Spectrally selective modules for Agrivoltaics

I. L. Thomas[1]

[1]*School of Photovoltaic and Renewable Energy Engineering, UNSW, Kensington, Australia*
ian.thomas@unsw.edu.au

To combat the existential threat posed by anthropogenic climate change it is generally agreed that anthropogenic greenhouse gas emissions are required to reach 'net zero' by 2050 [1]. If this is to be achieved cumulative global installation of photovoltaic (PV) generation will need to grow 100-fold from 0.9 TW today to approximately 70 TW by mid-century [2-4]. It is on land currently dedicated to agriculture that a majority of solar PV will be deployed globally. There are several drivers for this. Agricultural land is generally: already cleared, flat, free from protected status and close to existing transport infrastructure and population centres, allowing deployment and operation costs to be minimised. Most importantly though a large majority of solar PV deployment will occur close to existing electricity grid transmission infrastructure which is located around and between major population centres [4, 5]. The same areas in which the most productive agricultural land is located. This vast expansion of PV deployment into agricultural regions raises the pertinent question of how best to integrate solar PV with agriculture and as far as possible maximise the benefits to both.

Agrivoltaics is the co-location of PV and agriculture where the PV system is raised above crops and adapted to meet the requirements of crops below [6], Figure 1. It offers an effective approach to enable the sharing of high value land and negate land use conflict between energy and food production [6-8]. In addition, agrivoltaics can provide significant increases in economic value for farms, while also providing farmers with a more diversified income stream [9]. PV coverage of crops in agrivoltaic deployments can also provide benefits to the crops themselves, particularly in semi-arid climates, including reduction in evapotranspiration leading to increased water availability, maintaining stable soil and leaf temperatures during midday heat or cool periods overnight and the protection of crops from damaging hail or rain [8, 10]. While agrivoltaics offers extensive opportunities, it faces the central challenge of excessive reduction in the Photosynthetically Active Radiation (PAR, 400 – 700nm) available to crops with any significant coverage of PV modules and associated reduction in crop yields [6, 8, 11].

(a) (b) (c)

Figure 1: Agrivoltaic installations, (a) Baofeng Group, China (b) GroenLeven/BayWa r.e. demonstration project, Netherlands (c) Demonstration glasshouse using Solitek Modules

In the past decade a growing number of agrivoltaic specific technologies have been proposed or demonstrated. Most of these involve system level technologies that mount, orientate, or dynamically control typical opaque PV modules to best adapt them for use in agrivoltaic systems. A second approach is to develop module level technologies that are semi-transparent or otherwise spectrally selective. This approach seeks to modify the PV surface to best access the light from the solar spectrum that is in excess of crop requirements. This light can be taken from two sources, excess PAR above what is required by a specific crop for photosynthesis or from regions of the solar spectrum outside of PAR, Figure 2. Mostly agrivoltaic specific modules have been fabricated at scale by spacing out crystalline silicon (c-Si) cells in transparent module substrates to increase PAR transmission [12]. Another approach is to employ thin film PV modules, which can be made semi-transparent by reducing the thickness of the absorbing layer and utilising transparent electrodes and substrates. Thin film technologies that have been proposed or demonstrated at small scale for agrivoltaics are a-Si, OPV and DSSC [13-15]. Current performance of laboratory scale semi-transparent thin film cells, as reported by Lee at. al. [16], are presented in Figure 3 along with hollow markers representing agrivoltaic specific thin film technologies demonstrated at module level. Partially populated semi-transparent c-Si modules maintain superior performance to thin film semi-transparent devices by a large margin. 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 semi-transparent agrivoltaic module technology for the foreseeable future.

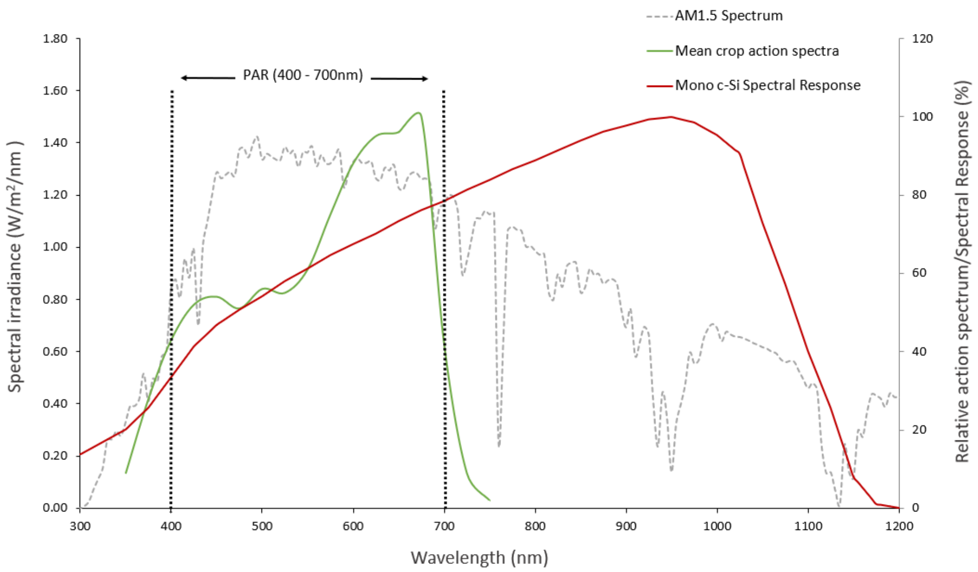


Figure 2: Spectral response of c-Si photovoltaics and crops showing PAR region

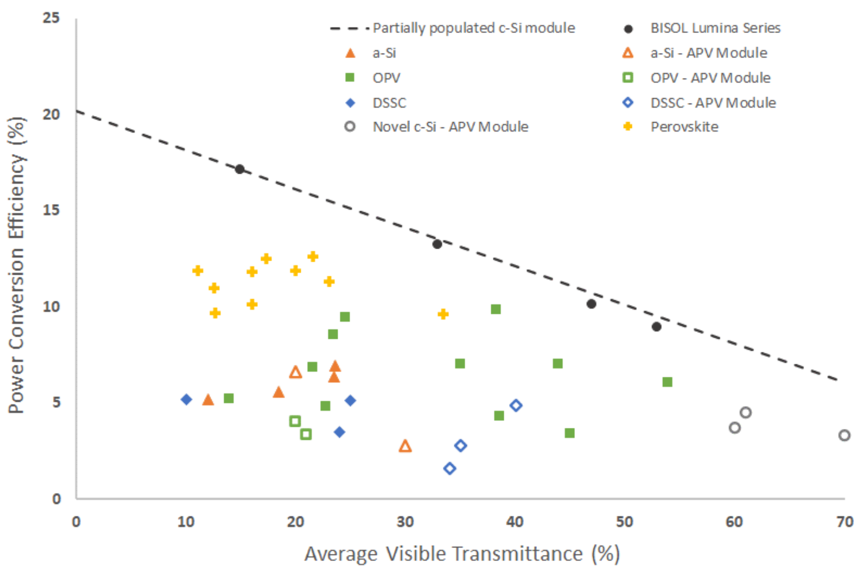


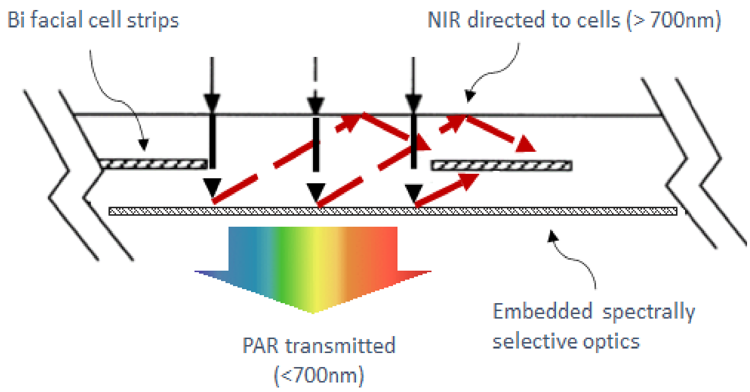
Figure 3: Performance of laboratory scale thin film solar cells as reported by Lee et. al. [16], solid markers, and for demonstrated semi-transparent agrivoltaic modules, hollow markers

Crystalline silicon solar cells offer particular opportunity for agrivoltaic applications as they utilise light in the near infrared (NIR) as well as the PAR region of the solar spectrum, with spectral response being highest in the NIR range, Figure 2. Due to the favourable spectral response in the NIR mono-Si cells generate approximately 50% of their current from wavelengths greater than 700nm. As such they offer a good spectral match for photosynthesis. The problem facing c-Si is that it is opaque to PAR. Partially populating glass-glass modules with cells or spacing out module rows increases the amount of PAR transmitted to crops below but gives up the available NIR radiation in the process.

A handful of technologies have been proposed to provide spectral selectivity in c-Si modules/systems to enable harvesting of solar spectrum regions not utilised by crops. Concentrated photovoltaic (CPV) systems in the form of a reflective dish or trough employing a dichroic mirror on the collector to enable wavelength selectivity have been demonstrated [17]. However, these are prohibitively expensive and cannot be effectively integrated into typical Agrivoltaic applications such as protected cropping. Loik et. al. [18] demonstrated luminescent solar concentrators for agrivoltaic applications, but due to high PAR absorption in the luminescent dye and optical losses these showed no performance advantage over partially populated c-Si modules.

A novel agrivoltaic specific PV module that takes the form of a glass-glass panel partially populated with c-Si cells along with novel thin film embedded optics is proposed, Figure 4. The spectrally selective optics allow PAR to pass through while redirecting NIR to the c-Si cells for electricity generation. This places the cells under low concentration and the module design can be termed a Low concentration Agrivoltaic Panel (LAP). Low cost, large area dichroic mirrors based on thin film technology are commonly used on windows in the building industry to enable reflection of unwanted NIR [19]. Appropriate adaption of this technology for PV uses offers a cost effective means of implementing the required spectral selectivity. A solution in this form not only takes advantage of the good spectral match between crops and c-Si but also utilises a form factor very similar to a typical PV panel and therefore relies mostly on contemporary materials and manufacturing techniques, enabling cost effective and timely development of a commercially relevant product. A project at the UNSW has been initiated to develop this LAP concept further with design, performance simulation and manufacture of representative small scale prototypes to be undertaken throughout 2023.

Agrivoltaics is a valuable approach to meeting the need of increasing both PV energy and food production on high value arable land resources while providing increased economic return and income diversification for growers. A novel low concentration agrivoltaic panel is proposed that could enable sufficient PAR transmission to crops below while collecting and redirecting NIR to c-Si cells for electrical generation. If successful, a LAP could significantly improve the electrical generation and economics of agrivoltaic installations.



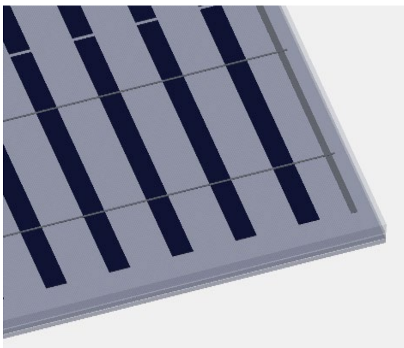


Figure 4: Low concentration Agrivoltaic Panel (LAP) development concept

References

[1] Masson-Delmotte, V. *et al.*, '*Global warming of 1.5°C An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels*', 2018.

[2] bp, '*bp Statistical Review of World Energy 2021*', 2021.

[3] Bogdanov, D. *et al.*, '*Low-cost renewable electricity as the key driver of the global energy transition towards sustainability*', Energy, vol. 227, 2021.

[4] Breyer, C. *et al.*, "Solar Photovoltaics in 100% Renewable Energy Systems," in *Encyclopedia of Sustainability Science and Technology*: Springer New York, 2021, pp. 1-30.

[5] Gorman, W. *et al.*, '*Improving estimates of transmission capital costs for utility-scale wind and solar projects to inform renewable energy policy*', Energy Policy, vol. 135, 2019.

[6] Dupraz, C. *et al.*, '*Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes*', Renewable Energy, vol. 36, no. 10, pp. 2725-2732, 2011.

[7] Trommsdorff, M. *et al.*, '*Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany*', Renewable and Sustainable Energy Reviews, vol. 140, pp. 110694-110694, 2021.

[8] Weselek, A. *et al.*, '*Agrophotovoltaic systems: applications, challenges, and opportunities. A review*', Agronomy for Sustainable Development, vol. 39, no. 4, pp. 35-35, 2019.

[9] Dinesh, H. and Pearce, J. M., '*The potential of agrivoltaic systems*', Renewable and Sustainable Energy Reviews, vol. 54, pp. 299-308, 2016.

[10] Barron-Gafford, G. A. *et al.*, '*Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands*', Nature Sustainability, vol. 2, no. 9, pp. 848-855, 2019.

[11] Gonocruz, R. A. *et al.*, '*Analysis of the Rice Yield under an Agrivoltaic System: A Case Study in Japan*', Environments, vol. 8, no. 7, pp. 65-65, 2021.

[12] Bisol. "*BISOL Lumina series*." https://www.bisol.com/premium.

[13] Thompson, E. P. *et al.*, '*Tinted Semi‐Transparent Solar Panels Allow Concurrent Production of Crops and Electricity on the Same Cropland*', Advanced Energy Materials, vol. 10, no. 35, pp. 2001189-2001189, 2020.

[14] Magadley, E. *et al.*, '*Organic photovoltaic modules integrated inside and outside a polytunnel roof*', Renewable Energy, vol. 182, pp. 163-171, 2022.

[15] Mourtzikou, A. *et al.*, "Semi-Transparent Dye Sensitized Solar Panels for Energy Autonomous Greenhouses," in *International Journal of Structural and Construction Engineering*, 2020, vol. 14, no. 3, p. 95.

[16] Lee, K. *et al.*, '*The Development of Transparent Photovoltaics*', Cell Reports Physical Science, vol. 1, no. 8, pp. 100143-100143, 2020.

[17] Liu, W. *et al.*, '*A novel agricultural photovoltaic system based on solar spectrum separation*', Solar Energy, vol. 162, pp. 84-94, 2018.

[18] Loik, M. E. *et al.*, '*Wavelength-Selective Solar Photovoltaic Systems: Powering Greenhouses for Plant Growth at the Food-Energy-Water Nexus*', Earth's Future, vol. 5, no. 10, pp. 1044-1053, 2017.

[19] 3M, '*3M ™ Prestige Sun Control Films*', 2017.