Agrophotovoltaics: harvesting the sun for power and potatoes

Applications | The question of whether to use valuable land for farming or solar power generation has been a subject of fierce debate in the green energy transition. But, as Boris Farnung, Maximilian Trommsdorff and Stephan Schindele of Fraunhofer ISE write, the two activities need not be in conflict with each other and, with a new generation of solar technologies, can in fact be mutually beneficial

Credit: Fraunhofer ISE

The pilot agrophotovoltaic system uses bifacial glass-glass modules arranged in rows of two

Agrophotovoltaics: solving the food versus fuel conflict

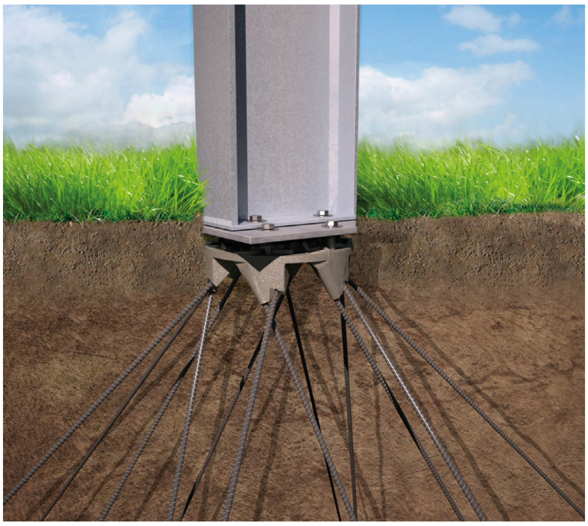
For farmers in Germany, energy harvesting is economically more beneficial than food production. Thus, for example about 18% of arable land in Germany is used for growing energy crops. And it is true that Germany must allocate new land for the production of solar electricity in order to meet the urgent expansion of renewables needed for the energy transformation. Studies show that photovoltaic installations in the range of 200GWp are required in order to meet the goal of reducing carbon emissions by 85% until 2050. This leads to a significant increase in the competition for land usage – "food versus fuel" – and at the same time presents an ethical dilemma: valuable, arable land is used to produce energy, while at the same time food is being imported from threshold and developing countries. As a result, these countries grow crops for export and less food is available for the indigenous population. But conflicts over land use are also arising in emerging and developing countries, as growing populations and rising living standards require more energy and food production.

Instead of being competitors, photovoltaics and photosynthesis can actually complement each other. So-called agrophotovoltaic (APV) systems make the efficient dual land usage possible: the farmer not only provides potatoes but also electricity – from the same piece of land – which dramatically increases the land use efficiency. The concept is not novel, quite the contrary: it was conceived by the founder of the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg, Prof. Dr. Adolf Goetzberger, and his colleague Dr. Armin Zastrow in a paper published in 1981 [1]. Since then, numerous large agrophotovoltaic (APV) systems have been installed worldwide. Leading countries in the field are France, Japan, China, Korea and the United States, with support schemes for agrophotovoltaics established. The overall installed capacity is estimated to be 2.1GW, with approximately 1.9GW in China alone. Nevertheless, only a few research plants exist, and the full scope of applications is still to be investigated.

Pilot project "Agrophotovoltaics–Resource-Efficient Land Use"

In the project "Agrophotovoltaics: Resource-Efficient Land Use" (March 2015 to June 2019), the technical, societal, ecological and economical aspects of the technology were investigated in a pilot demonstration project. The seven partners of the model project, led by Fraunhofer ISE and financed by the German Federal Ministry of Education and Research and FONA (Research for Sustainable Development), also wanted to clarify the political and energy economical boundary conditions that are required to help the new technology break into the market.

The pilot APV system was installed at the organic Demeter farm in Heggelbach, near Lake Constance. On a test field covering one third of a hectare, 720 bifacial modules with a total power of 194.4 kWp were installed at a height of five meters above the ground. This clearance height makes sure that the use of versatile agricultural machinery is not restricted. The rows of semi-transparent glass-glass modules are placed at a slightly larger distance so that the crops growing underneath receive at least 60% of the total incoming irradiation. Modules are arranged in rows of two, with a gap between the rows to better distribute


Credit: Spinnanker

The foundations were fixed by spinning anchor rods

rainwater. The modules' total surface measures 1206 square meters. The deviation from the south is 52 degrees, with an angle of inclination of 20 degrees.

Within the project, Fraunhofer ISE has developed accurate and validated calculation methods to design the system with a balanced ratio of light and shade. In addition, based on comprehensive light-management simulations, it is ensured that the irradiation is homogeneous over the designated area. Thus, Fraunhofer ISE is uniquely positioned to support project developers to define a system concept optimised for solar power and food production in the same area.

An important technical aspect was the possibility of deconstructing the plant without, for example, leaving foundations in the ground. The foundations were therefore laid using a spinning anchor system: up to eight-meter-long spinning anchor rods were turned down on a cast plate, in the center of which an Alpine anchor was drilled into the ground. In order to avoid damage to the facility by agricultural machineries, the posts were fitted with a ram protection, which was also fastened with anchor rods. In total, about 50 tons of steel were used.

One of the Demeter farmers' demands was that they could carry out their normal crop rotation under the plant: winter wheat, clover grass, celery and potatoes. The aim for the farmers was to achieve at least 80% of the usual yield. In order to be able to prove this, the same crops were cultivated on a reference area directly next to the test field. Over a period of three years, the experts for agricultural research of the University of Hohenheim accompanied the agricultural aspects of the project, from the measurement of the climatic conditions under the plant, through the yield and quality of the products to the effects on biodiversity.

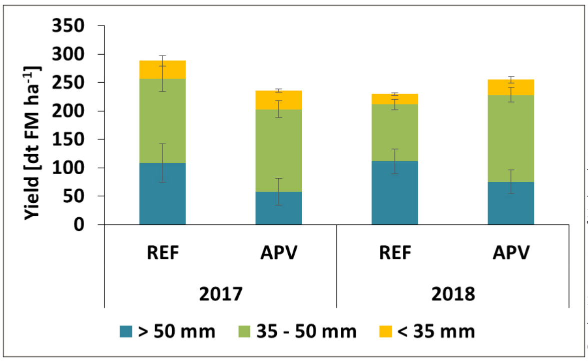
From September 2016 to June 2019, the solar power and the agricultural yield were assessed, accompanied by social science studies on the acceptance by the local population. Two full harvest cycles were completed during the project period.

Agricultural results: high yields in hot and dry summer

Over the first 12 months (October 2016 to October 2017), four crops (winter wheat, potatoes, clover and celery) were grown and harvested.

The University of Hohenheim investigated the response of the crops to the local changes in environmental conditions. Data on the microclimatic parameters such as photosynthetic active radiation (PAR), air and ground temperature as well as precipitation were collected. The analyses indicated that the PAR under the APV system is reduced by about 30%. In the first evaluated year, the local air temperatures under the APV system did not differ significantly to the reference plot. Washouts have been observed at single locations in the field, depending on the crop and its stage of development. In particular, the scientists observed a slightly less homogeneous distribution of rain water below the PV panels compared to the reference area.

While the clover yield was reduced only slightly (-5.3%) due to shading from the APV, the yield decrease for potatoes (-18.2%), wheat (-18.7%) and celery (-18.9%) was higher. The winter wheat and the potatoes growing under the PV array showed a slightly slower development than the same crops on the reference plot. At harvest, no mentionable difference in development was observable, so that the crops under the APV and on the reference field could be harvested at the same time. The results from the first year of practice showed that all four crops were qualitatively good and marketable. In comparison to the crops from the reference plot, a lower yield was observed, but it was still within the target horizon determined in advance by the farmers. It has to be noticed that the harvest was a bit too early for some of the plants under the APV array. Normally the potatoes and celery plants should have been given about two more weeks to ripen.



Credit: University of Hohenheim

The marketable share (35-50 mm) of the potato harvest was higher under the APV system.

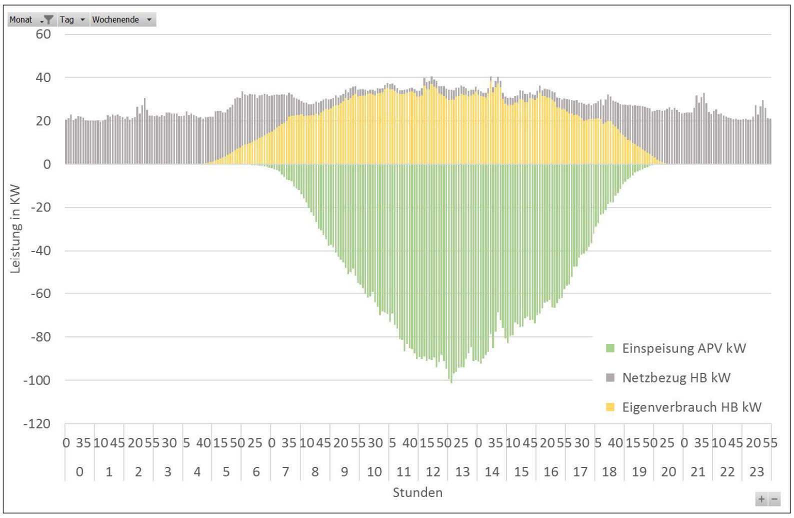
The second year, however, showed a different picture: In 2018, the yields from three of the four crops grown under the APV system were larger than the reference plot. The crop yields for celery profited the most by the system, with a gain of 12% compared to the reference. Winter wheat and potatoes produced a gain of 3 and 11% respectively, and clover a minus of 8%. In addition, in the case of potatoes, the marketable share (35-50 millimeters in size) was larger under the APV plant than under the reference area.

In spring and summer, the soil temperature under the APV system was less than on the reference field; while the air temperature was identical. In the hot, dry summer of 2018, the soil moisture in the wheat crop was higher than on the reference field, while in the winter months, it was less, as for the other crops. The agricultural scientists of the University of Hohenheim assume that the shade under the semi-transparent solar modules enabled the plants to better endure the hot and dry conditions of 2018. In their view, agrophotovoltaics could mitigate climate change effects on agriculture in many regions.

For the research project, no particularly shadow-tolerant or even shade-loving plants were selected, but varieties normally marketed by the Demeter farm. It can be assumed that shade-loving plants such as hops, leafy vegetables, legumes or certain wine and fruit varieties would have shown significantly better yields. Further follow-up research projects are needed to investigate this in more detail.

Solar energy harvest: yields exceed expectations

As for the solar yield, the project results of the first year already exceeded expectations, at least with respect to the initial specifications. In the first 12 months of operation, the PV plant produced 245,666kWh of electricity, or 1,266kWh



Credit: BayWa r.e.

During summer, the APV system covers the electricity load at the farm almost completely. The green area represents the feed-in of the solar power into the grid, the yellow area represents the own consumption, while the purchased power from the grid is plotted in grey

per kWp installed. The power output is mainly influenced by the use of bifacial module technology, but also by a larger distance from row to row which results in lower shading and temperature losses compared to conventional power plants. A detrimental factor with regard to the electrical yield is the orientation of the system, which is 52° off south.

In the second year of operation, the solar irradiation totalled 1,319.7kWh/m^2, an increase of 8.4% compared to the previous year. The energy output of the APV system amounted to 249,857kWh, corresponding to an extraordinarily good specific yield value of 1285.3kWh/kWp.

BayWa r.e. renewable energy GmbH, responsible for the construction and the load management of the APV system, also evaluated the self-consumption at the farm. Over the day, the power produced by the APV system was well matched to the power consumption on the Demeter farm. In the summer months, the load demand was covered almost fully by the APV system and in July close to 100%. The electricity generated could supply the annual demand of 62 four-person households. The Demeter farmers use it primarily for processing their products and charging their electrical vehicle. With the subsequent installation of a 150kWh battery in 2018, the farm community could increase the own consumption rate for the solar power to approximately 70%. This shows that if the electricity is stored and used on site, for example for the use of electric agricultural vehicles, additional sources of income arise due to synergy effects.

While the expected capex costs of an APV plant are about one-third higher than for a conventional open space plant, mostly due to the higher racking system and higher logistics costs, the OPEX costs tend to be about a quarter lower. This is due to synergy effects such as the avoided costs for mowing, surveillance or a fence. The electricity production costs of a typical APV system of 2MWp today are competitive with a small PV rooftop system (<10kWp). Further cost reductions due to economies of scale and learning effects are to be expected.

Land use efficiency dramatically increased

The results from 2017 already showed a land use efficiency of 160% compared to a single use of the land (i.e., either agriculture or PV). The performance of the APV system in the very hot and dry summer of 2018 greatly exceeded this value, as the partial shading underneath the photovoltaic modules improved the agricultural yield, and the sun-rich summer increased the solar electricity production. Based on the 2018 potato yield, the land use efficiency rose to 186% per hectare with the APV system.

The APV-RESOLA project examined not only technological and agricultural aspects, but also the acceptance of this new technology by the local population, as this could become an obstacle to higher market penetration ("not in my backyard"). In two citizen workshops, social scientists from the Institute for Technology Assessment and System Analysis (ITAS) of the Karlsruhe Institute of Technology discussed which forms of energy production they would accept in their immediate living environment. One workshop was carried out before the construction of the plant, the second one afterwards, and there was also a survey. The results showed that the acceptance of APV systems increases if local citizens recognize clear advantages for themselves, for example if they are involved financially within the framework of a citizens' energy cooperative. The aesthetics of the plant was a point of criticism, especially with regard to the tourist attractiveness of the region. Still, the citizens surveyed prefer the APV system to a conventional PV plant. They also pointed out that uncontrolled growth and "pseudo-agriculture" must be avoided, i.e. clear standards must be established by the legislator with regard to the definition of an APV system. While in France, Japan, Korea and the USA there are already financial support schemes with corresponding definitions, this is lacking in Germany.

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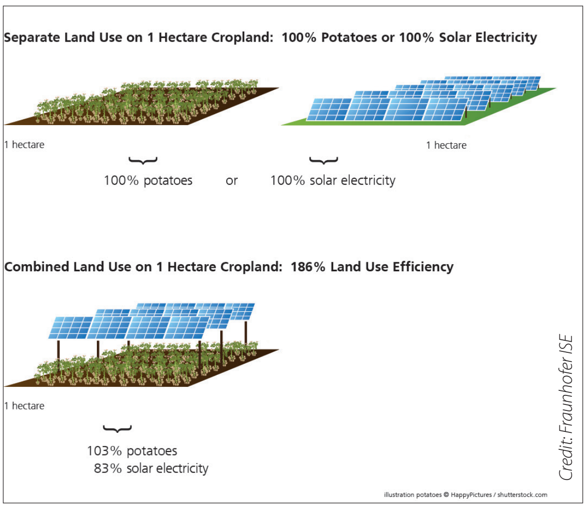

Credit: Fraunhofer ISE

The land use efficiency was dramatically increased during the hot and dry summer of 2018

Further research topics: horizontal and vertical technology development

Now that evidence of increased land use efficiency and economic viability has been provided, further horizontal and vertical technology development is needed to unlock the full potential of agrophotovoltaics. To provide the necessary proof-of-concept before market entry, other techno-economic APV applications must be compared and larger systems in the MW range need to be realised. Different possible applications shall be explored, such as the combination with fruits, berries, hops, wine crops and livestock farming. As far as vegetable cultivation is concerned, there is currently a trend towards closed cultivation. This serves on the one hand to adapt to climate change (protection against extreme weather conditions, improvement of the water balance) and to "green the deserts", but also helps to reduce the use of pesticides, as no pests can penetrate. To give an example, in France there are already large greenhouses with APV. In the future, a combination with organic photovoltaic modules or flexible photovoltaic foils would be conceivable: special absorber layers in the photovoltaic cells would allow certain parts of the sunlight, which are particularly conducive to plant growth, to pass through, while protecting the plants from excessive radiation.

Aquafarming is another possible application: in 2018, Fraunhofer ISE carried out a proof-of-concept study analysing the possibility of installing APV at shrimp farms located in the Vietnamese Mekong Delta. In this densely populated region with an energy consumption growing 10% annually, there is an increasing competition for land between aquaculture and renewable energy. The study showed that solar-aquaculture habitats have the potential to promote the deployment of renewable energy as well as enact measures to counteract climate change, expand shrimp production yet protect water resources, decrease land use and reduce CO2 emissions at the same time. Based on the first analyses, the pilot project in Bac Liêu can save about 15,000 tons of carbon dioxide emissions annually and reduce the water use by 75% compared to a conventional shrimp farm. The aquafarm operators appreciate other advantages from this technology, such as protection of shrimps and fish against predatory animals, improved working conditions due to shading and a stable or lower water temperature that helps to promote the shrimps' growth. The combination of aquaculture and photovoltaics is expected to significantly increase the land use rate.

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In order to exploit the technology on the vertical level, further development work is required in the areas of organic PV film technologies, energy storage, water treatment, irrigation systems, agricultural robotics, electro-mobility, tracking systems, materials research and structural design. Another aspect to be considered is the rising use of electric vehicles in agriculture, which could increase the own consumption of solar power on farms.

Two years ago, the agricultural machinery manufacturers Fendt and John Deere introduced the first fully electric battery-operated tractors. A future vision is "swarm farming", with automated solar-powered electric farm machines working under the APV array and receiving their power directly from the APV system. Already today, machines exist that autonomously cut weeds or eliminate pests such as the Colorado potato beetle without using chemicals, polluting the ground water or the soil. Thus, farming would become more sustainable not only with environmentally friendly machines but also through intelligent technology.

High potential for arid regions

Another current research focus addresses the transfer of APV technology to other climate zones. The technology of dual use may prove to be especially advantageous in semi-arid threshold and developing countries. The results from the summer of 2018 demonstrate the enormous potential of agrophotovoltaics for arid climate zones. Crops and livestock can benefit from the shade given by the PV modules, while the electricity can be used for seawater desalination, water treatment or irrigation pumps. Fraunhofer ISE is already working on several projects to transfer the technology to threshold and developing countries as well as for new applications. A pilot study that Fraunhofer ISE carried out for the Indian state of Maharashtra showed that shading effects and less evaporation might result in up to 40% higher yields for tomatoes and cotton crops. In certain cases, the experts expect the land use efficiency to almost double for the region. In another project, carried out within the EU Horizon 2020 programme, the Fraunhofer ISE researchers are working together with partners from Algeria to test the effects of APV systems on the water balance. Besides

Credit: Hofgemeinschaft Heggelbach

Using agricultural vehicles under an APV system is not a problem. In the future, these could be e-vehicles

less evaporation and lower temperatures, harvesting the rain water with PV modules also plays a role.

Together with Fraunhofer Chile, Fraunhofer ISE is currently testing three 13kWp APV systems in the Chilean communities of El Monte, Curacavi and Lampa, which are the first of their kind in Latin America. Investigations involve adapting and optimising the APV technology according to the specific climatic and economic conditions in Chile. The results of both the crop and solar power production are very positive. In the arid and semi-arid regions in Northern and Central Chile, there is great potential for APV, since a large percentage of the people live from agriculture, which is impacted by the increasing amount of dry periods, desertification and water scarcity due to climate change. The projects show that the partial shading of crops planted underneath APV can reduce their need for water and also offer livestock shelter from the sun. Also, it is expected that various fruits which normally do not grow well in dry climates with high solar radiation would grow underneath an APV system.

The three pilot plants will be monitored for three additional years, operating them as on-field labs. A long-term plan involving different type of crops has been coordinated with the farmers, so it will be possible to test the concept with a large variety of products.

Apart from the higher land use efficiency, APV systems can help to improve the socio-economic situation of rural areas in threshold or developing countries. In those villages often situated far from the grid, the quality of life is increased immensely just with the electric output of a few solar modules providing improved access to information, education, clean water and also better medical care. For example, in sub-Saharan Africa, about 92% of the rural populations have no access to electricity. APV offers new sources of income to the local population and at the same time reduces the dependence on fossil fuels, needed for diesel generators. Besides this, solar power can be used for cooling, processing and preserving agricultural crops, making them more profitable as they can also be marketed outside the harvest period. ■

Authors

Boris Farnung joined the Fraunhofer Institute for Solar Energy Systems ISE in 2008. He is head of group PV Power Plants and over the years has gained extensive experience in quality assurance, bankability support, testing and characterisation on both the module and the system level from projects worldwide. He is also operating agent of the IEA PVPS Task 13 - Performance and Reliability of Photovoltaic Systems.

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