Airflow is strongly modified by agrivoltaic systems. What are the consequences on energy and water exchanges?

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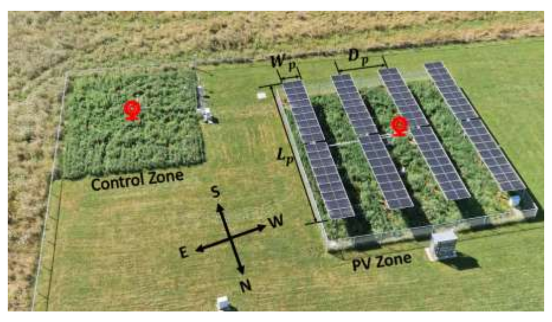
Context / Experimental Data

A combination of computational fluid dynamics (CFD) simulation and sensor-based observation data is used to analyze the impact of PV panels on airflow, ultimately on energy and water transfers at the SIRTA agrivoltaic experimental platform.

Agrivoltaic (APV) systems, which integrate photovoltaic (PV) panels above agricultural land, significantly modify the local microclimate.
✓ PV panels protect crops from heatwaves, drought, and frost.
✓ Crops may cool PV modules via cooler environment.

The SIRTA APV experimental platform is designed to compare plant cultivated beneath PV panels with plants in open field conditions. It consists of a "PV zone" and a "Control zone" without PV panels.



- PV panel length (L_p) $\approx 21\ m$
- PV panel width (W_p) $\approx 2.3\ m$
- PV panel height (H_p) $\approx 2.5\ m$
- Distance between tracker axes (D_p) $\approx 5.5\ m$
- PV panel tilt angle (α_{pv}) $\in [-60°, 60°]$

Figure 1. The SIRTA APV experimental platform.

The friction velocity: $u^* = (\overline{u'w'}^2 + \overline{v'w'}^2)^{0.25}$[1]

$\overline{u'w'}$, $\overline{v'w'}$: Reynolds stress tensor, representing turbulent momentum transport

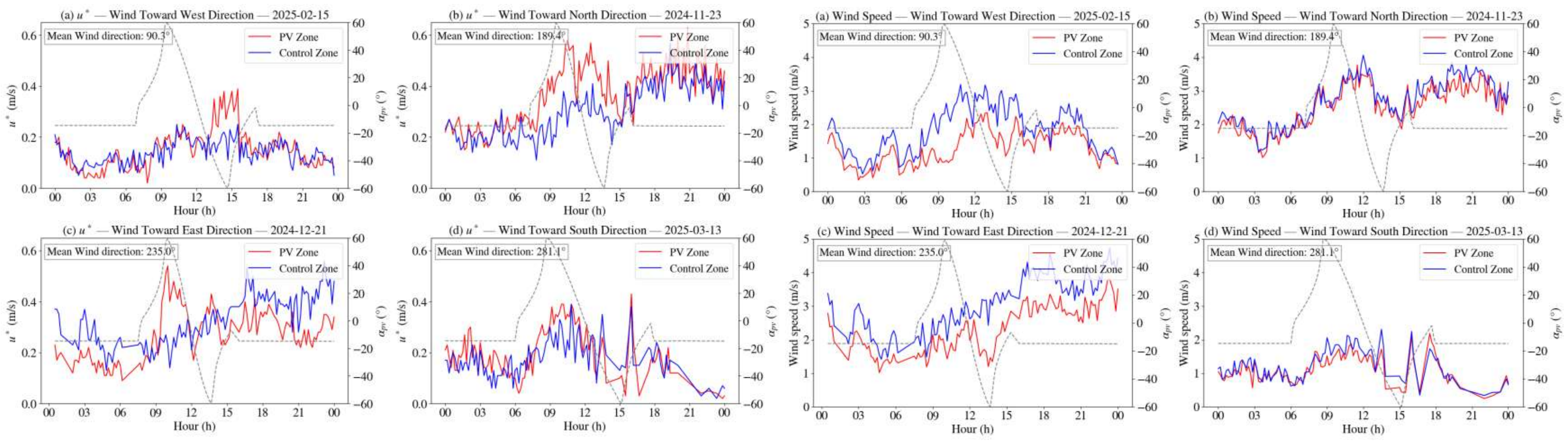


Figure 2. Measurements of u^* and wind speed under different wind directions and α_{pv} conditions.

- During daytime, PV panels attenuate wind speed, while they increase u^*.
- These increases and decreases depend on PV panel tilt angle and wind direction.

Wind speed and air mixing are reversely affected by PV panels, thus questioning the resulting effect on energy and water exchanges and how to model them.

Simulation of flow dynamics

The APV platform from SIRTA is numerically simulated using the CFD solver **code_saturne** [2]. The numerical investigation is conducted based on the **immersed boundary method (IBM).**

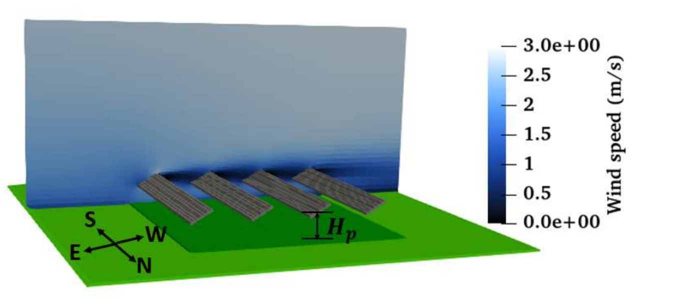


Figure 3. Simulation of the SIRTA APV platform.

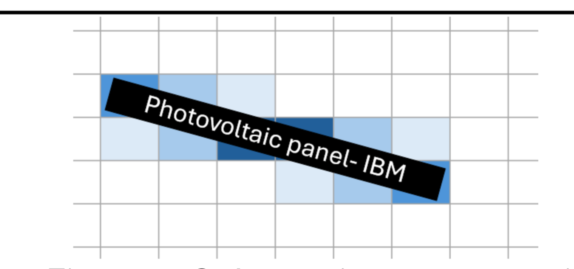


Figure 5. Schematic representation of a PV panel using the IBM.

The IBM consists in the implementation of a source term in the flow equation, for the mesh cells with a mix of fluid and solid (f_{IBM}).

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = \nabla . p + \mu \Delta u + f_{IBM}$$

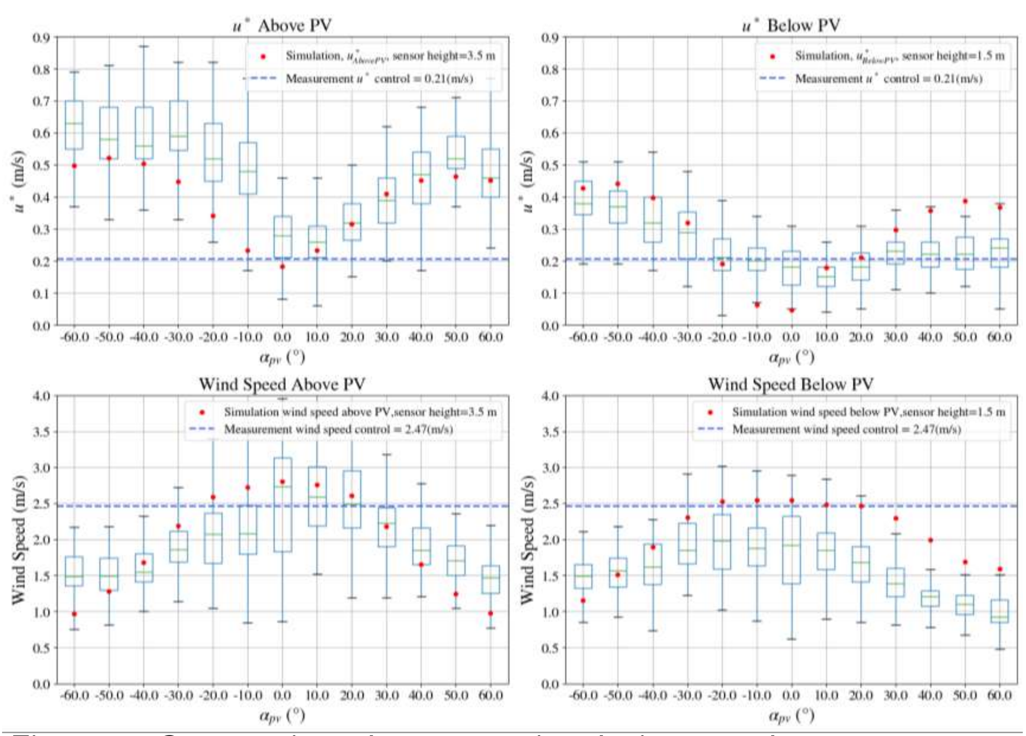


Figure 4. Comparison between simulations and measurements for wind towards west.

- In both the above and below PV regions, the simulated u^* and wind speed generally agrees well with the measurements.
- At the same sensor height, wind speed and u^* exhibit opposite trends with changes in PV panel tilt angle.

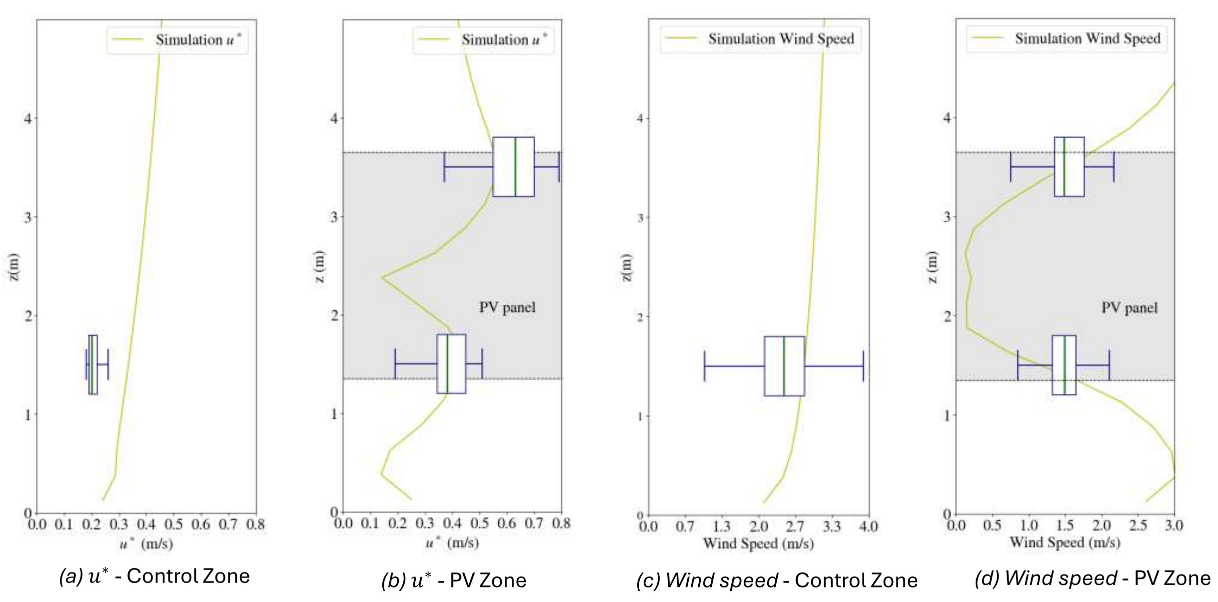


Figure 6. Vertical profiles of u^* and wind speed (α_{pv}= −60°) for wind towards west.

- Wind speed reaches a maximum at an approximative height of 1 meter, then, for 1.5m < z < 3.5m, it strongly decreases as it is altered by the turbulent wake, and finally, it increases above the PV panels.
- The vertical profile of u^* is even more complex as it reaches three maxima.

The relationships for wind speed or u^* between a reference height and the surface, derived under open field conditions, are modified by the presence of PV panels.

Impact on plant energy and water exchanges

Reference Evapotranspiration (ET$_0$) is a fundamental indicator for assessing plant water requirements, irrigation management, and yield.

$$ET_0 = \frac{0.408*\Delta*(R_n - G) + \gamma*(\frac{900}{T+273})*u_2*(e_s - e_a)}{\Delta + \gamma*(1+0.34*u_2)} \quad [3]$$

- Δ : the slope of the vapor pressure–temperature curve (kPa °C^{-1})
- R_n : the net radiation (MJ m$^{-2}d^{-1}$)
- G : the soil heat flux (MJ m$^{-2}d^{-1}$)
- γ : the psychrometric constant (kPa °C^{-1})
- T : the mean daily air temperature (°C)
- u_2 : the mean daily wind speed at 2 m height (m s^{-1})
- e_s- e_{ca}: the saturation partial pressure of water vapor at T (kPa)
- e_a : the partial pressure of water vapor in the air (kPa)

Evapotranspiration (ET_{EBL}) is derived from plant energy balance.

$$ET_{EBL} = \frac{\rho C_p}{\gamma}\frac{(e_{ca} - e_a)}{r_a} \quad [3]$$

- ρ: the density of air(kg m^{-3})
- C_p: the specific heat of air (J kg^{-1}°C^{-1})
- r_a : the aerodynamic resistance (s m^{-1})

r_a is a parameter that can be derived from u^*or wind speed[4].

Two major assumptions, that are challenged in APV conditions:
- there is a relationship between u^* and wind speed;
- there is a connection between flow dynamics at the surface and at a height z.

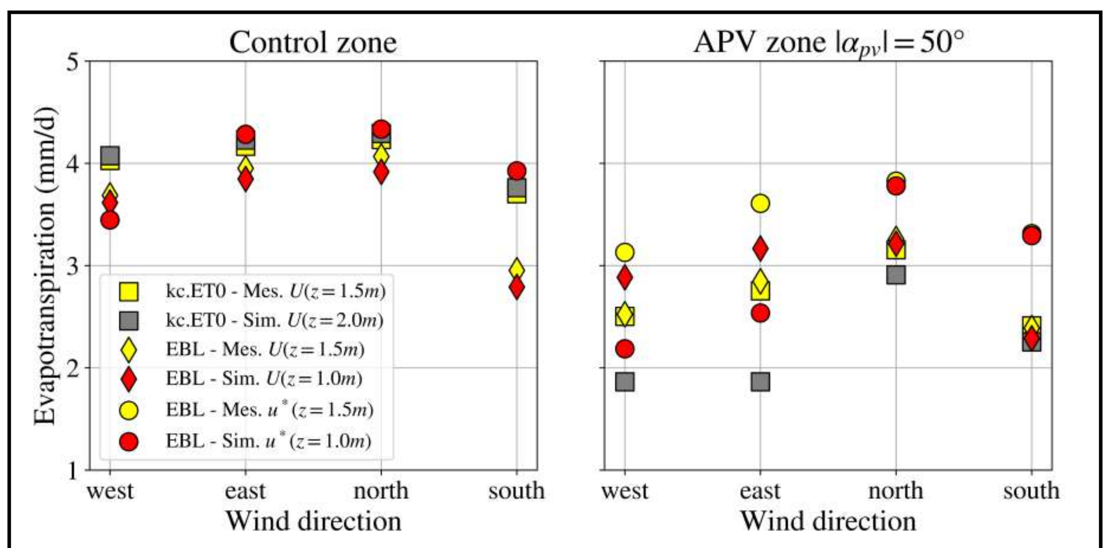


Figure 7. Estimation of evapotranspiration.

Evapotranspiration is estimated to be lower in APV zone. Using u^* or wind speed may modify the results by 30%. Changing the height at which the dynamics is considered modifies the results by 30%.

Conclusion

In APV conditions, wind speed and u^* are modified by PV panels. Their vertical profiles depend on PV panel tilt angle and wind direction. Therefore, reassessing current models of energy and water exchanges is essential for plants grown under PV panels.

References

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