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Shading Effect of Transparent Photovoltaic Panels on Crops Underneath Agrivoltaic Systems

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Abstract. Agrivoltaic systems combine soil-grown crops with photovoltaic (PV) panels erected several meters above the ground. Combining solar panels and food crops on the same land can maximize land utilization. Under the PV panels, however, microclimate factors like solar radiation, air temperature, humidity, and soil temperature change. An agrivoltaic system must optimize sunlight sharing between solar panels and crops to maximize food energy production. It has been challenging to improve and analyze the performance of agrivoltaic systems due to the lack of a defined crop-specific parameter. In this work, we present a practical option to partially replace bifacial modules with semi-transparent ones, providing comparable levels of crop protection and greater climate change resilience while generating green energy and increasing land-use efficiency. The agrivoltaic system must be tailored to satisfy the needs of crops. For this purpose, a simulation model was conducted, which examined the impact of module transparency and cell layout based on light availability.

Keywords: Semi-Transparent Photovoltaics, Agrovoltaics, Shading

1. Introduction

Population growth and economic development have led to a rise in global energy consumption, which is projected to double by mid-century [1], [2]. To fulfill energy demand, it will be essential to replace fossil fuels with renewable, eco-friendly energy sources [3], [4]. However, the move to cleaner energy generation is the largest obstacle scientists must surmount to combat the climate change catastrophe [5]. Solar energy is the most accessible and abundant renewable and clean energy source [6], [7].

A photovoltaic (PV) panel converts solar energy into electricity to generate power [8], [9]. Solar photovoltaic (PV) electricity is an appealing renewable energy source for the reasons listed below. PV reduces carbon emissions significantly, has a long lifetime (20–30 years), is a reliable, inexpensive, and abundant energy source, and is more efficient than photosynthesis in capturing solar energy [10]. The installation of PV systems on agricultural land generates a land-use conflict between food production and energy generation, which is a major challenge in areas with limited space or dense populations [3]. Agrivoltaics refers to systems that integrate solar PV with agriculture on the same parcel of land [11], [12]. Agrivoltaic systems decrease water use while meeting the world's rising food and energy needs [13]. Under an agrivoltaic system, however, the alteration of microclimate elements, such as the decrease in solar radiation, is one of the most critical aspects of agricultural activities [14]. The crop's average quantity of light may be diminished by PV panels' shade [15], [16]. Additional microclimate characteristics, including air temperature and humidity, are also changing.

A survey of the existing agrivoltaic systems reveals that PV arrays, which are situated 4 to 7 meters above the crop level and at a reduced density, can decrease shade and improve PV module sunshine sharing with crops. Recent field experiments and modeling studies have evaluated the agrivoltaic method for various crops, such as lettuce, wheat, corn, tomatoes, cucumbers, and peppers, under the conventional and reduced spatial density of PV arrays [17]–[20].

Marrou et al. [19] demonstrated that the variation in the intensity of radiation relative to open-sun conditions is the most important factor in determining the relative crop yield in an AV farm, even though other microclimate parameters, such as temperature and humidity, may also vary under the AV shades [21]. Although the necessity of controlling the sunlight balance between solar modules and crops is widely understood, there is no systematic approach to optimizing its APV designs.

Any systematic method to design optimization must depend on a measure to quantify farm production for a particular solar module-to-crop ratio. Unfortunately, the community has yet to identify an appropriate measure for usage during the design process.

Using a simple method, for instance, the sunlight sharing in AV might be measured by the quantity collected by the panels and the photosynthetically active radiation (PAR) accessible to the crops underneath the PV arrays. Incident PAR under panels is a crop-independent metric that cannot be used for crop-specific optimization. In contrast, complex mechanistic crop models [22] have been used to estimate crop production as a function of shading and other characteristics.

In this study, we replace bifacial modules with partially semi-transparent ones, therefore providing equivalent crop protection and improved climate change resistance, while also producing green energy and enhancing land-use efficiency. The agrivoltaic system must be customized to meet the requirements of the crops. To this end, a simulation model was developed to analyze the effect of module transparency and cell layout depending on available light.

2. Simulation Approach

2.1 Simulations for the design of the APV

The ground solar radiation is the primary variable in agrivoltaic settings, according to Marrou et al. [19]. This radiation affects the crop's transpiration and photosynthetic activity, two factors that have a significant impact on crop output [10]. The photosynthesis-active radiation, which ranges in wavelength from 400 to 700 nm in the solar spectrum, is crucial for crop development (PAR).

Radiation analyses were performed using the Ladybug tools, an Environmental analysis tool integrated with Grasshopper, an algorithmic modeling interface. The analysis simulations are based on the setup parameters of the APV and the local irradiation circumstances in Kayseri, Turkey (38.7205° N, 35.4826° E). The simulation results are obtained from the solar irradiance and the mean radiant temperature values of three different analysis points and a reference point.

The agrivoltaic prototype is designed at a height of 3 meters facing south. Twenty different kinds of agrivoltaic systems are simulated changing the module density and row spaces between module stripes. The first variable, which is the space between PV rows for crops, is chosen as 2 m, 2.5 m, 3 m, and 3.5 m. The second one is a PV density and different design layout including %33, %50, %50 with checkboard design, and %66 of transparent areas. The structure with a checkboard design is shown in Figure 1.

Figure 1. Agrivoltaic system with semi-transparent modules.

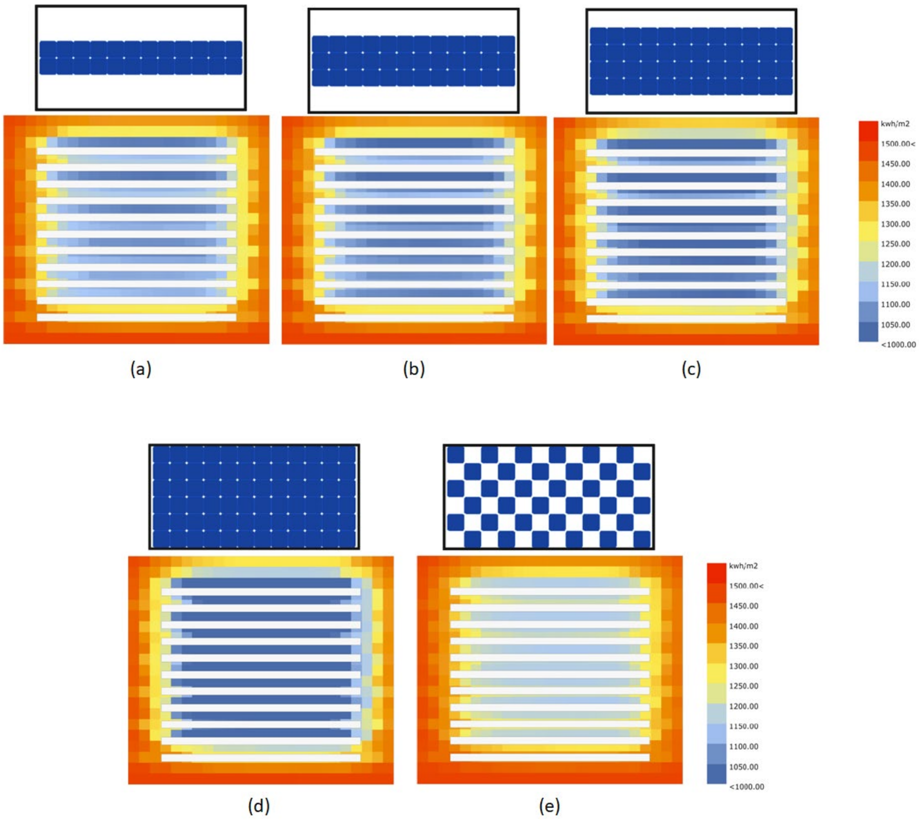

Figure 2. Modeling of relative yearly irradiation at ground level under agrivoltaic arrays differs by the PVP density ((a)%0, (b) %33, (c)%50, (d)%66, and (e)%50 checkboard transparent area) (The row distance of panels are 2m).

Simulation results in Figure 2 indicate that in straight line format, the amount of shading differs significantly under the same row. Consequently, the crops don't develop at the same pace, which leads to a heterogeneous crop output. Because of this, it is not possible to harvest the entire field all at once. Homogeneous radiation exposure is preferred to achieve uniform crop development, which is possible using a checkboard arrangement.

To assess the impacts of d and cells' transparency area on agricultural crop yield, the available photosynthetically active radiation (PAR) was considered under PV panels as a fraction of the full PAR. In equation 1, Ghor is determined by global horizontal radiation computed for the ground level radiation [kWh/ha], d is the row distance and α is the azimuth angle of panels in the system which is set to zero in this case.

$$PAR(d) = \frac{Ghor(d, \alpha; under\ module)}{Ghor\ Unshaded\ area} * 100 \tag{1}$$

The annual PAR results are obtained from the average of three different locations under PV panels (X_1: under the first row in the center, X_2: under the middle row in the center, X_3: under the first row in the center), are shown in Figure 3.

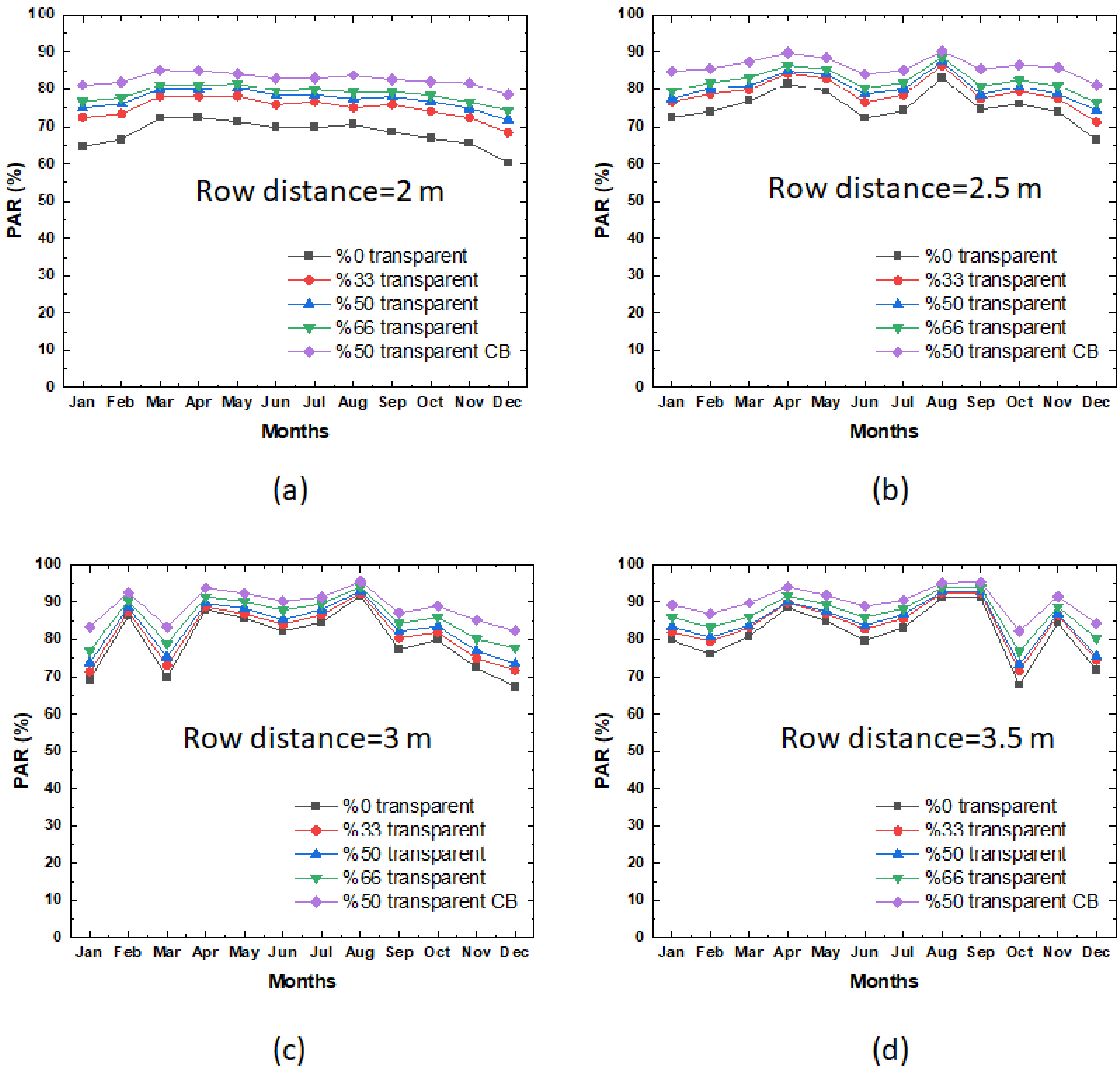

Figure 3. Comparison of PAR at ground level for different PVP densities (%0, %33, %50, %50 checkboard, and %66 transparent areas), and row distances of 2m, 2.5 m, 3m, and 3.5m.

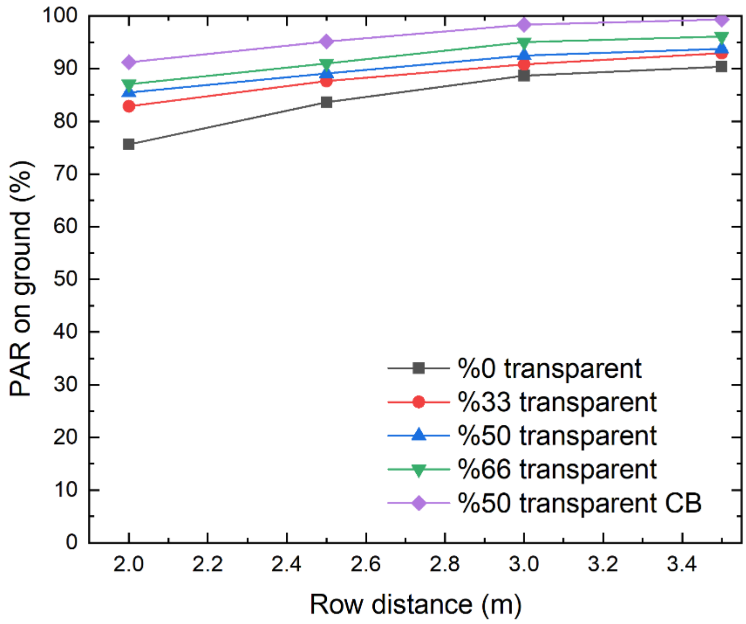

Figure 4. Annual amount of PAR on the ground to row distance between solar arrays.

As illustrated in Figure 4, the PAR amount is increased by increasing the row distance between arrays. Furthermore, by increasing the percentage of the transparent areas of modules the PAR amount will be increased as expected. Another important finding is that the checkerboard arrangement's lowest PAR value is 10–15% greater than the straight-line arrangement's lowest PAR value, which provides a benefit for limiting agricultural production losses. In a study carried out in Belgium, potatoes were grown below photovoltaic modules, and the microclimate was assessed. The results demonstrate lower temperatures and reduced soil and crop evaporation and transpiration beneath the PV modules. Under the PV modules, the leaf area of potatoes was bigger, indicating an improved capacity for light collection. Under the agrivoltaic checkerboard construction, there was little increase in overnight temperatures, indicating that this configuration may not offer much protection from frost [23]. The PV array's shade does not always result in a reduction in biomass yield. It is anticipated that the shade provided by the PV structures will benefit crop productivity by shielding crops from sunburn and drought stress [3]. Even in Belgium, which has an annual mean insolation of 1000 kWh/m^2, summers are becoming hotter and drier [24], which has a negative impact on crop yields [8]. For this reason, agrivoltaic systems must be tested.

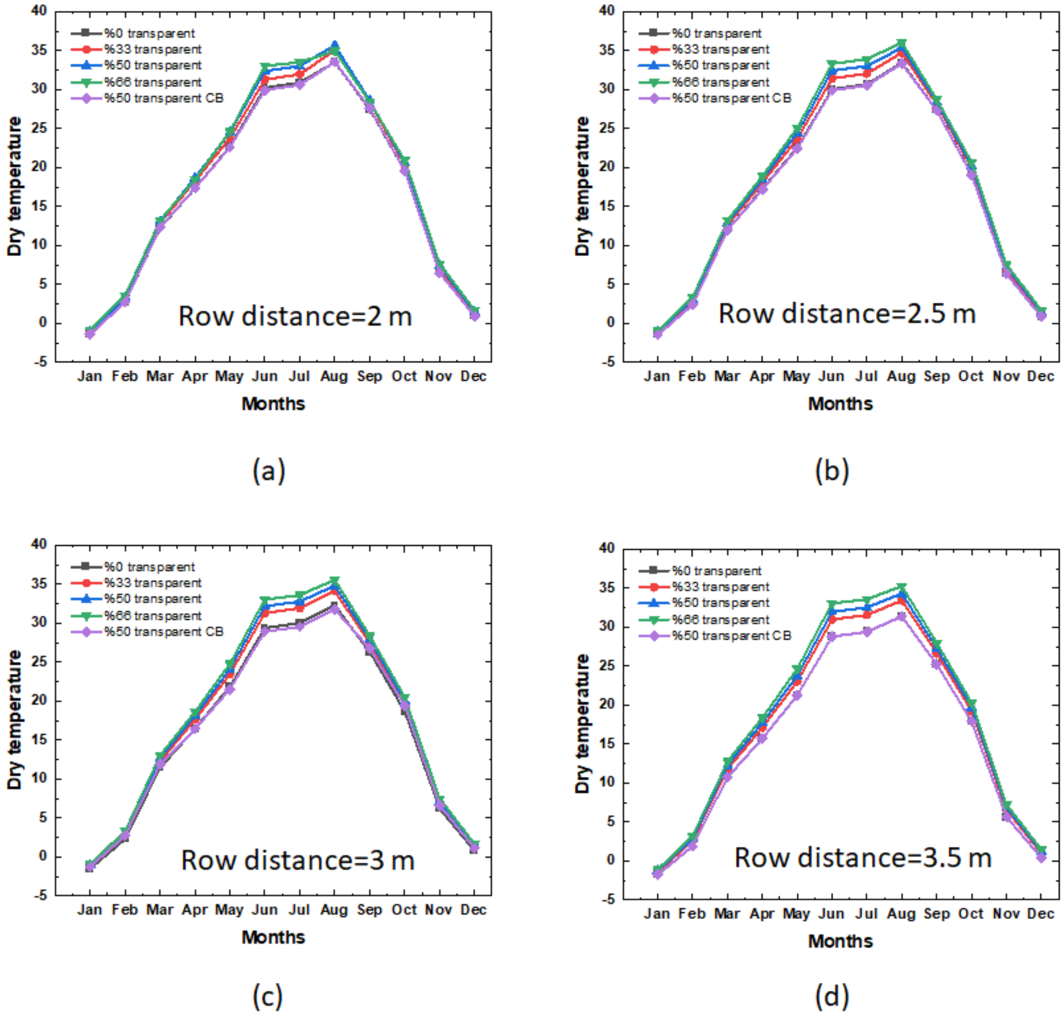

Figure 5. Comparison of dry temperature at ground level for different PVP densities (%0, %33, %50, %50 checkboard, and %66 transparent areas), and row distances of 2m, 2.5 m, 3m, and 3.5m.

The change in the intensity of radiation relative to open-sun conditions can change microclimate parameters, such as temperature and humidity, because of panels‘ shading. The change in monthly temperature is shown in Figure 5.

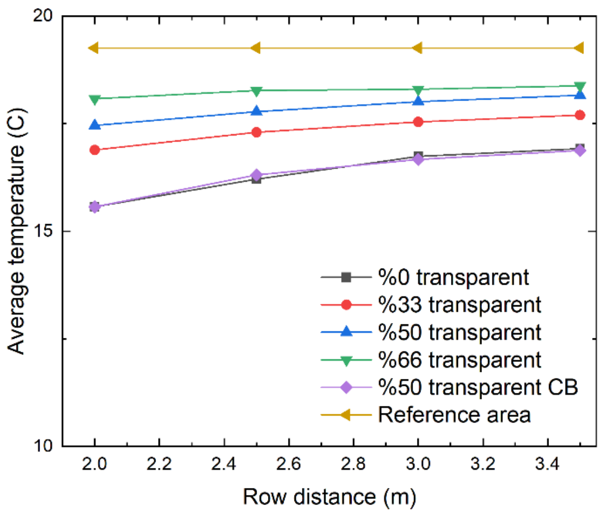

Figure 6. Annual average of dry temperature to row distance between solar arrays.

Figure 6 shows the temperature distinction between the reference and evaluation area. The decrease in radiation beneath the PV modules results in daytime air temperatures that are, on average, 3°C lower. This lower temperature might be advantageous for agricultural production, given that worldwide crop yields are expected to decrease as a consequence of global warming.

3. Conclusion

The Ladybug tool in Rhino software is used to carry out a simulation that estimates the global horizontal irradiation affected by PV modules in an agrivoltaic setup. Using modeling software, straight line and checkerboard configurations were modeled for modules with various transparent areas. This checkerboard pattern assures a uniform dispersion of irradiation, resulting in uniform crop development. Furthermore, the space between rows of PV modules was changed to investigate the effect.

The simulations indicate that the temperature under the PV modules is consistently lower than in the reference region, which is likely advantageous for biomass production in temperate and hot climates. The shift in relative humidity implies reduced transpiration and evaporation below the PV modules, which protects crops from drought stress and conserves irrigation water. Because of this, agrivoltaic systems may protect crops from drought and high heat that is caused by climate change.

Author contributions

Nasim Seyedpour Esmaeilzad: Conceptualization, Methodology, Investigation, Resources, Writing- Original Draft, Writing - Reviewing and Editing, Visualization, Data Curation, İpek Gürsel Dino: Software, Validation, Formal analysis, Dilara Güney: Software, Formal analysis, Yusuf Ersoy Yıldırım: Conceptualization, Methodology, Raşit Turan: Supervision, Talat Özden: Project administration, Funding acquisition, Writing - Reviewing and Editing.

Competing interests

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

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