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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 production 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 not only solar, but also energy from any other local renewable source, including bioenergy. Current approach to AV represents an evolutionary development of agroecology and integrated PV power supply to the grid. That results in nearly doubled income per unit area. While AV could provide a basis for revolution in large-scale unmanned precision agriculture and smart farming which is impossible without on-site power supply, chemical fertilisation and pesticides reduction, and yield processing on-site. These approaches could change the logistics and the added value production chain in agriculture dramatically, and so, reduce its carbon footprint. Utilisation of decommissioned solar panels in AV could make the technology twice cheaper and postpone the need for bulk PV recycling. Unlike the mainstream discourse on the topic, this review feature is in focusing on the possibilities for AV to be stronger integrated into agriculture that could also help in relevant legal collisions (considered as neither rather than both components) resolution.

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

1. Introduction

As the humanity population is growing, more food needs to be produced. The agriculture intensification suggests it becomes more energy demanding. Fossil fuel is substituted with renewables during the global energy transition. The installed capacity and generation of solar PV power plants in the world continue to grow almost exponentially, and the cost of electricity received in new projects has already reached minimum values in many countries as compared to the other generation methods [1]. While there is no developed infrastructure in the world 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 the ways of its use [3].

Particularly acute conflicts arise over the use of agricultural land [4], both in connection with the growing need for them 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 in the area of arable land per capita by 48%. 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 shared use of areas for both energy generation and other economic activities. For that, photovoltaic modules are integrated into buildings [7]; are located on waste land or in right-of-the-way of infrastructure objects [3]; installed at a height sufficient for other land use, for example, agricultural [8]. The latter way, called agrophotovoltaics, or agrivoltaics (AV), has been rapidly becoming popular recently [9], as it has

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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 on-site use [10]. The term and principle were proposed back in 1981 [11], but then it was very far from economic feasibility due to high prices for 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 currently [13].

In Germany, Japan, USA, Italy, Malaysia, Egypt and Chile, the first research and experimental agrivoltaic systems have been established. According to available estimates, by the beginning of 2020, about 2,200 AV systems with a total installed capacity of 2.8 GW were created in the world, 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 been adopted; India and Germany are discussing programs to stimulate the introduction of such systems in agriculture [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 the 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 either decrease or reach a 15-fold increase [19]. Negative effects occur due to changes in soil moisture and lighting regimes during the cultivation of some crops [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 also reduced compared to the traditional agriculture [23,24]. In addition, the output of agricultural products reduces the revenue sensitivity to photovoltaic converters degradation over time.

National Renewable Energy Laboratory (NREL) identifies 3 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 the open soil and greenhouses and determination of the final economic effect [31,32], incl. 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 in midday, while in the morning and evening hours, such decrease almost does not occur. The air temperature (dry bulb) under AV systems was lower by 2°C in 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 in the 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 powering 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 (for example, grapes from for such an increase it bloomed even earlier [38]). In general, it has been shown that the temperatures of air, soil and shoots are expected to be in a complex relationship with the AV parameters, local climatic conditions and the characteristics of the cultivated crop [39].

Although present focus of research in this area is 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 energy sources directly in the fields 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

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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 Arctic and 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 the rethinking of the chemical fertilisation scale, because the need to increase yields through those 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 relevant for hard-to-reach places, for example, for the processing of local natural gas into ammonia fertilisers, phosphates. E.g., 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 affects cost, carbon footprint, and overall sustainability of supplies making those dependent on too many factors.

Obtaining high-quality fertilisers when using agricultural wastes in biogas power plants, the operation of those is also possible in combination with thermal photoelectric modules [42]. Also, the production of bio-hydrogen from agricultural wastes is becoming more and more relevant [43]. The importance of hydrogen as an energy carrier has been rethought recently, and the global environmental agenda forces to shift the priorities in energy carriers towards hydrogen, moreover, produced in a "green" way, using renewable technologies, not fossil fuels.

This review is intended as a form of “user-guide” for researchers and practitioners on the main concepts and technologies currently proposed and exploited to use AV for the intensification of agriculture. We are not going to duplicate extensive current activities reviews given in [9,44–47], so section 2 is for the context understanding mainly, focusing on just several issues poorly covered in the literature such as irrigation, aquaculture, and cold storage. The novel part of this review is section 3 – Future trends arising from the recent progress in different areas of engineering and agriculture with a potential of significant synergistic effect once coupled with AV.

This approach to using AV energy on-site is in line with the global trends for intensification and robotisation [40] of agriculture, deep processing of products on site, the transition to the use of electric transport and renewable energy sources (RES). In many countries it could be demanded due to the difficulty for an agricultural producer to connect to power grids in general or as a prosumer (both consumer and generator) and loss of agricultural or ‘green tariff’ support since AV is considered as neither rather than both agricultural and renewable energy enterprise. It will also be relevant in places of decentralised energy supply and risky farming, incl. Arctic regions (especially in combination with wind power plants). There, it could change the way of farming drastically. In this way, not only ensuring food security in remote regions, but also improving the quality of people's life significantly, creating jobs, and reducing energy bills (by substitution of expensive to deliver 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, prices in the local agricultural and energy markets, the introduction of AV can lead to both losses and provide a 15-fold increase in income. The present focus of research in this area is shifted towards the change in irradiation, temperatures and humidity of soil and air both open and enclosed, aquaculture pools, storage of agricultural products when using heat pumps powered by AV.

To optimise microclimatic effects from AV, systems with sun tracking have been investigated, allowing to obtain 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), but at the same time there are no works investigating the effects of low-

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potential concentration of solar radiation, incl. with wavelength selection. In addition to the effect on biomass growth, changes in the nutritional [48,49] and other commercial [50–52] properties of crops were also 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 in grapes, measured at a fixed time due to a 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, the unobvious results of this approach may be an increase in the market price of products supplied outside the traditional high offer timeframe [50], 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], while without the inconvenience of farming associated with 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, little research has focused on assessing the effects on livestock production, only for lamb [62,63] and rabbits[64]. The mutual influence of low-lying AV and herbivores is shown. So, animals eating the grass are removing the cost of mowing it.

AV constructions reduce the costs of fencing the territory (the highest capital costs for rabbit farms), provide protection to animals from predators and adverse weather conditions (including too 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 from (4 to 40) to 1, depending on local conditions and process organisation. In addition, it has been shown that breeding rabbits gives less environmental consequences (in particular, the carbon footprint, the 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). For 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, 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, so, farming component was not affected [62]. AV pasture had lower herbage mass, but it was compensated by the higher forage nutritive value. Sheep preferred to stay in PV shaded area at solar irradiation over 800 W/m^2 [63] for idling mainly 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 (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 issued in compliance with all the requirements of this law and should help to increase the income from such honey. This form of AV seems to have the biggest share in over 11,000 acres in the USA.

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2.3. Harvesting, storage, and processing

PV systems installed to power air conditioning systems at fur farms and refrigeration machines and auxiliary devices at remote (e.g., alpine) dairy farms; charging batteries for electric agricultural machinery (with estimates of unit costs kW*h/ha for different crops) [65] can also be considered as AV ones.

At the moment, most of agricultural machines are internal combustion engines powered ones. Making those electric (with batteries) is possible, but will likely lead to higher capital and operational expenses. Without batteries, those need either on-board power source or connection to grid. The latter is mostly impossible so options for the former are considered mostly [40], but those still need batteries, and solar panel capacity factor is drastically reduced compared to AV. Unmanned agricultural machinery relies on GPS/GNSS navigation that is insufficient sometimes and data transmission often unavailable over public networks [66]. Availability of energy across arable land could significantly reduce idle trips for both terrestrial [67] and aerial [68] agricultural drones and the demand batteries in capacity; provide precise navigation signals and data networks also using the AV structural posts.

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

2.4. Aquaculture and irrigation

First effect of AV is water saving die 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 AV shading effect. As well as 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 a long-term iron-water flowbattery storage [77], which is similar to an earlier project in Gujarat, India [78].

Floating PV (floatovoltaics) [79] is another way to reduce water temperature and evaporation, while solar panels being cooled by water reciprocally. This approach could be also used in areas of arid coasts [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 for local needs and to reduce water evaporation (by up to 85%), as well as at water treatment plants (only in China there are 60 MW of such plants).

Power generated by AV could be used for water pumping [36,83]. For that, highly efficient solar pump inverters have been developed representing a mix of MPPT-controller and frequency converter, so the pump output could follow the actual PV production with no need in battery buffer. Consider greater demand in water is in 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.

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However, it should always be kept in mind that affordable (with payback time varying from 6 months to 3 years in Africa depending on crops grown and number of crop cycles) solar-powered irrigation can lead to ground water sources exhaustion. In hydroponic [84] and aquaculture [85] farms, AV could be used to power heat and mass transfer processes optimisation [86].3. Future trends

Energy can be used both in the traditional way – to drive agricultural machines and mechanisms, and in a less traditional way – to provide optimal conditions and stimulate physiological processes, incl. when 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 getting the maximum profit at the current level of development of electronic commerce), pest repelling [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 considered; control of temperature and light conditions; chemical composition, humidity, flow of air, water and substrate; power supply of agricultural machinery and equipment, incl. 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 supporting structures to create supports for plants, protective fences (e.g., against insects or hail), rails for machines and mechanisms. At the same time, we will not focus on passive change in microclimate associated with the AV, which is the present research mainstream in the world [25].

Currently, the problem of photovoltaic (PV) modules recycling after their lifetime expiry is emerging [96,97]. Older modules have 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 being 40 years old [99,100] (noteworthy, the inverters have been substituted 5 times). Newer solar panels have a guaranteed lifetime of 30 years with a potential to be improved to 50 years [101]. It should be borne in mind that, in this case, we do not mean a technical failure, but a decrease in productivity, as a rule, by 20% of the initial one. With the continued decline in the price of PV converters, recycling to recover and reuse materials is not always cost effective. Therefore, it is gaining popularity to send such PV modules for further use in countries where a decrease in output is not so critical compared to a 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 for a number of AV systems this approach will also be beneficial.

The 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 a 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 conversion processes – substrate heating, driving electric mechanisms, production processes monitoring, etc. Those are normally powered by burning the resulting biogas. In 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 getting higher biogas net output, and biogas becomes an energy storage to be used for dispatchable power supply in stand-alone systems [104–106]. Such combinations are also used in trigeneration systems including 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 in order to intensify the process of anaerobic digestion [108].

The use of photovoltaic modules in anaerobic bioconversion systems occurs in a rather narrow segment of the energy supply of systems due to the specific distribution of the shares of electricity and heat consumption of such systems, when the use of thermal energy for own needs prevails over

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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 all over the place, and the designs of such systems can be unusual - the installation of solar thermal collectors on top of the tank, where fermentation takes place and thus forming a sealed structure below ground level [109]. Basically, solar thermal collectors are used in systems with 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, thanks to which there is 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 meet the needs of farmers for cooking fuel in cold rural areas [112]. Efficient and stable operation of biogas plants in mesophilic and thermophilic conditions when the plant is supplied with heat using solar thermal collectors can be ensured even in cold and arid regions [113], but optimization plays a big 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, the shape of which 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 from the point of view of cost and optimization of energy flows is the simultaneous introduction of photovoltaic and thermal converters of solar radiation into anaerobic bioconversion systems, which will allow simultaneous electricity supply of 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 made as a single solar photovoltaic thermal module, which can be made in the form of the solar photovoltaic thermal roofing panel, the base of which is made of recycled plastic [117], and the structure itself provides protective and energy-generating functions when its electrical rating is 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, greenhouses, etc.), which will increase the generation of electrical and thermal energy and not use land for the location of solar modules, however, the optimal slope of solar modules when located above ground for a certain geographical area of the farm will also provide high production throughout the year. When growing crops under solar modules with their ground-based location, the allocation of land for the construction of a solar installation is offset by the sale of agricultural products from an economic point of view.

Also, 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 a siding panel, which function as a building material for facing the walls of buildings. Such a disposition of the solar module will provide high energy production in low solstice 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, and in winter provide better thermal insulation, which will reduce energy consumption for air conditioning and heating of the house space. The heated air of air-cooled photovoltaic thermal modules can also be used for drying agricultural products, when air cooling of photovoltaic converters increases their electrical efficiency.

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3.2. Growth stimulation

A huge amount of data accumulated by agricultural science in terms of managing the timing of growth, flowering and fruiting; productivity; commercial properties of various crops; methods of tillage, shoots, harvest; storage and processing of products – needs analysis from the point of view of technical and economic feasibility of use in combination with AV, which is missing in 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) change in the speed of movement and air composition, incl. sequestration of gases [118], fertilisers production [119], saturation of nutrient media, support of plant growth stimulating microorganisms [120]; 3) electric [121], thermal [122], magnetic [123], acoustic [95], mechanical [124] stimulation of plant growth; 4) power supply of 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 in photosynthesis [125] and the PAR flux could be higher than at natural lighting [126]. 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 [127]. It is especially interesting to initiate with the help of these energy processes involving additional sources of energy from the environment. The efficiency of converting electricity 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 [128]. A decrease in the PAR level under AV for potatoes [34] and lettuce [28] naturally led to an increase in the foliage area, which is an economically significant result for the latter.

Next, we will 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 [129].

There are two recent master theses on techno-economic analysis of AV application to greenhouses in Sweden and Spain [130,131]. It has been shown that unfavourable conditions in Sweden in terms of electricity price, no subsidies to renewable energy and solar irradiation in winter are making AV greenhouses economically unattractive. In northern regions, it is advisable to combine greenhouses heating with the costly thermal stabilisation of permafrost [132] 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 have performed such an experiment in Arkhangelsk, Russia (our unpublished data, used a facility similar to described in [133]) and got nearly doubled yields of cucumbers and tomatoes (compared to a usual unheated greenhouse). Considering the cost of aerial delivery of fresh vegetables to remote northern settlements, such a combination is rather profitable.

3.3. Electric and unmanned agricultural vehicles, robotisation

As manual labour in the field had mainly been substituted with agricultural machines, now operators of these machines are being substituted with computers [134,135]. Modern agricultural robots can provide more than just traditional machinery substitution (land preparation, sowing, planting, plant treatment, harvesting) [136], such new functions are mapping, insect pest monitoring, artificial pollination, yield estimation and phenotyping [137]. The major problems to be solved in unmanned agricultural vehicles [136] (the market worth of $10Bs) are: navigation [138]; stability [139]; power; data [140]. AV structures could ensure precise navigation and railing to ensure stability of the vehicles, as well as safe piping for irrigation and spraying. Ideally, the new agricultural vehicles

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should be electric, but their performance would be dependent on battery capacity or ability to recharge. AV provides energy all over arable land to ensure minor battery use at wireless power supply [141] and multiple recharge points are available. In rural areas the quality of electricity is often very poor (voltage drops and black-outs are the most usual troubles) that affects complex electronic devices operation. Introduction of the local AV source will resolve this issue. 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 [142,143] is ongoing in the well developed areas mainly, while the greater effect is expected in remote unpopulated areas with lack of skilled staff. One of the problems for taking that advantage is power and data transmission networks availability [144]. Those are missing because are not demanded at sufficient scale, thus forming a closed loop. When infrastructure fr agriculture 4.0 [142] is missing on-site, the investment needed is restrictively high.

At the moment satellite based information technologies (navigation and remote sening) appear to be the most wide-spread since can serve multiple clients. The insufficient spatial and temporal resolution of those for really precision farming is often discussed. But there is another less obvious, but potentially hazardous issue – destroy of satellites due to global conflict or Kessler syndrome progress [145]. Loss of space communication and navigation technologies will definitely induce an economic shock, if that strongly affects food production technologies as well, the consequences will be much harder. This means, for the sake of food security, navigation, data acquisition and transmission should have local backups. The same actually refers to energy since bulk production power and oil refinery plants are priority targets in case of war. AV provides possibilities to establish such distributed and highly resilient systems [146].

IoT in agriculture is represented by various sensors from traditional agrometeorology to individual plant or animal physiology monitoring ones. This topic is well covered in [140]. Vast nomenclature of such sensors uses WiFi or CAN networks for data transmission that limits the distance just within 100 m. That means not only network nodes, but power sources for those should be available within this or doubled range, that is tolerable for greenhouses but economically unreasonable for the fields. LoRa networks becoming more popular could resolve these issues to some extent, particularly considering its low energy consumption, but data rate is low compared to the potential number of sensors in the covered area.

3.5. Added value redistribution

Agricultural product supply chain basically consists of: supplier; farmer; processor; distributor; retailer; customer with logistics agents in between. Value chains differ a lot depending on the product, but added value is over 100% farmer to retailer anyway even for apples. Therefore, there are great possibilities for the farmers in getting a share of it. The important stages in that chain are bulking, cleaning, grading, processing, and packaging that used to be cheaper to be implemented at large-scale. The advent of retail food markets and human-less technologies has shifted many of these processes to the farm or neighbourhood scale to reduce the logistics expenses for raw products and long-distance delivery. Availability of electricity is the main obstacle for many rural communities to setup even a 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 input supply chain. We have already mentioned the posiibility to manufacture nitrogen fertilisers using AV energy, as well as lower demand for those at precise supply to the plants. P2V use of AV energy can reduce the delivery costs not only for own e-vehicles, but also for contractors who could be charge 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

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the year, while on a daily time scale there is a negative correlation between the production from PV and wind turbines [147]. 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 too reliable for use outdoors, it is reasonable to use direct current as much as possible on-site where long-distance transfer losses are negligible [148,149]. 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 needs to be investigated in the context of shading and an increase in electricity generation, cost of concentrators and PV panels (particularly with selective transmission) [150]. At the current level of technology development, it is in such concentration systems (selective and holographic concentrators of solar radiation) that it is easier to implement wavelength selection with the aim of minimising PAR shielding. It also suggests feasibility study of a ground-based PV in combination with plastic Fresnel lenses.

When PV are located on the ground, it is easier to divert heat from them to the soil, to reduce and localise shading [151], and the above-ground location of lighter and more flexible concentrators will facilitate supporting structures and increase their resistance to wind loads, and enhance the greenhouse effect for open ground. In such concentrators, it is also possible to implement such a dependence of the refractive index on the wavelength in order to reduce the YPF loss.

Feasibility study is needed in using 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 cover and underlying layers of the panels to convert solar radiation into the most efficient YPF compensating shading losses.

For sure, power availability all over agricultural sites opens great opportunities for plant physiology and agrochemistry experiments seemed to be impractical and expensive earlier.

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

4. Conclusions

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

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

Higher share of energy used on-site should remove the legal collisions 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 are summarising our estimates on potential AV benefits in different ways of using it.

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We suggest AV concept 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	Ifrastructure 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 & 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 – levelised 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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