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Review

A Mini-Review of Current Activities and Future Trends in Agrivoltaics

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Abstract: Agrivoltaics (Agri-PV, AV)—the joint use of land for the generation of agricultural products and energy—has recently been rapidly gaining popularity, as it can significantly increase income per unit of land area. In a broad sense, AV systems can include converters of solar energy, and also energy from any other local renewable source, including bioenergy. Current approaches to AV represent the evolutionary development of agroecology and integrated PV power supply to the grid, and can result in nearly doubled income per unit area. AV could provide a basis for a revolution in large-scale unmanned precision agriculture and smart farming which will be impossible without on-site power supply, reduction of chemical fertiliser and pesticides, and yield processing on site. These approaches could dramatically change the logistics and the added value production chain in agriculture, and so reduce its carbon footprint. Utilisation of decommissioned solar panels in AV could halve the cost of the technology and postpone the need for bulk PV recycling. Unlike the mainstream discourse on the topic, this review feature focuses on the possibilities for AV to become more strongly integrated into agriculture, which could also help in resolution of relevant legal disputes (considered as neither rather than both components).

Keywords: photovoltaics; biogas; agriculture 4.0; unmanned vehicles; smart grid

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1. Introduction

As the humanity population continues to grow, more food needs to be produced. The intensification of agriculture suggests that farming will become more energy demanding. During the global energy transition, fossil fuel is being substituted with renewables. The installed capacity of solar PV power plants across the world and the rates of energy they generate continue to grow almost exponentially, and the cost of electricity in new projects has already reached minimum values in many countries, compared with other generation methods [1]. While there is no developed international infrastructure for the transmission of electricity over very long distances, in most cases PV power plants are located in populated areas where treeless land plots are already largely used for economic activity. In addition, the fastest growing PV power plants are put into operation in economically developed countries [2], where land is expensive and there are many restrictions on its use [3].

Particularly acute conflicts can arise over the use of agricultural land [4], both in connection with the growing need to provide food for the growing population, and in connection with desertification and other types of degradation of such lands at a rate of approx. 50 million hectares per year (worldwide) [5]. As a result, from 1961 to 2016, there was a decrease of 48% in the area of arable land per capita. This led to the development of the UN FAO concept for the creation of integrated food and energy systems [6]. The solution to this problem is in the shared use of areas for energy generation and other economic activities. For these purposes, photovoltaic modules are integrated into buildings [7]; located on waste land or in the right-of-the-way of infrastructure objects [3]; or installed at a height sufficient for other land use, for example, agricultural [8]. The latter way, known as agrophotovoltaics, or agrivoltaics (AV), has recently been rapidly becoming popular [9], as it has been shown that its implementation can significantly increase income per unit area of land when used together for growing crops or grazing livestock and producing energy for sale to the grid and for on-site use [10]. The term and principle were proposed in 1981 [11], but then it was very far from economic feasibility due to the high cost of solar photovoltaic power plants. The installed capacity of AV plants by 2022 was over 14 GW [12]. If AV were deployed on just 1% of arable land in Europe, that would give over 900 GW of solar power, much more than installed [13].

The first research and experimental agrivoltaic systems have been established in Germany, Japan, USA, Italy, Malaysia, Egypt, and Chile. According to available estimates, by the beginning of 2020, about 2200 AV systems with a total installed capacity of 2.8 GW had been created globally, which is slightly more than all floating and concentrator PV power plants combined [14]. Japan, South Korea, China, France, and the USA (Massachusetts) have already adopted such systems; India and Germany are discussing programs to stimulate their introduction [15]. Research is being conducted on the perception of AV systems by society and an assessment of possible effects in this direction (for example, stopping the escape of young people from rural areas) [16].

The main advantage of such a tandem is the additional income received from the generation of energy, and the main problem is the decrease in yield of some crops due to shading and changes in the soil moisture regime [17]. As a result, the expected income per unit of farmland area increases on average by 60% [18], but it can also either decrease or reach a 15-fold increase [19]. Negative effects occur during the cultivation of some crops due to changes in soil moisture and lighting regimes [18]. The same effects can have a positive result for other crops [20], dampen the influence of dry or rainy seasons [21] and other weather hazards [22], and stabilise the income of an agricultural producer through diversification of revenue sources and guaranteed sales of electricity throughout the year [16]. The environmental impact of AV is furthermore reduced compared to traditional agriculture [23,24]. In addition, the output of agricultural products reduces revenue sensitivity to degradation of photovoltaic converters over time.

The National Renewable Energy Laboratory (NREL) identifies three fundamental approaches to the creation of AV systems: (1) power generation (continuous rows of PV modules with minimal gaps are characteristic); (2) agricultural crops (stand-alone PV with two-axis trackers); (3) joint effect (sparse PV lines). Current research in the field of AV systems is aimed at determining the effects of changes in the microclimate [25,26]—first of all, shading [27,28] and moisture redistribution [29,30]—on the productivity of certain crops, both in open soil and greenhouses, and determination of the final economic effect [31,32], including the final production of biogas [33]. Thus, it was shown in [34] that the level of photosynthetically active radiation (PAR) available under the AV is expected to decrease at midday, while in the morning and evening hours, such a decrease almost does not occur. The air temperature (dry bulb) under AV systems was lower by 2 °C at midday and by 1 °C at the beginning and end of the day (on average lower by 1.65 °C). At the same time, the relative air humidity under AV did not differ from the control site at midday—in the early morning it exceeded it by 7–10%, and in the evening by 3–5%. The greatest effect from the use of AV with this approach is expected in semi-arid and arid regions [20,35], and the most obvious direction of energy use is to power pumps for water supply [36,37] and land reclamation.

A decrease in temperature under AV at night, shown in [34], is an undesirable factor for northern agriculture, but comparison with other works [25] shows that the temperature can rise if AV screens more than 50% of the sky (with such an increase, for example, grapes bloomed earlier [38]). In general, it has been shown that the temperatures of air, soil, and shoots are expected to have a complex relationship with the AV parameters, local climatic conditions, and the characteristics of the cultivated crop [39].

The present focus of research in this area has shifted towards determining the degree of susceptibility of certain cultures to the influence of AV, and the spatial configuration of these systems, in order to achieve the maximum total effect [32]. At the same time, it is known that it is economically most efficient to use the energy on site, and the lack of direct energy sources in the field largely limits the economic feasibility of most measures to intensify agriculture. Moreover, there is a seasonal discrepancy between solar power plants energy output and the need for it in the grid, especially the isolated one, which is aggravated from the equator to the poles. Agricultural production has a similar seasonality to solar power plants, which makes the use of energy generated by AV for its intensification expedient and especially attractive in the Arctic and other remote regions.

Precision (intelligent) farming, vertical greenhouses, and unmanned electric machines [40] are being actively developed, and are impossible without IoT [41]. All those areas require power supply and support structures that AV can provide. Minimising human labour in such systems can help change agricultural practices in many ways, including rethinking the scale of chemical fertilisation, because the need to increase yields through chemical fertilisers might become less significant, especially given the higher cost of products with various “eco” labels. The resulting energy can be used for the production of fertilisers on site, which can be beneficial for hard-to-reach places, for example, the processing of local natural gas into ammonia fertilisers and phosphates. In Russia, raw materials are mined in the Arctic, processed in the southern regions, and then shipped all over the world. Such a complicated logistics process affects cost, carbon footprint, and the overall sustainability of supplies, making these dependent on too many factors.

High-quality fertilisers can be obtained using agricultural waste in biogas power plants, and the operation of these is also possible in combination with thermal photoelectric modules [42]. Furthermore, the production of bio-hydrogen from agricultural waste is becoming more and more relevant [43]. The importance of hydrogen as an energy carrier has recently been reconsidered; the global environmental agenda has forced a shift towards hydrogen in the priorities for energy carriers, moreover, produced in a “green” way using renewable technologies not fossil fuels.

This review is intended as a “user guide” for researchers and practitioners, referring to the main concepts and technologies currently proposed and employed to exploit AV for the intensification of agriculture. We do not duplicate extensive reviews of current activities reviews given in [9,44–47], so Section 2 of this paper provides contextual understanding, mainly focusing on several issues poorly covered in the literature, such as irrigation, aquaculture, and cold storage. The novel aspects of this review are presented in Section 3—future trends arising from the recent progress in different areas of engineering and agriculture with potential for significant synergistic effect when coupled with AV.

This approach to using AV energy on site is in line with global trends for the intensification and robotisation [40] of agriculture, deep processing of products on site, and the transition to the use of electric transport and renewable energy sources (RES). In many countries it may be demanded due to the difficulty for agricultural producers to connect to power grids in general or as prosumers (both consumer and generator), and loss of agricultural or ‘green tariff’ support since AV may be considered as neither an agricultural nor a renewable energy enterprise, rather than both. It will also be relevant in places of decentralised energy supply and risky farming, including Arctic regions (especially in combination with wind power plants). There, it could drastically change the way of farming, not only ensuring food security in remote regions, but also significantly improving the quality of people’s life, creating jobs, and reducing energy bills (by substitution for expensively delivered fossil fuel). Fresh vegetables and other relatively perishable products that cannot be frozen are in most cases delivered there by air, which makes their prices prohibitive.

2. Current Activities

2.1. Horticulture

Depending on the climatic conditions, the cultivated crop, and prices in the local agricultural and energy markets, the introduction of AV can lead to losses or provide up to a 15-fold increase in income. The present focus of research in this area has shifted towards changes in irradiation, temperature, and humidity of soil and air, both open and enclosed, aquaculture pools, and the storage of agricultural products when using heat pumps powered by AV.

To optimise microclimatic effects from AV, systems with sun tracking have been investigated, to enable maximum output with minimal shading, or to control the level of shading [31], which can be especially important in certain periods of crop growth (for example, when there is a deficit of degree days). However, there are no works investigating the effects of low-potential concentration of solar radiation including wavelength selection. In addition to the effect on biomass growth, changes in the nutritional [48,49] and other commercial [50–52] properties of crops have also been studied, which is especially important in connection with the general decrease in nutritional value caused by climate change [53–55]. In [56] it was experimentally shown that under translucent PV there is an increase in the efficiency of the use of PAR (+68% for spinach); energy during metabolism was redirected mainly to aerial tissues (+63% for basil); the phenotype of the aboveground part of plants significantly differed from the control; the amount of protein extracted from leaves (up to +53.1%), trunk (up to +67.9%), and root (up to +15.5%) increased.

In addition, it was shown that a decrease in the yield of some light-loving crops and a decrease in the sugar content of grapes, measured at a fixed time due to the slightly slower development of plants, can be fully compensated by a later (1–2 weeks) harvest [30,38] or increased share of larger (marketable) tubers for potatoes. Moreover, further results of this approach may include an increase in the market price of products supplied outside the traditional high-offer timeframe [50], and a decrease in the cost of harvesting and transporting crops outside the time of peak demand for machines and labour. Shading from AV can have a beneficial effect on the cultivation of crops that normally grow in shaded conditions under a forest canopy [50], without the inconvenience associated with farming in the presence of trees and shrubs.

Among the crops studied in combination with AV were wheat [14,25], corn [57], rice, beans, peanuts, potatoes [34,58], sweet potatoes, beetroot [59], grapes [38], lettuce [25,28], Welsh onion [60], basil [56], spinach [56], celery, fennel, chard, tomato, pepper, zucchini, cucumber [25], eggplant, watermelon, pumpkin, various cabbages, aloe vera [35], agave, taro, clover, alfalfa [61] and other pasture crops [39], raspberry, strawberry, cherries, citrus fruits, and mushrooms.

2.2. Livestock

So far, scarce research has focused on assessing the effects on livestock production, with published studies available only for lamb [62,63] and rabbit [64]. The mutual influence of low-lying AV and herbivores has been shown; animals eating the grass remove the cost of mowing it.

AV constructions reduce the costs of fencing the territory (the highest capital costs for rabbit farms), and provide protection to animals from predators and adverse weather conditions (including bright sun), increasing the final productivity of the herd. Moreover, the estimate of the ratio of income from the sale of electricity and breeding rabbits is between 4 and 40 to 1, depending on local conditions and process organisation. In addition, it has been shown that breeding rabbits has less severe environmental consequences (in particular, carbon footprint, use of water and fertilisers) than breeding cattle (in terms of total CO_2 emissions per 1 kg of meat, the difference is more than an order of magnitude). In harsh climatic conditions, rabbits are convenient because the production cycle (from 8 weeks) is comparable to the duration of the vegetation season, i.e., there is no need to keep a large number of animals during the cold season. They provide a high conversion to protein (approx. 20 kg/ha of pure meat per cycle only on pasture) and provide fur that is in demand on site.

For lamb, no difference in liveweight growth was found per pasture ha, indicating that the farming component was not affected [62]. AV pasture had lower herbage mass, but it was compensated by the higher nutritive forage value. Sheep preferred to stay in PV shaded areas at solar irradiation over 800 W/m^2 [63] for idling and needed less water. There are also references to the use of sheep (North Carolina, USA, approx. 15% of the total livestock) for mowing grass (adds 2 to 8% to income) at PV power plants, and the use of internal mobile electric fences is recognized as an effective feature. In addition, in this context, there are fragmentary reports that horses are too selective, cows need too much space, and goats like to jump on everything, chew wires, etc., which makes these animals unsuitable for such a task.

In Minnesota (USA), a law (the Pollinator-Friendly Solar Act) was passed, designed to provide optimal conditions for pollinators at PV sites. As a result, the trademark "Solar Honey" was created; the licence for its use is in compliance with all the requirements of this law and should help to increase income. This form of AV seems to have the biggest share across over 11,000 acres in the USA.

2.3. Harvesting, Storage, and Processing

AV installations include PV systems to power air-conditioning systems at fur farms, refrigeration machines and auxiliary devices at remote (e.g., alpine) dairy farms, or battery charging for electric agricultural machinery (with estimates of unit costs kW*h/ha for different crops) [65].

At present, most agricultural machines are internal combustion engine-powered. It is possible to making these electric (with batteries), but that would probably lead to higher capital and operational expenses. Without batteries, the machinery needs either an on-board power source or connection to the grid. The latter is usually impossible, so options for the former are generally considered [40], but these still require batteries and the capacity factor of solar panels is drastically reduced compared with AV. Unmanned agricultural machinery relies on GPS/GNSS navigation that is sometimes insufficient, and data transmission often unavailable over public networks [66]. Availability of energy across arable land could significantly improve travel efficiency for both terrestrial [67] and aerial [68] agricultural drones and reduce the capacity demand on batteries. Precise navigation signals and data networks can be provided using the AV structural posts.

Cold storage is the norm in developed countries, but not in developing ones due to lack of electricity [69]. Cold is responsible for 5% of GHG emissions in the global food system. Energy-independent ice cellars that were previously widespread over the Arctic are now degrading quickly due to climate change [70]. On average, 14% of food in the world is lost at post-harvest to retail. The highest percentage of losses (ca. 25%) is for roots, tubers, and oil-bearing crops; about 21% for fruits and vegetables; 12% for meat and animal products. In sub-Saharan Africa, 37% of food products are lost within the "first mile" from harvest to processing. More than half of tomatoes in Rwanda are lost along the value chain, with lack of cold storage considered a major factor. Given that solar powered is extremely important for small agricultural manufacturers since they can ship more processed products at once, so avoiding multiple middlemen who take the lion's share of the final cost (also using 'sell cheap or lose' pressure). Solar icemanufacture could be a good alternative to battery storage, using biogas to stabilise cooling capacity [71]. On-site solar-powered processing such as milling [70], drying [72], extraction (pressing) [73], fermentation [74], prepacking, sterilisation, cooking, preservation (sealing), etc. [75], can reduce the need for cold storage capacity and create added value.

2.4. Aquaculture and Irrigation

The first effect of AV is water saving due to reduction in direct sunlight [76]. Water-use efficiency in arid southwest United States was 157% higher for jalapeno and 65% greater for cherry tomato [17], with production doubled for the latter. Soil moisture also remained up to 15% higher due to the AV shading effect. AV solar panels were ca. 9 °C cooler in daytime than traditional arrays, so working with higher efficiency. The collected rainwater from AV can be used both for cleaning PV and irrigation [35]. 110 foot-wide PV shades will be mounted over irrigation canals in California (Project Nexus in Turlock Irrigation District) coupled with long-term iron–water flow battery storage [77], which is similar to an earlier project in Gujarat, India [78].

Floating PV (floatovoltaics) [79] is another method to reduce water temperature and evaporation, in which solar panels are reciprocally cooled by water. This approach could be also used in arid coastal areas [80] in combination with desalination plants and atmospheric water harvesting [81] for aquaculture [82]. Floating and above-water PV are used at fish breeding ponds to meet local needs and to reduce water evaporation (by up to 85%), as well as at water treatment plants (in China there are 60 MW of such plants).

Power generated by AV can be used for water pumping [36,83]. For this purpose, highly efficient solar pump inverters have been developed representing a mix of MPPT-controller and frequency converters, so the pump output can follow the actual PV production with no need of a battery buffer. Consider greater demand for water on sunny days, such a system is very efficient. In India, farmers using solar-powered irrigation reported 50% or more increase in their incomes compared to rain-fed pumping [69]. In Rwanda, yields were about a third higher and dry-season farming became available. However, it should always be kept in mind that affordable solar-powered irrigation (with payback time varying from 6 months to 3 years in Africa depending on crops grown and number of crop cycles) can lead to exhaustion of ground water sources. In hydroponic [84] and aquaculture [85] farms, AV could be used to power heat and mass transfer for process optimisation [86].

3. Future Trends

Energy can be used both in the traditional way to drive agricultural machines and mechanisms, and less traditionally—to provide optimal conditions and stimulate physiological processes, including converting to other forms of energy, creating conditions for processing and storing products on site (which reduces transportation costs compared to raw materials and allows maximum profit at the current level of development of electronic commerce), or repelling pests [87]. Options for using the obtained energy for electric [88], thermal [89,90], magnetic [91–93], mechanical [94], and acoustic [95] stimulation of plant growth will be explored. Research topics include control of temperature and light conditions, chemical composition, humidity, flow of air, water and substrate, power supply of agricultural machinery and equipment, including for primary processing and storage of products. In addition to energy, it is also proposed to consider the possibilities of the associated use of AV structures to create supports for plants, protective fences (e.g., against insects or hail), and rails for machines and mechanisms. In this report, we do not focus on passive changes in microclimate associated with the AV, which is the present research mainstream globally [25].

Currently, the problem is emerging of recycling photovoltaic (PV) modules after their lifetime expiry [96,97]. Older modules have a specified lifetime of 20 years [98], while Europe's first PV power plant TISO-10 in Switzerland is still working with 80% of its nameplate capacity at 40 years old [99,100] (notably, the inverters have been substituted five times). Newer solar panels have a guaranteed lifetime of 30 years with potential to be improved to 50 years [101]. It should be borne in mind that this refers not to technical failure, but a decrease in productivity, as a rule, 20% of the initial rate. With the continued fall in the price of PV converters, recycling to recover and reuse materials is not always cost effective. Therefore, it is becoming popular for such PV modules to be sent for further use in countries where a decrease in output is not so critical compared to the significant decrease in capital costs [96]. Usually the criterion is the availability of waste land for the placement of solar photovoltaic power plants [33,102]. It is quite possible that this approach will also be beneficial for a number of AV systems.

AV approaches will make it possible to create the prerequisites for farming at future extra-terrestrial bases. The nearest planned one is on Mars; there is also the potential for creating such bases on the Moon.

3.1. Conversion to Biogas

In order to utilise agricultural organic waste and obtain highly efficient fertilisers, the introduction of anaerobic bioconversion systems (biogas plants) has great potential. Conversion of agricultural waste allows harnessing CO_2 otherwise released to the atmosphere at putrescence. The main disadvantage in this case is the need for energy to maintain the conversion processes—substrate heating, driving electric mechanisms, production process monitoring, etc. These are normally powered by burning the resulting biogas. With AV, it is possible to convert solar radiation both for heating the substrate of biogas plants using solar thermal collectors, and for powering equipment using solar panels [103]. It is also possible to obtain both thermal and electric energy in one solar module (PV/T), as well as high temperatures for various technological processes of anaerobic bioconversion systems using solar concentrators. Using energy from AV allows higher biogas net output, and biogas becomes a store of energy to be used for dispatchable power supply in stand-alone systems [104–106]. Such combinations are also used in trigeneration systems that include an internal combustion engine and an adsorption heat pump [107]. PV panels can also be used in biogas plants for DC power supply of small power microbial electrolysis cells to intensify the process of anaerobic digestion [108].

The use of photovoltaic modules in anaerobic bioconversion systems occurs in a fairly narrow segment of system energy supply, due to the specific distribution of the shares of electricity and heat consumption when the use of thermal energy for local needs prevails over the use of electrical energy. Heating of the substrate during anaerobic treatment of organic waste to 35–55 °C with the help of solar thermal collectors is used in many locations. The designs of such systems can be unusual, such as the installation of solar thermal collectors on top of a tank where fermentation takes place thus forming a sealed structure below ground level [109]. Solar thermal collectors are used in systems that involve active mixing of the substrate [110], as well as with heat recovery systems [111]. Adding heat pumps to such systems also increases their efficiency. To solve the problem of unavailability of solar radiation at night, a hybrid system (solar, thermal, and electric) is proposed, which provides the necessary mesophilic conditions for the operation of a biogas plant [111]. Thermal energy obtained from solar thermal collectors can be stored in thermally insulated tanks, which provide a continuous supply of an anaerobic reactor with warm water [111]. Thermal energy storage can also take place with a phase change heat storage device, making solar anaerobic bioconversion systems more efficient in winter [111]. In thermostatic anaerobic bioconversion systems, the use of solar thermal collectors is also relevant to meeting the needs of farmers for cooking fuel in cold rural areas [112]. Efficient and stable operation of biogas plants in mesophilic and thermophilic conditions can be ensured when the plant is supplied with heat using solar thermal collectors, even in cold and arid regions [113], but optimization plays an important role in operating conditions and anaerobic digestion temperature [114,115].

Thus, along with photovoltaic modules and solar photovoltaic roofing panels, thermal converters of solar radiation are of great interest. Their shape in the form of roofing panels will also reduce roofing costs, and the use of recycled plastic will improve the ecological state of the environment. Due to the absence of expensive photovoltaic converters in the design of thermal solar roofing panels, the cost of such panels is low and even the most remote and low-budget households can afford to install such solar modules. The solar thermal roofing panel is designed to supply heat to agricultural facilities in an autonomous mode or in parallel with the existing heat network, and is built into the structural elements of the roofs of buildings and structures.

The most promising and valuable development from the point of view of cost and optimization of energy flow is the simultaneous introduction of photovoltaic and thermal converters of solar radiation into anaerobic bioconversion systems, which will allow simultaneous electricity supply to various components as well as thermal heating of the substrate. Such systems have shown their techno-economic feasibility of integration and operation [116]. The photovoltaic module and solar thermal collector can be constructed as a single solar photovoltaic thermal module, which can be fabricated in the form of a solar photovoltaic thermal roofing panel, the base of which is made of recycled plastic [117]. The structure itself provides protective and energy-generating functions with an electrical rating of about 40–50 years due to the use of a two-component polysiloxane compound in the sealing of high-efficiency photovoltaic converters, the electrical efficiency of which can reach 20%. The use of such planar solar photovoltaic thermal modules is advisable as a finishing material for agricultural buildings and facilities (cowshed, poultry house, greenhouse, etc.), which will increase the generation of electrical and thermal energy without using land for the location of solar modules. However, the optimal slope of solar modules when located above ground on a certain geographical area of the farm can also provide high production throughout the year. When growing crops under solar modules at a ground-based location, the allocation of land for the construction of a solar installation is offset from an economic point of view by the sale of agricultural products.

Moreover, for the heat supply of anaerobic bioconversion systems and agricultural facilities, it is advisable to use heat pumps (air, in particular), the power supply and heated coolant for which can be provided by air-cooled solar photovoltaic thermal modules in the form of siding panels that function as building materials for the walls of buildings. Such a disposition of the solar module will provide high levels of energy production on less sunny days, improve dust and precipitation removal from the surface of the module, and ensure cooling of the building walls during periods of high solar irradiation. It will provide better thermal insulation in winter, which will reduce energy consumption for air conditioning and heating of indoor space. The heated air of air-cooled photovoltaic thermal modules can also be used for drying agricultural products, while air cooling of photovoltaic converters increases their electrical efficiency.

3.2. Growth Stimulation

A wealth of data has been accumulated by agricultural science in terms of managing the timing of growth, flowering, and fruiting, productivity, commercial properties of various crops, methods of tillage, and harvest, and the storage and processing of products. This requires analysis from the point of view of technical and economic feasibility of use in combination with AV, which is absent from the published literature.

The methods considered are: (1) increasing the intensity and duration of exposure to photosynthetically active radiation when converting solar radiation into a yield photon flux (YPF) using LEDs and luminescent concentrators, as well as the use of organic photovoltaic cells and facet concentrators that skip ranges of maximum YPF, for converting other sections of the spectrum into electricity; (2) changes in the speed of movement and air composition, including sequestration of gases [118], fertiliser production [119], saturation of nutrient media, support of plant-growth-stimulating microorganisms [120]; (3) electric [121], thermal [90], magnetic [91], acoustic [95], and mechanical [94] stimulation of plant growth; (4) power supply for agricultural machinery, mechanisms, instruments, and equipment; (5) incidental use of structures to create pest barriers, plant supports, and equipment.

The efficiency of solar energy conversion in modern PV is much higher than photosynthesis [122] and the PAR flux can be higher than natural lighting [123]. Accordingly, if the electricity generated by the AV could be imparted in some way to the plants, this could contribute to an increase in yield [124]. This is especially interesting to initiate with the help of energy processes involving additional sources of energy from the environment. The efficiency of electricity conversion in narrow-band LEDs exceeds 50%. The balance between respiration and photosynthesis is achieved at a PAR level of about 125 μmol/m^2/s [125]. A decrease in the PAR level under AV for potatoes [34] and lettuce [28] naturally led to an increase in the foliage area, representing an economically significant result for the latter.

Next, we make a simple estimate: The nutritional value of potatoes is 770 kcal/kg (0.32 GJ/100 kg), and the average yield is about 5 t/ha, then the potential yield is (16 GJ/ha, or 4.44 MWh/ha) in 120 days. The specific installed capacity of a typical AV system is about 330 kW/ha. Focused on the joint effect, during the period of potato ripening with an installed capacity utilisation factor of 0.2 (in summer it is higher than the annual average), the generation will be 190 MWh/ha. Obviously, if at least some of this energy can be imparted to the plants, this will significantly increase yields. At the moment, conversion of solar energy to proteins appears even more realistic [126].

Two recent master theses have reported techno-economic analysis of AV application in greenhouses in Sweden and Spain [127,128]. It has been shown that unfavourable conditions in Sweden in terms of electricity prices and lack of subsidies for renewable energy and solar irradiation in winter are making AV greenhouses economically unattractive. In northern regions, it is advisable to combine greenhouse heating with the costly thermal stabilisation of permafrost [129] under buildings and structures (which is especially important in connection with climate warming) by heat transfer from the latter to the former using heat pumps, and in winter time to heat storage facilities without freezing. We performed such an experiment in Arkhangelsk, Russia (unpublished data, using a facility similar to that described in [130]) and obtained nearly double yields of cucumbers and tomatoes (compared to a conventional unheated greenhouse). Considering the cost of aerial delivery of fresh vegetables to remote northern settlements, such a combination is certainly profitable.

3.3. Electric and Unmanned Agricultural Vehicles, Robotisation

As manual labour in the field had mainly been substituted with agricultural machines, operators of these machines are now being substituted with computers [131,132]. Modern agricultural robots can provide more than merely substitution for traditional machinery (land preparation, sowing, planting, plant treatment, harvesting) [133], with new functions including mapping, insect pest monitoring, artificial pollination, yield estimation, and phenotyping [134]. Major problems remain to be solved in the use of unmanned agricultural vehicles [133] (market worth of USD 10Bs), including navigation [135], stability [136], power, and data [137]. AV structures could ensure precise navigation and provide railings to ensure stability of the vehicles, as well as safe piping for irrigation and spraying. Ideally, the new agricultural vehicles should be electric, but their performance would be dependent on battery capacity or their ability to recharge. AV provides energy over arable land to ensure minimal battery use with wireless power supply [138] and multiple recharge points available. In rural areas the quality of electricity is often very poor, with voltage drops and blackouts the most frequent troubles that affect the operation of complex electronic devices. Introduction of local AV sources will resolve this issue. The availability of power supply also gives virtually unlimited possibilities for monitoring, data transmission, and on-site analysis.

3.4. Internet of Things and Digital Transformation of Agriculture

Digital transformation of agriculture [139,140] is ongoing mainly in well developed areas, while greater effect is expected in remote unpopulated areas with a lack of skilled staff. One of the problems for obtaining that advantage is the availability of power and data transmission networks [141]. These are missing because they are not in demand on sufficient scale, thus forming a closed loop. When infrastructure for agriculture 4.0 [139] is missing on site, the investment needed is restrictively high.

Currently, satellite-based information technologies (navigation and remote sensing) appear to be the most widespread since they can serve multiple clients. The insufficient spatial and temporal resolution of these for precision farming has often been discussed, but there is another less obvious but potentially hazardous issue—destruction of satellites due to global conflict or the Kessler syndrome progress [142]. Loss of space communication and navigation technologies would definitely induce an economic shock, and if that also strongly affects food production technologies, the consequences will be much harder. This means that navigation, data acquisition, and transmission systems should have local backups, for the sake of food security. The same applies to energy, since bulk production power plants and oil refineries are priority targets in case of war. AV provides possibilities to establish the necessary distributed and highly resilient systems [143].

IoT in agriculture is represented by various sensors, from traditional agrometeorology to individual plant or animal physiology monitoring devices. This topic has been well covered elsewhere [137]. The vast available array of such sensors uses WiFi or CAN networks for data transmission that limits distance to within 100 m. That means not only network nodes but power sources for these should be available within this or double the range, which is tolerable for greenhouses but economically unreasonable for the fields. LoRa networks are becoming more popular and could resolve these issues to some extent, particularly considering their low energy consumption, but the data rate is low compared to the potential number of sensors in the covered area.

3.5. Added Value Redistribution

The agricultural product supply chain basically consists of supplier, farmer, processor, distributor, retailer, and customer, with logistics agents in between. Value chains differ greatly depending on the product, but added value is over 100% farmer to retailer invariably, even for apples. Therefore, there are great possibilities for farmers to obtain a share of profit. The important stages in that chain are bulking, cleaning, grading, processing, and packaging, which were formerly cheaper to be implemented on a large scale. The advent of retail food markets and human-less technologies has shifted many of these processes to the farm or neighbourhood scale, in order to reduce the logistics expenses for raw products and long-distance delivery. Availability of electricity is the main obstacle for many rural communities to set up even cold storage. For this reason, AV could make a great change in possibilities for storage, processing, and packaging. The development of e-commerce allows farmers to reduce the number of middlemen to the final customer, following the C2C business model.

The value chain could be also changed to the farmers' favour at the point of input supply. We have already mentioned the possibility of manufacturing nitrogen fertilisers using AV energy, as well as lower demand for these with their precise supply to plants. P2V use of AV energy can reduce the delivery costs not only for farmers' own e-vehicles, but also for contractors whose vehicles could be charged during loading/unloading at the farm.

3.6. Suggestions for Future Work

For power supply, a combination with kW-class wind turbines is also to be considered. The northern regions are well provided with wind resources, relatively evenly distributed throughout the year, while on a daily timescale there is a negative correlation between production from PV and wind turbines [144]. The use of wind turbines will increase the intensity and reliability of power supply, and the cost of their installation should be reduced due to the shared use of AV supports and other infrastructure.

Since DC is generated by PV, stored in batteries, consumed by electronic equipment and motor wheels, and the inverter is quite expensive and not especially reliable for use outdoors, it is reasonable to use direct current as much as possible on site where long-distance transfer losses are negligible [145,146]. These trends must also be taken into account in the development of methods for the local use of energy obtained from AV.

The possibilities of using low-potential solar concentrators should be investigated in the context of shading, increase in electricity generation, and the cost of concentrators and PV panels (particularly with selective transmission) [147]. At the current level of technology development, in such concentration systems (selective and holographic concentrators of solar radiation) it is easier to implement wavelength selection with the aim of minimising PAR shielding. This also suggests a feasibility study of a ground-based PV in combination with plastic Fresnel lenses.

When PV installations are located on the ground, it is easier to divert heat from them to the soil, to reduce and localise shading [148], and the above-ground location of lighter and more flexible concentrators facilitates supporting structures and increases their resistance to wind loads, enhancing the greenhouse effect for open ground. In such concentrators, it is also possible to implement a dependence of the refractive index on the wavelength in order to reduce the YPF loss.

Feasibility studies are needed for the use of special PV designs—transparent with a sparse arrangement of PV cells (to minimise shielding of scattered radiation and homogenization of soil illumination) with luminescence centres introduced into the panels' cover and underlying layers to convert solar radiation into the most efficient YPF and compensate shading losses.

Certainly, power availability across agricultural sites opens great opportunities for plant physiology and agrochemistry experiments that previously appeared impractical and expensive.

In addition to science and engineering, great legal work should be undertaken to make agrivoltaics attractive and easy to implement. The first national standard for this (DIN SPEC 91434) was developed in Germany in 2021. It establishes the priority of agricultural use over power generation. On-site energy use can make this approach stronger and more sustainable, as green tariffs become less applicable considering the current and future scale of solar power in the world and its LCOE compared to traditional methods of generating power.

4. Conclusions

The current form of AV implementation as a shared use of land both for farming and energy generation, totalling over 15 GW across the world, is able to increase farmers' revenue and make it more sustainable in different ways. The benefits include better environmental conditions, more marketable production, shared construction costs, and diverse sources of income. It has already been shown that AV could increase the income of low-margin farming multi-fold.

However, the current approach does not use the full potential of this symbiosis in terms of using generated energy on site for agricultural output improvement. Areas for improvement include powering intellectual farming, growth stimulation, fertilisers, pesticides, reduction of fuel use, on-site manufacturing, storage, and processing to obtain higher added value and reduce logistics costs, further reduction of human labour, and the expansion of agriculture in high-risk and remote areas. It should be stressed that AV makes implementation of agriculture 4.0 possible only in unpopulated areas that still hold considerable reserves of arable land. Distributed AV also makes precision agriculture and machinery less dependent on satellite data, and remote fuel and power supply in case of war or other major disasters affecting the centralised infrastructure.

A higher share of energy use on site should remove legal disputes when farmers' subsides are stopped because they are using their land for energy generation. Reuse in AV could be a better option for older solar panels not optimised for recycling (estimated 8M t by 2030 and 80M t by 2050). In Table 1, we summarise our estimates of potential AV benefits with its different methods of use.

We suggest that AV concept designers should also consider using small vertical-axis wind turbines and conversion to biogas to make power output less intermittent.

Table 1. The concluding estimates of AV benefits.

	Agriculture		PV		Total Benefits
	Yield	**Income Increase**	**Electricity Income Share**	**Infrastructure Sharing Savings**	
Horticulture	−30 . . . +60%	−30 . . . + 75%	50 . . . 90%	0 . . . 10%	60 . . . 1000%
Livestock	0 . . . +50%	0 . . . + 50%	50 . . . 95%	0 . . . 80%	50 . . . 4000%
Water use					10 . . . 30%
Growth stimul.					50 . . . 500%
On-site process.					30 . . . 300%
GHG emission					10 . . . 50%
Robotics and IoT					30 . . . 100%
Old PV utilis.					50 . . . 200%

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Nomenclature

AV	agrivoltaics
C2C	customer-to-customer
DC	direct current
GHG	greenhouse gases
IoT	internet of things
LCOE	levelized cost of energy
LED	light emitting diode
MPPT	maximum power point tracking
P2V	power-to-vehicle
PAR	photosynthetically active radiaton
PV	photovoltaics
PV/T	PV-thermal module
RES	renewable energy sources
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
YPF	yield photon flux

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