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Spectrally selective modules for agrivoltaics

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Agrivoltaics, the co-location of photovoltaics (PV) and agriculture where the PV is adapted to needs of agricultural production, is a valuable approach to help deliver the clean energy transition and is increasingly being deployed globally. When thoughtfully deployed, agrivoltaic installations can provide benefits to both energy and food production as well as the rural communities in which they are located. In order to adapt photovoltaics for optimal use in the most promising horticultural agrivoltaic applications commercial semi-transparent PV modules are required. Here, we review existing commercial and emerging semi-transparent PV technologies proposed for agrivoltaic applications. Performance comparison of the available PV technologies indicates partially populated c-Si modules with transparent substrates will be the dominant semi-transparent agrivoltaic technology for the foreseeable future. Therefore, we suggest that significant research effort should be devoted to developing methods that introduce spectral selectivity in these modules; with the objective of redirecting portions of the solar spectrum not required by crops for photosynthesis, particularly the near infra-red, to the c-Si cell matrix for conversion to electricity. A design concept to achieve this in a commercially viable format is proposed.

Broader context

In the energy transition from a system based on burning fossil fuels to renewable energy sources, solar photovoltaic energy will play the primary role. To meet 2050 decarbonisation goals, it is likely a 40-fold increase in deployed photovoltaic capacity will be required. A majority of this will be installed on productive agricultural land and raises the pressing question of how best to integrate photovoltaics with agriculture and maximise the benefits to both. It is possible to deploy photovoltaic generation above horticultural crops in '*agrivoltaics*', which can provide benefits to both energy and food production as well as the rural communities in which it deployed. Central to the success of horticultural agrivoltaics will be semi-transparent photovoltaic panels that can be spectrally selective and optimally share the solar spectrum between what crops require for photosynthesis and photovoltaics need for energy conversion. This work comprehensively reviews and compares the performance of semi-transparent photovoltaic technologies that have been demonstrated or suggested for agrivoltaics. We identify the need to develop methods that introduce spectral selectivity into efficient, affordable and reliable incumbent crystalline silicon photovoltaic modules, then propose a commercially relevant concept to do this.

Introduction

It is on land currently dedicated to agriculture that a majority of solar PV will be deployed, as the global energy system is transitioned to emission free renewable energy.[1,2] There are a number of drivers for this, agricultural land is generally already cleared, flat, free from protected status and close to existing transport infrastructure, allowing deployment and operation costs to be minimised. Most importantly, though, a majority of solar PV deployment will occur close to existing electricity grid transmission infrastructure, which is located around and between major population centres; the same areas as the most productive agricultural land.

The coming expansion of PV deployment into agricultural regions raises the pressing question of how best to integrate solar PV with agriculture and, as far as possible, maximise the benefits to both. It is the field of agrivoltaics (APV) that can provide some answers.[1,3–5] Here, ground mounted PV systems have inter-row spacing and heights adjusted to enable inter-spaced cropping or the PV system is raised above crops and adapted to meet the requirements of the crops below.

Integration of utility scale PV systems with pastoral activities, commonly known as 'solar grazing', is becoming more common and offers an immediate first step for APV.[6,7] However, herein we look at a closer relationship between the crops themselves and PV deployment in horticultural APV, Fig. 1. The central concept of all APV systems is the efficient sharing of the locally available solar resource for the co-production of PV electricity and crops to obtain greater total benefits than installing the PV systems on distinctly separate land. Designs for APV systems must overcome the constraints of crop coverage with PV that could cause substantial reduction in crop yields or profitability. In particular, PV system designs must be adapted such that desirable levels of sunlight reaching crops are maintained.

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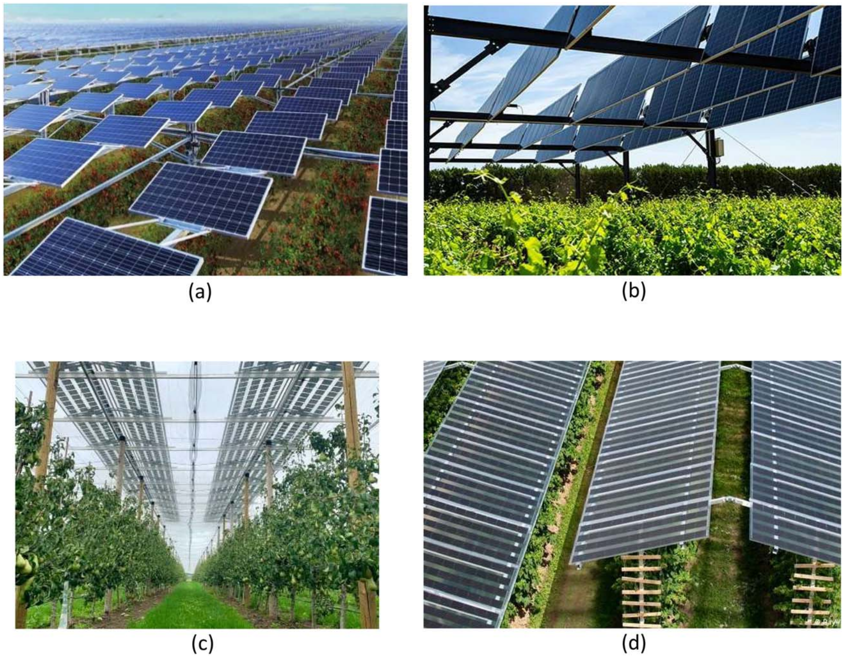

Fig. 1 Horticultural APV installations, (a) world's largest APV installation above goji berry plants, Huawei/Baofeng group, China, reproduced from ref. 13 with permission from Huawei, copyright 2023; (b) Sun'Agri demonstration project, France, reproduced from ref. 14 with permission from Sun'Agri, copyright 2021; (c) KU Leuven demonstration project over pears, reproduced from ref. 15 with permission from KU Leuven, copyright 2022; (d) BayWa r.e. demonstration, Netherlands, reproduced from ref. 16 with permission from BayWa r.e., copyright 2023.

Semi-transparent PV modules will be a critical enabling technology in this adaption, providing motivation to develop commercially viable technologies specifically for APV applications.

In 2023, global total primary energy supply (TPES) was approximately 166 000 TWh (600 EJ), of which fossil fuels contributed 82%.[8] The two renewable energy technologies that can scale as required to transition the global energy system, solar PV and wind, contributed approximately 1650 TWh and 2300 TWh respectively, or just 2.4% and 3.4% on an input equivalent basis.[8] A vast expansion of PV deployment is required and cumulative global installation of PV capacity will need to grow from ~2 TW_p today to ~70 TW_p by mid-century.[9–11] Roughly 10–15 TW of the required total could be deployed on buildings or otherwise in the built environment,[11] leaving ~55 TW deployed in large scale ground mounted installations. This would require ~400 000 km^2, roughly 0.3% of the world's total land area or 1% of land area used for agriculture globally.[12] Due to these small fractions, it is unlikely that the required growth in solar PV deployment would have a significant effect on overall average global agricultural production. However, land available for solar deployment and population are not as evenly distributed as solar resource. For many densely populated nations or regions the fraction of agricultural land required for solar PV deployment is at levels that would impact significantly on local food production and livelihoods if that deployment was to occur.[17]

It is not just through the lens of competition for arable land that APV should be viewed. Not only can APV systems provide efficient sharing of high value land close to existing grid infrastructure,[1] but also increased economic value and income diversification to farms[18] and reduced water consumption in semi-arid regions.[5,19] An APV approach can also negate land use conflict between PV and agricultural activities, though it is still unclear if this is leading to increased rural community acceptance of PV deployment.[20,21]

Increases in economic value to farms can arise from APV deployment due to the addition of a revenue stream from the sale of electricity, through cost savings from the reduction of imported grid electricity or through rental leases. The economic value of the APV system depends not only on the solar resource available above what the crops require, but also on the relative value of the crops and electricity, and the capital cost of the system.[18] Situations where APV systems are installed in high solar resource areas or for use with shade tolerant crops will show higher economic value.[5] However, self-consumption of electricity at the farm 'behind the meter' provides the highest contribution to value increase due to the cost of importing electricity from the grid being considerably higher than the price gained for exporting.[22] Dinesh *et al.*[18] simulated APV systems over lettuce crops located in Kansas USA, their results showed an annual increase in farm revenue of 30% is possible if a lettuce crop reduction of 34% is acceptable, or an annual revenue increase of 8% if larger spaces between panels are used and crop reduction is limited to 12%. These values could be conservative, as in actual trials of different lettuce varieties under an APV system Marrou *et al.*[23] showed that minimal yield loss, or even yield gains, occurred under an APV system when modules are installed at half their typical density.

Along with the increase in absolute economic value, farms can benefit from the diversification of income provided by an APV system. This is particularly important in areas that are susceptible to periods of drought where agricultural yield can decline significantly during this time.[5,7,24] In these situations, not only does the APV systems provide a reliable continuous income stream to the farm, but coverage by PV modules can assist in reducing crop yield losses by lowering the rate of evapotranspiration and conserving soil moisture. APV offers farms a valuable tool to adapt as climate change progresses and many agricultural areas become increasingly drier for longer periods.[22] APV deployments can also provide social benefits through new jobs, community income and tax revenue.[25]

Costs of APV systems can vary considerably due to the wide variety of implementations. Capital costs are higher than conventional ground mounted PV, with the main contributors being cost of the more elaborate high clearance mounting structures, if they are used, and increased site preparation and installation costs.[22,26,27] APV integrated with protected cropping systems, particularly on permanent crops, offers significant cost advantages over open field stilt mounted APV due to the existing support structures for crop protection and lower site preparation and installation costs.[26] While APV deployment can already be cost competitive with residential and commercial scale PV systems, it will require encouragement in the form of favourable regulation and incentives to bring the technology down the cost curve to compete with larger scale ground mount PV.[22,26] Special tenders that set aside a certain amount of installed capacity specifically for APV will drive initial deployment volumes and experience.[28] Enabling APV installations to access favourable feed in tariffs, or other remuneration schemes of well-defined duration, will encourage investment and uptake.

Realisation of the benefits provided by an APV approach and the dramatic fall in PV costs in the last decade have spurred interest in APV. Schindele *et al.*[26] estimate that 2.8 GW_p of global APV capacity has been installed by 2019, up from approximately 5 MW_p in 2012, and by 2021 global APV deployment had passed 14 GW_p.[22] Despite this recent rapid growth APV remains a relatively new field and commercial deployment of APV systems has been limited compared with the growth in typical ground mounted PV. China hosts the majority of global APV installed capacity, with 640 MW_p of that in the world's largest single APV project that covers Goji berry crops on the edge of the Gobi Desert, Fig. 1.[29] Japan accounts for a further 600 MW_p and other countries that have seen implementation of smaller scale APV projects include Italy, Germany, France, South Korea and the USA.[29,30] Government bodies have recently realised the potential of APV and have begun to define guidelines, standards and favourable policy for APV systems in an effort to increase deployment. In 2021 and 2022 Japan, Germany, France and Spain all released guidelines or standards for APV systems while South Korea has set a target of 10 GW_p of APV by 2030 under its Renewable Energy Plan for 2030.[31–34]

APV is just emerging from its nascent phase. Further efforts in research to understand the interaction of crops and PV will develop 'bankability' in APV. Efforts towards developing APV specific technologies and scale up will reduce costs and increase performance. Along with favourable policy and regulations from governments, this will all continue to drive the expansion of commercial APV installations into the large potential market available.

The solar spectrum and crops

Crops and PV both require sunlight. To understand the APV opportunity for sharing the solar spectrum between the two, and highlight desirable directions for APV technology development, a facile summary of complex plant biology is included here.

Photosynthesis is the process utilised by plants to convert light energy from the sun into chemical energy that can be used for growth. The rate at which photosynthesis, and consequently plant growth, occurs is influenced by a number of environmental factors including light intensity and wavelength, light homogeneity, availability of carbon dioxide and water, ambient temperature and humidity.[35] Chlorophyll *a* and *b* are the primary pigments in plants that absorb light for use in photosynthesis. They absorb strongly in the blue light (~400–500 nm) and red light (~600–700 nm) wavelength bands, Fig. 2. Green light is only weakly absorbed by chlorophyll and is diffusely reflected by plant cells giving them their characteristic green colour. However, thick leaf structures provide depth and multiple opportunities for absorption.[36] As a result, approximately 90% of red and blue light along with 70–80% of green light can be absorbed by the leaves of plants.[36,37] The relevant spectrum to consider when assessing the spectral efficiency of photosynthesis is not the absorption of chlorophyll, rather the plant action spectrum, which describes the rate at which photosynthesis occurs at different wavelengths.[38] Fig. 2 presents the averaged action spectra of 22 important cropping plants as reported by McCree.[39]

From an agricultural perspective it is generally considered that to photosynthesise plants can use the entire portion of the solar spectrum in the wavelength range 400–700 nm, which is referred to as Photosynthetically Active Radiation (PAR). However, red light is more effective at driving photosynthesis than blue or green light.[39] For many crop species a light spectrum with a large portion of red wavelengths supplemented

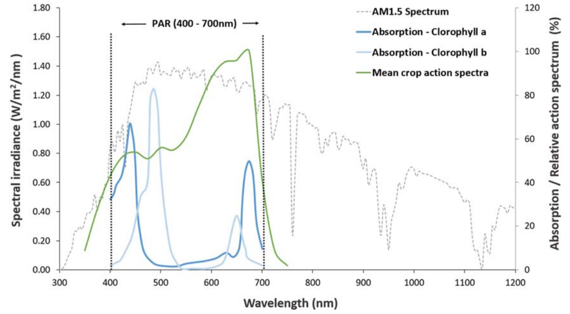

Fig. 2 Chlorophyll absorption and mean crop action spectra compared to AM1.5 spectrum. Crop action spectra data taken from ref. 39.

with blue light can increase yield.[40] Though, reducing the blue light portion too greatly eventually leads to decreases in yields.[41] Some previous studies have considered green light less effective at promoting growth, however it is now considered that appropriate proportions of green light improves photosynthetic efficiency, particularly in lower portions of the crop canopy.[36,42,43] Indeed, the photosynthetic efficiency of green light, when taken throughout a crop canopy, has been shown to be only slightly lower than that of red light in roses.[44]

The amount of PAR supplied to plants will increase the rate at which photosynthesis occurs up to a point where the plant is light saturated, denoted by the light saturation point, Fig. 3. After this point photosynthesis is no longer limited by the amount of incident light but the availability of moisture or carbon dioxide in the surrounding atmosphere. For a particular crop the rate at which photosynthesis occurs and the light saturation point is dependent on specific plant physiology and can vary widely. Some crops show higher rates of photosynthesis and light saturation points, while crops that undergo a lower rate of photosynthesis and have lower light saturation points can be termed 'shade tolerant', Fig. 3. Examples of high light requirements crops are corn, wheat and sugar cane while leafy greens, potatoes and berries are good examples of shade tolerant crops.[45]

While the instantaneous availability of PAR is important to the rate at which photosynthesis occurs, it alone does not correlate with plant growth and crop production. A measure that more accurately represents the PAR requirements of plants is the Daily Light Integral (DLI), which is the total amount of incident PAR on a plant during a day (mol m^{-2} day^{-1}) and can be found through the summation of the PAR across the light hours in one day. The DLI required for optimum growth of crops can vary significantly. Shade tolerant crops such as lettuce require DLI of 14–16 mol m^{-2} day^{-1} and higher light requirement crops such as tomatoes 22–35 mol m^{-2} day^{-1}.[46]

Along with the effect of light quantity and spectral distribution on the efficiency of photosynthesis, its effect on other specific factors of plant development, termed photomorphogenesis, needs to be considered.[35] Photomorphogenesis guides a number of plant structural traits including leaf area, plant height and root elongation, along with the timings of flowering, fruiting and seed development.[39,47,48] For example, red light promotes photosynthetic apparatus development while blue light regulates stomatal opening and plant height.[49,50] Wavelengths outside the PAR range can also affect plant development. UV light generally increases stress on plants leading to reduced photosynthesis, smaller plants and less biomass.[50] Small amounts of far red light (700–800 nm) are often required to regulate flowering and fruiting.[51]

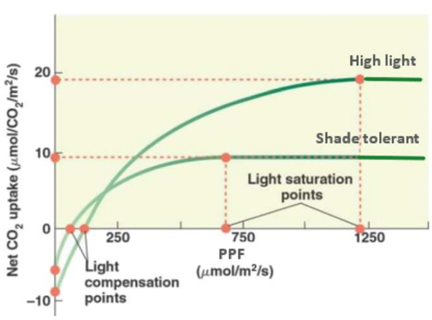

Fig. 3 Photosynthetic response curve showing light compensation and saturation points, reproduced from ref. 35 with permission from Wiley, copyright 2008.

The presence of an APV system most often lowers the available PAR and can possibly change the spectral distribution of incoming irradiance. Resulting effects on crop yield are strongly dependent on the specific crop, solar resource and local climate.[4,52,53] Some crops can also undergo adaptive changes to reduced light conditions, with leaf area or chlorophyll levels increasing to compensate for the reduced incoming PAR and assist in maintaining yields.[54,55] Foundational studies on crop yield under APV systems were performed in the 2010's.[5,23,56] Marrou *et al.*[23] studied lettuce, a typically shade tolerant crop, under an APV system. Findings showed installations of PV modules at typical full density reduced available PAR at crop level by 50% leading to crop reductions of 58% in the first season of the experiment and 21% in the second. Installation of PV modules at half density improved the availability of PAR, limiting reduction to 30%, leading to more favourable crop reductions of 19% in the first season and only 1% in the second. During investigations of their APV system in Arizona, USA, Barron-Gafford *et al.*[5] found that crop yields from peppers and tomatoes were both doubled under an APV system *versus* control crops. Demonstrating the strong synergies of APV systems with cropping in semi-arid environments. Water use efficiency by the jalapeño crops studied increased but crop yields remained stable due to shading from the APV system reducing light availability. More recently a significant number of studies on the effect of APV deployment on crop yields have been completed, Asa'a *et al.*[53] and Weselek *et al.*[4] provide good summaries of these.

The opportunity to co-locate PV with crops in APV arises through being able to utilise available solar resource that is in excess to crop requirements for electricity supply. Firstly, utilising PAR available above the DLI requirement for the crops grown, or that will reduce crop growth by an acceptably small amount. In this respect shade tolerant crops will be the most compatible with APV applications. Secondly, accessing portions of the solar spectrum outside the PAR region that are not used in photosynthesis. Light with wavelengths >700 nm in near infra-red (NIR) are not utilised for photosynthesis and contribute almost exclusively to negative effects such as excessive crop temperature and evapotranspiration yet represent just over 50% of the total available energy in the solar spectrum under clear sky conditions. Harnessing the NIR for electricity supply affords the greatest opportunity for APV systems.

Semi-transparent PV technologies for agrivoltaics

Semi-transparent APV (STAPV) are module level technologies that seek to modify the PV material or module surface to best access the light from the solar spectrum in excess of crop requirements. The goal is to generate electricity at the lowest

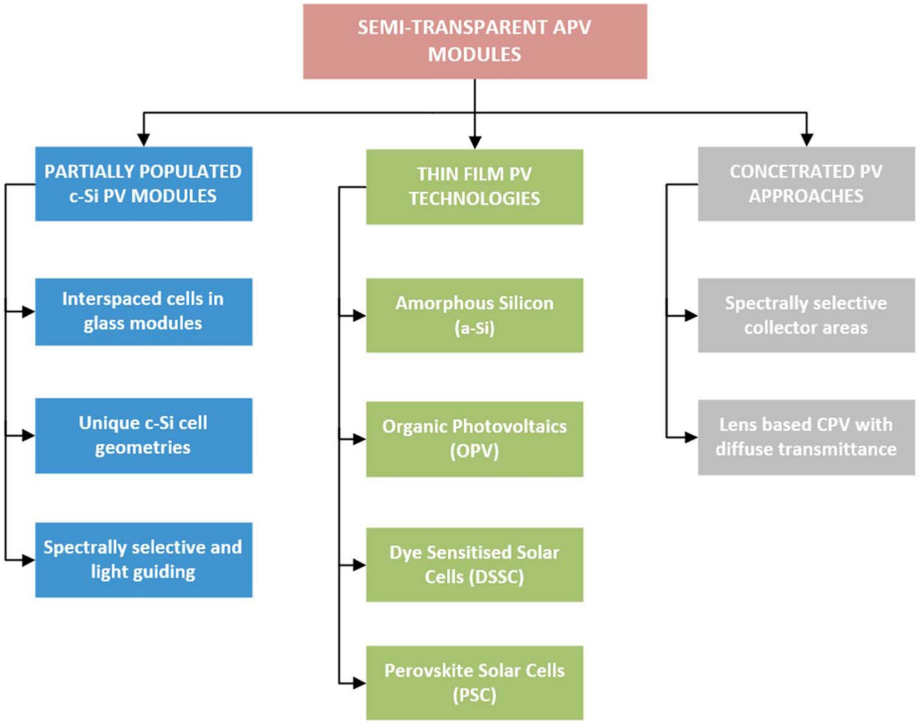

Fig. 4 Categorisation of semi-transparent PV technologies that have been demonstrated or proposed specifically for APV applications.

overall cost with small reductions or increases in crop yield while minimising interference with cropping practices. From a performance perspective there are two key metrics, power conversion efficiency (PCE) and PAR transmission through the module (equivalently average visible transmittance, AVT, as PAR and the visible spectrum both overlap in ~400–700 nm). Other important considerations for STAPV are cost, stability, lifetime, scalability and integration with balance of system components and the cropping application.

System level considerations for APV deployments also have a significant effect on PAR transmission to crops.[1,22,57] There are a variety of forms APV systems can take, interspaced ground mounted, overhead stilt mounted or open field/enclosed protected cropping.[22] Each of which has specific applications based on their suitability to the type of agriculture employed and the level of light transmission required. Important system level parameters that have a bearing on PAR transmission include PV module orientation, height clearance to crops, row spacing, density of panels within rows, mounting configuration and whether single axis tracking is employed.[57–61] These system level considerations have an important bearing on the selection of, and requirements for, semi-transparent module technologies that might be employed. Trommsdorff *et al.*[22] provide a good summary of APV system level considerations.

Varying approaches to create STAPV modules have been demonstrated or proposed, Fig. 4. These can be broadly placed into three categories: partially populating or otherwise dispersing opaque c-Si PV cells in a transparent module; employing semi-transparent thin film PV technologies such as Amorphous Silicon (a-Si), Organic Photovoltaics (OPV), Dye Sensitised Solar Cells (DSSC) or perovskite solar cells (PSC) as a continuous PV surface; and concentrated photovoltaic (CPV) approaches where the collector area is semi-transparent. In some cases, STAPV can be made spectrally selective by actively engineering either the PV material itself or integrating spectrally selective layers at a module or system level.[52]

Partially populated c-Si

Modules with wafer based c-Si solar cells currently account for over 94% of the global PV market, with an average module spot market price at the end of 2023 of US$ 0.12/W_p.[62,63] These solar cells are opaque to PAR and are typically mounted on a pane of glass with a white backing film. Spacing out cells and replacing the opaque backing film with transparent films or rear glass enables PAR transmission through spaces to create a semi-transparent module, Fig. 1c and d. As interest in APV has increased a handful of manufacturers have begun to release partially populated semi-transparent modules specifically for APV applications. Examples of these include the Solitek AGRO® series, Brite BSG® series or Feedgy Himalaya® module which have been created with transparencies in the range of 30–50%.[64–66] As APV installations are typically mounted further above the ground, the amount of light available to the back side of modules is particularly high and bi-facial PV modules are well suited to APV applications.[29]

The desired level of transmittance for a STAPV module can vary considerably and is dependent on a number of variables including the: crop type, local solar resource, APV system layout, relative value of electricity to crops and applicable regulations. Very few studies have been published that investigate the

Fig. 5 a-Si APV demonstrations, (a) growth units used by Thompson *et al.*,[54] reproduced from ref. 54 with permission from Wiley, copyright 2020; (b) residential a-Si APV glasshouse by Polysolar,[54] reproduced from ref. 54 with permission from Wiley, copyright 2020; (c) prototype APV a-Si glasshouse used by Aira *et al.*,[70] reproduced from ref. 70 with permission from MDPI, copyright 2021.

optimum transparency of a partially populated c-Si module in a specific APV application. Katsikogiannis *et al.*,[61] modelled an APV system integrated into the protected cropping of blueberries for a location in the Netherlands. To minimise reduction in blueberry crop yield, a yield loss of <17% was considered acceptable, while maximising electrical output a module transparency of 38% was determined optimum for the specific APV system considered.

Assessment of available APV studies indicates the useful range of PAR transparency for an APV module is 30–60%.[57,61,67] This target range assumes that for most APV systems the semi-transparent PV surface does not fully envelope the crops and there is a portion of light directly incident on the crops from their surroundings. It also considers that in some cases a crop yield reduction of 10 to 34% may be acceptable.[22,68]

Semi-transparent thin film PV

Thin film PV technologies are good candidates for APV applications as they can be made semi-transparent by reducing the thickness of the absorbing layer and utilising transparent electrodes and substrates. Although, most existing thin film PV materials generate primarily from wavelengths in the PAR region and reducing absorbing layer thickness to enable transmission leads to lower PCE. Thin film PV technologies that have been demonstrated or proposed for use in APV applications are a-Si, OPV, DSSC and PSC.

Amorphous silicon

Commercial a-Si modules produced by Polysolar® were used by Thompson *et al.*[54] in 'growth units' to test the effects on spinach and basil, Fig. 5. The Polysolar® modules had a PCE of 6.6% and an AVT of 20%. However, due to the small size of the growth units available PAR was only reduced to 43% of that in the control units. Biomass yields of both spinach and basil were reduced by 15% and 26% respectively. Polysolar® has released a product based on this for glasshouses in use in residential settings.[69] Aira *et al.*[70] installed a prototype APV glasshouse made from commercial a-Si modules produced by Onyx® Solar which had a PCE of 2.8% and an AVT of 30%, Fig. 5. The effect of the APV glasshouse on crops of lettuce and broad beans was studied with the authors concluding that while crop yields were reduced slightly, the technology is viable for horticultural production.

While an established technology, a-Si modules are generally only used in BIPV applications due to their aesthetics and lower sensitivity to non-optimal orientation or in low power electronic devices.[71] Cost for a-Si modules are not widely reported or readily available. PCE in hydrogenated a-Si is limited by light induced degradation due to the Staebler–Wronski Effect (SWE).[72] While efficiencies of up to 14% have been demonstrated in the laboratory, commercial products tend to have PCEs in the range of 6–10%.[71,73] After performance degradation

Fig. 6 Flexible OPV modules demonstrated in greenhouses (a) ASCA® modules deployed in an industrial greenhouse, France, reproduced from ref. 77 with permission from ASCA, copyright 2021; (b) testing of OPV modules installed on a polytunnel roof, reproduced from ref. 78 with permission from Elsevier, copyright 2022.

due to the SWE has conclude lifetimes of a-Si modules can be comparable to commercial c-Si at 20 years or more.[72]

The spectral response of a-Si falls almost entirely within the PAR region.[74] As a result, there is a direct trade-off between PAR transmission and PCE such that semi-transparent a-Si modules with any appreciable PCE will always be characterised by low PAR transmission. This limitation suggests that a-Si modules will not find significant popularity in APV installations where PAR transmission requirements are much higher than for BIPV applications.

Organic photovoltaics

Organic photovoltaics is an emerging PV technology that is of particular interest to APV due to its ability to achieve specular selectivity through use of specific OPV materials. To date laboratory scale semi-transparent OPV cells have shown PCE of 4–5% with AVT of approximately 60%.[75]

The few OPV modules developed at module scale however show considerably lower transparencies and module performance degradation is a significant issue. Industrial film producer ARMOR Group is commercialising their flexible OPV based solar film product ASCA® which shows a PCE of 4.0% and an AVT of up to 20%.[76] ARMOR group has suggested this film would be suitable for APV greenhouse applications and has deployed them to an industrial greenhouse in France as a demonstration,[77] Fig. 6. Magadley *et al.*[78] investigated the lifetime of OPV modules installed on the inside and outside of a polytunnel greenhouse roof, Fig. 6. The OPV modules were supplied by commercial group OPVIUS® with a PCE of 3.3% and AVT of 21% at installation. Modules showed degradation due to three main factors: exposure to harsh weather, mechanical stresses caused by movement of the greenhouse and dust accumulation. At the end of the six-month experiment PCEs had decreased to 32% and 47% of their original values for modules installed outside and inside the polytunnel roof respectively.

A techno-economic analysis of the OPV greenhouses was conducted by Emmott *et al.*[79] For different commercial conditions assumed in the economic model the minimum efficiency of the OPV required to provide an investment net present value of zero after 10 years was calculated. In the baseline scenario where OPV modules remain relatively expensive, €40 per m^2, an efficiency of 8.6% was required. Far above the modelled 1–2% PCE that could be achieved from a selection of OPV materials with transparencies that avoided unacceptable impacts on crop growth. With PCE in this 1–2% range OPV modules had to become extremely low cost, €0.06 per m^2. The authors concluded that semi-transparent OPV devices would struggle to perform better than modules partially populated with opaque c-Si cells. They also stressed the need for research into high efficiency OPV materials and highly transparent electrode and interlayer materials if OPV was to reach its full potential in APV applications.

Estimations of costs to produce opaque OPV modules at scale have been reported by Gambhir *et al.*[80] as being in the range of US \$0.23–0.34/W_p assuming a commercial sized module with a PCE of 7% could be produced. Machui *et al.*[81] are more optimistic suggesting at multi GW scale roll to roll fabricated OPV could be performed at US \$0.06/W_p if commercial modules with a 10% PCE could be achieved. Outdoor operational lifetimes for OPV modules can be several years and extrapolated T80 lifetimes of over 30 years have been reported for OPV modules with lower PCE.[82,83] However, well proven lifetimes of at least 10 years are required if OPV modules are to become commercially competitive.[82]

Organic photovoltaics show particular potential for APV applications due to the ability to achieve spectral selectivity, flexibility, low weight and potentially very low cost. These attributes could open up the possibility to integrate OPV modules into low cost polytunnel greenhouses or other protected cropping situations. To make APV system investment costs worthwhile OPV materials with higher PCE and AVT, that take advantage of portions of the solar spectrum outside the PAR region, will need to be developed. Significant stability and lifetime challenges currently faced by OPV cells will also need to be overcome.[82]

Dye sensitised solar cells

Similar to OPV, dye sensitised solar cells is an emerging thin film PV technology based on organic light absorbing dyes and also has the ability to be spectrally selective through the choice of specific dye materials. To date, the maximum PCE demonstrated for an opaque laboratory scaled DSSC is 13%.[73] Increasing the level of light transmittance significantly reduces the PCE with laboratory scale cells typically showing AVT of approximately 25% having PCE in the range 3–5%.[84]

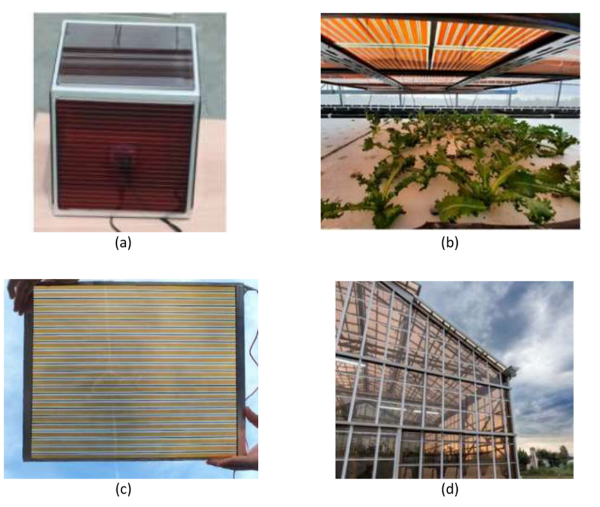

Fig. 7 DSSC developed for APV applications, (a) testbed developed by Kim *et al.*,[85] reproduced from ref. 85 with permission from Wiley, copyright 2014; (b) modules fabricated by Barichello *et al.*,[87] reproduced from ref. 87 with permission from MPDI, copyright 2021; (c) larger area DSSC modules developed by Mourtzikou *et al.*,[86] reproduced from ref. 86 with permission from World Academy of Science, Engineering and Technology, copyright 2020; (d) demonstration DSSC glasshouse, Mourtzikou *et al.*,[86] reproduced from ref. 86 with permission from World Academy of Science, Engineering and Technology, copyright 2020.

Kim *et al.*[85] developed a specific DSSC for use in APV applications with increased transmittance at red (625–675 nm) and blue (425–475 nm) wavelengths to align with the absorption spectra of chlorophyll. Transmittances of 62% at 660 nm and 18% at 440 nm were measured and a PCE of 5.0% was demonstrated. The authors then developed a small greenhouse 'testbed' based on small modules constructed with the cells developed, Fig. 7. Larger area glass DSSC modules, 50 × 50 cm, specifically for APV glasshouses were developed by Mourtzikou *et al.*[86] These modules showed transmittance of over 50% in the 600–700 nm red light region but much lower, <15%, in the 400–500 nm blue light region and PCE of 1.6–2.1% depending on the solar intensity. To validate the properties of the module a 100 m^2 experimental glasshouse for hydroponic tomato cultivation was installed in Greece, Fig. 7. Barichello *et al.*[87] fabricated DSSC modules with an area of 313 cm^2 to in order to investigate their suitability for greenhouse applications, Fig. 7. These modules had an AVT of 35% and a maximum PCE of 2.8% based on the total aperture area.

Estimations of large scale production cost for opaque modules based on DSSC have been reported as low as US $0.18/$W_p$.[91] Though, typical operation lifetimes of OPV modules are six years or less and will need to be improved to 20 years and over if they are to be commercially competitive.[92,93]

DSSC offer potential for APV applications due to the ability to achieve spectral selectivity with the development of specific dye materials and the potential for low-cost production. Importantly the DSSC also contain a light scattering layer in their construction and can increase the amount of diffuse light in a greenhouse or protected cropping situation. Improving light penetration and distribution though the crop canopy.[94] Current semi-transparent DSSC modules of any practical size show low PCE efficiencies and both PCE and transmittance will need to be increased at scale to make investment in APV systems worthwhile.

Perovskite solar cells

Perovskites are an emerging category of hybrid organic–inorganic thin film PV materials that show promise for semi-transparent applications.[95,96] Opaque PSC have rapidly progressed to show PCE significantly higher than OPV or DSSC, with a record PCE of 27.0% shown for a laboratory scale device.[97] Typically, PSC that show the highest efficiency have band gaps in the range of 750–820 nm and require the entirety of the visible spectrum, along with opaque top electrodes, to obtain high PCE.[96,98] As a result, increasing the level of visible light transmissions tends to significantly reduce the PCE.[98] Jafarzadeh *et al.*,[99] recently reported a laboratory scale flexible semi-transparent PSC achieving a PCE of 6.8% and AVT of 55.3%.

Development of semi-transparent PSC has been focused mainly on use in tandem PV and for building window applications and there has not yet been a broad effort in optimisation for APV applications.[98] Notably Subhani *et al.*[100] recently developed a semi-transparent PSC for greenhouse applications showing a PCE of 7.51% and AVT of 40%, though transmission at wavelengths <550 nm was minimal, which could pose challenges for light-mediated development of crops. In their laboratory experiment with radicchio seedlings Spampinato *et al.*[101] utilised a semi-transparent PSC that showed PCE in the range of 8–12% with AVT in the range of 20–34%. Seedlings were grown under LED illumination in the laboratory covered with either a typical glass cover or the semi-transparent PSC and, despite the significantly reduced light exposure, seedlings exhibited faster growth and larger leaves under the PSC than under the reference glass cover.[101]

One of the challenges with semi-transparent PSC is scaling them to larger areas while maintain sufficient performance.[52] Significantly, Matteocci *et al.*[102] recently reported a mini-module with a 48 cm^2 active area that demonstrated a PCE of 5.45% and AVT of 59.4% under laboratory conditions. While Rai *et al.*[103] developed a PSC device, enhanced with a down-converting phosphor material layer, that showed a PCE of 9.5% and APV of ~20% when used in a mini-module of 21 cm^2 in area.

Estimations of costs to produce opaque modules based on PSC at scale have been reported as US $0.25–0.96/$W_p$, with most studies assuming production plant capacity in the 100–200 MW range.[104–108] Though, it is still unknown what PSC configurations are amenable to large scale production, what efficiencies can be achieved at large areas and the lifetime of commercial products possible, making cost projections difficult.[104,109] Holzhey *et al.*[104] approached the cost estimation challenge by asking what combination of perovskite module PCE and lifetime would be required to make them competitive with c-Si in residential situations. They reported that rigid perovskite modules would need to achieve 20% PCE and lifetimes of 21–36 years, and flexible modules 17% PCE and 16–34 years lifetimes, to be competitive with c-Si in 2030. Most outdoor testing of PSC has shown useable lifetimes on the scale of months to one year.[104,110] However more recently, multiyear outdoor lifetimes have been demonstrated for small area PSC submodules with a PCE of 16%.[111] Perovskite modules of aperture 0.60 × 1.2 m, with a PCE of 15%, have also become commercially available domestically China.[107]

While semi-transparent PSC show promise, significant stability and lifetime challenges still remain and will need to be overcome if they are to become a commercial reality.[104,112] Additionally, a large number of the best performing PSC contain lead which, if leaked, can prove toxic in agricultural applications.[113,114]

Concentrating PV approaches

Concentrating photovoltaics (CPV) utilises large area refractive or reflective concentrating optical elements to concentrate light onto a smaller area of solar cell. To achieve medium or high concentration in these systems (concentration ratios >10) single or dual axis tracking is required to orient the optical elements towards the sun. To adapt CPV systems for APV applications two general approaches have been proposed. When a lenslet array concentrator is employed, the backplane can be made transparent and while the direct component of irradiance from the sun is collected and directed to the PV cells, a portion of the

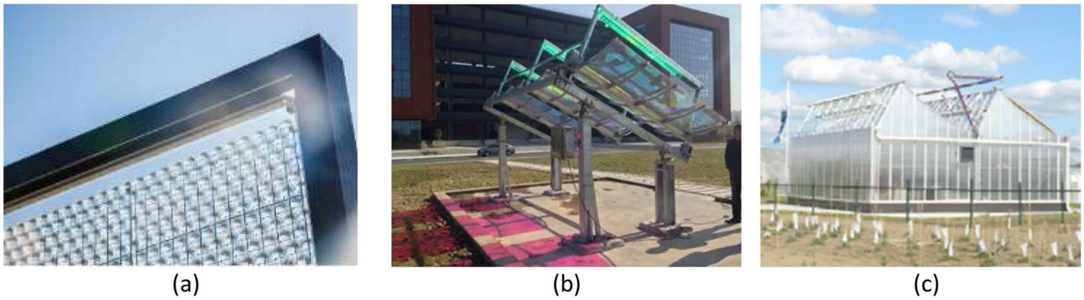

Fig. 8 (a) Lenslet array concentrator with transparent backplanes using Insolight CPV modules with planar micro-tracking,[88] reproduced from ref. 88 with permission from AIP Publishing, copyright 2019. Reflective CPV systems for APV applications that utilise dichroic mirrors, (b) trough based system developed by Liu *et al.*,[89] reproduced from ref. 89 with permission from Elsevier, copyright 2017; (c) glasshouse integrated parabolic reflector with movable receiver, Sonneveld *et al.*,[90] reproduced from ref. 90 with permission from Elsevier, copyright 2009.

diffuse sunlight can pass through the concentrator to crops below, Fig. 8a.[115–117] If a large area collector in the form of a reflective dish or trough is employed a dichroic mirror surface can be used on the collector to enable wavelength selectivity, with light in the PAR region required by crops being passed through the collector surface to the crops below and other regions of the solar spectrum being concentrated to the PV cells for electricity conversion Fig. 8b and c.[118–121]

Use of medium/high concertation CPV separates the collector and PV surfaces, enables small amounts of opaque PV material to be used and simple attachment of a dichroic to the collector surface. However, due to the increased complexity and mass required, CPV systems are expensive, they do not generate from the diffuse portion of the solar resource and critically they pose significant impracticalities for integration into APV systems. As a result, CPV approaches are not competitive candidates for large scale adoption in APV.

Table 1 Performance of semi-transparent PV technologies, reviewed herein, that have been demonstrated at a module or mini-module level for use in APV applications

Technology/study	Technology description	PV type	PCE (%)	AVT (%)	Ref.
Solitek AGRO®	Commercial frameless dual glass module with interspaced c-Si cells	c-Si	10.1	47	64
Brite BSG®	Commercial frameless dual glass module with interspaced c-Si cells	c-Si	11.6	49	65
Feedgy Himalaya®	Commercial framed dual glass module with interspaced c-Si cells	c-Si	14.8	33	66
Yano *et al.* (2014), Spherlar®	Micro-spherical c-Si cells encased in glass–glass module	c-Si	4.5	61	122
Loik *et al.* (2017)	Glass–glass module with spaced c-Si cells and luminescent dye dispersed throughout encapsulant	c-Si	3.7	60	123
ClearVue®	Commercial triple pane BIPV panel with spectrum splitting material and edge mounted c-Si cells	c-Si	3.3	< 70	124
Thompson *et al.* (2020), PolySolar®	Commercial glass–glass a-Si module	a-Si	6.6	20	54
Aira *et al.* (2021), Onyx® solar	Commercial glass–glass a-Si module	a-Si	2.8	30	70
ARMOR solar power film ASCA®	Commercial large area flexible OPV module	OPV	4.0	20	76
Magadely *et al.* (2022), OPVIUS®	Demonstration small area flexible OPV module	OPV	3.3	21	78
Kim *et al.* (2014)	Demonstration small area glass–glass DSSC module (AVT estimate)	DSSC	4.9	40	85
Barichello *et al.* (2021)	Demonstration small area glass–glass DSSC module	DSSC	2.8	35	87
Mourtzikou *et al.* (2020)	Demonstration large area glass–glass DSSC modules	DSSC	1.6	32	86
Matteocci *et al.* (2022)	Small area, 48 cm^2, laboratory PSC mini-module	PSC	5.5	59	102
Rai *et al.* (2021)	Small area, 21 cm^2, laboratory PSC mini-module	PSC	9.5	20	103

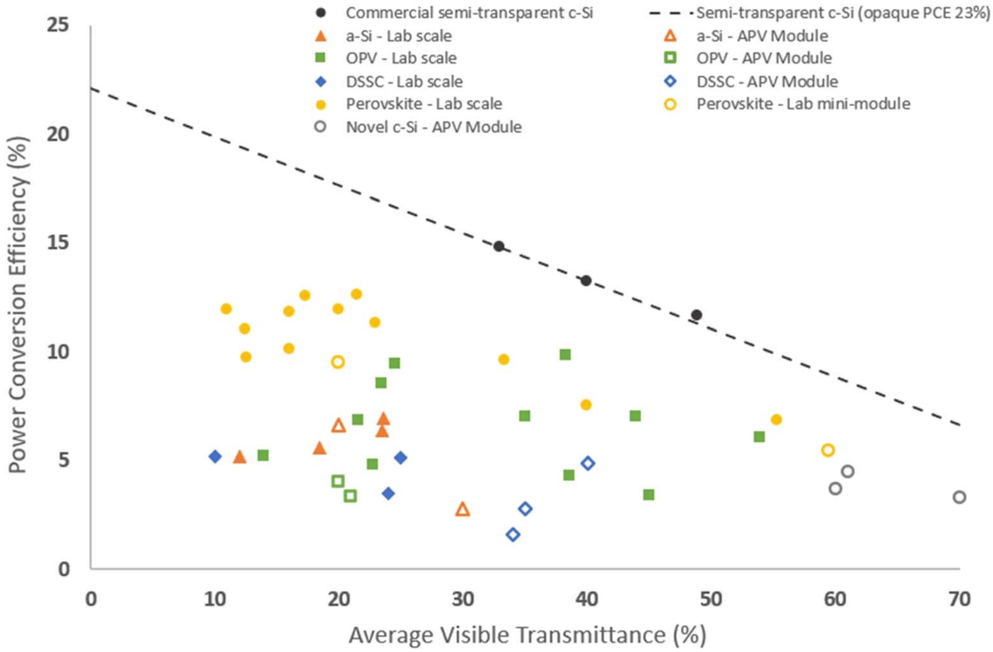

Fig. 9 PCE as a function of AVT for laboratory scale thin film solar cells as reported by Lee *et al.*,[84] Subhani *et al.*[100] and Jafarzadeh *et al.*,[99] solid markers; and for semi-transparent APV technologies demonstrated at the module or mini-module scale reviewed herein, hollow markers. Included for comparison are results for commercially available partially populated c-Si modules.

Prospects

Continuing expansion of commercial APV will drive research and development into a variety of APV specific technologies. To enable sufficient PAR transmission and homogeneity of light to crops STAPV will be critical. Table 1 presents a summary of the semi-transparent PV technologies demonstrated for APV applications, along with the key metrics of AVT and PCE. Only technologies that were demonstrated at a module or mini-module level have been included, and CPV systems are excluded due to their significantly different form factor and consequent impracticalities in their adaption to APV systems. Semi-transparent partially populated c-Si modules have been commercially released by a handful of PV manufactures and performance of three commercial semi-transparent panels have been included in Table 1 for comparison. These panels show superior performance to all other demonstrated STAPV technologies, by a very large margin.

The thin film PV technologies of OPV, DSSC and PSC show potential for APV applications due to their ability to achieve spectral selectivity and potentially low cost at high volume production. Current performance of laboratory scale semi-transparent thin film cells, as reported by Lee *et al.*,[84] Subhani *et al.*[100] and Jafarzadeh *et al.*[99] are presented in Fig. 9. Hollow markers have also been included representing the thin film STAPV module level technologies listed in Table 1. Again, performance of commercial semi-transparent c-Si panels have been included for comparison. Two things are clear. Firstly, significantly lower performance values than those reported at laboratory scale are observed for thin film STAPV when scaled to module level. Secondly, partially populated c-Si modules show superior performance to all the demonstrated thin film STAPV technologies, again by a large margin. While thin film technologies show promise for STAPV, to be competitive with c-Si significant improvements in PCE and AVT, *via* the development of absorber materials that utilise portions of the solar spectrum outside the PAR region, will need to be achieved. Stability and lifetime challenges currently faced by OPV, DSSC and PSC will also need to be overcome.

Considering their relatively high efficiency, low cost, stability and incumbency in the contemporary PV market it is likely that partially populated c-Si modules will be the dominate STAPV module technology for the foreseeable future. Near term research efforts to determine the optimum spacing and arrangement of c-Si cells for given combinations of crop species and local solar resource should be a priority. Concurrently spectrally selective techniques that seek to redirect the NIR portion of the solar spectrum for conversion by distributed c-Si cells while maintaining high transmission of PAR should be investigated.

Agrivoltaic c-Si modules: pathways to spectral selectivity

Aside from their overwhelming incumbency, c-Si offers particular opportunity in APV applications as it utilises light in the NIR as well as the PAR region of the solar spectrum, with spectral response being highest in the NIR range, Fig. 10. Due to the favourable spectral response in the NIR mono-crystalline silicon cells generate approximately 50% of their current from wavelengths greater than 700 nm. They therefore offer a good match for plants in a 'tandem' arrangement.

The following design principle is suggested to advance the opportunity provided by c-Si modules. Firstly, determine the

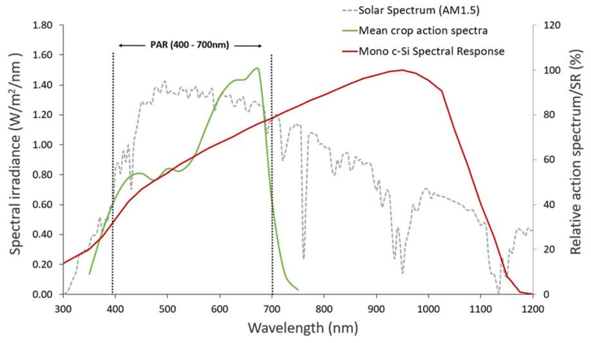

Fig. 10 Relative spectral response of monocrystalline silicon in relation to crop action spectra. Crop action spectra data taken from ref. 39.

optimal coverage of opaque cells based on specific crop PAR requirements and local solar resource. Then arrange the cells and insert spectrally selective optics to redirect the maximum amount of NIR to the cells with minimal effect on PAR transmission. To this end a small 'suite' of commercial modules with different PAR transparencies in the range of 30–60% could be developed. Any commercially relevant semi-transparent APV module would need to have a cost and lifetime comparable to that of a typical PV module, be mass manufacturable and in a format that is compatible with existing mounting structures and balance of system components. These requirements drive any solution to maintain the form of a typical glass–glass or glass-transparent back sheet flat plate PV module with spectrally selected optical layers incorporated at acceptable cost.

To date only a handful of groups have proposed or demonstrated adapting partially populated c-Si modules for spectral selectivity.[123,125,126] The spectrally selective layers in these approaches are based on one of three optical methods: luminescent solar concentrators (LSC), selective light scattering or holographic optical elements.

Luminescent solar concentrators

In a LSC arrangement a planar transparent substrate is imbued with a fluorescent dye or quantum dot mixture that absorbs light from shorter wavelengths and re-emits them at longer wavelengths.[127–129] A portion of the re-emitted light is at high angles relative to the substrate normal and is waveguided by total internal reflection (TIR) along the substrate to cells located along the edge. An LSC arrangement produces a static solar concentrator that can collect both direct and diffuse solar resource and one that can be partially transparent. However, LSC efficiency is reduced *via* losses related to the photoluminescent materials themselves including low absorption efficiencies and quantum efficiency, but also due to optical losses including light emitted at angles less than the critical angle in the 'escape cone' and absorption in the waveguide.[130]

Loik *et al.*[123] developed what they termed a wavelength selective photovoltaic (WSPV) module by combing LSC technology in a partially populated c-Si PV module to produce a module for express use in greenhouses, Fig. 11. The WSPV modules were composed of thin PV cell strips covering 12% of the module area and Lumogen Red 305 dye embedded in PMMA, covering the remaining 88%. The dye heavily absorbs light with wavelengths <600 nm and then re-emits a portion of the absorbed light in the 600–700 nm range, where crop action spectra are strongest, with the aim of increasing photosynthesis. Some of the re-emitted light is also directed by TIR to the PV cell strips to increase electricity production. The WSPV modules demonstrated PAR transmission of 60% and a PCE of 3.7%. An increase over the 3.0% PCE shown by control modules with the same coverage of PV strips in clear glass. Use of in-plane cells with a LSC, where cells can be directly illuminated and distances re-emitted light has to travel are minimised, helps limit some of the typical LSC (edge located cells) efficiency losses including re-absorption and waveguide losses. However, optical efficiency in the LSC format is still severely low, limited by the remaining dye and substrate absorption losses as well as light that is re-emitted by the dye at angles lower than the critical angle and lost.

Previously one of the most critical limitations with an LSC approach for APV was luminescent dyes not absorbing in the NIR portion of the spectrum, and not being gathered for use by the c-Si cells but transmitted to the crops. More recently, dyes have been developed that can access a limited portion of the NIR.[132,133] Although these dyes still absorb significantly in the red region of the PAR and redirect this away from the crops.

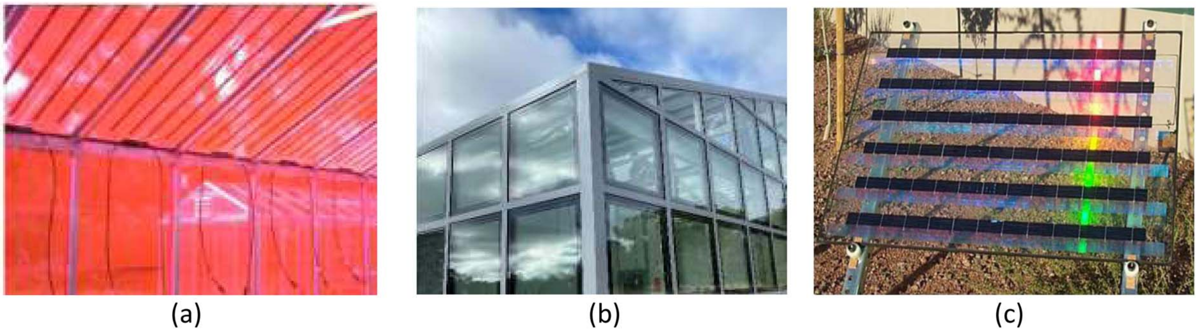

Fig. 11 (a) Wavelength selective photovoltaic modules using a LSC dye, Loik *et al.*,[123] reproduced from ref. 123 with permission from Wiley, copyright 2017; (b) ClearVue APV glasshouse demonstration, Perth Australia, reproduced from ref. 125 with permission from ClearVue, copyright 2024; (c) flat plate concentrator module using holographic optical elements, Kostuk *et al.*,[131] reproduced from ref. 131 with permission from SPIE, copyright 2007.

Despite significant efficiency limitations of an LSC arrangement, further research into dyes that can access NIR effectively for specific use in APV applications is warranted.

Selective light scattering

Australian company ClearVue® has developed transparent PV window glass for BIPV applications which it is now adapting to APV greenhouse applications.[125] The product takes the form of a triple glazed insulated glass unit with in plane c-Si cells around the edge. A spectrally selective light scattering layer is created by distributing nano-particles, of undisclosed type, in a polyvinyl butyral (PVB) film which allows PAR to pass through while scattering UV and NIR radiation, some of which is redirected by TIR to the PV cells at the panel edge. PAR transparencies of <70% and a PCE of 3.3% are claimed.[124] Limited data is publicly available to assess the design or effectiveness of this light scattering arrangement. ClearVue® has demonstrated its technology through construction of a APV greenhouse in Perth, Australia, Fig. 11. However, the low PCE coupled with the high costs involved with triple glazing it is unlikely the product proposed will be used widely in greenhouses and makes it unsuitable for open field protected cropping.

Holographic optical elements

The third approach to achieving spectral selectivity in a flat plate collector is to utilise holographic optical elements.[134] This has been demonstrated by Kostuk *et al.*[131,135,136] with the objective of reducing PV module cost at a time when c-Si cell costs where significantly higher than today. More recently Honsberg *et al.* have suggested such an arrangement could be applied to APV applications.[126] In this approach holographic elements in the form of diffraction gratings are used to diffract incident light past the critical angle into a transparent substate where the light is waveguided to PV cells mounted in plane. Either transmission holograms can be used on the front surface or reflection holograms on the rear side of the substate. The wavelength band diffracted into the substrate can be selected by changing the grating period, and a useful broadband dichroic can be formed by cascading multiple gratings.[136] Kostuk *et al.* produced a demonstration module, Fig. 11, utilising a single volume grating that showed an increase in current output from the PV cells of 25% (ref. 131) when light from the entire spectrum was considered available for use by the PV cells. The relative coverage of PV cells and holographic elements was not stated. Kostuk *et al.* also showed through analysis that collection efficiencies of 20–45% for the holographic collector area are possible over a suitable range of solar incident angles, again assuming all wavelengths across the solar spectrum are available for use by the PV cells.[136]

There is a lot to commend this approach for a spectrally selective APV applications. The collection optics takes the form of a low cost embedded thin film, light can be diffracted at large angles into the waveguide without the need for additional geometry and diffraction gratings can be selected and cascaded to redirect the NIR portion of the spectrum. Challenges with the approach include lower overall collection efficiencies, large movement in diffracted spectral bandwidth with solar incident angle and large changes in diffraction angle with solar incident angle.[136]

Multilayer thin film dichroics

Introduced here is a further approach to introduce specular selectivity to a partially populated c-Si APV module, utilising a thin film distributed Bragg reflector (DBR) as the dichroic. While a thin film dichroic has been demonstrated in use on the collector surface of a CPV APV prototype,[89] it could also be implemented in the required flat plate format. We propose an APV specific spectrally selective module that incorporates a distributed Bragg reflector as an embedded optical layer. This layer would be located at the rear of a glass–glass panel partially populated with c-Si strips and allow PAR to pass through while redirecting NIR to bi-facial c-Si cells, Fig. 12. In this manner electrical output of the cells can be significantly increased with minimal loss in PAR available to the crops below. Additionally, NIR reaching the crops and ground is reduced, lowering rates of evapotranspiration and as a result water consumption.

Utilising a thin film interference filter for the dichroic layer has the advantage of providing very high reflection and

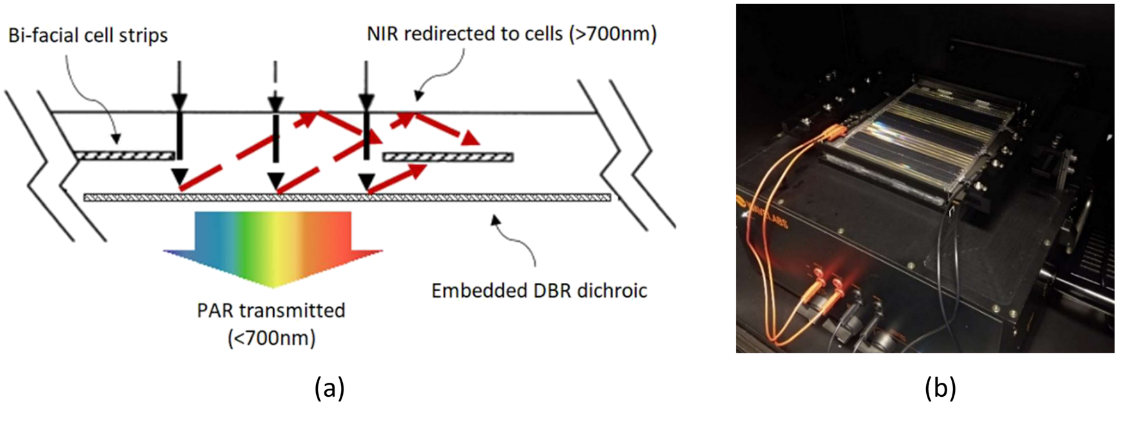

Fig. 12 (a) Spectrally selective APV module concept with DBR embedded layer. (b) Small scale prototype under test in a solar simulator.

transmission efficiencies over the broadband NIR and PAR bandwidths respectively, and doing so across an acceptably large range of solar incident angles. Although placement of the band edge has to be chosen carefully to account for the shift to shorter wavelengths with increasing incident angle as not to reflect significant amounts of light from the PAR region.[137] Commercial large area NIR reflective films have been developed for use in solar control windows for the building industry.[138] These are multilayer polymeric films that act as DBRs, produced *via* a coextrusion process, they utilise a birefringent PET and PMMA for high and low index materials respectively. Both are abundant, cheap and commonly available materials and therefore the films have potential to be very low cost if produced in high volume for PV module applications, possibly in the order of US \$1.0 per m^2.[139–141]

Use of a DBR as the dichroic requires an appropriate non-planar, small-scale geometry to effectively introduce light at high enough angles into the waveguide such that TIR can occur and the NIR is successfully redirected to the cells, and is one of the central design challenges to the approach. A flat plate concentrator arrangement can be used to achieve this. Flat plate concentrators incorporate grooved or Lambertian shaped rear reflectors to achieve static (*i.e.*, non-tracking) concentrators in the form of a typical flat plate module, where only a portion of the module surface is populated with PV cells.[142–144] They are low concentration devices with achievable geometric concentration ratios up to approximately three, corresponding to a cell coverage ratio of 33%. As with any light guide of this form, the range of solar incident angles at which light can be introduced is restricted by the critical angle at the inside front glass surface. Though with careful design, the range of solar incident angles over which the panel successfully captures NIR irradiance is large enough to provide useful annual performance.[142]

To utilise standard PV glass thicknesses of 2.0 or 3.2 mm, and optimise the performance of the module the c-Si cells will need to be arranged in strips of 8–20 mm in width, depending on the coverage fraction of PV desired. Widths as thin as these are not typically used in the contemporary PV industry. Though recently, PV modules of a 'shingled' design, where the edge of one cell strip overlaps the bus bar of the previous, have been employed.[145,146] These utilise half cut cell strips of width 20–30 mm that are electrically and mechanically connected with electrically conductive adhesive.[147,148] Cutting of these cell strips can be performed using thermal laser separation, a kerfless and damage free process that enables virtually no area loss due to cutting.[149,150] Using these techniques and contemporary cell stringing machines, cost increases in creating and handling cell strip sizes required should be minimal. Environmental sealing of the embedded dichroic can be achieved using typical EVA/polyolefin encapsulant and transparent back sheets employed in PV module manufacture.

To assess the expected performance of the proposed spectrally selective APV module concept we are developing a detailed raytrace model. This model will allow optimisation of module design parameters for desired PV coverage ratios and PAR transmission values. Additionally, small-scale prototypes to qualify the model have been manufactured, Fig. 12.

Conclusions

A profound transformation of the global energy system is underway and the next few decades will see a vast expansion solar PV deployment. The scale of PV deployment necessarily means it cannot be considered in isolation, separate from the ecological, economic or social systems in which it is deployed. At this juncture exists the opportunity to integrate the required PV supply in an environmentally and socially responsible way. APV offers particular opportunity. If done thoughtfully, APV can improve the sustainability of some of our most essential resources: energy, food, water and land. Protected cropping with integrated PV provides the most beneficial and cost-effective incarnation of horticultural APV due to strong synergies in the requirements for protection and, in many cases, shade along with the existence of support structures that reduce the marginal cost increase of implementing the APV. Commercial semi-transparent PV modules will be essential in protected cropping APV applications to provide protection while maintaining desirable amounts and even distribution of PAR to crops. The review of APV semi-transparent PV technologies herein shows that contemporary modules based on partially populated c-Si significantly outperform other technologies based on thin film PV and, considering their incumbency, will dominate the market for the foreseeable future. Due to favourable response of c-Si in the NIR and crops not utilising NIR for photosynthesis we identify substantial opportunity to introduce spectral selectivity in these modules. To retain commercial acceptability and low cost, the form factor of a typical PV module should be maintained and spectrally selective layers embedded in the panel. To date this approach has only been investigated by a handful of groups globally and further research effort should be applied. We propose a spectrally selective APV module concept that utilises an embedded distributed Bragg reflector on appropriate flat plate collector geometry. Such an arrangement has the potential to be low cost, mass producible and commercially viable if the requisite design and fabrication challenges are solved.

Author contributions

All conceptualisation, investigation, analysis and manuscript writing performed by I. L. T. Supervision and manuscript review/editing performed by N. E. D. Funding acquisition, supervision and manuscript review/editing by T. W. S.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data to support findings is available from the corresponding author upon reasonable request.

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