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Could Windbreak Effect Significantly Decrease Evapotranspiration in Vertical Agrivoltaics?

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Abstract. Bifacial vertical panels have been successful in agrivoltaics since the beginning of this system expansion worldwide. While the question of irradiation reduction effect on evapotranspiration has been largely addressed during last years, the question of wind modification and its impact on evapotranspiration has not been the object of a thorough attention yet. Wind modification is expected to be of greater importance in vertical agrivoltaics, panels acting like windbreaks. This preliminary research aims to assess the potential reduction of evapotranspiration in different climates and to highlight the importance of going further on aerodynamics and water demand topics. It shows that non negligeable amounts of water could be saved if those wind abatement rates are created by the rows of vertical panels compared with the evapotranspiration reduction expected induced by the irradiation reduction. Actually, modification in wind direction and speed will depend on geometrical parameters and wind direction. More measurement campaigns and comprehensive models of aerodynamics (CDF) and evapotranspiration are required to assess the relevance of vertical panels to tackle aridity in constrained climates.

Keywords: Windbreaks, Agrivoltaics, Vertical PV, Evapotranspiration, Wind, Water demand

Introduction

There are several reasons justifying the great interest in bifacial vertical panels in agrivoltaics since several years. This architecture is compatible with crop operations (Figure 1.a), allowing

Figure 1. Illustration of (a) the vertical PV compatibility with crop operations (agrivoltaic system of TotalEnergies at Channay) and (b) the typical bi-modal production of east-west oriented vertical panels [3]

to adapt the space between rows of panels to the size of agricultural machines and to preserve the flexibility of changes in agricultural activities. The structures suit complex topographies and those bifacial vertical power plants are cheaper than elevated agrivoltaics for the same capacity; although they remain more expensive than ground mounted power plants [1], [2]. Another reason is their bimodal electricity production when they are east-west oriented [3] that presents an attractive correlation with the electrical demand (Figure 1.b).

More broadly, agrivoltaics are expected to mitigate climate change and to protect from climatic hazards (radiation excess, water stress, night frosts and heavy rains or hails). So far, numerous studies aimed to quantify the effect of radiation abatement on water demand reduction and agriculture production through measurements campaigns and increasingly comprehensive models [4], [5]. Irradiance reduction has been the object of a thorough attention during the last years, while the question of wind modification has not been extensively assessed. This effect on wind could be of great importance especially in vertical bifacial agrivoltaics, where panels could act like windbreaks. Yet, the latter have long demonstrated their agronomic interest under constrained climates, reducing damages (caused by lodging, premature fruit drop, …), braking the spread of crop diseases as well as soil erosion and impacting the water demand from evapotranspiration [6], [7]. The aim of this preliminary study is therefore to assess the theoretical effect of wind reduction behind vertical panels in terms of water demand under different climates.

Material and methods

We based this research on the configuration of the agrivoltaic system built by TotalEnergies in Central France at Channay. Figures 2 and 3 show a picture and an aerial view diagram of the system.

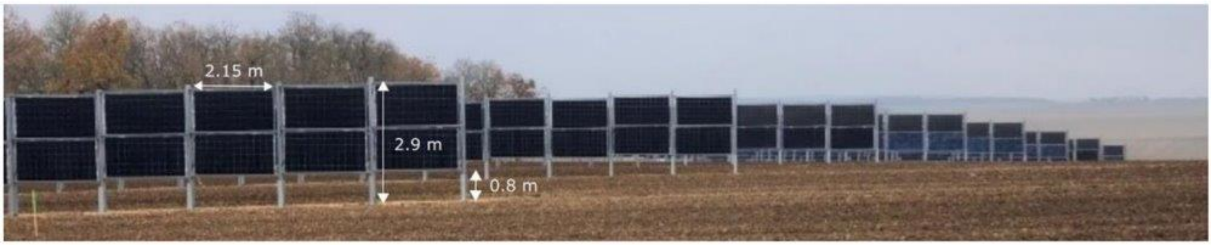

Figure 2. Studied configuration (agrivoltaic system in Central France at Channay)

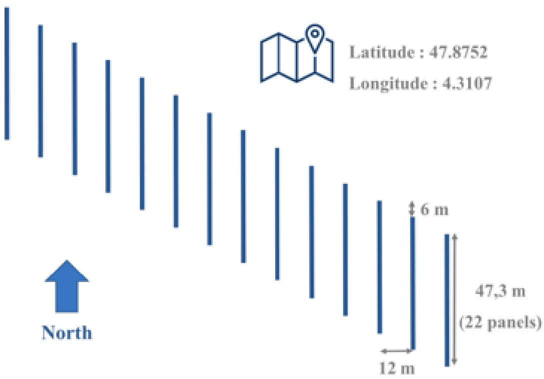

Figure 3. Aerial view diagram of the studied configuration

To have an idea of what could be the effect of different wind abatement rates on water demand in different climates, we assessed the daily water flux of a reference crop growing in this configuration (Figures 2 and 3) with the Penman-Monteith equation, known as the FAO 56 PM equation. Equation 1 gives the reference crop evapotranspiration [mm.day^{-1}] of a hypothetical green well-watered grass actively growing and completely shading the ground, where Δ is the slope of vapor pressure curve [kPa.°C^{-1}], R_n is the net radiation at the crop surface [MJ.m^{-2}.day^{-1}], G is the soil heat flux density [MJ.m^{-2}.day^{-1}], γ is the psychrometric constant [kPa.°C^{-1}], T is the daily mean air temperature at 2 m height [°C], U_2 is the wind speed at 2 m height [m.s^{-1}], e_s is the saturation vapor pressure [kPa] and e_a is the actual vapor pressure [kPa].

$$ET0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T+273}\,U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \tag{1}$$

As can be observed derivating Equation 1 according to radiation, ET0 is increasing linearly with incoming radiative energy. When derivating the effect of wind speed, it can be observed that ET0 increases asymptotically according to wind speed to a maximum value function of radiation and partial vapor pressure deficit. Daily ET0 assessment was performed for 5 theoretical locations (Sweden, Belgium, Central France, South of France and Tunisia) and 4 wind abatement hypotheses (100%, 75%, 50% and 25%) based on windbreak literature [8], [10] with one theoretical control area without panels. A python agrivoltaic framework jointly developed by Naldeo Technologies and Industries and DEAL lab (incorporated in AgriOPS tool of TotalEnergies) was used. A geometrical shading model using PVlib to get the local sun position was developed to compute the shade position at a quarter-hour time step as illustrated by Figure 4. The framework was also coupled with PVGIS and Agri4Cast to get the meteorological data at the different theoretical locations. From local GHI data decomposed into direct and

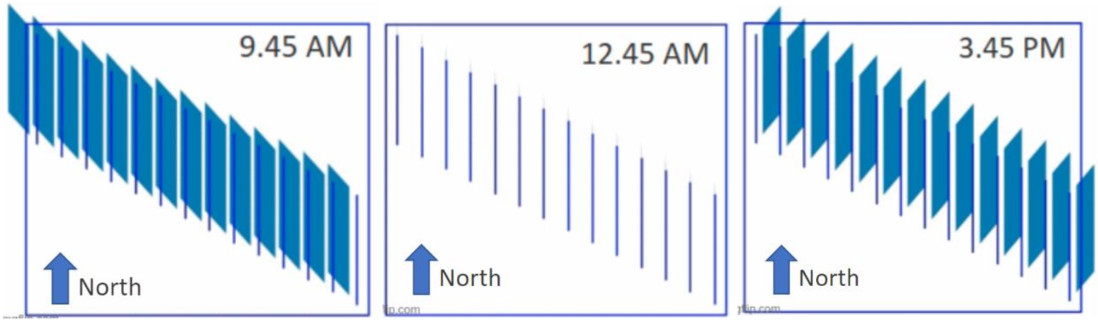

Figure 4. Aerial view of the shade generated by the vertical panels at 3 different moments on January the 8th at Channay

diffuse light and the geometrical shade model, the daily mean fraction of residual irradiation reaching the crop (Figure 5) was computed for each location during the year 2005. A spatial average value of residual irradiation was computed on a representative zone (green rectangle on Figure 5) between 2 rows of panels for each day. That daily spatial average was used in

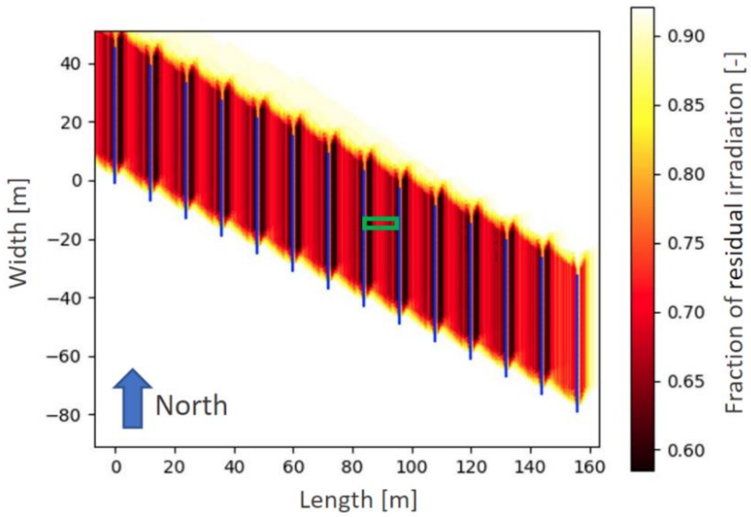

Figure 5. Heatmap representing the daily fraction of residual irradiation reaching the crop on January the 8th at Channay (the green area is the representative zone to compute the spatial average of the daily residual irradiation)

the calculation of the reference evapotranspiration. The wind speed at 2 meters height required in the Equation 1 was calculated from the wind at 10 meters height from PVGIS with the logarithmic profile and reduced by different abatement rates resulting from an expected boundary layer rugosity modification.

Results and discussion

Figure 6 shows the cumulative reference evapotranspiration (ET0) during year 2005 for the five theoretical locations. The hypothetical control scenario without any panels is the one with 100% of residual irradiation and 100% of wind. As expected, ET0 increases with a decreasing latitude, Tunisia having the highest values in our test locations. ET0 reduction caused by each abatement rate is significant and of similar range. Going from no wind abatement to 25% of wind, 316 mm of water are saved in Tunisia, 137 mm for the South of France, 148 mm for central France, 141 mm for Belgium and 116 mm for Sweden. In comparison, the amount of water saved through the reduction of irradiation is much lower, saving 59 mm in Tunisia, 68 mm in the South of France, 53 mm in central France, 51 mm in Belgium and 32 mm in Sweden.

For an intra-year analysis, the monthly cumulative ET0 in Central France at Channay for 2005 is represented in Figure 7. The impact of panels in terms of irradiation reduction makes the ET0 decrease as expected except in winter and end of autumn. The formalism of the equations used to compute the net radiation term in Equation 1 explains this increase of ET0. Reducing the amount of shortwave radiation that enters into the system because of panels induces a decrease in the relative shortwave radiation that represents the clearness of the sky (it acts like if less extraterrestrial radiation was going through the atmosphere because of sky nebulosity). More nebulosity implies less longwave radiation that goes out, and since this decrease is more important than the decrease of shortwave radiation in, the net radiation increases. In some way, this formalism takes into account the capacity of panels to act like barriers against longwave radiation leaving the system. Regarding wind abatement rates, reducing wind speed has a non negligible impact on water demand during the whole year compared with the effect of irradiation reduction. In fact, from a scenario with 100% of wind and a local reduction of irradiation to the same scenario with 25% of wind, 20 mm of water are saved in winter, 38 mm in spring, 53 mm in summer and 34 mm in autumn. While comparing the theoretical control scenario without panel with the local reduced irradiation scenario without

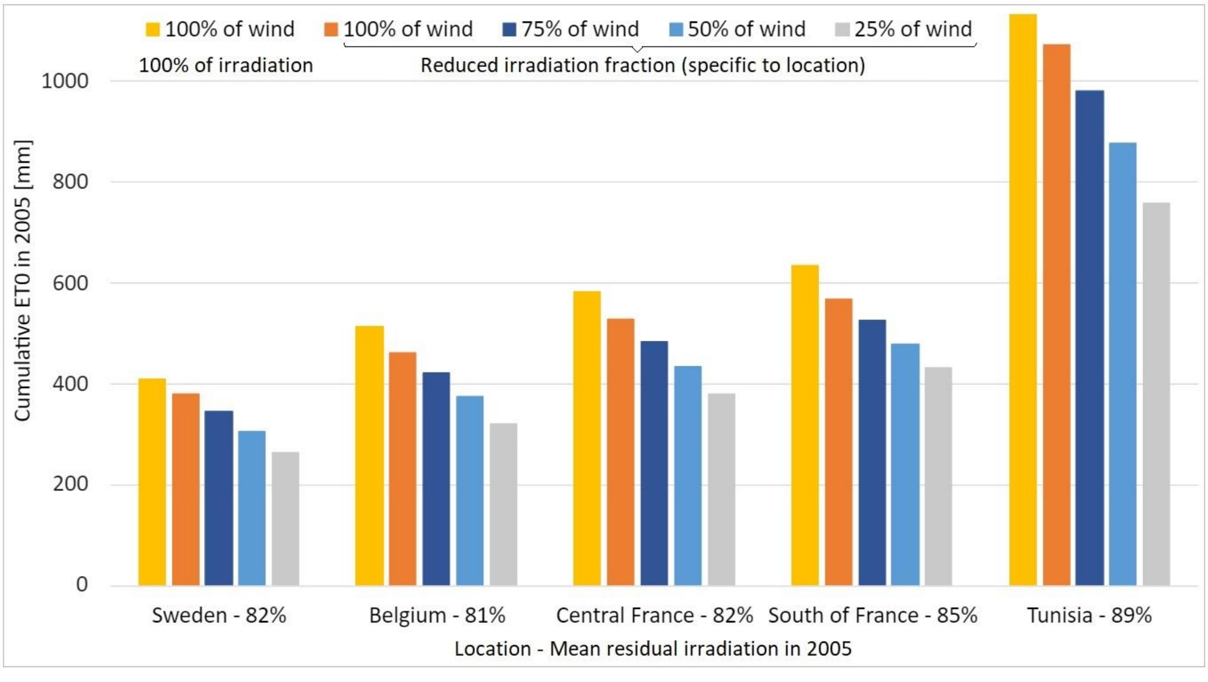

Figure 6. Cumulative ET0 at different locations in 2005 for 5 scenarios

any wind abatement, only 1 mm is saved in winter, 28 mm in spring, 24 mm in summer and a loss of 1 mm occurs in autumn.

Bifacial vertical panels could play an important role in the context of water shortage in locations with a high constraint of wind, reducing the evapotranspiration of crop. However, those wind abatement rates are too simple hypotheses knowing the complex effect of windbreaks on wind modification [6], [8]. Moreover, a limitation of the FAO 56 PM equation can be highlited: aerodynamic and surface resitances used in Equation 1 (70 $s.m^{-1}$ and $208/U_2$) are specific for the reference crop which is an extensive grass surface completely shading the ground, with a height of 0.12 m without any obstacles. Thus, there is an assumption that all fluxes are one-dimensional upwards. Vertical panels, based on windbreaks literature are

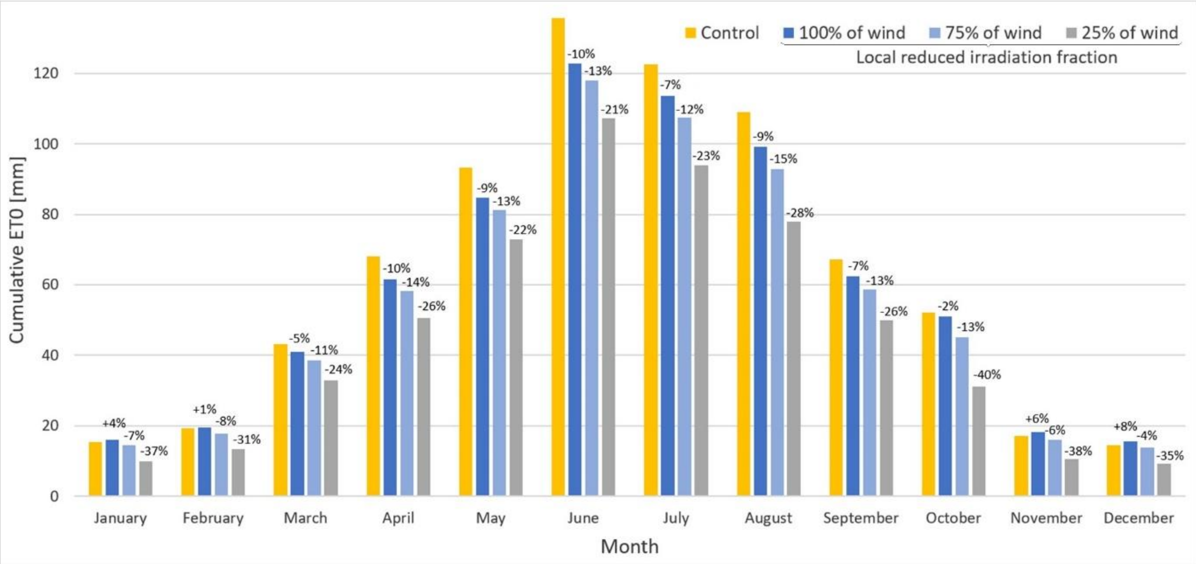

Figure 7. Cumulative ET0 along year 2005 in central France at Channay (percentages overhead the bars are the relative difference with the control scenario)

expected to create turbulence and to modify that aerodynamic resistance depending on the height of panels, distance between rows, panels porosity, wind direction and crop height. Adeh *et al.* showed that a classical south-oriented photovoltaic central could accelerate and reorient wind directions perpendicularly to the rows of panels, due to the local increase of temperature near the surface of panels, creating buoyant forces that cause anabatic flows [9]. More research should be done on fluid dynamics both with experimental campaigns and computational fluid dynamics (CFD) to assess the real effect of vertical panels on wind modification, analysing the sensibility to those different parameters. Increasingly comprehensive models of evapotranspiration are also required to be able to integrate the complexity of fluid dynamics. In fact, Sugita showed with a dual-source crop community model that the effect of windbreaks on evapotranspiration was not so clear, and highlighted the fact that other previous studies also presented contradictions [10].

All those questions require more researches in different climates and wind conditions. A complete monitoring of the agrivoltaic system of TotalEnergies at Channay has been implemented since April 2022 including PAR monitors, tensiometers and anemometers (Figure 8). The aim is really to focus on the aerodynamics and water demand to assess if bifacial vertical panels could help in the context of global aridity issue in some locations considering climate change while helping the energy transition. Future works will aim to separate the impact of windbreak effect from shade on crop to define the key parameters to optimize a vertical agrivoltaic configuration.

Figure 8. Agrivoltaic system of TotalEnergies at Channay in central France (left picture shows tensiometers that are used and right picture shows wheat growing in the system)

Conclusion

It is known that shade created by photovoltaics can reduce the water demand of crops behind or between rows of panels. This preliminary study indicates an important effect of wind abatement on the reference evapotranspiration reduction compared with the amount of water that can be saved thanks to irradiation decrease. Those results suggest that bifacial vertical panels could help in the context of water shortage issue, while participating to the increase of renewable energy generation worldwide. However, more researches should be done on this topic given the contradictions in windbreaks literature on their effect on water demand and the simplifying assumptions that are made with the FAO 56 PM. Increasingly comprehensive models of evapotranspiration and aerodynamics through CFD are required, taking into account geometric parameters of the photovoltaic system and crop, thermal increase along the surface of panels, as well as the capacity of panels to act like barriers against longwave radiation going out of the system. Those *in-silico* researches should be completed by experimental campaigns to be able to certify the relevance of vertical bifacial panels in arid conditions.

Data availability statement

Hourly meteorological data comprising GHI, air temperature and wind speed are extracted from PVGIS for year 2005 and those GPS coordinates: 37°00'58.0"N 9°58'10.3"E for Tunisia, 43°15'29.8"N 0°39'18.5"E for the South of France, 47°53'10.1"N 4°17'42.0"E for central France, 50°35'26.1"N 4°41'07.0"E for Belgium and 43°15'29.8"N 0°39'18.5"E for Sweden.

Author contributions

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Competing interests

The authors declare no competing interests.

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