Renewable and Sustainable Energy Reviews 158 (2022) 112126

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology

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ARTICLE INFO

*Keywords:*
Solar photovoltaics
Cultivation environments
Agrivoltaic systems
Shading impact
Semi-transparent technology

ABSTRACT

The world population and consequently the global need for food continue to grow. At the same time, areas will be used to generate clean electricity to cope with climate change and global warming. The combination of crop production and solar photovoltaics in the form of "agrivoltaic technology" offers advantages for both sides that provide an adequate, resource-efficient solution to the persistent problem of competition for arable lands. The implementation of agrivoltaic systems has been exponentially increased in recent years and reached the global installed capacity of 2.8 GW in 2020 from the initial capacity of 5 MW in 2012. The agrivoltaic systems installed worldwide mostly employ conventional opaque photovoltaic (PV) modules, causing a change in the microclimate under the panels that become critical when shading ratios are high. Semi-transparent PV (STPV) modules have been recently employed to mitigate this issue which is profoundly studied in this research by considering the use of semi-transparent technologies based on crystalline silicon (c-Si), thin-film photovoltaics, organic PVs (OPVs), dye-sensitized solar cells (DSSCs), concentrating PVs (CPVs), and luminescent solar concentrators (LSCs) in open (arable farming lands) and closed (cultivation greenhouses) agrivoltaic systems. The results indicated that c-Si STPV modules have the highest share of employment in agrivoltaic systems due to their extreme benefits of low costs, high stability, and high efficiency in comparison with other technologies, while in contrast, the use of thin-film STPV modules have been rarely reported in the literature. Additionally, STPV modules using OPVs and DSSCs offer the capability to achieve wavelength-selective transparency, causing the photosynthetic active radiation to pass through while the remained spectrum is utilized to generate electricity. Other potential solutions come from CPVs and LSCs, in which, diffuse light is available for the growth of cultivated plants, while direct concentrated sunlight can generate electricity. Although STPV modules are proven as a feasible solution for use in agrivoltaic systems, still more developments are required in terms of the modules' efficiency enhancement and costs reduction, while more detailed research is required to observe the response of cultivated plants to make this technology a viable sustainable solution in the future.

## 1. Introduction

Currently, most of the agricultural activities are powered by fossil fuels, increasing greenhouse gas (GHG) emissions and climate change as a consequence [1]. The 'Consultative Group on International Agricultural Research' (CGIAR) has claimed that agri-food chains consume almost 30% of the total global energy, contributing to about 19–29% of the annual global GHG emissions where cultivation activities solely contribute to about 20% of annual total carbon dioxide ($CO_2$) emissions [2,3]. Among various agricultural practices, electricity generation contributes to the highest carbon footprint share equal to 78.7% [4].

The productivity of the agriculture sector primarily depends on three main constituents of energy, water, and land resources. The steady

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https://doi.org/10.1016/j.rser.2022.112126
Received 21 May 2021; Received in revised form 11 October 2021; Accepted 10 January 2022
Available online 18 January 2022
1364-0321/

**Abbreviations**

| | |
|---|---|
| **APV** | Agri-photovoltaics |
| **AVT** | Average Visible Transmission |
| **BAPV** | Building attached PV |
| **BIPV** | Building-integrated PV |
| **c-Si** | Crystalline silicon |
| **CdTe** | Cadmium Telluride |
| **CFD** | Computational Fluid Dynamics |
| **CGIAR** | Consultative Group on International Agricultural Research |
| **CIGS** | Copper Indium Gallium Selenide |
| **$CO_2$** | Carbon dioxide |
| **CPV** | Concentrating PV |
| **CSTPV** | Concentrating STPV |
| **DNI** | Direct Normal Irradiation |
| **DSSCs** | Dye synthesized solar cells |
| **EPBT** | Energy Payback Time |
| **EROI** | Energy Return on Investment |
| **GaAs** | Gallium Arsenide |
| **GHG** | Greenhouse gas |
| **GMIs** | Ground-mounted installations |
| **HCPV** | High-concentration PV |
| **LCOE** | Levelized Cost of Electricity |
| **LCC** | Life Cycle Cost |
| **LCPV** | Low-concentration PV |
| **LSC** | Luminescent solar concentrator |
| **Mono-Si** | Mono-crystalline silicon |
| **OPV** | Organic PV |
| **OSTPV** | Organic STPV |
| **PAR** | Photosynthetic Active Radiation |
| **PCE** | Power Conversion Efficiency |
| **PIPV** | Product integrated PV |
| **Poly-Si** | Poly-crystalline silicon |
| **PPFD** | Photosynthetic photon flux density |
| **PV** | Photovoltaic |
| **RT-PV** | Rooftop PV |
| **Si** | Silicon |
| **STC** | Standard Test Condition |
| **STPV** | Semi-transparent PV |
| **UV/NIR** | Ultraviolet/Near-infrared |
| **WFE** | Water-food-energy nexus |
| **WSPV** | Wavelength Selective Photovoltaic System |

increases in fossil fuels and electricity costs, as well as the requisite for substantial reductions in GHG emissions, have created necessities to improve energy efficiency, resulting in seeking alternative energy sources [5,6]. The employment of renewable energies can sustainability improve crop production by reducing the reliance on non-renewable resources and among them, solar energy is known as the most abundant and reliable energy source with proven feasibility for being adopted to provide the power demand of various agricultural operations [7–9].

Photovoltaic (PV) is globally a fast-growing solar energy conversion technology with the most maturity among solar energy conversion technologies [6,10–12]. In recent years, pioneering progress has been observed in solar energy use across the nations, and PV technology has captured a massive market in the modern electricity sector with a production capacity of nearly 107 GW in 2020 [13,14].

PV technology uses semiconductors to directly convert sunlight into electricity, aiming to increase profitability, enhancing yields, accelerating production, and assisting in better management of natural resources. Although the conventional ground-mounted configuration of PV modules contributes a major share in global installation capacities, there also exists a significant contribution from emerging installation types including floating [15], building-integrated [16], and rooftop [17,18].

On the other hand, the advancements in PV cell technologies and innovative designs and materials could better fit the energy and interlinked services. The progress in PV technology can be strategically put under the following areas [19–21]:

- Innovation in materials for new solar cell developments;
- Optimized cell level fabrication procedures;
- Innovative and digital empowered methods for PV module manufacturing, meeting industry 4.0 standards;
- Options for customized PV modules;
- Novel installation approaches and application areas.

The most commonly used materials to construct commercial PV cells are silicon (Si), Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS) and, Gallium Arsenide (GaAs) [11,22]. The crystalline silicon (c-Si) PV modules are made of mono-crystalline and poly-crystalline silicon where the manufacturing process of the first type is more complex, causing a relatively high price of about 0.29 ~ 0.38 USD/Wp for it compared to poly-Si modules with the price range of 0.18~ 0.19 USD/Wp [23]. Fig. 1 depicts the global market share for the most common PV modules, while Fig. 2 represents the variation of modules price over time.

The highest confirmed efficiency for c-Si solar cells is 26.7 ± 0.5%, and 29.1 ± 0.6 for GaAs thin-film solar cells [24]. Some novel PV technologies with higher levels of efficiency have also been emerged including semi-transparent PV (STPV) modules based on recently developed dye synthesized solar cells (DSSCs) and organic PV (OPV) cells [25,26], mitigating undesirable shading effects of traditional opaque PV modules and manipulating the light spectrum.[1]

Employment of solar energy technology in crop cultivation environments benefits from sustainable agriculture including low-carbon emissions, long-term energy sources, high reliability, low maintenance, and less payback time. The employment of PV technology is globally growing up in the agriculture sector, providing energy self-sufficiency and environmental sustainability in cultivation environments. The installation of PV systems should be planned considering

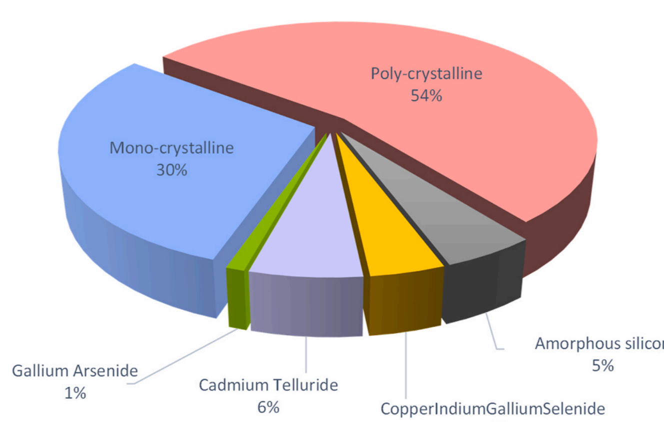


**Fig. 1.** Global market share of the most common PV modules [22].

[1] Detailed description of STPV technologies is presented in *Section 2*.

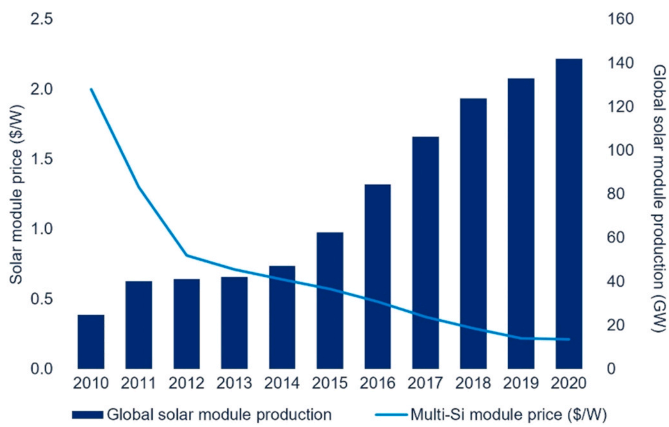


**Fig. 2.** PV module price versus global manufacturing capacity (2010–2020) [22].

both the energy requirements of farms and their potential role as energy producers [27]. The PV systems are more affordable in distributed electricity generation settings with the most operational feasibility in rural areas and remotely access agricultural environments including ranches, orchards, and greenhouses [28,29]. In small-to medium-sized cultivation environments, decentralized PV systems can provide electricity, while in larger farms, central PV power plants are more suitable to supply the power demand [29,30].

### 1.1. Agrivoltaics: concept and system designs

The process of co-developing of PV electricity generation and crop cultivation on the same land is called 'agrivoltaics' where the prefix 'agri' refers to the science and technology of producing crops in agriculture, and 'voltaic' refers to PV power generation [31]. This concept was firstly proposed by Goetzberger and Zastrow in 1982 [32] as a method in which the solar power plants are modified, enabling additional crop production in the same area. In this idea, the PV arrays were raised to 2 m above the farmland with increased space between them to avoid excessive shading on the cultivated crops beneath. After passing about three decades, the term 'agrivoltaics' was introduced by Dupraz et al. [33], but it is also known as 'agrophotovoltaics' [34,35], 'solar sharing', 'agrisolar', and 'agri-PV' in different countries around the world [36]. Schematic of a typical agrivoltaic system installed on an open field is shown in Fig. 3. As depicted in this figure, different distances between the modules on the module rows should help to determine the influences of different degrees of shade on the yield of the plants, and therefore, identifying the best coverage.

Agrivoltaic systems are broadly classified according to various measures (Fig. 4) including the type of the system (being closed or open), type of the structure (interspace PV, overhead PV, PV integrated greenhouses), the tilt of modules (fixed, one-axis tracking, two-axis tracking), and type of the application (grassland farming, arable farming, horticulture, and aquaculture. Moreover, the application of animal husbandry under closed opaque buildings is presented, although they are not typically considered as agrivoltaics.

Agrivoltaic systems can be installed both on open-field farms or integrated with protected crop cultivation environments of greenhouses. The interspace PV is mainly applied in pasture and arable farming, while overhead PV is mainly suitable for horticulture. Distinct configurations of agrivoltaic systems installed in an open-field farm, horticulture, and greenhouse cultivation environments are presented in Fig. 5. Agrivoltaic systems are still in their initial phases of development with plenty of room for technical advancements and new sectors of utilization [38]. According to the study by Pascaris et al. [39], in addition to the potential benefits of agrivoltaic systems, there are some barriers to the adoption of this technology including long-term land productivity with favorite certainty, market potential, and the required flexibility for the predesigned system to accommodate various scales. They also asserted that these adoption barriers are not insurmountable and may be successfully handled via careful planning and mutually beneficial land agreements between solar and agriculture sector participants. An overview of the benefits and barriers of agrivoltaic systems is presented in Table 1.

### 1.2. Problem statement

Because of their effective role in the water-food-energy (WFE) nexus, agrivoltaic systems have been the focus of several pieces of research in recent years. Demonstrative projects based on innovative conceptual designs for covering broad fields with PV modules have shown promising results. The plants cultivated under the sunshade of PV modules benefit from more effective water/rain redeployment [57], wind mitigation and temperature deviations protection [33,58], reduction in evapotranspiration, perfection in soil moisture, security in contrast to climatic uncertainty and risky happenings such as hailstones [59]. However, providing desirable levels of sunlight for the growth of plants is an important concern. As a rough estimation, a 1% light decrease can result in a 0.5–1% decrement in the product yield, depending on the type of the crops. However, under hot climate conditions, high intensity of solar radiation can cause adverse impacts as a consequence of supra-optimal air temperature and low humidity [60].

Several studies have investigated the impact of shading caused by PV modules in agrivoltaic systems on the growth parameters of plants (i.e., yield, size, dry and fresh weight, color, stem height, etc.). In this case, Dupraz et al. [33] proposed a combination of PV panels and food crops to maximize land use. For this purpose, they examined two agrivoltaic systems using different densities of PV panels. They modeled the light transmission at the crop level and used a crop model to estimate the yield of partially shaded crops. The results indicated that agrivoltaic systems might be highly efficient where a 35–73% increase in global land productivity can be predicted. In another study by Hudelson and Lieth [61], kale, chard, broccoli, peppers, tomatoes, and spinach were cultivated at various locations within a partial shade of a PV array oriented north-south and tracked east-west during daylight hours. For this purpose, three levels of shade as 7%, 55–65%, and 85% full sun, as well as a full sun control outside the array were examined. They reported that plant yields are affected by microclimate variations under PV arrays depending on location within a solar array. Gonocruz et al. [62] analyzed rice yield under agrivoltaic systems in Japan. The findings showed that the upper shading rate for agrivoltaic installations is between 27 and 39%, ensuring to sustain at least 80% of the rice output. They also asserted that the limit of solar panels' ratio to rice paddy area should be almost 23–36%. In another study, Ezzaeri et al. [63] investigated the shading effect of flexible PV panels, mounted on the roof area of the greenhouse in the checkerboard format, on the microclimate and the yield of tomatoes during summer and winter periods. The findings revealed that PV panels covering 40% of the roof area of a canary-type greenhouse have no significant impact on climatic parameters. While, during the hot season, PV panels lowered the temperature within the greenhouse, bringing it closer to the ideal range for tomato development. The effect of south-oriented PV roofs on crop productivity was investigated by Cossu et al. [64]. The study was conducted considering an east-west oriented greenhouse with a 960 $m^2$ area, where 50% of the area was covered with poly-crystalline silicon PV modules. When compared to the scenario without the PV (2684 $MJ/m^2$ on an annual basis), the PV reduced the availability of solar radiation within the greenhouse by 64%. On an annual basis, the reduction under plastic and PV covers was 46 and 82%, respectively. Additionally, only an 18% decrease was found on the plant rows furthest away from the span's PV cover.

The effect of PV arrays installed on the roof of a greenhouse on the growth of Welsh onion was studied by Kadowaki et al. [65]. For this purpose, two PV-array configurations were examined. The results

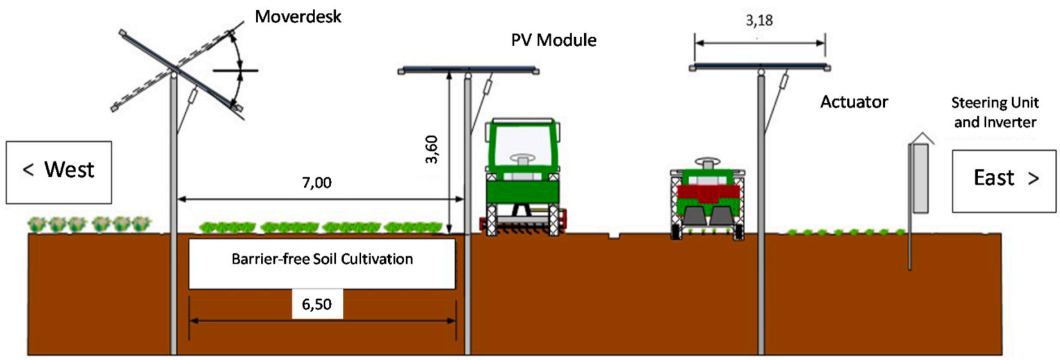


**Fig. 3.** Cross-section of a typical agrivoltaic system installed on an open field [37].

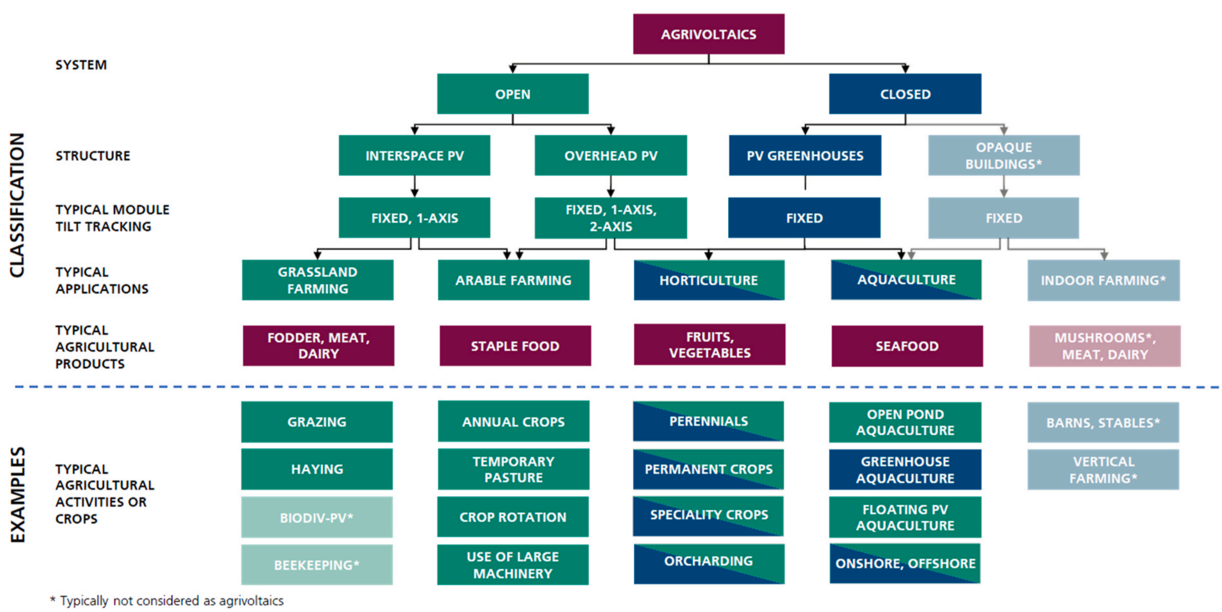


**Fig. 4.** Broad classification of agrivoltaic systems.

indicated that the straight-line configuration, providing the optimum inclination angle, is the best option for power production. However, it was reported that in northern plant positions, the straight-line arrangement blocks more than half of the photosynthetic photon flux density (PPFD). While in a checkerboard pattern, however, more than half of the PPFD was exposed to the whole cultivated plants. They concluded that the geometrical configurations of PV arrays have a significant impact on the development of plants growing beneath the arrays. The balance of permissible shadowing and power production is predicted to vary depending on plant species, region, weather, season, and greenhouse features. More research is needed to investigate the compatibility of plant production with power generation in PV greenhouses.

According to the literature, the integration of traditional opaque PV modules in crop cultivation environments causes adverse impacts on crop growth due to the shadow effect especially when high shading ratios are occurred [66–71]. With conventional modules, to increase the light transmission, the gaps can be expanded and the module frames can be replaced with clamp brackets (Fig. 5b). However, the adverse shadow impacts can be mitigated by employing some potential solutions; (i) cultivating crops grown under partially shaded environments such as leafy vegetables (e.g. lettuce), field forage (clover grass), various pome, stone, and berry fruits as well as other special crops (e.g. wild garlic, asparagus, and hops) [72]; (ii) installation of PV modules with modified patterns such as straight line and checkboard to increase the transmissivity of sunlight [73]; (iii) employment of one-axis and two-axis trackers to create dynamic shading throughout the day [74] (iv) employment of STPV modules [73]. Modules with enlarged transparent areas (i.e., STPV modules); protect plants from environmental influences without restricting the availability of light to the same extent. Bifacial modules can also be used, allowing the light to be arrived at the rear to generate electricity. With these modules, depending on the back radiation, higher electricity yields of up to %25 can be achieved. With concentrating photovoltaics (CPVs), the light is bundled onto small photoactive areas by lenses or mirrors. CPV modules must track the sun, except for systems that concentrate very little. Diffuse light is mainly transmitted. There are currently only very few commercial providers of CPV modules for use in agrivoltaic systems [75].

In the current study, the integration of STPV modules with agrivoltaic systems installed on open-filed farms and agricultural greenhouses as a solution to mitigate the adverse impacts of shadows created by conventional PV modules is comprehensively investigated and several case studies are discussed considering the challenges and benefits of each technology. In this regard, the integration of different types of STPV modules based on c-Si, thin-film (a-Si, CIGS, and CdTe), DSSCs, OPV, and perovskite, as well as novel technologies of concentrating PVs (CPVs) and luminescent solar concentrators (LSCs) are comprehensively investigated. In the end, the main concluding points along with the prospects for implementation of this technology in crop cultivation environments are presented.


**Fig. 5.** **a)** Elevated agrivoltaic plant with the possibility of cultivation with the potato harvester, **b)** Agrivoltaic plant installed in an orchard using PV modules with extended cell gaps in the Netherlands, **c)** PV module installed over tunnel types greenhouses [37].

## 2. Overview of semi-transparent photovoltaic technology

At present, there are about 24 different types of PV cell technologies and 22 types of novel PV installation approaches which mainly differ based on used materials, fabrication methods, installation medium, and configuration [21,76]. The advances in PV cell materials and fabrication methods have opened up the door to a new PV technology of semi-transparent modules [77]. While the usual primary purpose of STPV is to absorb photonic energy from the sunlight, at the same time, the key characteristic of transparency is to allow the photons to pass through its layers. This means, the material used for PV cells should encompass both features of photon absorption for electron flow and light penetration in one material and this triggered the research direction into developing thin layers. When the STPV cells evolved, scientists and researchers could achieve transparency to varying levels, but mostly limited to low percentages of less than10-20%. Now the transparency levels are being improved, and currently, work is in progress to achieve full transparency [76,77]. The STPV operation is the same as conventional PVs where the photons from the sunlight are absorbed by the cell, making it transmit a significant percentage of light. This displaces electrons to form the pairs of electrons and holes guided in one direction, creating an electric current. The space between the PV cells of a module is the major responsible parameter for the transparency and electricity output [77,78]. The transparency of PV cells varies based on the average visible transmission (AVT) property[2] as shown in Fig. 6 for different types of PV cells.

The first one is the opaque type which is the conventional PV. The rest two are broadly categorized as non-selective and ultraviolet/near-infrared (UV/NIR)-selective based on the wavelength. Under the non-selective wavelength category, thin PV and concentrator types are shown where they generate electricity from a wide absorption of sunlight including the visible spectrum, and reach AVT through segmenting opaque devices. When thin PV layers are used with fewer amounts of photoactive material in the solar cell, the transparency levels would further be increased. Overall, the non-selective type shows AVT ranging between 0 and 50%. These solar cells are available and fabricated in different colors and can be made in a more decorative manner favoring the outdoor architecture designs. The other category is UV/NIR wavelength-selective type, where the PV uses photoactive compounds to absorb the photons from the selected wavelengths and at the same time allowing the transmission of the visible wavelengths. In this type, most preference is given to the UV and NIR. The observed AVT for the UV/NIR type STPV is in the range of 50%–90% [77,79]. Therefore, it is understood that AVT is the most crucial parameter that drives the research on STPV, following by another most stressed parameter of power conversion efficiency (PCE) [78]. Table 2 represents optical and electrical properties of different PV materials along with few remarks that drive a proper solar cell selection for the desired application.

From the table, it is understood that a-Si and Perovskites are more suitable for STPV cells and the product integrated PV (PIPV) category such as sunroof, window, car-roof, greenhouse, etc. Currently, there are approximately nine fabrication technologies that are used to make STPVs with a detailed discussion presented in Table 3. Among these, screen printing technology for making STPV is the first evolved method, followed by near-infra and others. The most recent method is the quantum dots.

Each of the methods resulted in different efficiencies, and transparency levels (i.e., AVT). However, the highest recorded efficiency i.e., PCE was observed for tandem semi-transparent perovskite solar cells, i.e., 12.7% (AVT is 77%), followed by the screen-printed DSSCs, i.e., 9.2% (AVT is 60%). Recently many applications are explored for STPVs, grouped them under different PIPVs [76]. The STPV technology provides relatively good light transmittance besides power generation. Therefore, adopting this technology in agrivoltaic systems can be a promising solution [88,89]. The available STPV technologies considering two key parameters mentioned earlier as AVT and PCE are presented in Table 4.

[2] Average visible transparency; Transparency over the visible wavelengths (400–700 nm).

**Table 1**
Opportunities, barriers, and future research directions of agrivoltaic systems, adapted from Ref. [39].

| Opportunities | Barriers | Future research |
|---|---|---|
| • Contracted agreements that establish plans to return the land to prelease form after decommissioning of the solar system;<br>• The effects of modules, such as trace metal leaching [40,41] and reduced future agricultural output [42], are very unlikely;<br>• To reduce ground disturbance, PV racking can be installed on removable ballasted foundations or skids of precast or poured-in-place concrete ballasts [43];<br>• Driven piles (constructed of galvanized steel I-beams, channel-shaped steel or posts), helical piles (galvanized steel posts with split discs welded to the bottom at an angle), and ground screws (galvanized steel posts with welded or machined threads) can be removed and recycled [43,44]. | End-of-life impacts from solar infrastructure | • Empirical studies into the extent of solar infrastructure's long-term impacts on land (e.g., Ref. [45]), soil, and pasture-grass productivity. |
| • When compared to traditional south-facing designs, east-west tracking array layouts provide ideal conditions for plants growth [46];<br>• Create open-source racking systems [47,48] that are adaptable in terms of panel height, tilt angle, and spacing [49], as well as a mix of permanent and removable fences;<br>• Elevated racking structures let agricultural equipment pass through, potentially allowing almost any crop to be utilized in agrivoltaic production [50];<br>• Possibility of using STPV [51] or vertical bifacial PV modules [52];<br>• Improvements in water productivity and increased shade are expected to boost agricultural output in climate-change-affected dry regions [53];<br>• Several plants have been shown to maintain better soil moisture, improve water efficiency, and enhance late-season biomass beneath PV panels [54]. | Permanent structures interfering with agricultural production and future farming practice | • Empirical research aiming at determining the effects of solar PV infrastructure on the management of perennial pasture grasses;<br>• Optimized agrivoltaic installations;<br>• Analysis of the cost-benefit of open-source PV racking systems with changeable panel height, tilt angle, and spacing;<br>• A cost-benefit study of permanent and movable animal grazing agrivoltaic fence. |
| • Legitimate collaborations and contracts that specify upfront costs and remuneration for both parties;<br>• Local government strategy targeted at promoting solar PV growth [55,56];<br>• Education and outreach from the PV sector to the farming industry to remove knowledge hurdles and improve confidence. | Uncertainties in operation and business planning | • Policy research with a concentrate on market mechanisms to promote agrivoltaic systems for both the solar and agricultural sectors.<br>• Increased university extension program initiatives to enhance knowledge exchange and collaboration between energy and agriculture. |

## 3. Integration of STPV modules in agrivoltaic systems

In this section, the literature that correlates the integration of STPV modules with crop cultivation environments is discussed. This section is separated based on different applied technologies, starting with the most widely available c-Si and thin-film STPV modules, following by the OPV and DSSCs, and in the last part, novel solutions provided by CPVs and LSCs are discussed.

### 3.1. Integration of c-Si STPV modules

Hassanien et al. examined the effects of mono-Si STPV modules installed on a greenhouse with cultivated lettuce [90] and tomatoes [91] inside. The c-Si STPV modules with a nominal power of 170 Wp, an efficiency of 8.25%, and a transparency of 47% were installed on top of a south-facing greenhouse (Fig. 7), resulting in a 20% cover ratio. Although the measurements indicated that modules block 35–40% of light more than the polyethylene cover and decrease the air temperature, no significant variations in the growth trends of the lettuce or tomatoes were observed. At the same time, the produced electricity was found to be enough for the supplemental energy demands of the greenhouse, leading to a 9 years payback time [91].

In another study, Tani et al. [92] experimentally investigated the lettuce growth trend under three different small-scale pilot greenhouses; (i) without modules (control case), (ii) with c-Si STPV with 50% transparency (PV-T), and (iii) with a light diffusion film underneath the PV modules (PV-D). The results indicated that the growth trend of the lettuce plant in PV-D is comparable with the control greenhouse in terms of dry weight and relative growth rate from spring to autumn. While, for the PV-T greenhouse, lower yields were observed for the lettuce plants throughout the year. The differences were mainly attributed to the PPFD reaching the plants which was measured to be stable in the PV-D greenhouse while it was fluctuating in the PV-T greenhouse (Fig. 8). It was also found that although the net photosynthetic rate of the PV-D treatment is the lowest, the total carbon assimilated could be higher under diffuse light conditions due to light penetration to the lower parts of the leaves. They concluded that agricultural yield is improved by integrating STPV modules and diffuse films.

The agrivoltaic systems using c-Si STPV modules are also installed in orchards where the modules can substitute with already utilized structural supporting systems (nets and foils), protecting the cultivated plants against extreme weather conditions. In a recent report, Fraunhofer-Institute for Solar Energy Systems (ISE) announced the levelized cost of electricity (LCOE) for orchard agrivoltaic systems as 7.13 cents/kWh which is lower than 9.93 cents/kWh for arable farming's agrivoltaic systems [93].

This is mainly due to the smaller clearance height in orchards agrivoltaics that results in reducing the costs for mounting structure, site preparation, and installation operations. In another study by Willockx et al. [94], a techno-economic analysis of an orchard agrivoltaic system was conducted based on a novel 3D agrivoltaic tool developed by KU Leuven that simulates the light distribution, crop yields, and electrical efficiency. In this regard, four different configurations were tested; opaque PV modules in landscape formation, checkboard formation (Fig. 9a), PV modules with 40% transparency, and a reference without PV modules. The results indicated that the total radiation reaching trees is mainly affected by the ground cover ratio, but the light distribution depends on the size of the module's active area. They also found that the set-up with STPV modules causes a much more homogeneous light distribution (Fig. 9b). Additionally, the semi-transparent configuration indicated better agricultural yield in terms of pears per tree (82 pears/tree) and average weight per pear (149.6 g/pear) in comparison with checkerboard configuration (79 pears/tree, 144.50 g/pear) and opaque PV modules (60 pears/tree, 127.50 g/pear). Further, the highest yields (10 pears/tree, 170 g/pear) and the lowest total revenue of 11.57 USD/tree were achieved for the reference case, compared with the

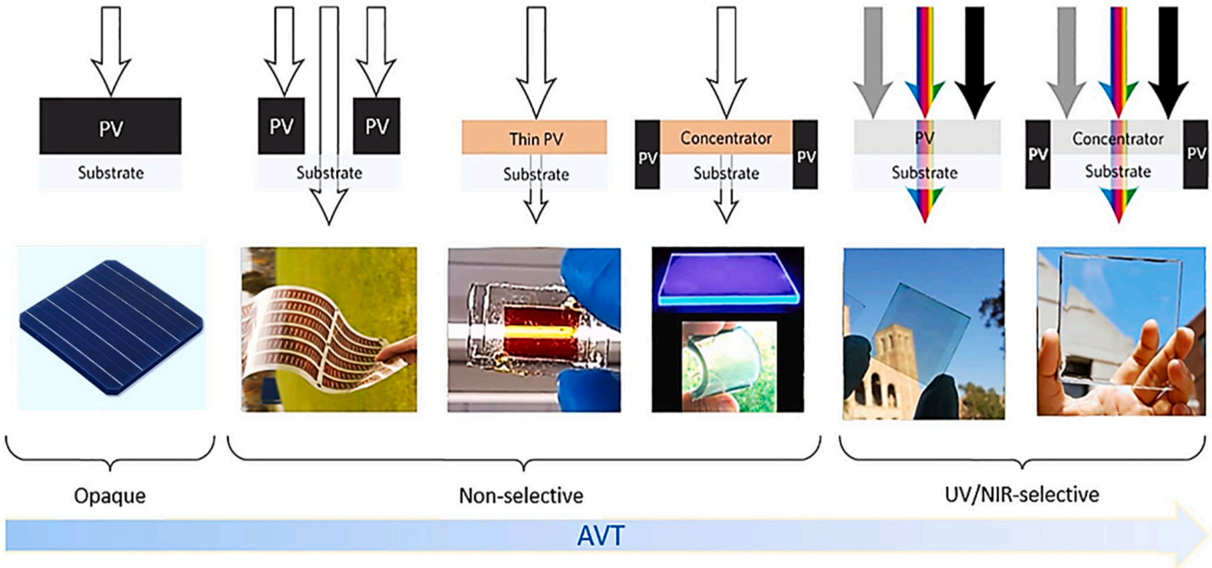


**Fig. 6.** Variation in AVT property for different opaque, non-selective, and UV/NIR selective PV cell technologies [77,79].

**Table 2**
Absorption and electric properties of four different PV materials [78].

| PV material | Thickness (μm) | Absorption properties | | Charge mobility ($cm^2\ v^{-1}\ s^{-1}$) | PCE (%) | Remarks |
|---|---|---|---|---|---|---|
| | | Band | Co-efficient | | | |
| Crystalline silicon | 300 | Broad | $10^3$ | $10^3$ | 26.6 | • Weak absorption;<br>• High charge mobility;<br>• High power conversion efficiency;<br>• Inflexible. |
| Amorphous silicon | 1 | | $10^4$ | $10^{-1}$ | 14.0 | • Favorable absorption;<br>• Moderate power conversion efficacies;<br>• Lower charge mobility;<br>• Due to low thickness, well suits for making semitransparent and flexible modules;<br>• Colors can be varied. |
| Perovskite | 0.3 | | $10^5$ | $10^1$ | 22.7 | • Higher absorption;<br>• Tunable optical properties;<br>• Considerably higher charge mobility;<br>• Can be integrated into products owing to their mechanical flexibility. |
| Polymer | 0.1 | Confined | $10^5$–$10^6$ | $10^{-3}$ | 11.5 | • High absorption;<br>• Very low charge mobility;<br>• Low power conversion efficiencies. |

revenues of 30.88 USD/tree for the case with opaque PV modules, 23.54 USD/tree for the case with STPV modules, and 19.37 USD/tree for the checkerboard case. Based on the results obtained from modeling, the scientists from the KU Leuven installed a 13.3 kWp agrivoltaic system in a pear orchard [95]. They used c-Si STPV modules with a nominal power of 185 Wp and a transparency of 40% achieved by employing 36 PV cells with 21% efficiency for each module. Additionally, the clearance height was considered as 4.6 m, allowing the machinery to pass below the panels as shown in Fig. 9c.

The c-Si STPV modules can be fabricated using spherical microcells. The innovative approach of fabricating spherical microcells (Sphelar®) is under commercialization efforts by the company Sphelar Power [96]. The Sphelar® cells can receive solar radiation from all directions because of their spherical shape, reaching high transparency levels. However, further technical developments are still required to improve their performance for entering the market. Yano et al. [97] developed two STPV module prototypes suitable for mounting on greenhouse roofs by integrating Sphelar® microcells between two glass substrates in which 39% of the surface of the first module and 13% of the second module were covered (Fig. 10a). The efficiencies of 4.5% and 1.6% were reported for the first and second modules, respectively. The results indicated that the annual produced electricity per unit area of the greenhouse is sufficient only in locations where the high potential of solar radiation is available. Cossu et al. [98] evaluated the performance of a novel STPV module fabricated from Sphelar® cells with a cell density of 2 cell/$cm^2$ and 73% transmissivity mounted on a greenhouse roof oriented at 26.5° from horizontal (Fig. 10b). The results indicated a slightly higher yield factor for STPV modules due to their specific ability to absorb both sky-incident and ground-reflected radiations. In another study, Li et al. [99] tested the electric performance of innovative modules on a prototype Venetian-blind-type system installed underneath a greenhouse glass (Fig. 10c). In this study, the inclination of the PV blind was dynamically controlled. The measurements indicated that during a test period of 5 months, the blind system generates surplus energy of 2125 kJ, resulting in annual surplus energy of 7.8 kWh/$m^2$/yr. Moreover, simulations showed that if the greenhouse is covered with blind systems of zero degrees inclination, the shading percentage would be 40%. They asserted that the shading percentage must be interpreted differently in spherical microcell modules since they do not cast explicit shadow patterns in the greenhouse due to their spherical shape.

**Table 3**
Comparisons between different types of TSPV cells based on the process and performance characteristics, adapted from Ref. [21].

| Solar cell's fabrication method | Year | AVT (%) | $J_{sc}$ (mA/cm) | $V_{oc}$ (V) | FF (%) | PCE (%) | Remarks | Refs. |
|---|---|---|---|---|---|---|---|---|
| Screen printing dye-sensitized solar cell | 2007 | 60 | 16.25 | 0.779 | 73 | 9.2 | • Transparency is controlled by screen printing through a screen made from a mesh stretched over a frame.<br>• The main properties that control film porosity and thickness are mesh count, mesh opening, thread diameter, open surface, and fabrication thickness.<br>• The pressure and speed applied on the squeegee also affect achieved by transparencies. | [80] |
| AV Near-Infrared organic photovoltaics | 2012 | 61 | 12.60 | 0.76 | 54.4 | 5.28 | • Photoactive compounds were used to absorb the sunlight from the near-infrared spectrum and at the same transmits visible light.<br>• Distributed Bragg reflector is grown on the quartz substrate which acts as a transparent mirror.<br>• In this, a heterojunction organic SPV is used which transmits the visible light. | [81] |
| Polymer solar cell | 2012 | 66 | 9.3 | 0.77 | 56.2 | 4.02 | • Active materials that are sensitive to ultraviolet and NIR wavelengths are sandwiched between two chosen electrodes.<br>• The used photoactive materials have potentially high AVT value and at the same time sensitive in absorbing the light from ultraviolet and NIR wavelengths. | [82] |
| Luminescent solar concentrator | 2014 | 86 ± 1 | 1.2 ± 0.1 | 0.5 ± 0.01 | 66 ± 2 | 0.4 ± 0.03 | • This is a new type of solar cell, where the light from ultraviolet and NIR wavelengths is captured by using fluorescent transparent dyes, which are then converted into visible light.<br>• The converted visible light is guided to the solar cell glass edges. | [83] |
| Perovskite | 2014 | 30 | 10.30 | 1.074 | 57.9 | 6.4 | • Metal oxide materials and organic transport materials are sandwiched together to form this type of solar cell.<br>• The materials used for absorption are ensured to have a lower bandgap when compared to the photons.<br>• The absorption material allows the visible light to pass through and at the same time absorb the infrared light. | [84] |
| Electrophoretic Technique dye-sensitized solar cell | 2015 | 55 | 14.83 | 0.68 | 71 | 7.1 | • Deposited electrodes on the glass plate act as cathode and anode.<br>• The reported AVT is 55%. | [85] |
| Dip-coater dye-sensitized solar cell | 2015 | ~70 | 16.17 | 0.738 | 68.8 | 8.22 | • The photoanode is based on the Coral-like $TiO_2$ nanostructure, with a counter electrode as a transparent polyaniline film.<br>• The AVT is reported as approximately 70%. | [85] |
| Quantum Dot solar cell | 2016<br>2016 | 22.74<br>24 | 12.83<br>0.56 | 0.58<br>18.2 | 52<br>53 | 3.88<br>5.4 | • The favorable optoelectronic properties make these materials suitable for STPV cells and also, the absorption spectrum can be varied as per the material cutting.<br>• Tunable bandgap observed in PbS quantum dot material is favorable and helps as a light absorber.<br>• The transparent property for the PbS quantum dot material allows them to use as STSPV cells. | [86]<br>[87] |

**Table 4**
AVT and PCE characteristics for STPV modules.

| Solar cell's fabrication method | AVT (%) | PCE (%) |
|---|---|---|
| Screen printing DSSC | 60 | 9.2 |
| NIR OPV | 55 ± 3 | 1.7 ± 0.1 |
| Polymer solar cell | 66 | 4.02 |
| Transparent LSC (TLSC) | 86 ± 1 | 0.4 ± 0.03 |
| Perovskite | 30 | 6.4 |
| Tandem semi-transparent perovskite | 77 | 12.7 |
| Electrophoretic technique dye-sensitized solar cell | 55 | 7.1 |
| Dip-coater dye-sensitized solar cell | ~70 | 8.22 |
| Quantum dot solar cell | 22.74 | 3.88 |
| | 24 | 5.4 |

In a study by Bambara and Athienitis [100], the energy and life cycle cost (LCC) analysis were performed to examine the installation of STPV cladding on the roof of a greenhouse located in Ottawa, Ontario, Canada. The results indicated that although the STPV cladding can provide the electricity demand of the greenhouse, it causes an internal shading where supplementary lighting consuming 43.7% of the generated solar electricity will be required. They also asserted that the use of STPV cladding is not economically viable at this time but there is a potential of almost 23% reduction in LCC in the future.

The German company BayWa r. e in collaboration with the Dutch company Groenleven installed four pilot orchard agrivoltaic systems in blueberry, blackberry, redberry, and strawberry farms in the Netherlands using glass-glass c-Si STPV modules with various transparencies and cell layouts. After installing pilot projects, a 2.67 MWp agrivoltaic system was implemented in Babberich, Netherlands where STPV modules with a nominal capacity of 258 Wp were installed over a 3.3 ha raspberry farm [101]. The photos of these projects have been shown in Fig. 11.

### 3.1.1. Highlighted points

The c-Si STPV modules are the most common types of modules used in agrivoltaic applications including arable farms, orchards, and greenhouses. The reason is that c-Si PV cells are spatially segmented, allowing part of the sunlight to pass through. Further, the level of transparency, cell layout, color, and type of glass substrate can be tuned, allowing great flexibility in the design. Further, these modules have higher values of cost per nominal capacity (USD/Wp) in comparison with the opaque PV modules. From the literature, it is concluded that:

- In some cases, no significant effect on the growth rate of cultivated plants is observed due to shading caused by the active areas of STPV modules installed;
- The use of diffuse films along with STPV modules can enhance agricultural yield due to their assistance in penetration of sunlight to lower parts of the cultivated plants;
- The use of STPV modules in comparison with opaque PV modules with checkboard patterns leads to more light distribution and consequently higher yields.


**Fig. 7.** Photos of the greenhouse setup integrated with STPV modules [90].

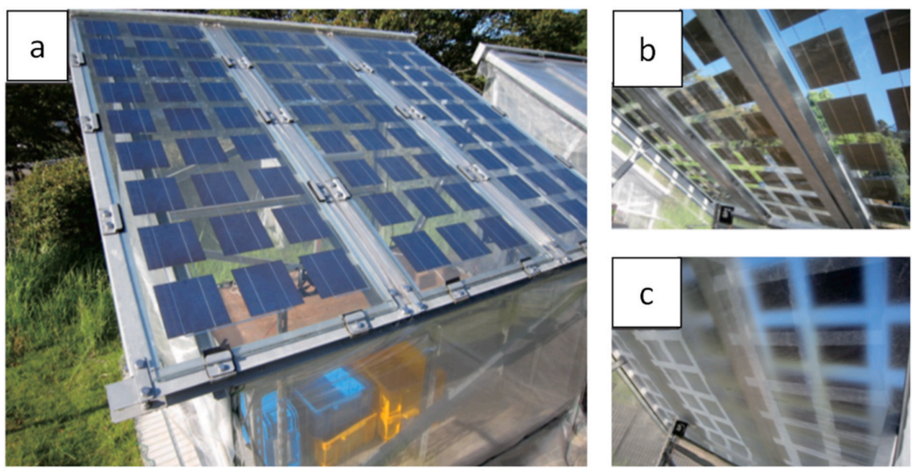


**Fig. 8.** **a)** Research greenhouse integrated with STPV modules [92]; **b)** without diffusion film, **c)** with diffusion film.

### 3.2. *Integration of thin-film STPV modules*

The Spanish company 'Onyx Solar' built a research greenhouse based on solar glass to demonstrate its techno-economic and environmental feasibility [102]. The Chinese thin-film module manufacturer 'Hanergy' integrated semi-transparent double-junction a-Si/microcrystalline-Si modules on a 0.52-ha greenhouse in Beijing [103]. The purpose was to develop a smart, ecological, and energy-saving greenhouse. Thompson et al. [51] studied an experimental setup consisting of growth units (Fig. 12a) where the effect of tinted a-Si STPV modules on the growth of basil and spinach was investigated. The modules used in the experiment were manufactured by the company 'Polysolar' in Taiwan with a nominal efficiency of 8% and power output of 66 W/m$^2$. They could absorb light in the blue and green part of the spectrum and let a red light pass through which gives them an orange tint (Fig. 12b). They found that the biomass yields are reduced for both basil and spinach by 15% and 26% respectively. Moreover, they observed morphological changes (basil with larger leaves and spinach with larger stem), redistribution of metabolic energy, and increased protein. In another study, Aira et al. [104] studied the viability of covering the entire roof of a greenhouse with a-Si solar glass. The prototype greenhouse with a rectangular structure (12 m $\times$ 2.5 m) and a monopitch roof was oriented toward the southwest with 35$^\circ$ inclination (Fig. 12c). The greenhouse was divided by a transparent wall into two equal sections with an area of 15 m$^2$, one covered with a-Si glass roof and the other with conventional glass. The results indicated that a-Si glass slightly reduces the vegetal mass production and speeds up the apical growth rate of heliophiles which was statistically insignificant. They asserted that the electricity produced by PV is sufficient to provide the power demand of the greenhouse. It was also concluded that the proposed technology is more suitable for horticultural production.

#### 3.2.1. *Highlighted points*

Thin-film module technologies can in principle achieve transparency by reducing the thickness of the absorbing layer or by making holes while applying transparent electrodes. The main conclusions are:

- Thin-film STPV modules have already been used in buildings as roof or façade elements. For façade applications, thin-film modules dominate the BIPV market over c-Si solutions due to advantages like appealing aesthetics, homogenous transparency, better temperature coefficient, lower weight, and lower sensitivity to non-optimal orientation;
- The application of thin-film STPV modules is very promising for use in greenhouses since they can substitute the currently used glass covers, resulting in a synergetic cost reduction potential;
- Greenhouses offer large installation surfaces, a parameter important for low energy density modules;
- Despite the high penetration in the BIPV market, only greenhouse research facilities have been reported using thin-film modules with possible explanations being the lower performance and relatively higher cost.

### 3.3. *Integration of semi-transparent OPV modules*

Semitransparent OPV (STOPV) cells due to their absorption characteristics have been of particular interest that can be employed to complement the spectral light needs for plant growth. Shi et al. [105]

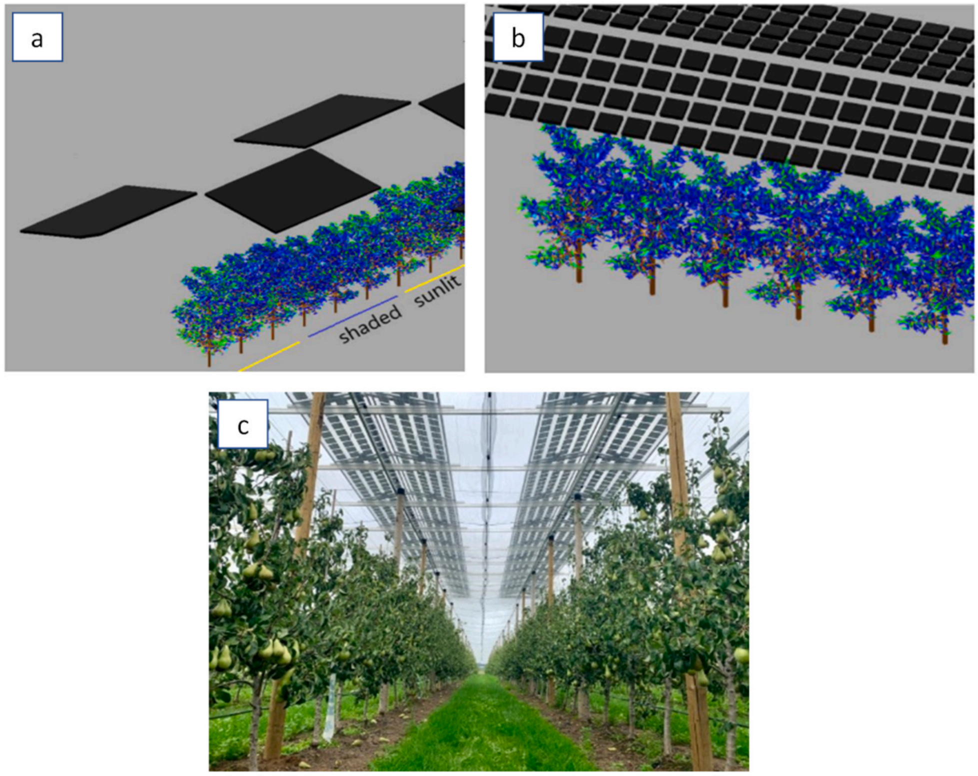


**Fig. 9.** **a)** Opaque PV modules in checkboard pattern, **b)** STPV modules with homogenous light distribution [94], **c)** Pear orchard agrivoltaics, installed in Bierbeek, Belgium [95].

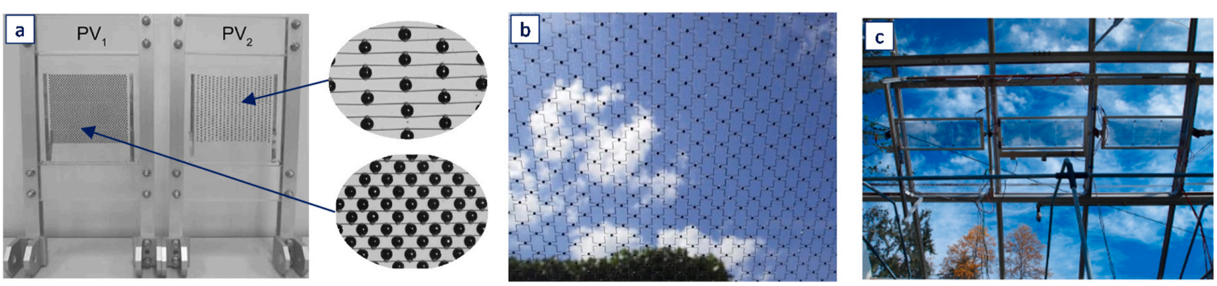


**Fig. 10.** **a)** STPV module contains spherical microcells [97], **b)** STPV module with Sphelar® cells installed on the greenhouse roof [98], **c)** STPV module with Sphelar® cells installed under a greenhouse glass [99].

developed a wavelength selective STOPV cell with a transmission spectrum that matches the absorption spectra of main photoreceptors (Fig. 13), allowing the wavelengths required for photosynthesis to reach the plants. The developed solar cell achieved an efficiency of 7.75% and a crop growth factor of 24.8%. However, it was found that the precise tuning ability is a challenging goal and requires extensive investigation.

Baxevanou et al. [106] investigated the effect on photosynthetic active radiation (PAR) availability of STOPVs installed on top of an arched greenhouse in Greece through computational fluid dynamics (CFD) radiation simulations. In this study, the OPV module had a 30% average PAR transmittance. As shown in Table 4, three different active material cover ratios were investigated, resulting in PAR transmittance of 30%, 45%, and 60%. The results were compared with a reference greenhouse covered with polyethylene and PAR transmittance of 89%. Further, they calculated the daily photosynthesis rate for tomatoes concerning the available PAR, finding reduced numbers compared to the reference case. They reported that only case C could satisfy the threshold of 4 MJ/m$^2$/day. Finally, the yearly power production was calculated per greenhouse length, resulting in considerable $CO_2$ savings (Table 5).

The energy production of STOPV modules integrated into a single-span gable-roof greenhouse was studied by Ravishankar et al. [107] through an energy balance model. The greenhouse had representative dimensions (29.4 m length, 7.3 m width, and 3 m gutter height). The simulations indicated that OPVs can cover the annual energy demand of the greenhouse in hot and mixed-humid climates with an annual PAR reduction of only 10% and 25% respectively (Fig. 14). Moreover, it was found that there is a reduction in the energy demand load when integrating OPVs. It was concluded that semi-transparent OPV modules have great potentials for achieving net-zero energy greenhouses.

Friman-Peretz et al. [108] studied the microclimate, yield, and physiological parameters of the tomato crop grown in two greenhouse tunnels (Fig. 15); (i) control (without shading screens in 2018, and with 25% shading screens in 2019), and (ii) covered with flexible STOPV modules (with 37% roof coverage and 23% shading-modules from 'OPVIUS' company). In the OPV tunnel without shading screens, the number of tomatoes and their average mass were found higher by 9.36% and 21%, respectively, despite the lower solar radiation entered the greenhouse which was claimed due to the lower ambient and leaf


**Fig. 11.** Orchard agrivoltaics installed in the Netherlands [101]; **a)** 60 kWp pilot project over strawberries, **b)** 95 kWp pilot project over blueberries, **c)** 130 kWp pilot project over blackberries, and d) 2.67 MWp project over raspberries.

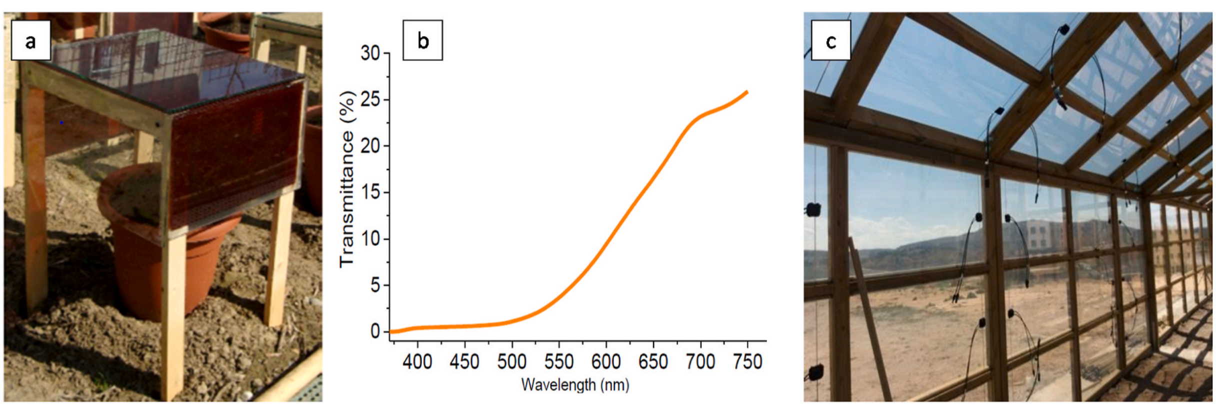


**Fig. 12.** **a)** The growth unit covered by a-Si solar glass, **b)** Spectral response of the a-Si STPV under the visible spectrum [51], **c)** Internal view of the greenhouse with a-Si solar glass installed on the roof [104].

temperature measured in the OPV tunnel. While in the OPV tunnel with 25% shading screens, no significant differences in the yield and microclimate were observed in comparison with the control tunnel with shading screens. It was concluded that OPV modules can substitute shading screens, protecting the plants and providing clean electricity.

A detailed economic study on OPVs as foil roofs for greenhouses was conducted by Emmott et al. [60]. Depending on the commercial conditions, a minimum efficiency required to make the investment self-sustaining in Spain (2200 kWh/m$^2$a) was calculated. The minimum required OPV's efficiency was calculated as 1–2% for cases in which either the electricity has a high value and the modules last for a long time (electricity price 0.18 USD/kWh, module price 34.65 USD/m$^2$, 10 years durability), or OPV modules are extremely cheap (0.1 USD/kWh, module price approx. 6 USD/m$^2$, 5 years durability). For the "Baseline" scenario (0.1 USD/kWh, 46.2 USD/m$^2$, 5 years durability), the minimum efficiency was calculated as 10%. They concluded that the values will be more reduced if significantly higher durability of more than 5 years is achieved. A 43 m$^2$ of ASCA® OPV films (composed of 79 modules) manufactured by the company 'ARMOR' were installed in greenhouses in France where different installation approaches were evaluated. In this case, modules were installed on the external vertical greenhouse façade, indoor horizontal shade sails, and indoor vertical shading curtain as shown in Fig. 16. According to manufacturers, these modules can reach up to 30% transparency with lightweight and flexibility, allowing them to become easily removable [109].

Regarding efficiency, opaque OPV modules offer smaller efficiencies than other module technologies [110]. When transparency is considered, according to Ref. [111], for AVT over 40%, OPVs can potentially be the most efficient modules. Currently, in laboratories, AVTs in a range of 60–65% with PCEs in a range of 4–5% have been achieved for OPV cells [78,112,113].

From the perspective of the environmental hazard, Hollingsworth et al. [114] reported that only five years lifetime of OPVs is less hazardous than silicon-based PV in terms of g$CO_2$/kWh. However, another important indicator of the energy return on investment (EROI) is lower than the silicon-based PV for the five-year lifetime of the OPV. On the

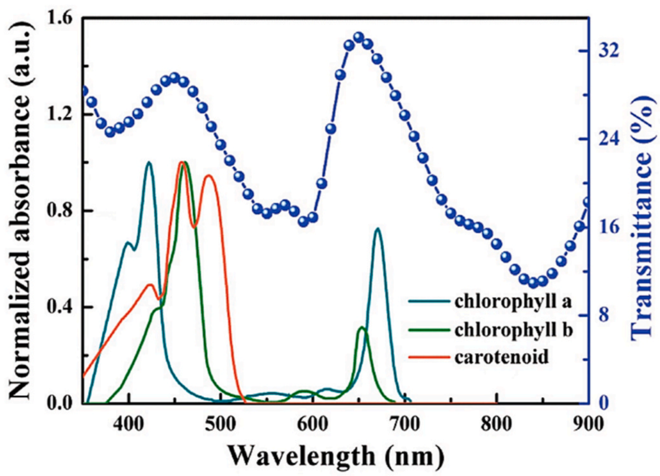


**Fig. 13.** Optical absorption spectra of chlorophyll *a*, chlorophyll *b*, and carotenoid, and the transmission spectra of the developed polymer solar cell [105].

**Table 5**
Results for CFD simulations of a greenhouse integrated with OSTPVs, data taken from Ref. [106].

| | Case A | Case B | Case C |
|---|---|---|---|
| Active cell material cover ratio | 75% | 56% | 37% |
| PAR transmittance | 30% | 45% | 60% |
| Reduction of PAR compared to reference case | −77% | −66% | −52% |
| Reduction of the daily average photosynthesis rate compared to the reference case | −33% | −21% | −12% |
| Yearly power production per greenhouse length (kWh/m/yr) | 323 | 242 | 158 |

other hand, regardless of the lifetime, the energy payback time (EPBT) for OPVs is considerably low. The feasibility of using OPV modules on a greenhouse roof in the Mediterranean was studied by Magadley et al. [115]. For this purpose, a detailed analysis of the outdoor behavior of OPV modules in terms of the impacts of environmental parameters and orientations of panels on their degradation and the electricity output was conducted. The results indicated that those OPVs installed on the roof yield the highest output, efficiencies, and FFs, while installations on East and West walls cause midday output peaks reduction, resulting in a more balanced power supply during the day. In another study, Waller et al. [116] analyzed a hydroponic tomato production greenhouse integrated with a roll-to-roll printed STOPV array as a shading roof during spring and summer, under climate conditions of the arid southwestern U.S. For this purpose, tomato growth and yield parameters were measured in both STOPV-shaded and non-shaded sections of the greenhouse. From the results delayed fruit ripening occurred in the STOPV-shaded greenhouse, causing lower total yields of 24.6 kg/m$^2$ in comparison with the control greenhouse with the yield of 27.7 kg/m$^2$ with no significant difference after the fourth harvest. They concluded that the use of STOPV as a seasonal shade is feasible in locations with high availability of solar radiation.

### 3.3.1. Highlighted points

Due to the property of narrow-band absorption, it is more difficult to achieve high solar efficiencies in OPVs but brings the chance to design solar cells, allowing the visible spectrum to pass through and using only invisible UV or IR for power generation [60]. The main conclusions are:

- Till now, OPVs and DSSCs are the only ones with unique features of wavelength-selective transparency together with low weight, flexibility, and color selection, making them more promising to be integrated with agrivoltaic systems [60];
- In greenhouses, OPVs can easily be integrated with the substructure or substitute with plastic materials such as polyethylene since they have similar properties, while in open fields, they can be used in orchards and be substitute with protecting foils or nets. Further, the OPVs can provide better light control, less intensive supporting structure, and better integration into the environment due to their different color choices [75];
- An important barrier for OPVs to be commercialized is their stability. Several factors affect the stability of OPVs such as oxygen ($O_2$), heating, water, irradiation, metastable morphology, diffusion of electrodes and buffer layers materials, and mechanical stress [117]. The instability makes the lifetime of OPVs unpredictable and lower than c-Si modules, while more than 10-years are required to be competitive in the market [118].
- Another important barrier for OPVs is their low commercialization level, causing them to become more expensive despite the existence of companies like 'ARMOR', 'Heliatek' and, 'Sunew' which are trying to bring this technology into mass production.

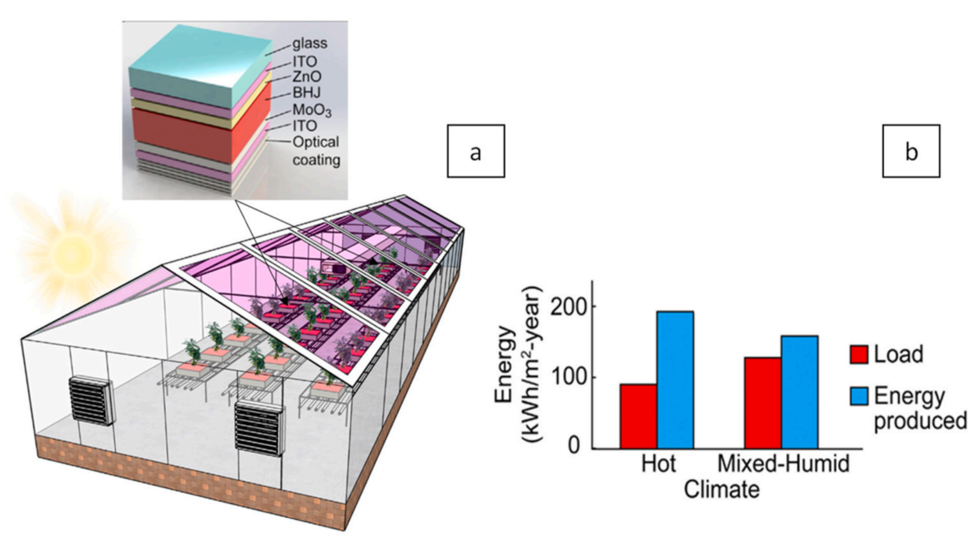


**Fig. 14. a)** The modeled greenhouse integrated with STOPV modules, **b)** Energy production compared to energy demand [107].

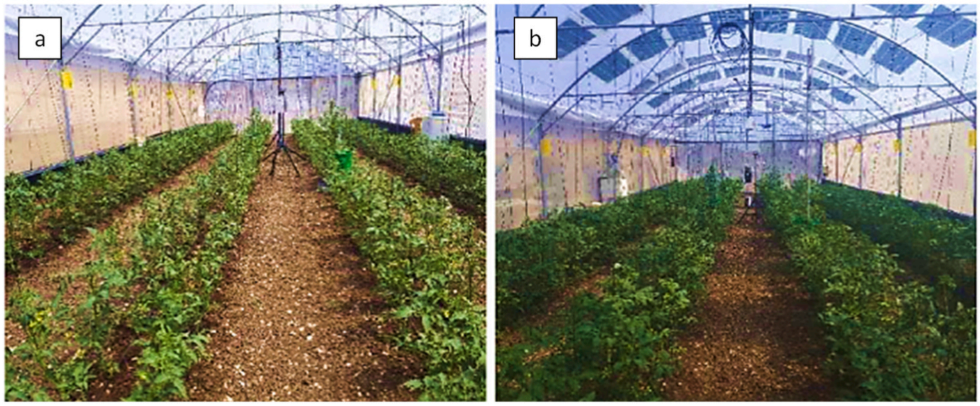


**Fig. 15.** Inside view of greenhouses [108]; **a)** The control tunnel, and **b)** The OPV tunnel.


**Fig. 16.** The ASCA® OSTPV modules installed on; **a)** Vertical greenhouse facade; **b)** Indoor horizontal shade; **c)** Indoor horizontal shade sails [109].

- There are though cost reduction potentials for OPVs in the future since they are based on abundant non-toxic materials, and low temperature, low cost, and fast manufacturing techniques [119]. They can be competitive in applications where they exhibit advantages over other technologies, like BIPV [107,119].
- Since there is little literature investigated the effect of OPVs on crop growth trends, except technical development of the modules, more researches are required to study the crop response with a special focus on the effects of altering the solar spectrum on plant physiology.

### *3.4. Integration of STPV modules using DSSCs*

Kim et al. [72] developed and characterized a special DSSC for greenhouse applications using novel Ruthenium (Ru) sensitizers to enhance the transmittance of the red and blue wavelengths. They measured 62% transmittance at 660 nm (red) and 18% at 440 nm (blue), and the sun to electricity efficiency of 4.96%. Mourtzikou et al. [73] developed a 50 $\times$ 50 $cm^2$ STPV module using DSSCs (Fig. 18a) with efficiency in the region of 2% and high transparency in the region between 600 and 900 nm (Fig. 18b). The STPV module was validated in a 100 $m^2$ greenhouse prototype in Greece with tomato cultivation (Fig. 18c) and compared with a reference greenhouse. The researchers found that tomatoes in the DSSC greenhouse grow better, while at the

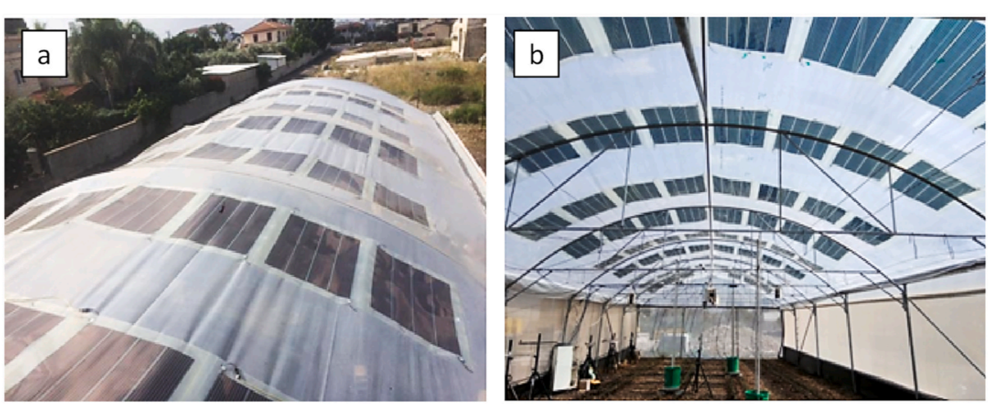


**Fig. 17.** Photos of the installation of OPV modules on the roof of the tunnel greenhouse [115]: **a)** Outside view; **b)** Inside view.

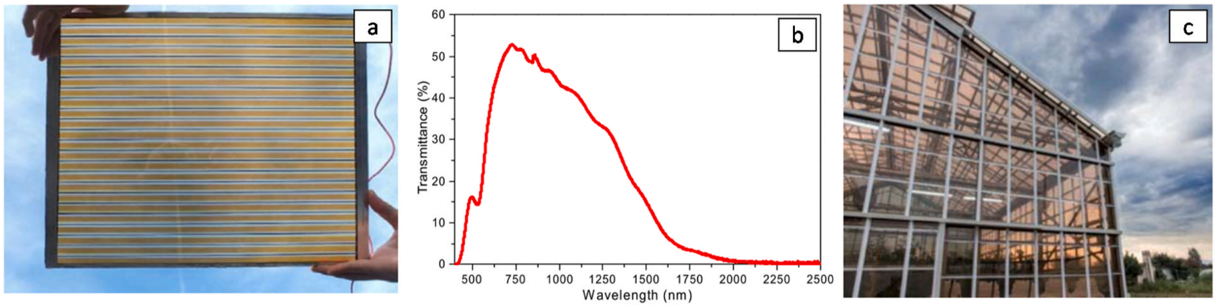


**Fig. 18.** **a)** A 50 × 50 $cm^2$ DSSC module, **b)** Transmittance of the module over the whole solar spectrum, and **c)** A 100 $m^2$ greenhouse prototype with DSSC [73].

same time the measuring sensors are operated by the electricity produced by the DSSC module. It was also found that in the DSSC greenhouse there is a reduction in the usage of pesticides due to the blocking of the UV light.

### 3.4.1. *Highlighted points*

DSSC is an electrochemical device that uses light-absorbing dye molecules to convert sunlight into electricity. Dye color varies and also defines the light absorption properties of the DSSC. Therefore, as like the OPVs, DSSC could also be manipulated and absorb the certain solar spectrum band [74]. The main conclusions are:

- In DSSCs, titanium dioxide ($TiO_2$) is used as a semiconductor material and its good insulation properties also make this technology quite suitable for use in greenhouses [120]. Furthermore, it is more aesthetic and colorful than conventional systems, which helps to increase social acceptance [121];
- DSSCs are flexible, lightweight, and can be used as a roll-able screen which means they hold the advantages of OPVs. Additionally, another similarity with OPVs is that DSSCs also work under diffuse light conditions since their performance is independent of the incidence angle of the light;
- One of the most important properties of DSSCs is that they employ a light-scattering layer to enhance light absorption. It scatters the direct light that is reached to the canopy and improves the diffusion of light [120].
- Transferring sunlight through photo-selective films and increasing the amount of diffuse light in the greenhouse improves the light penetration and homogeneity into the plant canopy, assisting in reaching the light all over the cultivated plant[3] [120].

After many years of research, DSSC technology has started to enter the market. Above mentioned properties make them attractive for usage in BIPV, greenhouses, and agrivoltaics. However, real practices and experiments are required to understand the technology better. There are still stability problems and the resistance of the module under real working conditions is not as well-known as conventional systems. Efficiency is another factor that should be improved to make the technology more attractive. Furthermore, more research is required to be performed to understand the effects on the plants.

## 3.5. *Integration of concentrating STPV modules*

CPVs use optical reflectors or refractors to concentrate received sunlight on a solar cell. The CPVs are categorized depending on the concentration ratio as high-concentration PVs (HCPVs) and low-concentration PVs (LCPVs). The key advantage of CPVs is that the concentration of light reduces the required PV area, allowing the use of expensive, highly efficient III-V multijunction solar cells. The CPVs usually require a tracking system since they can only use direct irradiation, making them more economically attractive for regions with direct normal irradiation of more than 2000 kWh/$m^2$a [122].

Depending on the concentrator optics, two approaches can make CPVs semi-transparent. For semi-transparent CPVs (STCPVs) that use Fresnel lenses, diffuse sunlight can pass through, thus being available for the plants. On the other hand, when curved mirrors are used, special dichroic mirrors can be applied, allowing wavelength-selective transparency. As indicated in Fig. 19a, Fresnel lenses allow most of the diffuse light to reach the plants and are utilized for photosynthesis, making these modules suitable for dual land applications in agrivoltaic systems. Another widely used concentration optics in CPVs are curved mirrors in various shapes. In this case, wavelength-selective transparency can be achieved by coating concentrators with dichroic materials or polymeric dichroic mirrors, allowing the PAR region to pass through while reflecting the NIR to the solar cell (Fig. 19b) [123].

Based on the concept of STCPVs [124], a small prototype module was developed by Hirai et al. [124] and its performance was evaluated under outdoor conditions () where arrays of lenses concentrate the direct sunlight to III-V triple-junction solar cells. They measured an average module conversion efficiency of 28.2% and a diffuse sunlight transmittance of over 70%, for any diffuse-to-global ratio. Moreover, they compared the solar irradiation reaching the plants and electrical yields of a system with CSTPV modules and traditional c-Si modules. The simulation indicated that light homogeneity and quantity are much higher in the CSTPV case while electrical yield is slightly lower.

The Swiss start-up company 'Insolight' has started commercializing a micro-concentrator module with integrated planar micro-tracking [125–127]. The module is composed of biconvex 180x lens arrays and highly efficient III-V solar cells. The developed modules come into two versions, one hybrid (Fig. 20a) where c-Si are introduced on the backplane to catch the diffuse light, and one transparent (Fig. 20b) called THEIA where most of the diffuse light is allowed to pass through. Measurements on the hybrid module showed a 29% module efficiency under concentrated STC Results indicated that micro-scale CPVs using solar cells with a size below 1 mm have better performance and at the same time a much lower form factor, allowing module widths comparable to normal c-Si modules [125].

Nardin et al. [126] simulated the performance of Insolight's THEIA CSTPV module and compared its performance with the c-Si STPV module under the same amount of transmitted solar radiation to the plants. The simulations showed that THEIA modules have higher electric yields in four different locations, where direct normal irradiation (DNI) values ranged from 1500 to 2500 kWh/$m^2$/yr. It was also claimed that THEIA modules can allow the whole radiation to reach the plants, if necessary, during their growing phase, by misaligning the backplane, allowing for dynamic control of the sunlight. Except for dynamic light control and homogenous light, the THEIA modules can be installed at a fixed tilt angle that makes their integration into greenhouses easier (Fig. 21c).

The potential of transparent tracking-integrated CPVs with lenses for dual land use purposes was evaluated by Apostoleris and Chiesa [129].

[3] Plants use diffuse light more efficiently than direct light.

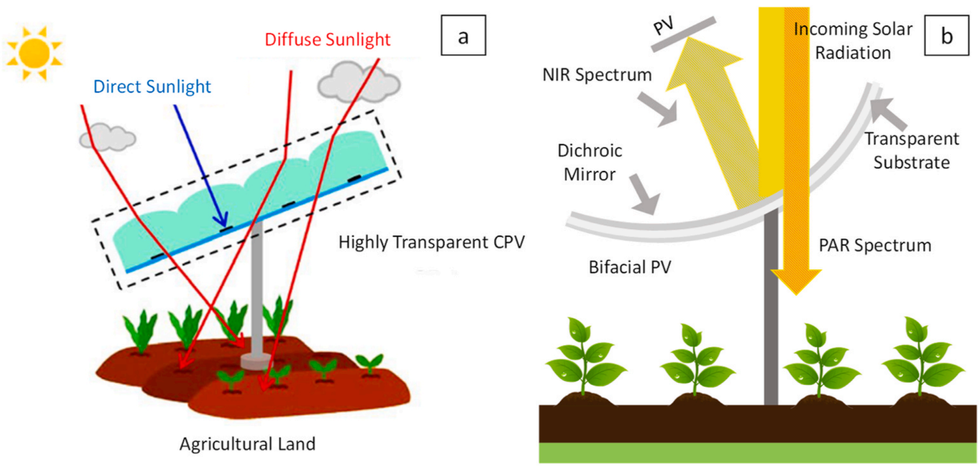


**Fig. 19. a)** Concept of CSTPV module using Fresnel lens [128], **b)** Illustration of the basic parts of the dual-axis tracking dish type CPV system with a beam filter [123].

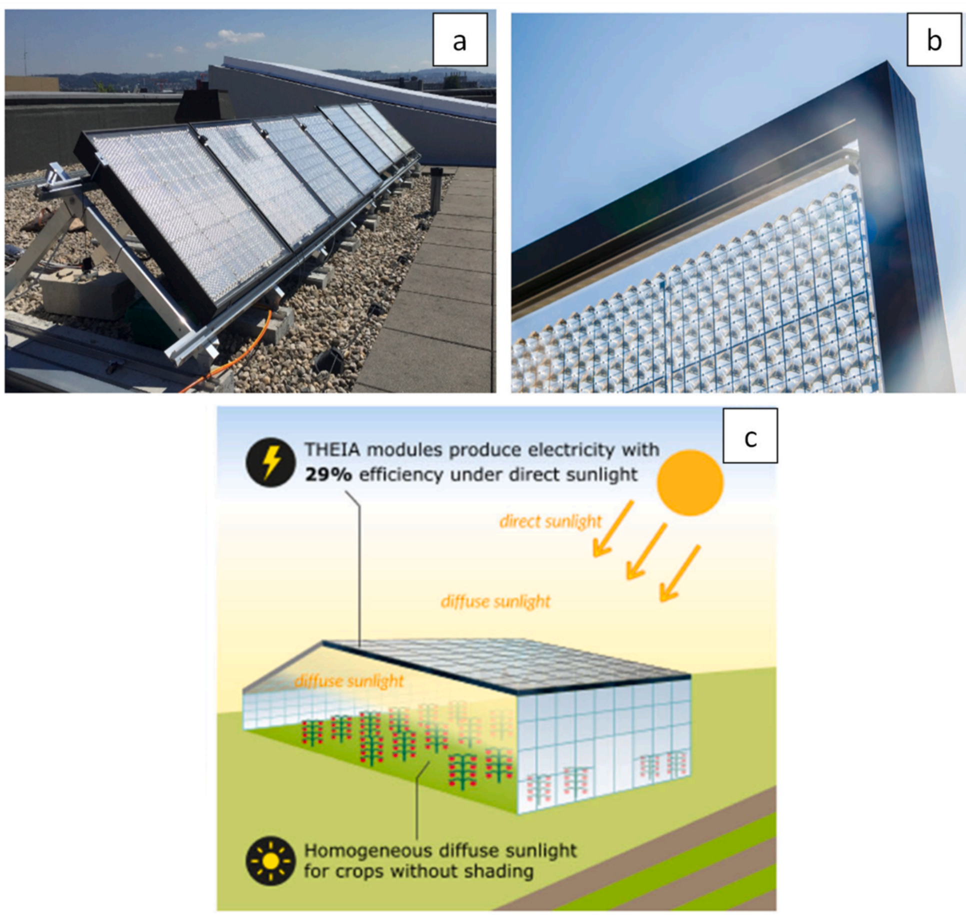


**Fig. 20. a)** Rooftop pilot plant with Insolight hybrid CPVs modules, installed in Lausanne, Switzerland [125], **b)** An assembled transparent micro-tracking CPV module; **c)** Illustration of THEIA modules integrated into a greenhouse [126].

They compared the electric yield of c-Si modules (16% efficiency) with CPV modules (29% DNI efficiency, 70% transmittance of the diffuse light, and three different acceptance angles, ±40°, ±50°, and ±70°) under the weather conditions of Massachusetts by simulations. The results indicated that the CPV module can provide comparable electricity production while at the same time allow enough light for the plants to be transmitted. In a study by Huang et al. [130], the effect on plants and electric yields of a beam filter applied to a dish-type concentrator through simulations was evaluated. The beam filter was a 160-layer dielectric film with high transmittance at the blue (420–460 nm) and red (630–670 nm) chlorophyll absorbing wavelengths (Fig. 21). The results indicated that the system can meet the light requirements of the most important Chinese plants (wheat, rice, corn, nectarine) regarding light intensity, quality, and duration and at the same time achieve promising electric yields with a c-Si solar cell at the focal point. Moreover, they stated that the beam filter can be customized to each type of

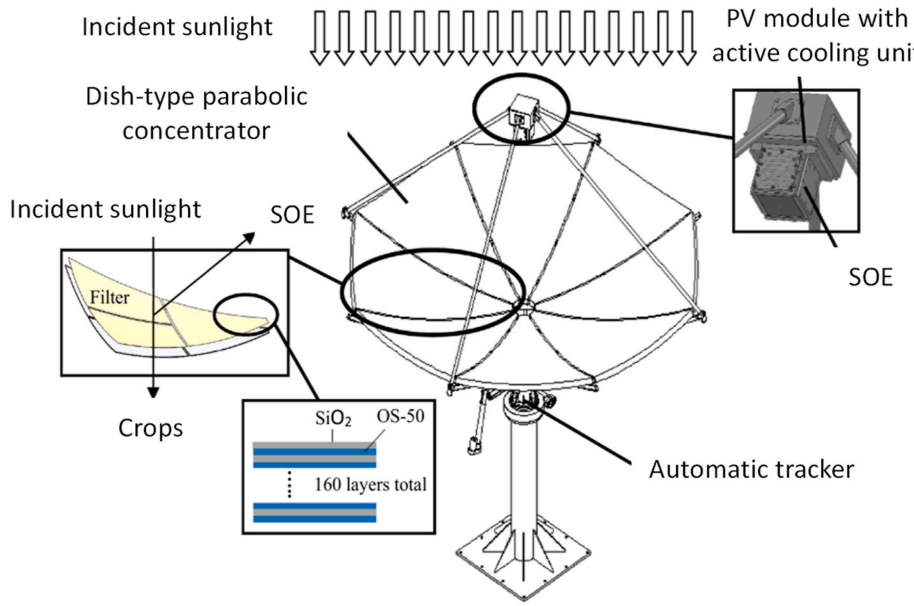


**Fig. 21.** Illustration of a CPV module with a dichroic mirror, allowing the PAR spectrum to reach the plants while NIR is reflected on a PV cell [130].

plant allowing for optimum wavelength selection.

A novel APV-CPV consisting of a parabolic concentrator was developed (Fig. 22a) [131,132]. The concentrator is coated with a special dichroic film, allowing red and blue light to be transmitted to the plants (Fig. 22b), while the rest wavelengths are reflected on the focal point where a c-Si solar cell is located. Moreover, an additional solar cell installed on the top of the focal point directly receives the light. The system can provide 90 W/m$^2$ with an overall measured efficiency between 8% and 9%, although a 16% efficiency can be theoretically reached. Experiments performed with three different plants (lettuce, cucumber, and water spinach) showed that those under the films grew better than those directly exposed to the sun, showing the higher photosynthetic rate and higher contents of soluble sugar [131]. Moreover, an economic analysis showed that under a massive production scenario, the average cost of the system is 1.5 USD/W, with the spectral system being almost 1/3 of it. Finally, several pilot projects are planned by the researchers to further develop and research the system [132].

### 3.5.1. Highlighted points

Before being widely adopted for agrivoltaics further improvements in the module performance, reliability, and production technologies are required, which together with increased commercialization can take the costs down and compete with available technologies. Finally, during the design phase of systems with CPVs, the site's diffuse-to-global ratio is a very important factor that must be considered, since it determines the percentage of light available for plants and electricity. The main conclusions are:

- The literature survey demonstrates that the potential of CSTPV modules using lenses makes them a possible solution for dual land use applications. They act as a solar splitter, using the direct sunlight for electricity production and the diffuse sunlight for plants' growth [133], turning the disadvantage of CPVs of not utilizing the diffuse sunlight into an advantage. While concentrators coupled with spectral splitting dichroic mirrors can allow wavelength-selective transparency, which can offer a strategic advantage for agrivoltaics.
- The use of highly efficient multijunction solar cells makes the electricity production comparable to or even higher than conventional c-Si PV modules, while at the same time diffuse light is available to the plants [126,128]. However, more investigation on the module effects on plants' growth under real conditions is required.
- The efforts by the company 'Insolight' show that the commercialization of these systems is not far away and a pilot production line is to be finished in 2021 [126]. The remaining challenges before the mass production of the modules are the development of industrial production processes and a suitable norm to define the nominal characteristics of the module.

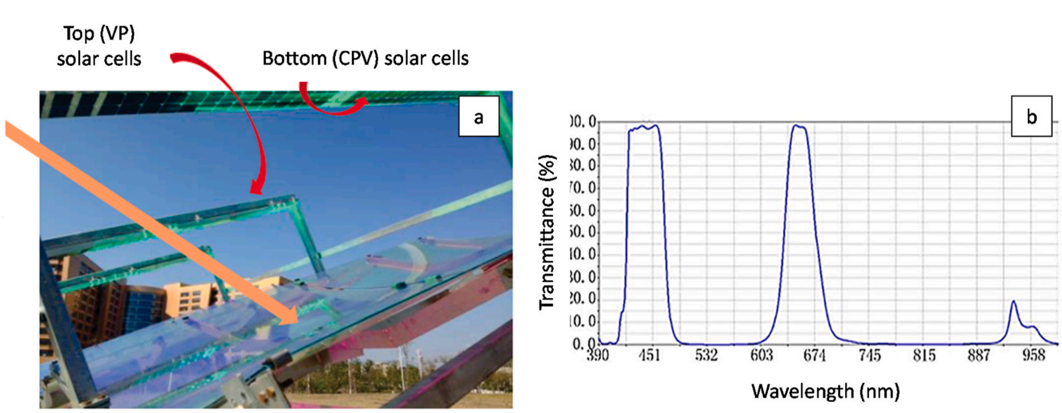


**Fig. 22. a)** Novel APV-CPV system [132], **b)** Transmission spectrum of the designed dichroic film [131].

- Although CPVs modules are widely commercial, systems coupled with solar beam splitting materials are still at a pilot phase. Further studies and investigations are needed regarding the performance and validity of solar splitting materials and their effects on both the electrical performance of the CPV and the plants' physiology. Moreover, effective industrial productions must be developed to reduce the price and make them competitive in the market.

### 3.6. Integration of luminescent solar concentrators (LSCs)

A group of scientists from the University of California [134–136] developed a semi-transparent system combining an LSC with conventional c-Si solar cells, which they named Wavelength Selective Photovoltaic System (WSPV). In contrast to the usual approach, they placed the cells in front of the module, allowing for direct sunlight utilization and reducing the traveling distance of the light. They asserted that the luminescent dye absorbs some of the blue and green wavelengths which remits into red wavelengths and guides to the solar cells for electricity production, while the rest of the sunlight is available for the plants. A variety of panels with different cell layouts and cover ratios were manufactured and tested. Cover ratios of 21% led to a panel efficiency of 6.8% while a cover ratio of 15% led to 3.7% PCE [135].

In a later study, Corrado et al. [134] compared the performance of various WSPVs panels covering a greenhouse, with a reference case, where c-Si cells of the same size were incorporated on clear glass, without luminescent material. The LSC panel showed improved efficiency (3.8%) compared to the non-LSC panel (2.9%). The authors concluded that a greenhouse covered fully with the WSPVs would generate 57.4 kWh/m$^2$/yr which is three times higher than the electricity demand of a typical greenhouse in California. Moreover, in the same study, the 20-year reliability of the luminescent material was confirmed under the UV testing system. Loik et al. [136] examined the response of tomatoes' cultivars grown under a greenhouse covered fully with WSPVs and one reference covered by the clear glass (Fig. 23). The WSPVs had 12% of their surface covered by c-Si stripes and showed 60% AVT transparency. Under low light conditions, the photosynthesis rate of tomatoes was found similar, while the light-saturated photosynthesis was slightly lower for tomatoes under WSPV. On the other hand, small water savings potentials were found for plants under WSPVs. Regarding the total number of fruits and fruits' mass per plant, differences were observed between cultivars. Some cultivars showed no changes between WSPV and clear glass, while others had slightly lower or higher numbers. Lastly, they calculated the photosynthetic efficiency via the light-adapted energy transfer in photosystem II for 18 species, founding similar responses under WSPVs and clear glass, while 5 of them showed improved efficiency under WSPVs.

#### 3.6.1. Highlighted points

- The WSPVs can directly substitute the plastic and glass coverings used till now in greenhouses, offering the opportunity for electricity production and light control for the plants. The luminescent material used in the WPSVs can increase the panel's efficiency, adapt the light to the needs of plants, and at the same time is relatively cheap (10 USD/m$^2$) [136].
- Moreover, the first preliminary studies showed positive plants' responses [136]. These advantages made the system commercial from the USA company 'Soliculture'. On the other hand, there is space for further improvements of the technology, for both electricity production and plant productivity [134].
- Key targets are the optimum adaptation of the optical properties of the luminescent dye to the plants' needs and the increase of the panel's efficiency [134]. Additionally, further studies on the impacts of the altered light environment on plant growth and quality are necessary [136].

## 4. Conclusions and prospects

The employment of PV technology is globally growing up in the agriculture sector, providing better energy self-sufficiency and environmental sustainability in cultivation systems. The PV systems are more affordable in distributed electricity generation settings compared with grid electricity or diesel generators having the most operational feasibility in rural areas and remotely access agricultural environments including ranches, orchards, greenhouses, etc. The agrivoltaic systems can be installed both on open-filed farms and in closed cultivated environments of greenhouses. At this time, most of the PV systems installed in cultivation environments are using conventional opaque PV modules. But, the main problem with these modules is their adverse impacts on crop growth when there are high shadowing ratios. One potential solution for this issue is employing STPV modules. Therefore, in the present study, the recent advances of using STPV module technologies based on c-Si, thin-film, organic, and DSScs as well as emerging technologies of C STPV modules in cultivation environments are investigated and profoundly discussed. In this regard, the most highlighted findings from this study are as follow:

- Several technologies possibly offer transparency in PV modules, but the assessment over STPV technologies suggests thin-film and Perovskite solar cell technologies as more suitable options to fabricate STPV modules. However, in terms of their usage in crop cultivation environments, the AVT and PCE must be given equal importance while choosing the most appropriate technology to ensure the synergies between energy and crop production.

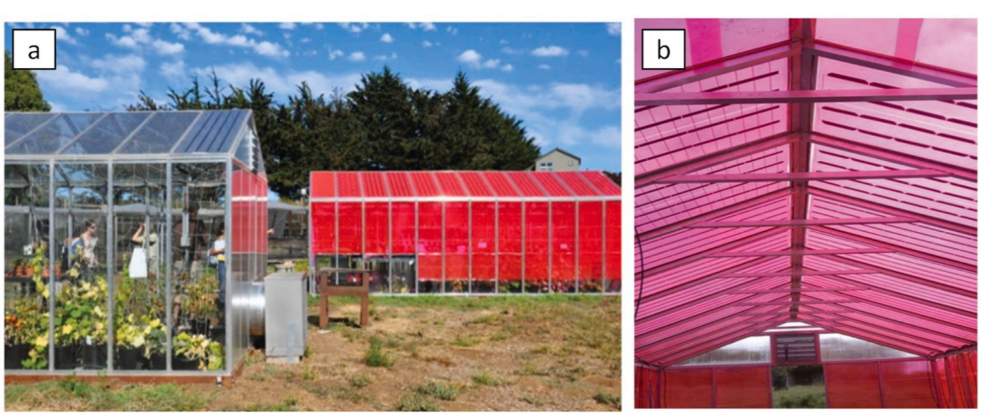


**Fig. 23.** **a)** Photo of greenhouses, one covered with clear glass (left) and one covered with WSPVs (right) [134], **b)** Inside view of the greenhouse constructed with WSPVs, at the University of California Santa Cruz Arboretum [136].

- Among different STPV module technologies, c-Si are already widely available with research and commercial installations on both greenhouses and orchard agrivoltaics. Their low cost, stability, and high efficiency make them dominate the market. Initial studies demonstrated already their advantages over opaque modules on plant responses.
- Other commercially available STPV options are thin-film modules (a-Si, CIGS, CdTe), but till now, very little literature or projects were found on these technologies. Both commercially available c-Si and thin-film technologies offer non-wavelength selective transparency, meaning that there are limitations on the maximum AVT transparency that can be achieved. At the same time there is a direct trade-off between efficiency and transparency, making STPV modules less efficient and with higher per nominal power cost.
- A solution that could potentially overcome the limitations of the current technologies could derive from STPV modules based on OPVs or DSSCs. These technologies can achieve wavelength-selective transparency, allowing the PAR to pass through and utilizing the rest of the spectrum for electricity production. In principle, high AVT levels can be achieved while maintaining relatively high efficiencies. A literature survey shows that using OSTPVs has several advantages including selective transparency, low weight, flexibility, and tunable color, making them a promising solution for installation in cultivation environments and substitution for directly applied to protect materials (glass, foil, nets).
- Although there are many companies active on semi-transparent OSTPV modules, further technical improvements are required to bring them into mass production. Additionally, more research is needed to improve their efficiency, AVT levels and solve the stability issues that accompany this technology. Except for the technological side, detailed studies on the plant response are also crucial, especially with regards to photomorphogenic effects due to the reduced infrared wavelengths.
- The STPV modules based on DSSCs also carry the same advantages and disadvantages as OSTPVs, but the corresponding literature is much lower for this technology. While there are additional potential solutions that come from the field of CPVs integrated with lenses as concentration optics in which diffuse light is available for the plants' growth and direct concentrated sunlight is used for electricity production. In CPVs used in crop cultivation environments, the concentrated light along with the use of highly efficient solar cells make this technology having potentially higher efficiencies than other STPV modules.
- Although CPVs coupled with concentrating mirrors offer the possibility of wavelength-selective transparency and pilot systems have already been developed, because of the lower form factor of lens-based CVPs compared to mirror-based CPVs, their integration on dual land purposes is much easier. In general, CPV is a promising technology for agrivoltaic applications, especially in regions with high direct normal irradiation (DNI). In these regions, the electricity production is higher and the plants' protection against high insolation is essential, while at the same time the diffuse radiation remains high. On the other side, improvements in the module's performance, reliability, and manufacturing processes are crucial for the technology to gain a position in the market.
- The coupling of luminescent materials and c-Si have shown positive effects on the panel's efficiency. Improvements on the luminescent material properties and overall module efficiency are further research goals of this technology. However, for both CPVs and LSCs options, the literature regarding the plant responses is scarce. In-depth research regarding the photomorphogenic and photosynthetic effects of the altered radiation is required.
- In agrivoltaic systems using STPV modules, similar to those using conventional ones, the PV modules are exposed to soiling due to installation in agricultural environments. Dust accumulation on the surface of PV modules can diminish their transparency, affecting their power output. Therefore, regular cleaning of PV modules or wetting of disturbed soil is required depending on the type of agricultural activity [137,138]. Cleaning of PV modules in agrivoltaic systems can be accomplished as a routing standard farming activity or performed using spray irrigation since PV arrays can act as irrigation or rainwater runoff channel which can then be directly used by crops. Therefore, the water used to clean modules can be consumed by plants cultivated beneath, increasing the water use efficiency [138]. As an additional solution, in excessively dusty environments, the use of PV modules with self-cleaning glass surfaces has been suggested, assisting in keeping the modules clean all the time [71,139]. However, more research is required to technically and economically investigate the feasibility of employing these approaches.

In agrivoltaic systems, the performance of the PV depends upon the quality of the solar radiation as a function of light intensity which is itself a function of the weather, cloud cover, daytime, altitude, and latitude of the location, while the crops yield is a function of the efficiency of the process of converting the PAR to generate biomass [71]. Therefore, creating a balance between the solar radiation requirement for solar electricity generation and crop production is crucial to both improve the power and agricultural yield production. Regarding this, finding the optimal sites for the construction of agrivoltaic systems, designing the best structure and arrangement of PV arrays to maximize the exposure of high-quality solar radiation for PV arrays and optimal PAR for crops, as well as selecting the most suitable crops are crucial factors that should be taken into account for the implementation of agrivoltaic systems. Simultaneous development of fabrication methods can bring those technologies to mass production and reduce their current high cost gradually. At the same time with the technological research, equally important is the further study of the plant responses on the different technologies, in terms of both photomorphogenic and photosynthetic effects. The literature in this regard is rather scarce, but recently the field of agrivoltaics has gained attention.

### 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.

### Acknowledgments

The authors would like to thank the advisory support from the Fraunhofer Institute for Solar Energy Systems ISE and Tarbiat Modares University (http://www.modares.ac.ir) for the financial supports given under the IG/39705 grant for 'Modares Renewable Energy Research Group'. All permission for the reproduction of copyrighted materials has been duly obtained from the publisher or the rights holder.

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