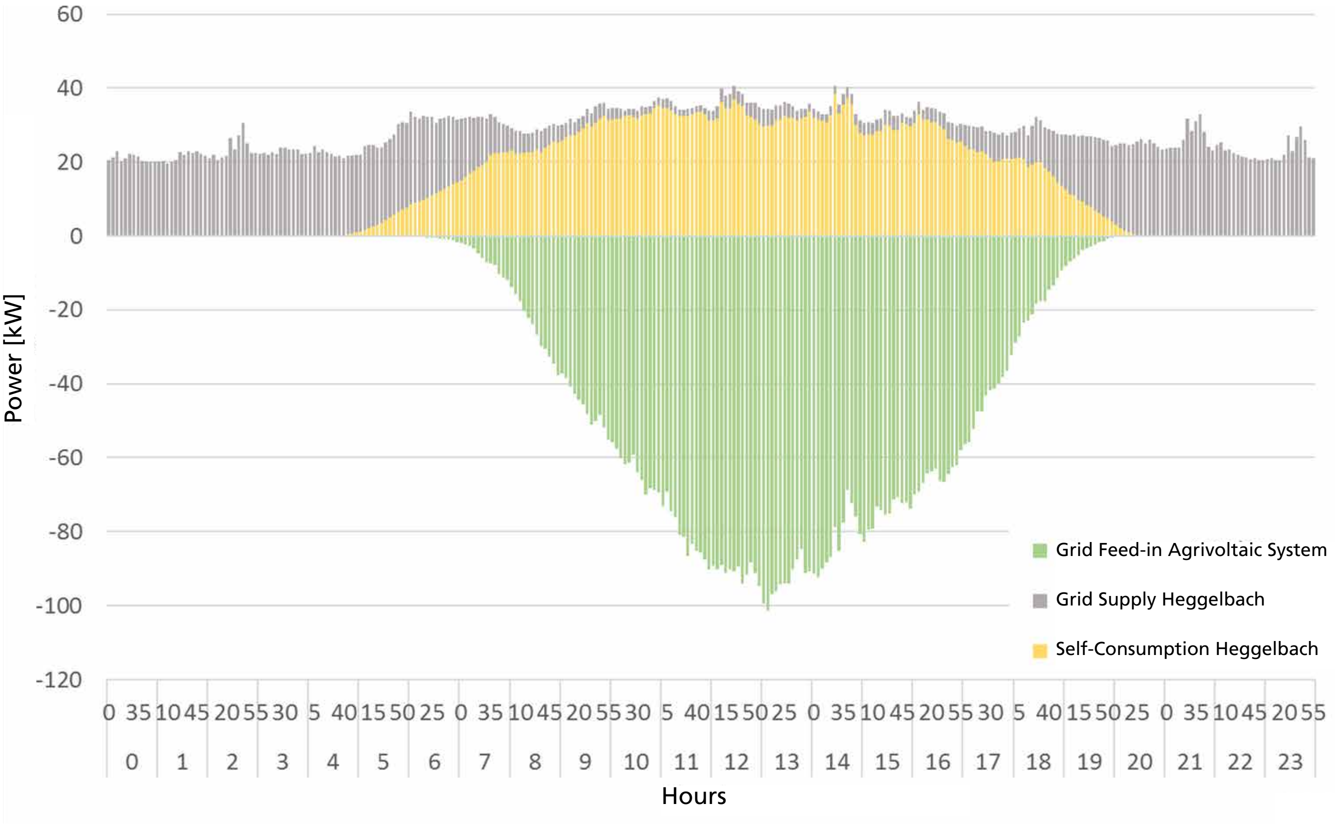


Figure 12: The Hofgemeinschaft Heggelbach was able to cover almost all its electricity needs with power generated by the agrivoltaic system in the summer of 2017. © BayWa r.e.

plants receive a sunlight distribution as even as possible. The 5m clearance height and distance between the supports also permits cultivation with large agricultural machines such as combine harvesters with no major restrictions. On average, the installed capacity of the research plant is sufficient to supply 62 four-person households annually. The system's installed capacity is lower per hectare compared to conventional ground-mounted systems because of the larger spacing between the rows. With an average size of two hectares, the costs for such a system are already competitive with those of small rooftop solar installations.

2.4.2 Results 2017

An increase in the land usage rate to 160 percent was already proven in 2017, the first year of the project. Thus the agrivoltaic system has proven itself as suitable for daily use. The crop yields under the modules remained above the critical 80 percent level compared to the reference plot without solar modules and thus were economically profitable.

The agrivoltaic system generated 1,266 kWh of electricity per installed kW_p of capacity in the first twelve months (September 2016 through September 2017). This result is one third above the average of 950 kWh per kW_p across Germany. That is due on the one hand to the relatively high level of solar radiation in the region and, on the other hand, the increased yield through the use of bifacial modules.
The daily electricity production curve of the PV array on the field matches the load curves on the farm well. About 40 percent of the generated solar power was used directly in the farm community to charge the electric vehicle and for product processing. The agrivoltaic system covered almost the entirely daily load during the summer months. By optimizing their consumption behavior and using electricity storage with a capacity of 150 kWh, the Demeter farmers are striving to increase the proportion of self-consumed electricity to 70 percent. Excess electricity is purchased by the project partner Elektrizitätswerke Schönau .

2.4.3 Results in the Hot Summer of 2018

Since the summer of 2018 was particularly hot, the results of the previous year were considerably exceeded. Partial shade under the solar modules increased the farm's crop yields and high levels of solar radiation increased solar power production. The land use efficiency for potatoes increased by 86 percent.

The research partners believe that the plants were better able to compensate for dry conditions in the hot summer of 2018 thanks to shading by the semitransparent solar modules. This finding highlights the potential of agrivoltaics for arid regions,

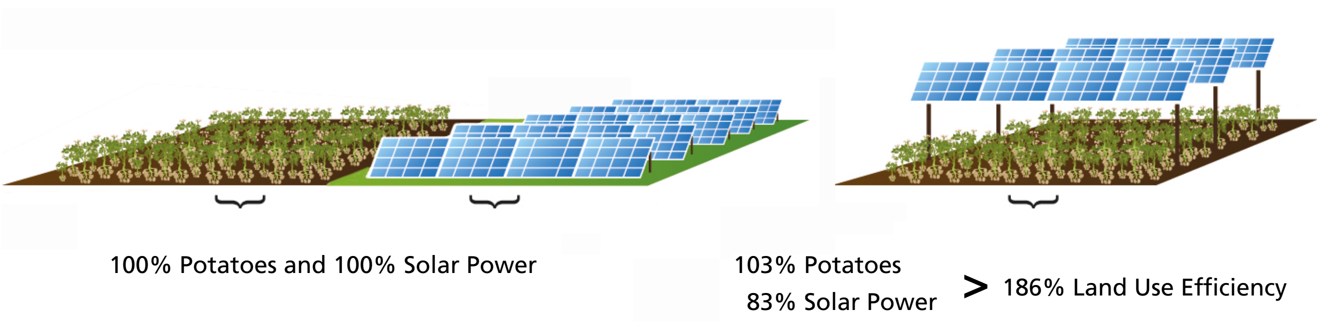


Figure 13: Through the combined use of land, the land use efficiency with agrivoltaics on the test site in Heggelbach is up to 186 percent. (Illustration of potatoes © HappyPictures/shutterstock.com)

but also points to the need for conducting further tests in other climate regions and with additional crops. Solar radiation in 2018 with 1,319.7 kWh per square meter was 8.4 percent higher than 2017. This increased solar power generation in 2018 by two percent to 249,857 kWh, corresponding to an unusually high specific yield of 1,285.3 kWh per installed kW_p of capacity.

The results of the pilot project in Heggelbach indicate agrivoltaic's yield stabilizing effect: Especially during periods of drought, cultivated plants benefit from additional shade.[4]

2.5 International Development

The multiple benefits of the agrivoltaic technologies can be exploited particularly in threshold and developing countries in arid and semi-arid regions. In addition to providing shade for crops and grazing animals (and simultaneously reduces water consumption), agrivoltaics also supplies electricity for water catchment and treatment. This may help to counteract the trend towards desertification and soil degradation. Fruit varieties that normally cannot be grown in semi-arid regions with a dry, hot climate and high levels of solar radiation

Figure 14: Module rows with bifacial modules at the agrivoltaic system in Heggelbach. ©Fraunhofer ISE

could be cultivated with agrivoltaics. Decentralized solar power generation is another added benefit in villages that are remote from the public grid. Agrivoltaic technology can help people gain access to information, education and better medical care (e.g. cooling of vaccines and medications), and enable them to develop new sources of income – without taking land away from food production.

At the same time agrivoltaics helps reduce fossil fuel dependence in rural communities,i.e. the use of diesel generators. Solar power can be used to cool and further process agricultural products so that they keep longer, are more marketable, and can be sold in the post-harvest seasons and in turn generate higher revenues. Political and economic challenges still have to be overcome in order to realize the high technical potential that exists for development cooperation in many countries. In particular, political stability and the limited capital reserves are hurdles for technology transfer and long term investments in agrivoltaic technology.

With more than 2.8 GW_p agrivoltaic installations installed worldwide, China holds the largest share with about 1.9 GW_p (as of 2020). The world's largest system is located in China: Photovoltaic modules of 700 MW_p capacity tower over crops of berries grown on the edge of the Gobi Desert and help to combat desertification. Japan and South Korea also are among the Asian countries that have recognized opportunities in agrivoltaics, however, both countries are betting on smaller systems momentarily. In Japan, more than 1800 systems have currently been installed. In South Korea where migration into cities is rampant, the government is planning to build 100,000 agrivoltaic systems on farms as a retirement provision for farmers (monthly income of around 1000 US dollars from electricity sales) and thus to slow the extinction of farm communities.

A preliminary study by Fraunhofer ISE at a site in India's federal state of Maharashtra indicates that the effects of shading and reduced evaporation from agrivoltaic systems

Figure 15: Pilot plants of the Fraunhofer Chile Research Institute in Curacavi and Lampa. Fraunhofer Chile is investigating which plants benefit from reduced solar radiation. © Fraunhofer Chile

can boost tomato and cotton yields by up to 40 percent.[13] The researchers expect the land use efficiency for this region to nearly double.

In the course of a project under the EU's Horizon 2020 program, in cooperation with partners in Algeria, Fraunhofer ISE researchers investigated the impact of agrivoltaics on the water supply. Aside from reduced evaporation and lower air and soil temperatures, rainwater collection with PV modules also plays a role. Rainwater collection using the modules is of great interest for many countries, including parts of Germany, especially as the frequency of droughts increases.[14]

2.5.1 Research Project in Chile

In an agrivoltaic project in cooperation with Fraunhofer Chile which concluded in spring 2018, three systems each with a capacity of 13 kW_p were built in the environs of Santiago, in the municipalities of El Monte, Curacaví, and Lampa. The region has high solar radiation and low annual precipitation. An ongoing drought in the already dry and sunny climate has caused precipitation to decrease by 20 to 40 percent in the last ten years. Due to the climate conditions, farmers are actively searching for shading installations to protect plants from sunburn and drying out. In this case, the use of agrivoltaics harbors great potential for synergies.

In the project supported by the local government, the project partners investigated which of the crops benefit from reduced solar radiation. The three farms exhibited very different profiles: One farm grows broccoli and cauliflower using professional methods delivered solar power for post-harvest processes such as cleaning, packaging, and cooling. A second pilot plant was built in a family farming operation that specializes in growing herbs. A third plant is located in a remote region with a poorly developed infrastructure and unreliable electricity supply. It provides seven families with reliable energy – among other things for an incubator to hatch chicken eggs.

The three facilities in Chile are the first of their kind in Latin America. The adaptation and optimization of agrivoltaics for the specific climatic and economic conditions of their country were investigated based on these three facilities. The results of the crop production and solar power generation are very positive. As a result, Fraunhofer Chile will expand its research here with the support of the local governments. Monitoring of the three pilot plants in field operation will continue into 2021.[15]

2.5.2 France

France is also promoting agrivoltaics. Separate tenders have been in place for agrivoltaics since 2017, and an installation capacity of 15 MW per year is planned. Contracts are awarded partially based on the offer price and partially on the innovation of the project. The synergy effects for agriculture, which have been identified to date, are also positive. The maximum project size is three megawatts installed power (MW_p). In the first public call for tenders, contracts were awarded only for greenhouses. In the second and third round, 140 MW_p will be tendered each for agrivoltaic plants with a capacity between 100 kW_p and 3 MW_p. Granted projects can obtain feed-in tariff for 20 years. 40 MW_p was awarded for agrivoltaic projects in March 2020. Agrivoltaic systems with tracking are found in France as well: In 2018 the largest system with a tracking to date is used for viticulture and located in Tesserre, Département Pyrénées-Orientales in the Occitania region.

Despite this, agrivoltaics faces a major acceptance problem in France. Since clear criteria for agrivoltaics were not defined in the first round of tenders, the share of agricultural production is very low or even non-existent in some of the projects. These types of deadweight effects have led to a certain resistance towards agrivoltaics, especially in the agricultural sector. ADEME (Agence de l'environnement et de la maîtrise de l'énergie), the French environmental and energy agency, is currently working on clear guidelines for agrivoltaics.

2.5.3 USA

Agrivoltaic systems are also installed in the USA. For example, a research plant in Massachusetts was able to demonstrate the dual use of crop production and power generation. The state provided funding for dual use starting in 2018. The financial assistance is tied to specific requirements: Only those systems are funded, which are built on land zoned as agricultural and do not exceed 2 MW_p. The bottom edge of the modules must be at least 2.4 meters high in non-tracking or fixed systems and at least 3 meters high in systems with module tracking. Also, no point in the field is permitted to have less than 50 percent shade during the main growing period.[4]

The US Department of Agriculture also provides funds to support solar installations in rural areas within the framework of the Rural Energy for Advancement Program (REAP). This could drive the expansion of agrivoltaic systems as well. Additional systems are located in Arizona, Colorado, Indiana, and Oregon. Facilities that promote habitats with a high diversity of species instead of focusing on agricultural use are especially popular. Several universities and research institutions are working on developing effective business models that make agrivoltaic systems with a focus on agricultural use more attractive.

Figure 16: Studies with various types of lettuce under the agrivoltaic research system of the University of Montpellier, France. © Christian Dupraz

3. AGRICULTURE

Crop protection measures are increasingly being employed in agriculture to address the challenges of climate change, water protection and the desire for higher yields. Aside from growing crops in greenhouses and foil tunnels, this includes the use of hail protection nets in orcharding, for example. Especially for high-priced special crops, frost and hail protection measures range from heating wires and antifrost candles to stationary gas or oil burners up to helicopters or cloud seeders that spread ultrafine silver iodide particles under the cloudbase. The use of such technical and mechanical plant protection measures is expected to gain considerable importance in the coming decades because of climate change.

Weather extremes over the past years have shown that global warming is not merely an abstract danger, but already has a major effect on German agriculture. Spring precipitation is especially important for plant growth and has in fact decreased over the last few years.[16] Additional irrigation can bridge these drought periods and safeguard yields. In the light of rising need for irrigation in Germany's agricultural sector and the existing restrictions on drawing groundwater and surface water, additional possibilities for adaptation should be considered. Other weather extremes such as heavy rainfall and hail, which are often regionally limited, endanger the growing of cultivated plants. Farms are facing economic challenges more frequently due to pronounced yield fluctuations.

The dual use of farmland for food production and PV power generation presents the chance to address many of these challenges simultaneously. Agrivoltaics provides farms the opportunity to diversify their income and close internal operating cycles. The lower evaporation rate and increased protection against hail and frost are important factors here. Additional protective systems can be integrated cost-effectively by using existing framework structures. This can considerably increase the productivity and value of farmland. There are, however, restrictions and challenges with regard to agricultural production that come with agrivoltaics as well. In particular, these are changed lighting conditions and the more difficult cultivation due to the support structure. In order to minimize risks and utilize synergy effects to the fullest advantage, selected crops should be combined with an appropriate system design.

3.1 Research Results from the Project APV-RESOLA

In the research project APV-RESOLA, a sequence of several crops encompassing a grass/clover mixture, winter wheat, potatoes, and celery were grown under the pilot plant in Heggelbach according to biodynamic principles. The suit-

Figure 17: Crops studied in Heggelbach (wheat, celery, potatoes, grass/clover mixture). © University of Hohenheim

ability of growing plants under agrivoltaics was successfully demonstrated. A high dependency of crop yields on weather fluctuations was evidenced as well. With potatoes, for instance, the crop yield under the agrivoltaic system varied from minus 20 percent in 2017 to plus eleven percent in the hot, dry year of 2018, compared to the reference system.

Crop cultivation under an agrivoltaic system can reduce evaporation and protect against intense solar radiation, depending on the geographic region and local climate conditions. In the light of increasingly frequent heat waves in Central Europe, this aspect will become important in Germany as well.[17] With potatoes, it also turned out that the proportion of marketable tubers can be increased with agrivoltaics.

Scientists at the University of Hohenheim collected data on crop development, crop yield, and the quality of the harvest as well as the microclimatic conditions, both under the agrivoltaic system and on a reference plot without PV modules (Figure 18). Photosynthetically active radiation under the agrivoltaic system was around 30 percent lower compared to the reference plot. Aside from solar radiation, agrivoltaics primarily affected the distribution of precipitation and the soil temperature. In case of agrivoltaics, the latter was lower compared to the reference plot in the spring and summer while the air temperature remained unchanged. In the hot, dry summer of 2018, the soil moisture in the wheat field was higher compared to the reference plot.

The initial results for yields on the test plots in 2017 were promising: For the grass/clover mixture, the crop yield only fell slightly by 5.3 percent, compared to the reference plot. For potatoes, wheat and celery, on the other hand, the yield reduction due to shading was somewhat more pronounced at 18 to 19 percent.

In the very dry year of 2018, higher yields were obtained for winter wheat, potatoes and celery compared to the reference plots without PV modules. Celery benefited the most with a yield increase of 12 percent. The yields of potatoes and winter wheat increased by eleven and three percent respectively. For the grass/clover mixture, the yield dropped by eight percent compared to the reference plot. To calculate the total yield reductions, the land loss due to the strips between the supports that cannot be cultivated in practice also had to be taken into account at about eight percent.

3.2 Crop Cultivation and Selection

Even though adaptation measures are reduced by using the appropriate system design, crop cultivation under PV modules is not the same as farming and gardening on open fields. These include the practical aspects of field work (3.2.1), crop management (3.2.2) and crop selection (3.2.3).

3.2.1 Adjustment of the Mounting Structure for Farm Machinery

When planning an agrivoltaic system, the practical requirements of agriculture must be taken into account in order minimize the impact on crop cultivation. It is vital that the system is oriented in the same direction as that of the field work, and the distances between the supports of the mounting structure shall be compatible with the height and widths of conventional farm machinery deployed. Cultivation under the agrivoltaic system requires increased driver attentiveness, especially at the outset, to prevent collisions with the supports. For this reason, the supports in the pilot plant in Heggelbach are equipped with fenders, which prevent damage to the system. The actual land loss due to the supports

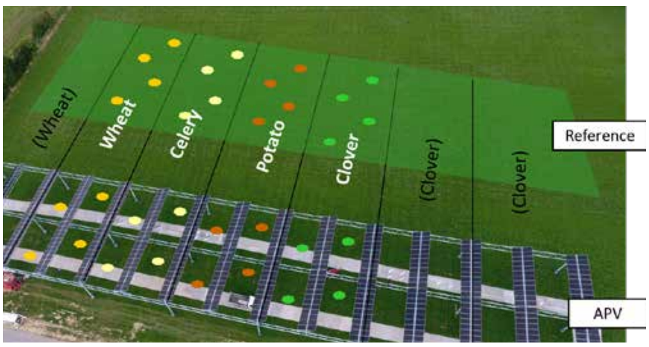


Figure 18: Field layout for the 2017 test setup with measuring stations. © BayWa, modified by the University of Hohenheim

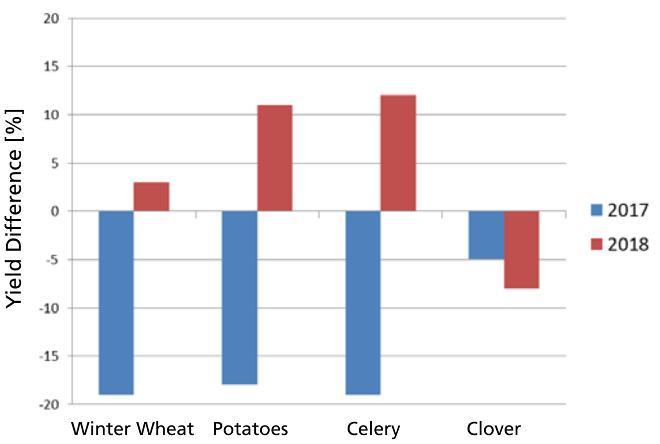


Figure 19: Crop yield differences under agrivoltaics compared to reference plots. 2017 (blue) and 2018 (red) in Heggelbach (excluding land loss due to supports). Data: University of Hohenheim

and fenders in Heggelbach was less than one percent of the arable land. However, since cultivation of the strips between the supports is not practical when working with machines, approximately eight percent of the arable land cannot be used. For manual cultivation or row cultivation, the amount of land loss is reduced to the area that is actually sealed. Innovative cabling techniques can help solve this problem (Section 4.3). The use of precision farming and automatic guidance systems facilitates cultivation.

3.2.2 Microclimate under Agrivoltaic Systems

Shading of the field results in a slightly altered microclimate under the modules. Aside from the studies in Heggelbach described above, the possible effects on the microclimate were also investigated in the USA [18] and France [8]. Researchers found various changes in the microclimate depending on the system location and design. In connection to the findings from APV-RESOLA, however, the following summary can be seen as generally applicable:

1. The solar radiation available to the plants can vary depending on the technical design (e.g., distance and orientation of PV modules). Reducing the radiation by about one third is considered an acceptable benchmark for Germany.
2. The lower the height of the supports, the more pronounced the microclimatic changes.
3. The soil temperature and to a lesser extent also the air temperature is reduced on particularly hot days.
4. The wind speed can decrease or increase depending on the orientation and design of the system. This means that wind tunnel effects and their impact on plant growth should be taken into account during system planning.
5. Soil moisture losses are reduced under agrivoltaics, while the air moisture level can simultaneously increase.

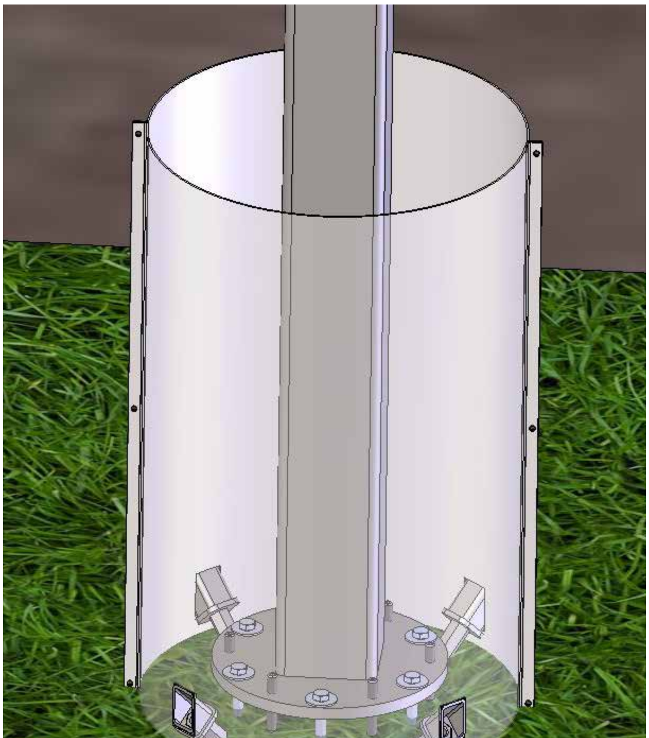


Figure 20: Fenders on the supports of the system in Heggelbach protect against damage from farm machinery. © Hilber Solar

Partial roofing of the arable land leads to an uneven distribution of precipitation on the drip edge of the PV modules. Measures should be taken to minimize risks for soil erosion and related problems like run-off of nutrient-rich topsoil, silting, washing out of seedlings or eutrophication of surface water. Some possible measures are listed in the technical section (Section 4.4).

These insights acquired from the project play an important role for agricultural practices. For systems that only block rain partially or not at all, for example, possible changes in air circulation, air moisture, and infection risks of for fungal diseases must be considered when selecting the type of crop. A lower plant temperature can also extend the time required to reach crop maturity. Therefore, a timely and uniform maturity has to be ensured by appropriate crop selection.

Aside from practical considerations, knowledge regarding the microclimatic effects of agrivoltaics serves as the basis for the selection of suitable cultivated plants. Partial shading under the system, in particular, is a determining factor in selecting suitable crops.

Figure 21: Illustration of an agrivoltaic apple orchard. © Fraunhofer ISE

3.2.3 Suitable Crops

Based on the current state of knowledge, all types of crops are generally suited for planting under an agrivoltaic system; however, different effects on the yield are to be expected due to shading effects. Highly shade tolerant crops such as leafy vegetables (lettuce), field forage (grass/clover mixture), various types of pomaceous and stone fruits, berries, soft fruits, and other special crops (such as wild garlic, asparagus, and hops) appear particularly suitable.

Permanent and Special Crops

Agrivoltaics likely offers the greatest potential for synergy effects with special crops in the areas of wine growing, orchards, and vegetable cultivation. This is due to the high value creation per unit area and often relatively sensitive crops are accompanied by a greater need for protective measures. The meaningful design of the agrivoltaic structure can ensure direct protection against environmental influences such as rain, hail and wind. Furthermore, the supports can also be used for the integration of additional protective elements such as hail protection nets and foil tunnels. Agrivoltaics can help reduce the use of foils and the associated soil contamination by plastic. The costs for conventional protective measures and the yield risk can be reduced at the same time.

Positive experiences with agrivoltaic systems have already been made in leafy vegetable cultivation with lettuce. As the celery crop in Heggelbach, the lettuce responded positively to a light reduction of about 30 percent showing increased leaf area growth.[19]

In wine growing, increased solar radiation and temperature changes due to climate change can strongly affect the quality of the harvest, depending on the grape variety. It may also lead to sunburn and the fruits drying out on the vine.

Figure 23: Agrivoltaic system as weather protection for raspberries. 300 kW_p test system of BayWa.r.e in the Netherlands. © BayWa r.e.

An increase in global radiation increases the sugar content of the grapes, in turn raising the alcohol content of the wine and reducing its quality. This results in a shift of the growing regions and harvest times. Partial shading at high temperatures, therefore, has a positive effect on growth and simultaneously prevents premature ripening.[20] Compared to other types of agricultural, wine growing only requires a height of two to three meters for agrivoltaic systems (Figure 22). This can significantly reduce the costs of the mounting structure. The possibility of integrating the agrivoltaic system into existing protective structures also leads to cost reductions. Agrivoltaic system applications in vineyards are becoming increasingly funded and implemented in France (Section 2.3.2).

Systems in conjunction with pomaceous fruits, such as apples, also show promise. Costly protective systems are often needed in Germany to alleviate the induced risks to yields and apple quality due to climate change. Agrivoltaics can reduce these costs. At the same time, only 60 to 70 percent

Figure 22: Agrivoltaics with solar tracking system in France. © Sun'Agri

Figure 24: Demo project in berry cultivation shows high added value in agriculture. © BayWa r.e.

Figure 25: Wheat harvest with combine harvester. © Fraunhofer ISE

Figure 27: Vertically oriented bifacial modules in the Eppelborn-Dirmingen solar park, Saarland, with 2 MW_p capacity, constructed by Next2Sun GmbH. © Next2Sun GmbH

of the available light is sufficient for optimal apple yields.[21] Fraunhofer ISE is planning a pilot plant in an organic orchard in Rhineland-Palatinate in order to study the effects of the PV modules on pest infestation and crop yields in comparison to the use of conventional protective devices. Synergy effects are expected in hop cultivation as well: The mounting structure can be used for both the hops and the PV modules, thus substantially reducing the costs for cultivation. Crop types and cultivation systems in which fungus disease due to moisture cannot be reduced by accompanying measures appear less suitable on the other hand.

The protected cultivation of berry bushes is another area of application for special crops. PV modules can partly assume the role of foil tunnels here, protecting against rain and hail.

Added benefits for permanent and special crop applications are expected regarding economic viability (Section 3.3), social acceptance (Section 5), and regulatory feasibility (Section 6).

Arable Farming

The results in Heggelbach with various relevant agricultural cultivated plants show that these can clearly benefit from shading by the agrivoltaic system, especially in arid regions. In hot, dry years, the positive effect on the yield is particularly significant. In normal years with high precipitation levels, on the other hand, yield reductions of up to 20 percent may be expected for crops such as potatoes, wheat and other types of grain (barley, rye, or triticale) under fixed mounting structures. Corn is unsuitable for growing in partial shade in temperate regions due to its characteristics as a C4 plant (higher heat and light demand). Experience with other important crops such as canola, turnips, and legumes is still pending. A general recommendation, also regarding broad acceptance by the population and the agricultural sector, is that total yield reductions should not exceed 20 percent. The results from Heggelbach show that this can be achieved through suitable light management for certain arable crops that are relevant in Germany, i.e. with a reduced module density and

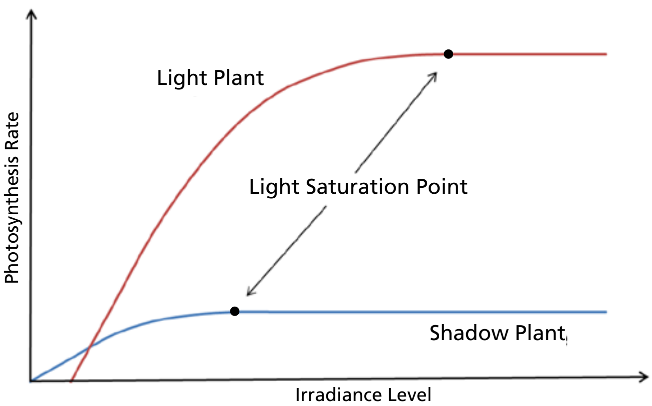


Figure 26: Schematic: Photosynthesis rate depending on the light intensity for sun and shade plants (Source: modified according to [21])

LIGHT SATURATION POINT

Plants need light for photosynthesis, and the ability to utilize incident light differs from plant to plant. Depending on the plant species, the rate of photosynthesis stagnates at a certain light intensity (see Figure 26). The light saturation point is an important criterion for determining the crop suitability for agrivoltaics. From this point on, the plants are not able to convert additional light into photosynthesis output and may even be damaged. The lower this light saturation point is for a plant, the better suited it is for growing under an agrivoltaic system.[21]

adjusted module alignment. Yield losses can be reduced with moveable agrivoltaic systems, whereby the amount of available light can be increased during critical growth phases.

Grassland

Dual use of ground-mounted photovoltaic systems with sheep farming is commonly practiced in Germany. With this approach, the systems are typically optimized only on the PV side. The expected synergy effects tend to be low compared to other agrivoltaic systems, in line with the agricultural value creation per unit area. Concrete research results in this area are however still pending.

The installation of vertical agrivoltaic systems is a new approach that largely permits land cultivation notwithstanding supports close to the ground (Figure 27). Two reference systems have already been built in Germany, in Donaueschingen (Baden-Württemberg) and Eppelborn (Saarland). Benefits for plant growth are expected mainly in windy areas, for instance, close to the coast where the modules serve as windbreaks and thus help reduce wind erosion.

3.3 Economic Viability and Business Models

The costs of agrivoltaics can vary considerably from case to case, depending on factors such as the installed capacity, agricultural management, field location, chosen PV module technology, etc. Capital expenditure are generally higher compared to a conventional ground-mounted photovoltaic system, mainly due to the taller and more elaborate mounting structure. The clearance height and distance between the supports of the mounting structure play a crucial role. Smaller agricultural machines and a high proportion of manual work steps should therefore have a positive impact on economic viability in most cases. Perennial row crops also offer cost advantages since the supports can be integrated into the rows with no significant reduction in the area under cultivation. In contrast to conventional ground-mounted photovoltaic systems, fencing is generally not needed with agrivoltaic systems, thereby eliminating this cost factor.

Small savings in operation are expected for agrivoltaic systems, because some work such as weed control under the modules is performed anyway in the course of normal cultivation. Only the strips between the supports that cannot be cultivated should be maintained to prevent the spread of unwanted weeds. Cost savings from dual use can also be expected on leased land.

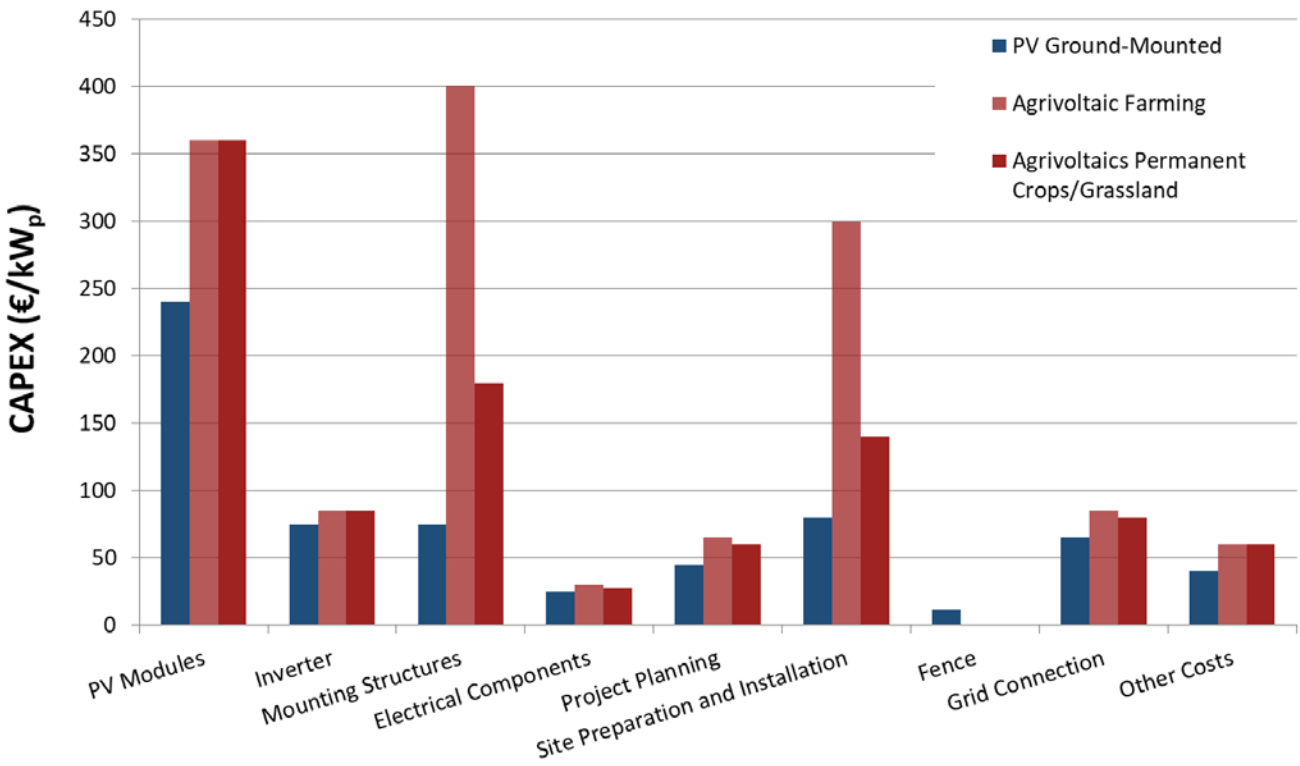


Figure 28: Investment costs for ground-mounted photovoltaic systems and agrivoltaics. Data from [4, 22]

For the following cost estimations, applications in arable farming and for permanent and special crops are differentiated. These are compared to the costs of ground-mounted photovoltaic systems and rooftop systems. Agriculture revenues and expenses were not considered in this estimate.

The result: Systems with higher installed capacity tend to be required in arable farming in order to economically implement agrivoltaics. Smaller systems appear to be feasible in conjunction with permanent and special crops under favorable preconditions. In case of permanent crops, the consistent crop management makes it possible to technically adapt the PV design entirely to meet the agricultural needs. For cultivations with crop rotation, the agrivoltaic design should be based on the average values for the different crops being grown.

3.3.1 Investment Costs

The estimated investment costs are based on an area of two hectares per system and, for the rooftop system, on an installed capacity of 10 kW_p. Since a low amount of shade and therefore a lower yield per unit area appears appropriate for typical arable crops such as wheat, barley, or canola in Germany, a capacity of 600 kW_p per hectare is assumed in the cost estimate for arable farming. The clearance height and support spacing of the mounting structure correspond to the dimensions of the Heggelbach system. For permanent crops of low height, for instance in berry growing, a capacity of 700 kW_p per hectare and a clearance height and width of three and ten meters respectively is assumed.

A capacity of one megawatt-peak per hectare was assumed for ground-mounted photovoltaic systems. An optimistic and a conservative scenario reflect the range of the expected costs respectively. Possible risk premiums or additional legal costs that would be added as of 2020 were not considered in the agrivoltaic scenarios. Thus, the values correspond to the assumed costs over the medium term in case of an agrivoltaic market launch. The differences in the expected investment costs for ground-mounted photovoltaic systems and agrivoltaics are shown in Figure 28.

The differences in the investment costs can be mainly traced back to three cost centers:

1. The module price can increase since, for example, the size or light transmission of the modules must be adapted to the needs for plant growth in case of low structural heights (Section 4.2). With the use of bifacial glass-glass modules, an average increase from 220 euros per kW_p to 360 euros per kW_p compared to standard PV modules was therefore assumed in the sample calculation. These additional expenditures are partially compensated by higher power generation per installed capacity.
2. Average costs of 400 euros per kW_p are expected for the mounting structure in arable farming compared to 75 euros per kW_p in case of ground-mounted photovoltaic systems. However, this estimate is subject to considerable uncertainties, which fluctuate between 320 and 600 euros per kW_p depending on the design, learning effects, and economies of scale. The mounting structure costs for special and permanent crops are considerably lower at 130 to 220 euros per kW_p.

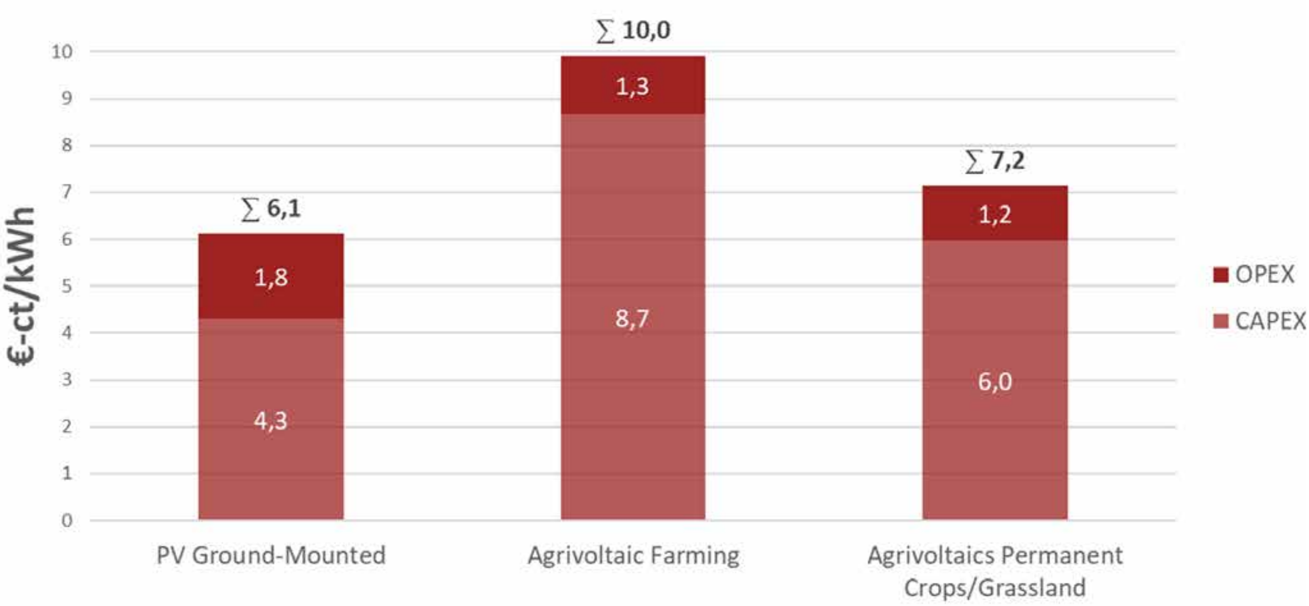


Figure 29: CAPEX / OPEX of ground-mounted photovoltaic systems and agrivoltaics in comparison. Data from [4, 22]

3. The costs for site preparation and installation are considerably higher as well, and estimated at 250 to 350 euros per kW_p in arable farming (ground-mounted photovoltaic systems: 70 to 100 euros per kW_p). Cost drivers include soil protection measures, such as the use of construction roads, and reduced flexibility regarding installation since project planning has to be based on cultivation periods in agriculture. For special and permanent crops, a considerably smaller cost increase is expected with costs ranging between 120 and 180 euros per kW_p.

Aside from the aspects mentioned above, the costs for inverters, electrical components, and project planning, for example, are comparable in most cases according to the current state of knowledge and hardly differ from ground-mounted photovoltaic systems on average. Savings can be achieved on a small scale if fencing is omitted.

3.3.2 Operating Costs

In contrast to the investment costs, savings compared to ground-mounted photovoltaic systems tend to be expected for the operating costs. Savings mainly consist of the following:

1. The cost for providing the land drops from around 3 to 0.8 euros per kW_p in arable farming and 1 euro per kW_p for permanent and special crops. This estimate is based on the assumption that land costs for agrivoltaic systems are aligned with agricultural lease rates and are evenly shared between the farmer and the operator of the agrivoltaic system. This value can, however, vary considerably depending on the ownership structure and business model. Potential savings in arable farming may be higher since lower lease rates are generally expected here compared to permanent and special crops.
2. Agricultural use eliminates the PV-side costs for land maintenance under the modules.
3. On the other hand, higher costs can be expected for cleaning the modules or making repairs to the system when this has to be carried out at greater heights, using lifting platforms, for example. But since cleaning costs for modules only play a minor role in Germany to date because of regular rainfall, the added cost is manageable. In regions with a higher likelihood of soiling, the added costs for cleaning may, however, carry considerably more weight depending on the cleaning technique. There is no experience to date regarding the long-term effects of fertilizers and plant protection agents on the mounting structure and PV modules.

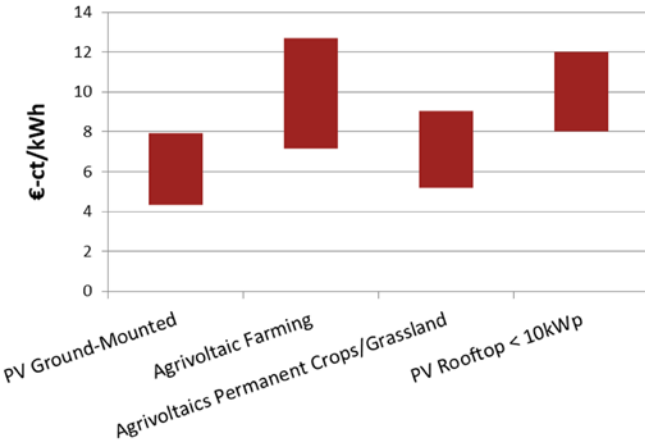


Figure 30: Estimated average levelized cost of electricity for ground-mounted photovoltaic systems and agrivoltaics, representation by Fraunhofer ISE, data from [3, 4, 23, 24]

3.3.3 Levelized Cost of Electricity

On the bottom line, the generation of electricity in arable farming over a 20-year term with a levelized cost of electricity of 9.93 euro cents per kWh on average is almost twice as costly as the average ground-mounted photovoltaic system and is comparable on average with small rooftop systems. For permanent crops with a low clearance height, the levelized cost of electricity at an average of 7.13 euro cents is, on the other hand, only about one third higher compared to ground-mounted photovoltaic systems. The range of the levelized cost of electricity for agrivoltaics compared to ground mount photovoltaic systems and small rooftop systems is shown in Figure 30.

The cost estimate does not take into account that economies of scale in agrivoltaic systems with arable farming (and the tendency to larger field sizes) may result in a cost advantage, compared to systems coupled with special and permanent crops. This economic advantage should also apply to the fixed costs of the project planning, since grid connection, for example, is a key factor for the total fixed costs and therefore the overall economic viability for small systems. On the other hand, small systems may benefit economically when farms use the electricity generated on site. Given a corresponding regulatory framework, added incentives for the construction of agrivoltaic systems can be created for sites that are decentralized with electricity generation close to the consumers.

3.3.4 Self-Consumption and Electricity Revenues

Electricity from an agrivoltaic power plant is most valuable when it is self-consumed, since this directly reduces external electricity purchases. At a commercial electricity price of 14 to 16 cents (ct) per kWh [25] and a levelized cost of electricity around 9 ct/kWh, for example, savings of 5 to 7 cents per kWh can be realized. A consumption profile similar to the generation profile, with peaks around the mid-day and the summer half-year, is advantageous for a high level of **direct consumption**.

For applications with a **storage capability**, such as cooling, the daily consumption profile can be adapted to electricity production through thermal storage, for example. The generation profile can also be considered in charging electric vehicle batteries, thereby increasing self-consumption.

In view of the falling costs for **stationary energy storage systems**, their use with a favorable consumption profile may also be economical and should be examined on a case-by-case basis. A customer has to be found for PV electricity that cannot be used directly or stored. EEG models or electricity supply contracts are generally suitable here.

EEG remuneration is currently possible only when the agrivoltaic power plant is built on strips along highways or railways. For power plants with a nominal output over 750 kW_p, the successful participation in a tender is also mandatory and self-consumption is not permitted.

Various energy suppliers offer to buy electricity from PV power plant operators under **electricity supply contracts**. The UmweltBank, for example, has developed a sample electricity supply contract for ground-mounted photovoltaics projects on the basis of power purchase agreements (PPA).

3.3.5 Business Models

Due to the inclusion of the agricultural sector, the complexity of an agrivoltaic business model often exceeds that of a ground-mounted photovoltaic system. Various parties with different functions are involved in the implementation, depending on the constellation of the project partners.

At least four functions can be differentiated here:

1. Providing the land (ownership)
2. Agricultural management of the land
3. Providing the PV system (ownership/investment)
4. Operating the PV system

In the simplest business model, all four functions can be handled by one party – typically by a farm. This model is expected primarily for small, on-farm agrivoltaic systems in the old federal states, when the investment cost is manageable and ownership of the land is likely. Aside from the low costs for project planning and contract negotiation as well as the high degree of decentralization, the main benefit is that the possible advantages and disadvantages of an agrivoltaic system can be taken into account more readily and dynamically when the interactions between the agricultural and photovoltaic levels impact the same economic unit. This is particularly relevant for agrivoltaic systems due to the possible interdependencies between the two levels. With bifacial PV modules, for example, the albedo and therefore the electricity yields can be increased through the selection of the crop plants and agricultural management. The possibility of

Table 3: Constellations of different agrivoltaic business models (based on [4]).

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 investor	Farm
4. Cultivation and operation only	Land owners	Farm	PV investor	Farm
5. Cultivation only	Land owners	Farm	PV investor	PV operator

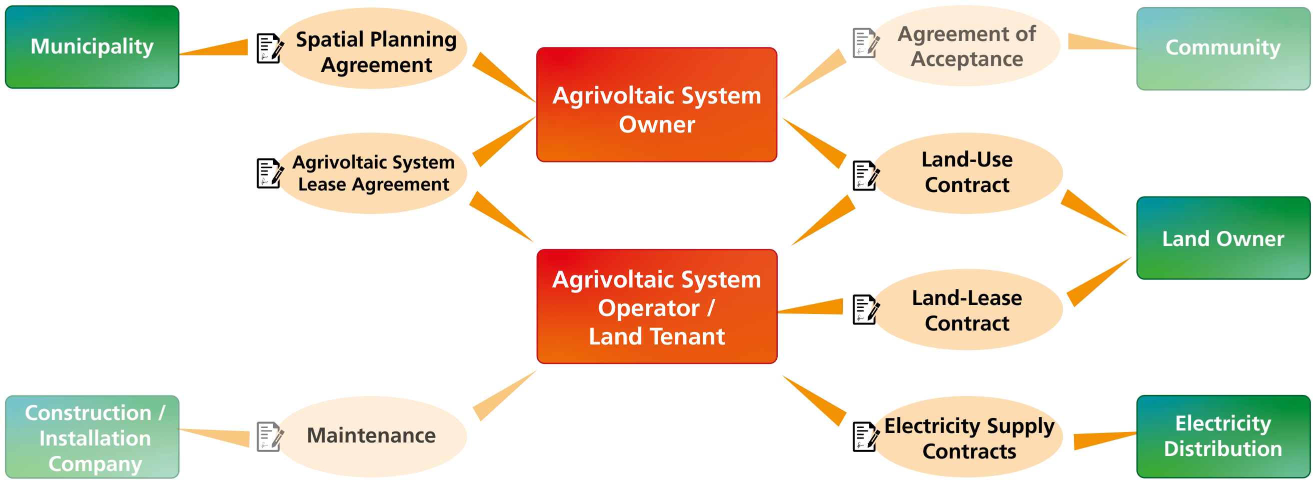


Figure 31: Stakeholders and contract model.

using the generated electricity on site and the fact that many farms already have experience with the operation of PV systems through rooftop installations also speak in favor of this business model.

In many cases however, the land will not be owned by the farm. This is indicated by the high proportion of leasing in Germany, especially in the new federal states.[26] When all other functions remain with the farm, the synergetic added benefits also accrue in one place with this constellation. As with ground-mounted photovoltaic systems, long-term contracts for land leasing and use are essential, generally with a 20-year term.

Ownership of the PV system is probably less common for larger agrivoltaic systems as well, increasing the likelihood of external investments. Partial ownership could help maintain the incentive structure for the synergetic dual use of land in this case. The higher the proportion of outside capital, the more difficult it will however be to keep in mind the benefits of both production levels during operation. Scaling opportunities and possible optimization through a greater division of labor speak in favor of this business model.

WHAT SHOULD A FARM IDEALLY BRING TO THE TABLE?

Beneficial factors for the economical realization of agrivoltaics:

- Row cultivation
- Permanent crops
- Protected growing
- Low employment of machines / low clearance height
- Large, contiguous area (>1 hectare)
- Low slope
- High and flexible energy consumption (e.g. cooling, drying, processing)
- Willingness to invest

The composition of the players in Heggelbach is relatively complex. Neither ownership of the land or PV system nor the operation of the farm or PV system are in one hand. The basic structure of the contracts required in this case is shown in Figure 31. What constellations will establish themselves in Germany remains open at this point and depends largely on the future regulatory framework. Cooperative models in which multiple farmers work together are conceivable as well.

3.4 Reports from Farmers

While the experiences of the farmers in Heggelbach are mostly positive, they clearly illustrate the limits of legal regulations in Germany. In an interview, Thomas Schmid and Florian Reyer explain why they decided in favor of an agrivoltaic system, how viable it is, and how legal regulations should be changed. Thomas Schmid is co-founder of the Demeter-Hofgemeinschaft Heggelbach which was established in 1986. Retired from active agriculture in the meantime, he is a member of the Demeter Association's Supervisory Board and works as a consultant in Baden-Württemberg. Florian Reyer has been a shareholder of Hofgemeinschaft Heggelbach since 2008 and is responsible for renewable energy, technology, arable farming, and vegetable gardening.

INTERVIEW WITH THOMAS SCHMID AND FLORIAN REYER

Figure 32: Thomas Schmid and Florian Reyer. © AMA Film

What motivated you as agricultural practice partners to take part in the pilot project and make your land available for a pilot plant?

Thomas: We have been pursuing the ideal of achieving a closed energy cycle in addition to a closed operating cycle on the farm for 15 years. That is why we already invested in various energy sources (note: woodgas power, rooftop PV) in the past. When Fraunhofer ISE approached us in 2011, the energy transition was already a big issue. We saw agrivoltaics as a suitable way to make our contribution to a successful energy transition and, through dual land use, to present an alternative to biogas production on farmland.

Florian: We are also very interested generally in innovative developments in the renewable energy sector.

How did planning and construction go? Were all your requirements, such as maintaining the soil functions, taken into account?

Thomas and Florian: As full practice partners, we were involved in the entire planning process and participated in the decisions on all aspects, so that our farming needs and high demands for maintaining soil fertility were taken into account from the outset. For example, a temporary construction road was built to install the system, and concrete foundations were omitted thanks to a special anchoring system.

How viable is cultivation under the system for you?

Florian: Considering the benefits of dual use, it is absolutely viable. While there are certain restrictions for cultivation, those are not relevant. If you want to do it, you can.

How do you benefit from power generation with the system?

Thomas: Our goal is to use as much as possible of the generated power ourselves, thereby reducing energy costs. We are therefore attempting to further increase our self-consumption (note: due to the lack of feed-in tariff) and, with the help of our practice partner Elektrizitätswerke Schönau (EWS) , to adapt storage, management, and consumption to generation.

Would you decide to build this system again from today's perspective?

Florian: As a research plant yes, otherwise under the current conditions no.

Why? From your perspective, what has to change for the successful application of agrivoltaics in the future?

Florian: It's a question of preconditions. Everything has to change!

Thomas: These are currently not given in Germany. By building the system, we no longer receive agricultural subsidies for the land. At the same time, we get no EEG feed-in tariff for the electricity that is produced.

Florian: A new technology needs a boost to implement in practice. That also requires the political will to adapt the framework accordingly.

Thomas: More research is also needed to adapt the technology to other areas of application, such as hops growing, orcharding, or in conventional agriculture as well.

4. TECHNOLOGY

The way that power generation works is the same for agrivoltaics and ground-mounted photovoltaic systems. However, the requirements for the technical components and supports for the system are entirely different for agrivoltaics due to land cultivation: the height and alignment of the system, the mounting structure or foundation and, where applicable, the module design – everything should be adapted to cultivation with agricultural machines and the needs of the plants. Sophisticated light and water management are also important to maximize yields.

To make the dual use of farmland for arable farming and power generation possible, the solar modules are typically installed at a height of three to five (in hop growing also more than seven) meters above the field. This makes it possible for large agricultural machines, such as combine harvesters, to work the land underneath the agrivoltaic system. To ensure that plants get sufficient light and precipitation, the spacing between the module rows is typically larger compared to conventional ground-mounted photovoltaic systems. That reduces the degree of surface coverage to about one third. In combination with the high supports, this approach ensures homogenous light distribution and therefore uniform plant growth. When tracked modules are installed, light management can be specifically adapted to the development stage and needs of cultivated plants.[27]

Here the choice of the mounting structure, and in part also the solar modules, is generally quite different from ground-mounted photovoltaic systems. Various technologies and designs shall fulfill the site-specific requirements and farming conditions. Taking light management into account in planning the system is therefore recommended. In general, agrivoltaic systems should be state of the art and comply with the commonly accepted rules and standards.

4.1 Approaches for Agrivoltaics

Agrivoltaic systems, as in France and Japan, for example, are often mounted on tall supports. Here the clearance height describes the vertical unobstructed space between the ground and the lowest structural element. Various possibilities for the dual use of farmland are described in the following.

Figure 33: PV modules with spatially segmented solar cells and protective function in the Netherlands. © BayWa r.e.

Figure 34: System with high mounting structure, permitting cultivation underneath the modules with the potato harvester. © Hofgemeinschaft Heggelbach

Systems with tall supports harbor great potential for synergy effects (Section 3). However, they must allow for cultivation under the PV modules. (Figure 34)

The PV modules can also assume an important protective function against hail, rain, night frost and other extreme weather events. Figure 33 shows a research plant of the company BayWa r.e. over an orchard. This plant in the Netherlands was built using modules with a larger cell spacing, which enhances the roofing and protective function while simultaneously providing more sunlight for the plants than other PV systems.

Synergy effects can also be realized with modules installed close to the ground. Next2Sun accomplishes this with bifacial modules that are installed vertically. While this type of system is more cost effective due to the low height of the mounting structure, the available light management options are also reduced. Systems installed close to the ground could however provide a benefit by reducing the wind speed, which also affects evaporation.

Tubular PV modules installed horizontally on supports, implemented by the company TubeSolar AG, are another option. This innovative approach promises even light and water permeability over the surface area, which is important for uniform plant growth.The partner company Agratio GmbH combines these novel modules with low-cost supports. Here the solar tubes are mounted on stays and suspended over the area under cultivation, resulting in half shade that is favorable for most agricultural applications.

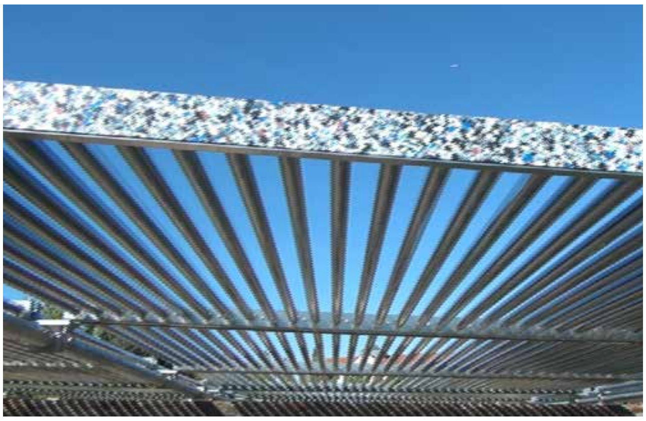


Figure 37: Special tube modules with flexible PV strips from the company TubeSolar. © TubeSolar AG

Figure 35: Bifacial modules installed vertically, Donaueschingen. © Next2Sun GmbH

Figure 38: Semi-shade by tubular PV modules, installed between tension cables by the company TubeSolar. © sbp sonne gmbh

Figure 36: PV modules over a foil tunnel. © BayWa r.e.

Figure 39: System with high mounting structure and narrow PV modules. © REM Tec

Very narrow modules are installed over arable land in Japan under the name "solar sharing" in order to adjust the availability of light. Here the agrivoltaic systems serve as an additional source of income and retirement provision for farmers. Many other technical solutions are conceivable, with various advantages and disadvantages.

4.2 Module Technologies

Fundamentally, all types of solar modules can be used in agrivoltaic systems. Modules with wafer-based silicon solar cells account for about 95 percent of the global PV market. The accepted composition calls for a glass pane on the front and a white covering film on the back. Opaque solar cells are serially connected at a distance of 2-3 mm and laminated between these two elements. A metal frame is used for mounting and stabilization.

In case of a **transparent back covering** (glass, foil), the spaces between the cells allows the light to largely pass through and reach the plants below. With conventional modules, the spaces between the cells make up four to five percent of the surface area. The spaces can be enlarged and the module frames replaced by clamp mountings to increase light transmission. Modules with a greater ratio of transparent to total area can protect plants against environmental influences without reducing the availability of light to the same extent.

Bifacial modules can also use the ambient light incident on the reverse side for power generation. Depending on the radiation level incident on the reverse side, electricity yields can be increased by up to 25 percent (typically between 5 and 15 percent). Since the row-to-row distance tends to be larger and the supports tend to be taller in agrivoltaics, the amount of light available on the reverse side of the modules is particularly high. Therefore, bifacial modules are well suited for agrivoltaics. Bifacial glass-glass modules were used in the Heggelbach research project. Another advantage of modules with a double glass structure is the residual strength in case of glass breakage – benefitting occupational health and safety.

Thin film modules (CIS, CdTe, a-Si/µ-Si) can be realized on flexible substrates, making cylindrical bending possible. With an otherwise identical structure, their mass per unit area is approximately 500 g/m2 (grams per square meter) lower compared to modules with wafer-based silicon solar cells. The efficiency is somewhat lower, however. The cost per unit area for thin film modules is also slightly reduced.

This applies correspondingly for **organic photovoltaics (OPV)**. Selective spectral adjustment of the active layers of OPV is also possible in principle, which means that part of the solar spectrum can be transmitted and used by crops growing underneath. However, OPV is still in the market launch phase. Low efficiency and durability are among the challenges.

In **concentrator photovoltaics (CPV)**, the light is focused by lenses or mirrors onto small photoactive surfaces. CPV modules have to be implemented with solar tracking, except for very low concentrating systems. Diffuse light is largely transmitted. Only very few suppliers of OPV and CPV modules currently exist for applications in agrivoltaics.

Figure 40: System with high mounting structure and continuous rows of PV modules. © Sun'Agri

4.3 Mounting Structure and Foundation

4.3.1 Design of the Mounting Structure

The type of mounting structure must be adapted to the specific agricultural application and its respective needs. Examples include planning the system height and the distances between the steel supports. Here it is important to determine the headlands, clearance height and working width of agricultural machines to be used into account. The research plant in Heggelbach was designed so that even large harvesters can drive underneath. The distance between the ground and the bottom of the structure measures five meters. Aside from the possible synergy effects (Section 3), the benefits of a large clearance height include easy vehicle access to the land and more homogenous light distribution underneath the system. On the other hand, the investment costs for the mounting structure are generally lower for lower clearance heights, because less steel is required and the statics demands are correspondingly reduced.

The row spacing, alignment, and height of the agrivoltaic system are of crucial importance since they help determine the light availability. These parameters should always be adapted to meet the needs of the crops grown underneath the agrivoltaic system. The row spacing for the research plant in Heggelbach, for example, is 9.5 meters with a module row width of 3.4 meters. Higher or lower values are possible depending on the shade tolerance of the cultivated plants. Yet, much larger row spacing does increase the land requirement and thus the system costs in relation to the electricity yield.

4.3.2 One and Two-Axis Tracking

There are systems, for instance in France, that work with 1 or 2-axis tracking, meaning that the solar modules follow the sun using a tracking mechanism. With single-axis photovoltaic tracking, the modules follow the sun horizontally according to the sun's angle of incidence (elevation) or vertically according to the sun's orbit (azimuth). Two-axis trackers do both and therefore maximize the energy yield. However, two-axis systems with large module tables can create an umbra underneath the modules, while other parts of the field receive no shade at all. Tracking of the PV modules was considered uneconomical for sites in Germany during preliminary investigations for the system in Heggelbach. Notwithstanding the higher acquisition and maintenance costs, tracking can however optimize the energy yields and light management for plant cultivation [27] (Section 4.4 Light Management). Through flat roofing, two-axis tracking systems have the potential to protect the plants against hail or extreme sun while shade can be reduced during the growth phase.

4.3.3 Anchoring and Foundations

The anchoring or foundation ensures the statics and stability of the agrivoltaic system. Proof of fulfilling these safety requirements must be provided when building a system (Section 4.8.2. Installation and Operation). For agrivoltaic systems, permanent concrete foundations are not recommended in order to preserve valuable farmland. Alternatives include piled foundations or special anchoring with Spinnanker anchors. Since no concrete is used, the system can be disassembled without leaving any trace.

Mobile agrivoltaic concepts make it possible to assemble the system, disassemble it again, and install it in another location without the use of larger machines. A possible benefit: A building permit may not be required since this is not a structural alteration. Therefore, mobile agrivoltaics allows for flexible adaptation to agricultural farming, including spontaneous deployment in crisis regions.

Figure 41: Single-axis tracking system of a demonstration agrivoltaic system in France. © Sun'Agri

Figure 42: The Spinnanker anchor with anchor plate and threaded rods provide the foundation for the installation system. © Spinnanker

Figure 43: Illustration of different types of agrivoltaic systems with east-west, south- and south-east orientation. © Fraunhofer ISE

4.4 Light Management

Shade on farmland varies according to the sun's daily course and changing position over the course of the year. Homogeneous light is desirable for healthy plant growth, uniform ripening and maximizing synergy effects. This can be achieved in various ways:

1. A southern orientation (0°) was not chosen in Heggelbach. Based on simulations and measurements, a south-west or south-east orientation, respectively with a 45° deviation from south, is most suitable. A power generation reduction of about five percent was included in the calculations. The actual alignment may deviate due to local conditions.
2. Another option is to retain the southern orientation and use narrower PV modules, as with solar sharing in Japan.
3. Homogenous lighting can also be obtained with an east-west alignment of the modules. Shade movement over the course of the day is maximized with this orientation. To avoid an umbra under the fixed modules that are entirely impervious to light, the width of the 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 the width of the module rows. This factor should be at least 2 for tracked modules. Transparent modules on the other hand reduce the factor in both cases, depending on the degree of light transmission (see Section 4.3.2 Tracking).
4. Two-axis tracking of the PV modules is another option for selective light management and higher electricity yields. As already described in Section 4.3.2, however, this is associated with higher investment and maintenance costs. Systems with large module tables and two-axis tracking tend to be unsuitable for growing cultivated plants because of the umbra behind the modules. Other parts of the field are in turn permanently exposed to full sunlight.

In Heggelbach, the spacing between the rows of PV modules with an inclination of 20° was increased by around 60 percent compared to conventional ground-mounted photovoltaic systems, making around 69 percent of the total solar radiation available to the plants.

Figure 44: The shaded strip under the solar modules moves with the sun's position. © Universität Hohenheim

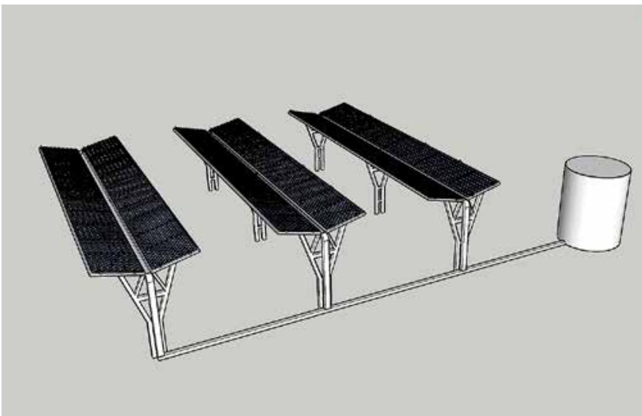


Figure 45: Concept of a rainwater harvest system with underground storage tank. © Fraunhofer ISE

4.5 Water Management

Rainwater running off the eaves of the modules can cause soil erosion by washing away the soil.

To avoid negative consequences for plant growth in at-risk locations and applications, various water management approaches can be considered in the system design: Similar to light management, narrow or tubular PV modules can prevent the accumulation of larger amounts of water under the module edge. If the modules are intended to provide structural protection for the crops, on the other hand, tracking the PV modules [28] to distribute precipitation coming off the eaves or channeling the rainwater are better options. In the latter case, sufficient water has to be provided through irrigation. Collecting and storing rainwater can help to conserve groundwater resources, especially in arid regions, or make agriculture possible in the first place.

4.6 Size of the PV System

The average size of installed agrivoltaic systems varies considerably from country to country. Aside from economic viability, decentralization and social aspects, the key criteria to be considered include the impact on the landscape and thus the social acceptance. Smaller systems with 30 to 120 kW_p are found in Japan, for example. On the other hand, power plants of several hundred MW_p have already been built in China.

Figure 46: Agrivoltaic system in Heggelbach with 194 kW_p capacity. © BayWa r.e.

Figure 47: 2 MW_p Solarpark Eppelborn-Dirmingen with vertical PV modules by Next2Sun. © Next2Sun GmbH

CHECKLIST FOR POSSIBLE TECHNICAL ADAPTATIONS

- What local conditions, such as the field location, driving direction, headlands of the agricultural machinery, or irrigation systems influence the alignment of the modules?
- Are the mounting structure and dimensions of the supports and carriers adapted to the working width of the agricultural machinery? Should fenders be installed on the mounting structure?
- What module technology is to be used? The choice should always be adapted to the agricultural use and products.
- What anchoring or foundation system is to be used to ensure removal of the system that leaves no trace?
- What are the wind and snow loads, and what are the additional loads due to the support height for the mounting structure?
- Are you in a region with very high precipitation? The installation of rainwater distributors or a collection system may be beneficial.
- Is the use of storage batteries technically and economically reasonable?
- In which months do favorable, dry soil conditions exist to enable construction? When is the field fallow so that ground slabs for machines can be laid? This prevents soil compaction.
- What measures can be implemented to prevent an impairment of the cultivated landscape?

Table 4: Overview of approval steps for agrivoltaics.

Process steps	Institution	Comments
Building permit	Municipality	Zoning map and development plan
Required expert opinions	Certified expert	Environmental, soil, and glare protection report. Wind load testing.
Recording of the easements	Notary	Right of way and ownership structure, for example
Insurance	Insurance company	A study conducted in cooperation with the Gothaer Versicherung insurance company showed that the amount insured for an agrivoltaic system should not be significantly more costly than for a comparable, conventional solar installation

What path Germany is going to take remains open and will likely be viewed differently depending on the region. Smaller systems, typically installed over special crops, accommodate the regions of southern Germany which is characterized by smaller land parcels and higher aesthetic sensitivity. In regions of northern and eastern Germany with large areas of land, on the other hand, bigger agrivoltaic systems may make sense for the large agricultural farms, in order to economically compensate for the lower annual solar radiation through economies of scale.

The land requirement for agrivoltaic systems is typically 20-40 percent higher compared to ground mount photovoltaic systems with the same nominal output. Currently an agrivoltaic system has a capacity of 500 to 800 kW_p per hectare, while a conventional PV system has a capacity of 600 to 1100 kW_p per hectare depending on the design. Using bifacial modules can increase the electricity yield: In the first year of operation, the output of the research plant in Heggelbach was 1284 kWh per kW_p of capacity, while a conventional solar installation at that site only produces 1209 kWh per kW_p.

4.7 Approval, Installation and Operation

4.7.1 Approval 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 technology partners. An overview of the required permits, expert opinions and documents is provided in table 4.

In the research plant in Heggelbach, the arable land under the agrivoltaic system was identified as a special use area. Thus, the claim to agricultural land subsidies was permanently lost, even though arable farming continues. Furthermore, the agrivoltaic technology is neither supported through the ordinance on tenders for ground-mounted photovoltaics nor through the EEG feed-in tariff. Further information on approval processes is found in Section 6.1.

There is no certification system for agrivoltaic systems in Germany to date. Fraunhofer ISE is currently working with project partners to prepare a DIN specification that defines quality standards which serve as criteria for tenders, funding eligibility or simplified planning processes. This includes the definition of agrivoltaic indexes and corresponding test procedures, which can be applied by certifiers such as the VDE (Association for Electrical, Electronic & Information Technologies) or the TÜV.

Figure 48: Construction roads to prevent soil compaction.

© BayWa r.e.

4.7.2 Installation of an Agrivoltaic System, Using Heggelbach as Example

An agrivoltaic system should be adapted to the respective local conditions and cultivation methods. Project planning and land use planning are usually handled by a specialist firm. These tasks were assumed by BayWa r.e. for the research plant in Heggelbach.

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

- finding partners to purchase the excess electricity and for feeding it into the grid
- material procurement and logistics planning
- construction of site setup and soil protection
- system setup
- concept for connection, lightning protection, and monitoring
- grid-connection
- technical maintenance and removal

The first hearing on the development plan for the research plant by the Herdwangen-Schönach municipal council took place on 13 October 2015, and the building application was submitted only six months later on 6 April 2016. Fraunhofer ISE obtained approval for the grid connection from Netze BW on 24 July 2015. The building permit was issued on 3 May 2016. However, construction approval was tied to a review of the statics by an independent test engineering office. A soil report was also prepared to calculate and document the actual holding force of the foundation. The results of this expert report and feedback from the test engineer were incorporated in the revision of the agrivoltaic mounting structure.

Contracts for the installation of the agrivoltaic system were awarded to various companies in accordance with the procurement ordinance, and the construction sequence was coordinated in detail and in close consultation with the Hofgemeinschaft Heggelbach. The power electronics and wiring of the agrivoltaic system were installed so the research plant could be quickly connected to the grid upon completion. Statics calculations were performed and the agrivoltaic system was adapted accordingly. Among other things, an Alpinanker anchor had to be installed for the foundation of the agrivoltaic system in addition to the Spinnanker anchors.

According to the original schedule, the start of construction was planned for July of 2016. However, preliminary work could not be completed on time due to various building law delays, so the start of construction was delayed until August of 2016. Nevertheless, the system was successfully completed in time for the opening ceremonies on 18 September 2016.

4.7.3 Agrivoltaics in Operation

The solar modules are not fully accessible at all times due to the crop cultivation and the height of the support structure. Maintenance and repairs should therefore be carried out when fields are fallow. Safety comes first and not all maintenance vehicles are suitable for use on fields. An applicable maintenance and repair concept is to be developed in the future, establishing maintenance intervals and the scope of maintenance work as well as calculating possible costs.

Figure 49: Maintenance work on the agrivoltaic system in Heggelbach.
© Fraunhofer ISE

5. SOCIETY

Aside from the technical, economic and ecological aspects of agrivoltaics, the early involvement and trusting cooperation with various stakeholders and affected citizens – starting with the planning process – is of crucial importance. Developing a shared understanding of the sustainability objectives to be achieved for regional food production, species conservation, and protecting the cultivated and leisure landscape along with the decentralized generation, storage, and use of renewable energy is of particular importance. An interdisciplinary and transdisciplinary approach helps in taking various interests and expectations but also preferences and concerns into account, reducing acceptance problems, and driving the energy transition on site with local investors. Thus the range of players on the investor side and local value creation are increased, and the interests of the population are taken into account leading up to the decision to build an agrivoltaic system.

The accelerated expansion of renewable energy generation generally finds broad acceptance in all social strata. This is confirmed by opinion polls in recent years, with approval in the range of 70 to 90 percent. Youth movements such as Fridays for Future are also committed to a faster and more consistent transformation of the energy system. Nevertheless, the expansion of the renewable energy supply falters when it comes to finding suitable sites for the construction of ground-mounted photovoltaic or wind power systems, or realizing concrete projects, even when proper planning law and municipal policy procedures are followed.[29] There are many reasons for the general social acceptance of the energy transition and a very concrete, hostile attitude towards the expansion of renewable energy generation systems for the local implementation of the energy transition. However, a subjective weighing of risks and benefits plays a significant role: It leads to fears of possible financial, health, and aesthetic disadvantages that would be associated with local changes to the environment, notably land allocation and the visual landscape.[29]

The observations apply in particular to the construction of solar parks, which are now being built on a large scale in Germany even without EEG subsidies. The Solarpark Weesow-Willmersdorf in Brandenburg planned without government compensation is a prominent example. With an installed capacity of more than 180 megawatts on an area of 164 hectares, it provides a sustainable energy supply for around 50,000 households. The land requirement for solar parks increases the demand for farmland with limited availability. This can exacerbate regional land use competition, leading to higher lease rates and social controversy.

5.1 Involvement of Citizens and Stakeholders

To prevent conflicts, citizens and other stakeholders should be included in infrastructure projects early on. In the course of the APV-RESOLA research project, the Institute for Technology Assessment and Systems Analysis (ITAS) of the Karlsruhe Institute of Technology (KIT) therefore got regional

Figure 50: Workshop with citizens within the project APV-RESOLA. © ITAS

stakeholders and local citizens involved in the project and analyzed their expectations and concerns.[30] Various social perspectives and perceptions were thereby captured.

The focus in the project was on the application-specific identification and analysis of opinions and normative value systems, possible obstacles, and drivers.[31] Here the intention was to work out success factors and answer socially relevant future questions related to a sustainable, decentralized energy supply. Accordingly this type of research in the concrete technical development project was designed to capture the insights, experiences, perspectives, and preferences of citizens and stakeholders, to analyze similarities and differences in the individual perception, assessment, and evaluation of the agrivoltaic technology, and to identify possible lines of conflict early on. Suitable surrounding conditions and provisions for acceptable agrivoltaic systems were to be worked out on this basis in the technology development process and system planning on behalf of citizens and other players.

Since an agrivoltaic system is an interdisciplinary, cross-sector enterprise between agriculture and the energy supply sector, communication with all participants is very important. The research project showed how important it is to bring together agriculture, the energy sector, network operators, municipalities, and citizens in order to establish a mutual understanding of interests, preferences, and concerns, and to develop a shared vision for the energy transition, work out the conditions for success, and identify suitable sites. That helps with preparing a concrete plan for the design of the decentralized renewable energy supply and the conservation of valuable farmland, biodiversity, and "untouched" recreational landscapes.

5.2 Approaches and Methods for Involvement

Involving citizens and stakeholders in the research process requires a clear framework for participation and should be based on a shared understanding of the problems, such as man-made climate change, and a jointly developed vision, such as the decentralized energy transition. The research and project objectives should be communicated clearly and openly in order to avoid misunderstandings regarding roles and the process for citizen and stakeholder participation and not to create any false hopes.[29] If these conditions are not met, disappointments and conflicts may occur due to various unmet expectations and the previously established bond of trust between the players may be impaired or even destroyed. The communication process should allow the inherent logic and self-interests of the participants to be overcome: On the one hand, those of science seeking scalable solutions and interested in publications according to scientific standards, on the other hand those of practice seeking tailor-made, easy to implement, effective, and marketable solutions.[29]

Transdisciplinary research builds on methods and tools of the empirical social sciences and, depending on the problem and question, utilizes a broad range of approaches ranging from citizens' forums to stakeholder workshops. The transdisciplinary research format for the joint handling of matters with practical relevance by science, industry and the economic system, politics, administration, and society is characteristic for the co-design approach in technology development. When these developments are tried and tested on a small scale "on site" prior to their market introduction, lines of conflict can be identified early on and the acceptance criteria for new technologies and investment decisions can be fathomed.

In the APV-RESOLA project, a multi-stage transdisciplinary process was conducted on land owned by the Hofgemeinschaft Heggelbach in the Lake Constance region in order to involve the citizens and stakeholders using various formats and at several points in time. After an information event for all interested parties, the Institute for Technology Assessment and Systems Analysis (ITAS) asked all citizens aged between 18 and 80 years in the immediate vicinity of the planned pilot plant to indicate their interest in taking part in the process. Then an open brainstorming session regarding the opportunities and challenges of agrivoltaics was conducted with all interested parties. One year after the system was constructed, the participants from the first event were invited again. The goal of the citizens' workshop was to analyze

Figure 51: Model of the agrivoltaic system in Heggelbach for workshops. © Fraunhofer ISE

possible changes in the opinions and value systems. A business game was also developed and used to generate site selection criteria. Before the second citizens' workshop, the researchers conducted a survey to compare the results of the first citizens' workshop, based on the agrivoltaic concept, with the impressions of the public after personally inspecting the pilot plant for the first time.

Subsequently stakeholders from technology development, marketing firms, politics, municipal, regional, and state administrations, agriculture, nature conservation, the energy sector, energy cooperatives, tourism, and the citizens discussed the results of the citizens' workshop as well as the citizens' suggestions and ideas for the more sustainable design of the agrivoltaic technology and its framing. Some aspects were identified as key success factors and still implemented during the test stage. Increasing the resource efficiency through the local storage and use of the generated electricity is a prominent example.

5.3 Success Factors

Transdisciplinary research in the agrivoltaic project identified the following ten key success factors for the agrivoltaic technology:

1. Utilizing the existing PV potential on rooftops, industrial buildings, and parking lots should take priority over identifying sites for agrivoltaic systems.
2. The agrivoltaic systems should be integrated into the 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.
3. The agrivoltaic systems should be combined with an energy storage system to increase the resource efficiency, so the available electricity can be used to meet local demand.
4. Farming under agrivoltaic systems has to be mandatory to prevent the one-sided optimization of power generation with "pseudo-agriculture" under the PV modules.
5. Agrivoltaic systems should be built on sites where synergies can be realized through dual use of the land, such as shading to reduce heat stress for cultivated plants, gener-

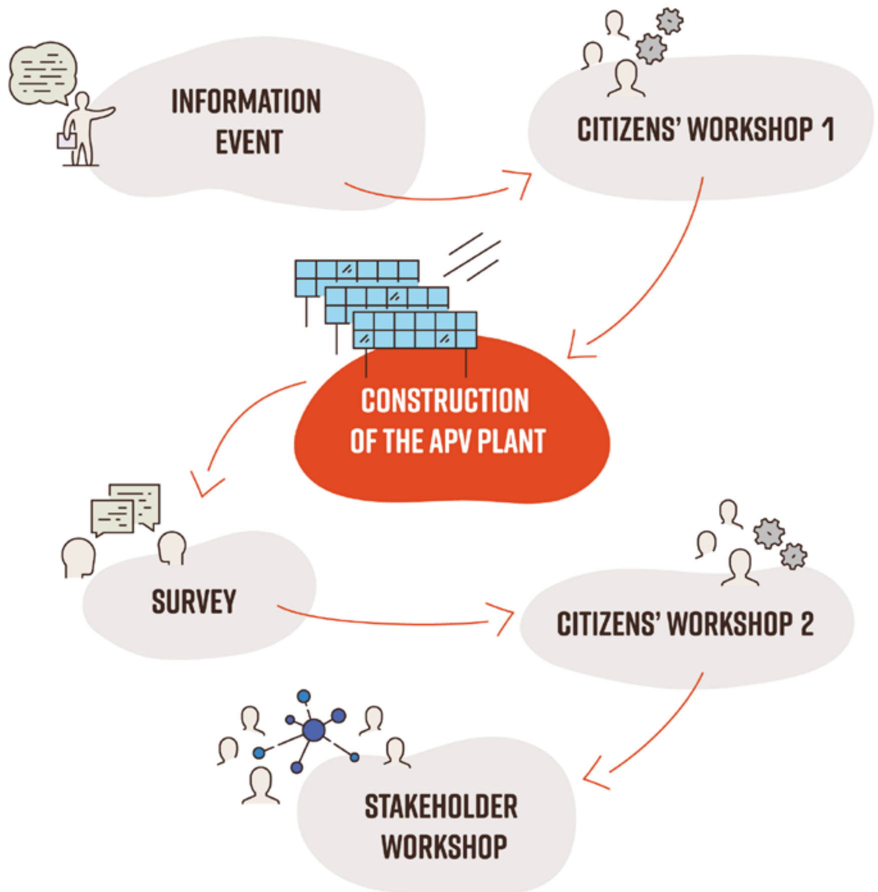


Figure 52: Multi-stage transdisciplinary agrivoltaic research approach. © ITAS

ating electricity to irrigate the crops, or digital land cultivation with electrified and future autonomous systems.

6. The size and concentration of the agrivoltaic systems should be limited and, similar to wind power plants, minimum distances to residential areas should be established under consideration of local site characteristics and social preferences.
7. Agrivoltaic systems are not permitted to negatively alter the quality of local recreation, tourism, and the attractiveness of the landscape. Sites that are naturally screened from view (e.g. at the edge of a forest) or flat sites should be preferred for the best possible integration of the systems into the landscape, making them "invisible".
8. Approvals for agrivoltaic systems should be issued according to strict legal regulations and with citizen participation to avoid the uncontrolled growth of agrivoltaics, as seen with biogas plants due to privileged building laws for the agriculture sector. Municipalities and citizens should have codetermination rights in the identification of sites for agrivoltaic systems.
9. Agrivoltaic systems should preferably be constructed and operated by local farms, energy cooperatives, or regional investors.
10. The strips along the agrivoltaic systems that cannot be farmed should be used for erosion protection and serve as corridor biotopes to maintain biodiversity in the agricultural landscape.

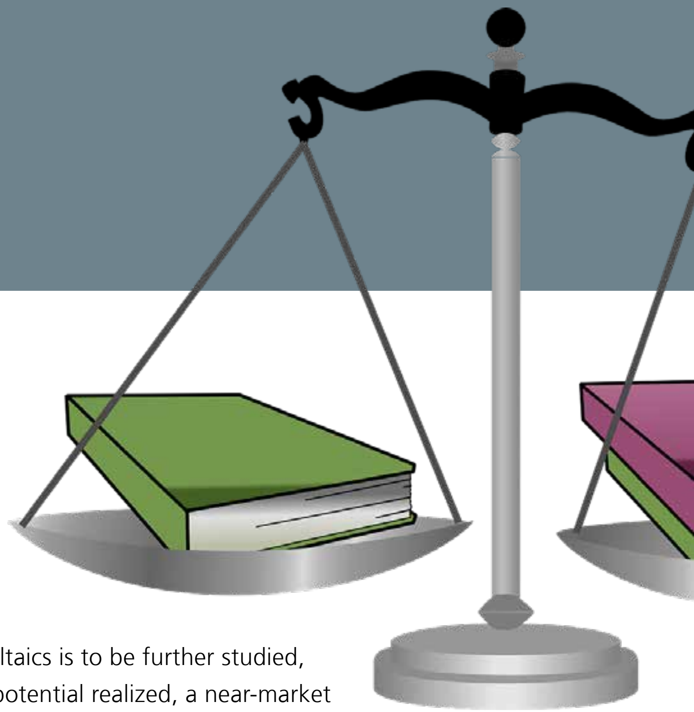
Differences in Acceptance Regarding Various Agricultural Applications

Greater social acceptance for special and permanent crops is generally expected than for arable farming. For one thing, the visual impact is reduced by a lower clearance height. For another, the appearance of the landscape is already impacted here by foil tunnels or hail protection nets, even without agrivoltaics. The possible added benefits of agrivoltaic applications over special and permanent crops is one of the most important drivers of a possibly higher acceptability among the population and also the potential users. Added value for agriculture can be comprised of various benefits from the agrivoltaic system, such as the reduction of heat stress for the cultivated plants through shade, erosion protection, irrigation powered by renewable electricity, greater biodiversity, or stable yields even under more difficult conditions due to climate change. Proving and realizing these benefits will likely play a crucial role in improving the acceptability of agrivoltaic systems to the population, and for realizing the potential associated with the integration of photovoltaics in agriculture.

The field sizes for special and permanent crops are usually smaller compared to arable farming, so the system size should typically be smaller as well. This could improve the integration of agrivoltaic systems into the landscape and allow PV electricity to be used for own consumption, which in turn would have a positive impact on acceptance.

Figure 53: The intermediate strips that cannot be farmed within agrivoltaic systems could be used to maintain or increase the biodiversity on arable land. © Fraunhofer ISE

6. POLITICS AND LAW



The German federal government has set the goal of increasing the proportion of electricity generated from renewable sources to 65 percent of the gross electricity consumption by the year 2035. Currently the planned 2021 EEG amendment sets the goal of achieving the greenhouse gas-neutral generation of all electricity in Germany before the year 2050. Scenarios indicate that PV needs to be expanded to as much as 500 GW_p in order to reach this goal. This means the current PV capacities have to by roughly increased tenfold. A considerable proportion of the photovoltaics expansion will likely be realized with ground-mounted systems, which are currently the lowest-cost option.

However, an expansion of ground-mounted photovoltaic systems conflicts with the political goal of reducing land use. Accordingly the use of new land areas for settlements and transport is to be reduced to 30 hectares per day by 2030 and to net zero by 2050. Among other things, this is intended to conserve fertile soil for food production. Currently around 56 hectares of land per day is newly designated for settlements and transport in Germany. That corresponds to land consumption equal to about 79 soccer fields. Aside from photovoltaic systems on roofs, facades, sealed areas, and open pit mining lakes, agrivoltaics could also contribute to space-neutral and simultaneously climate-friendly power generation.

Without integration into the legal framework, the economical implementation of agrivoltaics in Germany will however hardly be possible in the foreseeable future. Agricultural subsidies, regulatory approval aspects, and financial support according to the Renewable Energies Act (EEG) are of essential importance in the highly regulated agricultural and energy sectors. This applies in particular to new technologies, where learning effects and economies of scale have yet to be realized, but that nevertheless have to compete with established technologies.

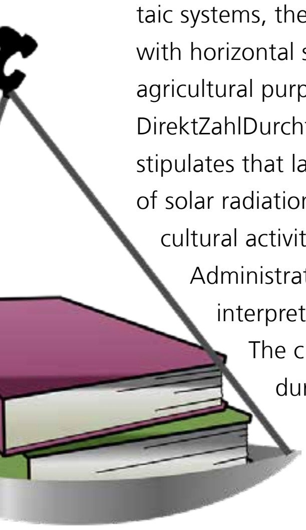
If agrivoltaics is to be further studied, and its potential realized, a near-market implementation of operational systems therefore appears sensible in addition to further research projects. This allows insights to be gained regarding acceptance, economic viability, and the various fields of application for the technology hand in hand with the farmer and solar enterprise. Germany has the opportunity to learn from experiences in France and to pave the way for a further development of the technology with suitable funding tools. A special EEG tender and corresponding expansion of the land area for agrivoltaics could be a next logical step.

6.1 Legal Framework

An overview of key aspects of the legal framework is provided in the following. Examining all legal aspects, cases, and situations is not possible here. Ultimately each case has to be examined and considered individually.

6.1.1 EU Direct Payments

As part of its agricultural policy, the EU grants direct payments for land used primarily for agriculture. So, an important question is whether farmland loses its eligibility for financial support due to the use of agrivoltaics. A verdict of the Federal Administrative Court (BVerwG) on what is known as a corn maze is of interest in this context[1]. In the opinion of the Federal Administrative Court, such a corn maze does not affect the eligibility for financial support because, to put it briefly, it does not severely limit the agricultural use of the land. What can be derived from this verdict for agrivoltaics?



Both vertically and horizontally mounted agrivoltaic systems permit the mixed use of solar electricity production and agriculture on the same area. While agricultural use takes place in the spaces between the rows with vertical agrivoltaic systems, the area underneath the modules is cultivated with horizontal systems. Whether the land is mostly used for agricultural purposes is decisive here. No. 3 of Section 12(3) DirektZahlDurchfV (direct payment implementing regulation) stipulates that land areas with systems for the utilization of solar radiation energy are used primarily for a non-agricultural activity. Following the perspective of the Federal Administrative Court, this provision however has to be interpreted under consideration of European law: The crucial criterion is that all the intensity, type, duration, or timing of agrivoltaics does not severely limit the agricultural use of the land. This perspective was also followed by the Regensburg Administrative Court in a case where sheep grazed under a PV system[2]. A severe limitation of agricultural use would exist if there were real and significant difficulties or obstacles for the respective operations in carrying out farming activities because another activity is carried out in parallel. In the case in question, this was not given. The court therefore considered the financial support to be granted[3].

Since with proper planning and installation of an agrivoltaic system, the agricultural use is not impaired, or only to a very minor extent (due to the supports of the mounting structure, for example), there are good arguments supporting the view that farms meet the requirements for direct payments under EU law. Therefore, they can and should receive the EU agricultural subsidies for cultivation of the land even with an agrivoltaic system installed. Defining this in concrete terms in the national DirektZahlDurchfV (direct payment implementing regulation) could establish planning reliability for operators. As long as this is not the case, consulting the authorities early on and convincing them that the requirements are met is generally recommended.

6.1.2 Public Law

Agrivoltaic systems are generally considered physical structures in terms of building regulations law. A building permit[4] is usually required for their construction. This is issued if public law regulations do not speak against it. The applicable regulations under public law include building regulations law requirements (determined according to the state building codes) and building design law requirements (determined according to the Federal Building Code BauGB).

Permissibility under building design law depends on the location of the plot of land: If the land is located in an area covered by a development plan, the requirements of the development plan have to be taken into account (see Sections 30, 31, 33 BauGB). On a plot of land not covered by a development plan, permissibility under building design law depends on whether the project is part of an urban area (see Section 34 BauGB) or outside an urban area (see Section 35 BauGB).

Typically the area in question is outside urban areas. Here the BauGB differentiates between privileged projects and other projects: Privileged projects according to Section 35(1) BauGB are only prohibited in exceptional cases when they conflict with public interests. In contrast, other projects outside urban areas are generally prohibited according to Section 35(2) BauGB unless they do not conflict with public interests. Certain public interests are explicitly listed in Section 35(3) BauGB. Depictions in zoning maps and requirements in land use plans are among them.

Section 35(1) BauGB contains a complete list of privileged projects. These privileged projects include, for example, a project that

- serves an agricultural or forestry operation and only takes up a minor proportion of the operating premises (no. 1),
- serves a horticultural production operation (no. 2), or
- serves to use solar radiation energy on rooftops and exterior walls of permissibly used buildings, provided the system is structurally subordinate to the building (no. 8).

Thus agrivoltaics are not explicitly listed as privileged projects. This can considerably increase the effort required to justify the classification of agrivoltaics as privileged projects. The term "serves" (no. 1) makes this clear: According to the Federal Administrative Court, this requirement is only met "when a reasonable farmer, would implement this project with about the same intended purpose and about the same design and configuration. Furthermore, it is to be recognized externally that this project is assigned to a concrete

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1 Federal Administrative Court, verdict of 4 July 2019, file no. 3 C 11.17.

2 See verdict of 15 November 2018, file no. RO 5 K 17.1331.

3 Also EuGH, verdict of 2 July 2015, file no. C-684/13 (Demmer verdict); Munich Higher Administrative Court, verdict of 19 April 2016, file no. 21 B 15-2391.

4 The Federal Immission Control Act (BimschG) does not apply because agrivoltaic systems are not listed in the annex to the fourth ordinance for the implementation of the Federal Immission Control Act (4th Federal Emission Protection Ordinance (BimSchV)).

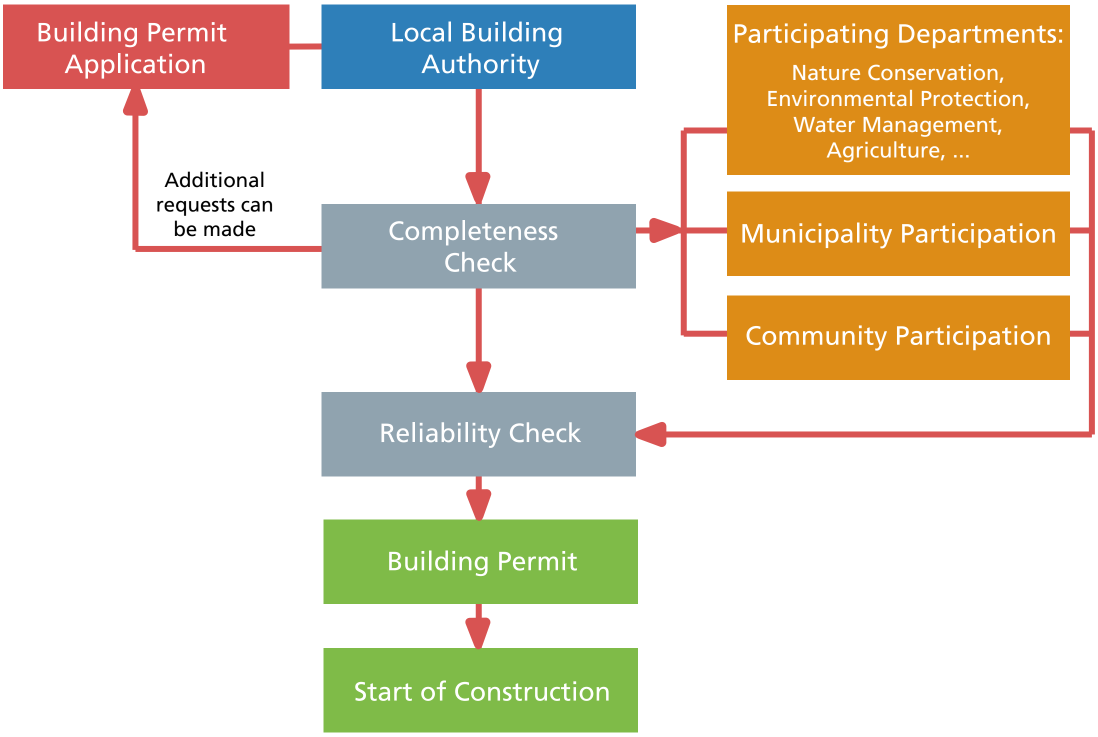

Figure 54: Example for the process of a building application.

operation."[5]. What does this mean for agrivoltaic systems? Systems required to supply energy for the buildings and production operations fundamentally meet this requirement. Whether the proportion of energy generation compared to the system's total capacity carries significant weight is decisive: If it fails to considerably exceed the proportion intended for feeding into the public grid, the "serving" function of the system is lacking. The Federal Administrative Court has considered the use of about two thirds of the electricity produced by a wind power plant in an agricultural operation to be sufficient[6]. The mentioned shaping of the operation by the project likely also demands a certain physical proximity of the agrivoltaic system to the focal points of operating processes.

The term agriculture used in no. 1 of Section 35(1) BauGB is separately defined in Section 201 BauGB. Horticultural production is also mentioned there. Thus the privilege according to no. 2 of Section 35(1) BauGB should also apply to operations that grow plants in pots, containers, and other receptacles, notably in greenhouses.

If the project is not permissible outside urban areas according to Section 35 BauGB, preparing a development plan – possible with a partial amendment of the zoning map – should be considered. Then "only" the requirements of the development plan have to be met. However, what is known as the "standardization requirement" is problematic in this respect, because the municipality is bound by the stipulations of Section 9 BauGB and the Federal Land Utilization Ordinance (BauNVO). Establishing "photovoltaics" as a "special area" according to Section 11 BauNVO could be a solution. However, this poses the question of whether agricultural use can be additionally stipulated at the same time. By passing what is known as a project-specific development plan, planning law leeway can be utilized since the municipality can then permit the project without considering Section 9 BauGB and the BauNVO. However, the stipulations of the BauGB[7] and BauNVO always have a guiding function. Orderly urban development therefore has to be observed, even within the scope of a project-specific development plan[8].

Regularly the question arises whether agrivoltaics is an intervention in the natural environment. Avoiding intervention takes priority, unavoidable significant impairments have to be compensated[9]. However, in this context exists the privilege that land use according to the rules of good agricultural practice does not constitute intervention[10]. If an area is used

[5] Federal Administrative Court, verdict of 3 November 1972, file no. 4 C 9.70.
[6] Federal Administrative Court, decision of 4 November 2008, file no. 4 B 44.08..
[7] Notably Section 9 BauGB.
[8] Federal Administrative Court, NVwZ 2003, 98
[9] See Section 13(1) BNatSchG.
[10] See Section 13(2) BNatSchG.

for the generation of electricity, this currently constitutes an intervention in terms of Section 14(1) of the German Federal Nature Conservation Act (BNatSchG). For example, the APV-RESOLA research project was also considered an intervention and eco-points had to be utilized according to the Eco-Account Ordinance (ÖKVO). This ordinance defines requirements for Baden-Württemberg for the recognition and assessment of advance nature conservation and landscape care measures (eco-account measures) to be assigned as compensation measures to an intervention project at a later date.

Since the benefits of agrivoltaics for the agricultural use of land can be significant, at least it should be considered whether the land allocation follows the rules of good agricultural practices and thus does not constitute an intervention according to the German Federal Nature Conservation Act (BNatSchG). Taking this concept further, one could even ask whether an agrivoltaic system can generate eco-points according to the ÖKVO.

6.1.3 Renewable Energies Act (EEG)

Agrivoltaic systems are systems for the generation of electricity from renewable energy according to Section 3(1) EEG. The operator of an agrivoltaic system is entitled to priority grid connection by the grid operator according to Section 8(1) EEG. This involves determining the grid connection option with the lowest total economic costs. Once this option has been identified, it becomes clear who has to bear which costs. In principle, the grid expansion costs are borne by the grid operator and the grid connection costs by the system operator.

The operator of an agrivoltaic system is also entitled to the priority purchase of the generated electricity according to Section 11(1) EEG. However, the system operator does not have to feed the electricity into the grid but can, in principle, also use it directly[11] or supply it to a third party "before" the grid[12].

The feed-in tariff for the electricity supplied to the grid is more complicated. First of all, operators of systems with an installed capacity of more than 100 kW_p are obligated to market the electricity to a third party. Thus the grid operator can only purchase the electricity in exceptional cases[13]. However, in case of subsidized direct marketing, the system operator is entitled to the "market premium" according to Section 20 EEG, in addition he or she receives the agreed remuneration for the delivered electricity from the direct marketer.

Operators of a system with an installed capacity of more than 750 kW_p have to successfully take part in a tender. They cannot claim feed-in tariff from the grid operator according to the EEG unless they have a surcharge and a "payment entitlement"[14]. Of importance is also Section 27a EEG: In principle, electricity from systems subject to the tendering procedures cannot be used for own supply. When systems are no larger than 750 kW_p, the stipulated values in Section 48 EEG apply, whereby the degression must always be taken into account.

For ground-mounted systems, the "10 MW_p limit" among others, defined in no. 5 of Section 38a(1) EEG also has to be observed: If the system is larger, no financial support can be claimed in this respect.

The feed-in tariff is paid for 20 years starting on the date the system is put into operation. For systems whose financial support is established by law, the payment is extended to December 31st of the 20th year.

In addition to the general requirements for feed-in tariffs according to the EEG, further special requirements for solar energy must be observed. However, these can only be outlined and therefore not fully described in the following:

As specified in Section 48 EEG, there is an entitlement to financial support if the system is installed on or in a building or other physical structure that was built primarily for purposes other than the generation of solar power. Ultimately this is about installing the solar system on an area that is being used "anyway" ("dual use"). The PV system can also be installed as the roof[15]. In case of PV systems on greenhouses, for example, it is necessary to ensure that the use of the greenhouse in its actual function remains the main focus. Among other things, this does not apply when plants that do not require a greenhouse are cultivated. This requires a detailed examination of each individual case. However, for "non-residential buildings" in unplanned rural areas according to Section 35 BauGB – such as greenhouses – the restriction according to Section 48(3) EEG has to be observed.

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[11] IThe EEG levy may be reduced in this case.

[12] Since the general supply network is not used in this constellation, network charges are not incurred. This applies correspondingly to network charges and levies (such as the cogeneration levy, Section 19(2) StromNEV levy, offshore network levy, concession fee). Thus the system operator can, for example, offer the electricity to the customer at a favorable price.

[13] See no. 2 of Section 21(1) EEG.

[14] See Section 22(3) EEG; in determining the "750 kW limit", the "system combination rules" contained in Section 24(1) and (2) EEG also have to be observed.

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

If these requirements are not met, funding eligibility is nevertheless possible, among others according to no. 3 of Section 48(1) EEG: The prerequisite in such cases is always the availability of an approved development plan. If this development plan was prepared or amended after 1 September 2009 with the purpose of building a solar installation, the agrivoltaic systems have to be located on certain areas, such as along highways or railways within a corridor of 110 meters measured from the outer edge of the roadway, or in what is known as a conversion area.

An extension to this land area is only possible for systems that have to participate in tenders. A feed-in tariff is also applicable to areas whose parcels of land have been used as arable land or as grassland at the time of the resolution on the establishment or amendment of the development plan. To be brief, the area cannot be allocated to any other land category than the one mentioned in Section 37(1) EEG and they are located in a disadvantaged area[16]. However, this only applies if the federal government has passed a regulation for tenders on the corresponding areas. To date this has only occurred in Bavaria, Baden-Württemberg, Hesse, Saarland, and Rhineland-Palatinate.

6.2 Political Recommendations

6.2.1 Explicit Privilege for Agrivoltaic Systems

An explicit privilege for agrivoltaic systems according to Section 35(1) BauGB appears fundamentally reasonable, since they are a natural part of the outdoors due to their agricultural use. Public interests are hardly affected by agrivoltaic systems: The systems serve climate protection purposes, improve climate resilience, and reduce water consumption. The landscape is however impaired by the systems. Preference should therefore be given to sites outside of distinctive landscapes, such as areas along the edge of a forest.

Practical example, raspberry plantation: To protect raspberries against hail and strong solar radiation, a row of PV modules above the espalier fruit can achieve a dual benefit. Nevertheless, raspberry cultivation takes precedence over the PV level in the value chain.

6.2.2 Addition of "Special Agrivoltaic Area" to BauNVO

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

6.2.3 Possible Subsidization Criteria and Scenarios

Different frameworks for the propagation of agrivoltaics can be established respectively in the interplay of the EU, federation, and state/municipality. A 30-field program/100-field program is a possible subsidization scenario: Corresponding to the 1000-roof program for PV systems in the 1990s, a field program could give agrivoltaics a boost. Research and development of the agrivoltaic technology could be significantly accelerated as a result. With the 1000-roof program, the federation and states subsidized the system and installation costs.

Adding agrivoltaics to the EEG also constitutes a possible subsidization instrument: Thus the conservation of farmland and the positive effects on agricultural products could be remunerated. The amendment of the EEG should be as "minimally intensive" as possible. Since agrivoltaics means dual use – for agriculture and energy – the circumstances are similar to the dual use of buildings and other physical structures[17]. This speaks in favor of treating both constellations equally in the legal design of the provisions. A development plan could then be omitted in view of the EEG along with the existence of a certain area category. Continued agricultural use has to be possible, largely without restrictions. This is important for acceptance reasons alone and avoids valuation contradictions within the EEG. The prerequisites for the EU direct payments should be applied in order to ensure this. That increases legal certainty as well. The applicable jurisprudence[18] could then be transferred to the "new" provision in the EEG. What could the implementation look like?

Among other things, a new no. 2 could be added after no. 1 in sentence 1 of Section 48(1) EEG. The regulation would then be worded as follows:

» *For electricity from solar installations, where the applicable value is determined by law, this is [...] cents per kilowatt hour if the system*
[…]
No. 2 has been constructed on farmland and the agricultural activity on this area is carried out without being severely limited by the intensity, type, duration, or timing of the operation of the system,
[…] «

16 See points h.) and i.) of sentence 1, Section 37(1) EEG.

17 Also see above regarding no. 1 of sentence 1, Section 48(1) EEG.

18 Also see above regarding DirektZahlDurchfV.

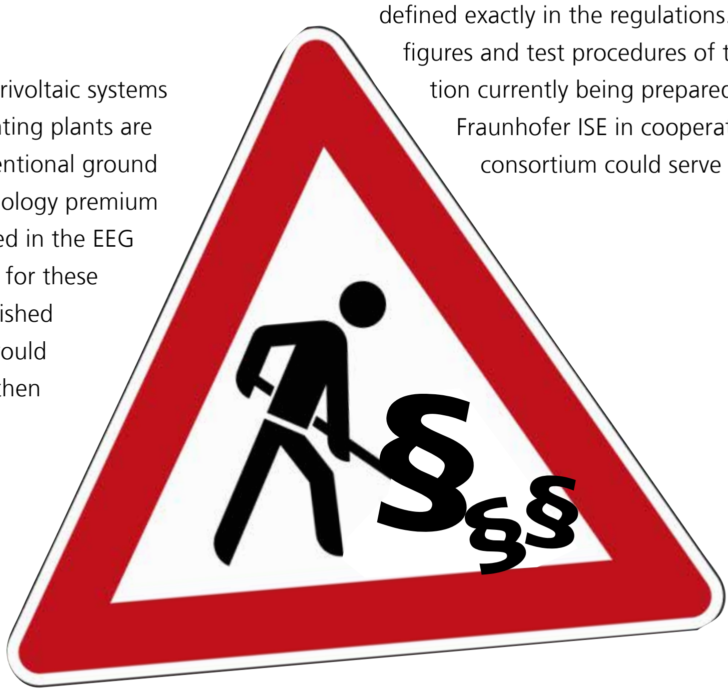
In view of proof of the prerequisites, the following sentence 2 could be added after sentence 1:

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

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

Currently the investment costs for agrivoltaic systems and other land use neutral PV generating plants are somewhat higher compared to conventional ground mount photovoltaic systems. A technology premium (cents per kWh) could be implemented in the EEG to provide the market boost required for these innovative systems: The legally established remuneration (see Section 48 EEG) would be increased accordingly and would then be adequate. This premium would be reduced year by year and reach a value of zero as soon as the new PV generating plant technologies are competitive so that a market boost is no longer needed. In the current tenders (see Sections 37ff. EEG), land use neutral solar generating plant technologies hardly stand a chance today due to the described cost structure. The technology premium could compensate for these competitive disadvantages. The idea is that it would increase the award value accordingly, meaning it would only be taken into account after the conclusion of the tender. Bidders could therefore take part in the tender with a lower bid, making them more competitive with conventional ground mount photovoltaic systems.

In order to ensure the benefits for the farmer are realized, the requirements for an agrivoltaic system should also be defined exactly in the regulations. The performance figures and test procedures of the DIN specification currently being prepared for Germany by Fraunhofer ISE in cooperation with a broad consortium could serve as a starting point.



7. PROMOTING AGRIVOLTAICS

Humanity is faced with challenges of previously unknown magnitude due to climate change, water scarcity, and the steadily increasing demand for energy and foodstuffs. Whether and how humanity will overcome the global challenges will be decided in the coming years. To maintain the quality of life in developed countries and improve it in developing countries and emerging markets, we need to find ways to reach seemingly conflicting goals: Maintaining prosperity, enabling development and a livable future, and reducing the consumption of natural resources and the emission of climate-damaging substances. Agrivoltaics can make a relevant contribution here.

This guideline describes the current state of agrivoltaic technology, its potential, and various areas of application. Aside from more efficient land use, agrivoltaics can help reduce water consumption in agriculture, generate stable additional sources of income for farms, and make many farms more resilient against harvest losses. The early involvement of local citizens is a key criterion for success in the concrete implementation of agrivoltaics.

With a levelized cost of electricity between seven and twelve euro cents per kWh, agrivoltaics is already competitive with other renewable energy sources today. However, the economically viable implementation of agrivoltaics in Germany is only possible in very rare cases because a corresponding legal and regulatory framework is lacking. Adapting the regulatory framework to the technical developments of agrivoltaics could encompass, for example:

- the recognition of agrivoltaics in the DirektZahlDurchfV to maintain land subsidies for agricultural operations, for instance as an exception in no. 3 of Section 12(3)
- a privilege for agrivoltaics according to Section 35(1) BauGB to make approval processes easier
- remuneration for electricity from agrivoltaic systems according to the EEG, falling in between that for ground mount photovoltaic systems and rooftop systems, for instance in the form of special tenders for agrivoltaics

Horticultural applications appear especially well suited for a market launch of agrivoltaics. Reasons include the frequent close physical proximity of the growing area to the farmyard, the high synergy potential of the cultivated plants, the lower cost of supports, and the comparatively simple integration into the management methods for permanent crops. Benefits regarding approval can also be expected in horticulture. A general increase in agricultural value creation could be another benefit in horticulture. This is because many horticultural applications are highly productive. With only about 1.3 percent of the farmland, horticulture contributes more than 10 percent of the value added in agriculture. Creating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incentives for agricultural operations to become more active in this sector by subsidizing agrivoltaics in horticulture could therefore serve as leverage for the total agricultural production in Germany, even with a very small proportion of land used for agrivoltaics. This applies in particular in the area of berry production.

In discussions about agrivoltaics, the argument is often made that the potential of roof areas in Germany should be better utilized first. There is no doubt that rooftop systems will continue to be an important element of the PV expansion going forward, and not only because of their decentralization and land use neutrality. Nevertheless, good reasons speak in favor of also pursuing agrivoltaics as a complement to the existing renewable power generation technologies. For one thing, agrivoltaics – especially in case of larger systems – can be realized more cost effectively on average than rooftop systems due to economies of scale, which contributes to keeping renewable electricity affordable. For another, the modules can in the best case offer added benefits for plant growth while rooftop systems are "only" land use neutral. It is true that a decrease in crop yields was observed for the bulk of the systems studied to date. The harvest results of the research plant in Heggelbach in 2018 however indicated that agrivoltaics, even in this early stage of the technology, could provide a possible answer to the various challenges faced by farmers, among them the increasing periods of drought in Germany. The fact that the average temperature, extreme weather events, and in case of Central Europe also the solar radiation will increase due to climate change suggests that a possible protective function of PV modules for plants will gain greater importance going forward.

Other research aspects concern the combination with energy storage, organic PV foil, and solar water treatment and distribution. Harvesting with electrical agricultural machines is conceivable. One future vision is "swarm farming" with smaller, automated, solar electrified agricultural machines working under the agrivoltaic system, harvesting the required energy directly in the field. Machines for autonomous weeding or the elimination of potato beetles using lasers already exist today – entirely without chemicals or the contamination of the soil or groundwater. Thus agriculture can become more sustainable, not only thanks to climate-friendly drive systems but also through intelligent technology. The mounting structure and power generation of an agrivoltaic system offers favorable conditions for the integration of such smart farming elements. Automated field cultivation is currently being integrated into the mounting structure of an agrivoltaic system at Fraunhofer ISE for testing on 1.2 x 3 meter of arable land.

Over the long term, PV will become the energy supply's primary pillar. Climate change and increasing water scarcity demand new approaches in agriculture, in part to make operations more economically and ecologically resilient. To alleviate land use competition, the agrivoltaic technology offers a way to expand the PV capacity while conserving farmland as a resource for food production. The dual use of the areas considerably increases the 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 climate-friendly energy to cover the demand of agricultural operations.

The first plants in Germany have shown that the technology works. Subject to further development through research, industry, and politics in the future, the tremendous potential of agrivoltaics could be realized. This would be a positive development, not just for the climate.


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8.2 List of Figures

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8.4 Abbreviations

W	Watt
Wh	Watt hour
W_p	Watt peak, capacity measured under standard test conditions
kW	Kilowatt
kWh	Kilowatt hour
kW_p	Kilowatt peak, measured under standard test conditions
MW	Megawatt
MW_p	Megawatt peak, measured under standard test conditions
GW	Gigawatt
GW_p	Gigawatt peak. Capacity in gigawatt, measured under standard test conditions
GWh	Gigawatt hour
TWh	Terrawatt hour
min.	Minimum, minimal
max.	Maximum, maximal
m²	Square meter
EEG	Renewable Energies Act (Erneuerbare-Energien-Gesetz)
REAP	Rural Energy Advancement Program
PV-GM	Ground-mounted photovoltaic system
PPA	Power purchase agreement
CIS	Copper-Indium-Selenide
CdTE	Cadmium telluride
a-Si	Amorphous silicon
µ-Si	Microcrystalline silicon
OPV	Organic photovoltaics
CPV	Concentrator photovoltaics

8.5 Links to Further Information

Website Agrivoltaics (Fraunhofer ISE)
https://agri-pv.org/en/

Short film about the APV research facility in Heggelbach (German):
https://www.youtube.com/watch?v=BlXPf-e1a0U

Guideline for ground mount solar systems: link to the website of the Ministry of Environment, Climate and Energy Baden-Württemberg (German):
https://um.baden-wuerttemberg.de/fileadmin/redaktion/m-um/intern/Dateien/Dokumente/2_Presse_und_Service/Publikationen/Energie/Handlungsleitfaden_Freiflaechensolaranlagen.pdf

Agrivoltaics, link to the website of Fraunhofer ISE:
https://www.ise.fraunhofer.de/en/business-areas/photovoltaics/photovoltaic-modules-and-power-plants/integrated-photovoltaics/agrivoltaics.html

Project website APV-orcharding, link to the website of Fraunhofer ISE:
https://www.ise.fraunhofer.de/en/research-projects/apv-obstbau-orcharding.html

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