REVIEW OF RESULTS OF AGRO-PHOTOVOLTAIC SYSTEM IMPLEMENTATION IN AGRICULTURE

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Abstract. The article provides an overview of agro-photovoltaic systems already implemented and researched or tested in the world, describes the results of exploitation of such systems, their efficiency, benefits for agriculture, possibilities for further research, and for the development of green electricity production. Some information is also provided in order to show the viability of the development of photovoltaic power plants, their environmental friendliness, and their important role in halting climate change. The results of the researches of the globally implemented agro-photovoltaic systems show the indisputable efficiency of these systems and their obvious advantage over the traditional agricultural technologies. As the results of the research show, dual land exploitation for agriculture and electricity generation by agro-photovoltaic systems almost doubles the land use efficiency (up to 186%). Some suggestions are discussed for further researches of agro-photovoltaic systems. The history of implementation of agro-photovoltaic systems began less than 20 years ago. So far, now we have only a small group of leading countries in this area, but in most of the remaining countries, these systems are still unknown and untested. Therefore, the goal of this overview was to disclose the efficiency of the agro-photovoltaic systems, their viability, and to contribute to the dissemination of information in order to pave the way for acceleration of progress in this promising field of agriculture.

Keywords: horticulture, livestock, agro-photovoltaics, electricity, efficiency.

Introduction

In the electricity generation sector, there is constant competition on a global scale between different technologies according to many parameters. The aim of the competition is to reduce the price of electricity produced, improve the efficiency of the primary energy source utilisation, increase energy independence and reliability of electricity supply. Solar and wind power plants have already caught up with the cheapest fossil fuel power plants in terms of the price of electricity without subsidies. In addition, it is very important to take into consideration the ecological characteristics of electricity generation technologies. The absolute champions in this field are RES-based technologies.

Another type of competition appeared in rural areas for the land after the development of solar modules for electricity generation, which can be installed not only on roofs and water bodies, but also on the ground. However, the world does not have so much land suitable for farming. In addition, the price index of photovoltaic modules was still very high in the last decades of the last century. So, ecologically efficient but expensive photovoltaic technology for power production was initially not met friendly in rural areas, despite the fact that German scientists A. Goetzberger and A. Zastrow in 1981 proposed the concept of dual-use land – both for agricultural needs and for electricity generation using photovoltaic power plants (PVPP). This concept was published in their publication in 1982 [1].

Over time, the price index for solar modules dramatically fell down and reached a level that researchers became interested in the concept of dual land use again. In Japan, Prof. Akira Nagashima began experimenting in this area in 2003 [2]. After this, the prices of solar modules have continued to fall very rapidly and the operational efficiency of the modules has increased significantly. Conditions for the installation of PVPP and agro-photovoltaic systems (APVS) became attractive. Presently a group of leading countries has already performed a significant number of projects in the area of APVS, but there are many countries, where these systems are still unknown, untested, and unused.

The total power of the PVPP built per one year in the world presently is the highest among all electricity generation technologies. According to the data of the International Energy Agency (IEA) for 2020-2025, together with the newly built wind farms presently they account for 80% of total annual capacity, leaving only about 20% for all other technologies [3]. Photovoltaic (PV) power plants are very suitable for installation in rural areas as well, especially when the concept of land double use is applied. Significant progress has been made over the last 15 years in the implementation of APVS. Solar power plants are now successfully combined with the cultivation of potatoes, many types of vegetables, flowers, herbs, plants, some spices, grapes, olives, and other species. When the soil areas are fenced, there can be kept geese, chicks, ducks, bees, sheep, deer, goats, cows, etc.

Materials and methods

The material for this article has been searched on a global scale in various sources of information – in articles of scientific journals, proceedings of scientific conferences, in scientific books, doctoral dissertations, in periodical online publications of universities and research institutes, and in other available sources of information. Part of the found information sources is presented in the references of this paper, where readers will find useful additional information on the APVS.

Conventional methods were used to overview the available information regarding the APVS. Selected information sources were studied and analysed, the most important information was summarized. After this, the main results of the study were described and discussion about the perspectives of development of dual land use in agriculture was presented. The main insights on the agro-photovoltaic systems were formulated and presented as the conclusions of the review.

Results and discussion

A review of available sources of information showed that photovoltaic arrays can be mounted on the roofs of greenhouses, over arable land, and on the surface of water bodies (floating PV arrays). Each case of APVS is more or less unique. Some examples of APVS adapted to different species and used for cultivation of crops or keeping livestock are described in Table 1. A greenhouse for the growing Welsh onions was built for research of APVS operation in Shimane Agricultural Technology Centre, Japan [4]. The PV array was installed on the top of the greenhouse. 30 panels of 24 W were used to form the PV array. Coverage of the greenhouse roof was not significant – 12.9%. Straight-line and checkerboard layouts of the PV modules were tested on the roof of the greenhouse. The checkerboard layout option was better – the onions received more sunlight and the yield was better.

Two Canary Islands greenhouses for APVS research were built in 2017 in Agadir, Morocco [5]. The areas of both greenhouses were the same – 172 m^2 each. 32 PV modules of 100 W (3.2 kW) were installed on the roof of the main greenhouse. They occupied 10% of the roof area. The second greenhouse was used as a control for the comparison of the research results and was free from PV modules. Tomatoes were grown in the both greenhouses, where eight crops were harvested per year. Comparison of the harvests in both greenhouses showed a slight advantage of the PV greenhouse – about 105% against 100% in the control greenhouse. In addition, it was observed that there were slightly fewer tomatoes eating pests *Tuta absoluta* in the experimental PV greenhouse.

An interesting APVS for growing vegetables and producing electricity was developed by the Indian Institute CAZRI in Jodhpur, Rajasthan [6]. They found a way to make more efficient use of their system and additionally installed a system to collect rainwater running from the PV modules. The accumulated water was for additional watering of vegetables. The amount of rainwater harvested per year from the PV modules was 150 m^3 per acre. The capacity of the installed PVPP was 105 kW.

One of the simplest options for APVS is when solar modules are installed on the meadow and all available land around it is fenced. Free-range animals (sheep, goats, deer, cows, horses, etc.) or poultry (geese, ducks, chickens, turkeys, etc.) can be kept in the enclosure. In this case, only the height of the PV module elevation above the land surface may be relevant depending on the species of animals and on their behaviour. This type of APVS is already installed in many farms – in Benbole Farm, Wadebridge, Cornwall [7], in Newlands Farm, Axminster, Devon [7] (both in the UK), in Tsukuba, Ibaraki, Japan [2], in Princeton University solar field, New Jersey, USA [8] and elsewhere.

The well-known project APV-RESOLA was designed to explore the possibilities of growing vegetables and cereals under the PV arrays. The full programme of this project was implemented in Heggelbach, region Bodensee-Oberschwaben, Germany in the years 2015-2020 [2; 9]. Coordinator of this project was the Fraunhofer Institute for Solar Energy Systems (in German – Fraunhofer Institut für Solare Energiesysteme or shortly – Fraunhofer ISE). One of the studies listed in the project program was to check the possibility of growing potatoes on the same land area under the modules and in the spaces between the strings of modules of the PV array. Three plots of land of equal size (1 ha) with equal soil were selected for the research. Only potatoes were planted in one (control) plot of land. The PV array with solar modules mounted as usual was installed nearby on another control plot of land. The total capacity of the PV array was 194.4 kW. The PV array with the same capacity (194.4 kW) was mounted and the potatoes were planted in the last experimental plot of land. However, the PV array was mounted differently in this case for the convenience of agricultural machinery (so that agricultural machines could pass under the PV modules). Once the potatoes were grown, they were harvested and weighed. Quantities of electricity produced in the experimental and control plots were also measured. Potato yields and electricity generated on control plots were equated to 100%. Interesting results were obtained in the experimental dual-use land area: potato yield was 103%, and electricity production – 83%. The efficiency of dual-use land area exploitation was 186%.

Table 1

Already researched or practically tested APVS in the world

Location of APVS	Type of APVS	Parameters of the system	Benefits for agriculture
Shimane Agricultural Technology Center, Japan	PVPP and greenhouse Welsh onions [4]	Greenhouse 84.6 m^2 PV array of 30 modules mounted in 2007 (720 W), covered 12.9% of roof.	Electricity produced per year – about 800 kWh. Crop of Welsh onions.
Agadir, Morocco, Atlantic coast	PVPP and tomatoes in one greenhouse, only tomatoes in control greenhouse [5]	2 Canarian greenhouses 172 + 172 m^2, height 5 m. PV array 3 200 W mounted in 2017 covered 10% of roof area.	8 harvests were performed in both greenhouses. Average yield in the photovoltaic greenhouse was about 5-6% higher.
Institute CAZRI, Jodhpur, Rajasthan, India	PVPP and vegetables of various types [6]	Land area – 1 ha, PV power plant – 105 kW installed in 2016 with rain water harvesting system for supplemental irrigation	Electricity produced per year – about 130 MWh. Rainwater harvested per year – 150 m^3·ac^{-1}·a^{-1}. Income from crops.
Benbole Farm, Wadebridge, Cornwall, UK	PVPP and geese [7]	Land area – 4 ha, PV power plant – 1.74 MW, installed in 2011.	Electricity – for the farm. Grass for a flock of geese. No need to cut the grass.
Newlands Farm, Axminster, Devon, United Kingdom	PVPP and sheep [7]	Land area – 13 ha, PV power plant – 4.2 MW, installed in early 2013.	Electricity – for the farm. Grass for a herd of sheep. No need to cut the grass.
Tsukuba, Ibaraki, Japan	PVPP, goats and chickens [2]	Land area – 0.1 ha, PV power plant – 41 kW, installed in 2014, Shading rate – 3%	Electric energy produced per year – about 45 MWh for the farm. Grass for chicken and goats.
Princeton university solar field, New Jersey, United States of America	PVPP and sheep [8]	Land area – 27 ac (11 ha), PV power plant – 4.5 MW, installed in 2011. A herd of 75 sheep settled in the solar field in 2018.	Electricity – for the Princeton university. Grass for a herd of sheep. No need to cut the grass and weeds or to use herbicides.
Heggelbach, Region Bodensee-Oberschwaben, Germany	PVPP and potatoes [2; 9]	Experimental area – 1 ha. PV array – 194.4 kW. Efficiency for potatoes – 103%, for power – 83%.	Electricity – for the farm needs. Potato harvest can be sold, and lower quality can be fed to farm cattle.
Bolton Bees, St. Paul, Minnesota, United States of America	PVPP and beehives [10]	3 PV array sites: 1.2 ac + 40 ac + 40 ac. Honey extracted per year – up to 4 000 lb (1 814 kg).	Honey and protection of bees; preservation of plant species; better crop yields due to the pollination.

Beekeepers also can easily install PV array with the normal density and usual elevation of solar modules in their apiary, to place the rest components of the solar power plant in a metal cabinet or in a nearby building, and to plant the surrounding land with long-blooming honeyed flowers. Such APVS with apiary already operate in Bolton Bees, St. Paul, Minnesota, USA [10], and elsewhere.

There are no major problems for installations of APVS in fisheries that have sufficiently large bodies of water for shrimps and fish breeding, too. Floating PV arrays can be installed on the fishery's water body and connected by cables to the rest part of the PV power plant. After this, the fish breeding business can be continued along with generating electricity in the own solar power plant [2; 11].

A review of the researches described in scientific articles showed that the development of APVS requires consideration of crop tolerance for shade, the height of the PV modules elevation, the distance between the rows (strings) of PV modules, the size of the agricultural machinery, the expediency of rainwater collection from the PV modules, the ways of crop irrigation and fertilizer usage and other factors. Highly efficient water-saving crop irrigation systems through the capillaries are widely used in Israel. In this case, the plants are fed by water along with fertilizer directly through the plant roots. Such irrigation systems could also be applied to APVS. The distance between the strings of PV modules should be chosen according to the degree of tolerance of the crop to the shadows. Crops have to receive the optimum amount of solar energy. High supports are also useful for better homogenizing crop lighting. Different requirements must be met when developing APVS for livestock, poultry, bees, greenhouses, or fisheries. The cases when 2-3 types of fauna (e.g., sheep, chickens, and bees) are kept in the same APVS could be researched, too. Harmonization of all requirements is important as well.

With regard to APVS, a number of important facts need to be mentioned about the key component of these systems, namely, about the permanent progress and current state-of-art of solar power plants. First of all, PVPP, as well as other power plants based on renewable energy sources and nuclear power plants, has a huge superiority against technologies based on fossil fuels because of the very low carbon intensity of power generation measured in grams of CO2 equivalent per kWh (g CO2 eq per kWh). The average carbon intensity of power generation by technologies is shown in Fig. 1 [12]. The carbon intensity of PVPP is decreasing as the improvement of PV cells leads to less energy consumption.

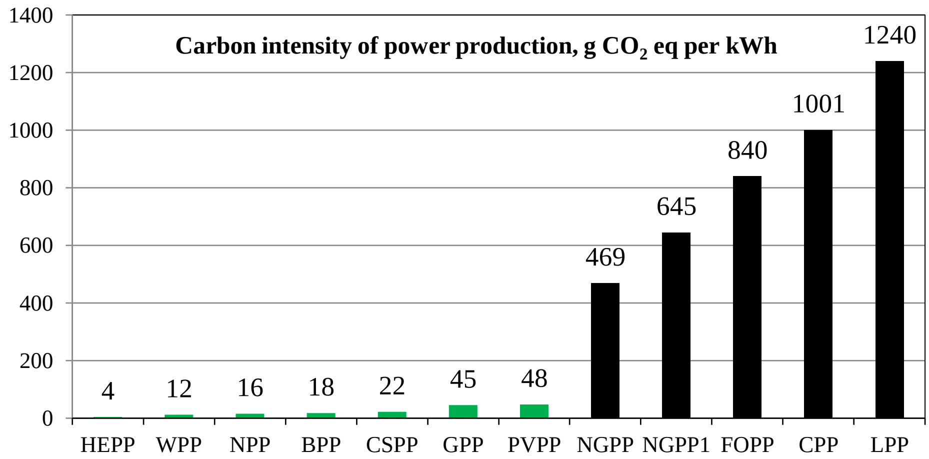

Fig. 1. **Average carbon intensity of power generation by the technologies [12]:**
HEPP – hydroelectric power plants, WPP – wind power plants, NPP – nuclear power plants, BPP – biomass-based power plants, CSPP – concentrated solar power plants, GPP – geothermal power plants, PVPP – photovoltaic power plants, NGPP – power plants running on high quality natural gas, NGPP1 – power plants running on worse quality natural gas, FOPP – power plants running on fuel oil, CPP – coal-based power plants, and LPP – lignite-based power plants

The first PV modules were developed in the USA. They were used only to generate electricity for satellites and space stations because they were very expensive. At first, no one thought that PV modules would be used on the ground as well, that PVPP would be so powerful, and that the electricity they produced would be so cheap. But thanks to the perseverant work of scientists, all this has been achieved. Key parameters of the main power generation technologies, such as levelized cost of electricity (2020) [13] and full global operating capacity (2019 and prediction up to 2025) [3] together with the evolution of the price index of crystalline silicon PV modules for years 1975-2020 [14] are presented in Table 2. Predictions for the NPP global capacity in the 1970s varied between 2 910 and 5 300 GW but in reality, only 350 GW were operating in 2000 and 370 GW in 2019 [15].

Levelized cost of electricity (LCOE) includes the cost of power plant construction, on-going fuel costs, operating and maintenance costs over its lifetime, and cost of the power plant decommissioning. A 528.5-fold decrease of the price index of PV modules dramatically reduced the LCOE of PVPPs. The LCOE of PVPP and wind power plants (WPP) now has the lowest values in the world, so their common global capacity (PVPP + WPP) is projected to have the fastest growth - from 4th place in 2019, they both will rise to the 1st place in 2025. Many countries around the world have set ambitious goals in the field of PVPP. Already in 2020, the total capacity of all PVPP installed in the world was 132 GW per year, and the target for 2021 is 194 GW [16]. The world's most powerful PVPP of 10 GW is being built in northern Australia to meet Singapore's energy needs [17]. Meanwhile, the world's largest NPP operating in Kashiwazaki-Kariwa, Japan has a net capacity of 7.965 GW [18]. The data presented show that PVPPs are a viable source of energy for the future.

Table 2

Comparison of key parameters of the main power generation technologies development and evolution of the price index of crystalline silicon PV modules

Year	**Levelized cost of electricity, USD per MWh [13]**				
	PVPP + WPP	**HEPP**	**NGPP**	**CPP**	**NPP**
2020	37(PV), 40(W)	50 [19]	59	112	163 [13]
Full global operating capacity, GW [3]					
2019	1 226 (4)	1 305 (3)	1 788 (2)	2 124 (1)	370 [15]
2021	1 583 (3)	1 350 (4)	1 853 (2)	2 139 (1)	No data
2023	1 953 (2)	1 398 (4)	1 935 (3)	2 132 (1)	No data
2025	2 349 (1)	1 427 (4)	1 999 (3)	2 079 (2)	No data
Evolution of the price index of crystalline silicon PV modules, 1975-2020, USD per W [14]					
1975	1980	1990	2000	2010	2020
105.7	29.3	7.9	4.9	2.0	0.2

Therefore, many PVPPs are intended to be installed globally for power needs of agriculture. Israeli government decided to combine agriculture and electricity generation, too. Recently they adopted a plan, which anticipates a striking increase of the PV power generation by installation of APVS. The goal of this huge project is to have 15 GW total electric power capacity from the APVS by 2030 [20].

Seeing a very successful development of solar power plants around the world, it is safe to predict that development of APVS will also be successful. In 2020, the highly successful first World Congress AgriVoltaics 2020 took place online. The congress was attended by 350 participants from 38 countries around the world. The next World Congress AgriVoltaics 2021 will be held in June 14-16 (online).

Conclusions

1. The very successful development of PVPP has led to the development of APVS.
2. The review allows predicting that rapid development of APVS will be efficient and successful.
3. Global studies show that implementation of APVS increases the land use efficiency by up to 186%.
4. Leading countries around the world are in a hurry to reap the benefits of APVS by investing billions of euros to provide a new low-cost multi gigawatt power of electricity.

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