

Climate-resilient agrivoltaic systems: enhancing agricultural sustainability in Southeast Spain

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37.8 kWp

72 bifacial modules on a dynamic 174 m² canopy, 4.2 m clear height

38,671 kWh·yr⁻¹

on-site generation per structural module → 5.80 t CO₂ avoided

2,547 m³·ha⁻¹·yr⁻¹

rainwater harvested by the roof when it closes

10–15 %

of the crop carbon footprint cut by the way the water is sourced

1 INTRODUCTION

- The Mediterranean is a climate-change hotspot: summer warming, declining rainfall and sharply increasing drought.
- Campo de Cartagena (SE Spain) receives **283 mm·yr⁻¹** against a structural deficit above 400 mm, yet irrigates **≈10,000 m³·ha⁻¹·yr⁻¹** of open-field vegetables.
- Rain arrives in a few torrential events — 285 mm in three days in December 2016 — producing runoff, soil detachment and nitrate leaching towards the Mar Menor lagoon.
- Water carries energy: **1.41 kWh·m⁻³** in the current supply mix, **2.78 kWh·m⁻³** under full desalination. Irrigation alone causes **45 %** of crop GHG emissions, 60 % if the transfer were fully replaced by desalinated seawater.
- Agrivoltaics relieve the competition for land, but fixed canopies constrain crop choice and fit poorly with ordinary farm machinery.

Water and carbon are the same problem here. What is missing is a PV roof managed as an **agronomic actuator**: an aperture that follows the crop in real time, closes against hail and torrential rain, and turns the intercepted volume into a stored irrigation resource.

2 OBJECTIVES

- Design a dynamic, **coplanar** PV roof compatible with conventional machinery.
- Quantify the modulation of transmitted radiation and the fall in evapotranspirative demand.
- Estimate the rainwater recoverable when the roof closes, and the runoff and leaching avoided.
- Assess on-site generation and the resulting carbon balance.

3 METHODS · PROTOTYPE

Site. Experimental farm at El Algar, Cartagena (37° 39 N, 0° 52 W; ~30 m a.s.l.), semi-arid Mediterranean climate, 283 mm·yr⁻¹ of rainfall.

Structure. Two-pitch steel portal frame: 12.80 m span, 13.56 m bay, **4.20 m clear height**, PV planes at 11°, footprint 173.6 m². Tractors, ploughs and boom sprayers work underneath without any change to the farming calendar.

Generator. 72 bifacial modules of 525 Wp = **37.8 kWp**. The lower module row slides *under* the upper row within the same plane, so the aperture is commanded continuously from **50 % shading** (18.9 kWp) to **100 % occlusion** (37.8 kWp) without altering tilt. Closure is automatic on meteorological alert and on crop-specific radiation thresholds.

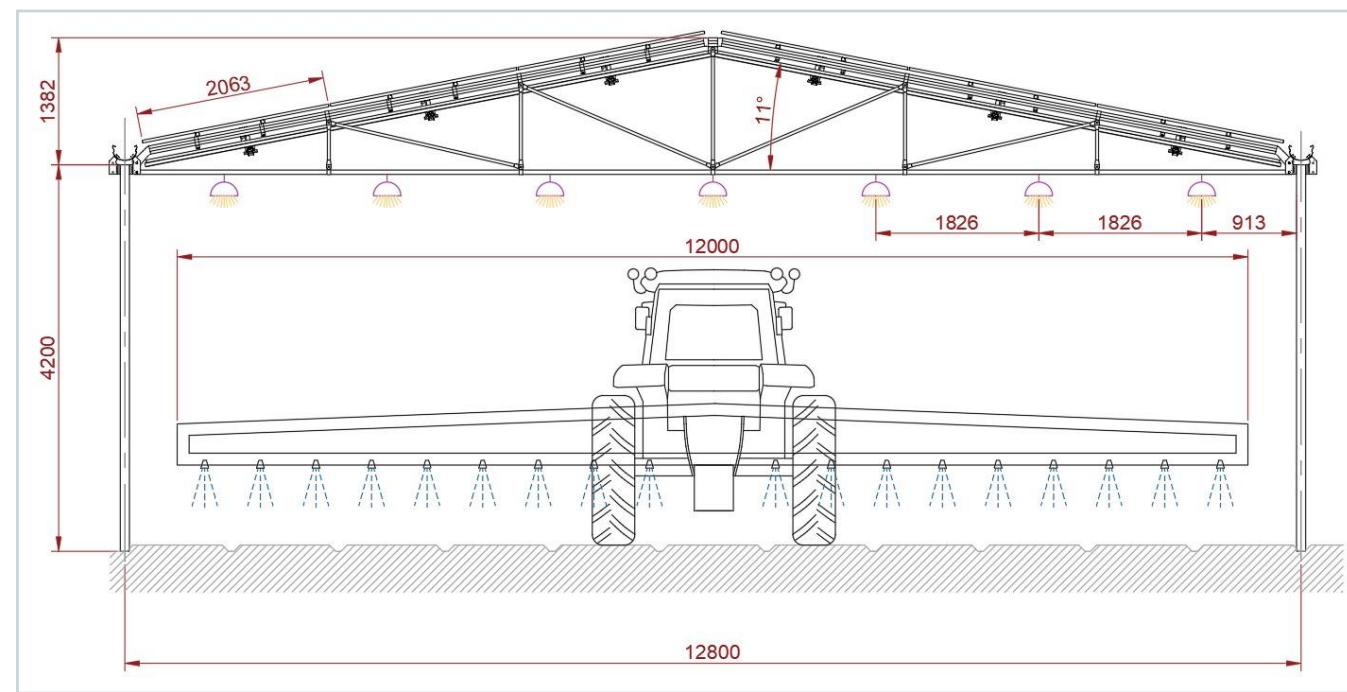


Fig. 1. Cross-section of the agrivoltaic portal frame (mm). The 12,000 mm boom sprayer is superimposed to verify that the implement fits between pillars.

4 METHODS · MODELLING

Radiation. Three-dimensional shading model (SketchUp) solved at 10-min steps over the solar year for 50 / 75 / 100 % aperture, giving the geometric transmission τ_{AV} ; $f_{PAR} = 0.50$, $C_q = 4.57$ mol·MJ⁻¹.

$$DLI_{AV} = R_s \cdot f_{PAR} \cdot C_q \cdot \tau_{AV} \quad (1)$$

Water balance. FAO-56 Penman–Monteith adapted to the attenuated microclimate: net radiation $\times \tau_{AV}$, wind speed $\times \mu_{AV} = 0.80$. **Harvesting.** The closed roof drains to a reservoir, with $A = 174$ m², $C_r = 0.90$ and interception factor $f = 1$ (0.85 as conservative bound).

$$V = A \cdot P \cdot C_r \cdot f \quad (2)$$

Energy and carbon. PVGIS v5.3 for the actual geometry, tilt and aperture schedule; $FE_{mix} = 0.15$ kg CO₂·kWh⁻¹. Water saved or substituted avoids the specific energy e_{mix} of the district supply (1.41 or 2.78 kWh·m⁻³).

$$CO_{2,water} = (V_{harv} + V_{ET}) \cdot e_{mix} \cdot FE_{mix} \quad (3)$$

Control. Agroclimatic station, soil-moisture, canopy-temperature and PAR sensors above and below the roof feed cloud-hosted models that drive the aperture set-point, the irrigation scheduling and the fertiliser injection.



Fig. 2. VOLTAGRO prototype at El Algar: a conventional tractor with a mounted plough working under the elevated canopy.

5 RESULTS · RADIATION ON DEMAND

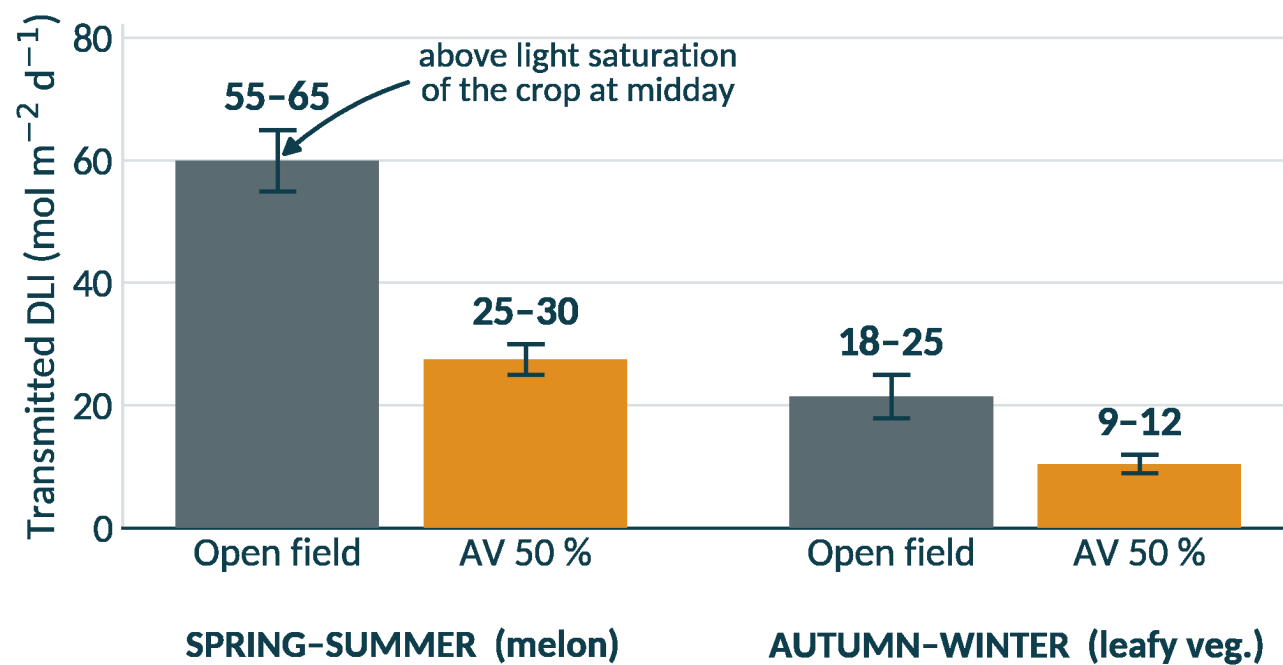


Fig. 3. Transmitted daily light integral at 50 % aperture vs. the open-field reference.

At 50 % aperture the transmitted DLI stays **within the physiological optimum** of both crops, whereas the open field exceeds light saturation during the central hours, when stomatal closure and photoinhibition suspend net assimilation. Peak PPFD falls from >2000 to 1000–1200 $\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ in summer, and at 100 % closure the crop is **fully protected** against hail, torrential rain and radiative frost.

6 RESULTS · WATER AND CARBON

Microclimate, water saving and interception

Evapotranspirative demand falls by **25–30 %** (spring–summer) and **14–25 %** (autumn–winter): about **2,000 m³·ha⁻¹·yr⁻¹** of abstraction avoided.

Closed, the 174 m² roof becomes an elevated impervious catchment yielding **44.3 m³·yr⁻¹ per module** $\approx$ **2,547 m³·ha⁻¹·yr⁻¹**, a quarter of the gross irrigation requirement. A single 100 mm cut-off low delivers 15.7 m³ per module in a few hours — water that would otherwise leave the plot as runoff, carrying soil and nitrates to the Mar Menor.

Decarbonising the water supply · SUSTAQUA

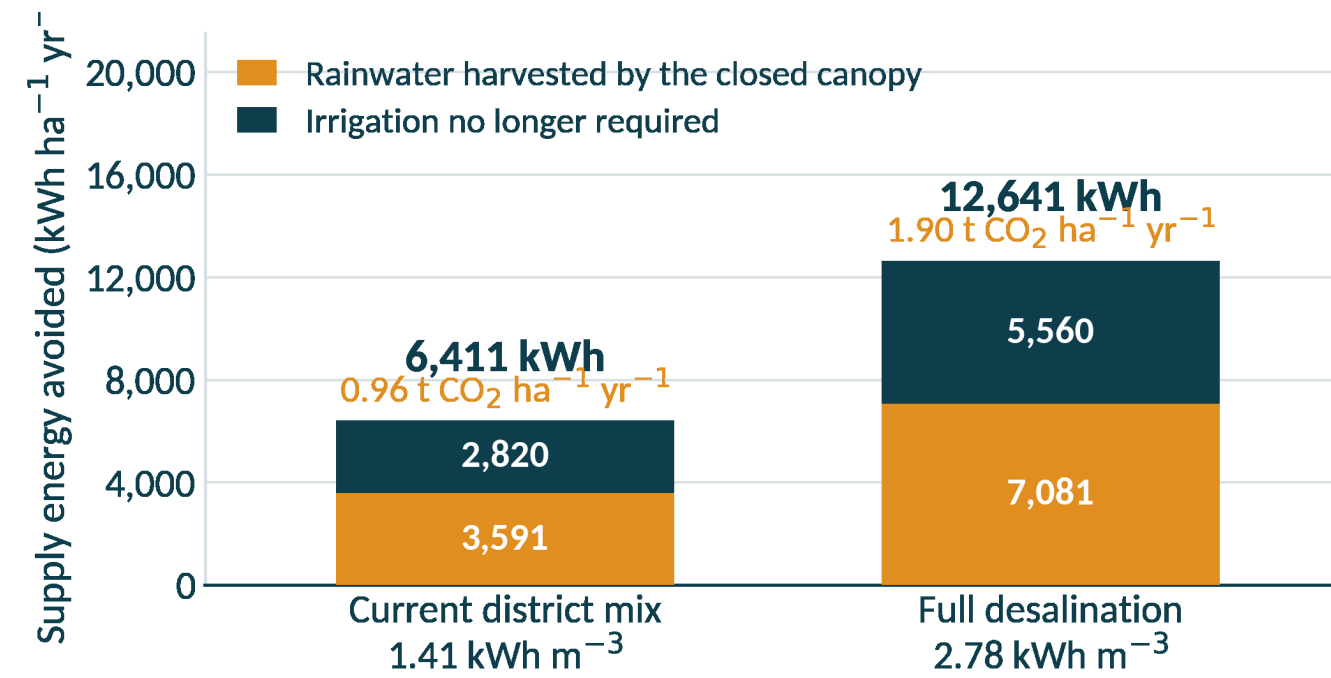


Fig. 4. Supply energy and emissions avoided by the water harvested and no longer required.

The 4,547 m³·ha⁻¹·yr⁻¹ harvested or no longer needed displace **6,411–12,641 kWh·ha⁻¹·yr⁻¹** of supply energy and **0.96–1.90 t CO₂·ha⁻¹·yr⁻¹** — 10–15 % of the carbon footprint of an open-field vegetable rotation, obtained *solely from the way the water is sourced*.

7 RESULTS · ON-SITE GENERATION

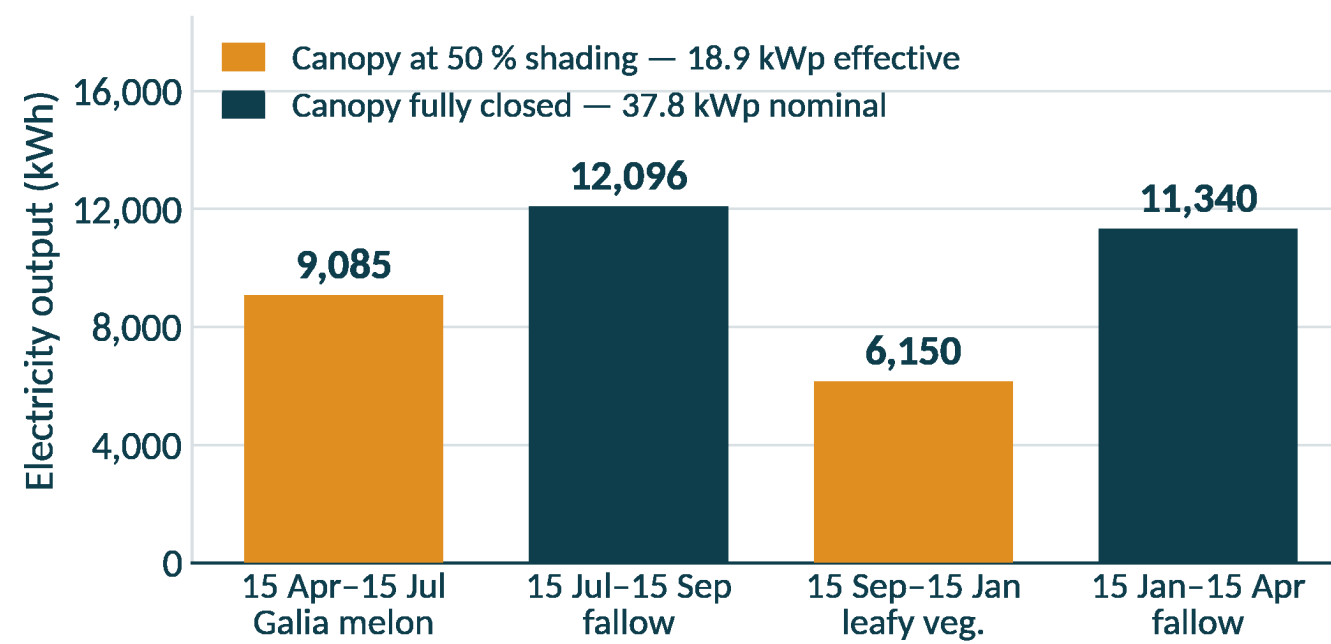


Fig. 5. Annual output of one structural module by aperture regime.

38,671 kWh·yr⁻¹ per module — **2.5× the cropping cycles alone** — avoiding **5.80 t CO₂·yr⁻¹**, against the **≈245 kWh·yr⁻¹** needed to irrigate the same footprint: crop protection and peak conversion coincide.

8 CONCLUSIONS

- The PV roof works as an **agronomic actuator**: radiation commanded in real time (25–30 mol·m⁻²·d⁻¹ in summer, 9–12 in winter) and complete physical protection on demand.
- 14–30 %** less evapotranspirative demand and **≈2,550 m³·ha⁻¹·yr⁻¹** of clean water harvested, while erosion, runoff and nitrate leaching are suppressed.
- The plot behaves as a **carbon sink**: 5.80 t CO₂ per module plus 0.96–1.90 t CO₂·ha⁻¹·yr⁻¹ from decarbonised water sourcing — the contribution to SUSTAQUA.
- Crops, machinery and calendar are preserved, addressing the main **adoption barrier** of agrivoltaics. Figures are predictive; experimental validation is under way at El Algar (2026–2027).