MICROCLIMATE EFFECTS AND SYNERGIES OF ELEVATED AGRIVOLTAIC SYSTEMS IN AN ECOLOGICAL VINEYARD: A CASE STUDY IN ALMERÍA, SOUTHERN SPAIN

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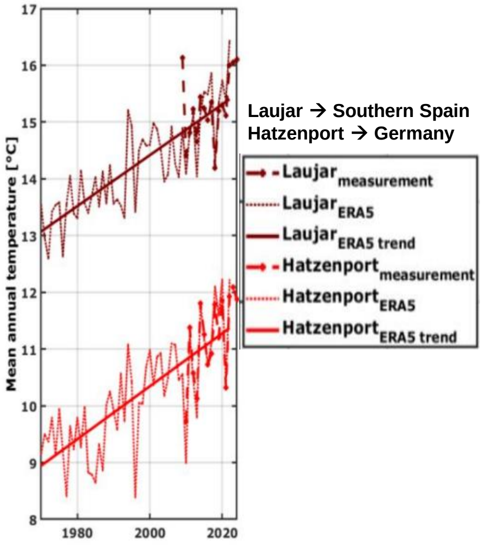
BACKGROUND

Background

Viticulture & Climate Change

- In 2024, global wine production fell to lowest level since 1961 due to extreme weather events (droughts, heatwaves and hail) in many winemaking regions [1].
- Climate change is reshaping Europe's wine regions
  - Traditional winemaking regions, such as Spain and southern France, are struggling with scarce precipitation and extreme heat.
  - Regions at northern latitudes are becoming more suitable for wine production.
- Since 1970, temperature has risen by ~2.5 ºC in winemaking regions in Germany and Spain [2].
- Some future climate projections by 2100 indicate:
  - Higher average temperatures (↑ 4ºC in some months, particularly in summer).
  - More frequent and intense heat waves in Europe.
  - Higher probabilities of droughts, specially in southern Europe.
- These events may negatively affect crop development, leading to:
  - Heat stress.
  - Water stress.
  - Phenological shifts (earlier budburst and accelerated ripening).

Berries after a heat wave



Historical average annual temperatures in two winemaking locations. Source of data: ERA5. Plot in [2].

[1] https://www.decanter.com/wine-news/global-wine-production-falls-to-lowest-level-since-1961-545528/
[2] Hanrieder et al., "Agrivoltaic System Potential to Mitigate Effects of Climate Change in Viticulture", EU PVSEC 2025

Background

DLR

Viticulture & Agrivoltaics

- In some vineyards, shading nets have been installed to mitigate and adapt the effects of climate change.


Source: Marigliano et al. [1]


Source: Vinethos


Source: EyouAgro


Source: Wine Business Analytics

- APV systems as a replacement for these shading nets → Simultaneous crop protection and energy generation. Multiple APV installations have been deployed in Europe/Spain in the last decade:


Piolenc, France
Source: Sun'Agri


Virgilio, Italy
Source: RemTec


Ihringen, Germany
Picture taken at the Weinbauinstitut Freiburg


Puglia, Italy
Source: Gazzeta dal Tacco


Ribera del Duero, Spain
Source: Powerfultree


Fuentealbilla, Albacete, Spain
Source: Grupo Tornasol


Laujar de Andarax, Spain
Source: DLR, Cortijo el Cura

This study

[1] Marigliano et al. (2022), https://doi.org/10.3389/fagro.2022.898870
[2] Dal sole al vino: il Convivio Agrivoltaico racconta la Puglia che innova-Gazzetta dal Tacco
[3] Harvesting the sun, protecting the vines – innovation for sustainable agriculture

Aim of the study

Viticulture & Agrivoltaics

Preserved Crop yield + Energy generation

How do elevated agrivoltaic systems influence vineyard microclimate, crop performance, and energy production in southern Spain?

DESCRIPTION OF THE SYSTEM

Description of the system

- **Pioneering APV project** in Almería, southern Spain, located within an organic vineyard[1]. Installation date: **January 2025**.
- **Overhead PV system** with a checkerboard layout, covering **120 m²** and shading 32 Merlot vines. Planting pattern: 2 m x 2 m spacing (2003). Ground Coverage Ratio – GCR: **38%.**
- System classified as **Category I – Use 1A** under **DIN SPEC 91434 (Germany)**.
- **Eco-friendly foundation** using ground screws to **prevent soil compaction**.
- **PV capacity**: **10.8 kWp** from **18 bifacial modules**. **Inverter** of **10 kWn**.
- **Energy use**: Electricity is used **on-site for self-consumption** by the main winery building.

[1] Cortijo El Cura-Ecobodega. https://cortijoelcura.com/

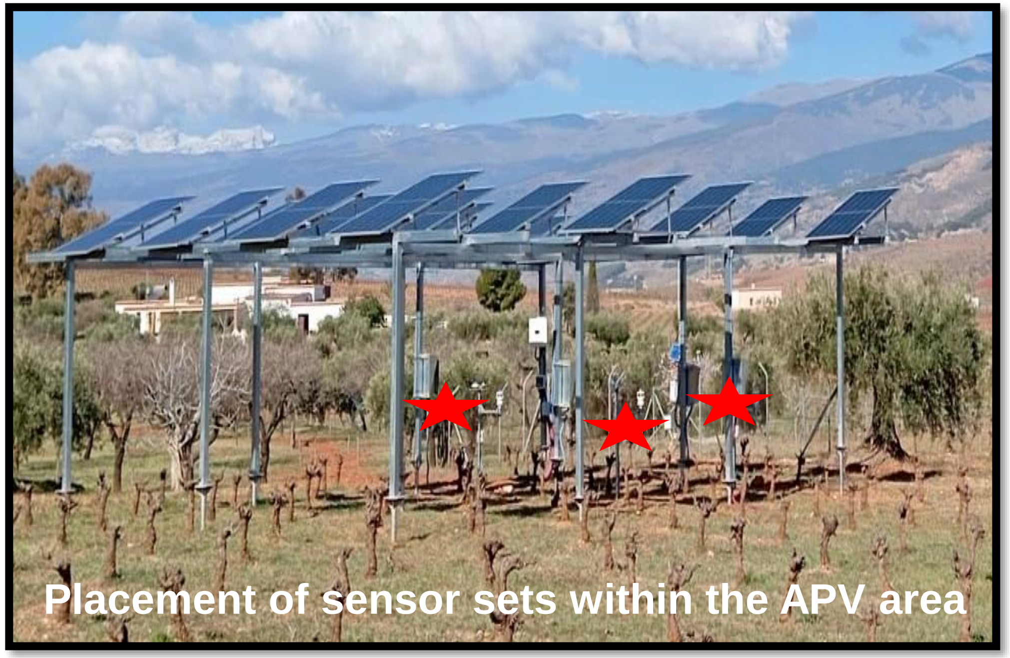
Description of the system

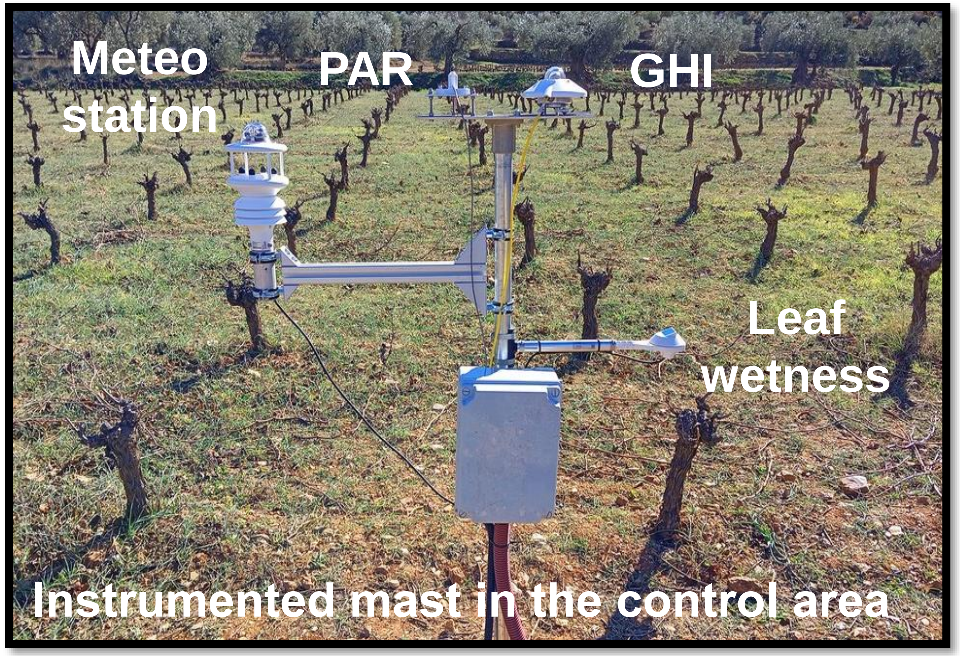
Monitoring system

4 measurement zones to assess the impact of shading on microclimate, soil and crop performance:

- Under the PV structure (x3) → APV area
- Control area (no shading)

Category	Parameters Measured
Meteorological	• Air temperature • Relative humidity • Wind speed and direction • Precipitation
Irradiance	• Solar irradiance (PAR, GHI, G_{POA_f}, G_{POA_r})
Soil	• Soil temperature • Soil moisture
Crop	• Leaf wetness • Brix (sugar content) • Physiological traits • Yield quantity and quality


Placement of sensor sets within the APV area



Instrumented mast in the control area

Description of the system

Monitoring system

Other sensors

- Soiling

Measurements of the **electrical losses caused by dust**, **pollen and other particulates** that deposit on the PV modules.
  - **Higher seasonality** of soiling losses due to agricultural management and pollen when compared with traditional GM PV installations.
  - **Higher risk of bird droppings** that can cause hotspots, leading to non-reparable defects in PV modules.

Side-by-side reference cells (soiled vs clean)

- Pyranocam + Albedocam

Measurements of **all irradiance components → Direct, Diffuse and Global**.
  - Use of a **pyranometer + sky eye camera**.
  - Useful for quantifying the **amount of diffuse light**, which plants like.
  - **Monitoring of albedo** (reflected irradiance) changes throughout the crop cycle → Impact on PV yield of bifacial modules.

Credit: Niklas Blum (DLR)

- Crop monitoring

Refractometer (Pre-harvest)
  - Measures the **sugar concentration (°Brix)** in grape juice to assess **fruit ripeness and harvest timing.**

Hydrometer (Post-harvest)
  - Measures the **specific gravity** of grape must or wine to track **fermentation progress.**

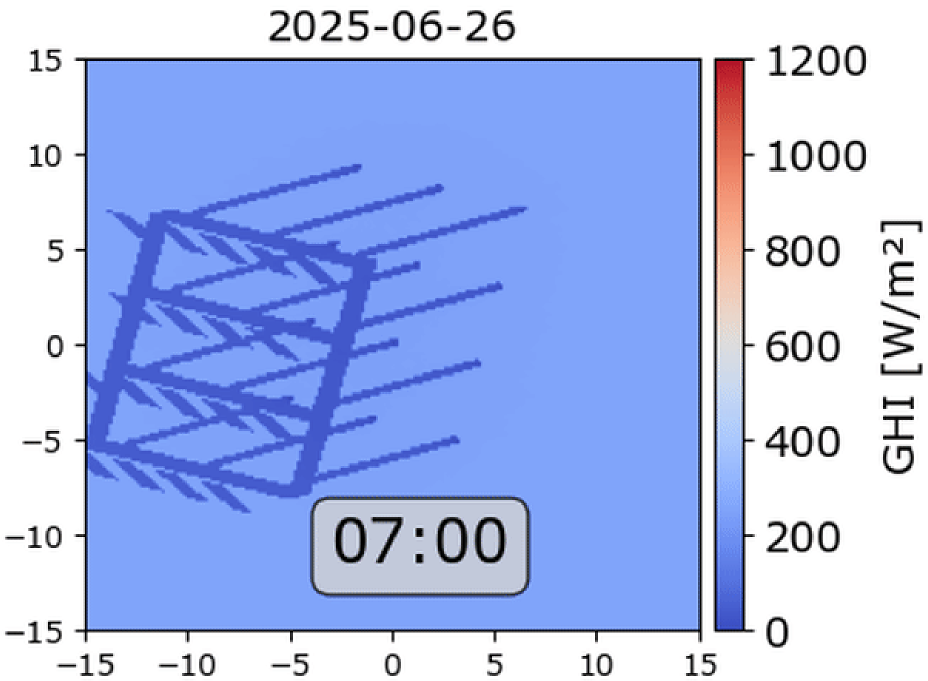
RESULTS

Results

Microclimate: GHI – Ground level (Simulations)

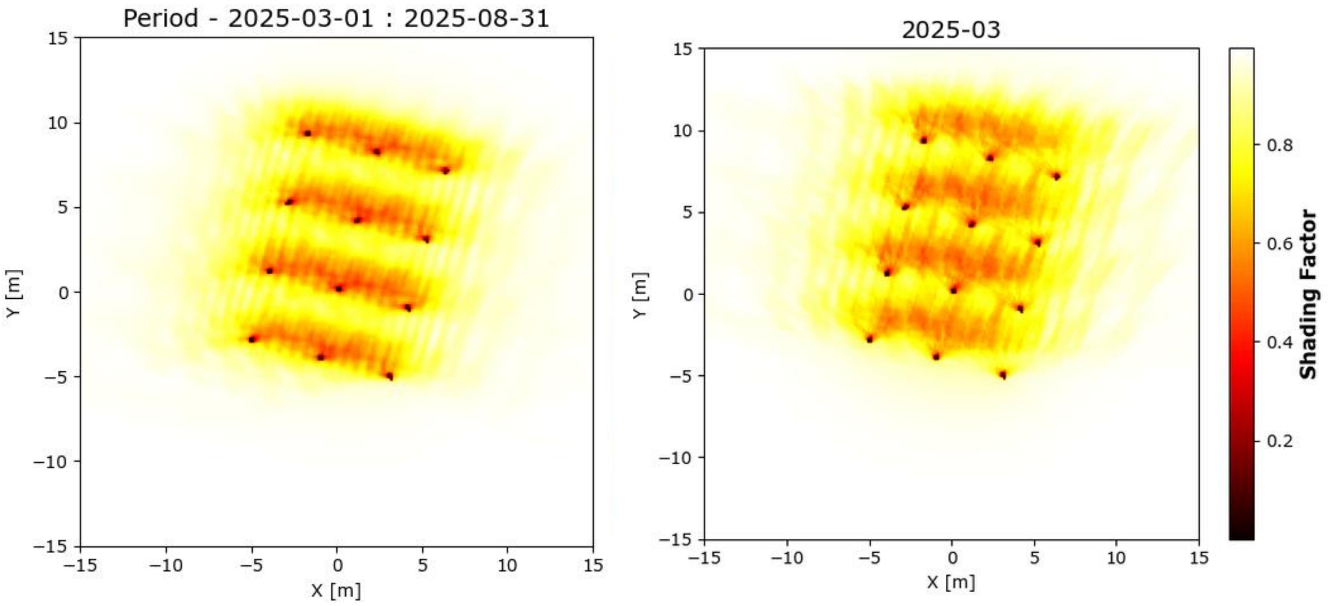
Instantaneous GHI simulations

- Potential to optimize modules' positions in tracked APV systems as a function of light requirements of crops.
- Possibility to conduct simulations up to 1-min resolution – based on *Anna Kujawa et al. [1].*



Shading Factor

- Simulations of spatial distribution of accumulative solar radiation reduction (*1 – Shading Factor*).
  Shading Factor = 0.6 → Radiation received: 60% of unshaded area.
- Support in APV design optimization and crop choice.
- Possibility to use both TMY data or measured (reanalysis or on-site measured) irradiance data as inputs.



[1] Kujawa et al. (2025), "A Ray-Tracing-Based Irradiance Model for Agrivoltaic Greenhouses: Development and Application", https://doi.org/10.3390/agronomy15030665

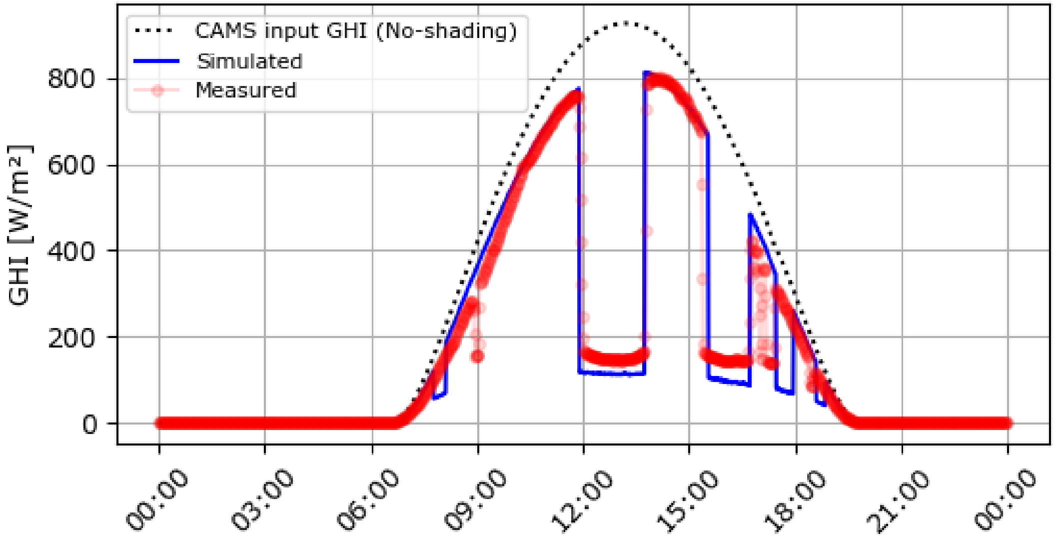
Results

Microclimate: GHI profile – Simulations validation

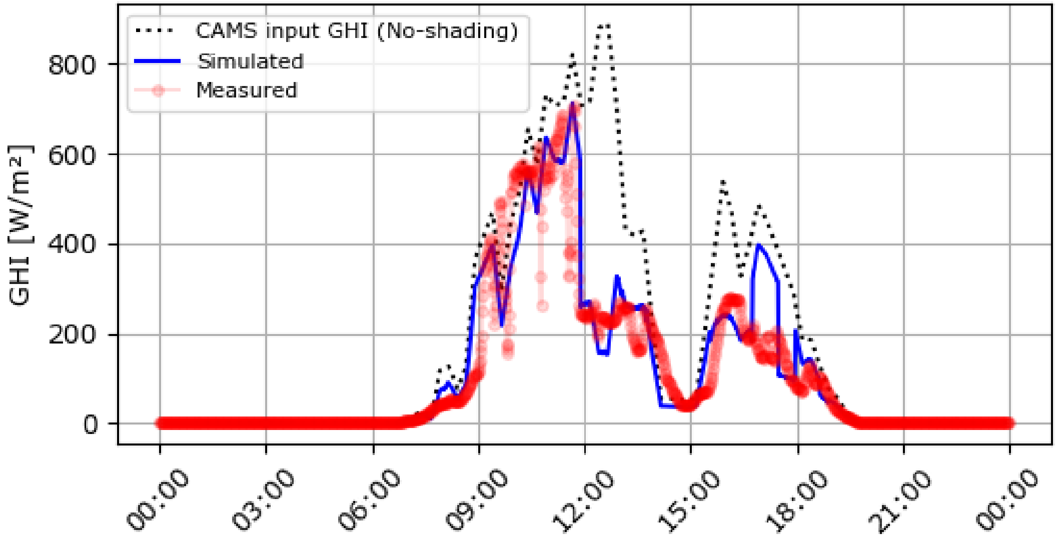
Instantaneous GHI simulations vs measurements

- Validation of simulations using CAMS reanalysis irradiance data (0.1º resolution, ~10 km).
- Simulated shading patterns closely match pyranometer measurements.
- Future work will explore using models to derive PAR from GHI.

Clear-sky day



Cloudy day



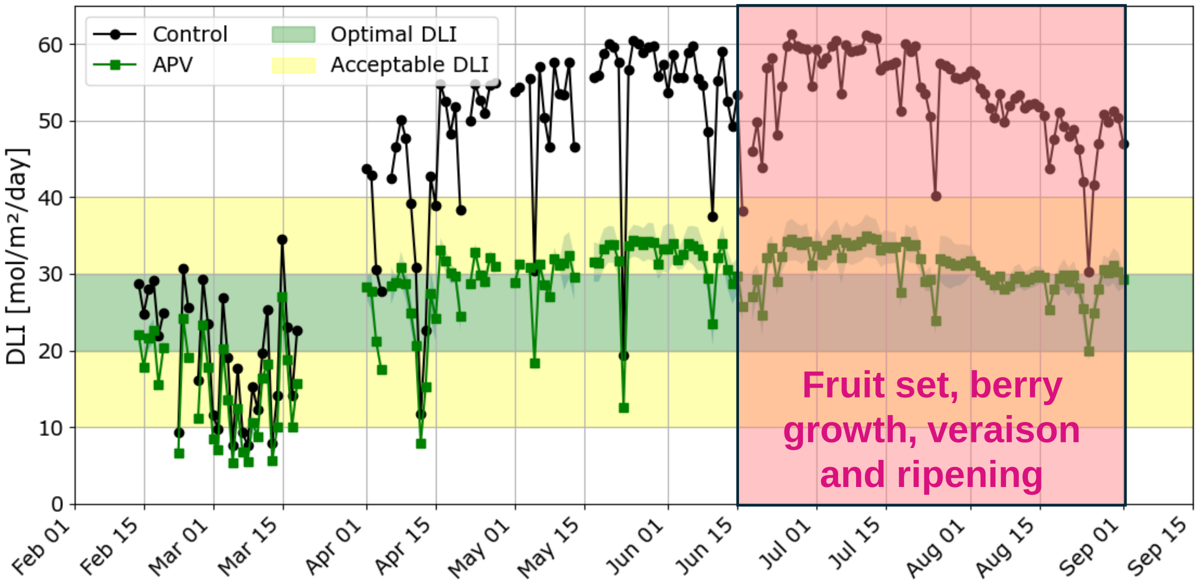
Results

Microclimate: Radiation – DLI

- PAR (DLI) was monitored with EKO ML-020P PAR sensors at 1.5 m height.
- In APV zone, excessive DLI values are partially mitigated.
- Optimal DLI for grapevines: 20–30 mol m^{-2} d^{-1} (stage & weather dependent) [1].
- DLI > 20 mol m^{-2} d^{-1} in both APV and control zones, except on very cloudy days.
- During berry growth–ripening, DLI in APV zone stayed within the acceptable range, ~40% lower than control.

DLI evolution during the crop cycle

$$DLI = \int PPFD\ (PAR)\ dt$$



[1] Photone Growth Light Meter, "Light Requirements for Plants". https://growlightmeter.com/light-requirements-for-plants/

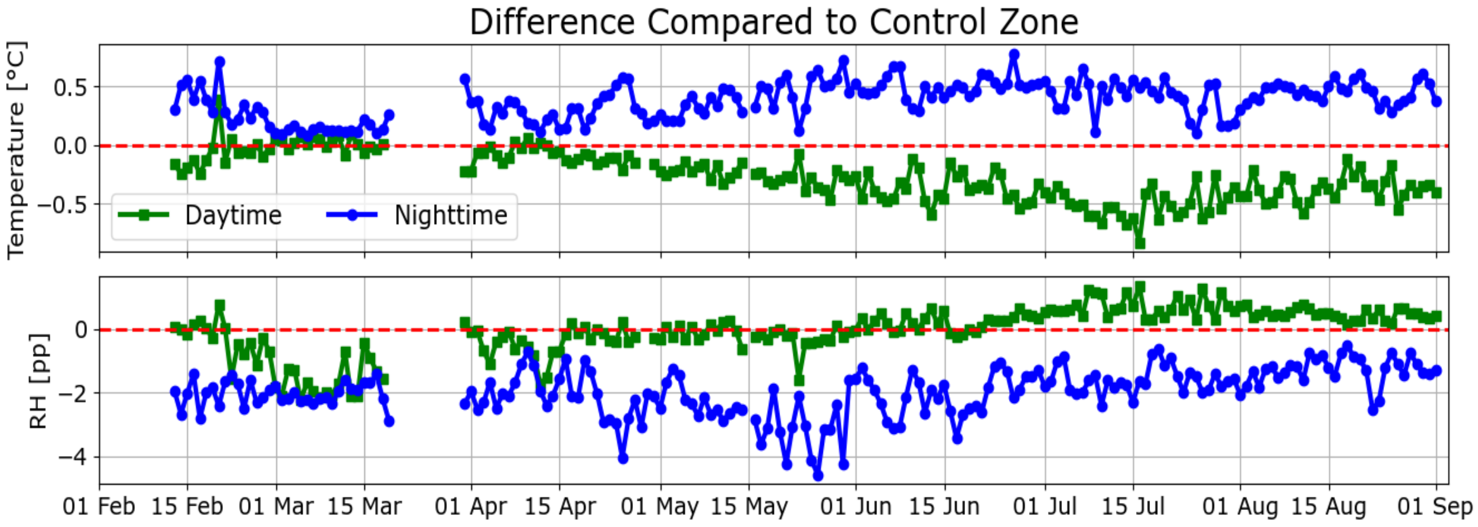
Results

Microclimate: Air Temperature, RH and soil moisture

Microclimate Effects in the APV Zone

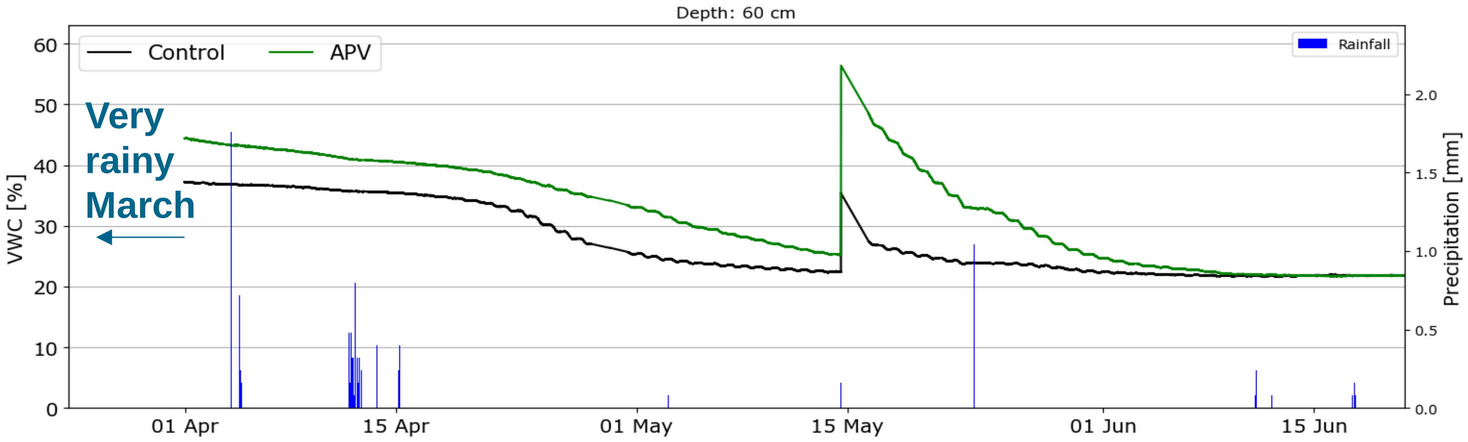
😊 **Daytime:**
⬇️ Temperature up to **–0.5 °C**
➖ Relative Humidity **similar**

🌙 **Nighttime:**
⬆️ Temperature **+0.6 °C**
⬇️ Relative Humidity up to **–4 pp**



Soil moisture

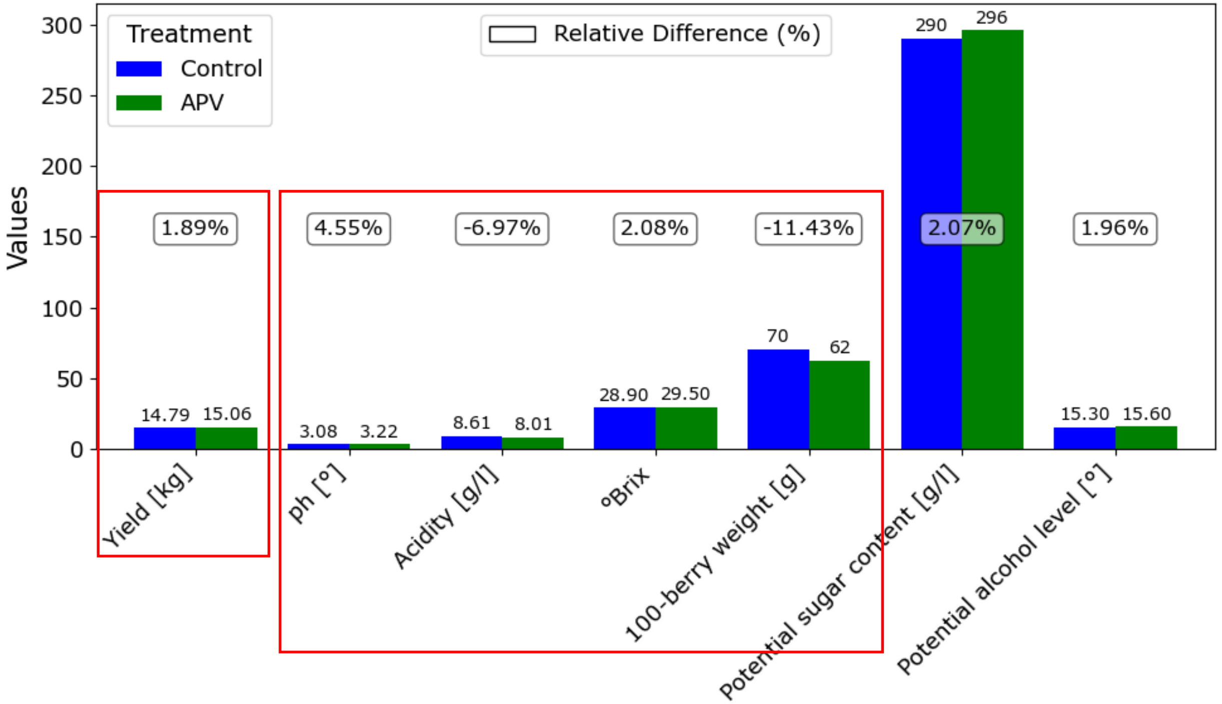
- Measurements of volumetric water content (VWC) at different depths.
- Extended soil moisture retention in the APV area, suggesting lower evapotranspiration.



Results

Crop yield

- 28 plants were harvested in each zone.
- As expected due to the relatively small size of the system:
  - **No differences were observed during the crop cycle**. All phenological stages had the same start and end dates in both areas.
  - **Yield** → Slightly positive impact in the APV area (~2% higher), aspect that should be further analyzed in upcoming years.
- **Smaller grapes** in the APV area, but with slightly **higher sugar content**, **lower acidity** and **higher pH** than the grapes in the control zone.
- **More advanced technical maturity in the APV area** despite reduced light.

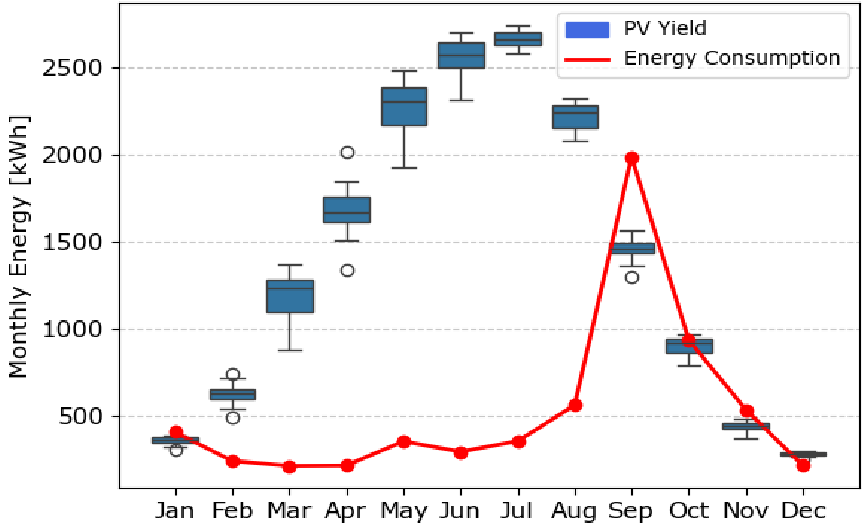


Results

Energy yield

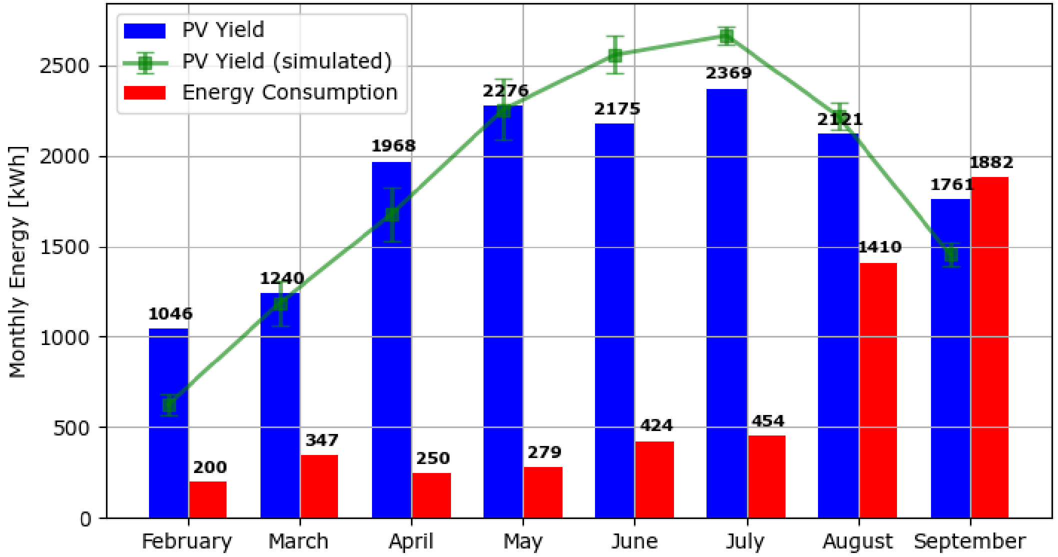
Simulations

- **PV yield**: 16400 ± 280 kWh/year (2.6 × winery demand); based on 19 years of weather data (2005 – 2023).
- **Consumption profile**: energy use is concentrated post-harvest, peaking between end August – October.



Actual data (2025)

- The APV installation has reduced grid dependence by **53%** since February.
- PV yield in line with the simulations, with the exceptions of:
  - February → Better performance (sunnier than normal)
  - Summer → Underperformance (higher thermal and soiling losses than expected)

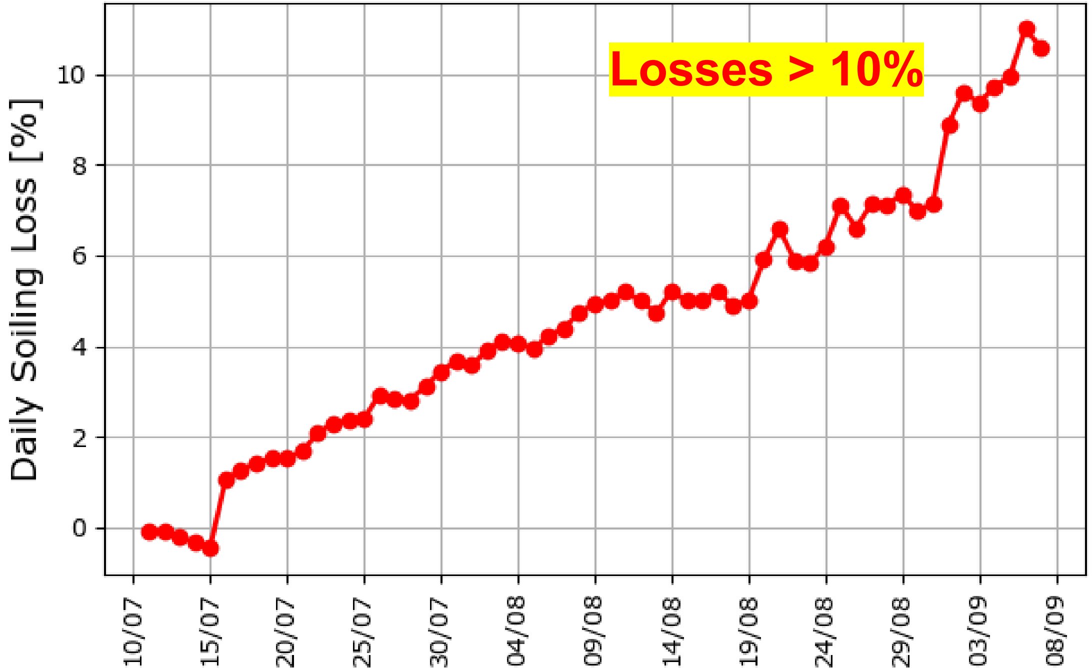


Results

Energy yield

Impact of soiling losses

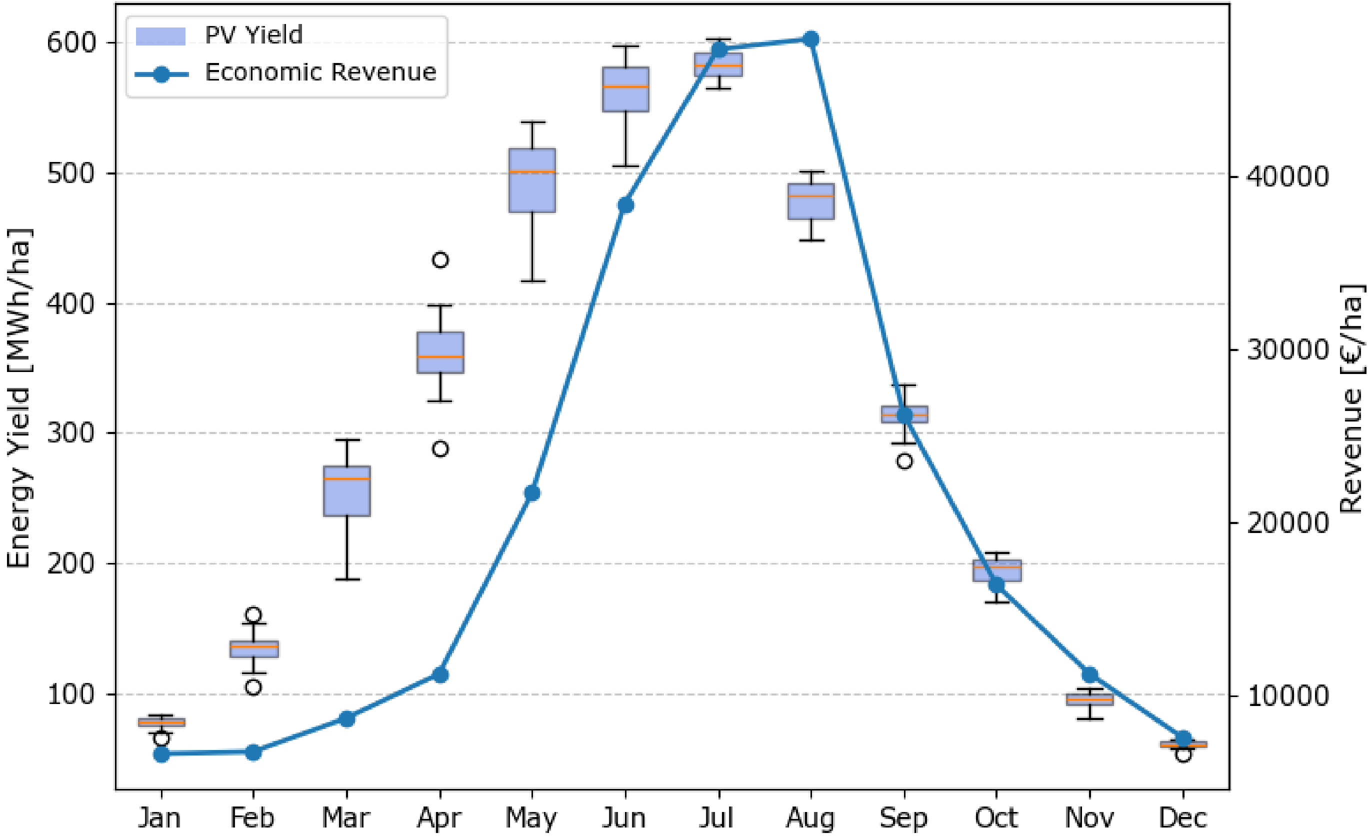
- **Agricultural activities** and **pollen** can greatly impact the impact of soiling in elevated APV systems.
- Several modules affected by **bird droppings**, which rain might not effectively fully clean.
- We have measured **losses higher than 10%** using reference cells, but the actual losses could be even higher due to the non-uniform distribution of them across the modules.



Results

Energy yield

Simulations: Potential Energy Yield and Economic Revenues per ha of APV in Laujar



** Costs were not considered.*

- Revenues calculated considering monthly average electricity prices in Spain from 2024*.
- Annual Energy Yield = 3630 MWh/ha
- Energy income: 250 k€/ha per year
- Wine-related revenue: 1.145 €/ha** [1]

  *** average value in Almería*

💡 **Energy income ≈ 250× wine revenue**
Agrivoltaics: a solution for climate change *AND* a new business model for farmers.

[1] Junta de Andalucía – Consejería de agricultura y pesca, "Caracterización del Sector Agrario y Pesquero de Andalucía 2023: https://ws142.juntadeandalucia.es/agriculturaypesca/caracterizacion-sector-agrario-pesquero-2023/index.html#p=1)

CONCLUSIONS

Conclusions

- The **motivation** of this **pilot APV system** was to **meet farmer's urgent needs** in **mitigating climate change impacts** on grape yield.
- **Microclimate benefits**: Positive effects observed, helping to mitigate the impacts of extreme weather conditions.
- **Crop performance**: No negative impact on yield or quality during the first year of operation.
- **Farmer benefits**: Reduced electricity bills and crop protection against excessive radiation and hail.
    - ❑ This pilot site demonstrated that **simultaneous energy and grape production** is feasible and can enhance yield.

Next steps

- Farmer ready to **scale up APV system with storage** for optimizing self-consumption.
- **Multi-year validation** of shading impacts on crop performance.
- Implementation of technical solutions to **optimize rainfall distribution** below panels.
- Assess **O&M challenges** (e.g., soiling) in elevated APV systems.

DLR's Expertise and Activities in Agrivoltaics

DLR

Experimental Infrastructure

- Currently installing a **tracked APV experimental system** in **Tabernas** (semi-arid climate), aimed to **optimize light management** for different crops.

🌍 International Collaboration and Leadership

- Active participants in **IEA PVPS Task 13 (Performance & Reliability of PV Systems)** and **Task 16 (Solar Resource)**.
- **Authors of the IEA PVPS Agrivoltaics Report** (scan the QR code).
- Engaged in the **IEA-PVPS Agrivoltaics Action Group** for knowledge exchange and best practices in the APV field.

Research Focus

- Investigating **climate change impacts** on APV performance, crop yield, and water use in **Spain**.
- Integrating **irradiance modelling,** and **PV energy–agriculture interaction studies** for APV.

IEA PVPS Agrivoltaics Report

Bettergy

DLR

Let's connect on LinkedIn

¡Muchas gracias por su atención!

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¡Abiertos a colaborar en agrivoltaica y análisis climático! ¡Contáctanos!

- **Dr. rer. nat. Natalie Hanrieder (Agrivoltaics Team Leader at DLR): Natalie.Hanrieder@dlr.de**
- **Dr. Álvaro Fernández Solas (Agrivoltaics and PV soiling scientist)**

¿Listo para una experiencia única en Almería? Visítanos y descubre lo que la Alpujarra almeriense y Cortijo el Cura pueden ofrecerte (y no te olvides de visitar el sistema AgriPV ☺!!!)

Cortijo el Cura
Eco - Bodega

¡Estás a un solo click!
Experiences - Cortijo El Cura Eco-Winery Laujar Wine Tasting Almeria