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Review

Nexus between agriculture and photovoltaics (agrivoltaics, agriphotovoltaics) for sustainable development goal: A review

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ABSTRACT

The coexistence of agricultural land and solar photovoltaics (PV) can be named Agriphotovoltaics (APV). APV concept was developed two decades ago however its actual implementation is happening nowadays. APV directly solves SDGs 7, and 11 by generating benevolent renewable energy without damaging the land and keep producing food for people. In this work, a comprehensive review of the APV system is documented. Currently available software tools, field experiment results, and PV for APV are described in this work which identified that for forecasting APV, a more robust tool is required. Vertically placed Bifacial PV, transparent, and semi-transparent tilted PVs can be suitable for shade-intolerant crops whereas opaque PVs are appropriate for shade-tolerant crops. The knowledge gap between various stakeholders such as solar PV researchers, agricultural researchers, and land users needs to be more rigorous. Economic and policymakers should share dialogue to improve the growth of APV which not only solves SDG 7, and 11 but also meets the target for SDG 5, 8, 9,12, and 15.

1. Introduction

According to United Nations 2021 reports, globally over 1 billion people are without electricity whereas 0.8 billion people are still suffering from starvation & malnutrition. On the other hand, 92 % global population will have electricity while 670 million people will still have no access to electricity by 2030. The lack of electricity (energy) impedes any kind of development particularly the economy and health of humans. Therefore, security from food and energy must be ensured to tackle the conditions created due to the growth of the world population and climate change. Food security and energy are probably the two essential welfare commodities for human beings globally. Thus, a sustainable development goal (SDG) is currently in place to demolish these social issues. United Nations sustainable development goals (SDG) are in place e.g. SDGs 2 (zero hunger), 7 (affordable and clean energy), and 13 (climate action) are devoted to tackling these challenges.

According to the Consultative Group on International Agricultural Research (CGIAR), agriculture and food chain sectors consume close to 30 % of global energy, which also contributes 19–29 % of GHG emissions annually [70]. The reason for this high emission is due to the use of traditional fuel, which has a significant impact on the environment. In 2015, at the Conference of Parties 21, 195 nations agreed to limit the increment of global temperature to less than 2 degrees above the pre-industrial levels during this century *(United Nations Framework Convention on Climate Change; UNFCCC, 2015)*. The inclusion of renewable energy by replacing traditional sources can be a solution for the above target. However, the key drawback of renewable energy systems is that they occupy significant land and globally majority of the land is used for food production. According to the SDG 15 report, for living, 2.8 billion people directly depend on agriculture, which necessitates a substantial amount of land. In terms of land coverage by the various renewable resources, Biomass occupies the maximum land, while wind takes less than solar [44]. Among the various renewable energy sources solar energy can take the leading role as they need only the sun which is free, abundant, and green. If we consider the area of the earth's surface which is $A = 4\pi R^2$ (R = 6400, 000 m), the peak solar radiation incident on unit area (P) = 1300 W/m^2. At any given time if the ½ of the earth is illuminated, with ½ of the peak illumination, this will yield of ($total = \frac{AP}{4}$) ~ 167,358 terawatts [177]. According to the National Renewable Energy Laboratory (NERL), the actual number is approximately 173,000 terawatts. This amount of power can meet the global energy demand effortlessly. Thus, the exploitation of solar energy by photovoltaic (PV) systems is championed as they work under the sun and can easily be placed near the demand. Also during operation, it has low noise and no deadly impact on birds, which is very common in wind generation [56,129]. In 2021, solar PV generation crossed the 1000 TWh threshold which was a 22 % increase compared to 2020. Presently, solar

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Nomenclature

AgriPV	AgriPhotovoltaics
APV	Agrivoltaics
bPV	Bifacial Photovoltaic
BIPV	Building Integrated Photovoltaic
CAGR	Compound Annual Growth Rate
DSSC	Dye-Sensitized Solar Cell
EV	Electric Vehicle
LCOE	Levelized Cost of Energy
PAR	Photosynthetically Active Radiation
SDG	Sustainable Development Goal
VIPV	Vehicle Integrated Photovoltaic
WPV	Water based Photovoltaic

PV is accounting for 60 % of expansion compared to other renewables [78].

For renewable power generation from PV, the most common integration type is ground-mounted PV. However, because of the significant use of land for PV installation, various other options are also in phase such as building integration [59,64], water-based PV (WPV) [57], and vehicle-integrated PV (VIPV) [153,37]. However, one of the other options is agriphotovoltaics (APV). This is a combination of agriculture and photovoltaics. The concept behind it is to install PV using the land for agriculture. Integration of PV systems with agriculture production could be one of the sustainable approaches by employing improved land productivity. This can eradicate the growing land use competition and astonishing demand for energy and food in a country. Thus, 'APV' indicates that by sharing the same land and light, energy and food both can be produced. The idea of this APV was first introduced in 1982 by Goetzberger and Zastrow [66] and in 2013 France, the first detailed performance of APV was reported [108]. Since 2014, the governments of China, France, Japan, the USA, and South Korea introduced new policies to support the APV. Schindele et al. reported in 2020 that globally almost 2200 APV systems have already been installed, totalling 2.8 GWp capacity [142]. Therefore, APV technology helps to obtain sustainable development goals, by decreasing the competition between lands used for electricity versus land used for food. Fig. 1 shows the historical improvement of APV systems.

Previously 98 journal-based review work has been done where it was identified that investigation in APV area having over 1 MW is less compared to < 100 kW level. They identified that among the 98, 50 works dealt with small-scale (<100 kW) level APV whereas only 26 dealt with > 1 MW. The key lacking factor of this APV study is the financial model. Most of the work investigated energy & crop yield from an APV system [8]. Other review work summarised some key valuable points such as a one-third decrement in solar light can reduce crop productivity, however up to 70 % land productivity is also possible. APV also enhances the economic value of farming by generating benevolent decentralised electricity [167]. Based on past studies, the future of APV in India is summarised in another work. Not only power generation from PV and agriculture but the thermal regulation of PV using crops is also investigated [162]. Work reported by Abidin et al. 2021., highlighted the quality and quantity of sunlight both are essential for the APV system. Also, future shareholder decisions can play a significant for this type of agreement. They also recommended that the adjustment for crop selection and management can produce better success. Finally, they inferred that it's not only agriculture and PV but a combined nexus between food energy and water security [2]. Recently, Reasoner and Ghosh reported APV where they studied various engineering aspects suitable for higher growth of APV system. However, they only considered the last five years of work [127]. One recent work reviewed the progress of the APV system and concluded that mounting height and spacing between solar PVs should be optimized to have maximum crop yield and energy generation as well. Their recommendation is to study a model that will optimize the elevation, spacing, and tilt angle of the solar PVs and factors responsible for crop growth and yield, to have maximum crop yield and energy production [141]. Various solar energy technologies such as solar PV modules, solar thermal and PVT systems were investigated for agriculture farming [43] while solar desalination, water pumping, and crop dryers were investigated by [152]. The primary focus was on India and its different schemes to improve solar and APV research growth [152]. In a mini-review effect of PV shading on crop yield, and quality, considering the open field and PV-integrated greenhouse was investigated. It was anticipated that a PV shading threshold of 25 % is enough and above that crop growth will be stopped [155].

In this review work a comprehensive literature review has been performed to investigate the APV and its future to meet SDGs. In addition, various challenging factors and simulation techniques required for APV are critically analysed. Design for APV and how PV and visible light intensity have a crucial contribution to the success is discussed. In addition, country-wise APV investigation and issues related to integrated PV-crop simulation tools were also highlighted. Section 2 summarised the details of APV and the essential factors associated with APV. Section 3 detailed various experimental and software-based APV work. Section 4 summarised the discussion based on the knowledge gap, cost, and technical challenges, and section 5 concluded the work.

2. Details of APV & essential factors

Agriphotovoltaics/Agrivoltaics (APV), as the name indicates, is a combination of Photovoltaic systems and agricultural land where land is used for both PV power generation and food production. It can also be termed as agroPV, agrivoltaics (AV), solar sharing [144], dual use of land, and aglectric [112]. Recently solar energy generation with

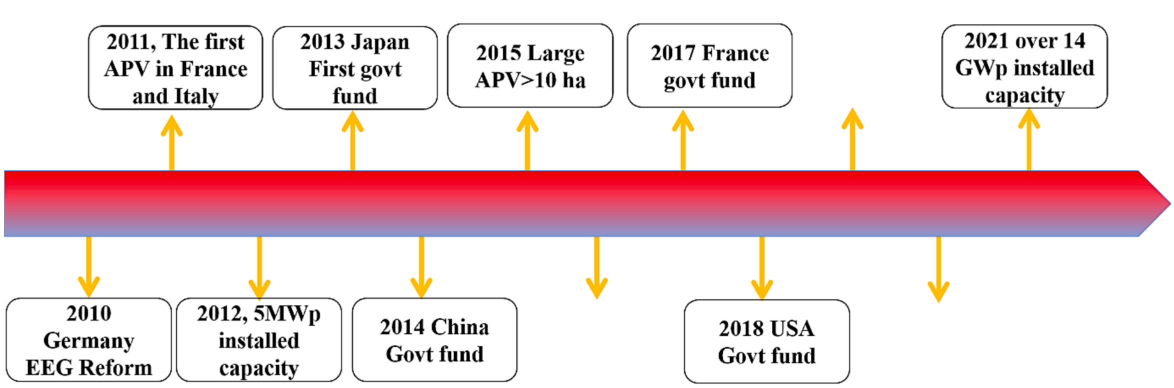

Fig. 1. History of the APV system. Redrawn from [151].

domestic livestock has been named Rangevoltaic [38]. According to NREL, an APV system should influence each other (PV and agriculture). If rooftop PV has a direct impact on the livestock, soil, and vegetation, then it will be counted as an APV system. A few other criteria are also now associated with the APV definition, e.g. in Germany, APV is only allowable if the land has yielded at least 66 % without solar which is 80 % in France & Japan.

As previously mentioned the first concept of APV was developed back in 1982 and at that time, the plan was to use the available space under the solar collector-based solar power plant mainly for crop growth [66]. Solar collectors were installed 2 m high above the ground and maintained enough space between two solar collectors so that crops could be planted without excessive shading. It was assumed that one-third of the solar radiation is required for the solar collector (48° tilt) because of their design, and two-thirds of the solar radiation could be used for other purposes such as crop production. Fig. 2 shows a typical concept of the APV system. For dry areas, the presence of PV [172] or other covering elements [7]also aids in improving the microclimate by increasing soil health and moisture.

APV systems possess several positive attributes and challenging factors as below.

Advantages of APV

- ***Land productivity***: Combined setup can potentially increase 70–80 % land productivity and distribute the co-benefits of agriculture and PV power generation more widely by selling electricity, leasing land, and enhancing agricultural-sector production plants.
- ***Water usage efficiency***: Most solar panels need water washing to eliminate dust from the top of the surface to enhance solar radiation efficiency. If plants grow under PV panels, the same water can be used and run off on the ground for vegetation irrigation.
- ***Soil health improvement/ less dust generation***: Covering the soil surface by introducing vegetation prevents the top soil layer from washing off. This will improve soil health. In addition, the presence of crops under the PV panels produces less dust from the soil.
- ***Low local ambient temperature:*** The practice of agriculture under PV panels can also keep the solar panels cool due to the moist and humid soil. Often this temperature is below the ambient which helps to produce higher power from PV. The presence of PV offers shading under the PV panels, which improves the balance of evapotranspiration and water irrigation.
- ***Reduce impact of drought:*** In the food sector, water scarcity is a big threat. The presence of shading from APV eliminates the evatransportation which in turn improves crop yield during drought conditions [143,9].
- ***Stops migration:*** This type of scheme can have the potential for social development and integration of technology and agriculture and can create new educational institutes and jobs. Migration from rural to urban can be minimized as most of the agricultural place is in a rural location where new offices should be set up. Women empowerment is possible by employing them in crop plantation.
- ***Human factor:*** Farmers' health such as skin cancer and heatstroke are the two common factors who do farming in hot, sunny weather [96,125]. APV can provide relief from the scorching sun by providing plenty of shade for farmers to work in which is much needed but often overlooked.
- ***Livestock production:*** Animal farming in APV can also be another potential. Though often it is considered that animals cannot be a potential option for agricultural cropland. However, once the crop is fully grown or ripened, they are cut and collected. Thus, after this harvesting, the land can be easily used for animal grazing. If land productivity is evaluated using the PV generation and the meat is produced from sheep, rabbit [102], lamb [14], and emu then the overall profit from benevolent power and meat price is enormous.
- ***Source of EV charging station:*** Electrification of the transport sector can also get benefit from APV. Range anxiety is a key issue for the user to take electric vehicles (EVs) for long-distance travel, particularly in the countryside or rural locations [60]. Most often in these locations, EV charging stations are not present. If APV is deployed this can be a source of energy for the EV charging station [149]. Hence people will be keener in the future to use EVs for holiday trips and other countryside trips.
- ***Source of energy for rural off-grid/grid electrification:*** Globally most of the agricultural lands are in rural locations and the rural populations are deprived of the electricity infrastructure. The UN has set a target for affordable electricity so that rural areas will not deprived of energy anymore. In this context, APVs can be prospective to be a source of rural electrification. APV can be the major source of off-grid systems in rural locations.

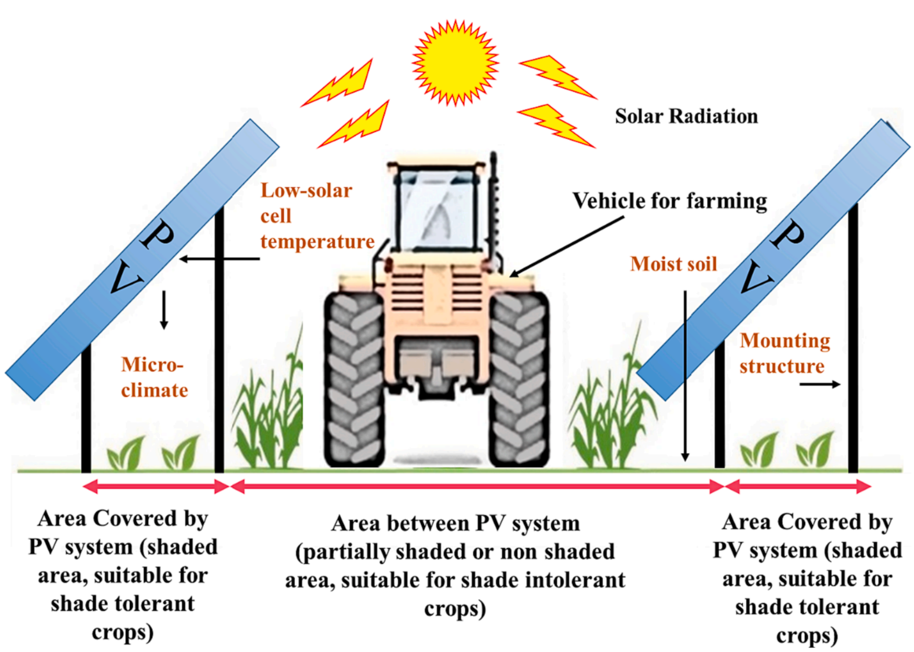

Fig. 2. Schematic of APV design showing space between panels that allows farming and equipment to pass between rows. Redrawn from [41].

Disadvantages of APV

- ***Agricultural land loss***: For APV, regardless of the layout, some agricultural land loss is evident. However, the quantity of loss is crop-specific and fully depends on the panel's dimension. Most of the traditional panels are rectangular in shape hence it's hard to comment that this particular shape can accommodate entire land, as land size, dimension, and shape vary significantly from place to place.
- ***Increased labour cost:*** APV requires technical expertise, which includes knowledge of solar PV and knowledge of agriculture. Farmers lack knowledge of solar PV whereas people who are experts in solar cannot tackle the crop issues. Thus, labour costs will be included every time there is any maintenance or need to grow new crops. For APV system O&M purposes, two different types of experts are required who can work together. In this aspect, the government should intervene and provide a scheme where particular APV experts can be produced.
- ***Crop cycle:*** To improve the crop yield generally all the agricultural land changes the crop generation. If the same agricultural plantation is applied year after year, it will have an impact on that section of the field. Thus, the rotation of crops is an important component of APV [89]. Hence, for this, the crop yield analysis must be done for a variety of different crops before applying APV.
- ***Not suitable for greenhouse application***: APV for greenhouses stops light penetration. This can often reduce the crop's growth. For a particular work, it was reported that an opaque PV-covered greenhouse resulted in a 64 % reduction in crop output [31].
- ***Anti-soiling coating:*** It must be kept in mind now that if PV is employed for APV any chemical used for anti-soiling coating can be damaging to the crops. Thus, it's not a straightforward approach like BIPV or ground mounted where the key criteria are low refractive index and high transmission for an anti-soiling coating [120], 2020). However, it is believed that the APV system faces less dust issues than typical ground or building integrated as plants help to stop soil erosion.
- ***Impact of APV on ecology:*** Though solar glass has high transmission still it has reflection which is close to 4 % or more [170]. As PV panels can reflect polarised light, birds often mistake it for a water source. Because of landing on hard and warm surfaces, most often they die or get injured [38]. Some insects are attracted to polarised light [74]. Significantly high avian mortality is reported which also included PV and concentrated solar systems [87].

Currently, APV can be classified depending on the configuration of PV systems. Fig. 3 shows primarily three types such as interspace, elevated or overhead, and the greenhouse which is now the most common type. For interspace type, this is the most common which can be seen for ground-mounted PV installation. Between the two PV systems, the space is used for crop growing. Depending on the spaces available, a range of various farming vehicles can go inside for farming activities. Crops mostly get direct sunlight and shading often is possible during the morning and afternoon time from the PV modules. For elevated or overhead structures, crops are grown directly under the PV systems. In this type, crops get protection and shade is available almost all day. Lower values crops such as grains, grasses, and hardy vegetables are popular for inter-spacing structures while special expensive or higher-valued crops are used for elevated structures. Integration of PV into a greenhouse for APV application is another option. In this particular type, PVs are installed above or as envelopes to modulate light. Currently, most of the PVs are silicon type, however, others types have potential and are discussed in section 3.2. Animal husbandry and live stocks are also possible by using the space around, directly adjacent, underneath solar PV for an APV system. Cattle, honeybees, poultry, rabbits, and sheep have the potential for animal operations which can be seasonal, or yearlong depending on the requirements.

2.1. Impact of light on crops

For the photosynthesis of plants and planetary energy balance, solar radiation is the main driver. Similar to PV, it is essential to distinguish the intensity of direct and diffuse solar radiation. Global horizontal irradiance (GHI) is key for PV systems, likewise photosynthetically active radiation (PAR) for crops [163]. Fig. 4 shows the different light intensity levels and photosynthesis.

Plants need efficient temperatures during the daytime to grow while some plants need high humidity. For photosynthesis, light parameters are crucial. Carotenoids, chloroplast pigments, and chlorophylls absorb and harvest visible light by the photosynthetically active radiation (PAR) mechanism. Chlorophyll can have numerous chemical structures and among them, chlorophyll *a* and *b* are the two primary [26]. Chlorophyll *a* absorbs blue light while chlorophyll *b* absorbs red light. Plants are green because of their inability to absorb the green light. PAR can be defined as part of electromagnetic radiation within the waveband of spectral range from 400 nm to 700 nm that can be used as the energy source for plant photosynthesis. Outside this wavelength, such as IR and UV are called non-photosynthetically active radiation (n-PAR) [171]. UVs are not useful for Photosynthesis as they have a higher level of

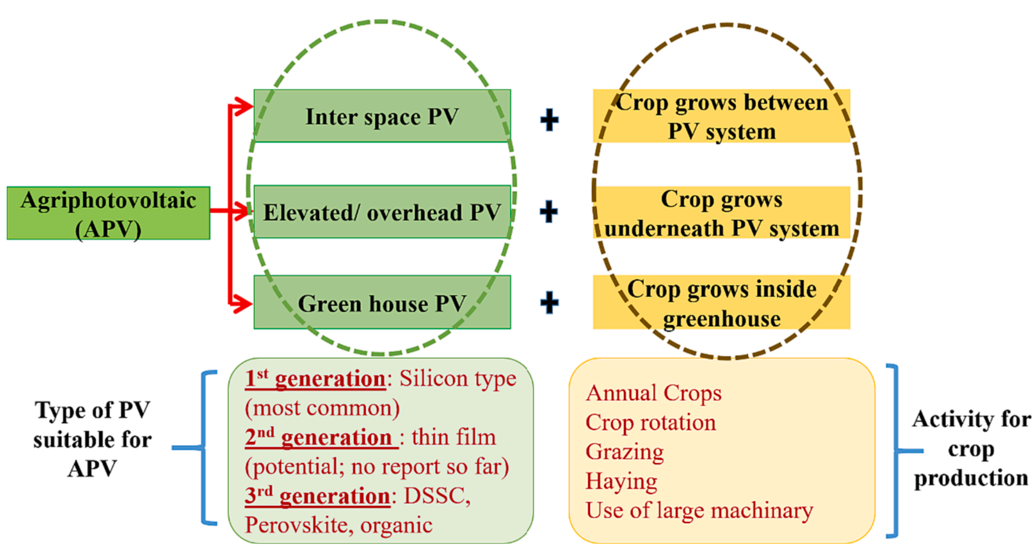

Fig. 3. Schematic details of the type of different Agriphotovoltaics (APV) approaches, potential PV that can be used, and activity involved for crop production.

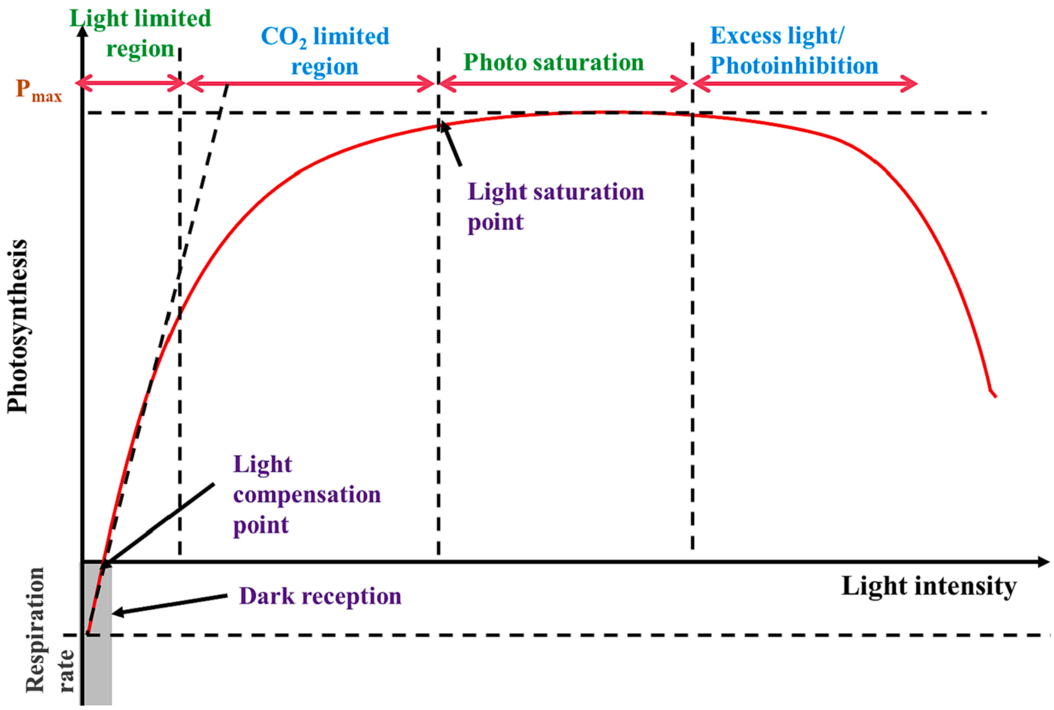

Fig. 4. Light intensity-dependent photosynthesis where P_{max} indicates the maximum photosynthesis rate. The plant shows a gain of carbon fixation at the light compensation point which is the minimum level of light requirement. In the light limitation region, the net photosynthesis rate has a linear rise with increased light. The photosynthesis process gets saturated after a further increase in light intensities, (photo-saturation). Under excess light intensity photosynthesis declines which is called photo-inhibition. Redrawn from [101,23].

energy which damages molecular bonding, and other essential structures. NIR suffers from low energy content which is not enough to process photosynthesis. How plants react with the different wavelengths of light can be expressed [109] as equation (1) where P represents the photosynthesis rate, I is the intensity, and a is the slope at zero I and 1/b is the value of P at infinite L [139,110].

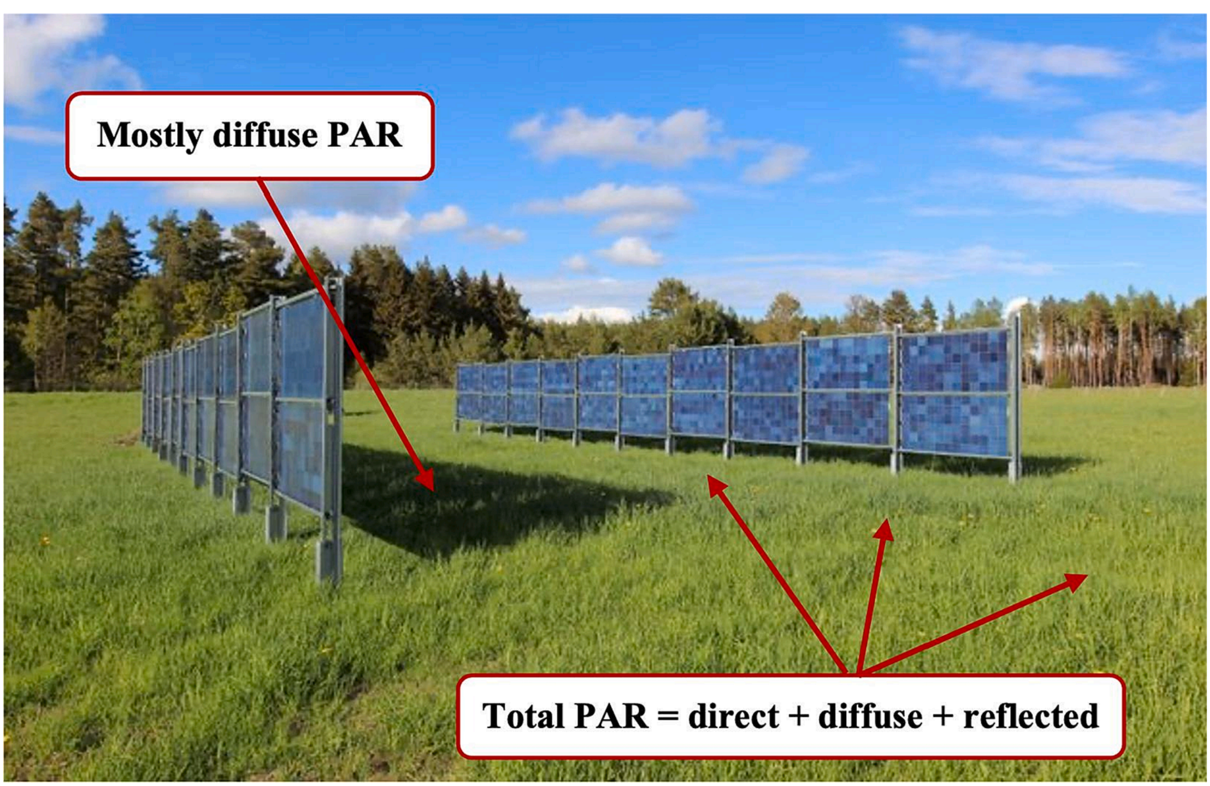

Fig. 5. Schematic diagram of the PAR (photosynthetically active radiation) received in a crop field having a vertically oriented bifacial PV system located in Kärrbo Prastgård (Sweden) [101].

$$P = \frac{bI}{1 + aI} \quad (1)$$

Available light under an APV system varies continuously. This variation is prominent from season to season. The growth of crops is light-dependent. Light quality and quantity both can have an impact on the plants under APV. PAR varies under the APV system and thus can have an influence on summer, winter, long-cycle and short-cycle crops. Surface global or total PAR includes direct, diffuse and reflected as shown in Fig. 5. Table 1 listed the nature of corps for different light conditions. Based on Table 1 it can be considered that shade-intolerant crops cannot cope with shading from PV. Table 2 listed the details of the yield reduction due to shading. However, a study on sweetcorn showed a different outcome. Sweetcorn, which is shade intolerant crop, was planted for an experimental farm operated by the CHO Institute of Technology in Ichihara City, Chiba Prefecture, Japan (Latitude: 35.37°, Longitude: 140.13°) in early April 2018 and harvested in late July. The typical growth period of corn is approximately 90 days and grows up to a height of 2 m. Thus, It is possible to grow shade-intolerant crop corn, under the shade of PV systems [144]. A possible reason to have a higher yield from a shade-intolerant crop could be 1), crops actually need a small fraction of sunlight for photosynthesis. Even if the light level increases, there will be a point where the light has no impact on photosynthesis, 2) exposure to sunlight also provides UV, which is damaging. Hence, too much sunlight may not be a good option, 3) the PV shading creates a reduction of water evaporation, which is beneficial in the hot, and dry seasons. Shading from PV panels reduces the diurnal variations of sunlight and ambient temperature, which is good for the crop. Because of the reduction of moisture evaporation, PV modules also alleviate soil erosion [144]. Some researchers claimed that 730 nm-based monochromatic red light can improve the 6.5 % photosynthesis rate of lettuce in a greenhouse [175].

2.2. PV technologies for APV

Choosing slopes close to the latitude and orientations facing the equator can provide higher power generation from ground-mounted PV. To achieve direct solar radiation throughout the day, PV must face true south in the northern hemisphere and true north in the southern hemisphere. However, for APV, PV system integration does not follow traditional design where tilt angle and orientations play a significant role in extracting maximum power from PV. APV design varies for every project. Solar PV, which is one of the key components for APV systems, is now mostly silicon type. PV types include first-generation silicon type, second-generation thin film, and third-generation advanced type. Advanced third-generation types consist, of perovskite [18,62], Dye-Sensitized Solar Cell (DSSC) [136,63], organic [52] and tandem [99] types. Though these types possess significant improvement in terms of efficiency, their stability challenges are still a barrier for large-scale outdoor applications. Recently researchers argued that organic PV can be a potential option for APV application if the stability issues can be eliminated [148]. The light absorption of perovskite, DSSC, and organic be tailored in the NIR region and the visible region can be used for crops. Second-generation thin film-based modules are mostly semi-transparent in nature and were developed to reduce the high cost of solar cell material. They are commercially available and have high durability and mostly their structures are glass-PV-glass [10]. Thus, they are also favourable choices for APV application.

Table 1
List of crops under different shades. [8].

Light condition		Plant for agriculture
Shade intolerant Plant		Cabbage, corn, cucumber, pumpkin, rice, tomato, turnip, and watermelon
Shade Tolerant	Full shade Light	Alfalfa, arugula, Asian greens, broccoli, cassava, chard, collard greens, hog peanuts, kale, kohlrabi, lettuce, mustard greens, parsley, scallions, sorrel, spinach, sweet potatoes, taro, and yam
	Moderate Light	Beans, carrots, cauliflower, coriander, green peppers, and onions
	Low Light	Mushroom

Table 2
List of crop that has low yield under APV [95].

Type of Crop	Condition	APV yield (kg/m^2)	Conventional yield (kg/m^2)	Reference
Bok Choy	Under PV panel	0.10	1.15	
Corn	Under PV panel (high density)	3.23	3.35	[144]
Lettuce	greenhouse	2.18	2.03	[158]
Lettuce	Under PV panel	2.65	4.50	[45]
Kiwi	Under PV panel (low density)	1.66	1.71	[82]
Winter cabbage	Under PV panel	0.32	0.35	[115]

Silicon mono and multi-crystalline PV are now the most common in the commercial sector for outdoor applications because of their mature technology. Mono-facial-based PV is the most investigated type as shown in Fig. 6 **a & b**. Modelling-study showed 30-degree tilt south-facing mono-facial silicon PV-based quarter densities solar array could provide 80 % direct sunlight and half density could provide 60 % direct sunlight compared to an open field in Phoenix, Arizona [104]. The growth of tomato plants was investigated by using semi-transparent organic PV and silicon PV-based APV greenhouses. It was evaluated theoretically that the use of organic PV can improve the production of tomatoes by 46 % more than standard Si PV greenhouses. Ground-measured weather data from Geraldton (Australia) was employed for this study. For the crop model, a tomato growth model was used. The transmittance data from a semi-transparent organic solar cell having PTB7-Th: IEICO-4F as the active layer was employed for PV. Organic semi-transparent cells with 9.4 % power conversion efficiency and 24.6 % average visible transmittance [139]. Recently [159] et al. reported thin film-based APV work in Colorado USA 40 % semitransparent CdTe, opaque cdTe, and opaque multi-crystalline PV systems were employed. The thin film allowed three times higher lights under the panel suitable for crop growth. In the future thin film-based light flexible PV and other types of PV can also be an alternative for APV systems which will make the system integration much simpler and may reduce the overall cost. For semi-transparent type PV, the advantage is through the PV light passes (mainly PAR) which can even help to plant shade-intolerant crops. However, the type of light passing through PV can play a significant role in choosing the crops.

However, a recent trend is to apply bifacial-based PV (bPV) as shown in Fig. 6 **c & d**. The advantage of the bifacial is it can collect light from the rear side of the PV. Also, at latitudes above 40°, a bifacial module for any direction is more cost-effective than a mono-facial even for a minimum albedo between 0.12 and 0.30 [135]. The structure of bifacial modules is glass-PV-glass, which is different from the mono-facial one. This particular structure is potential, particularly in the northern latitude climate where the solar radiation intensity is not strong. Thus, light still can penetrate from the non-PV covered area. However, for APV application, reflection from the crop is always a challenging scheme [86]. Also, in terms of degradation, this glass-PV-glass structure which is common with bPV is more beneficial than glass PV black sheet mono-facial structure [145]. A bifacial PV-based APV system was investigated theoretically where bPV was mounted vertically. The overall model included three main components such as crop yield, solar radiation and shadings, and photovoltaics. All these components were validated using experimental data and commercial software. Potatoes and otas were employed as key products. Results indicated that PAR distribution gets affected due to the row distance between bPV. If the row

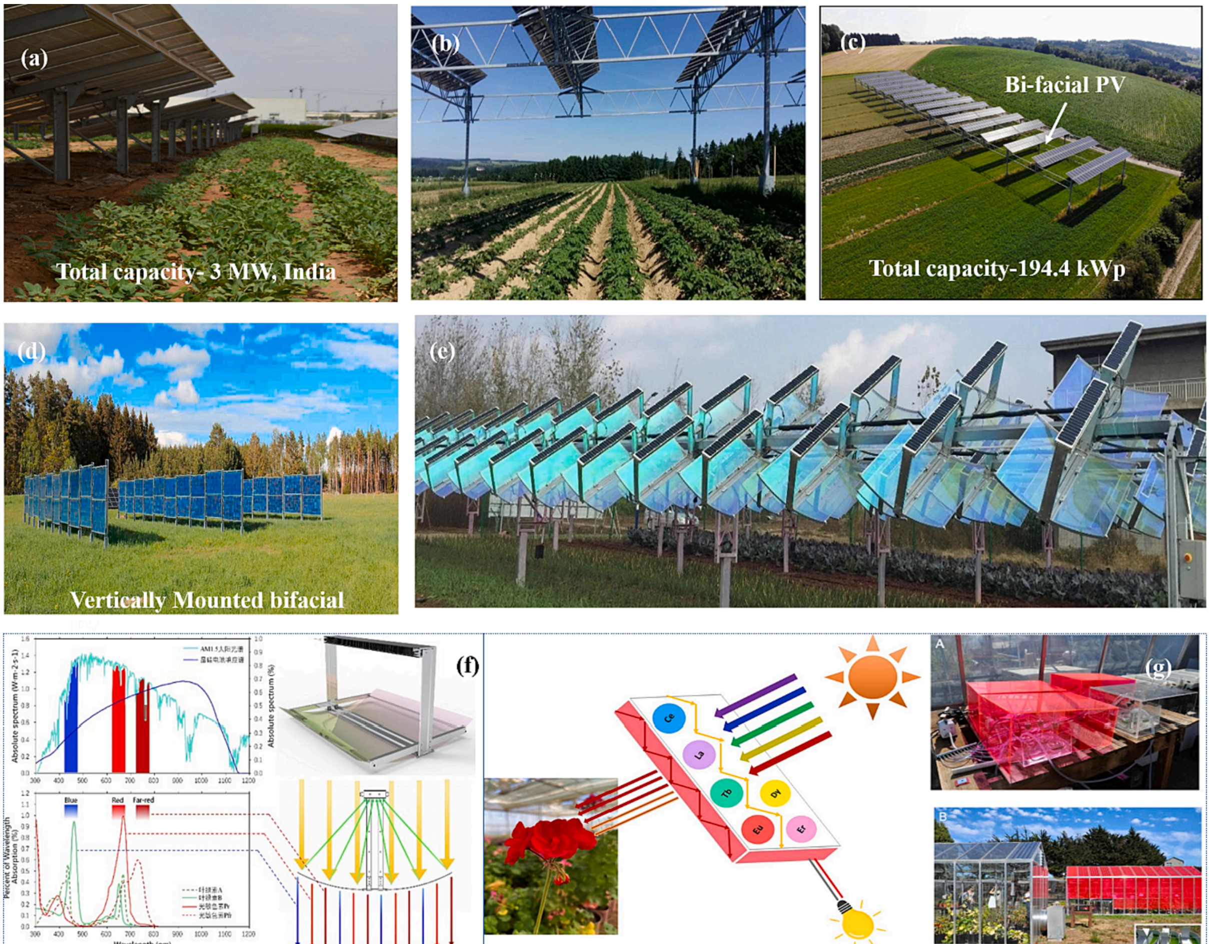

Fig. 6. (a) Silicon-based monofacial PV 3 MW grid-connected solar power plant at Bhatkota village, Taluka Modasa, Aravali District, Gujarat, India [121], APV RESOLA and is located at Heggelbach, administrative district of Sigmaringen, Germany [167] (c) APV power plant in operation from 2018, producing Demeter-certified organic potatoes, winter wheat, clover, and celery. [142](d) vertically mounted bifacial PV at Karrbo Prastgård, Vasterås, Sweden [29] (e) Large-scale APV system in Fuyang City, Anhui Province, China [71,9] (f) novel concentrator for APV system showing transmitted red and blue light for plant growth and remaining for PV power generation [100](g) Organic LR305 based LSC used for algae cultures. Greenhouse without LSC for salina cultures (left) and LSC (right) [42]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

distance were reduced to 5 m from 20 m, potatoes and oats productivity would be reduced to 50 % [29]. A study investigated in Lahore, Pakistan, shows that denser and E/W bPV integration gives a higher crop yield while mono-facial N/S provides a higher energy yield [133].

Concentrating PV (CPV) is another option to employ in APV work. The CPV is an old concept but has slow progress due to the high installation cost, reliability issues, unavailability of field data and expertise, and no information on operating and maintenance costs. Based on the concentration ratio, CPVs can be high, medium, and low types. To perform well, CPV systems need direct solar radiation. The concentration ratio of CPVs is mostly represented in the units of the sun. The low concentration ratio has $\leq$ 10 suns, medium concentrator 10–100 suns, and high concentrator $\geq$ 100 suns. Large-scale CPV based APV is working in Fuyang City, Anhui Province as shown in Fig. 6**e**. Liu et al. [100]developed a polymer film made of Ta_2O_5, TiO_2, and SiO_2 and a two-axis tracking system which helped to grow larger plants with higher net photosynthetic rates and contained more soluble sugar as shown in Fig. 6**f**. The cost of the proposed concentrating APV was USD0.8/Watt which was 33 % lower than conventional silicon-based PV panels (USD1.2/Watt). Overall APV system efficiency was 6.8 % higher and 26 % water evaporation reduction was possible due to lower temperature under the film [100]. Huang et al. [77] conducted dish-shaped CPV with a beam filter acting as a splitter for the solar spectrum through which the most effective bands for plant growth were transmitted while others were reflected into the PV module. They investigated lettuces as crops and GaInAsP/GaInAs double junction solar. Ma et al. [103] investigated spectral splitting PMMA-based cover with compound parabolic concentrator and triple-junction solar cells (GaInP/GaAs/Ge). NIR blocking rate was 78 % and over 40 % visible light transmission was possible with this system which is essential for crop growth. Crops need PAR and most of the solar cells absorb PAR which can influence the crop's yield. Luminescent solar concentrators (LSC)-based integration is now also in research. LSC consists of polymer material and fluorophores or luminophores (dye) [32]. These dyes capture the UV or NIR radiation from solar light and convert it to visible light by up or down-shifting methods [134]. The emitted photon is then concentrated in the solar cell which is located at the edge of the concentrator. Rare earth-based LSC has been introduced for the Agri LSC [52] as shown in Fig. 6**g**. To improve the power generation from PV tracking solar/ dynamic tilt is a great choice.

Dust impact on the APV system is a crucial consideration. Dust deposition on the top of the PV system reduces power production significantly. Though it is considered due to plantation dust generation will be less, agricultural-related work can create significant dust [90]. Dust impact on CPV systems is more adverse than non-concentrating PV [174,34]. Also keeping the PV in a vertical direction is useful for the location where the dust impact is prominent. It is well reported that the vertically tilted PV suffers less dust issues than other tilt angles

[35,33,61]. Soiling or dust impact on PV is mentioned in various research journals where PV is land-based or building-integrated. Cleaning mechanisms for this soiling issue are also well documented where self-cleaning [120,119], robotic [54], manual & electrodynamics dust shield [138]. However, no research work is reported on any long-term study on soiling and cleaning for APV systems. Table 3 listed the issues related to PV systems that can have an impact on the overall performance of APV systems.

2.3. APV design

The design of an APV system is probably one of the key challenges, as this includes two different expertise, from both the farmers and PV developers. The availability of a standardised APV design format can help both sectors. For APV design, technological, construction, and safety-based issues should be dealt with priority which further can help to tackle the economic aspect. In the technical aspect, the type of crop that will be cultivated and the type of PV that should be suitable for a particular location are significant. Further, shading impact on the crop from PV and self-shading from two different PV modules must be counted. For structural construction, ground-mounted PV, and other types of land-based applications, aluminum-based mounting frames are employed and a concentre-based solid mixture is used to hold them tightly with the ground. These concrete mixtures can have a negative impact on the agricultural field later on. Thus, the sustainable design of APV is vital which can have a positive impact on land, crop, and PV. The impact of snow and wind load on the PV module structure could be an issue that should be counted during the designing process of APV. Safety aspect consideration during APV design is a precondition. For agriculture, the land under the APV system must undergo major investigation as a solid base is not possible and due to farming the soil often becomes moist, wet, or dry.

In Germany, the German Institute for Standardisation developed some guidelines that can be influential with very similar types of climatic conditions. According to them the key criteria that must be fulfilled before developing APV systems are a) agricultural usability of the area must be maintained, b) after installing the PV, the land lost must not be over 10 % (while PVs are above 2.1 m as shown in Fig. 7**a**) and 15 % (while PVs are below 2.1 m as shown in Fig. 7**b&c**), c) light (solar light) and water must be available, d) any damage due to PV on the ground such as soil erosion must not be allowed, e) yield from agriculture must be 66 % compared to reference yield. Reference yields are calculated from the last three years' average data.

Shading from PV systems can often not be very impactful on crop growth. Though there is a scheme to select shade-tolerant and intolerant crops for APV, however, the flexibility of moving the PV system can possess more benefits. This partial shading from PV depends on the heights, orientation, and density of PV systems [30].

Table 3
Issues that can have an impact on the power generation from APV system and the overall performance of APV.

Factors	Impact
Tilt Angle	Due to not optimising the tilt angle, power generation from PV will be lower compared to an optimized tilt PV. This is only true when all the other factors remain the same for both cases.
Temperature	As it is expected the PV in the APV system may experience lower temperatures due to the presence of crops hence performance can be improved which may offset the tilt angle issues.
Dust impact	As the surrounding lands will be covered with crops hence less soiling is expected hence this phenomenon can reduce the cleaning cost of PV and enhance the performance.
Transparency of PV	Solar cell material transparency has an inverse relation with power generation. Hence the more the cell is transparent the more power generation from that cell will be low compared to a fully opaque cell. On the other hand, the presence of transparency will allow daylight which is essential for crop yield.

In Germany, one APV system was developed in cooperation with the Demeter farming community Heggelbach and BayWa r. e. Solar Projects, Hilber GmbH. The system was oriented in 52.5° azimuth and SW direction and started working from September 2016. For the foundation of PV modules, a Spinnanker system was implemented (shown in Fig. 8 **a&b**). This is a special type of concrete-less foundation and works in a similar principle to tree roots. In a circular ground plate, threaded steel rods having a 1 cm diameter were screwed. Threaded rods (6 or 12) and the bar length (2–8 m) both were variable and gave flexible adaptation on the soil. The advantage of this system is quick and easy installation and dismantling without performing major adverse effects on the ground, and potentially reusing some of the parts afterward [157]. Fig. 8 **c and d** show the installation of the APV system.

For investigation purposes, various research groups apply different designs. Recently researchers from Belgium investigated vertical and single-axis APV in Grembergen, Belgium (51.02°N, 4.12°E). Row-to-row distances were 9 m apart so that farming machinery could be used. As the location was near a residential area, the height of the PV system structure was kept below 2.6 m. Single-axis tracker ranged between −50° (east) to + 50° (west) and was run by programmable logic control software tool. For both cases, PVs were bifacial type (Phono solar Half-cut PERC 455 Wp) with dimensions of 2.13 × 1 m and a bifacility factor of 0.7. PV mounting structure was made by using pile drilling which has an easy removal process as shown in Fig. 8 **e and f**. The depth of the foundation varied between 2 and 3.8 m depending on the soiling types [169]. The overall monitoring system is shown in Fig. 8 **g,h,i**.

One theoretical analysis was performed for the safety of the PV module structure for APV application [97]. In this work, the author considered steel steel-based structure for construction, PV module had a 30-degree tilt, the snow load was 0.42 kN/m^2, the wind load for PV was 0.77 kN/m^2 and the structure was 0.849 kN/m^2 [97]. Also, modules were kept in landscape and portrait orientation. The outcome showed that the APV system is vulnerable to wind load and structural failure depending on the spacing between two columns. Modules at a high distance from each other reduced the structural safety but enhanced the power generation for the low shading impact. If the column is narrower they are not advantageous for crop production and initial investment however good for power generation. Portrait mode produced more power than landscape mode.

The cost of the PV racking system is still expensive compared to the reduction of PV cell prices in this decade. Except for the metal-based mounting or racking structure, other alternatives are wooden-based racking [160,161]. Free -swinging bifacial PV systems for APV application were investigated using an open-source SAM energy performance tool. This free-swinging generated 12 % higher energy than a vertically fixed tilt PV in a case study location in Ontario, Canada, and showed 31 % lower Levelized Cost of Energy (LCOE) than a seasonally adjusted wood racking, commercial fixed-tilt metal racking and optimized fixed-tilt wood racking PV [75].

3. Theoretical and field experiments with APV systems

3.1. Software tools & fundamental equations for APV

Calculation/techniques to understand the APV

To understand the overall productivity of APV systems, land equivalent ratio (LER), land productivity factor (LPF), and price-performance ratio (PPR) are the three different methods that are often used.

The land equivalent ratio (LER) is shown in Equation (2).

$$LER = \left(\frac{Y_{cropAPV}}{Y_{monocrop}}\right) + \left(\frac{Y_{electricityAPV}}{Y_{electricityPV}}\right) \quad (2)$$

Where $Y_{cropAPV}$ indicates Grain yield in APV scenario (kg/m^2), $Y_{monocrop}$ indicates Grain yield in full light scenario (kg/m^2), $Y_{electricityAPV}$

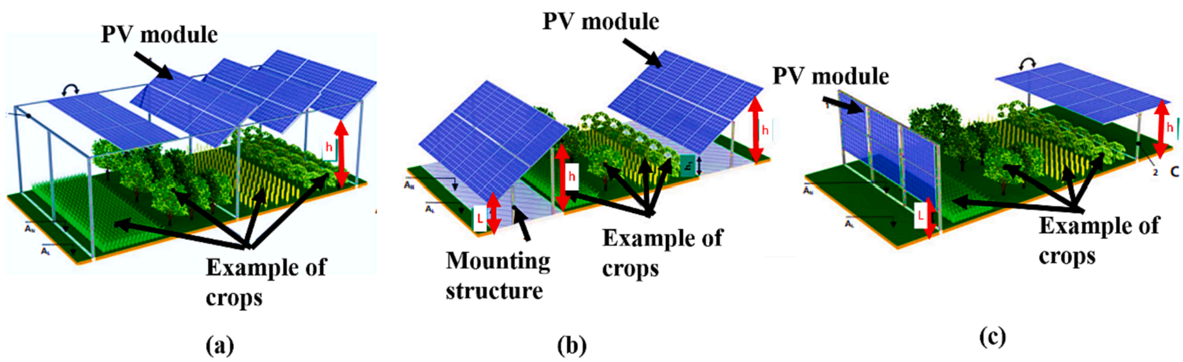

Fig. 7. Schematic illustration of APV systems design developed by DIN SPEC 91434. (a) Overhead PV with vertical clearance > 2.1 m, (b), & (c) Interspace PV with vertical clearance < 2.1 m. Image courtesy Fraunhofer ISE(Fraunhofer ISE, 2022) [55].

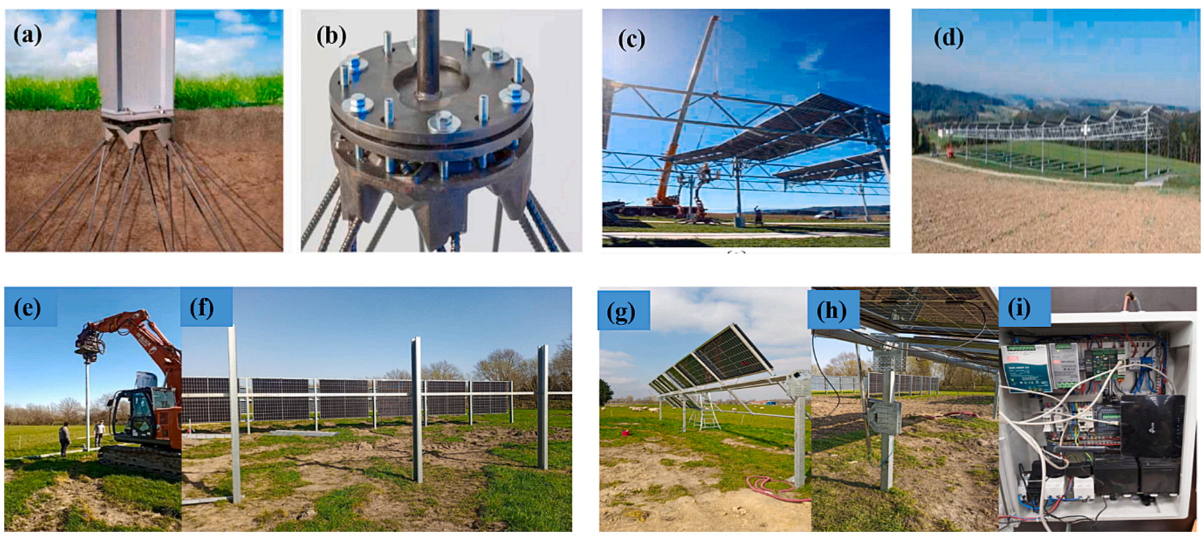

Fig. 8. (a) & (b) Tree root inspired Spinnanker, a concrete-free foundation for APV mounting structure [157] (c) cranes for lifting the PV systems during APV installation, [157] (d) final installation of APV in a farm land in southern Germany [157] Credit source: Fraunhofer ISE (e) pile drilling for PV structure installation [169] (f) steel structure for APV, [169] (g), (h), (i) APV step up and data monitoring process [169].

Electricity yield in APV scenario from PV (kWh/m^2), $Y_{electricityPV}$ Electricity yield in a ground-mounted scenario from PV (kWh/m^2).

LER > 1, APV design is more suitable than producing only energy or only crop from the land.

LER < 1 indicates that energy-food production is less productive than single production. The land losses need to be considered for efficient analysis as the land under the PV structure is not cultivated.

Land productivity factor (LPF) as shown in equation (3) was proposed by [132]where PAR stands for Photosynthetically Active Radiation

$$LPF = \left(\frac{PAR}{100}\right) + \left(\frac{Y_{electricityAPV}}{Y_{electricityPV}}\right) \quad (3)$$

Schindele et al. proposed PPR method [142] as shown in Equation (4)

$$ppr = \frac{p}{pb} \quad (4)$$

ppr = price performance ratio, p = price, p_b = performance benefitif ppr = 1, APV implementation is a reasonable investment, If ppr > 1; Not reasonable to support APV; If ppr < 1; If the price of maintaining cropland is lower than the economic performance of the same cropland (ratio less than 1, a result policymakers seek),

Theoretical analysis of the APV system needs software tools that can predict the overall performance before employing the real set-up. As the APV system includes both agriculture and PV, a combined tool or two separate tools are essential. For Crop yield evaluation various tools' names are listed in Table 4. For PV generation mostly used software is PVSyst and Helioscope.

The Simulateur mulTIdisciplinaire les Cultures Standard (STICS) crop model uses generic parameters suitable to extract for any crops. Crop yield at various conditions can be simulated here. Plants' growth, soil interaction, and water content in the soil, all could be managed [27]. [45] employed PVSYST for PV production and STICS for an agricultural production model. The investigated location was Kansas USA and their result found that 30 % enhancement of the economic value of the farm due to a lettuce-based APV system.

To understand the profit from the APV system, STICS simulation techniques for crop models were employed in a work in France. LER method, light transmission at the crop level due to the presence of PV, and production from partially shaded crops by using a crop model were used in the simulation tool. It was found that the use of APV can improve land productivity by as high as 60–70 % [46]. They also recommended the potential limit of STICS model which can't fully simulate crop production under dense shading.

The performance of an APV system in North Italy location was investigated using PV as a solar tracking system and maize as a crop. Crop growth simulator GECROS was employed while 40 years of climatic data were used. Panel density had a higher impact to have always LER > 1 than panel management (i.e. sun tracking or static PV). Reduced

Table 4
Tools that can be used for crop yield analysis.

Software tool	Possible Study	Reference/ source
APSIM (Agricultural Production Systems sIMulator)	Modelling and simulation of agricultural systems	APSIM
APEX (Agricultural Policy/ Environmental eXtender)	APEX can simulate one hundred different crops for hundreds of years	APEX
CROPWAT 8.0	Calculation of crop water requirements and irrigation requirements based on soil, climate and crop data	CropWat
CLIMWAT	Calculation of crop water requirements, irrigation supply and irrigation	CLIMWAT
DSSAT (Decision Support System for Agrotechnology Transfer)	Has the potential to simulate crop growth of over 42 different crops	DSSAT
GroIMP (Growth Grammar related Interactive Modeling Platform)	Modelling backbone' consists in the language XL For modelling and visualization, GroIMP provides a complete set of 3-d geometry	GroIMP
STICS (Simulateur mulTI-disciplinaire pour les Cultures Standard)	A generic crop growth model	STICS

radiation helped to keep the low soil temperature, eva-transportation, and water balance of the soil. Grain yield was higher in rain-fed conditions for the APV system than in open-air conditions. LER was always 1 for this system [11].

Based on the APV field trial data, a model for microclimate underneath the APV was developed by [106], 2013b, 2013c). They employed a measuring unit to measure air temperature, humidity, soil moisture and temperature, and solar radiation for an hourly interval to achieve temporal resolution. In addition, crop-specific parameters including crop cover rate, temperature, stomatal conductance, wind speed, and precipitation were also measured. Further, to have more precise temporal and spatial resolution, soil surfaces and rainwater distribution are also essential [48,49]. In another work, using digital twining and machine learning framework, a bifacial PV-based APV system is employed to explore the accelerated development of APV [177].

LCA analysis of an APV plant in the northwestern region was developed where the PV plant had a total capacity of 2 MW (5-ha plant, and power density of 400 kW/ha). Each hectare had 22,500 aloe vera plant. Detailed life cycle analysis including, cultivation to process of aloe vera, energy generation from PV, energy consumption off-grid and grid, greenhouse gas emission (GHG) and economic feasibility, the balance of system for PV plants, construction, operation, decommissioning and recycling were performed. The simulation result suggested that power generation from the APV system is significantly high and the grid tie option gives much economic value to the land owner. For aloe vera yield Monteclaro simulation was applied whereas for PV, the HOMER platform was employed [126]. Due to the infancy of the technology, it's hard for solar developers to understand the crop yield by varying different PV and layouts. To have success in APV this must be addressed by the researchers. Currently, SPADE is developed by Sandbox Solar which has the ability to work together with crop and PV [147,165].

3.2. Field, simulation, and prediction study of APV systems

Field experiment of the APV system has been investigated in the region including the USA, EU, and Asia. However, very little work is reported in the region of the UK. The reported work we evaluated was mostly taken from peer-reviewed journals.

Europe

To make Europe the first carbon–neutral continent by 2050, the 'European Green Deal plan' developed in 2020, created ambitious packages to mitigate climate change. Among them, one of the actions is the reduction of 55 % of greenhouse gas by 2030 [39]. Employing large-scale PV in terms of APV will definitely be one of the lucrative options. Though the first concept of the APV was developed in the EU region [66], the real application of APV is not massive in this region yet. Except, for Germany, France, and Italy the growth of APV is not widely available. Also, the research article which investigated the real work is also limited.

The real prototype of APV was investigated in Montpellier France (43.6°N, 3.9°E) France for a period from March 22nd, 2011 to August 31st, 2011 which counted the spring and summer of 2011. PV panels were mounted in an east–west direction and PV modules which were 0.8 m wide, mounted at a height of 4 m with 25° tilt [107], 2013c). PV panels were arranged in full density which offered 50 % sunlight, half density which allowed 70 % light and 100 % allowable sunlight. Four different types of lettuces including two crisphead lettuces (Varieties "Emocion" and "Model"), and two cutting lettuces (varieties "Kiribati and "Bassoon"). This APV system saved 14–29 % of Evatranspired water and this was impacted more than plant transpiration [106], 2013b, 2013c). Another APV system was built in 2019 at Seine et Marne, France (48.3°N, 2.84°E) which covered an area of 1440 m^2 to grow alfalfa biomass. After two years of the experiment, alfalfa biomass increased by an average of 10 % where the shade of the APV plant varied between 29 % – 44 % in comparison to full sunlight. Photovoltaic generation was reduced by 15 % due to the optimised tracking for plant growth. This combined production allowed to achieve an LER of 1.51 [47].

In Italy, one APV system in the PoValley with a tensile structures-based solar tracking system was patented with the name Agrovoltaico which had 1 MJ of electricity delivering capacity to the grid. The capital cost of the system was close to 1.5 Million euro which is due to the reason for the construction cost. LCOE was close to 90 euro/MWh which was 15 euros higher than roof-integrated PV and 5 euro higher than ground mounted. According to the author, this system can satisfy at least 14 SDGs out of 17 (partnership for the goal, quality of education, and gender equality were excluded) [5].

Four crops including celeriac, grass-clover, potato, and winter wheat were established under the APV system in Lake Constance in south–west Germany (47.85° latitude, 9.14° longitude, approx. 660 m above sea level) where bifacial south-west oriented PV had a capacity of 194 kWp. Corp yields were monitored from the start of 2017 to the end of 2018. PAR was reduced by about 30 % under the APV system while soil temperature was reduced during summer. Overall it was concluded that crop yield was reduced but in dry and hot conditions yield increased [166,157]. The first practical APV applications in Germany can be found in the Bavaria location. Since 2008, various crops have been growing under a PV system (height of 1.5 m) by an electrical engineering company, Guggenmos [157]. In 2013, the 28 kW capacity of the APV system was further introduced in Bavaria by the Weihenstephan-Triesdorf University of Applied Sciences to analyse the crop performance of pointed cabbage and Chinese cabbage [157]. In Germany, the growing of apples is particularly suffered from Hail storms. An economic study showed that APV in apple farms has the ability to abate the investment cost of farming by 26 % due to hail protection [156].

Three different APV configurations including single-axis horizontal tracking, static optimal tilt, and vertically mounted bifacial were investigated theoretically in the Denmark location. It was found that single-axis tracking and vertical produced higher uniform irradiance on the ground, and 30 W/m^2 capacity is suitable for APV. Later based on the same model, 100-m-resolution based on land cover APV in every region within the European Union was evaluated which showed 51 TW APV in Europe resulted in 71,500 TWh of electricity in a year [118].

In Sweden, bifacial PV was investigated for the APV application. It was recommended that bPV can be influential as its operative temperature is lower than the ground-mounted hence this can improve the overall power generation and the overall performance of the APV system will be improved [84].

In Belgium, single-axis and vertical bifacial PV-based APV were investigated for sugar beet cultivation. Results were collected for 2021 and 2022 which showed tracking PV performed superior compared to vertical fixed PV. 30 % energy yield and 20 % enhancement of lab use efficiency were also obtained from this APV [169].

Asia

In India at Odisha (20.1624° N, 85.7011° E), the APV system having a capacity of 0.675 kWp covering 11 m^2 land area produced 1.5 kg turmeric which is a shade-tolerant medicinal crop. The payback period was 9.49 years for this system while LER was 1.73, benefit-cost ratio 1.71, and price-performance ratio 0.72 [65]. Investigation of the APV system in Nashik, India showed that 30 % shade tolerant grape farming had 15 times higher production than the conventional method while the PV systems were Trina Solar 310 W TSM-310-PD14 polycrystalline silicon [105].

In Japan, an experimental APV system was investigated where a crop was rice. Japan's government (Japanese Ministry of Agriculture, Forestry and Fisheries) has a strict policy that anything on agricultural land is only possible if the rice yield is at least 80 %. For this, the shading element from APV is only possible up to 27–39 %. Thus, rice fields with 28 % PV density, can generate 284 million MWh/year. It was estimated that this power can meet 29 % of Japan's electricity demand based on 2018 energy consumption data [67]. Large-scale employment of APV technology for grid integration using rice paddy land in rural farming areas in Japan showed benefits compared to 35 % of the total cultivated land. For this study, the effect of battery storage and expanded transmission line capacities were also considered (using 8760 h temporal resolution) which did not bring any extra benefit for APV systems [68].

A case study in Shandong province, China (Latitude 36.43, Longitude 120.36) investigated five different PV greenhouses (Terraced-PVGs, Doubled film-column PVGs, Part-shaded spring PVGs, Part-shaded winter PVGs, Bricked winter PVGs) APV system which showed that 4–8 years discounted payback period and Annual Return on Investment (AROI) variation from about 9 % to 20 % [98].

In South Korea, rice production using APV was investigated. The capacity of this bifacial PV-based APV system was 107 kW which was located at the Jeollanamdo Agricultural Research and Extension Center in Naju-si (35.0272° N, 126.8247° E), Jeollanam-do, South Korea. APEX model was used to predict the outcome which had 88 % of preduction accuracy. Experimentally it was found that 32 % of the shading ratio for the bi-facial APV had the highest total profit of 3.65 USD/m^2/day [92].

In Asia, rice is one of the most valuable crops, particularly in Bangladesh, China, Indonesia, Japan, and Thailand. Rice is sensitive to shading hence developing APV is a challenge in this area. However vertically placed PV in an APV system for rice crops, yield can be significant. Recent theoretical work showed that high solar radiation locations such as Damietta in Egypt and Haryana, India, 22 to 115 times higher APV yield than those just producing rice [6].

USA

APV system within the Phoenix Metropolitan Statistical Area (MSA) was investigated using agricultural land, which has a 1-degree slope suitable for PV installation. Half panel density patterns in privately owned agricultural lands in the APS and SRP service territory can generate about 3.4 and 0.8 times the current total energy requirements of the residential using solar PV (Photovoltaics) systems thus reducing land commitment and preserving the agricultural land in the process. Farmers could grow Alfalfa, Cotton and Barley. Each farmland can generate about 600 MWh/acre per year with half-density panel distribution [104]. In another study in Arizona, experiments on APV system for south-facing PV panels having a tilt angle of 32 and 1 m of row spacing (32.578989 °N, 110.851103 °W, elevation 1,381 m above sea level) and 2 replicate plants of each of three agricultural species from the same family (Solanaceae) [17]. A bifacial PV-based APV system was investigated in Boston. Among the E-W vertical, S-N and E-W oriented APV, S-N faced system proved to be best for shade-tolerant crops while E-W is good for permanent crops. For APV design grasshopper and CAD model was employed, while radiance and daysim helped to analyse the irradiance model [88]. Life cycle analysis of sheep APV showed tremendous potential in the USA. 3.9 % less global warming potential was found for this type of PV integration compared to the traditional one. For grazing shifting sheep to PV farms can save 5.72E8 kg CO_2 per year [73]. A recent work investigated the microclimatic condition under APV using the CFD model. It was found that a PV system having a 4 m height above the ground for APV can keep the PV cell temperature 10 °C lower than a ground-mounted PV system having 0.5 m height above the ground [168].

Russia

APV potential in the southern region of the Russian Federation was investigated by [94]. Two different configurations of APV systems having 3.2 m and 6.4 m spacing between photovoltaic (PV) arrays were considered while the PV was 4 m above the crop. For simulation, the Krasnodar region was selected which has an average annual solar insolation of 4,20 kWh/m^2. With this radiation and 3.2 spacing, NPV was 558,277 USD while 6.4 m spacing gave 424,216 USD. The cost of energy was 0.7USD/kWh for 3.2 m spacing and 0.723USD/kWh for 6.4 m spacing [94].

Australia

Safat Dipta et al. [139] in vestigated the growth of tomato plants by using semi-transparent organic solar cells (24.6 % visible transmittance, 9.4 % efficient, active layer of PTB7-Th: IEICO-4F) and silicon PV-based APV greenhouses. It was evaluated theoretically that the use of organic solar PV can improve the production of tomatoes by 46 % more than standard Si PV greenhouses. For this analysis, ground-measured weather data was collected for the location of Geraldton in Australia while the crop was a tomato.

Africa

Land use and land cover is changing significantly in Africa [15]. Particularly in sub-Saharan, east, and west Africa, this is prominent. In this scenario inclusion of APV can be one of the beneficial options. The potential of APV was investigated for the Niger location which is in West Africa which has 23 million population according to 2019 data. Agricultural land availability is significantly low here which is only 35 % and the rest of the area is either used for the built environment or dessert. The LER was obtained at 1.13 and 1.33 for two including and excluding the shading included PV power production, respectively [25].

Table 5
Large-scale APV development in various parts globally.

Location	System Details (capacity; Location; Crop type)	Reference
Bangladesh	3.77 MW, Soudia Agro Solar PV Power Plant 12.5 acres of land in the Pabna	[80]
China	1GW near Yellow River in the Ningxia Crop: goji berries Panels are installed 2.5 m above the land.To date, this is the largest APV system globally.	[21]
France	111 kW, TotalEnergiers and InVivo	[123]
Italy	Research Project, Overall capacity is not available	[140]
Germany	2 MW German EPC contractor Goldbeck Solar Arc-shaped PV having 2.5–3 m height	[51]
Netherlands	2.7 MW PV plant near Arnhem Corps: blueberries, red currants, raspberries, strawberries, and blackberries	[22]
Saudi Arabia	Miral solar spin-off of KAUST developed foldable solar PV for APV application	[19]
South Korea	100 KW, Three villages Guryang-ri, Duseo-myeon, and Ulju-gun Rice Modules are having 4 m height	[20]

Table 5 listed various APV systems while Fig. 9 shows the image of those installations.

3.3. Solar PV for other agricultural applications

There are a few other ways where solar energy can be employed in agriculture applications which can help pollution reduction, and increase this sector's independence.

The water pump is an essential component of the agricultural land as shown in Fig. 10. Most often these water pumps are run by gird energy or oil which are not sustainable. The use of solar energy by using solar PV is an option to run these water pumps which is environmentally benign [81,36]. Solar photovoltaic water pumping (SPWP) consists solar PV system, a pump, and a motor. A battery storage facility with a charge controller is also possible if essential. The presence of a maximum power point tracker definitely boosts the efficiency of a solar-powered pumping system. Solar pumping system capacity depends on pressure, water flow, and pump power [114].

Presence of moisture, vegetables, and fruits are prone to damage and rot which creates significant monetary losses for the products. It is estimated that 25 %-30 % of the productivity is lost in post–harvest. Drying of those products can be an option and the use of solar technology for this drying is one the most suitable option. This will minimise the chance of fungus and germs growing on those vegetables and fruits. Dried one can be preserved for a long time without the use of any preservative. In addition, dried products reduce the packaging volume and weight and make the overall transportation and storage system easier and lower cost. Also, the use of solar drying methods offers a way to process fruits and vegetables without the consumption of any electricity.

4. Challenges and potential possibilities of APV

The progress of APV depends on various factors which are expanded on in this section. The nexus between land use and energy, the knowledge gap between various sectors, APV for rural electrification, and economic aspects are described in detail here.

Fig. 9. APV application in different countries.

Fig. 10. Solar power water pump and drying system.

4.1. Land and energy nexus

Food is the primary and essential need for humans and 38 % of terrestrial land is under use for food production [111]. Food demand has increased twice due to the rapid growth of the population. However, there is still some place where food is not available. Particularly the African continent where 264.2 million people are still undernourished [24]. UN has a strict plan that by 2030 achieve zero hunger and provide food to all. In this context, more food production by using the land is essential. One of the main obstacles to using land for food production is urbanization [176]. Fig. 11 shows how the land capacity is reducing every decade. It is unforgettable that if food is essential then agriculture is the main resource of that food and land is a key foundation for agriculture.

On the other hand deployment of Renewable energy is now gaining a higher pace to tackle the global climatic condition. After 2021, some member states in the EU raised their target to generate more electricity from renewable sources. For example, Ireland's National Development Plan now set a plan to contribute 80 % share in renewable electricity while Italy's Ministry of Ecological Transition proposed 72 % of renewable electricity [78]. The European Union (EU) has considerably enhanced the solar PV deployment strategy. Previously it was 300GW and 500GW of solar PV installed in capacity by 2028 and 2030 respectively. After the war between Russia and Ukraine [93,150], the new target is 320 GWac/400 GWdc and 600GWac/700GWdc by 2025 and 2030 as their new strategy is to not use any oil and gas from Russia [78]. In the USA, 75 % or over 280 GW of renewable energy (solar and wind mainly) capacity is expected to be installed from 2022 to 2027. Though Solar PV takes higher land coverage still its positive attributes are not inevitable. Thus, almost all the major continents consider PV installation to enhance renewable energy capacity to achieve zero emissions. In addition, improvement is going on with PV efficiency hence in a couple of years space coverage may not be a challenge for solar PV.

Because of the land issue and maintaining the food generation APV is the best choice. However, solar PV integration into buildings such as BIPV and rooftops is also in consideration [58,137]. Also nowadays PV integration using water bodies is also common [40,53]. Indeed, Building alone can't make the EU region PV-dependent unless all the other

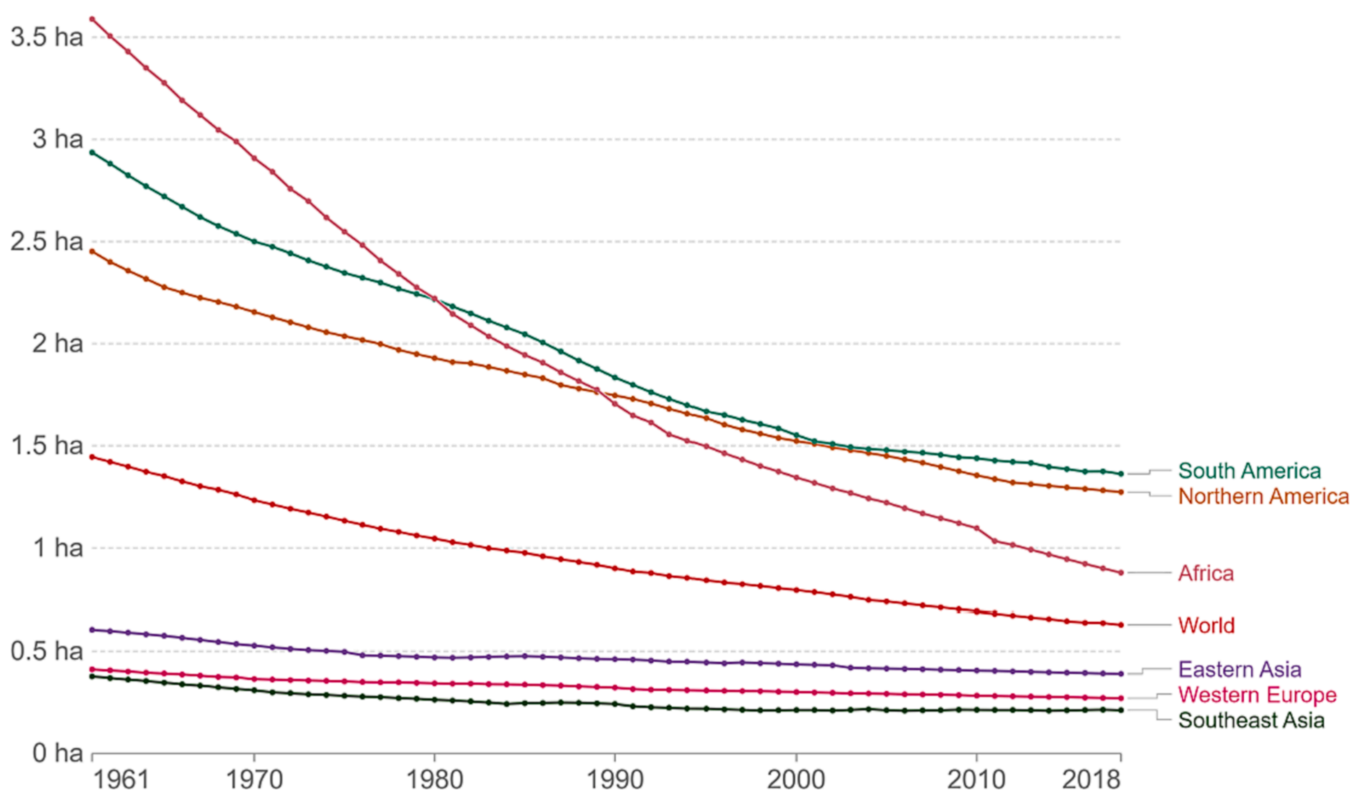

Fig. 11. Agricultural land per capita Agricultural land is the sum of cropland and land used as pasture for grazing livestock. Source our world in data.

integrations (water, agri, vehicle) are considered [113]. APV application is popular, particularly in some parts of Europe (Germany, France, and the Netherlands) and Asia (Japan, China, and India) but a more rigorous effort is crucial. APV has a high potential in India, because of the high solar irradiation, the second most populous country after China with a high population density (424 people/ square kilometre). Also, 60 % of the land is used in India for agriculture [72,122]. Recently researchers from South Korea suggested combining rooftop BIPV with APV application which can be promising in the future [91]. In a case study, the use of 105 km^2 of (854,000 number of rooftops) urban rooftops in Shenzhen, China, could produce 9.84 × 105 tonnes/year of lettuce to fulfil the whole city's demand, while, the installed 2106 MW solar PV was produced on average with 1899 GWh/year electricity. This generation met 0.2 % of the whole city's electricity demand [83].

The introduction of APV has significant positive attributes, particularly from the farmer's point of view. The real added values include the food, energy, and economic benefits of the landowner. To mitigate food and energy insecurity, poverty-alleviation programs using solar energy are useful. From 2010 to 2019, an 82 % reduction in solar PV costs was experienced and in addition, the use of sunlight hours exceeded 1200 h for most countries [173]. However, to achieve net zero emissions by 2050 average annual PV generation growth should be 25 % in the period 2022–2030.

4.2. Knowledge gap & public acceptance

The real challenge in the APV sector is that there is definitely a gap in knowledge in both sectors (energy and agriculture). It is evident that Solar PV researchers do not possess a concrete knowledge of agriculture likewise agricultural researchers do not possess knowledge of the PV system. Thus, cross/interdisciplinary knowledge sharing is essential to have better success in the future. Except for a few countries (Japan, Germany, Italy), most of the countries don't have any scheme or regulation or policy for APV. More knowledge exchange should be taken place. Initiatives should come from different ministries such as finance, energy, and agriculture. Local land use policies are not often clear which is one of the bottlenecks for the growth of APV. Awareness of these can also help significantly for those countries that are under the low economic zone where theft of PV panels is common [16]. The economic analysis of APV implementation worldwide is very crucial for the farmers, research & development, and investors.

Landscape issue for APV application is not widely studied but one study argued that this can have potential issues and can be an obstacle to public acceptance. APV can have a negative impact due to the elevated PV structure on the natural landscape This elevation is clearly visible from a distance [146]. Table 6 listed the scope to mitigate challenges from APV by improving design and technology.

Table 6
Scope to mitigate challenges from APV by improving design and technology.

Challenges	Solution by improved design	Solution by improved technology
Maximize electricity generation	Tilt angle close to latitude Avoid shading from the other modules and crops	Semi-transparent type PV, LSC can be helpful.
Maximize crop production	Need knowledge of shade-tolerant and intolerant crops. Depending on the crops PV can be selected for vertical or tilted orientation	If the crops are shade intolerant, the choice should be vertical bifacial PV.In shade-tolerant crops, suitable semi-transparent PV is needed.
Public acceptance	Lower reflection and more improved design are essential.	Finding appropriate crops for the location and based on the light requirement choosing the PV

4.3. APV for rural electrification

Globally, supplying grid electricity to rural locations is a particular challenge. Countries such as the African continent [13] and South East Asia face this trouble and many are still under no electricity or partly electricity conditions. On the other hand, electrifying the transport sector is also growing simultaneously and is of utmost priority for most of the countries. Most often travellers from urban places use EVs but lack interest in using them for the long run and specifically to go to rural locations [60,124]. Also, the investigation of the use of EVs in rural areas is very limited [85].

Both issues can be solved by employing APVs in rural locations. To electrify rural locations, off-grid small or large-scale renewable energy sources can be potential, and solar energy particularly can be the best solution [116,117]. In rural areas where the agricultural land capacity is higher, developing large-scale solar parks is an issue that can be mitigated by employing APV systems [154]. The presence of APVs can supply electricity to those areas. On the other hand, for a battery EV, a charging facility is essential. Most of the EV charging stations are powered by grid electricity. However, PV systems can also be a source for this type of charging station [12,128,28,164]. There is a possibility to charge EV charging stations with APV systems as well. In this way, customer unwillingness to drive EVs in rural areas will be reduced.

A recent investigation in the Philippines showed that 10 % of APV integration in the Philippines can produce 95.75 TWh energy which can eliminate even the official carbon emission target of the country [69]. A simulation study of the village of Dar Es Salam in Niger west Africa showed that the installation APV system can produce 323 kWh/ year energy which can be potential to supply the electricity of a village having 400 households [25]. Agir et al. [4] conducted real-time interviews with farmers in Turkey to investigate the perspective of APV. Farmers showed a positive attitude towards APV as they believed that APV would reduce the grid power dependency. Crop production and power generation in the same land concomitantly will enhance their overall income.

4.4. Economic aspect

Financial and economic analysis on APV is very limited. In addition, economic viability is investigated with only a few corps. APV needs long-term investment while most analysis has concentrated on short-term outcomes. The degradation of PV due to long-term exposure to outdoor conditions should also be into consideration. A universal framework for any location and any type of APV system will be beneficial however due to the use of various types of crops and PV, this is a hard task. Fig. 12 shows the estimated cost analysis using LCOE for various ground-mounted and APV systems that are suitable for Germany. It seems that APV for arable farming has higher LCOE than ground-mounted PV. The costs for APVs are variable factors and depend highly on the installed capacity of PV, type of used PV systems, agricultural activity, and position. In general, the acquisition cost is usually higher compared to a conventional ground-mounted PV system as it needs a higher substructure to place the PV modules. The spacing between the two PV systems and the clearance height both contribute significantly to the substructure cost. The use of more manual activities or smaller machinery for farming can abate the overall cost for APV. Perennial row crops also provide cost advantages, because the substructure posts can be integrated into the rows with no appreciable loss of acreage.

5. Discussion & perspective

This section will discuss the policy for APV's growth, APV's relation to SDG, the future market for APV, and the perspective for the progression of APV.

Policy

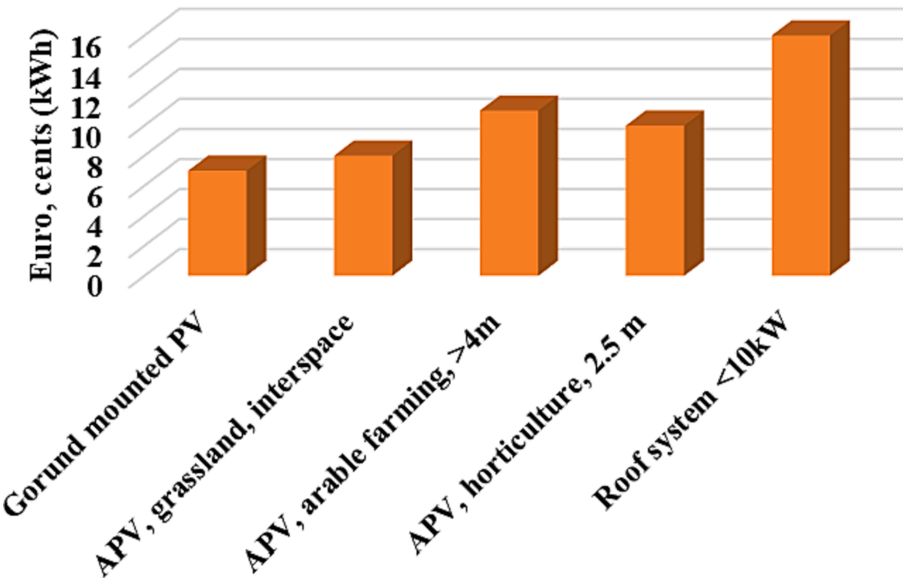

Fig. 12. Comparison of estimated levelized costs of electricity (LCOE) for APV and ground-mounted PV. Redrawn from [76].

A tangible policy is a precondition to the further development of APV and success in the future. Presently no international standard is present to guide the installation process of APV systems. Recently only Germany developed a new technical specification DIN SPEC 91434 [1] which seems to be too site-specific [50]. The primary factor that must be kept in mind is that during the making of standards, the inclusion of agriculture and PV should be done concomitantly. The different plant has different light-absorbing capacity. Farmers must be at the centre of APV developments. To boost this sector, at the beginning subsidy scheme can be started. Such an approach can definitely benefit the farmer's income and draw attention to PV and agriculture both sectors. In countries like India, government schemes are present such as Pradhan Mantri Kisan Urja Kisan Suraksha Evam Utthan Mahabhiyan where farmers can get support for solar power pumps for farming. From 2019 this scheme will be available where farmers in the barren land can get support to install up to 10,000 MW of solar pumps. This will definitely help to achieve India's 2050 non-fossil fuel energy generation target. A similar concept can be adopted for APV as well. French Standardization Association only allows land for APV if the reference yield from that land is a minimum of 80 % which is also the case for Japan. In Germany, according to DIN SPEC 91434 this is 66 %. In 2022, Italy published "Guidelines for The Design, Construction, and Operation of Agrovoltaic Plants" which clearly indicates that for APV 70 % of the area must have solar PV. A similar type of written criteria is useful for landowners or business developers to select the land for APV. A recent work reviewed and commented that the existing policies for land legislation, frameworks, and guidelines for land utilization can be used for APV by changing slightly [81]. However, trouble will still be there in developing a universal policy as the APV projects differ from country to country and one single criterion will not be suitable for every country.

Relation to SDG

APV is probably one of the best suitable PV technologies that satisfies at least two SDGs directly by generating benign electricity (SDG 7) and producing food (SDG 2), abating the competition between land for energy and food. In addition, APV maintains a satisfactory relationship between irrigation water saving, crop production, and electricity production. APV also opens up the possibility of engaging women in social development (SDG 5 & 8). In rural areas where land is available for agriculture, the inclusion of the APV system create a micro business that can offer job opportunities for women worker. In India, in one village in Gujrat state, this scope has already been proven. For this particular APV, 215 people from four villages in Aravali foothills got a job [121]. Conventional solar farms stop agricultural employment which is not the case for the APV as the presence of agriculture jobs is secured. Also, it helps farmers to improve the food miles and provide fresh food. Fresh food definitely has health benefits, but APV, offsets pollution that is directly also linked to human health. APV reduces land area conflicts which counteract the development of non-developed land for green energy purposes and farming. Thus, it also targets SDG 15 which tackles Life on land. As APV opens up new research and developments, there is a scope to enhance the industry with innovation that can meet SDG 9. Integration of agriculture and energy will facilitate sustainable food production in a responsible way which can meet SDG 12 (Responsible consumption).

Future market

Allied Analytics which is an India-based market research company, forecasted that APV will be a market of USD 9.3 billion by 2031. Its compound annual growth rate (CAGR) will be 10.1 % from now to 2030. According to them, the major market developers are BayWa, Enel Green Power, Insolight SA, JA Solar, Mirai Solar, Namaste Solar, Ombrea, Sun'Agri and Next2Sun, Sunseed APV [130].

Precedence market research group predicted that by 2030 the global APV market share will be close to 8.9 billion USD having a CAGR of 12.15 % as shown in Fig. 13. Another market research group MarkeNtel also forecasted by using historical data from 2017 to 2020 and predicted that by 2027 the CAGR will be 38 %. [3]. "UnivDatos Market insights" a market research group predicted a 45 % CAGR during the forecasted year of 2021–2027. Hence, it is clearly evident from all the market research groups that the APV system has huge significance and in the future, more and more installation is expected globally [79].

Perspective: To have better success in APV, consistent support for every APV project is essential. Communication between various sectors such as location finding, geospatial panning, and PV experts all must work together in a fast-track mode. APV has a win–win possibility hence it is a combination of energy-food security, conserving water, offering reliability and independence, and helping to mitigate climate change. Thus helping to meet all the SDGs. It is undoubtedly said that Research and Development, Education and awareness of the community, strict regulation and policies for APV technology, standards for APV technology application, and financial incentives for adopting APVs are essential policies for promoting APV development. APV works as an interface between two central systems and a lack of understanding of "the other system" is a key barrier to APV diffusion. The environmental and ecological impact study is also essential for APV. However, the use

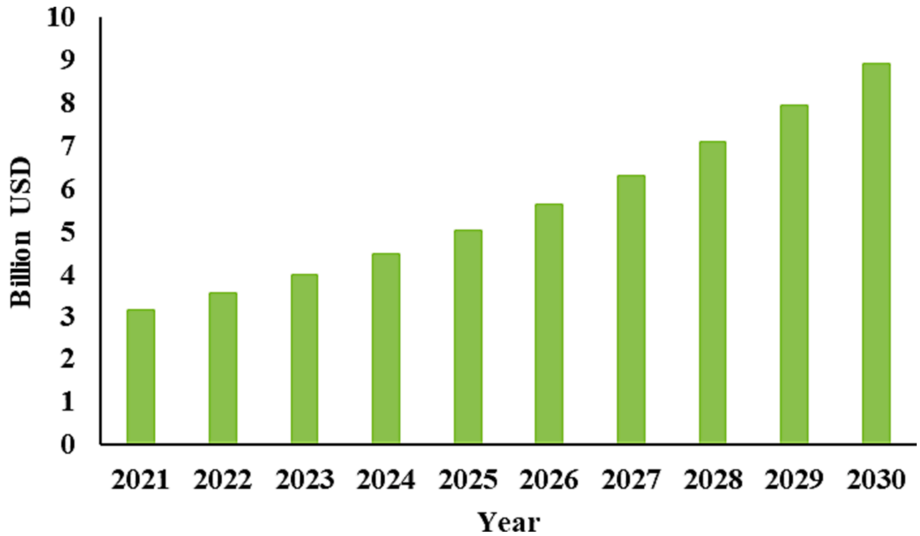

Fig. 13. APV market size according to Precedence Research. (Research, 2022) [131].

of LER is often criticized because the reference case, converting farmland to a regular PV park is not actually allowed. LER does not consider investment costs and is not a useful parameter for decision-making. LER assigns equal justification for crop and PV. If LER is higher, means one is increasing by abating the value for the other which should not be the case. Also if ecovoltaics are considered how PV panel will have an impact on humidity, radiation balance temperature, turbulence and wind turbulence inside and outside PV systems are still an area that must have deeper attention. Ground-mounted solar has the lowest installation costs and is ideal for fast deployment on large scale, but requires land which, in contrast to roof-mounted solar, has value for other purposes, spanning from agriculture and forestry to recreational, aesthetical, and preservation of natural habitats which must be appreciated for APV. For rural electrification with an off-grid system, APV can be the best option.

6. Conclusions

In this work, a comprehensive review based on the agrivoltaic/ agriphotovoltaic (APV) system has been performed focusing on its implication for the United Nations SDG goals. Agrivoltaic/agriphotovoltaics (APV) are probably one of the best solutions in the near future where food security and energy security both can be achieved by using single land. Though APV is promising and can meet the majority of the SDG goals, the nexus between the production of electricity production, crops, and savings of irrigation water must need further investigation through R&D and pilot schemes. Bifacial vertically placed PV or semi-transparent PVs can be the best-suited PV system for APV application. Shade tolerant and intolerant both need photosynthetically active radiation (PAR) at a certain level for the growth of the crops. Low-cost PV mounting which is also beneficial for agricultural land must be in priority for APV design.

So far the limitations of APV systems are

- Technological barriers: Due to the high initial cost, combined robust integrated PV-crop simulation software tool development is essential which will give liberties to the solar researcher and farmers and other stakeholders a clear forecasted analysis for the farms before real experiment or investment.
- Economic barriers: Overall cost analysis is missing from most of the APV studies. Also, LCOE is the only study that has been considered in a few studies for economic analysis. Considering PV degradation and crop rotation more depth study is essential. This will also be beneficial for societal factor
- Societal barriers: Huge initial costs and blocked landscape will definitely be a factor that will demotivate most of the agricultural land owners. In this context, a strict policy and government support will definitely help and full economic benefits availability will also help them to understand the APV scenario.

Undoubtedly the current global energy crisis and its growing challenges can be solved by employing the APV system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Agri-photovoltaic systems – Requirements for primary agricultural use English translation of DIN SPEC 91434:2021-0. https://doi.org/https://www.agrivoltaics.in/_files/ugd/0c91be_10d7b0628c4042048cc6f44e9762f0d3.pdf.

[2] M.A.Z. Abidin, M.N. Mahyuddin, M.A.A.M. Zainuri, Solar photovoltaic architecture and agronomic management in agrivoltaic system: a review, Sustain. 13 (2021) 18–21.

[3] Advisors, M., 2022. Global Agrivoltaics Market Research Report: Forecast (2022-2027) [WWW Document]. https://doi.org/https://www.marknteladvisors.com/research-library/agrivoltaic-market.html.

[4] S. Agir, P. Derin-Gure, B. Senturk, Farmers' perspectives on challenges and opportunities of agrivoltaics in Turkiye: An institutional perspective, Renew. Energy 212 (2023) 35–49, https://doi.org/10.1016/j.renene.2023.04.137.

[5] A. Agostini, M. Colauzzi, S. Amaducci, Innovative agrivoltaic systems to produce sustainable energy: An economic and environmental assessment, Appl. Energy 281 (2021), 116102, https://doi.org/10.1016/j.apenergy.2020.116102.

[6] M.S. Ahmed, M.R. Khan, A. Haque, M.R. Khan, Agrivoltaics analysis in a techno-economic framework : Understanding why agrivoltaics on rice will always be profitable, Appl. Energy 323 (2022), 119560, https://doi.org/10.1016/j.apenergy.2022.119560.

[7] A.A.G. Al-Shammary, A. Kouzani, Y. Gyasi-Agyei, J. Rodrigo-Comino, A comparison of different solarisation systems and their impacts on soil thermal characteristics—an application in cultivated soils close to Baghdad, a highly populated city in Iraq, Environ. Monit. Assess. 192 (2020), https://doi.org/10.1007/s10661-019-7985-z.

[8] M.A. Al Mamun, P. Dargusch, D. Wadley, N.A. Zulkarnain, A.A. Aziz, A review of research on agrivoltaic systems, Renew. Sustain. Energy Rev. 161 (2022), 112351, https://doi.org/10.1016/j.rser.2022.112351.

[9] Ali Abaker Omer, A., Liu, W., Li, M., Zheng, J., Zhang, F., Zhang, X., Osman Hamid Mohammed, S., Fan, L., Liu, Z., Chen, F., Chen, Y., Ingenhoff, J., 2022. Water evaporation reduction by the agrivoltaic systems development. Sol. Energy 247, 13–23. https://doi.org/10.1016/j.solener.2022.10.022.

[10] H. Alrashidi, A. Ghosh, W. Issa, N. Sellami, T.K. Mallick, S. Sundaram, Evaluation of solar factor using spectral analysis for CdTe photovoltaic glazing, Mater. Lett. 237 (2019) 332–335, https://doi.org/10.1016/j.matlet.2018.11.128.

[11] S. Amaducci, X. Yin, M. Colauzzi, Agrivoltaic systems to optimise land use for electric energy production, Appl. Energy 220 (2018) 545–561, https://doi.org/10.1016/j.apenergy.2018.03.081.

[12] Amir, M., Zaheeruddin, Haque, A., Bakhsh, F.I., Kurukuru, V.S.B., Sedighizadeh, M., 2023. Intelligent energy management scheme-based coordinated control for reducing peak load in grid-connected photovoltaic-powered electric vehicle charging stations. IET Gener. Transm. Distrib. https://doi.org/10.1049/gtd2.12772.

[13] A.O. Amole, S. Oladipo, O.E. Olabode, K.A. Makinde, P. Gbadega, Analysis of grid/solar photovoltaic power generation for improved village energy supply: A case of Ikose in Oyo State Nigeria, Renew. Energy Focus 44 (2023) 186–211, https://doi.org/10.1016/j.ref.2023.01.002.

[14] Andrew, A.C., Higging, C.W., Bionaz, M., E.t.al., 2021. Pasture Production and Lamb Growth in Agrivoltaic System. AIP Conf. Proc. 060001.

[15] E.S.P. Assede, H. Orou, S.S.H. Biaou, C.J. Geldenhuys, F.C. Ahononga, P. W. Chirwa, Understanding Drivers of Land Use and Land Cover Change in Africa: A Review, Curr. Landsc. Ecol. Reports 8 (2023) 62–72, https://doi.org/10.1007/s40823-023-00087-w.

[16] C.L. Azimoh, F. Wallin, P. Klintenberg, B. Karlsson, An assessment of unforeseen losses resulting from inappropriate use of solar home systems in South Africa, Appl. Energy 136 (2014) 336–346, https://doi.org/10.1016/j.apenergy.2014.09.044.

[17] G.A. Barron-gafford, M.A. Pavao-zuckerman, R.L. Minor, L.F. Sutter, I. Barnett-moreno, D.T. Blackett, M. Thompson, K. Dimond, A.K. Gerlak, G.P. Nabhan, J. E. Macknick, food – energy – water nexus in drylands, Nat. Sustain. 2 (2019), https://doi.org/10.1038/s41893-019-0364-5.

[18] A.S.R. Bati, Y.L. Zhong, P.L. Burn, M.K. Nazeeruddin, P.E. Shaw, M. Batmunkh, Next-generation applications for integrated perovskite solar cells, Commun. Mater. 4 (2023) 1–24, https://doi.org/10.1038/s43246-022-00325-4.

[19] E. Bellini PV shade screens for greenhouses, agrivoltaics PV Mag. https:// 2022 doi.org/https://www.pv-magazine.com/2022/11/28/pv-shade-screens-for-greenhouses-agrivoltaics/.

[20] E. Bellini Agrivoltaics for rice growers PV Mag. https:// 2022 doi.org/https://www.pv-magazine.com/2022/05/30/agrivoltaics-for-rice-growers/.

[21] E. Bellini Giant agrivoltaic project in China PV Mag. https:// 2020 doi.org/https://www.pv-magazine.com/2020/09/03/giant-agrivoltaic-project-in-china/.

[22] E. Bellini Special solar panels for agrivoltaics PV Mag. https:// 2020 doi.org/https://www.pv-magazine.com/2020/07/23/special-solar-panels-for-agrivoltaics/.

[23] M. Benedetti, V. Vecchi, S. Barera, Dall'Osto, L.,, Biomass from microalgae: The potential of domestication towards sustainable biofactories, Microb. Cell Fact. 17 (2018) 1–18, https://doi.org/10.1186/s12934-018-1019-3.

[24] F. Beyene, M. Senapathy, E. Bojago, T. Tadiwos, Rural household resilience to food insecurity and its determinants : Damot Pulasa district, Southern Ethiopia. J. Agric. Food Res. 11 (2023), 100500, https://doi.org/10.1016/j.jafr.2023.100500.

[25] S.N. Bhandari, S. Schlüter, W. Kuckshinrichs, H. Schlör, R. Adamou, R. Bhandari, Economic feasibility of agrivoltaic systems in food-energy nexus context: Modelling and a case study in niger, Agronomy 11 (2021), https://doi.org/10.3390/agronomy11101906.

[26] S.E. Bilodeau, B. Wu, A. Rufyikiri, S. Macpherson, M. Lefsrud, An Update on Plant Photobiology and Implications for Cannabis Production, Front. Plant Sci. 10 (2019), https://doi.org/10.3389/fpls.2019.00296.

[27] N. Brisson, C. Gary, E. Justes, R. Roche, B. Mary, D. Ripoche, D. Zimmer, J. Sierra, P. Bertuzzi, P. Burger, F. Bussie, C. He, An overview of the crop model, Eur. J. Agron. 18 (2003) 309–332.

[28] A. Caines, A. Ghosh, A. Bhattacharjee, A. Feldman, The grid independence of an electric vehicle charging station with solar and storage, Electron. 10 (2021) 1–20, https://doi.org/10.3390/electronics10232940.

[29] P.E. Campana, B. Stridh, S. Amaducci, M. Colauzzi, Optimisation of vertically mounted agrivoltaic systems, J. Clean. Prod. 325 (2021), 129091, https://doi.org/10.1016/j.jclepro.2021.129091.

[30] F.J. Casares de la Torre, M. Varo-Martinez, R. López-Luque, J. Ramírez-Faz, L. M. Fernández-Ahumada, Design and analysis of a tracking / backtracking strategy for PV plants with horizontal trackers after their conversion to agrivoltaic plants, Renew. Energy 187 (2022) 537–550, https://doi.org/10.1016/j.renene.2022.01.081.

[31] S. Castellano, Photovoltaic greenhouses : evaluation of shading effect on co m m er c ia l us e on on l, J. Agric. Eng. XLV. (2014), https://doi.org/10.4081/jae.2014.433.

[32] S. Castelletto, A. Boretti, Luminescence solar concentrators: A technology update, Nano Energy 109 (2023), 108269, https://doi.org/10.1016/j.nanoen.2023.108269.

[33] Y.N. Chanchangi, A. Ghosh, H. Baig, S. Sundaram, T.K. Mallick, Soiling on PV performance influenced by weather parameters in Northern Nigeria, Renew. Energy 180 (2021) 874–892, https://doi.org/10.1016/j.renene.2021.08.090.

[34] Y.N. Chanchangi, A. Ghosh, L. Micheli, E.F. Fernández, S. Sundaram, T. K. Mallick, Soiling mapping through optical losses for Nigeria, Renew. Energy 197 (2022) 995–1008, https://doi.org/10.1016/j.renene.2022.07.019.

[35] Y.N. Chanchangi, A. Ghosh, S. Sundaram, T.K. Mallick, Angular dependencies of soiling loss on photovoltaic performance in Nigeria, Sol. Energy 225 (2021) 108–121, https://doi.org/10.1016/j.solener.2021.07.001.

[36] S.S. Chandel, M.N. Naik, R. Chandel, Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies, Renew. Sustain. Energy Rev. 49 (2015) 1084–1099, https://doi.org/10.1016/j.rser.2015.04.083.

[37] Z. Chen, A. Ghosh, N.S.A. Lopez, Optimisation of a standalone photovoltaic electric vehicle charging station using the loss of power supply probability, Heliyon 9 (2023) e20836.

[38] R.Y. Chock, B. Clucas, E.K. Peterson, B.F. Blackwell, D.T. Blumstein, K. Church, E. F. Gabriel, F. Alison, P. Kemp, G.M. Pinho, P.M. Sanzenbacher, Evaluating potential effects of solar power facilities on wildlife from an animal behavior perspective, Conserv. Sci. Pract. 1–11 (2021), https://doi.org/10.1111/csp2.319.

[39] Commission, E., 2020. European Green Deal: New financing mechanism to boost renewable energy. https://doi.org/https://commission.europa.eu/news/european-green-deal-new-financing-mechanism-boost-renewable-energy-2020-09-17_en.

[40] E. Cuce, P.M. Cuce, S. Saboor, A. Ghosh, Floating PVs in Terms of Power Generation, Environmental Aspects, Market Potential, and Challenges, Sustain. 14 (2022) 2626.

[41] R.I. Cuppari, C.W. Higgins, G.W. Characklis, Agrivoltaics and weather risk : A diversification strategy for landowners, Appl. Energy 291 (2021), 116809, https://doi.org/10.1016/j.apenergy.2021.116809.

[42] A.M. Detweiler, C.E. Mioni, K.L. Hellier, J.J. Allen, S.A. Carter, B.M. Bebout, E. E. Fleming, C. Corrado, L.E. Prufert-Bebout, Evaluation of wavelength selective photovoltaic panels on microalgae growth and photosynthetic efficiency, Algal Res. 9 (2015) 170–177, https://doi.org/10.1016/j.algal.2015.03.003.

[43] M. Dhonde, K. Sahu, V.V.S. Murty, The application of solar-driven technologies for the sustainable development of agriculture farming: a comprehensive review, Rev. Environ. Sci. Biotechnol. 21 (2022) 139–167, https://doi.org/10.1007/s11157-022-09611-6.

[44] T.J. Dijkman, R.M.J. Benders, Comparison of renewable fuels based on their land use using energy densities, Renew. Sustain. Energy Rev. 14 (2010) 3148–3155, https://doi.org/10.1016/j.rser.2010.07.029.

[45] H. Dinesh, J.M. Pearce, The potential of agrivoltaic systems, Renew. Sustain. Energy Rev. 54 (2016) 299–308, https://doi.org/10.1016/j.rser.2015.10.024.

[46] C. Dupraz, H. Marrou, G. Talbot, L. Dufour, A. Nogier, Y. Ferard, Combining solar photovoltaic panels and food crops for optimising land use : Towards new agrivoltaic schemes, Renew. Energy 36 (2011) 2725–2732, https://doi.org/10.1016/j.renene.2011.03.005.

[47] S. Edouard, D. Combes, M.V. Iseghem, M. Ng, W. Tin, A.J. Escobar-guti, Increasing land productivity with agriphotovoltaics : Application to an alfalfa field, Appl. Energy 329 (2023), https://doi.org/10.1016/j.apenergy.2022.120207.

[48] Y. Elamri, B. Cheviron, J. Lopez, C. Dejean, G. Belaud, Water budget and crop modelling for agrivoltaic systems : Application to irrigated lettuces, Agric. Water Manag. 208 (2018) 440–453, https://doi.org/10.1016/j.agwat.2018.07.001.

[49] Elamri, Y., Cheviron, B., Mange, A., Dejean, C., Liron, F., Belaud, G., 2017. Rain concentration and sheltering effect of solar panels on cultivated plots. Hydrol. Earth Syst. Sci.

[50] Emre, O., Ketzer, D., Weinberger, N., Ro, C., 2022. Agrivoltaics : solar power generation and food production. https://doi.org/10.1016/B978-0-323-89866-9.00012-2.

[51] Enkhardt, S., 2021. Arc-shaped PV system for agrivoltaics from Germany. PV Mag. https://doi.org/https://www.pv-magazine.com/2021/07/23/arc-shaped-pv-system-for-agrivoltaics-from-germany/.

[52] Essahili, O., Ouafi, M., Moudam, O., 2022. Recent progress in organic luminescent solar concentrators for agrivoltaics: Opportunities for rare-earth complexes. Sol. Energy 245, 58–66. https://doi.org/10.1016/j.solener.2022.08.054.

[53] L. Essak, A. Ghosh, Floating photovoltaics: a review, Clean Technol. 4 (2022) 752–769.

[54] B. Figgis, V. Bermudez, J.L. Garcia, PV module vibration by robotic cleaning, Sol. Energy 250 (2023) 168–172, https://doi.org/10.1016/j.solener.2022.12.049.

[55] Fraunhofer ISE, 2022. Agrivoltaics: Opportunities for Agriculture and the Energy Trans. https://doi.org/https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/APV-Guideline.pdf.

[56] M. Frolova, J. Li, Energy Research & Social Science Conceptualizing the patterns of land use conflicts in wind energy development : Towards a typology and implications for practice, Energy Res. Soc. Sci. 95 (2023), https://doi.org/10.1016/j.erss.2022.102907.

[57] A. Ghosh, A comprehensive review of water based PV : Flotavoltaics, under water, offshore & canal top, Ocean Eng. 281 (2023), 115044, https://doi.org/10.1016/j.oceaneng.2023.115044.

[58] A. Ghosh, Fenestration integrated BIPV (FIPV): A review, Sol. Energy 237 (2022) 213–230, https://doi.org/10.1016/j.solener.2022.04.013.

[59] A. Ghosh, Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: A comprehensive Review, J. Clean. Prod. 123343 (2020), https://doi.org/10.1016/j.jclepro.2020.123343.

[60] A. Ghosh, Possibilities and Challenges for the Inclusion of the Electric Vehicle (EV) to Reduce the Carbon Footprint in the Transport Sector : A Review, Energies 13 (2020) 2602.

[61] A. Ghosh, Soiling Losses : A Barrier for India ' s Energy Security Dependency from Photovoltaic Power, Challenges 11 (2020) 1–9, https://doi.org/10.3390/challe11010009.

[62] A. Ghosh, S. Bhandari, S. Sundaram, T.K. Mallick, Carbon counter electrode mesoscopic ambient processed & characterised perovskite for adaptive BIPV fenestration, Renew. Energy 145 (2020) 2151–2158, https://doi.org/10.1016/j.renene.2019.07.119.

[63] A. Ghosh, P. Selvaraj, S. Sundaram, T.K. Mallick, The colour rendering index and correlated colour temperature of dye-sensitized solar cell for adaptive glazing

application, Sol. Energy 163 (2018) 537–544, https://doi.org/10.1016/j.solener.2018.02.021.
[64] A. Ghosh, S. Sundaram, T.K. Mallick, Investigation of thermal and electrical performances of a combined semi- transparent PV-vacuum glazing, Appl. Energy 228 (2018) 1591–1600, https://doi.org/10.1016/j.apenergy.2018.07.040.
[65] N.C. Giri, R.C. Mohanty, Agrivoltaic system: Experimental analysis for enhancing land productivity and revenue of farmers, Energy Sustain. Dev. 70 (2022) 54–61, https://doi.org/10.1016/j.esd.2022.07.003.
[66] A. Goetzberger, A. Zastrow, On the Coexistence of Solar-Energy Conversion and Plant Cultivation, Int. J. Sol. Energy 1 (1982) 55–69, https://doi.org/10.1080/01425918208909875.
[67] R.A. Gonocruz, R. Nakamura, K. Yoshino, M. Homma, T. Doi, Y. Yoshida, A. Tani, Analysis of the Rice Yield under an Agrivoltaic System : A Case Study in Japan, Environments 65 (2021) 1–18.
[68] R.A. Gonocruz, S. Uchiyama, Y. Yoshida, Modeling of large-scale integration of agrivoltaic systems: Impact on the Japanese power grid, J. Clean. Prod. 363 (2022), 132545, https://doi.org/10.1016/j.jclepro.2022.132545.
[69] R.A.T. Gonocruz, Y. Yoshida, A. Ozawa, R.A. Aguirre, E.J.H. Maguindayao, Impacts of agrivoltaics in rural electrification and decarbonization in the Philippines, Appl. Energy 350 (2023), 121832, https://doi.org/10.1016/j.apenergy.2023.121832.
[70] S. Gorjian, E. Bousi, Ö.E. Özdemir, M. Trommsdorff, N.M. Kumar, A. Anand, K. Kant, S.S. Chopra, Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology, Renew. Sustain. Energy Rev. 158 (2022), https://doi.org/10.1016/j.rser.2022.112126.
[71] S. Gorjian, F. Jalili, A. Gorjian, H. Faridi, Technological advancements and research prospects of innovative, Appl. Energy 337 (2023), 120799, https://doi.org/10.1016/j.apenergy.2023.120799.
[72] Goswami, M., Gupta, A.K., Kishan, R., Baidya, S., Khan, Y.D.I., Prakash, S., 2023. An evaluation of climate resilient agricultural practices in India : a narrative synthesis of literature. Environ. Sustain. https://doi.org/10.1007/s42398-022-00255-4.
[73] R. Handler, J.M. Pearce, Greener sheep: Life cycle analysis of integrated sheep agrivoltaic systems, Clean. Energy Syst. 3 (2022), 100036, https://doi.org/10.1016/j.cles.2022.100036.
[74] Harrison, C., Lloyd, H., Field, C., England, N., 2017. Evidence review of the impact of solar farms on birds , bats and general ecology (NEER012). Manchester. https://doi.org/10.13140/RG.2.2.24726.96325.
[75] K.S. Hayibo, J.M. Pearce, Vertical free-swinging photovoltaic racking energy modeling: A novel approach to agrivoltaics, Renew. Energy 218 (2023), 119343, https://doi.org/10.1016/j.renene.2023.119343.
[76] Hermann, C., Ise, F., Schönberger, F., Ise, F., 2022. Agrivoltaics : Opportunities for Agri- culture and the Energy Transition Publishing notes.
[77] Huang, W., Lv, H., Liao, J., et al, 2017. A dish-type high-concentration photovoltaic system with spectral beam-splitting for crop growth. J. Renew. Sustain. Energy.
[78] IEA, 2022. Renewables 2022 Analysis and forecast to 2027. https://doi.org/https://iea.blob.core.windows.net/assets/ada7af90-e280-46c4-a577-df2e4fb44254/Renewables2022.pdf.
[79] Insights, U.Ma., 2022. Agrivoltaic Market: Current Analysis and Forcast (2021-2027) [WWW Document]. https://doi.org/https://univdatos.com/report/agrivoltaic-market-current-analysis-and-forecast-2021-2027/.
[80] Islam, S., 2021. Bangladesh's first agri-PV plant set to get green light. PV Mag. https://doi.org/https://www.pv-magazine.com/2021/12/27/bangladeshs-first-agri-pv-plant-set-to-get-green-light/.
[81] U. Jamil, J.M. Pearce, Energy Policy for Agrivoltaics in Alberta Canada, Energies (2023) 1–31.
[82] S. Jiang, D. Tang, L. Zhao, C. Liang, N. Cui, D. Gong, Y. Wang, Y. Feng, X. Hu, Y. Peng, Effects of different photovoltaic shading levels on kiwifruit growth, yield and water productivity under " agrivoltaic " system in Southwest China, Agric. Water Manag. 269 (2022), 107675, https://doi.org/10.1016/j.agwat.2022.107675.
[83] R. Jing, J. Liu, H. Zhang, F. Zhong, Y. Liu, J. Lin, Unlock the hidden potential of urban rooftop agrivoltaics energy-food-nexus, Energy 256 (2022), 124626, https://doi.org/10.1016/j.energy.2022.124626.
[84] F. Johansson, B.E. Gustafsson, B. Stridh, P.E. Campana, 3D-thermal modelling of a bifacial agrivoltaic system : a photovoltaic module perspective, Energy Nexus 5 (2022), 100052, https://doi.org/10.1016/j.nexus.2022.100052.
[85] A. Jones, J. Begley, N. Berkeley, D. Jarvis, E. Bos, Electric vehicles and rural business: Findings from the Warwickshire rural electric vehicle trial, J. Rural Stud. 79 (2020) 395–408, https://doi.org/10.1016/j.jrurstud.2020.08.007.
[86] G.F. Jones, M.E. Evans, F.R. Shapiro, Reconsidering beam and diffuse solar fractions for agrivoltaics, Sol. Energy 237 (2022) 135–143, https://doi.org/10.1016/j.solener.2022.03.014.
[87] L.J.W. Jr, K.E. Rollins, K.E. Lagory, K.P. Smith, S.A. Meyers, A preliminary assessment of avian mortality at utility-scale solar energy facilities in the United States, Renew. Energy 92 (2016) 405–414, https://doi.org/10.1016/j.renene.2016.02.041.
[88] O.A. Katsikogiannis, H. Ziar, O. Isabella, Integration of bifacial photovoltaics in agrivoltaic systems: A synergistic design approach, Appl. Energy 309 (2022), 118475, https://doi.org/10.1016/j.apenergy.2021.118475.
[89] G.G. Katul, Agrivoltaics in Color: Going From Light Spectra to Biomass, Earth's Futur. 11 (2023) 1–6, https://doi.org/10.1029/2023EF003512.
[90] D. Ketzer, P. Schlyter, N. Weinberger, R. Christine, Driving and restraining forces for the implementation of the Agrophotovoltaics system technology – A system dynamics analysis, J. Environ. Manage. 270 (2020), https://doi.org/10.1016/j.jenvman.2020.110864.
[91] S. Kim, S. Kim, Design of an Agrivoltaic System with Building Integrated Photovoltaics, Agronomy 13 (2023), https://doi.org/10.3390/agronomy13082140.
[92] S. Kim, S. Kim, K. An, An integrated multi-modeling framework to estimate potential rice and energy production under an agrivoltaic system, Comput. Electron. Agric. 213 (2023), 108157, https://doi.org/10.1016/j.compag.2023.108157.
[93] J. Korosteleva, The Implications of Russia ' s Invasion of Ukraine for the EU Energy Market and Businesses, Br. J. Manag. 33 (2022) 1678–1682, https://doi.org/10.1111/1467-8551.12654.
[94] N. Kostik, A. Bobyl, V. Rud, I. Salamov, The potential of agrivoltaic systems in the conditions of southern regions of Russian Federation, IOP Conf. Ser. Earth Environ. Sci. 578 (2020), https://doi.org/10.1088/1755-1315/578/1/012047.
[95] M. Kumpanalaisatit, W. Setthapun, H. Sintuya, Current status of agrivoltaic systems and their bene fi ts to energy, food, environment, economy, and society, Sustain. Prod. Consum. 33 (2022) 952–963, https://doi.org/10.1016/j.spc.2022.08.013.
[96] Kurniyawan, E.H., Junanda, A.I., H, H.M.P., Katrin, M., Cayani, D., Afandi, A.T., Kurniawan, D.E., Rosyidi, K., Nur, M., 2023. Ultraviolet Lights Effect on Farmer Health and Productivity : Literature Review. Nurs. Heal. Sci. J. 3, 24–31.
[97] Lee, S., Lee, J. hyuk, Jeong, Y., Kim, D., Seo, B. hun, Seo, Y. jin, Kim, T., Choi, W., 2023. Agrivoltaic system designing for sustainability and smart farming: Agronomic aspects and design criteria with safety assessment. Appl. Energy 341, 121130. https://doi.org/10.1016/j.apenergy.2023.121130.
[98] C. Li, H. Wang, H. Miao, B. Ye, The economic and social performance of integrated photovoltaic and agricultural greenhouses systems : Case study in China, Appl. Energy 190 (2017) 204–212, https://doi.org/10.1016/j.apenergy.2016.12.121.
[99] K. Liu, A.A. Miskevich, V.A. Loiko, S. Yue, Z. Huang, C. Li, Y. Wu, J. Wang, Z. Zhao, J. Liu, S. Wu, Z. Wang, S. Qu, Z. Wang, Interference effects induced by electrodes and their influences on the distribution of light field in perovskite absorber and current matching of perovskite/silicon tandem solar cell, Sol. Energy 252 (2023) 252–259, https://doi.org/10.1016/j.solener.2023.02.003.
[100] W. Liu, L. Liu, J. Ingenho, C. Guan, F. Zhang, M. Li, H. Lv, P. Yao, A novel agricultural photovoltaic system based on solar spectrum separation, Sol. Energy 162 (2018) 84–94, https://doi.org/10.1016/j.solener.2017.12.053.
[101] S.M. Lu, S. Zainali, B. Stridh, A. Avelin, S. Amaducci, M. Colauzzi, P.E. Campana, Photosynthetically active radiation decomposition models for agrivoltaic systems applications, Sol. Energy 244 (2022) 536–549, https://doi.org/10.1016/j.solener.2022.05.046.
[102] W. Lytle, T.K. Meyer, N.G. Tanikella, L. Burnham, J. Engel, C. Schelly, J. M. Pearce, Conceptual Design and Rationale for a New Agrivoltaics Concept : Pasture-Raised Rabbits and Solar Farming, J. Clean. Prod. 282 (2021), 124476, https://doi.org/10.1016/j.jclepro.2020.124476.
[103] Q. Ma, Y. Zhang, G. Wu, Q. Yang, Y. Yuan, R. Cheng, Y. Tong, H. Fang, Photovoltaic/spectrum performance analysis of a multifunctional solid spectral splitting covering for passive solar greenhouse roof, Energy Convers. Manag. 251 (2022), 114955, https://doi.org/10.1016/j.enconman.2021.114955.
[104] D. Majumdar, M.J. Pasqualetti, Landscape and Urban Planning Dual use of agricultural land : Introducing ' agrivoltaics ' in Phoenix Metropolitan Statistical Area, USA, Landsc. Urban Plan. 170 (2018) 150–168, https://doi.org/10.1016/j.landurbplan.2017.10.011.
[105] P.R. Malu, U.S. Sharma, J.M. Pearce, Agrivoltaic potential on grape farms in India, Sustain. Energy Technol. Assessments 23 (2017) 104–110, https://doi.org/10.1016/j.seta.2017.08.004.
[106] H. Marrou, L. Dufour, J. Wery, How does a shelter of solar panels influence water flows in a soil – crop system ? Eur. J. Agron. 50 (2013) 38–51, https://doi.org/10.1016/j.eja.2013.05.004.
[107] H. Marrou, L. Guilioni, L. Dufour, C. Dupraz, J. Wery, Agricultural and Forest Meteorology Microclimate under agrivoltaic systems : Is crop growth rate affected in the partial shade of solar panels ? Agric. for. Meteorol. 177 (2013) 117–132, https://doi.org/10.1016/j.agrformet.2013.04.012.
[108] H. Marrou, J. Wery, L. Dufour, C. Dupraz, Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels, Eur. J. Agron. 44 (2013) 54–66, https://doi.org/10.1016/j.eja.2012.08.003.
[109] K. McCree, Physiological Plant Ecology I, Springer, Berlin Heidelberg, Berling Heidlberg, 1981.
[110] K.J. McCree, The action spectrum, absorptance and quantum yield of photosynsthesis in crop plants, Agric. Meterology 9 (1972) 191–216.
[111] Z. Mehrabi, Likely decline in the number of farms globally by the middle of the century, Nat. Sustain. 6 (2023) 949–954, https://doi.org/10.1038/s41893-023-01110-y.
[112] C.K. Miskin, Y. Li, A. Perna, R.G. Ellis, E.K. Grubbs, P. Bermel, R. Agrawal, Sustianable co-production of food and solar power to relax land-use constraints, Nat. Sustain. 2 (2019), https://doi.org/10.1038/s41893-019-0388-x.
[113] A.K. Mohammad, A. Garrod, A. Ghosh, Do Building Integrated Photovoltaic (BIPV) windows propose a promising solution for the transition toward zero energy buildings ? A Review. J. Build. Eng. 79 (2023), 107950 https://doi.org/10.1016/j.jobe.2023.107950.
[114] C. Mohan, S. Kumar, S. Singh, M. Kumar, Y.M. Nimdeo, R. Raushan, A. V. Deorankar, T.M.A. Kumar, P. Kumar, C.S. Chanotiya, V.D. Pakhale, A. Deepak, Solar energy : A promising renewable source for meeting energy demand in Indian agriculture applications, Sustain. Energy Technol. Assessments 55 (2023), 102905, https://doi.org/10.1016/j.seta.2022.102905.

[115] H.-W. Moon, K.-M. Ku, Impact of an Agriphotovoltaic System on Metabolites and the Sensorial Quality of Cabbage (Brassica oleracea var. capitata) and Its High-Temperature-Extracted Juice, Foods 11 (2022).
[116] E. Mulenga, A. Kabanshi, H. Mupeta, M. Ndiaye, E. Nyirenda, K. Mulenga, Techno-economic analysis of off-grid PV-Diesel power generation system for rural electrification: A case study of Chilubi district in Zambia, Renew. Energy 203 (2023) 601–611, https://doi.org/10.1016/j.renene.2022.12.112.
[117] I.J. Mwakitalima, M. Rizwan, N. Kumar, Standalone Solar Photovoltaic Electricity Supply to Rural Household in Tanzania, IETE J. Res. (2021), https://doi.org/10.1080/03772063.2021.1920854.
[118] K.A.K. Niazi, M. Victoria, Comparative analysis of PV configurations for agrivoltaic systems in Europe, Prog. Photovoltaics 1–13 (2022), https://doi.org/10.1002/pip.3727.
[119] S. Nundy, A. Ghosh, T.K. Mallick, Hydrophilic and Superhydrophilic Self-Cleaning Coatings by Morphologically Varying ZnO Microstructures for Photovoltaic and Glazing Applications, ACS Omega 5 (2020) 1033–1039, https://doi.org/10.1021/acsomega.9b02758.
[120] S. Nundy, A. Ghosh, A. Tahir, T.K. Mallick, Role of Hafnium Doping on Wetting Transition Tuning the Wettability Properties of ZnO and Doped Thin Films : Self-Cleaning Coating for Solar Application, ACS Appl. Mater. Interfaces 13 (2021) 25540–25552, https://doi.org/10.1021/acsami.1c04973.
[121] B. Patel, B. Gami, V. Baria, A. Patel, P. Patel, Co-Generation of Solar Electricity and Agriculture Produce by Photovoltaic and Photosynthesis — Dual Model by Abellon, India, J. Sol. Energy Eng. Trans. ASME 141 (2019), https://doi.org/10.1115/1.4041899.
[122] P. Priyadarshini, P. Chirakkuzhyil, An empirical analysis of resource efficiency and circularity within the agri-food sector of India, J. Clean. Prod. 385 (2023), 135660, https://doi.org/10.1016/j.jclepro.2022.135660.
[123] PV magazine, 2022. TotalEnergies, InVivo switch on vertical agrivoltaic system in France. PV Mag. https://doi.org/https://www.pv-magazine.com/2022/08/22/totalenergies-invivo-switch-on-vertical-agrivoltaic-system-in-france/.
[124] N. Ra, A. Ghosh, A. Bhattacharjee, IoT-based smart energy management for solar vanadium redox flow battery powered switchable building glazing satisfying the HVAC system of EV charging stations, Energy Convers. Manag. 281 (2023), 116851, https://doi.org/10.1016/j.enconman.2023.116851.
[125] K. Ratnapradipa, S. Watanabe-galloway, E.H. Mph, R.H. Mba, P.A. Farazi, Predictors of cancer risky and preventive behaviors among the Nebraska farmers population, J. Rural Heal. 392–401 (2023), https://doi.org/10.1111/jrh.12731.
[126] S. Ravi, J. Macknick, D. Lobell, C. Field, K. Ganesan, R. Jain, M. Elchinger, B. Stoltenberg, Colocation opportunities for large solar infrastructures and agriculture in drylands, Appl. Energy 165 (2016) 383–392, https://doi.org/10.1016/j.apenergy.2015.12.078.
[127] M. Reasoner, A. Ghosh, Agrivoltaic Engineering and Layout Optimization Approaches in the Transition to Renewable Energy Technologies : A Review, Challenges 13 (2022).
[128] A.U. Rehman, Z. Ullah, A. Shafiq, H.M. Hasanien, P. Luo, F. Badshah, Load management, energy economics, and environmental protection nexus considering PV-based EV charging stations, Energy 281 (2023), 128332, https://doi.org/10.1016/j.energy.2023.128332.
[129] K. Reid, G.B. Baker, E.J. Woehler, An ecological risk assessment for the impacts of offshore wind farms on birds in Australia, Austral Ecol. 1–22 (2023), https://doi.org/10.1111/aec.13278.
[130] Research, A. market, 2023. Agrivoltaics Market by System Design (Fixed Solar Panles, Dynamic), by Cell Type (Monocrystalline, Polycrystalline), by Crop (Vegetables, Fruits, Crops, Others): Global Opportunity Analysis and Industry Forecast, 2021-2031 [WWW Document]. https://doi.org/https://www.alliedmarketresearch.com/agrivoltaics-market-A47446.
[131] Research, P., 2022. Agrivoltaics Market Size Analysis 2022 To 2030 [WWW Document]. https://doi.org/https://www.marketstatsnews.com/agrivoltaics-market/.
[132] M.H. Riaz, H. Imran, R. Younas, M.A. Alam, N.Z. Butt, Module Technology for Agrivoltaics: Vertical Bifacial Versus Tilted Monofacial Farms, IEEE J. Photovoltaics 11 (2021) 469–477, https://doi.org/10.1109/JPHOTOV.2020.3048225.
[133] M.H. Riaz, H. Imran, R. Younas, N.Z. Butt, The optimization of vertical bifacial photovoltaic farms for efficient agrivoltaic systems, Sol. Energy 230 (2021) 1004–1012, https://doi.org/10.1016/j.solener.2021.10.051.
[134] B.S. Richards, I.A. Howard, Luminescent solar concentrators for building integrated photovoltaics: opportunities and challenges, Energy Environ. Sci. 16 (2023) 3214–3239, https://doi.org/10.1039/d3ee00331k.
[135] C.D. Rodríguez-Gallegos, M. Bieri, O. Gandhi, J.P. Singh, T. Reindl, S.K. Panda, Monofacial vs bifacial Si-based PV modules: Which one is more cost-effective? Sol, Energy 176 (2018) 412–438, https://doi.org/10.1016/j.solener.2018.10.012.
[136] Roslan, N., Ya'acob, M.E., Radzi, M.A.M., Hashimoto, Y., Jamaludin, D., Chen, G., 2018. Dye Sensitized Solar Cell (DSSC) greenhouse shading: New insights for solar radiation manipulation. Renew. Sustain. Energy Rev. 92, 171–186. https://doi.org/10.1016/j.rser.2018.04.095.
[137] P. Roy, A. Ghosh, F. Barclay, A. Khare, E. Cuce, Perovskite Solar Cells: A Review of the Recent Advances, Coatings 12 (2022) 1–24, https://doi.org/10.3390/coatings12081089.
[138] S. Saeidpour, B. Khoshnevisan, Z. Boroumand, N. Ahmady, Effect of electrode design and dust particle size on electrodynamics dust shield procedure, Phys. Open 14 (2023), 100131, https://doi.org/10.1016/j.physo.2022.100131.
[139] S. Safat Dipta, J. Schoenlaub, M. Habibur Rahaman, A. Uddin, Estimating the potential for semitransparent organic solar cells in agrophotovoltaic greenhouses, Appl. Energy 328 (2022), 120208, https://doi.org/10.1016/j.apenergy.2022.120208.
[140] Santos, B., 2023. Adapting agrivoltaics to different climates, crops. PV Mag. https://doi.org/https://www.pv-magazine.com/2023/01/23/adapting-agrivoltaics-to-different-climates-crops/.
[141] A. Sarr, Y.M. Soro, A.K. Tossa, L. Diop, Agrivoltaic, a Synergistic Co-Location of Agricultural and Energy Production in Perpetual Mutation : A Comprehensive Review, Processes 11 (2023).
[142] S. Schindele, M. Trommsdorff, A. Schlaak, T. Obergfell, G. Bopp, C. Reise, C. Braun, A. Weselek, A. Bauerle, P. Högy, A. Goetzberger, E. Weber, Implementation of agrophotovoltaics: Techno-economic analysis of the price-performance ratio and its policy implications, Appl. Energy 265 (2020), 114737, https://doi.org/10.1016/j.apenergy.2020.114737.
[143] A.H. Schweiger, L. Pataczek, How to reconcile renewable energy and agricultural production in a drying world, Plants People Plan. 1–12 (2023), https://doi.org/10.1002/ppp3.10371.
[144] T. Sekiyama, A. Nagashima, Solar sharing for both food and clean energy production: Performance of agrivoltaic systems for corn, a typical shade-intolerant crop, Environ. - MDPI 6 (2019), https://doi.org/10.3390/environments6060065.
[145] A. Sinha, D.B. Sulas-kern, M. Owen-bellini, L. Spinella, Glass / glass photovoltaic module reliability and degradation : a review, J. Phys. d. Appl. Phys. 54 (2021), 413002.
[146] I. Sirnik, J. Sluijsmans, D. Oudes, S. Stremke, Circularity and landscape experience of agrivoltaics: A systematic review of literature and built systems, Renew. Sustain. Energy Rev. 178 (2023), 113250, https://doi.org/10.1016/j.rser.2023.113250.
[147] Solar, S., 2023. SPADE. https://doi.org/https://www.agrivoltaic.design/contact.
[148] W. Song, J. Ge, L. Xie, Z. Chen, Q. Ye, D. Sun, J. Shi, X. Tong, X. Zhang, Z. Ge, Semi-transparent organic photovoltaics for agrivoltaic applications, Nano Energy 116 (2023), 108805, https://doi.org/10.1016/j.nanoen.2023.108805.
[149] C.L. Steadman, C.W. Higgins, Agrivoltaic systems have the potential to meet energy demands of electric vehicles in rural Oregon, US. Sci. Rep. 1–8 (2022), https://doi.org/10.1038/s41598-022-08673-4.
[150] B. Steffen, A. Patt, A historical turning point ? Early evidence on how the Russia-Ukraine war changes public support for clean energy policies, Energy Res. Soc. Sci. 91 (2022), 102758, https://doi.org/10.1016/j.erss.2022.102758.
[151] System, F.I. of S.E., 2022. Agrivoltaics: Opportunities for Agriculture and the Energy Tran. https://doi.org/https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/APV-Guideline.pdf.
[152] A.K. Thakur, R. Singh, A. Gehlot, A.K. Kaviti, R. Aseer, S.K. Suraparaju, S. K. Natarajan, V.S. Sikarwar, Advancements in solar technologies for sustainable development of agricultural sector in India: a comprehensive review on challenges and opportunities, Environ. Sci. Pollut. Res. 29 (2022) 43607–43634, https://doi.org/10.1007/s11356-022-20133-0.
[153] C. Thiel, A. Gracia Amillo, A. Tansini, A. Tsakalidis, G. Fontaras, E. Dunlop, N. Taylor, A. Jäger-Waldau, K. Araki, K. Nishioka, Y. Ota, M. Yamaguchi, Impact of climatic conditions on prospects for integrated photovoltaics in electric vehicles, Renew. Sustain. Energy Rev. 158 (2022) 1–17, https://doi.org/10.1016/j.rser.2022.112109.
[154] Thomas, S.J., Thomas, S., Sahoo, S.S., G, A.K., Awad, M.M., 2023. Solar Parks: A Review on Impacts, Mitigation Mechanism through Agrivoltaics and Techno-Economic Analysis. Energy Nexus 11, 100220. https://doi.org/10.1016/j.nexus.2023.100220.
[155] S. Touil, A. Richa, M. Fizir, B. Bingwa, Shading effect of photovoltaic panels on horticulture crops production: a mini review, Rev. Environ. Sci. Biotechnol. 20 (2021) 281–296, https://doi.org/10.1007/s11157-021-09572-2.
[156] M. Trommsdorff, M. Hopf, H. Oliver, M. Berwind, S. Schindele, K. Wydra, Can synergies in agriculture through an integration of solar energy reduce the cost of agrivoltaics ? An economic analysis in apple farming, Appl. Energy 350 (2023), https://doi.org/10.1016/j.apenergy.2023.121619.
[157] M. Trommsdorff, J. Kang, C. Reise, S. Schindele, G. Bopp, A. Ehmann, A. Weselek, H. Petra, Combining food and energy production : Design of an agrivoltaic system applied in arable and vegetable farming in Germany, Renew. Sustain. Energy Rev. 140 (2021), https://doi.org/10.1016/j.rser.2020.110694.
[158] G. Trypanagnostopoulos, A. Kavga, M. Souliotis, Y. Tripanagnostopoulos, Greenhouse performance results for roof installed photovoltaics, Renew. Energy 111 (2017) 724–731, https://doi.org/10.1016/j.renene.2017.04.066.
[159] M. Uchanski, T. Hickey, J. Bousselot, K.L. Barth, Characterization of Agrivoltaic Crop Environment Conditions Using Opaque and Thin-Film Semi-Transparent Modules, Energies 16 (2023), https://doi.org/10.3390/en16073012.
[160] N. Vandewetering, K.S. Hayibo, J.M. Pearce, Open-Source Vertical Swinging Wood-Based Solar Photovoltaic Racking Systems, Designs 7 (2023), https://doi.org/10.3390/designs7020034.
[161] N. Vandewetering, K.S. Hayibo, J.M. Pearce, Impacts of Location on Designs and Economics of DIY Low-Cost Fixed-Tilt Open Source Wood Solar Photovoltaic Racking, Designs 6 (2022), https://doi.org/10.3390/designs6030041.
[162] R. Waghmare, R. Jilte, S. Joshi, P. Tete, Review on agrophotovoltaic systems with a premise on thermal management of photovoltaic modules therein, Environ. Sci. Pollut. Res. (2022), https://doi.org/10.1007/s11356-022-23202-6.
[163] L. Wang, O. Kisi, M. Zounemat-kermani, B. Hu, W. Gong, Modeling and comparison of hourly photosynthetically active radiation in different ecosystems, Renew. Sustain. Energy Rev. 56 (2016) 436–453, https://doi.org/10.1016/j.rser.2015.11.068.

[164] R. Watts, A. Ghosh, J. Hinshelwood, Exploring the potential for electric retrofit regulations and an accreditation scheme for the UK, Electron. 10 (2021), https://doi.org/10.3390/electronics10243110.

[165] Weaver, J.F., 2023. New software modeling tool for agrivoltaics. PV Mag. https://doi.org/https://www.pv-magazine.com/2023/03/31/new-software-modeling-tool-for-agrivoltaics/.

[166] A. Weselek, A. Bauerle, J. Hartung, S. Zikeli, I. Lewandowski, P. Högy, Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate, Agron. Sustain. Dev. 41 (2021), https://doi.org/10.1007/s13593-021-00714-y.

[167] A. Weselek, A. Ehmann, S. Zikeli, I. Lewandowski, S. Schindele, P. Högy, Agrophotovoltaic systems: applications, challenges, and opportunities, A Review. Agron. Sustain. Dev. 39 (2019), https://doi.org/10.1007/s13593-019-0581-3.

[168] H.J. Williams, K. Hashad, H. Wang, K. Max Zhang, The potential for agrivoltaics to enhance solar farm cooling, Appl. Energy 332 (2023), 120478, https://doi.org/10.1016/j.apenergy.2022.120478.

[169] B. Willockx, C. Lavaert, J. Cappelle, Performance Evaluation of Vertical Bifacial and Single-Axis Tracked Agrivoltaic Systems on Arable Land, Renew. Energy 217 (2022), 119181, https://doi.org/10.1016/j.renene.2023.119181.

[170] G. Womack, K. Isbilir, F. Lisco, G. Durand, A. Taylor, J.M. Walls, The performance and durability of single-layer sol-gel anti-reflection coatings applied to solar module cover glass, Surf. Coat. Technol. 358 (2019) 76–83, https://doi.org/10.1016/j.surfcoat.2018.11.030.

[171] B. Wu, A. Rufyikiri, V. Orsat, M.G. Lefsrud, Plant Science Re-interpreting the photosynthetically action radiation (PAR) curve in plants, Plant Sci. 289 (2019), 110272, https://doi.org/10.1016/j.plantsci.2019.110272.

[172] S. Yue, M. Guo, P. Zou, W. Wu, X. Zhou, Effects of photovoltaic panels on soil temperature and moisture in desert areas, Environ. Sci. Pollut. Res. 28 (2021) 17506–17518, https://doi.org/10.1007/s11356-020-11742-8.

[173] Zhang, H., Liang, S., Wu, K., Qiu, Y. (Lucy), Cai, Y., Chan, G., Wang, S., Zhou, D., Zhou, Y., Li, Z., 2022. Using agrophotovoltaics to reduce carbon emissions and global rural poverty. Innov. 3, 100311. https://doi.org/10.1016/j.xinn.2022.100311.

[174] N. Zhao, S. Yan, N. Zhang, X. Zhao, Impacts of seasonal dust accumulation on a point-focused Fresnel high-concentration photovoltaic/thermal system, Renew. Energy 191 (2022) 732–746, https://doi.org/10.1016/j.renene.2022.04.039.

[175] S. Zhen, M.W. van Iersel, Far-red light is needed for efficient photochemistry and photosynthesis, J. Plant Physiol. 209 (2017) 115–122, https://doi.org/10.1016/j.jplph.2016.12.004.

[176] Y. Zhu, Z. Wang, X. Zhu, New reflections on food security and land use strategies based on the evolution of Chinese dietary patterns, Land Use Policy 126 (2023), 106520, https://doi.org/10.1016/j.landusepol.2022.106520.

[177] T.I. Zohdi, A digital-twin and machine-learning framework for the design of multiobjective agrophotovoltaic solar farms, Comput. Mech. 68 (2021) 357–370, https://doi.org/10.1007/s00466-021-02035-z.