REVIEW OF LATEST ACHIEVEMENTS IN AGRIVOLTAICS

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Abstract. A considerable number of new, interesting and very useful researches have been carried out in the world in the field of agrivoltaics over the past few years. The results obtained have repeatedly confirmed the high efficiency of this very interesting hybrid technology. On the one hand, this technological system uses currently the cheapest photovoltaic power plants (PVPP) in the world, which convert solar irradiance into electricity. As it is well known, solar irradiance does not need to be supplied or purchased as a source of power – it arrives from our Sun at the speed of light to all solar power modules located on our planet Earth in a few minutes. On the other hand, the cultivation of various types of vegetables, grapes and other agricultural products at all geographical latitudes is faced with significant fluctuations in the air temperature, which often have a significant impact on the yield and quality of different agricultural productions. As a result, it is possible to achieve good results not only in the field of agriculture, but also to produce inexpensive electricity needed for the farm on the same plot of land. Research shows that agrivoltaics is a very good method of agricultural production intended for growing significant numbers of shade-tolerant vegetables, fruits, as well as livestock, and poultry. Ecologists are also interested in agrivoltaics. Agrivoltaics research also aims to balance this technology with bees and other pollinators, wildlife, and thus help endangered species survive. Summarizing the information read in scientific and technical articles, we can conclude that agrivoltaics is a very useful, efficient, ecologically clean and environmentally friendly hybrid method of simultaneously growing agricultural products and generating electricity on one plot of land, which is worth trying for all smart farmers who would like to achieve better results in their agricultural business faster.

Keywords: agrivoltaics, double exploitation of land, optimal solar irradiation, additional yield, efficiency.

Introduction

A very important parameter in an agrivoltaic (AV) system is the optimal area occupied by solar modules, which is different for different plants. The most suitable solar radiation is the one that allows for the highest yield per unit area. Experimental researches of these systems have shown that the yield increase is up to 50% and more compared to the case when the same plants, vegetables or fruits are grown in the open field without any shadows from the solar modules. The shadows from the PV modules protect the plants from the excessive total solar irradiation received during the entire vegetation period on sunny days. The required exposure to incoming solar radiation in kWh/m^2 in an AV system can be determined by choosing the optimal distance between the rows of solar modules installed above the crops grown in such systems. Positive results are also obtained when sheep, cows, horses and other animals are kept in AV systems. In addition, prices for agricultural companies using AV technologies are significantly higher because they generate more income due to higher yields and electricity production.

Solar modules create better well-being for animals in these systems: create better conditions for ruminant animals to rest, hiding from rain, sun, and for growing lusher grass. More information about AV systems and the latest developments in this promising field of renewable solar energy utilization is provided in this article. Significantly more detailed information can be found in the articles included in the references for this paper.

Over the past few years, interest in AV systems and the annual number of publications in scientific and technical journals have increased very significantly. This shows that the popularity of these hybrid agricultural systems is growing rapidly and deservedly. Unfortunately, there are still a number of countries that prefer outdated, environment polluting and climate-damaging energy production technologies. Meanwhile, today there is no other electricity generation technology in the world that could produce energy more cheaply than solar power plants, would be so clean and environmentally friendly, would allow agricultural business to be conducted on the same land area, and would even contribute to increasing the yield of many agricultural products by selecting the optimal area of solar modules for one or another agricultural crop, under which the plants would receive optimal irradiation and grow the highest yield. The world's climate varies across geographical coordinates, so when reading articles about research results obtained in AV systems, it is necessary to assess the climate zone in which the research was conducted. The study may need to be repeated in your country if the climate described in the scientific article is significantly different from the climate on your farm.

Materials and methods

The main method used to prepare a review article on the chosen topic is a search for the latest scientific literature sources. This is followed by studying the literature sources, assessing the usefulness and shortcomings of the information found. The formulation of conclusions about the effectiveness and usefulness of the ideas described in the articles for electricity production, horticulture, viticulture, animal husbandry, poultry farming and other agricultural sectors, reduction of global environmental pollution and climate warming on our planet are presented at the end of the article. The article provides brief summaries of the articles reviewed, while more detailed information about the research conducted by the authors of the articles and the results they obtained can be found in the provided list of references.

Results and discussion

The article presents significant progress achieved in scientific research in the field of agrivoltaics over the last few years. Very good research results achieved in various AV plots of land and the additional benefits of agrivoltaics due to the possibility of generating electricity, benefits for nature due to reducing environmental pollution, benefits due to increasing fruit and vegetable yields, benefits due to improving the well-being of sheep, cows, horses, and chickens are described in this article**.** The impressive scale of the potential of AV systems is demonstrated by calculations made by scientists at the Michigan Tech University, which show that the total power generation of solar power plants in the United States alone would increase by between 40 and 70 GW if all the lettuce produced in this country were grown in AV systems [1]. Excessive solar irradiation damages the crops that tolerate shade to a certain extent. They are less sunburned by sun rays in AV farms, what is resulting in higher yields. In addition, the electricity needed by the farms is also produced. Therefore, the economic value of AV systems increases by about 30% compared to conventional farming [1].

AV power plants are rapidly gaining popularity and the number of AV systems already installed in the world is increasing. Scientists in some countries have already calculated the potential of AV systems in their countries. The results of the calculation of the APP potential calculated by German scientists are presented in the article [2] together with the potentials of car parking (PPVPP) and floating solar power plants (FPVPP). The article presents the predicted limits of the APP potential: a minimum limit of 3215 GW and a maximum limit of 5437 GW. A small potential of FPVPP of 4.7 GW is expected due to significant restrictions. The potential of PPVPP for car parking of 24.6 GW is calculated based on the minimum number of car parking spaces. The predicted installed capacity of AV systems by 2040 should reach 400 GW. For comparison, the installed capacity of all PVPP operating in Germany (2025) has already exceeded 100 GW, and in China – 1000 GW or 1 TW.

A review article [3] explains how and why the need to create AV systems arose. As the population of our planet grew, the need for food constantly increased, and the area of arable land for growing edible plants and animals gradually decreased, as the areas of large cities and towns grew. Back in the 20th century, German scientists proposed the idea of how land could be used twice - both for agricultural needs and for generating electricity in solar power plants. Their experiments showed that in principle such systems are possible, but at that time they were not profitable, because the electricity produced in solar power plants was very expensive. However, over about 30-40 years, the cost of electricity production in solar power plants gradually became very much cheaper (about 100 times) and from about 2010, intensive and constantly accelerating development of solar power plants began, because now they produce electricity in the cheapest and cleanest way. Another positive feature of AV systems is that farmers have the opportunity to diversify their sources of income from selling electricity or using it for the farm needs (then they will need to buy less electricity or not at all). A small negative feature of AV systems is that when working the land, solar modules can collect dust, which needs to be wiped off or occasionally washed if they are not washed off by the wind.

The Northern country of Canada has ambitious plans to significantly reduce greenhouse gas emissions into the Earth’s atmosphere despite being the second largest country in the world (its area is about 10 million sq. km). In an article [4] written by Canadian scientists, they present the results of their research, which shows that by 2030, using AV systems, it would be possible to produce in their country so much ecologically clean electricity that green, emission-free electricity would account for 90%. The scientists chose AV systems for their research with vertically mounted bifacial solar modules. The PV arrays had three different distances between vertical solar modules (5 m, 15 m, and 45 m) that were

tested in different Canadian farming locations in the provinces of Winnipeg, Calgary, and London. The results of the research show that in all three provinces participating in the study, properly selected plants for AV systems can ensure that these systems can obtain a sufficiently good yield and produce at least 84% of the total national electricity needs in all three provinces.

An interesting and valuable scientific article on the topic of agrivoltaics was published by scientists from Flanders (Northern Belgium) [5]. This work was financially supported by the European Union through the Horizon Europe Research and Innovation programme Symbiosyst and other funds. As already mentioned in the article [3], the growing world population requires more food and energy. The main conclusions of the article state that currently crystalline silicon (c-Si) technologies dominate the production of solar modules in AV systems, but other technologies being developed may yield new and better results in the future. According to the authors of the article [5], AV systems provide an opportunity to increase the efficiency of land use, which is recognized by the vast majority of scientists. AV systems can reduce part of the harvest, but can also increase it, depending on the solar irradiation in the area and the shade tolerance of the plants grown.

Researchers in the Apulia region of Italy, which is characterized by high solar irradiation rates, have achieved particularly good results by using AV systems [6]. They obtained very high grape yields in their experimental AV system (under solar modules), which were as much as 277% higher than in control grape trees growing in the open sun. The electricity production rate of this AV system was also good, accounting for about 90% of the electricity produced using a ground-mounted PV array. The land equivalent ratio (LER) is 3.54. This figure confirms that Southern Italy is a good region for installing PVPP, but much greater benefits are obtained with the installation of AV systems.

Indian scientists also support the cultivation of grapes in AV systems. They also see several benefits from it [7]. According to the calculations made by scientists, the economic value of such systems in India could increase by more than 15 times compared to traditional ancient methods of grape cultivation. Implementation of the innovative method in AV systems with dual land use throughout India would allow the production of more than 16 TWh of electricity, which could be consumed by rural residents who do not yet have electricity.

Research on grape growing in PV systems was also conducted by the French agricultural company Sun'Agri in the South of France [8]. Grape yields in 2024 increased in all experimental PV systems by 20 to 60% depending on the grape variety compared to old grape growing methods, as the PV modules helped reduce excessive solar irradiation. The yield of Chardonnay grapes increased the most – 60%, and the yield of Marselan variety increased by 30%. Researchers found that PVPP optimized the microclimate under the solar modules and reduced the need for irrigation by 20-70%.

A French specialist from the Sun'Agri Company presented interesting results on the Brinkhoff agrivoltaic system for growing eggplants [9]. During the season, 800 kg of eggplants were grown in this system. In parallel, eggplants were also grown on an open plot of the same size, not covered with solar modules, in order to make sure which method of growing these vegetables would be more effective. After harvesting in both areas, it turned out that the AV system won this competition, since only 500 kg of eggplants were grown on the control plot of land, and they were of worse quality. Eggplants grown under solar modules had a higher biomass, which is a sign of better plant development. Other fruits and vegetables were also successfully grown in this AV system – tomatoes, cucumbers, eggplants, peppers, celery, fennel, spinach, lamb's lettuce and green beans.

The article "Financial analysis of agrivoltaic sheep: Breeding and auction lamb business models" written by Canadian scientists provides information after conducting research on agrivoltaic sheep farms [10]. The most important achievements in this research were competitive ROI (Return of Investments), optimal land use and reduced emissions. Now Canadian sheep supplies abroad can increase export volumes and long-term profitability is guaranteed in the event of market fluctuations. The return on investment for the sheep breeding business ranges from 16 to 31%, and for the business of selling raised sheep – from 22 to 43%. The results achieved show that the sheep breeding business in Canada in agrivoltaic farms is quite profitable.

Australian renewable energy developer Lightsource bp has highlighted the potential of high-power agricultural solar power plants to supplement overall income without compromising farm productivity at its 174 MW Wellington Solar Farm in New South Wales, Australia [11]. The findings show that on-

farm electricity generation combined with sheep grazing does not negatively impact wool quality, even when high quality standards are applied. Some parameters even show an improvement in the wool quality, although further long-term measurements are needed to determine the ultimate benefit. Farm workers explained that good results can be achieved from both electricity generation and sheep farming. Tests on sheep wool have shown that grazing sheep wool is around 20% superior in terms of wool growth, weight and bristle thickness, measured in microns. In addition, the sheep eat almost all the grass on the farm, so it only needs to be cut twice a year.

Engie Green, the French energy giant, has been operating a dual-purpose vertical AV system for two years, which was designed to graze cows [12]. The National Institute for Agricultural Research (INRAE) participated in the research. The solar modules were mounted vertically so that the solar power plant could produce electricity for a longer period of time (from 5 am to 8 pm in summer). The initial results were good, and the pilot 100 kW power plant produced 30 percent more energy than a power plant of the same capacity built using the most common method of mounting solar modules. Animal observations showed that vertically arranged solar modules changed the microclimate of the pasture. The distances between the rows of solar modules were 18 m or 12 m. The wind speed between the rows of modules was reduced by about half. Over several months, the researchers measured a halving of the wind speed without any significant changes in the wind direction. During the day, light and heat indicators in the inter-row meadows differed from those in the open field. The grass in the 18-meter-wide meadow was of slightly better quality than in the 12-meter-wide meadow.

Researchers at the University of New England in Australia are working on ecovoltaics to help find the right balance between wildlife conservation and livestock farming in AV systems [13]. Australia is a relatively large country with small population and relatively low energy needs. They would need 1,200 km2 of land (0.02% of Australia's land area) to power the entire country from renewable energy sources. Eric Nordberg, a researcher at the university, is looking to find the best ways to use land that has more than one purpose. AV systems are precisely that kind of land that has a dual purpose. Nordberg explained his goal in this area as follows: "We are interested in working with companies in the early stages to avoid removing key wildlife habitat, minimizing disturbance, and strategically placing panels to maintain habitat connectivity and travel corridors for wildlife" [13].

The amount of land used to build promising solar PV systems is increasing every year around the world. Canadian scientists from the state of Minnesota conducted an interesting project to determine how high-power solar PV systems promote biodiversity under and between solar panels [14]. They created plant habitats in three locations in the state of Minnesota within the PV systems. They planted 8 different seed mixtures for pollinators and other insects in these systems. The scientists then observed how the seed mixtures established themselves in all three experimental plots under and between the solar panels with the help of local pollinators. The seed mixture increased from 10% to 58% in the soil of all three PV systems within one year of planting. Compared to the seed coverage under natural conditions (control experiments were conducted outside the PV system, where solar radiation was not regulated), the coverage increased from 9.6% to 70% over the same period. This indicates that the seed mixture is growing successfully under local conditions, although to a slightly less extent than under full sun.

The European Union highly values AV technologies in agriculture and proposes to spread their usefulness among the largest possible number of farmers. Currently, more than 200 projects are underway in the EU in the field of agrivoltaics [15]. The integration of solar energy into agriculture increases climate resilience by providing mobile shade, reducing water use, restoring soil, and protecting crops and livestock from extreme heat. According to the European Commission, the transition to regenerative agriculture and the proper use of solar energy can significantly increase the profits of every farmer. Policy Advisor at SolarPower Europe Lina Dubina said: "The European Commission should now translate this vision into action. We are asking for specific amendments to the EU Common Agricultural Policy and specific guidelines that would help Member States better inform and spread the benefits of Agrisolar to many more farmers and rural areas across Europe" [15].

Europe was the world's pioneer of AV systems. German scientists published the first paper on this topic in 1982 [16]. Back in the second half of the 20th century, they found a very good way to grow agricultural crops and produce electricity in solar power plants on the same plot of land. This dual method of land use began to be exploited more and more often, when the cost of energy produced in

solar power plants had fallen significantly over the past 30-40 years. Now AV systems are rapidly spreading across all continents of our planet, because this area of activity is extremely useful for successful agriculture, power production, and exploitation of agricultural land much more efficiently, to reduce environmental pollution by greenhouse gases and prevent further climate change. Unfortunately, climate change is accelerating presently at a very high rate. Last year, our planet exceeded the permissible average annual air temperature above the planet's surface (1.5 deg. C), which it had pledged not to exceed. Unfortunately, in 2024, the excess of the Earth's average air temperature reached 1.55 deg C. Climate warming is also very evident in Lithuania. The average air temperature in Lithuania in January this year was positive for the first time in the entire 250-year history of temperature measurements. Therefore, all authors of this article strongly support the European Commission proposal to significantly expand the use of AV systems throughout the European Union.

As already mentioned, the land equivalent ratio (LER) achieved in a vineyard in the Apulia region of Italy was 3.54 [6]. But this is not the best LER result achieved in the world at the moment. Recently the Cornell University, Ithaca, New York (Northeast USA) conducted an interesting experiment in the AV system in 2024. They optimized their AV system according to economic and environmental indicators. Barley, oats, wheat, cabbage, potato, soybean, and tomato were grown in this system. The priority was given to solar power in order to achieve higher profits and higher LER. After conducting experiments, LERs were obtained from 3.84 to 4.40 depending on the crop type [17]. This type of AV system is also useful because for some farmers, getting a higher income is more important than having a slightly more diverse crop. US farmers are very active in the field of PV systems. They already have more than 500 exploited PV systems in their country, with a total solar power capacity of more than 9 GW [18].

A lot of useful information about PV systems is provided in the booklet "Solar power from fields. Dual use of agricultural land" [19] published by the Hannover Messe. The fair took place in November 12-15, 2024, Germany.

Many people are trying not to pollute the environment and to restore a normal climate in our only home, the Earth. There are people who organize senseless waste of energy and unnecessary environmental pollution in wars. The total amount of greenhouse gas emissions into the atmosphere during the first 2 years of the conflict in Ukraine amounted to 175 million tons of CO2 equivalent. These data were calculated and published by an international group of scientists [20]. Now it is the fourth year of the war. The total amount of greenhouse gases released into the atmosphere during this conflict is already approaching 300 million tons of CO2 equivalent. Such irresponsible environmental pollution has also concerned ecologists. They published information about the environmental damage caused by this political crisis in the journal EcoWatch [21]. The worst thing is that a large part of the planet's population does not pay attention to all this. It is a pity that the words spoken many years ago by Nobel Prize winner A. Einstein are forgotten: "The world will not be destroyed by those who do evil, but by those who watch them and do nothing". Such indifference of the people, and especially the heads of states, allows not only massive pollution of the Earth's environment with greenhouse gases, but also the senseless killing and maiming of millions of the most productive and healthy people participating in the war, who are needed to perform constructive, not destructive, work.

Conclusions

1. Good conditions for the development of AV systems were created by the unprecedented decrease in the prices of solar modules, dual use of land, and the ability to select the most suitable solar radiation for crops by selecting the optimal area and rated power of solar modules.
2. This review of the latest achievements in agrivoltaics confirmed the high efficiency of these systems, which can be proved by the more than 200 large-scale PV system projects already underway in the EU and the European Commission's intentions to increase development in this area many times over.
3. Currently, many scientific and technical journals publish articles that report very high research results achieved in agrivoltaics systems. If only agricultural crops are grown on a simple plot of land intended for agricultural purposes, it can be considered that the utilization factor of such a plot is equal to unity. But if an agrivoltaic system is installed on the same plot of land, then the utilization factor (or land equivalent ratio – LER) of that plot may increase very significantly.

4. The review showed that achievements in this area are not uniform across the EU. There are several lagging countries that would benefit from significantly improving their performance in the area of AV system deployment.
5. Agrivoltaic systems do not have major drawbacks. They were developed to improve the land equivalent ratio, increase the crop yield and quality, and create better conditions for farming. This idea has worked, so these systems are now widely implemented in agriculture on all continents of the world.

Author contributions

Conceptualization, formulation of the idea of the article, search for information sources and their analysis, evaluation of the significance of information sources (V.A., G.Š., A.D.), writing and draft first version preparation (V.A.), reading of the draft version and discussion (G.Š., A.D., V.A.), editing of the article (G.Š.), discussion of the article (V.A., G.Š., A.D.), preparation of the final version (G.Š.), preparation of report slides (A.D.), acquisition of financing, presentation of the report at the conference (G. Š.). All authors have read and agreed with the final published version of the manuscript.

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