Enhancing realism in orchard simulations using raytracing

Advancements in daylight modelling and tree geometry representation

Odysseas Alexandros Katsikogiannis, Olindo Isabella, Hesan Ziar

Delft University of Technology, PVMD Laboratory, EKL, P.O. Box 5053, 2600 GB Delft, The Netherlands

(Contact: O.A.Katsikogiannis@tudelft.nl)

Striking a balance between canopy light interception and shading involves tailoring the design of PV arrays to the adopted *tree-training system*—a method used to control and shape canopy growth. Yet, fine-tuning these experimentally is impractical, making accurate light simulations essential.

To be effective, modelling tools must capture the complex interplay between daylight and voluminous canopy geometries.

What aspects should light modelling tools aim to support?

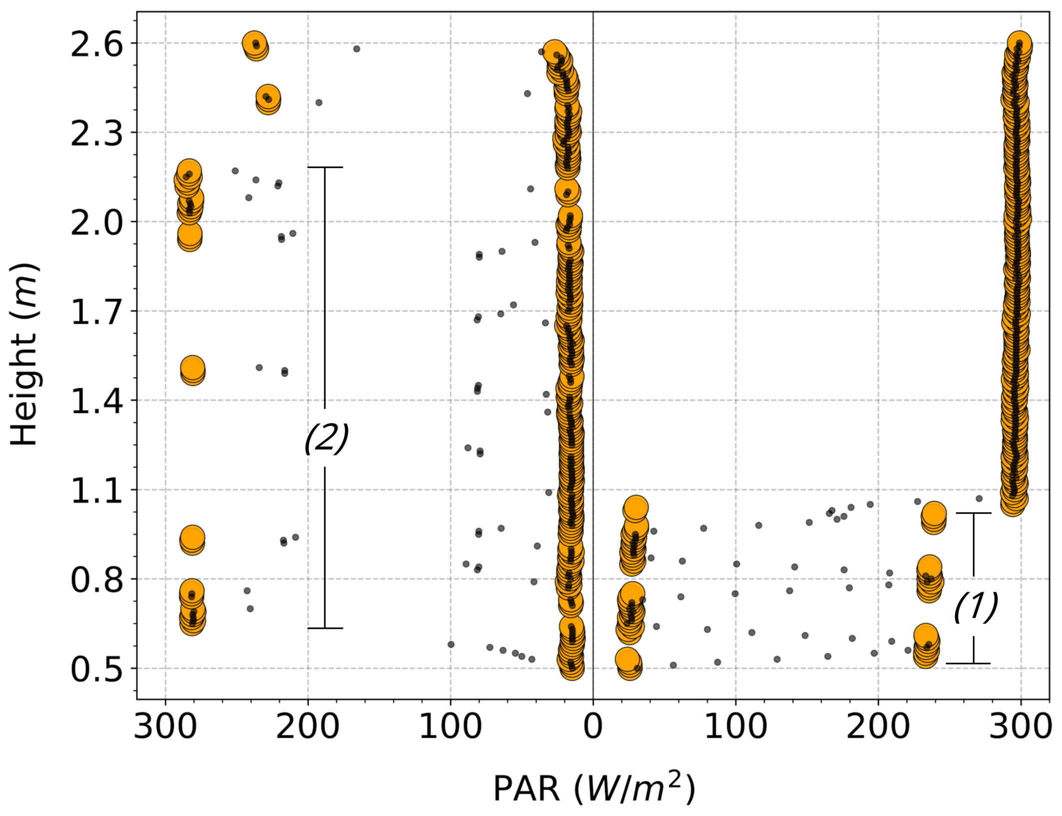
- Spectrally-resolved simulations accounting for local atmospheric conditions
- Porous, phenology-dependent canopies, adaptable to a range of training systems
- Solar disc modelling, to capture soft, extended shadows *(penumbra)* that differ from sharp-edged shading *(umbra)*

Apple orchard case study

Narrow-trained orchard systems (such as the Double Guyot) consist of porous, wall-like canopies that optimize resource-use.

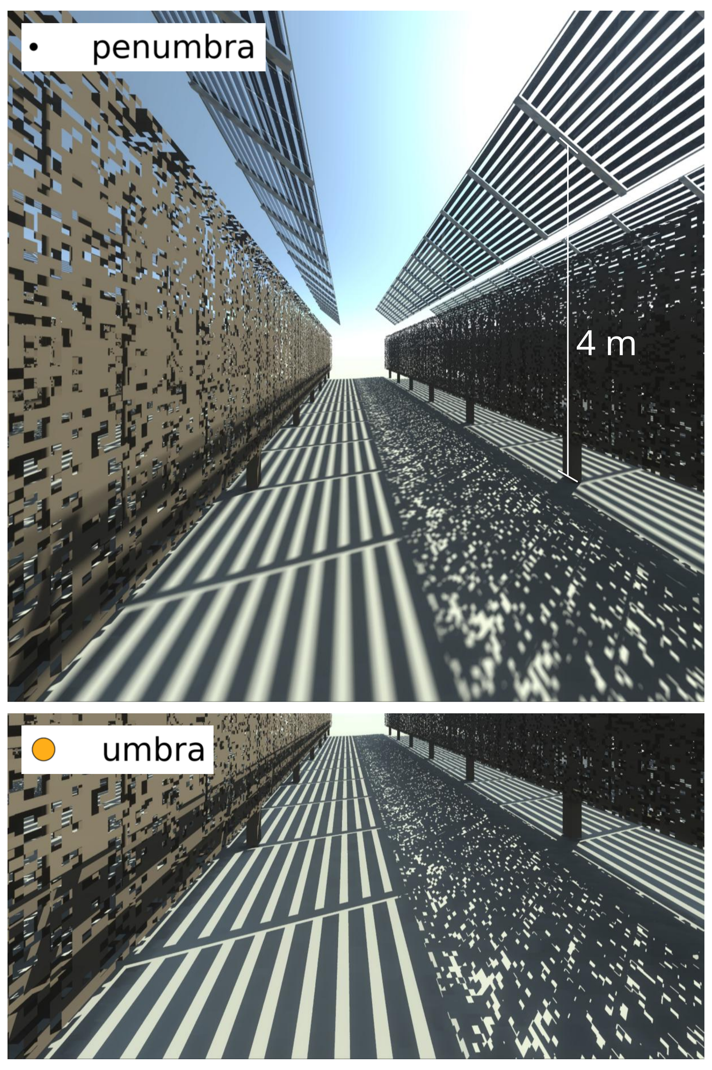
2. Significance of penumbra shadows

While mean light levels across the porous canopy remained unchanged, modelling penumbra altered the spatial distribution of light under clear skies.



(1) Penetration through glass and between PV cells
(2) Penetration between canopy gaps (sunflecks)

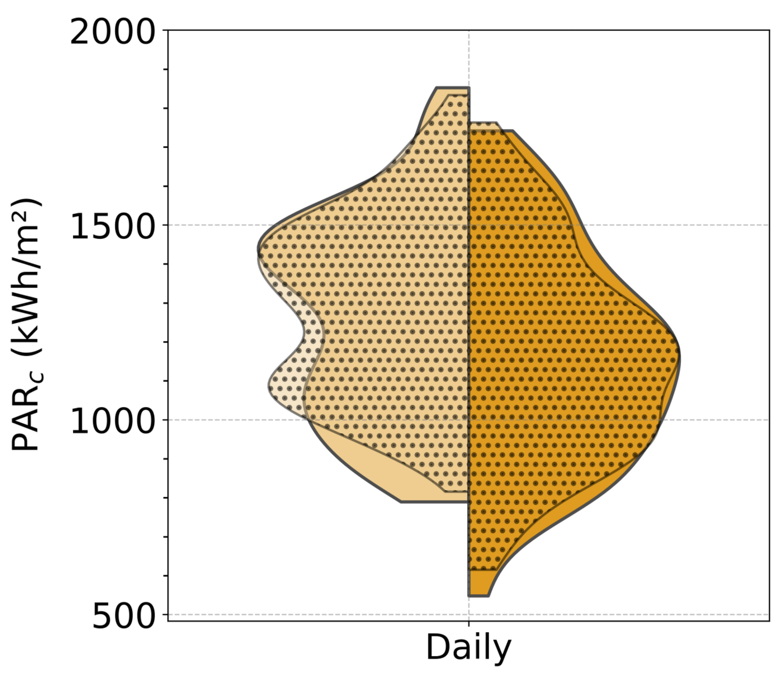
The PV array consists of half-cell modules with increased cell spacing, enhancing transmittance by a third.



Daily PAR distributions became more homogeneous, exhibiting shorter, thinner tails and increased density near the mean—indicating a **reduced likelihood of excessive shading or overexposure.**

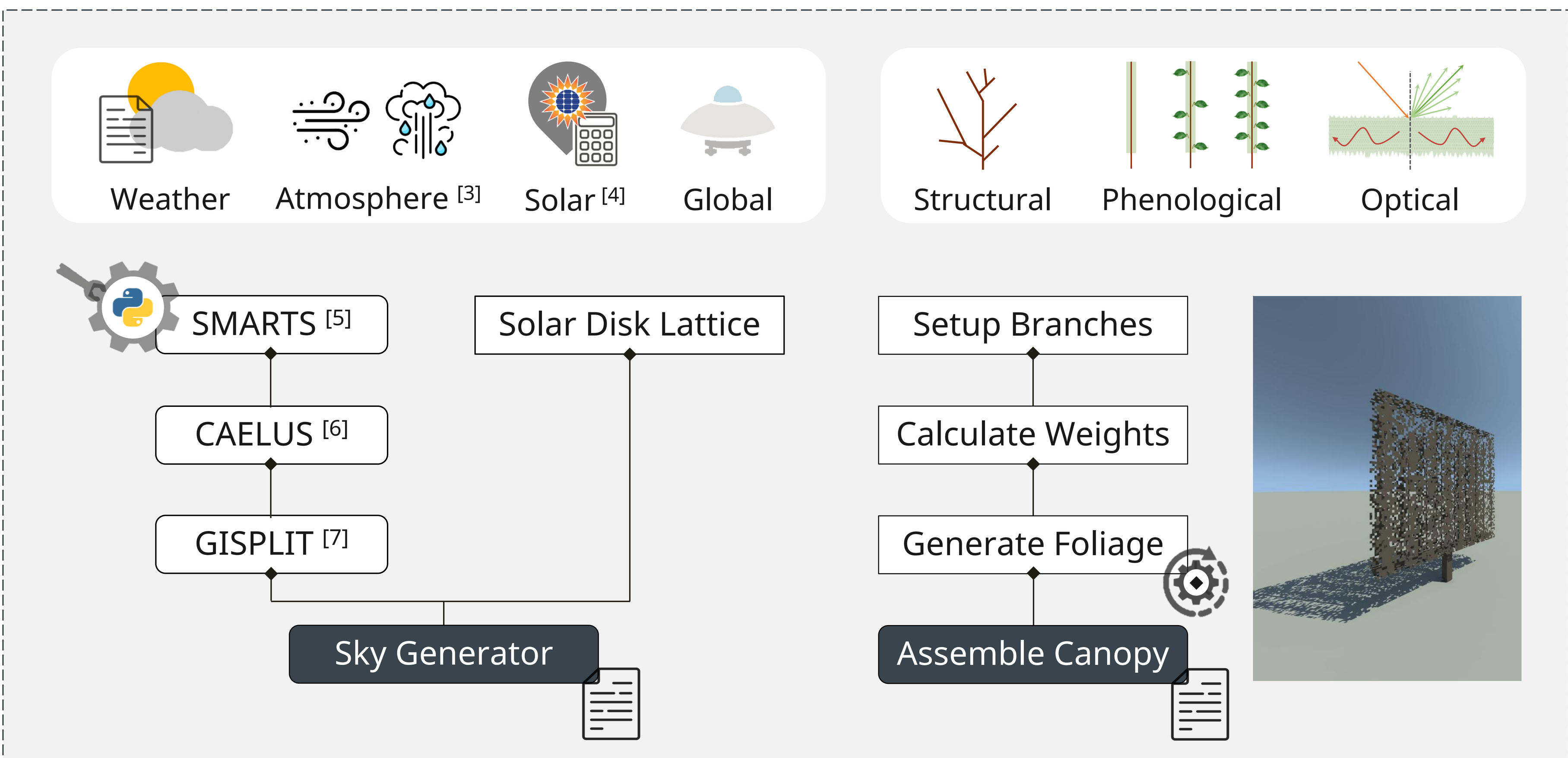
The magnitude of this effect depends strongly on:

- The size of shading geometries (PV cell width)
- Their distance from the projection plane (height)



4. Advancements in raytracing-based irradiation modelling

Built on the validated **Radiance** engine [1, 2] our framework introduces *high-resolution spectral skies, penumbra shadow rendering, and a flexible canopy reconstruction method for narrow-trained orchard systems*—all seamlessly integrated in Python.



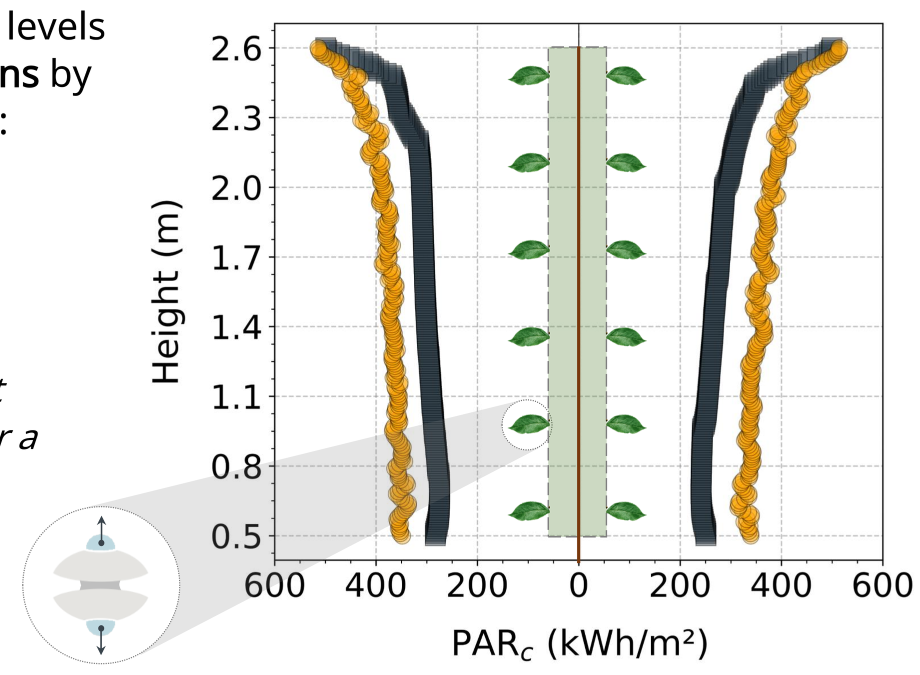
1. Canopy-model comparison

We evaluated the sensitivity of simulated light levels to canopy geometry under **open-field conditions** by comparing models across different timescales:

- opaque-static
- porous-dynamic

Photosynthetically active radiation (PAR) —visible light that drives crop growth—served as the target variable. The subscript "c" denotes cumulative over a specified time range.

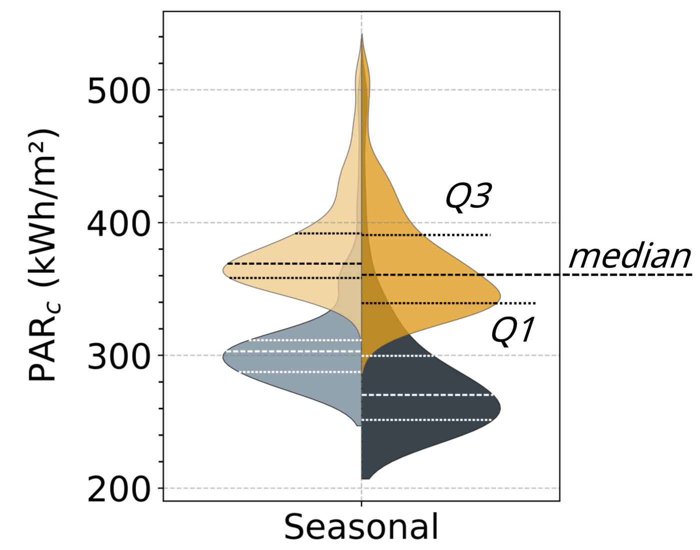
Light sampling was restricted to the central tree, with virtual sensors positioned along the outer canopy envelope.

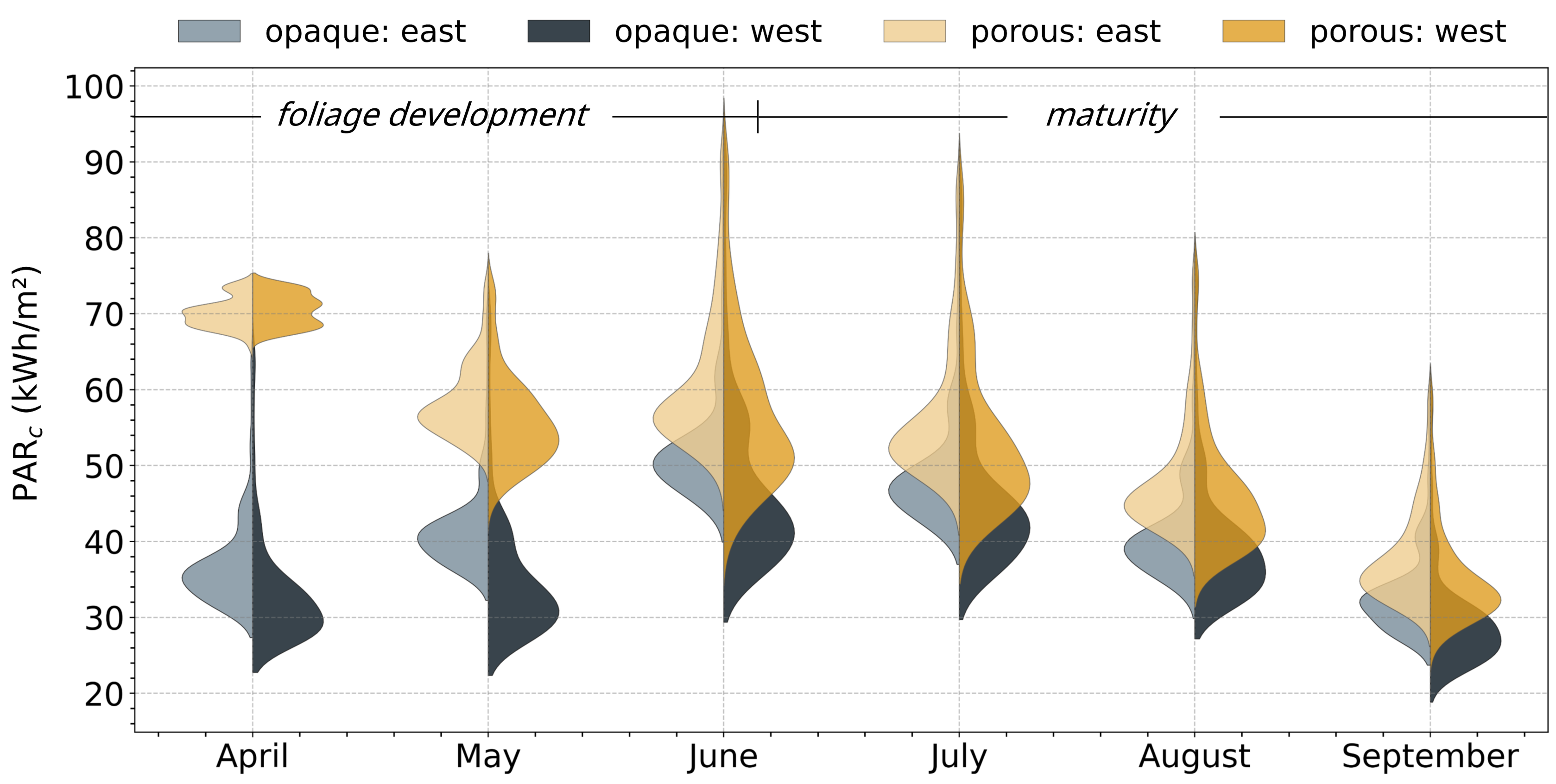


Throughout the season, the porous canopy:

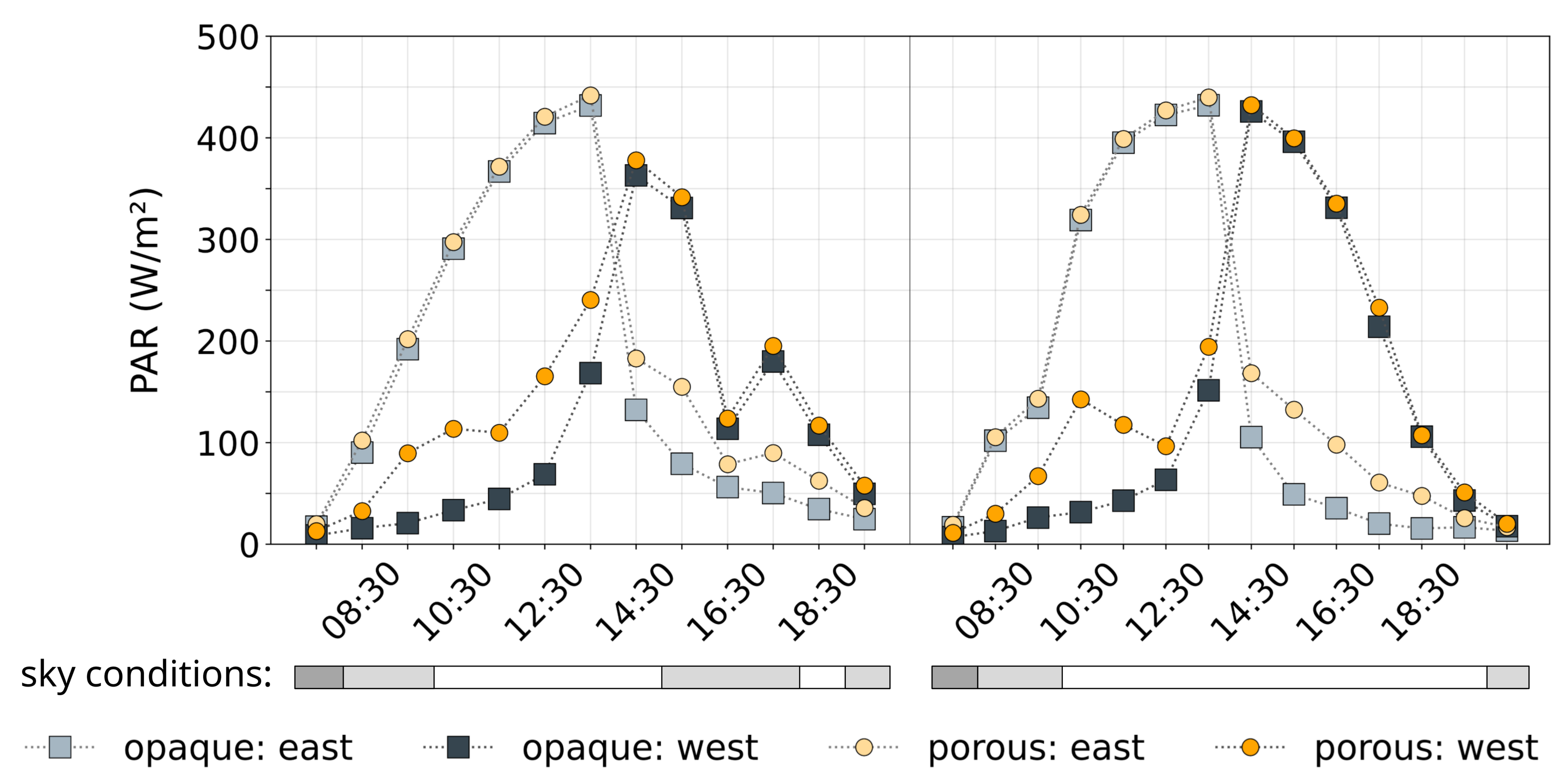
- Enhanced PAR by 26%
- Produced a more compact PAR distribution attributed to *sunflecks*—brief bursts of direct light passing through small canopy gaps

Backside leaf illumination (not shown) contributed 14% to the front-and-backside PAR.





As the season progressed, differences between canopy models reduced, leading to distributions increasingly similar in both shape and magnitude—a convergence largely driven by foliage maturity.



A consistent diurnal weather pattern promoted PAR inhomogeneity between canopy sides. This asymmetry was partially mitigated by porosity, particularly benefiting the west-facing side during morning hours.

3. Implications for agrivoltaic orchard design

Open-field simulations are essential for **diagnosing suboptimal light conditions** and guiding site-specific agrivoltaic designs.

Our porous-dynamic canopy model **captured key spatio-temporal aspects of light transmission** in narrow-trained systems. However, further developments in canopy reconstruction techniques remain necessary.

Although the **impact of penumbra shadows is limited** under conventional PV modules, modelling them opens new design pathways—especially in regions with frequent clear skies.

[1] G.J. Ward, *Proc. 21st Annu. Conf. Graph. Interact. Tech.* (1994).
[2] O.A. Katsikogiannis, et al., *Proc. 41st EUPVSEC*, (2024).
[3] D. M. Giles, et al., *Atmos. Meas. Tech.*, **12**, 169-209 (2019).
[4] K. Anderson, et al., *J. Open Source Softw.*, **8**(92), 5994 (2023).
[5] C.A. Gueymard, *SMARTS code, Version 2.9.5*, Solar Consulting Services (2005).
[6] J.A. Ruiz-Arias, C.A.Gueymard, *Sol. Energy*, **263**, 111895 (2023).
[7] J.A. Ruiz-Arias, C.A.Gueymard, *Sol. Energy*, **269**, 112363 (2024).

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