

Toward a micrometeorological assessment of agrivoltaic farms: a Feature Tracking Velocimetry-based analysis

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ABSTRACT

We investigate the flow dynamics around a model of an array of photovoltaic panels via laboratory experiments conducted in a water channel. The model farm consists of transparent polycarbonate panels with varying tilt angles, simulating different configurations typical of agrivoltaic systems. Velocities are measured using a feature tracking velocimetry technique. Results reveal distinct flow structures depending on the tilt angle of the panels and the distance between them, with varying numbers of recirculation regions observed. An increase in the distance between panels stretches the recirculation regions along the streamwise direction. Turbulent kinetic energy is more intense with negative tilt angles, and upstream turbulence penetrates more between panels. These findings suggest different transport and heat transfer properties, particularly relevant for tracker PV arrays that adjust tilt angles throughout the day. Understanding these dynamics is crucial for optimizing the design and operation of agrivoltaic farms to maximize energy production while minimizing impacts on agricultural productivity and the surrounding environment.

1. Introduction

The increasing demand for renewable energy installations calls for the development of photovoltaic farms that do not compete with agriculture for land use. Agrivoltaic farms combine energy harvesting with cultivating crops alongside these installations and exemplify a potential blend of energy generation and preservation of the landscape (Dupraz et al. 2011, Dinesh et al. 2016). An effective coexistence of agriculture and photovoltaic panels requires a better assessment of the micrometeorological impact and integration within the environment. Yet, there is limited understanding regarding the effect of the presence of solar panels on the soil-atmosphere and boundary-layer exchanges and the consequences on growing crops. As a matter of fact, transport phenomena between and around the panels are inevitably influenced by the flow structures developing in the panel canopy. The flow configuration resembles that of urban canyons though at a slightly smaller scale. In addition, decreased albedo (due to the solar panels presence) combined with slowly recirculating flow lies the foundations for heat island effects (Oke 1982, Santamouris et al. 2015). As a matter of fact, reduced airflow below the panels can affect hydrological balance and, in turn, crop growth. Note that, in photovoltaic farms, the tilt angle of the panels varies during the day, giving rise to several potentially different flow behaviors even when limiting our analysis to the case of orthogonal wind. In this work, we perform a laboratory study on a model of an array of solar panels in the surface boundary layer generated in a water

channel. We systematically vary the panels' arrangement to assess the mean flow and turbulence features at the panel scale.

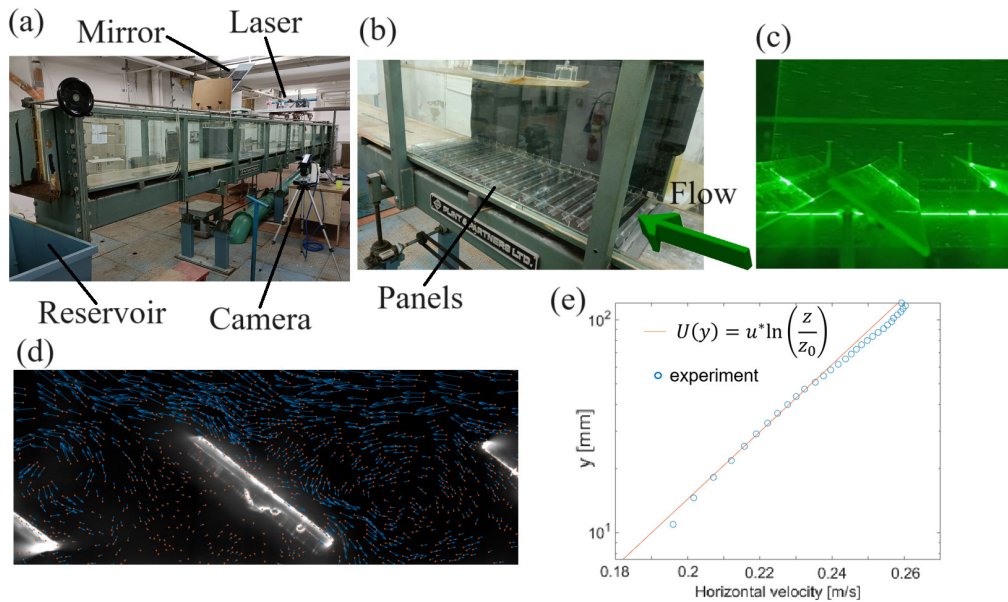


Figure. 1 (a) Water channel with elements of the experimental apparatus. (b) Array of panels placed with the water channel. (c) Photo of the panels invested by the flow highlighted through the laser beam. (d) Feature tracking velocimetry algorithm: instantaneous distribution of features (points) associated with their velocity (arrows) overlaid to the background pattern; (e) Experimentally measured velocity (dots) as a function of the height, in the absence of panels. The experiments well collapse onto a logarithmic profile (solid line).

2. Experimental setup

We perform laboratory experiments in a water channel, 8.00 m in length, 0.40 m in width, with a water height of 0.50 m (fig. 1a). The constant flow rate is ensured by a closed loop and tuned via the combined regulation of a sharp-crested weir at the discharge and a gate valve downstream of the pump feeding the channel. A 0.10 m thick honeycomb acts as a flow straightener at the inlet of the channel and is followed by irregularly distributed pebbles (5 mm in mean diameter) at the bottom of the channel for 3 m to develop a fully turbulent boundary layer upstream of the array of panels (fig. 1b). The model farm consists in an array of 20 equidistant and transparent polycarbonate panels, 1.5 mm thick and $l = 30.0$ mm wide, spanning the whole channel width. These panels are colored in black except in the vicinity of the mid-section of the channel and present a groove at their center along the spanwise direction, where they are glued to steel bars of 2mm diameter, supported at their ends by two holes in lateral end plates of 10mm thickness. Vertical set screws allow to lock the position of the bars at the prescribed angle. The uniform panel orientation is guaranteed via specific templates to set the panel angle, which are removed before the experiment. In the experiments here presented, the panel pitch angle is varied both clockwise and counterclockwise.

Non-buoyant particles dispersed in the water are illuminated at the spanwise mid-plane of the

channel by a 2mm thick light sheet generated by a diode laser (fig. 1c) projected from above through a transparent optically rectified glass carefully placed just at the water surface. A high-speed camera (2240×1740 pixels² in resolution), placed orthogonal to the measurement plane, acquires 330 frames per second. The measuring area is set at the seventeenth panel to grant a fully developed boundary layer above the panel canopy (Brown et al. 2000). As shown in fig. 1d, images are analysed via a feature tracking velocimetry technique (Badas et al. 2020): Harris corner detection algorithm allows for the feature identification, and displacements are computed by comparison with a window in the successive frame by minimizing the window dissimilarity measured by a Lorentzian estimator (Besalduch et al. 2013). Particle velocities are obtained by dividing the displacements by the corresponding interframe time interval (fig. 1e). Velocities are made non-dimensional with the average velocity, U , recorded in the considered camera field of view ($U = 0.15$ m/s).

3. Results

We first describe the mean flow obtained by averaging 6600 instantaneous velocity fields. Fig. 2 shows velocity fields developing when the tilt angle of the panel is positive or negative, and increasing the distance d to mimic an agrivoltaic configuration effectively. Depending on the tilt angle, none, one or two recirculation regions are observed. Specifically, positive (fig. 2a) and low tilt angles depict a configuration with no recirculation regions. An increase of the tilt to $\varphi = 20^\circ$ shows a different configuration, i.e., two predominant counter-rotating recirculation regions develop, one localized on the upper part of the panels and the other in the vicinity of the ground.

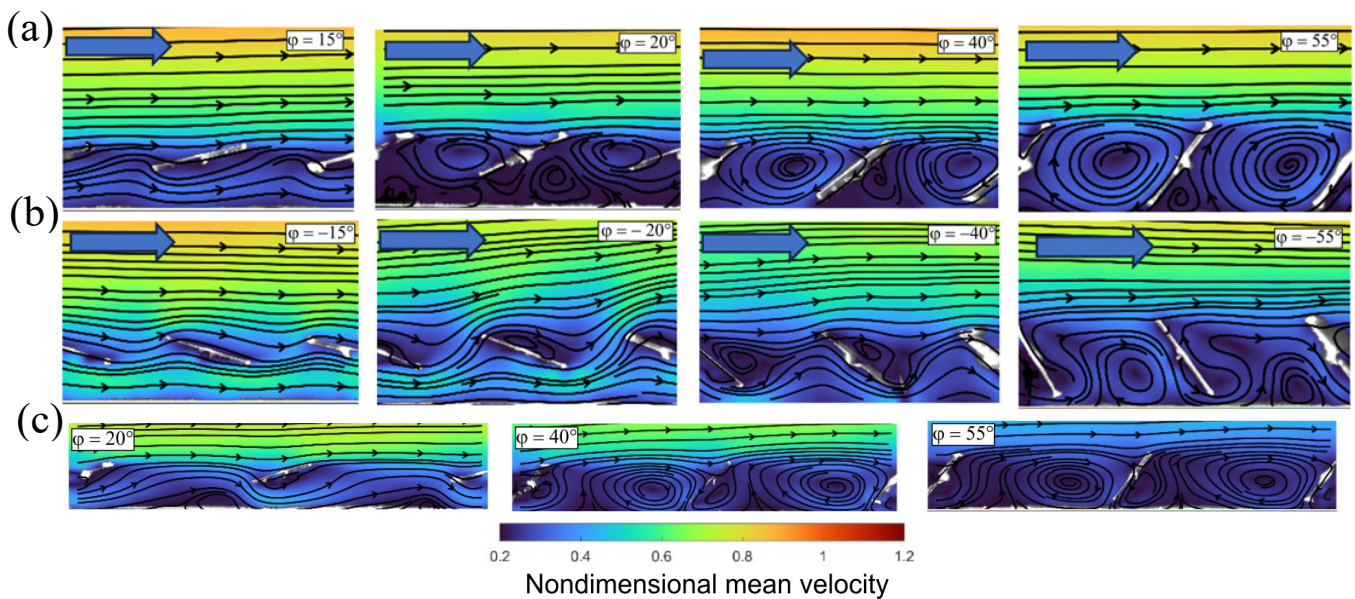


Figure. 2 Mean velocity field: streamlines overlaid with colormaps of the velocity magnitude, for different tilt angles φ and distance (a,b) $D/L=1.66$ and (c) $D/L=3.33$.

A further increase in the tilt angle leads to an increase in size of the larger recirculation that involves almost the whole space between the panels, for $\varphi = 55^\circ$. Conversely, for low ($\varphi = 15^\circ, 20^\circ$) negative tilt angle (fig. 2b), only one small recirculation region forms, attached to the upper side of the panel. Also, higher velocities are observed in the gap between the panels and the ground. A further increase, however, shows an intricate structure characterized by three cores of low velocity. An increase in the distance between the panels (fig. 2c) shows the formation of very similar recirculation regions, although they are stretched along the streamwise direction.

The turbulent kinetic energy (defined as the magnitude of the variance of the three instantaneous velocity components and normalized with the square of the reference velocity, fig. 3) appears to be more intense close to the canopy when panels present a negative tilt. Conversely, the positive tilt angle cases depict a neat separation between the overlying flow of high turbulent intensity and the flow between the panels. In the negative tilt case (both for small and large distance), upstream turbulence seems to penetrate more between the panels, with the formation of coherent regions of high turbulence that propagate from the panels' edges.

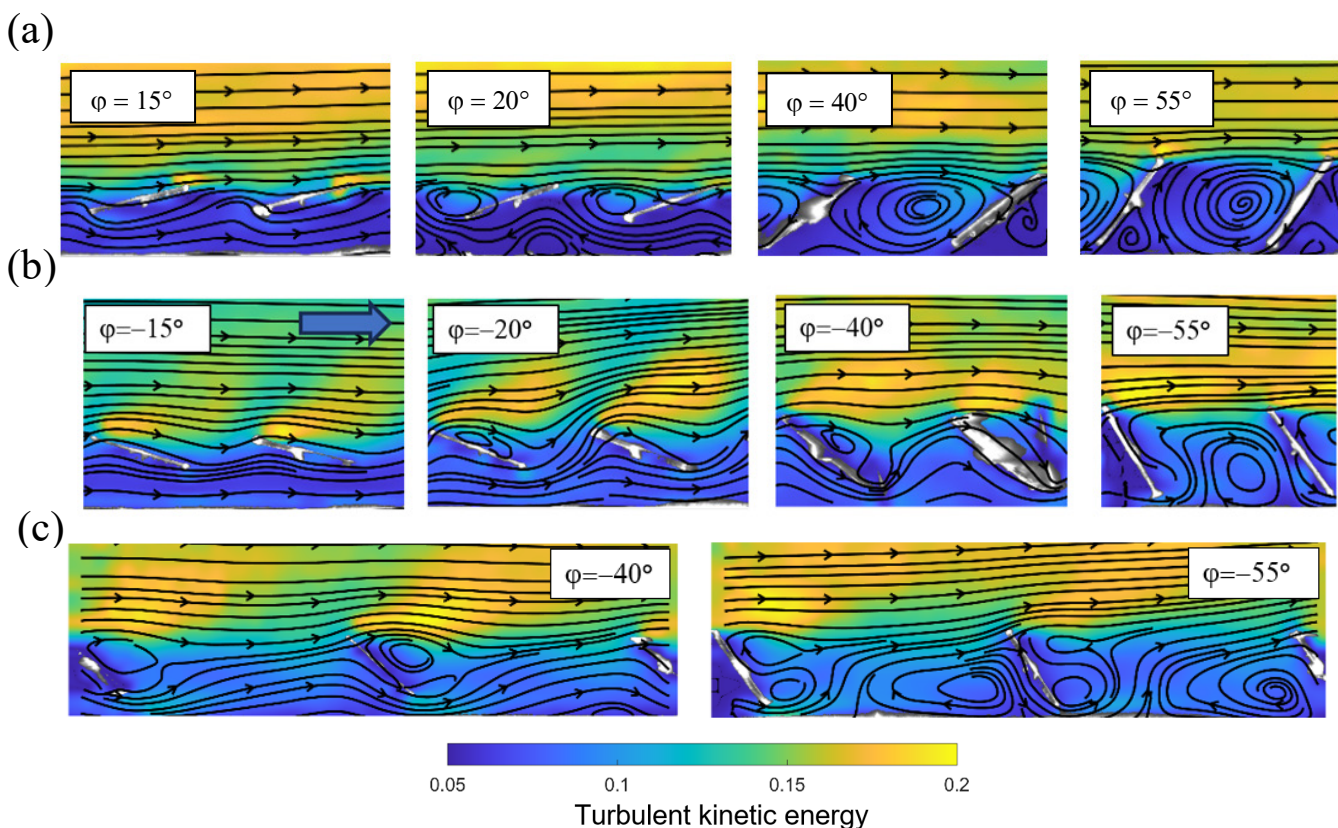


Figure. 3 Nondimensional turbulent kinetic energy colormaps overlaid with streamlines of the mean velocity field, for different tilt angles φ and distance (a,b) $D/L=1.66$ and (c) $D/L=3.33$.

(b)

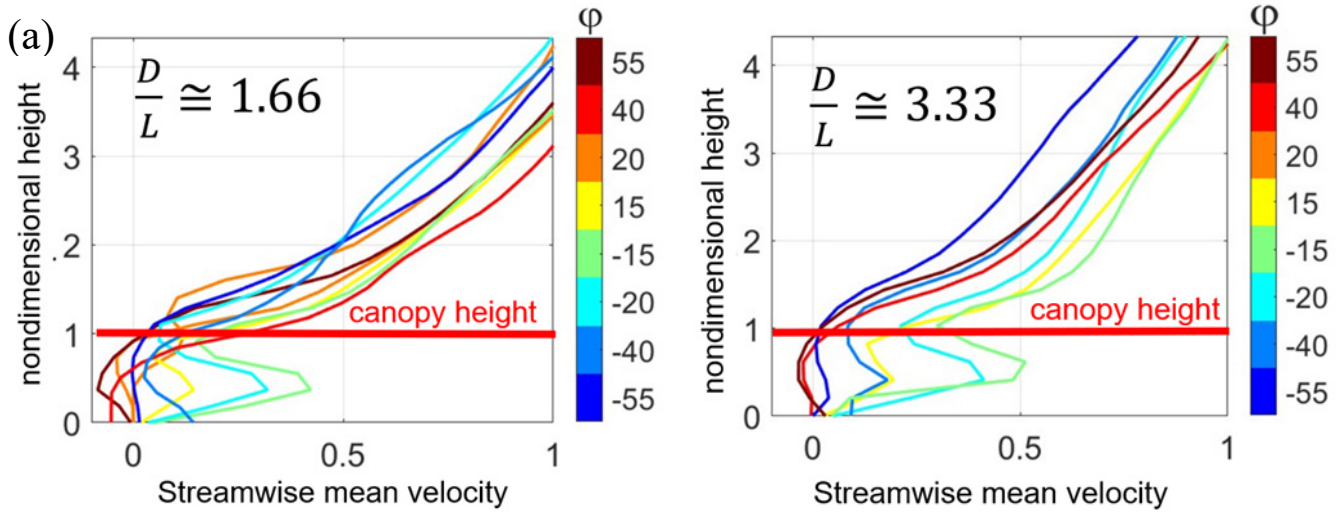


Figure. 4 Horizontally-averaged streamwise mean velocity for the configurations reported in fig. 2. The red dashed line denotes the panels' maximum height.

Flow features are reminiscent of regimes observed within urban canyons (Oke et al. 2017), with the presence of one recirculation confined between the panels when the spacing is small (so-called skimming flow) and a large recirculation attached to one panel at larger gaps (likewise the wake interference regime). These features affect turbulence between the panels and the exchange with the overlying boundary layer.

Fig. 4 shows the horizontally averaged mean velocity as a function of the height, giving an idea of the roughness effect exerted by the panels. The streamwise velocity is reminiscent of the logarithmic profile observed in atmospheric flows close to a canopy. Conversely, at the panel height, slightly negative average velocities are observed for positive tilt angle, and vice versa. These mean streamwise flow properties will have consequences on the transport between the gaps and the overlying boundary layer, as well as the structure of the boundary layer itself. Combining this information with the streamline distribution in fig. 2, a negative tilt angle seems to promote a stronger mean transport from the boundary layer to the gap, while positive tilt angles show strong recirculating flow with a weaker penetration of turbulent features within the canopy.

4. Discussion and conclusion

The growing global demand for renewable energy sources has prompted the need for innovative approaches to solar energy generation that do not compete with agricultural land use. However, the successful coexistence of agriculture and photovoltaic panels requires a comprehensive understanding of the micrometeorological impacts and environmental integration. The transport

phenomena within and around solar panels are inevitably influenced by the flow structures that develop within the panel canopy.

As a primary block to understand these challenges, laboratory experiments were conducted to investigate the flow dynamics around an array of solar panels within the boundary layer generated in a water channel. The model farm comprised 20 equidistant transparent polycarbonate panels spanning the channel width, with varying tilt angles. Velocities were measured using the feature tracking velocimetry technique. Mean flow features revealed distinct flow structures depending on the tilt angle of the panels and the distance between them, with none, one or more recirculation regions depending on the tilt angle. Flow characteristics resembled regimes observed in urban canyons, impacting turbulence between panels and the exchange with the overlying boundary layer.

The presence of several flow structures depending on the tilt angle and distance highlights the richness of the considered problem, which suggests different transport and heat transfer properties when varying continuously the tilt angle, as typical of tracker PV arrays that follow the course of the Sun during the day. As a matter of fact, these peculiarities will in turn influence the hydrological balance and crop growth: these aspects are essential for the design and operation of agrivoltaic farms to maximize energy production while minimizing environmental impacts on agricultural productivity. In addition, the roughness effect exerted by the panels can be studied more in detail to understand micrometeorological modifications at the mesoscale, which can be included into weather forecasting models to faithfully model the effects on the surrounding environment.

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