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Case Study of Impact Evaluation of Agrivoltaic Structure Sizing on Water Availability for Wheat

Microclimate Simulations for Agrivoltaics System Performance Assessment

Paul Gigant[1][https://orcid.org/0009-0000-4621-7000], Caroline Godard[2], Amira Guellim[1], Blandine Thuel[2], and Stéphane Heraud[1][https://orcid.org/0009-0004-9449-9929]

[1]Agrisoleo, France

[2]Acte Agri Plus, France

Abstract: Agrivoltaic (AV) Systems are a new solution for cropping conditions improvement by mitigating extreme weather conditions. Indeed, AV Systems affect microclimate, notably Air Temperature, Irradiance or Evapotranspiration that determines Soil Water Availability. To evaluate crop water stress protection and ensure optimized AV Systems sizing, a methodology was developed using a microclimate simulation tool. This paper presents a case study of Wheat focused on Water Availability, from a project located near Orléans, Center France. The methodology uses Irradiance Simulations at crop level by AGRISOLEO software, which has been parameterized with the structures sizing under study and a panel steering algorithm adapted to wheat phenology. The results are used for evapotranspiration modelling following the FAO-56 Penman-Monteith equation. For this case study, results showed that AV Systems under test reduced irradiance up to 40%. This effect may be reduced up to 17% by controlling the panels rotation angle to maximize irradiance during crop's key development stages. Furthermore, AV Systems reduced Water Stress up to 48%. Microclimate simulation tool demonstrated possibility to assess AV Systems sizing impact on irradiance received by crop and Water Stress protection. Moreover, controlling the solar panels at key development stages of the crop is the central lever in the synergy of dynamic AV Systems. The methodology presented here applies not only to Wheat but to a wider range of crops and climate conditions, hence opening promising perspectives to optimize AV systems sizing and agronomic benefits.

Keywords: Agrivoltaic Systems, Wheat, Water Balance, Irradiance Simulation, Water Availability

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported increased frequency and severity of extreme weather events worldwide, among which severe droughts are one of the most impacting on agricultural yields. For example, 2003 heatwave cut agricultural yields by 20% to 30% in France and neighbouring countries [1]. In this context, agrivoltaic (AV) systems are a new solution to improve cropping conditions in agrosystems by smoothing extreme weather conditions. These systems have been found to decrease evapotranspiration and reduce hydric stress risks. It is therefore relevant to study AV systems sizing impact on water balance during project design stage. Here is presented the evaluation of the impact of various ground coverage ratios on water availability for wheat production for an AV project located near Orleans, Center France. Indeed, wheat crop is particularly subject to hydric stress risk during the end of its cycle and should directly benefit from AV systems. As for all cereal crops, wheat yield is affected by hydric stress caused by high temperatures. Namely, from 25°C grain development is lowered during boot and flowering stages. And beyond 28 °C grain development is stopped without recovery, and it was reported that grain abortion happens at the beginning of grain filling [2].

This work firstly introduces the used methodology for water availability study for AV systems. A validation of the AGRISOLEO irradiance simulations is then presented using data from PVSYST®, a recognized commercial software. Finally, a case study for wheat is presented to demonstrate the need for this method for AV structure sizing optimization.

2. Methodology

2.1 Water balance approach

In agroecosystems, evapotranspiration (ET) is the sum of two terms: transpiration, which is water entering plant roots and finally being passed through leaves of the plant into the atmosphere in the vapor form, and evaporation which is water evaporating from soil or leave surfaces. In this study, the potential evapotranspiration (ET_0) is estimated by using the FAO-56 Penman–Monteith equation [3] on meteorological hour time step datasets. The crop's evapotranspiration (ET_c) is determined by multiplying the calculated ET_0 by a crop coefficient, K_c, depending on crop phenological stage, following Equation 1. K_c represents the ratio between crop and reference ET [4].

$$ET_c = K_c \times ET_0 \tag{1}$$

The irradiance received by crop under the AV structure was simulated by AGRISOLEO software and was used for ET_0 estimation. Soil Water Availability for crops (AW) at time t is evaluated from a water balance in equation 2 using ET_c, precipitation data PP and the Soil Water Availability at time t-1.

$$AW_t = AW_{t-1} + PP - ET_c \tag{2}$$

Crop water stress thresholds are defined as shown in figure 1.

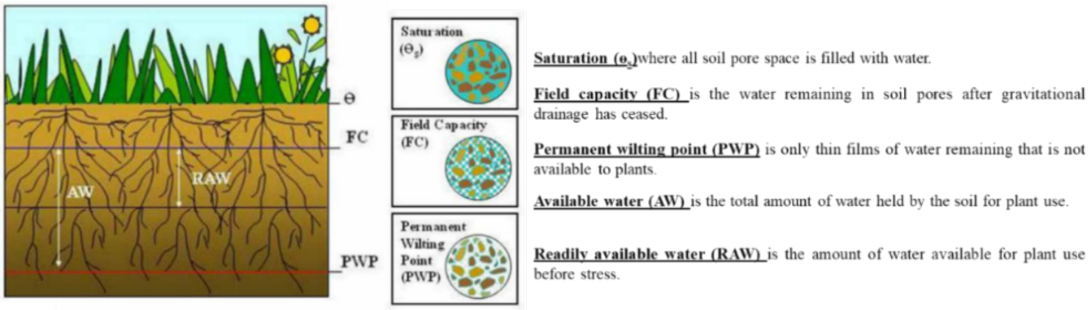

Figure 1. Diagram of water content in the root zone. Credits: D. Dukes et al., 2009 [5]

Meteorological input data used in ETC estimation, namely wind speed, temperature, pressure, air relative humidity and rain were extracted from METEONORM at field plot scale. The effect of the AV structure inter-row dimension on soil water availability is evaluated. Irradiation simulations at an hour time step integrate the different crop phenological stages and the corresponding panel steering algorithm. The example of panel steering adapted to wheat crop is given in table 1. For the present case study, panel steering algorithm is clock-based and is customized for the key wheat phenological stages considering irradiance needs for first leaves development, during meiosis and flowering.

Table 1. Photovoltaic panels steering algorithm.

Crop	Phenological Stage	Steering	
		Position	Time
Wheat	Sowing → Plant Emergence	Horizontal	Night
	Plant Emergence → Tillering	Horizontal	Night
		Maximum Irradiance	Morning
	Winter	Horizontal	Night
	Meiosis → Flowering	Maximum Irradiance	Morning
		Maximum Shading	Afternoon
	Grain Development	Maximum Shading	Afternoon
	Ears Drying	Maximum Irradiance	Afternoon

2.2 Irradiance model performance assessment

AV studies differ from traditional photovoltaic studies by the necessity to predict the hourly irradiance received by the crop as well as the irradiance received by the solar collector. Indeed, it is key to assess both crop and electrical yields to optimize AV structure sizing and evaluate AV system synergy. AGRISOLEO developed its own tool that enables irradiance calculation at each point located in a studied field, see figures 2.1 and 2.2, from a 3D AV scene.

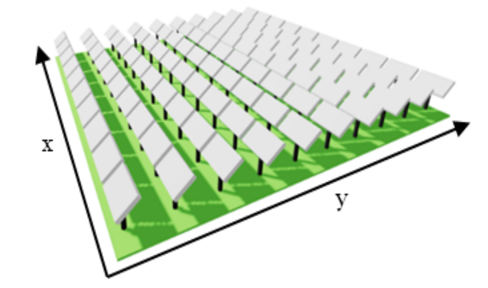

Figure 2.1. 3D visualization of AV structure and shading.

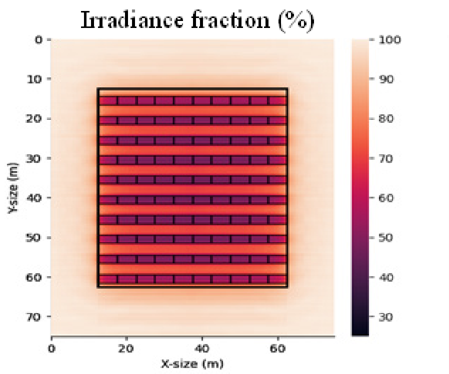

Figure 2.2. Irradiance fraction at crop level.

The model used the definition of the irradiance introduced by R. Perez [6]. It defined the global horizontal irradiance GHI as the sum of two components: the beam horizontal irradiance BHI and the diffuse horizontal irradiance DHI.

$$GHI = DHI + BHI \quad (3)$$

For photovoltaic consideration, it is important to take the circumsolar contribution into account because it has a significant impact on electrical yield. In most usual meteorological dataset, the circumsolar contribution is accounted with the diffuse component [7]. The hypothesis is then to consider the diffuse component isotropic for any part of the sky seen from the studied field.

The irradiance calculation is performed both for the beam and the diffuse components following a purely geometrical approach similar to P.E. Campana [8] by calculating the beam and diffuse shading factors ($SF_{b,d}$).

The shading factor for the beam component SF_b. is dependent of the solar position and is then calculated at each step of the simulation using the cast shadow method. SF_b is then a spatial matrix representing the discretization of the field with values between 0 and 1. The beam component at a specific time step and location is then represented by equation 4 below:

$$Bh_{t,(x,y)}=SFb_{t,(x,y)}\times Bh_t \tag{4}$$

The shading factor for the diffuse component SF_d for a fixed structure is independent of the sun's position and can then be calculated once. SF_d is calculating by discretizing the sky dome with respect to altitude and azimuth angle similarly as [8]. SF_d is computed for each spatial locations and the diffuse component Dh at each time step is calculated by:

$$Dh_{t,(x,y)}=SFd_{(x,y)}\times Dh_t \tag{5}$$

With tracking structure configuration, the SF_d is recalculated at each time step to take into account the geometric change of the structure and equation 5 becomes:

$$Dh_{t,(x,y)}=SFd_{t,(x,y)}\times Dh_t \tag{6}$$

In practice, to save computational time, SFd is computed for many panel tilts and interpolated for each specific values during the simulation.

The modelling performance is here assessed by comparing its output data with PVSYST® ground irradiance for different AV structure configurations with panel tilt varying from 0° to 90°. PVSYST® is a commercial software, using embedded shading scene construction tool for simulating complex shadings [8]. The agreement between PVsyst® and AGRISOLEO software is evaluated by looking at the R-squared and the root mean squared (RMS) error over a typical meteorological year (TMY) in France as shown by figure 3.

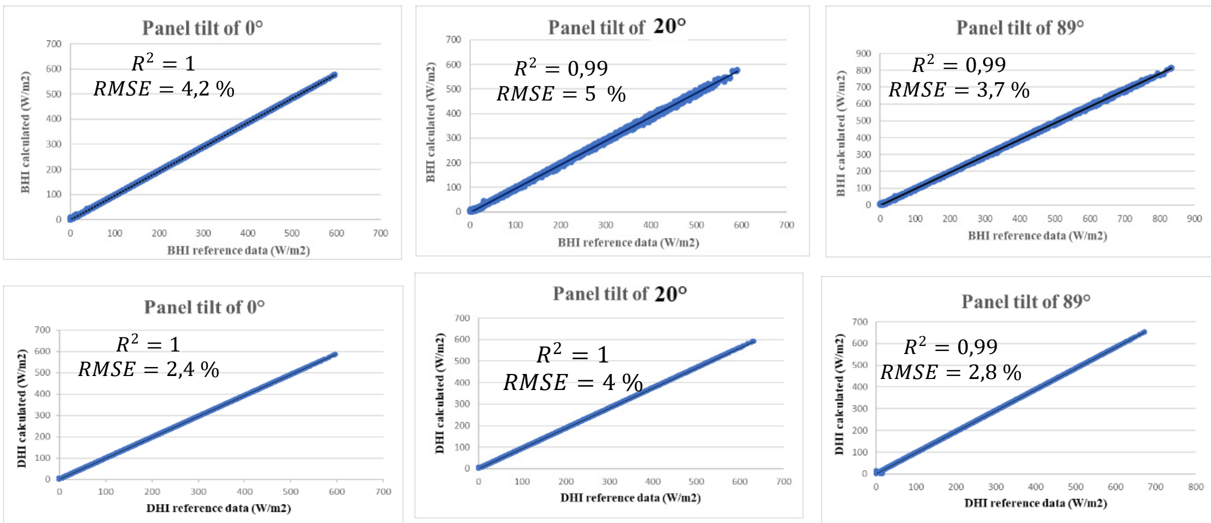

Figure 3. Performance assessment of beam and diffuse components calculation.

The r^2 correlation between the two models is constant and equal to 1 for each configuration, while the RMSE accuracy is less than 5%, showing model performance. A difference in the skydome discretization angle resolution can lead to a constant shift between the two models outputs for the beam and diffuse components. These results can be computed for every time step and spatial location. For this case study, the irradiance values used for ET_0 calculation are computed by AGRISOLEO software for a tracking structure that follow the panel steering algorithm described in Table 1.

2.3 Wheat case study presentation

A wheat crop followed by a cover crop, near Orléans, Center of France, is the case studied here, accompanied by ACTE AGRI PLUS. In the current paper, the effect of panel steering based on crop phenological stage on intermediate variable irradiance is analyzed for a 11m pitch AV tracking structure. Then the effect of two AV structure inter-row dimensions (5m and 8m pitches) on soil water availability is evaluated.

3. Results

3.1 Effect of phenological panel steering algorithm on irradiance

The irradiance simulated in the center of inter-rows is rather similar, whatever the wheat height corresponding to various crop phenological stages (figure 4). However, two gradients of irradiance are simulated both horizontally and vertically from the ground. The irradiance is the lowest (39-40% of incoming irradiance) for a wheat crop at the ripening – grain drying (senescence) stage grown at the foot of the panels.

Panel steering based on crop phenological stages leads to an increase of irradiance received by crop by an average 17% (figure 5).

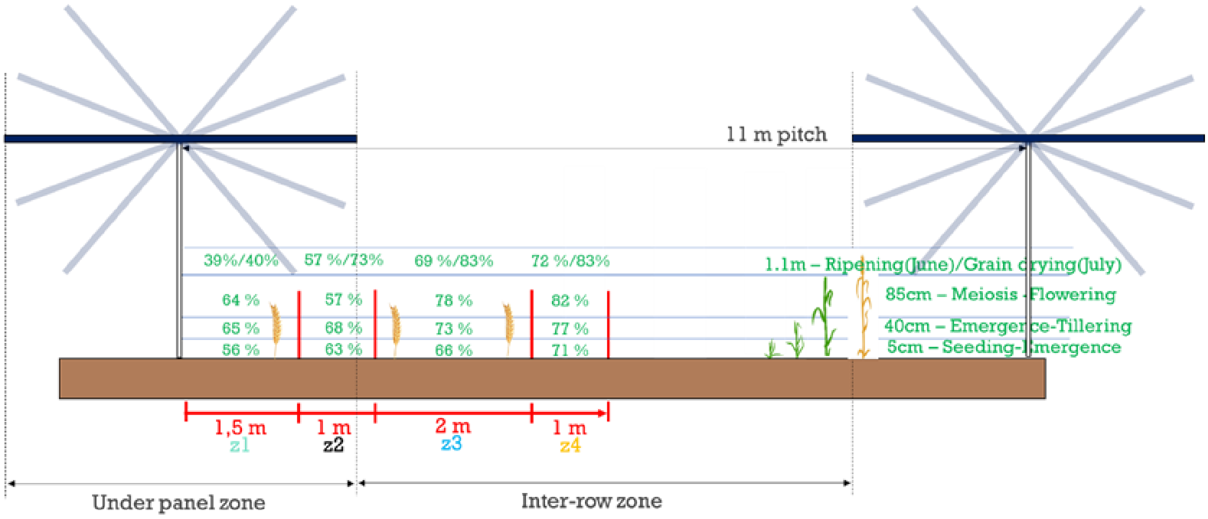

Figure 4. Simulated irradiance fraction of in under-panel and inter-row zones at various wheat heights, with a panel steering based on crop phenological stages.

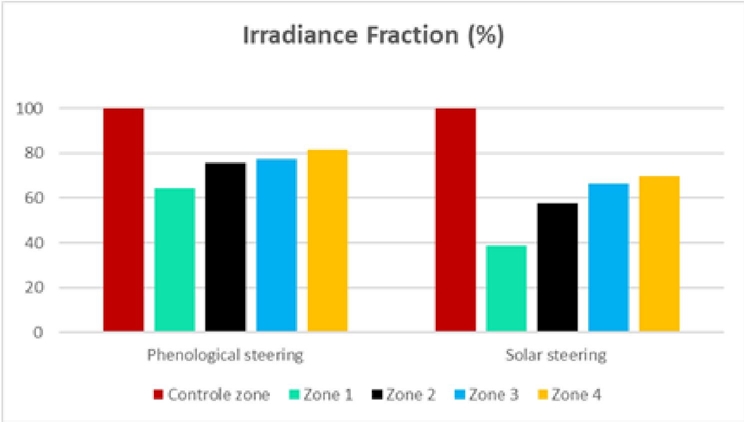

Figure 5. Comparison of the effect of panel steering on simulated irradiance for under panel and inter-row zones during the whole wheat growth cycle.

3.2 Effect of AV structure on water availability for crop

As shown in figure 6, the 8m pitch AV system induces an average 35% ET_c reduction compared to the control zone. Moreover, ET_c is more reduced under an AV structure with a 5m pitch: it reaches a maximum of 40% for a 5m pitch compared to a 30% reduction for a 8m pitch in July.

The RAW (Readily Available Water) is a significant indicator of plant water stress integrating both plant and soil water state at a given time period. For an Available Water Capacity (AWC) of 37 mm (figure 7), the risk of water stress is higher between June and August. This water stress is reduced by 48% and 34% respectively with the 5m and 8m pitch AV structures.

Figure 6. Monthly wheat crop evapotranspiration (ET_c).

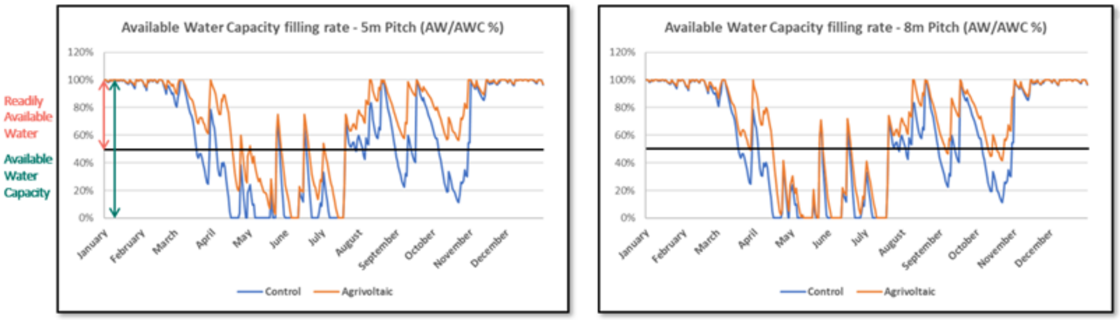

Figure 7. Available Water Capacity filling rate for the 5m and 8m pitch structures.

4. Conclusion

We have presented the water balance modelling approach and the irradiance simulation tool performance assessment which shows a good correlation to reference for multiple AV structure configuration with varying angles and can be applied to fixed and tracker structures with agronomic steering algorithm. We then could perform simulations for a specific use case of AV tracker structure with agronomic panel steering algorithm, applied at specific development stages of the wheat.

Available Water simulations using AGRISOLEO software at a specific field plot, here Orléans, show that a 5m pitch leads to a maximum reduction in wheat evapotranspiration compared to 8m pitch. Thus, AV structure sizing can be optimized to reduce water stress risk and enhance rainfed crop resilience. The analysis can be extended using various weather scenarios, various panels steering algorithms and focus on the critical phases of wheat yield build up. Another use of these simulations is to evaluate the savings in irrigation water.

Currently water balance is simulated under the hypothesis of a constant root front deepness for each crop. Integrating the evolution of crop roots deepness in the current modelling approach would enable an AW evaluation consistent with crop development. This potential evolution as well as the parameterization to other crops widens the application of the proposed modelling approach during the design stage of AV projects. Indeed, it has already been tested for wheat, sunflower, and dwarf bean and is ready for other annual and perennial crops. The irrigation management adaptation and forecast adapted to both crop and AV structure is an example of current methodology application. Moreover, a typical use of the presented simulation tools is optimization of panels steering industrial algorithms.

Data availability statement

Data supporting results of the current paper can be accessed upon request from the authors.

Author contributions

Paul Gigant contributed at the data curation, software and writing original draft steps, by conducting the underlying simulations irradiance and water balance of the current paper and wrote the original draft, including visualization. Caroline Godard contributed to the methodology and conceptualization of current research, to investigation (phenological stages parameterization), and to the writing of the original draft, including visualization, as well as reviewing and editing the current paper. Amira Guellim contributed to the investigation of the paper. Blandine Thuel reviewed and edited the current version of the paper. Stéphane Héraud reviewed and edited the draft and final paper.

Competing interests

The authors declare no competing interests.

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