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On the Advent of Solar Concentrating Photovoltaic Modules in Crop Cultivation Environments

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ABSTRACT

Energy is a crucial component of the agri-food sector since almost 30% of the world's energy is consumed by this sector. Under such circumstances, the employment of renewable energies can be a sustainable solution to mitigate the adverse environmental impacts as consequences of the greenhouse gas (GHG) emissions from the agri-food supply chain. Generation of electricity using photovoltaic (PV) technology to supply the power demand of the agriculture and food production sectors requires large areas of land. To solve this problem, the co-generation of solar PV electricity and crop production (agrivoltaic concept) is expected to relieve this restriction. An emerging agrivoltaic technology is the installation of concentrating PV (CPV) systems in crop cultivation environments to both provide the power demand and produce food on the same land. This study presents an overview of agrivoltaic systems and CPV technology with a special focus on the advent of CPV modules in agricultural environments. In this case, the main benefits and challenges of this technology are presented and discussed.

Keywords: Sustainable agriculture; Crop production; Solar concentrators; Agrivoltaics.

1. INTRODUCTION

The global population follows a growing trend so that since the early 1960's it has been doubled, expecting to reach over 9 billion people by 2050 (1). This growing trend is envisaged to menace the global concept of '*Food Security*' which is interpreted as the major facet of sustainability. According to the definition presented by the United Nation's Committee on World Food Security (CFS), food security is defined as (2):

"*All people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their food preferences and dietary needs for an active and healthy life*".

There is a well-known framework that analyses the interconnection between water, food, and energy which is called *WEF nexus*. This framework includes synergies, conflicts, and trade-offs among the mentioned resources. The role of renewable energy technologies (RETs) in the WEF nexus is promising, able to address the trade-offs between water, food, and energy. In this case, the competition between sectors can be alleviated by offering less resource-intensive processes (3).

Energy supply for all stages of agri-food value chains including crop and dairy production, forestry, post-harvest, processing, transportation, and distribution of food mainly relies on fossil fuels, causing the agri-food production and processing sector to be a significant emitter of greenhouse gas (GHG) emissions (4). At the same time, solar energy is considered the most abundant renewable energy source with the greatest adaptability with a wide category of agricultural operations (5). Two main technologies which are employed to harness the energy coming from the sun are photovoltaic (PV) and solar thermal. Using PV technology, solar cells are utilized to directly convert solar radiation into electricity, while thermal collecting systems convert solar radiation into heat by using low- to medium-temperature

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collectors or high-temperature concentrators (6). The employment of solar energy technologies (SETs) in agriculture and food production systems enhances reliability, eliminating the heavy reliance of many farm operations on fossil fuels and mitigating the release of GHG emissions to a large extent (7).

1.1 The concept of agrivoltaics

The co-developing of the solar PV electricity generation and crop production on the same land is called '*agrivoltaics*' which was firstly introduced by Dupraz et al. (8). In this concept, the solar PV system structures are modified in a way to allow crop production at the same time and on the same land. This idea was firstly proposed by Goetzberger and Zastrow in 1982 (9). In their proposed modification, the PV array was installed at a height of 2 m with increased space between the panels, creating a situation in which excessive shading on the cultivated crops beneath is avoided. A schematic representation of a typical agrivoltaic system installed on an open field is shown in **Figure 1**.

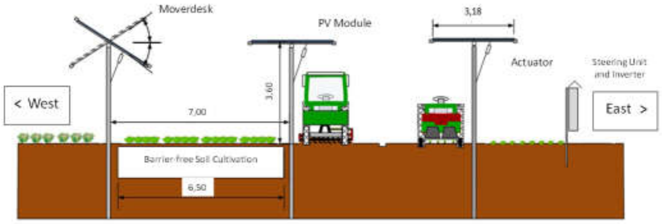

Figure 1. Cross-section of a typical agrivoltaic system installed on an open field (10).

There are various criteria that agrivoltaic systems are classified based on including the type of the system (closed or open), type of the structure (interspace/overhead PV, integrated with greenhouses), the tilt of the PV modules (fixed, one-/two-axis tracking), type of the PV modules (opaque, semi-transparent, bifacial) and type of the application (grassland farming, arable farming, horticulture, and aquaculture). According to this classification, agrivoltaic systems can be installed on both open-field farms or integrated with protected crop cultivation greenhouses. Considering the structure, the interspace PV is mainly installed in pasture and arable farming, while overhead PV is more suitable for horticulture.

1.2 Benefits and challenges of agrivoltaic systems

Despite the pass of over three decades from when the concept of agrivoltaic was introduced, this technology is still in the initial phases of development with plenty of room for technical advancements and new sectors of utilization. According to Pascaris et al. (11), although agrivoltaic systems can offer potential benefits, several obstacles still exist in the way of the adoption of this technology. Some of the main points that should be considered are the long-term productivity of the land with the desired certainty, the potential of the market, and the flexibility requirement for the predesigned system to incorporate different scales. As discussed in this study, these adoption barriers can be handled by precise planning and mutually beneficial land agreements between two participants of the solar and agriculture sector. Agrivoltaic systems have also an effective role in the WFE nexus. In this realm, the plants cultivated beneath the sunshade of PV modules can benefit from effective water/rain redeployment, wind mitigation, temperature deviations protection (12), reduction in evapotranspiration, perfection in soil moisture, security in contrast to climatic uncertainty and risky happenings such as hailstones. Although providing desirable levels of sunlight for the growth of plants is an important concern, under hot climate conditions, high intensity of solar radiation can cause adverse impacts as a consequence of supra-optimal air temperature and low humidity (13).

In this study, the integration of concentrating PV (CPV) modules in agrivoltaic systems is investigated and associated benefits and challenges are introduced. Additionally, main concluding points along with the prospects for implementation of this technology in crop cultivation environments are presented and discussed.

2. LIGHT ABSORPTION AND PHOTOSYNTHESIS

Plants and algae are photosynthetic organisms that utilize electromagnetic radiation from the visible spectrum to drive the synthesis of sugar molecules (14). The energy of specified wavelengths of light is absorbed by special pigments in chloroplasts of plant cells, resulting in a reaction of the molecular chain known as light-dependent reactions of photosynthesis (15). The most desired wavelength of visible light for photosynthesis[1] lies within the blue range (425–450 nm) and red range (600–700 nm). In this regard, those wavelengths of light that fall outside of these ranges are not utilized by most plants, and longer wavelengths can cause heat build-up in plant tissues. Leaves of plants absorb some part of light energy and convert it to chemical energy at the first stage of photosynthesis

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[1] Photosynthetically active radiation (PAR)

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during light-dependent reactions. As depicted in **Figure 2**, this chemical energy is stored in carbohydrate molecules which are synthesized from carbon dioxide (CO_2) and water (H_2O) (16).

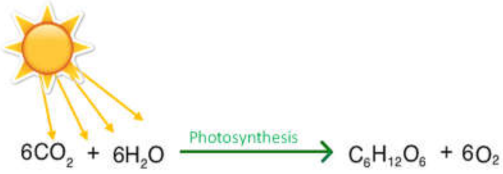

Figure 2. Photosynthesis process (17).

The photosynthetic efficiency which is equal to the fraction of light that is converted to chemical energy by plants is usually 3-6%, where the remaining portion is primarily dissipated as heat with a very small fraction (1-2%) which is re-emitted (18). It is worthy to be noted that photosynthetic efficiency depends on several parameters including light frequency, light intensity, amount of leaf area that captures the light, temperature, water availability, and the concentration of the CO_2 in the atmosphere. Comparing with PV modules, the conversion efficiency of light to electricity is approximately between 6-20% (19).

3. CONCENTRATING PHOTOVOLTAIC MODULES

Concentrating photovoltaic (CPV) modules are capable of concentrating a significant number of solar rays on a small PV cell through utilizing lenses or curved mirrors. The Fresnel lenses are amongst the most widely-used owing to their light weight, small volume and relatively low cost. These lenses, basically made of polymethylmethacrylate (PMMA) or silicone on glass (SOG), feature small concentric grooves on their surface which act as prisms to precisely focus the light on the solar cell. On the other hand, curved mirrors, especially parabolic trough or dish concentrators, focus light on solar cells placed at the focal line or point. Reflectivity of the mirror, absorptivity of the receiver, incident angle and tracking error can influence the performance of these systems (20). **Figure 3** shows the schematic of a Fresnel lens and a concentrating mirror used as CPV modules. CPV's cells can convert about 46% of incident solar power to electricity while the rest is often wasted. III-V triple-junction solar cells, made of semiconductor materials on top of each other, have been used commercially in CPV systems to attain efficiencies over 40%. As shown in **Figure 4**, triple cells are usually a combination of Gallium Indium Phosphide (GaInP) in the top layer, Gallium Indium Arsenide (GaInAs) in the middle layer, and geranium (Ge) as the bottom layer. Miscellaneous materials are used in solar cells to augment efficiency through the capture a larger portion of the solar spectrum (21).

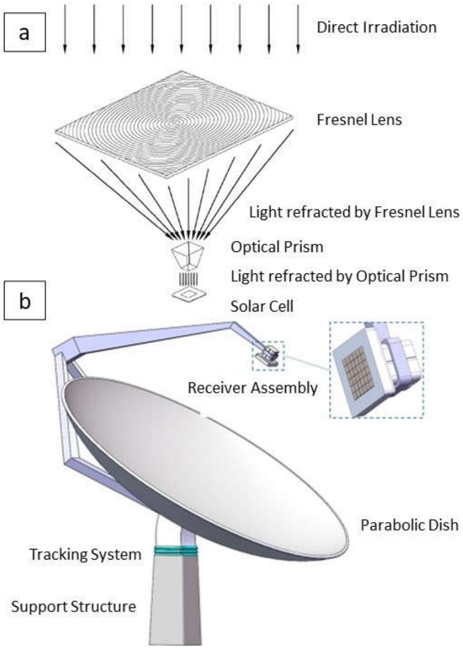

Figure 3. CPV modules using; a) Fresnel lens, and b) Point-focus parabolic mirror (22).

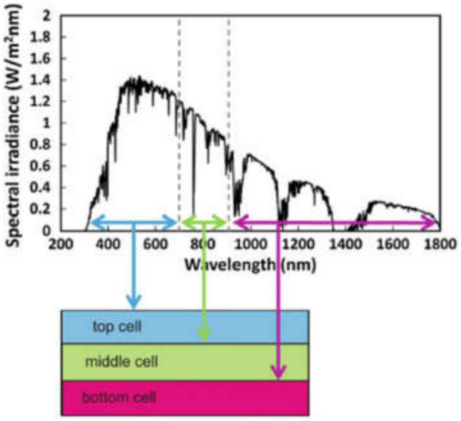

Figure 4. Triple-junction GaInP/GaInAs/Ge solar cells and their efficient wavelengths (21).

CPVs can be classified in terms of optics, tracking system, concentration factor, and cooling system (**Figure 5**). Regarding optics, refractive (lenses) and reflective (mirrors) systems might be linear or point-focus, proportional to the application. In terms of the tracking system, CPVs are mainly divided into two groups of one-axis and two-axis, the second of which can trace the sun rays in two directions to hold the CPV module perpendicular to them and attain the maximum incident radiation.

Concentration ratio (CR), often stated in the units of suns, illustrates how far the incident solar radiation flux rises on solar cells and is categorized into low concentration (≤ 10 suns), medium concentration (10-100 suns), and high concentration (100-2000 suns). Low concentration PV systems (LCPVs) usually employ linear-focus systems like holographic or luminescent and do not require any trackers, whereas medium concentration PV systems (MCPVs) are mostly composed of parabolic trough or linear Fresnel lenses along with a single or dual-axis tracking system (21).

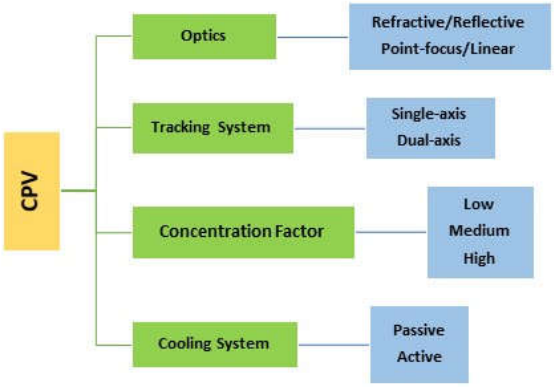

Figure 5. CPV classification criteria (21).

Last but not least, high concentration PV systems (HCPVs) with high optical efficiencies need to make use of dual-axis tracking systems and high-efficiency multi-junction solar cells. The last two kinds generally have to be accompanied by cooling systems. They are implemented not to allow the fall of PV cell efficiency due to temperature increase over limits and cell degradation. The cooling can be done either passively by using air convection or actively by conduction and a cooling fluid through a heat exchanger. While the former is adopted in MCPVs and needs roughly large areas to dissipate heat with no need of supplement power, the latter such as microchannel heat sinks, heat pipes and impinging jets are commonly utilized in HCPVs and photovoltaic/thermal (PVT) systems to reuse the heat in other applications (22).

4. APPLICATIONS OF CPV MODULES IN AGRIVOLTAICS

CPV modules have to be installed at an elevated height (5 m or higher) to provide sufficient space for crop growth, livestock movement, activities of farmers, and farming machines (23). However, the problem of shading on crops might hinder their premium-quality growth. Distinct studies have suggested favorable approaches to undermine this concern, amongst which two solutions are of more efficiency.

The first approach, mostly in open farming lands, uses a parabolic glass panel covered with a multi-layer polymer dichroitic film which reflects the light in the NIR region on solar cells located in the parabolic local line and transmits the red and blue light which consists the vital wavelength bands for the plant's growth. To elaborate more, these panels merely let pass the photons which are located in the PAR region, namely the blue region in the range of 420-460 nm and the red region in the range of 630-670 nm, as shown in **Figure 6**. Within these two wavelength bands, lie the absorption peaks of *chlorophyll a* and *chlorophyll b* of plants which are fundamental for photosynthesis. Hence, the remaining bands are reflected on solar cells to generate electricity. This selective solar spectrum-splitting technique can not only mitigate the shading problem but also provide crops with higher qualities. Liu et al. (24) implemented the same approach using a polymer film based on Ta_2O_5, TiO_2, and SiO_2 along with a dual tracking system and reported taller and bulkier plants containing more soluble sugar and higher net photosynthetic rate. Another notable result was a 2-4 ˚C decrease in the temperature at the surface of leaves causing a 26% fall in evaporation of water.

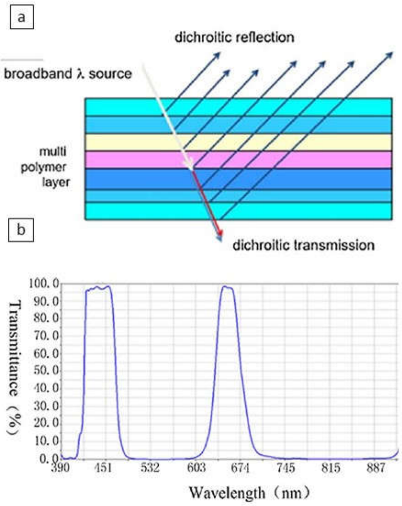

Figure 6. a) Schematic and b) Transmitting wavelengths of solar spectrum-splitting technique (24).

In the second approach, which is commonly used for covering the roofs of greenhouses, highly transparent solar-tracking lamellae or Fresnel lenses concentrate the direct sunlight on solar cells located beneath them at the focal point or line for electricity production and transmit the diffuse sunlight to the ground for the growth of crops (**Figure 7**). The daily light requirements of plants vary widely but diffuse sunlight is roughly able to supply most of them (25). Although the diffuse sunlight is shadowless for plants, the tracking of the CPV module creates a dynamic shaded area (26). Wu et al. (27) utilized this system by a row of Fresnel lenses in a Chinese greenhouse and concluded that the maximum power generation efficiency was about 18% while no detrimental change occurred for crops cultivation. In another study, Apostoleris et al. (25) made use of a transparent tracking CPV made of Fresnel lenses along with high-efficiency cells on a greenhouse roof with consideration of light requirements of plants and illustrated that this system not only can generate comparable electricity to normal PV systems, but also it supplies an adequate amount of light for most crops. Furthermore, Sonneveld et al. (28) carried out a research on retaining the heat load of a greenhouse low by using an absorption cooler employing a Fresnel CPV module on its roof, and finally showed that cooling a greenhouse can result in a 90% fall in water consumption required for cultivation.

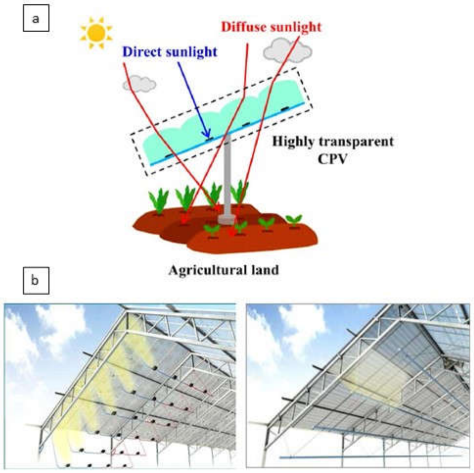

Figure 7. a) Schematic of a highly transparent CPV module, and b) CAD drawing of two point-focus and linear CPVs using Fresnel lenses in a greenhouse (29,30).

5. CONCLUSIONS AND PROSPECTS

The main focus of this study is to provide an overview of solar energy utilization in agriculture for co-production of electricity and agricultural crops. Among the different technological solutions, an emerging technology is using CPV modules that can be installed in open fields as well as in greenhouses. Considering the literature, very few studies have been conducted on this type of agrivoltaic systems and very few of the CPV modules have been commercialized. In some cases, specific solar splitting spectrum films have been utilized to improve the growth trend of crops by providing light at the PAR range and providing NIR for electricity generation by the PV cell. In HCPVs, the main limitation is the necessity of using a two-axis sun tracker that can impose additional costs. However, it is estimated that this can be compensated by an increase in the production of electricity and crops. The investigated studies show that Fresnel lenses are more appropriate concentrators for use in agricultural environments mainly because of their transparency. However, there is still room for technical and economical improvements of CPV modules for their specific use in cultivation applications.

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