HARMO22

22nd International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
10-14 June 2024, Pärnu, Estonia

IMPACT OF RENEWABLE ENERGY INTEGRATION: A NUMERICAL STUDY OF ATMOSPHERIC FLOW AROUND MODELS OF AGRIVOLTAIC FARMS

Pier Giuseppe LEDDA, Federico ANGIUS, Maria Grazia BADAS and Giorgio QUERZOLI

DICAAR, Università degli Studi di Cagliari, Cagliari, Italy

Abstract: Agrivoltaic systems combine solar energy harvesting with crop cultivation. Here, we leverage Computational-Fluid-Dynamics simulations to investigate their impact by analyzing airflow patterns, temperature distributions, and moisture transport across the panels. The panel configuration affects temperature and heat exchanges, with implications for crop growth and energy harvesting. An increase in spacing or height lowers temperatures within crops and affects moisture distribution. These findings could be employed to suggest design guidelines to balance energy efficiency and agricultural productivity, e.g., by tuning the spatial arrangement.

Key words: *renewable energy sources, integration, agrivoltaic farms, fluid dynamics*

INTRODUCTION

Current circumstances often push toward the transition from traditional land use to the integration of renewable energy sources. However, the impact on the landscape is a key factor that goes beyond its physical appearance to include environmental dynamics and how it interacts with human activities. Realizing renewable energy sources, and in particular photovoltaic (PV) farms, naturally results in local changes such as alterations in temperature, humidity, and wind field. Agrivoltaic farms combine energy harvesting with agricultural activity on the same soil and exemplify a potential blend of energy generation and land-use preservation with possible improvements in the agricultural production. However, these plants can alter the soil/atmosphere exchanges, which in turn change the micrometeorology and hydrological budget. Reducing of near-surface wind velocity and albedo can generate local warming effects with implications for crop growth. Conducting a fluid dynamic analysis and addressing small-scale impacts of the PV farm (e.g. to offer partial shading and adjust moisture balance) is an essential step in the overall assessment of agrivoltaic plants into the environment.

To this aim, we numerically perform Computational-Fluid-Dynamics (CFD) simulations of the flow around a generic array of PV panels. We developed a two-dimensional multiphysics model based on the open-source code OpenFOAM (Weller et al. 1998) to analyze different operative conditions, which allowed us to investigate the temperature and moisture differences between the bare soil condition and in the presence of the PV-farm.

METHODS: PHYSICAL MODEL AND NUMERICAL IMPLEMENTATION

The airflow obeys the Reynolds-Averaged Navier Stokes (RANS) equations, coupled with the energy equation, for the mean turbulent flow with buoyancy effects induced by density variations due to temperature. The employed closure model for turbulent stresses is the well-known k-ω SST model.
The inlet boundary condition is the classical logarithmic atmospheric wind profile with a speed of 5.9 m/s at 80 m above the mean sea level, together with the relative turbulence properties for the atmospheric boundary layer. The radiative heat transfer is based on a solar ray-tracing algorithm, which detects the faces exposed to solar radiation and evaluates their heat flux.

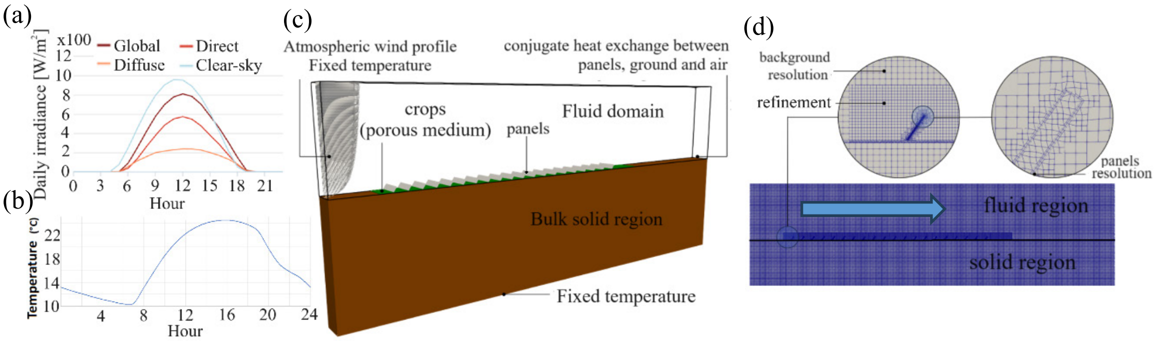

Figure 1. (a,b) Considered (a) solar irradiance and (b) mean atmospheric temperature. (c,d) Sketch of (c) the domain of interest and of (d) the discrete mesh.

Boundary conditions include the typical values for radiative properties of ground and PV panels, essential to define the heat fluxes across each region, which are coupled with the airflow dynamics. Fig. 1(a,b) shows the radiation intensity and temperature on a hypothetical spring day, employed in our simulations. The presence of vegetation is included in the CFD simulations as a permeable medium through a sink term ($\boldsymbol{S}=LAD\ C_F\ |\boldsymbol{u}|\ \boldsymbol{u}$) in the RANS equations (Thom, 1971; Wilson, 1985), where *LAD* is the so-called Leaf Area Density, i.e., the ratio of the leave surface to the canopy volume. The friction coefficient C_F, for generic plant canopies, can be reliably approximated as C_F = 0.2 (Molina-Aiz et al. 2006). For example, based on existing literature, we estimated LAD ≈ 5 for alfalfa crops (Walter-Shea et al. 1997). These values will be employed in a porous region of height H ≈ 0.6 m from the ground. Evapotranspiration from plants and ground involves different factors that can hardly be represented in their entireness when considering the scale of a PV farm. In a first approximation, our model does not directly include the interaction between moisture, temperature and airflow, but moisture transport is a consequence of the previously evaluated velocity and temperature fields. We thus neglect the temperature reduction due to evaporation and transpiration. Therefore, our analyses are conservative since slightly larger temperatures will be observed. The vapor flux at the ground level can be approximated as $E_s = K(c-c_0)$ (Jacobs et al. 1997) and implemented as a flux in the built-in scalarTransportFoam solver, which solves the advection-diffusion equation for the concentration of moisture *c*. The value of *K* depends on several parameters (e.g. the Nusselt, Schmidt, Prandtl and Rayleigh numbers) that are estimated from the temperature and velocity fields.

The multiphysics model is implemented via built-in steady CFD-solver buoyantSimpleFoam with the heat-transfer solver of the family Conjugate Heat Transfer. We simulate a steady thermal balance state. The domain of fig. 1(c) consists of a fluid region with incoming atmospheric wind, several solid regions for the (twenty) panels, modeled as thin plates of length 5 m, and a large portion of the ground for the heat transfer modeling. These equations are solved within the OpenFOAM framework, whose numerical discretization is reported in fig. 1(d). We considered different hours of the day to determine the effect on the temperature and moisture. Note that the position of the PV panels changes during the day so that the panels are perpendicular to the solar radiation. We also vary the distance between the rows and the height of the panels from the ground. Equations for humidity transport are instead solved in a simplified version of the domain, which includes only the fluid part, with constant moisture at the inlet and the previously defined moisture flux at the ground surface. The simulation is assumed to be convergent when residuals and the mean temperature reach a constant value with residuals lower than 10^{-3} for all variables at play.

RESULTS

We begin our analysis by examining a 12-meter separation between panel rows, with their pivot point at 2.5 meters above the ground. The presence of the PV panels has a significant impact on the atmospheric conditions at the crop level. As an initial observation, after approximately 6 –7 panels, the canopy layer is fully developed, and the airflow attains a streamwise periodicity. Fig. 2 depicts the airflow patterns between the panels at several hours during the considered hypothetical spring day.

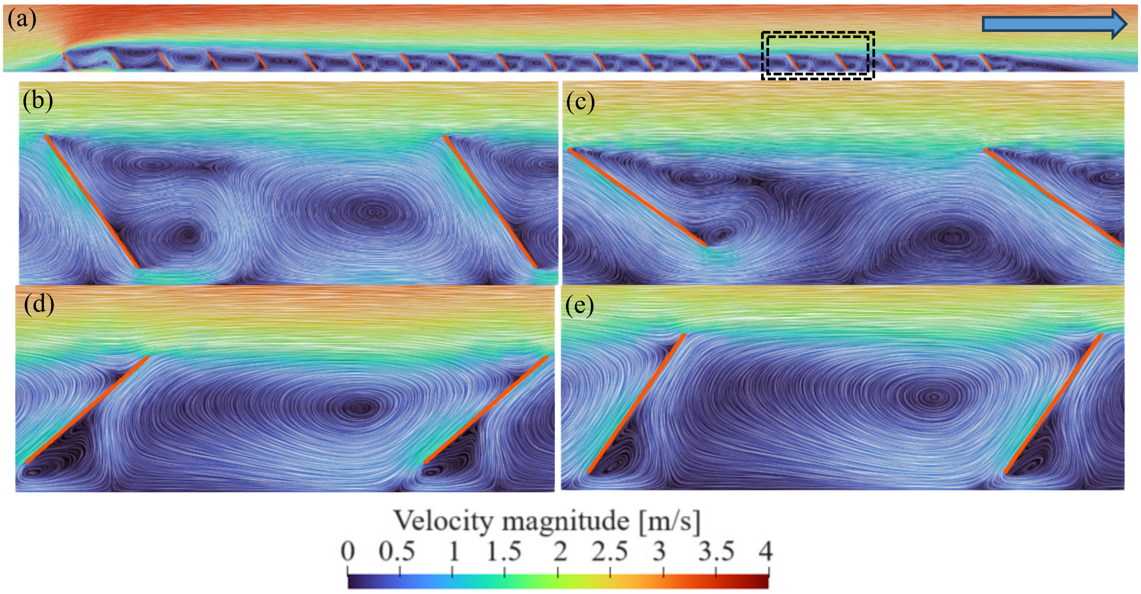

Figure 2. Distance d=12 m and height h=2.5m. Airflow streamlines (visualized through Line Integral Contours) overlaid with colormaps of the velocity magnitude for different times of the day. (a) Visualization of the whole array for 9:00 a.m. (b,c,d,e) Zoom in the region of interest shown in (a) for: (b) 9:00 a.m., (c) 11:00 a.m., (d) 3:00 p.m., (e) 5:00 p.m. The flow goes from the left to the right according to the arrow in (a). Panels are colored in orange.

Depending on the tilt angle of the panels, we observe none, one, or multiple recirculation regions between the rows. Panels set at steeper angles result in larger recirculation regions due to a dual effect: they act as more substantial barriers to the airflow and decrease the bleeding flow between the panels and the ground. This is evident when comparing more horizontally aligned panels with inclined ones, in fig. 2. A primary consequence of this phenomenon is the decrease of heat exchange between the atmosphere and the ground, attributed to the presence of these recirculating, slow, airflow patterns. Fig. 3 provides a comparative view of the air velocity and temperature fields before and after PV panel installation, for the 3:00 p.m. configuration. The installation of panels leads to a reduction in air velocity compared to the case with no panels on the ground, for the same height. The highest temperatures are localized just beneath the panels, where we observe a jet of high temperature originating from the ground. Consequently, non-uniformities in the temperature field are expected beneath the panels, at the scale of the crops. The mean temperature at the ground also increases after the installation of solar panels (as depicted in fig. 5b) if we disregard the temperature reduction due to evapotranspiration. In summary, the presence of the panels reduces the mean velocity through the crops associated with recirculating flow and, consequently, the convective heat transfer. Overall, the mean ground temperature increases. The highest values are found directly beneath the panels due to their high temperatures and the preferential transport driven by the recirculating airflow.

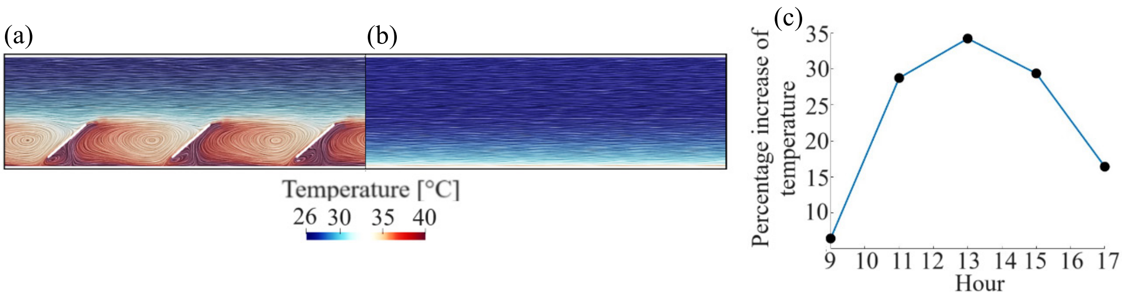

Figure 3. (a,b) Temperature colormaps overlaid with velocity streamlines visualized through Line Integral Contours for (a) distance d=12 m, height h=2.5m and (b) bare soil (no panels), for the same hour of the day, i.e., 3:00 pm. (c) Percentage increase of temperature with respect to the bare soil condition as a function of the hour of the day.

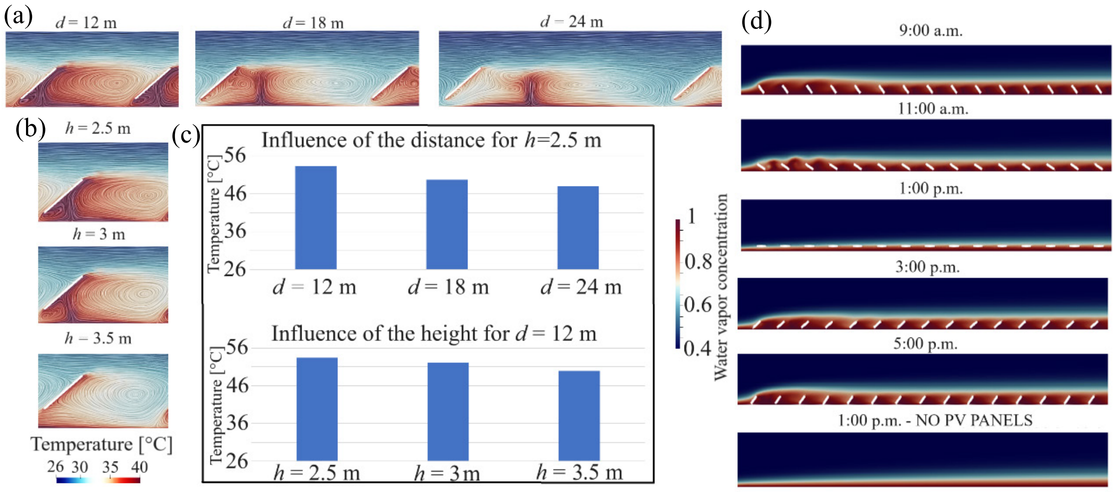

Figure 4. (a,b) Airflow streamlines overlaid with colormaps of the temperature for 3:00 p.m.: increase of (a) the distance between panels with *h*=2.5 m and of (b) the height of the panels with *d*=12 m. (c) Influence of distance and height on the mean temperature on the panels. (d) Colormaps of the concentration of water vapor for different hours of the day.

Starting from these findings, we consider diverse configurations, with (i) variable height (*h*=2.5, 3, 3.5 m) and a fixed separation distance of 12 m and (ii) variable separation distance (*d*=12, 18, 24 m) with a fixed height of *h* = 2.5 m, for the 3:00 p.m. configuration. As shown in fig. 4, an increased spacing between the panels mitigates the local "heat island" effect observed in the case of a 12-meter separation, and, therefore, lower temperatures within the crops are attained. The maximum temperature is now localized in an intermediate region between the shaded and sun-exposed areas. This temperature decrease can be attributed to the interplay between the recovery of convective heat transfer and the increased direct solar irradiance reaching the ground as the separation distance between panels increases. An increase in the panels height, as depicted in fig. 4(b), yields a decrease in the air temperature between the rows. Specifically, the increased bleeding flow between the panels and the ground disrupts the coherence of the uprising flow from the ground to the panels, introducing cooler air at the crops level. At the same time, the average temperature on the panels decreases (fig. 4c), which could be beneficial for the harvesting of solar energy.

We then turn our attention to the vapor transport due to the incoming wind and evapotranspiration from the ground. In our assumptions, we consider the soil to be fully saturated with water, while the incoming wind carries a humidity level of 40%. As depicted in fig. 4(d), the inclination of the panels plays a key role in defining the distribution of water vapor. At the maximum inclination, we observe the highest humidity levels beneath the panels. The decreased airflow results in moisture accumulation throughout the volume both within and beneath the panels. In contrast, in the 1:00 p.m. configuration with horizontal panels, we encounter a situation akin to that of bare soil.

DISCUSSION AND CONCLUSIONS

Our analysis provides preliminary information within the context of the impact of agrivoltaic farms. We observe that atmospheric conditions strongly depend on the hour of the day under consideration. Specifically, configurations that are nearly horizontal (fig. 4d) create large, shadowed areas on the ground, while convective heat transfer and moisture transport are minimally affected, with respect to the bare soil case (fig. 3b). Conversely, when panels are inclined (figs. 2 and 4a,b), shadows are reduced and temperatures increase, especially beneath or just downstream of the panels. Therefore, guidelines pertaining to crop harvesting must inevitably account for the variable conditions throughout the day and compared to the daily variation observed with bare soil.

As concerns tilted configurations, we observed a localized temperature increase beneath the panels. This is attributed to their warm surface and reduced convective heat transfer due to decreased ventilation airflow.

These patterns exhibit non-uniform features. Ground temperature also exhibits a slight increase compared to bare soil conditions. However, it is worth noticing that we have not considered the effect of evapotranspiration when moisture transport is coupled with airflow and heat exchange. Higher humidity levels, when compared to the bare soil conditions, imply a reduction in evapotranspiration since its rate is proportional to the humidity difference between the air and the ground.

An increase in row spacing and/or panel height is advantageous in terms of energy harvesting, as it lowers the operating temperatures of the panels. In both cases, convective heat transfer is enhanced due to increased airflow speeds between the panels. However, greater row spacing also exposes more ground surface to direct sunlight. Interestingly, an increase in the height leads to larger shaded regions and enhances convective heat transfer, making it a potential approach for minimizing their impact.

In summary, smaller spacings are suitable for crops that do not require direct solar radiation and can withstand higher temperatures. In cases of larger spacing between the rows, the areas beneath the panels can be employed for crops sensitive to higher temperatures and direct sunlight. In areas subject to direct sunlight, crops must endure large temperatures and direct light. Increasing the height is beneficial, but crops must be capable of withstanding the high-velocity bleeding flows that occur in the gap between the panels and the ground. These results may find further developments within the context of a thorough hydrologic study of how the evapotranspiration contribution is modified by the presence of the panels and their quantitative consequences on crop growth, or within the perspective of including these considerations in large-scale weather forecasting (WRF) models, to assess the effect of extensive agrivoltaics farms on the surrounding environment. Other analyses may focus on the role of the wind intensity: presumably, as the wind velocity decreases, the role of buoyancy becomes predominant, giving rise to different flow dynamics.

FUNDING

This work has been developed within the framework of the project e.INS- Ecosystem of Innovation for Next Generation Sardinia (cod. ECS 00000038) funded by the Italian Ministry for Research and Education (MUR) under the National Recovery and Resilience Plan (NRRP) - MISSION 4 COMPONENT 2, "From research to business" INVESTMENT 1.5, "Creation and strengthening of Ecosystems of innovation" and construction of "Territorial R&D Leaders".

REFERENCES

A.F.G. Jacobs and A. Verhoef, 1997: Soil evaporation from sparse natural vegetation estimated from Sherwood numbers. *Journal of Hydrology* **188**: 443-452.

F.D. Molina-Aiz, D. L. Valera, A. J. Alvarez and A. Madueño, 2006: A wind tunnel study of airflow through horticultural crops: determination of the drag coefficient. *Biosystems engineering*, **93**(4), 447-457.

A.S. Thom, 1971. Momentum absorption by vegetation. *Quarterly Journal of the Royal Meteorological Society,* **97**(414), 414-428.

E.A. Walter-Shea, J. Privette, D. Cornell, M. A. Mesarch and C. J. Hays, 1997: Relations between directional spectral vegetation indices and leaf area and absorbed radiation in alfalfa. *Remote Sensing of Environment*, **61**(1), 162-177.

H.G. Weller, G. Tabor, H. Jasak and C. Fureby, 1998: A tensorial approach to computational continuum mechanics using object-oriented techniques. *Computers in Physics*, **12**, 620-631.

J.D. Wilson, 1985: Numerical studies of flow through a windbreak. *Journal of Wind Engineering and Industrial Aerodynamics*, **21**, 119-154.