

Monitoring and assessment of elevated agrivoltaic systems in southern Spain

Álvaro Fernández Solas^{a,*}, Natalie Hanrieder^a, Anna Kujawa^a, Marta Sánchez-Piñero^b,
María José Martín-Palomo^{b,c}, Mireia Corell^{b,c}, Alfonso Moriana^{b,c}

^a German Aerospace Center (DLR), Institute of Solar Research, Calle Doctor Carracido 44, 04005 Almería, Spain

^b Agronomy Department, ETSIA, Universidad de Sevilla, Crta de Utrera Km 1, Sevilla E-41013, Spain

^c Unit Associated to the CSIC de Uso Sostenible del Suelo y el Agua en la Agricultura (US-IRNAS), Crta de Utrera Km 1, Sevilla E-41013, Spain

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ABSTRACT

Agrivoltaics is a promising solution to alleviate several challenges that society currently faces, such as the impact of climate change on agriculture, the continuous rise in energy demand, and the associated land use competition between renewable energy projects, particularly solar photovoltaic, and agricultural areas. This study assesses the performance of two experimental agrivoltaic installations in southern Spain, an important agricultural region that is increasingly affected by the impacts of climate change. An approach combining simulations and field measurements is used. The results show the agrivoltaics potential to reduce excessive radiation on crops, with annual reductions of up to 50 % beneath the panels. They also indicate a positive impact on the microclimate, including lower daytime temperatures of up to 2 °C on hot days and higher nighttime temperatures up to 0.5 °C. Relative humidity values were up to 4 percentage points lower underneath the panels, with site-dependent differences associated with the cultivated crop, growth conditions and irrigation practice. Energy and crop assessments at the demonstrators show performance ratio values higher than 0.9, and potential to maintain crop yield while saving water below the panels. The work also presents identified challenges and recommendations that can support advances toward enhancing performance assessment in agrivoltaics.

1. Introduction

The global population is projected to increase by about 50 million people each year until 2050 [1], which will intensify the challenges of ever-higher food and energy demand. However, these two demands are expected to grow at different rates. While most scenarios indicate that food demand will grow almost in proportion to population growth [2], energy demand is forecasted to increase even more rapidly. This accelerated growth is driven by factors such as increasing cooling needs due to more extreme temperatures, higher industrial energy consumption, the electrification of the transport sector, and the expansion of data centers and artificial intelligence (AI) use [3,4]. Consequently, meeting future energy needs while ensuring food security will require integrated strategies that simultaneously address efficiency, sustainability, and resilience across both sectors. Such strategies are essential to achieve several Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [5].

Since the 1990s, the adoption of global plans for sustainable development has promoted an exponential expansion of renewable energy (RE) systems to reduce the dependence on fossil fuels [5]. Among all RE technologies, photovoltaic (PV) energy has become nowadays the most widely installed and the fastest-growing, as reflected in global capacity figures: by the end of 2024, the cumulative PV capacity reached 2.26 TW, of which 47 % was installed between 2021 and 2024 [6]. One of the main drivers of this massive deployment of PV has been the exponential drop in its levelized cost of electricity (LCOE), with the global average LCOE of utility-scale PV systems decreasing by approximately 90 % between 2010 and 2024. This cost reduction has made PV the cheapest source of electricity generation in most regions of the world [7]. However, the installation of new large-scale systems is starting to cause land-use compatibility issues, as most suitable areas for such installations often correspond to fertile flat agricultural lands [8].

To tackle this emerging conflict, agrivoltaic (APV) systems, which are defined as the co-location of PV energy generation and agricultural production on the same area [9], have emerged as a promising solution to alleviate the competition for land use while simultaneously mitigating

* Corresponding author.

E-mail address: alvaro.fernandezsolas@dlr.de (Á. Fernández Solas).

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Nomenclature			
Abbreviations			
AC	Alternating Current	GDD	Growing Degree Day [$^{\circ}\text{C day}$]
AI	Artificial Intelligence	GHI	Global Horizontal Irradiance [W m^{-2}]
APV	Agrivoltaics	G_{POA}	Plane-of-Array Irradiance [W m^{-2}]
a.s.l.	above sea level	$G_{\text{POA,eff}}$	Effective Plane-of-Array Irradiance [W m^{-2}]
CAMS	Copernicus Atmosphere Monitoring Service	G_{STC}	Irradiance at STC [W m^{-2}]
Csa	Hot-summer Mediterranean climate (Köppen-Geiger classification)	H_{POA}	Plane-of-Array Radiation [Wh m^{-2}]
DC	Direct Current	IAM	Incidence-Angle Modifier [-]
ECMWF	European Centre for Medium-Range Weather Forecasts	k_t^*	Clear-sky index [-]
ERA5	Fifth generation ECMWF reanalysis	LCOE	Levelized Cost of Electricity [€ kW^{-1}]
LoRaWAN	Long Range Wide Area Network	M	Air Mass Modifier [-]
POA	Plane-of-Array	MBE	Mean Bias Error [kWh]
PV	Photovoltaics	nMBE	Normalized Mean Bias Error [%]
pp	Percentual point	nRMSE	Normalized Root Mean Square Error [%]
RDI	Regulated-Deficit Irrigation	PAR	Photosynthetically Active Radiation [$\mu\text{mol m}^{-2} \text{s}^{-1}$]
RE	Renewable Energy	P_{AC}	AC Power [kW]
SDG	Sustainable Development Goal	$P_{\text{AC, rated}}$	Nominal AC Power of the inverter [kW]
Sim	Simulations	P_{DC}	DC Power [kW]
STC	Standard Test Conditions	P_{STC}	DC Power at STC [kWp]
Symbols		PR	Performance Ratio [-]
a_i	Air mass coefficients of the PV module	$\text{PR}_{\text{T-corr}}$	Temperature-Corrected Performance Ratio [-]
AM	Air Mass [-]	R^2	Coefficient of determination [-]
AOI	Angle of Incidence [$^{\circ}$]	RH	Relative Humidity [%]
DAT	Days After Transplanting [day]	RMSE	Root Mean Square Error [kWh]
DHI	Diffuse Horizontal Irradiance [W m^{-2}]	SC	Soil Cover [%]
DLI	Daily Light Integral [$\text{mol m}^{-2} \text{day}^{-1}$]	SCR	Self-Consumption Ratio [%]
DNI	Direct Normal Irradiance [W m^{-2}]	SR	Soiling Ratio [-]
DW	Dry Weight [g]	SSR	Self-Sufficiency Ratio [%]
E_{AC}	AC Energy [kWh]	T	Air Temperature [$^{\circ}\text{C}$]
ET_c	Crop Evapotranspiration [mm day^{-1}]	T_c	Cell Temperature [$^{\circ}\text{C}$]
FW	Fresh Weight [g]	TF	Thermal Factor [-]
GCR	Ground Coverage Ratio [%]	Y_r	Reference Yield [kWh kWp^{-1}]
		Y_f	Final Yield [kWh kWp^{-1}]
		η_{inv}	Inverter efficiency [%]
		γ	Power temperature coefficient [$\% ^{\circ}\text{C}^{-1}$]

the adverse effects of climate change on crops and, in some cases, protecting farmers and communities from economic insecurity, offering a buffer against crop yields and market volatility [10,11]. In addition to these aspects, APV is also expected to increase social acceptance for PV project's deployment [12,13], and to simultaneously contribute to the achievement of multiple SDGs targets [14]. Although the concept of APV appeared for the first time in the 1980s [15], the market remained almost completely frozen until mid-2010s, when different countries began to establish policies, legal frameworks and initiatives to regulate and support the deployment of APV installations [16–21], as the first experimental installations had already showcased their potential benefits for both the agricultural and the energy sectors [22–24].

The synergies and co-benefits of APV systems have already been documented in the scientific literature [25,26]. From an agricultural perspective, the partial shading created by modules can alter the microclimate below and between them: daytime temperatures are reduced, nighttime temperatures are moderated, evapotranspiration declines, and wind speed is reduced. These changes can improve crop development and increase yields [27–30]. In addition, several studies have reported positive effects on soil quality, such as higher soil resistivity [31] and reduced salinity [32]. From the energy side, the presence of crops can lead to benefits in PV performance. Cooler module temperatures attributed to plant transpiration enhance PV efficiency [33,34]. In APV systems equipped with bifacial modules, albedo changes throughout the seasons and crop development stages can notably impact PV performance by affecting the irradiance that reaches

the rear side of the panels [35,36]. Notwithstanding all of the above mentioned, the co-existence of panels and crops can also lead to potential drawbacks, as APV sites can experience higher soiling losses than conventional ground-mounted PV systems. Agricultural activities, such as plowing, harvesting and fertilization, the presence of pollen and irrigation and pesticide use can increase the magnitude and persistence of soiling on the panels [37,38].

Previous APV studies involving lettuce and grapevines, the two crop species evaluated in this work, have analyzed their potential to benefit from the aforementioned synergies associated with open-field APV installations. In lettuce cultivation, Marrou et al. [24] paved the way by evaluating the growth and yield of lettuce plants in an APV installation in France under two different panel densities. They reported a 52 % reduction in yield relative to full-sun conditions at a shading level of 70 %. However, the yield decline was proportionally smaller than the reduction in photosynthetically active radiation (PAR), suggesting that negligible yield losses, or even yield increases, could be achieved when PAR availability is reduced by less than 30 %. More recently, a study conducted in Canada [39] evaluated lettuce growth under different PV technologies, including spectrally selective modules with several levels of transparency. The authors found that all APV technologies improved yield relative to full-sun conditions, highlighting the potential of APV systems to enhance crop resilience under heat stress. Among the technologies tested, crystalline silicon modules with 44 % transparency resulted in the greatest yield increases.

For grapevines, simulation-based studies provided insights into the

suitability and economic viability of integrating PV generation with viticulture. Williams et al. [40] evaluated both vertical and overhead APV systems for vineyards in a region of the United States and found that increases of 21 % in grape yield and 15 % in grape price would be required for the systems to become profitable. Strub et al. [41] found that APV systems were not profitable under the prevailing conditions in Germany in 2024. Regarding field experiments, most experimental systems consisted of elevated PV structures. Magarelli et al. [42] evaluated a fixed-tilt overhead system in Italy with a ground coverage ratio of 43 %. Their results revealed microclimatic benefits, including lower daytime air temperatures (up to 1.1 °C cooler) and higher soil moisture content, while grape yields below the panels increased up to 59.9 % compared with the reference full-sun conditions. A multi-year study conducted in northern Italy [43] assessed an APV system with a high panel density corresponding to a shading level of 75 %, evaluating its effects on microclimate, yield, and grape quality. The authors reported reductions in both air and soil temperatures beneath the panels, reaching up to 2 °C and 3 °C, respectively, during the hottest days of the growing cycle in August. In the first year, yields under the APV system were comparable to those observed in the unshaded control area. However, in the next two years, vines grown under the panels produced, on average, 9–14.3 % lower yields than those in the control zone. As indicated by Hanrieder et al. [44], additional APV installations over vineyards have been established in Mediterranean countries such as Spain and France. However, detailed performance data from these systems are scarce, limiting the current understanding of the synergies between PV energy production and grapevine cultivation.

Despite the increasing number of APV studies, some knowledge gaps remain. Most field experiments focused on a limited set of performance indicators, typically assessing crop productivity, microclimatic effects, or PV energy generation separately. There is a lack of comprehensive evaluations that integrate these dimensions within a unified framework, particularly under Mediterranean climatic conditions. Furthermore, although several APV installations have recently been established in Spain, detailed experimental evidence regarding their agronomic, environmental, energetic, and economic performance is still limited. Additional field-based studies are therefore required to improve the understanding of APV synergies and trade-offs across different crops, climatic conditions, and system configurations.

The true potential of APV installations can be accurately assessed only when the three core aspects, which are crop productivity, microclimate conditions and PV energy generation, are analyzed simultaneously and interpreted in an integrated framework. Therefore, integrated simulation platforms [45] and monitoring solutions [46,47] are essential to evaluate APV performance. Because APV systems vary widely in configuration (e.g., panel height, tilt, spacing, etc.), module technology, and crop type, a single, universally applicable monitoring scheme is unrealistic. This diversity further highlights the need for comprehensive assessment methodologies that can be adapted to specific APV configurations while generating datasets that support model development, system optimization, and cross-site comparisons [48,49].

To help fill these gaps, this study presents a comprehensive assessment of two elevated APV installations in southern Spain cultivating lettuce and grapevine, two crops of particular relevance to Mediterranean agriculture. The work combines field measurements and simulation models to evaluate crop performance, microclimate impacts, PV energy generation, and economic implications within a unified framework. By investigating two different cropping systems and validating modeling approaches with experimental data, the study contributes new empirical evidence from Mediterranean conditions and advances the methodological basis for APV design, monitoring and optimization. In addition, the work provides valuable insights by reporting the challenges encountered and lessons learned, which can then inform researchers, engineers, and APV developers during the design phase and support the optimization of operation in similar APV installations.

The paper is organized as follows. A complete description of the two

APV case studies, including information about the location (2.1), the configuration of the system (2.2), the crops and the monitoring system (2.3), is included in Section 2, which also details the methodology for the shading and PV simulations (2.4) and indicates the employed error metrics (2.5). Section 3 includes the shading simulations and analyses (3.1), the evaluation of the microclimate measurements (3.2) and the energy and crop assessments (3.3 and 3.4) at both installations. Section 4 presents the challenges and lessons learned of APV installations, focusing on Spain and discussing the difficulties encountered at both experimental sites. Finally, the conclusions of the work are summarized in Section 5.

2. Description of the sites and experimental methodology

2.1. Site description and climatic context

Two experimental APV installations located in Andalusia, southern Spain, are analyzed in this study. According to the Köppen-Geiger climate classification, both sites have a hot-summer Mediterranean climate (Csa), characterized by mild winters and hot summers with scarce precipitation. However, despite being situated within the same region and separated by a relatively short distance of 270 km, the two sites differ notably in terms of their surrounding environments. The Seville site is located in an urban area on the outskirts of the city, within one of the University of Seville campuses [50], in a valley of one of Spain's largest rivers at an altitude of only 21 m above sea level (m a.s.l.). In contrast, the Laujar de Andarax site (hereafter referred to as Laujar) is situated in a rural setting, in a fertile elevated valley at 949 m a.s.l., surrounded by high mountains [51]. This difference in altitude contributes to some differences in climatic conditions between the sites, with Laujar experiencing colder winters and milder summers compared to Seville. This is reflected in the lower annual mean temperature, as shown in Table 1, which summarizes the average climatic conditions at both locations.

2.2. Technical and agricultural configuration of the installations

Both APV installations consist on elevated PV structures designed to allow agricultural production below and in between the panels. Table 2 summarizes the main technical specifications and characteristics of both systems.

At the Seville site, the APV system consists of six monoposts with concrete foundations. Each monopost has 5 monofacial PV modules installed at 3 m height. Also, each pair of consecutive monoposts (see Fig. 1-left) is connected to an inverter, resulting in a modular system that facilitates scalability and maintenance. This latter aspect is also optimized by the possibility of manually adjust the tilt of the panels when needed due to agricultural management requirements. Regarding the agricultural side, experimental crop cycles with lettuce varieties (*Lactuca sativa* L.) were performed during 2024 and 2025. For the study, the system was divided into 9 plots to enable a comprehensive evaluation of different irrigation strategies along with the impact of the PV modules.

Table 1

Summary of the geographic and climatic characteristics of the two experimental APV sites. The climatic values have been derived from historical ERA5 data for the period 2005–2023 [52].

	Seville, Spain	Laujar, Spain
Coordinates	37°21'N; 5°56'W	36°58'N; 2°56'W
Altitude [m a.s.l.]	21	949
Annual accumulated global horizontal radiation [kWh/m ²]	1840	1940
Annual average temperature [°C]	18.9	14.3
Annual average wind speed [m/s]	2.3	1.8
Annual precipitation [mm]	506	499

Table 2

Main specifications of the experimental APV sites.

	Seville, Spain	Laujar, Spain
Commissioning year	2024	2025
Rated capacity	13.5 kWp	10.44 kWp
Module type	Monofacial	Bifacial
System's layout	Six monopost structures, each supporting five PV modules; two monoposts connected per inverter	18 modules arranged in 4 rows in a checkerboard layout with a 4.2 m pitch and 1.2 m spacing between modules
Orientation	South	Southeast (15° offset from due South)
Tilt	Adjustable (between 0° and 65°)	17°
Height	3 m	3 m
Inverter's topology	3 inverters with a nominal power of 5 kW and European efficiency of 98.0 %	One 10 kWn-inverter with European efficiency of 98.1 %
Crop	Lettuce	Wine grape
Ground coverage ratio	32 %	38 %
Planting pattern	0.2 m x 0.4 m	2 m x 2 m
Crop cycle period	September – November, Fall 2024; May – June, Spring – Summer 2025	March – August
Irrigation	Yes – Drip irrigation, 1.6 L h ⁻¹	No
Control area	3 control areas per treatment (x2), with 400 plants per area	1 control area with 28 plants

The total area of each plot was 63 m², of which 20 m² was occupied by the PV panels, resulting in a ground coverage ratio (GCR), defined as the ratio of PV panel area to total plot area, of 32 %. A completely randomized design was employed, comprising three distinct treatments:

control irrigation supplied at 100 % of the crop's evapotranspiration demand (ET_c), regulated-deficit irrigation (RDI) adjusted according to the phenological stage of the lettuce crop by reducing water supply to 50 % of ET_c during the rosette formation stage, and an APV treatment combining RDI with the shading effect of PV panels. Each treatment was replicated three times, with each individual plot containing a minimum of 400 plants arranged in seven crop rows spaced 1.5 m apart and surrounded by guard rows to minimize border effects. The soil had a sandy-loam texture and a depth of about 0.5 m. The top 0.3 m layer had a pH of 8.2, 12 % total limestone, and 1.2 % organic matter, while the 0.3–0.5 m layer had 16 % total limestone and 0.6 % organic matter. The soil was not saline, and thus did not limit crop development. Lettuce plants were grown in two seasons: *cv. Parrales* in fall 2024 and *cv. Celestina* in spring-summer 2025, both selected for their adaptability to local climate conditions. Transplanting occurred on September 19, 2024, and May 10, 2025, with plants spaced 0.20 m × 0.40 m on ridges covered with black plastic mulch. Irrigation was provided through two drip lines (1.6 L h⁻¹) with emitters spaced every 0.3 m. The harvests were conducted on December 3, 2024 and June 27, 2025. For the agronomic analyses, only the plants located in the four central rows of each plot were evaluated.

At the Laujar site, the APV system consists of a fixed structure with 18 bifacial PV modules arranged in a checkerboard pattern. The panels cover 38 % of the total surface (122 m²) and are mounted at a height of 3 m above ground level (Fig. 1 – right). The modules face southeast and are tilted 17°, while ground-screw foundations were used to avoid damaging the existing vines and to minimize soil compaction during and after installation. With regards to the agricultural side, full production non-irrigated Merlot grapevines with a planting pattern of 2 m x 2 m are located underneath the panels. To assess the impact of the shading from the modules on the crop yield, the yield of a control area of 4000 m² was also quantified. Within this control area, 28 plants located south of the installation were selected to track their development throughout the



Fig. 1. Aerial views of the experimental APV installations (top) and close-ups of the plants beneath them (bottom). Left: Seville site; Right: Laujar site.

crop cycle to evaluate potential differences in growth with respect to the plants located below the panels. The crop yield and fruit quality assessments were not limited to these 28 plants, but were based on random berry samples collected throughout the full control area. It is important to note that because this site consists of a single APV area and a single control area, treatment replication at the plot level was not available. Consequently, crop yield and quality parameters were analyzed descriptively, and no inferential statistical tests were performed to compare treatments. The differences between APV and control conditions should therefore be interpreted as indicative trends rather than statistically demonstrable treatment effects. The soil is a calcareous, gypsum-bearing sandy-loam with a pH of 8.1, low organic matter and field capacity, high permanent wilting point and moderate salinity (electrical conductivity of 2.3 dS m^{-1}), giving it a loose, poorly compacted structure that limits water retention and locks nutrients. Only ecological agricultural management practices are implemented to enhance nutrient availability (e.g. application of manure and other organic compounds to enrich the soil) and to prevent fungal diseases (e.g. use of sulfur to protect against powdery mildew). In the analyzed crop cycle, the first signs of budbreak were observed on March 30, 2025, and harvest took place on August 26, 2025.

The general configuration of the systems differs between the two sites, reflecting the different agronomic requirements: high-intensity and water-managed horticulture in Seville compared to perennial and rain-fed organic viticulture in Laujar.

2.3. Monitoring setup

Integrated monitoring systems are deployed at each APV site to assess the agronomic and the PV performance. Despite some differences with regards to the number and distribution of sensors, a similar architecture is used, allowing direct comparison between APV and control plots. For the Seville site, data of 2 consecutive lettuce cycles in fall 2024 and spring-summer 2025 were recorded. For the Laujar site, continuously measured data have been stored since its commissioning in March 2025, allowing to have data for the whole grapevine growing cycle (March – August) of 2025.

2.3.1. PV and microclimate

Table 3 and Table 4 show the different sensors used for monitoring both microclimate and PV performance parameters at the Seville and Laujar sites, respectively. All sensors were manufacturer-calibrated prior to deployment and operated following routine maintenance and

verification procedures; no recalibration was performed during the crop cycles because the original calibration certificates remained valid according to the manufacturers' guidelines.

At the Seville site, all the sensors, with the exception of the ones associated with the electrical PV parameters, are wired to two *Campbell Scientific®* dataloggers that store the data as 15-minute averages.

As at the Seville site, all sensors at Laujar, except the soiling sensor and the inverter, which upload data directly to the manufacturer's web service platform via a 3G connection, are wired to Campbell Scientific dataloggers. These dataloggers record the various parameters as 1-min averages, except for the soil probes, which store soil temperature and moisture as 15-min averages. Regarding data handling, raw files from the dataloggers are uploaded every 24 h to a cloud-based server via a router.

As previously mentioned, and as indicated in Table 3 and Table 4, both sites have at least an APV and a control plot to permit direct calculation of the shading effect of the modules on the microclimate and on the agricultural yield and quality. At Laujar, 28 control plants are identified and located 30 m south of the APV array. The Seville site includes a total of nine experimental areas, comprising three APV plots and six control plots with two different irrigation treatments.

At both sites, the distribution of microclimate and radiation sensors in the APV area is represented by three independent measurement locations, providing redundancy of the different parameters. Fig. S1 and Fig. S2 in the Supplementary Information show maps of both sites with the sensor distribution.

2.3.2. Agronomic monitoring

The agronomic performance at both sites was assessed through a set of yield-related and quality-related parameters. The measurements and evaluated indicators were customized for each crop and farming management.

At the Seville site, where lettuce (*Lactuca sativa L.*) plants were cultivated, the following parameters were measured:

- **Stomatal conductance.** Leaf-level gas exchange was measured with a portable infrared gas analyzer (*LI-6400XT*, *LI-COR Biosciences*) on specific days for different plants in the APV, RDT and control plots. Measurements were taken on days 14, 22, 33, 50 and 61 after transplanting in 2024, and on days 16, 23, 30 and 47 in 2025 providing a temporal profile of the plants' capacity to regulate water loss and CO_2 uptake.

Table 3

List of sensors and measured microclimate and PV-related parameters at the Seville site.

Sensor model (Manufacturer)	Measured parameter(s)	Quantity	Placement	Resolution / Accuracy	Sampling frequency / Storing frequency
ATMOS 14 (METER)	Air temperature, relative humidity and barometric pressure	9 (3 under the panels and 6 in the control areas)	30 cm height at the center of each plot	Air temperature: $0.1 \text{ }^\circ\text{C} / \pm 0.2 \text{ }^\circ\text{C}$; Relative humidity: $0.1 \% / \pm 2 \%$	1 min / 15 min
TEROS 21 (METER)	Soil matric potential (availability of soil water to plants)	9 (3 under the panels and 6 in the control areas)	At a 15 cm depth at the center of each plot	$0.1 \text{ kPa} / \pm 10 \%$	1 min / 15 min
SQ-421X (Apogee)	Photosynthetically active radiation (PAR)	7 (6 under the panels at two different positions and 1 in a control area)	Within the APV plots, at distances of 1.5 m and 3 m from the second monopost, and at a height of 30 cm	N/A / $\pm 5 \%$ (calibration for uncertainty)	1 min / 15 min
SMP3 (Kipp & Zonen)	Plane-of-array global irradiance, global tilted irradiance at rear side and albedo irradiance	3	Two sensors are mounted on one monopost with the same panel tilt and orientation. The albedo sensor is installed in a control area at a height of 3 m	$<0.1 \text{ W/m}^2 / \pm 1 \%$ (non-stability: change/year)	1 min / 15 min
Thermistor ST-110-SS (Apogee)	Module temperature (front and rear)	2	Placed on the surface of one of the panels	$0.01 \text{ }^\circ\text{C} / \pm 0.1 \text{ }^\circ\text{C}$	1 min / 15 min
SAJ R5-5K-T2 Inverter	DC and AC voltage, current and power	3	N/A	N/A	5 min / 5 min

Table 4

List of sensors and measured microclimate and PV-related parameters at the Laujar site.

Sensor type	Measured parameter(s)	Quantity	Placement	Resolution / Accuracy (Uncertainty)	Sampling frequency / Storing frequency
Weather station MetSENS 6000 (Campbell Scientific)	Air temperature, relative humidity, wind speed and direction, barometric pressure and precipitation intensity	4 (3 under the panels and 1 in the control zone)	At three different positions below the panels. At 2 m above ground	Air temperature: 0.01 °C / ± 0.3 °C; Relative humidity: 0.1 % / ± 2 %; Wind speed: 0.01 m/s / ± 3 %; Barometric pressure: 0.1 hPa / ± 0.5 hPa	5 s / 1 min
EP100GL-08 (EnviroPro)	Soil moisture and soil temperature	4 (3 under the panels and 1 in the control area)	At three different positions below the panels and at a depth of 80 cm, with measurements at 10 cm intervals	Moisture: 0.01 % / ± 2 %; Temperature: 0.01 °C / ± 1 %	30 s / 15 min
ML-020P (EKO)	Photosynthetically active radiation (PAR)	4 (3 under the panels and 1 in the control area)	At three different positions below the panels and at a height of 1.5 m	0.1 $\mu\text{mol} \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ / calibration certificate issued in December 2023	5 s / 1 min
CMP10 (Kipp & Zonen)	Global horizontal irradiance (GHI)	4 (3 under the panels and 1 in the control area)	At three different positions below the panels and at a height of 1.5 m	<0.1 W/m ² / ± 0.5 % (non-stability: change/year)	5 s / 1 min
Reference cells SOZ-03 (NES Sensors GmbH)	Rear and front side tilted global irradiance	2	Adjacent to one of the central panels with the same tilt.	0.01 W/m ² / calibration certificate issued in September 2024	5 s / 1 min
RT1 (Kipp & Zonen)	Front tilted global irradiance and module temperature	1	Adhered to the corner of one of the central panels (irradiance sensor) and to the back of the panel (temperature sensor)	Irradiance: 0.1 W/m ² / ± 3 %; Module temperature: 0.1 °C / ± 1 °C	5 s / 1 min
ARES (FracSun®)	Soiling loss	1	At the southwest corner of the system – same height and tilt of panels	0.1 % / ± 0.5 %	2 min / 1 day
SUN2000-10KTL-M1 (Huawei)	AC voltage, current and power	1	N/A	N/A	5 min / 5 min

- **Soil-cover assessment.** The proportion of the soil covered by the plant's structure was measured weekly with *Canopeo* [53]. Photographs were analyzed to obtain the percentage of covered area, which is an indicator of crop growth and development.
- **Fresh weight (FW) per plant.** The fresh weight of one plant per plot (APV, RDI and control) was measured with a calibrated electronic precision balance (± 0.01 kg) on 6 different days in 2024 (days 13, 33, 48, 55 and 62 after transplanting) and on 3 days in 2025 (days 16, 30 and 47 after transplanting), and at final harvest. These measurements allowed the construction of growth curves, the detection of any water-stress effects on biomass accumulation and differences between the development of plants in the different zones.
- **Dry weight (DW) per plant.** The same plants collected for the fresh weight measurements were evaluated. After those measurements, the samples were then dried in a forced-air drying oven at 65 °C until a constant weight was reached, after which the dry biomass was recorded.
- **Final yield.** At the end of each crop cycle, all marketable produce was harvested and weighed on a calibrated electronic precision balance (± 0.01 kg). The total fruit weight was extrapolated to t ha⁻¹.
- **Number of leaves.** At final harvest, 6 lettuce heads per plot were selected and the leaves of each head were counted manually. This morphological parameter can be linked to marketability and consumer preference.
- **Growing Degree Days (GDD).** This indicator is a measure of the cumulative heat units required for plant growth, calculated as the difference between daily air temperature and a base temperature of 10 °C. Daily GDD were added throughout the crop cycle to obtain the total accumulated GDD for each treatment.
- **Applied water depth.** The drip-irrigation flow meters recorded the volume of water delivered at each irrigation event. These volumes were summed over the crop cycle and converted to a depth (mm) by dividing by the irrigated area. This metric was used as input for the calculation of the irrigation water productivity.

- **Irrigation water productivity.** It represents the ratio between the amount of applied water with irrigation and the final yield. It is expressed in kg/m³. The higher its value the better the water productivity.

At the Laujar site, where Merlot wine grapes are cultivated, the focus of the agronomic monitoring was on the post-harvest measurements. For the quality analyses in a certified laboratory, about 500 berries per plot were sampled. The post-harvest measurements conducted (both yield-related and quality-related) are listed below:

- **Final yield.** All the harvested clusters from both plots (APV and control) were weighed on a balance (± 10 g) and extrapolated to t ha⁻¹.
- **Mean-berry weight.** From the harvested clusters of each plot, 100 berries were randomly selected and weighed on a calibrated electronic balance (± 0.001 g). The results were extrapolated to estimate the mean-berry weight in g.
- **°Brix.** Brix degrees represent the soluble-solid content. The measurements were conducted with a manual refractometer (*HI 96801 – Hanna Instruments*) at ambient temperature.
- **pH and total acidity.** These parameters represent the degree of grape maturity and the amount of organic acids present in the grapes, respectively. They were measured with an automatic titrator (*Titralab AT1000 – Hach*).

As above mentioned, at the Seville site, where irrigation is used, an additional assessment of water productivity was conducted, aiming to identify whether the shading effect could reduce irrigation requirements without compromising final yield. At the Laujar site, the agronomic results focused on a single crop cycle, so further evaluation will be needed in upcoming experimental campaigns. These future trials should evaluate crop performance under shading over medium- and long-term periods, considering interannual weather variability as well.

2.4. Modelling approaches

2.4.1. Shading model

A ray-tracing-based methodology was employed to model the impact of the PV system on the radiation at crop height by simulating global horizontal irradiance (GHI), using the approach presented in [54] and applied in [55]. This methodology uses *Radiance*, a lighting visualization system that employs backward ray-tracing algorithms [56]. First, virtual representations of the APV sites were created. Then, the necessary inputs for the ray-tracing calculations were introduced: (i) historical irradiance data from the Copernicus Atmosphere Monitoring Service (CAMS) [57], (ii) the sun's positions for the corresponding timestamps were calculated using the “*get_solarposition*” function from *pvlb*'s Python library [58]. These two input datasets were then used by *Radiance* to generate the light sources, i.e. the sun and the sky dome. Finally, a grid of sensors was established at the crop canopy level, with a spatial resolution of 5 cm in both directions, to indicate the locations where the radiation was to be evaluated.

The outputs of the ray-tracing simulations, i.e. the GHI at each pixel of the grid, were then processed to generate heatmaps that represent the shading factor. This indicator accounts for the ratio between the radiation at the sensor's positions in the APV plot and the radiation received on a point in the control unshaded plot and it is calculated through equation (1). The lower its value, the higher the radiation reduction.

$$\text{Shading Factor} = \frac{\sum_k \text{GHI}_{APV}}{\sum_k \text{GHI}_{\text{control}}} \quad (1)$$

where GHI_{APV} and $\text{GHI}_{\text{control}}$ are the GHI at a position within the APV plot and at the unshaded control plot, respectively.

2.4.2. PV model

The energy performance of the systems was assessed through a comprehensive model that enables the estimation of the final yield without the need for on-site measurements. The sources for the required model inputs were selected to facilitate the potential replication of this approach in future studies. Accordingly, solar irradiance and weather data (air temperature, wind speed, and precipitation) for both sites were obtained from CAMS [57] and ERA5 [52], respectively, with the data downloaded from the CAMS Atmosphere Data Store [59]. The intermediate calculations involved in this methodology included the derivation of plane-of-array (POA) irradiance from the values of the different irradiance components, the PV modules' configuration (tilt and azimuth), and the sun's positions (zenith and azimuth) through transposition models implemented in the *pvlb* functions “*get_total_irradiance*” and “*pvinfos_timeseries*” for monofacial (front POA irradiance) and bifacial (front and rear POA irradiance) modules, respectively [58].

To account for losses, four factors were calculated:

- **Angular losses:** These are represented by the incident angle modifier (IAM), which depends on the angle of incidence (AOI). For the calculation of the IAM, which ranges between 0 and 1, the physical model presented in [60] was employed.
- **Spectral losses:** These were computed from the air mass modifier (M), which represent the spectral correction factor. It was computed using empirical polynomial coefficients through equation (2):

$$M = a_0 + a_1 \cdot AM + a_2 \cdot AM^2 + a_3 \cdot AM^3 + a_4 \cdot AM^4 \quad (2)$$

where AM represents the relative air mass calculated using thekasten-Young model [61], and a_i [$i = 1, 2, 3, 4$] are the empirical module-dependent coefficients. As the specific module coefficients were unavailable, typical coefficients of crystalline-Si modules based on the Sandia database [62] were used: $a_0 = 0.93$, $a_1 = 0.06$, $a_2 = -0.015$, $a_3 = 0.002$, $a_4 = -0.0001$.

- **Temperature losses:** These were calculated using the Sandia Array Performance Model [62], with coefficients associated with open rack mounting and glass/glass modules for both sites. The cell temperature was then used in conjunction with the temperature coefficient of the modules in the PVWatts model [62] to obtain the thermal factor.
- **Soiling losses:** These were calculated using the Kimber model [63], with a soiling rate of 0.15 % and a cleaning threshold of 0.5 mm of daily accumulated rain. These model inputs were customized based on measured soiling data collected at the Laujar site, which were used to assess and minimize deviations between Kimber model estimations and observed soiling behavior. Monthly average values based on 10 years of precipitation (2015–2024) from ERA5 [52] were used.

The DC power (P_{DC}) was calculated using the PVWatts model, incorporating to it the previously calculated angular and spectral losses to derive the effective irradiance received by the modules, and soiling losses as a loss factor, known as soiling ratio (SR), which is equal to 1 – soiling loss. Other residual system losses (e.g. module mismatch, cable losses, etc.) were represented through a conservative fixed derate factor of 2 %, accounting for minor losses not otherwise specifically modelled. This value is consistent with commonly adopted assumptions for residual electrical losses and was selected to avoid double-counting losses already explicitly estimated through the temperature, angular, spectral and soiling sub-models [64,65]. Considering all of these aspects, equation (3) was used to compute P_{DC} .

$$P_{DC} = P_{STC} \cdot \frac{G_{POA,eff}}{G_{STC}} \cdot TF \cdot SR \cdot (1 - \text{derate factor}) \quad (3)$$

where P_{STC} represents the DC capacity of the system at standard test conditions (STC) ($G = 1000 \text{ W/m}^2$, $T_c = 25^\circ\text{C}$ and AM 1.5), $G_{POA,eff}$ is the effective plane-of-array irradiance calculated through equation (4), TF is the thermal factor, which represents the temperature losses, calculated through equation (5), and SR is the soiling ratio.

$$G_{POA,eff} = G_{POA} \cdot IAM \cdot M \quad (4)$$

$$TF = 1 + \gamma \cdot (T_c - T_{c,STC}) \quad (5)$$

where γ is the power temperature coefficient of the modules expressed in $\%^\circ\text{C}^{-1}$, T_c is the cell temperature in $^\circ\text{C}$, and $T_{c,STC}$ is the cell temperature at STC, 25°C .

The AC power (P_{AC}) was then obtained by considering the inverter efficiency and the rated power of the inverter(s) to account for potential clipping effects [66] using equation (6). Since inverter efficiency curves were unavailable for both sites, inverter performance was represented using the manufacturer-reported European efficiency values, while rated inverter power was used to model clipping. Finally, the energy yield was calculated by integrating the AC energy over time.

$$P_{AC} = \min(P_{DC} \cdot \eta_{inv}, P_{AC, rated}) \quad (6)$$

where η_{inv} represents the inverter efficiency (European weighted efficiency) and $P_{AC, rated}$ indicates the total nominal power of the inverters.

The overall performance of the systems was also quantified through the calculation of the performance ratio (PR) [67], which can be defined as the ratio of the actual AC energy yield of a PV system to the theoretically achievable energy under the measured irradiance conditions. It is a unitless metric that reflects the combined impact of all system losses (temperature losses, angular losses, soiling losses, DC/AC conversion losses, etc.) on PV performance. It is commonly expressed through equation (7):

$$PR = \frac{Y_f}{Y_r} = \frac{\sum_k \frac{P_{AC,k}}{P_{STC}}}{\sum_k \frac{G_{POA,k}}{G_{STC}}} = \frac{E_{AC} \cdot G_{STC}}{P_{STC} \cdot H_{POA}} \quad (7)$$

where Y_f and Y_r are the final and the reference yields, respectively, expressed in kWh/kW_p ; P_{AC} and E_{AC} are the AC power [kW] and the AC

energy [kWh], respectively; G_{POA} and H_{POA} represent the plane-of-array irradiance [$W\ m^{-2}$] and the plane-of-array radiation [$Wh\ m^{-2}$], respectively.

Additionally, the temperature-corrected PR [68] was calculated to remove the effect of temperature by using equation (8).

$$PR_{T-corr} = \frac{\sum_k \frac{P_{AC_k}}{G_{POA_k}}}{\sum_k \frac{G_{POA_k}}{G_{sc}} \bullet (1 + \gamma \bullet (T_{c,k} - T_{c,sc}))} \quad (8)$$

For the Laujar site, additional simulations were performed using on-site measurements of front- and rear-side solar irradiance, module temperature, and soiling to model energy generation and assess the extent to which measured inputs reduced uncertainties and improved agreement with monitored system performance.

2.5. Error metrics

To analyze the accuracy of the energy simulations, three different statistical indicators were calculated to evaluate the agreement between the simulated monthly energy estimations and the measured monthly energy yield at both sites.

The mean bias error (MBE) provides the average deviation of the simulations from the measurements. Negative values indicate that the simulations underestimate the measured energy, whereas positive ones show overestimation of the energy generation.

$$MBE = \frac{1}{N} \sum_{k=1}^N (E_{measured,k} - E_{simulated,k}) \quad (9)$$

To facilitate comparison across datasets with different magnitudes, the normalized MBE (nMBE) is also calculated as a percentage of the mean measured value.

$$nMBE = \frac{MBE}{E_{measured}} \bullet 100 \quad (10)$$

The root mean square error (RMSE) indicates the average prediction error. Its value is always positive, and the lower its value the better the simulations match the measurements.

$$RMSE = \sqrt{\frac{1}{N} \sum_{k=1}^N (E_{measured,k} - E_{simulated,k})^2} \quad (11)$$

where N is the total number of months considered for the error calculations.

Similarly to the MBE, the normalized RMSE is also computed, expressed as a percentage of the mean measured value.

$$nRMSE = \frac{RMSE}{E_{measured}} \bullet 100 \quad (12)$$

The coefficient of determination (R^2) shows how the simulations agree with the measurements, with a value of 1 indicating a perfect agreement.

$$R^2 = 1 - \frac{\sum_{k=1}^N (E_{measured,k} - E_{simulated,k})^2}{\sum_{k=1}^N (E_{measured,k} - \bar{E}_{measured})^2} \quad (13)$$

3. Results

In this section, the results of the integrated assessment of APV performance, which combine simulations and measurements, at both sites are presented.

3.1. Radiation and shading evaluation

The impact of the PV modules on the received radiation at crop level was assessed through the application of a previously validated shading model [54] together with on-site measurements from PAR sensors at the

two APV installations. The model was used to estimate the spatial and temporal distribution of shading across the crop area and to compare the two APV configurations. Available field measurements were used to verify the consistency of simulated irradiance patterns at representative crop locations.

Fig. 2 shows the annual accumulated shading factor plot for one monopost-pair at the Seville site in 2024 (Fig. 2- left) and the accumulated shading factor plot for the Laujar site during the 2025 crop cycle (Fig. 2- right). It can be seen that at both sites, the lowest shading factors are obtained in the areas located beneath the panels, with values below 0.6 (i.e. 40 % radiation reduction) and local peaks reaching up to a 50 % radiation reduction in the vicinity of structural elements. In the central region in between posts (Seville site) and in between rows (Laujar site), accumulated shading factors fluctuate around 0.8 (i.e. 20 % radiation reduction).

The consistency between simulated and measured irradiance was evaluated using field observations at representative points within each installation (APV-1 in Seville and the pyranometer in zone A in Laujar; see Figs. S1 and S2, respectively) under different sky conditions. For the Laujar site, where both simulated and measured irradiance were available as GHI, error metrics (RMSE, MBE, and R^2) were computed to assess model agreement. For the Seville site, only PAR measurements were available, while the model outputs GHI; therefore, a direct quantitative comparison in absolute terms was not possible and the analysis was limited to normalized profiles to evaluate the temporal irradiance dynamics. Fig. 3 presents the comparison between simulated and measured irradiance for both sites under clear-sky (17 October 2025 and 27 August 2025 for Seville and Laujar sites, respectively) and cloudy conditions (16 October 2025 and 25 August 2025 for Seville and Laujar sites, respectively). The classification of days into clear-sky and cloudy conditions was based on the clear-sky index (k_t^*), defined as the ratio between the daily-integrated measured GHI and the corresponding clear-sky GHI obtained from a clear-sky model. In this work, the Ineichen clear-sky model [69] implemented in the pvlib function “*Location.get_clearsky*” was used to compute the reference clear-sky irradiance. The clear-sky index is expressed as:

$$k_t^* = \frac{\sum GHI_{measured}}{\sum GHI_{clear-sky\ modelled}} \quad (14)$$

A day is considered a clear sky day if the k_t^* is higher than 0.75, and a cloudy day otherwise.

The results indicate that the model can reproduce the temporal evolution of irradiance at the monitored locations, with quantitative agreement at the Laujar site confirmed by the error metrics, with R^2 higher than 0.75 and RMSE values below $100\ W/m^2$. It should be noted that the available measurements are limited to single-point observations, and therefore do not allow a full spatial validation of the simulated shading field.

The impact of the APV system on the radiation at crop level was further quantified using in situ measurements from PAR sensors at both sites. The measurements were processed to calculate the daily light integral (DLI) [70], which represents the daily integral of PAR radiation and is a metric typically used to identify the light requirements of crops [71]. Fig. 4 and Fig. 5 shows the comparison of the DLI obtained in the control plot and the average DLI registered by the different PAR sensors in the APV area.

At the Seville site, 2 different crop cycles are represented in Fig. 4. Significant differences between the cycles can be observed. During the cycle in fall 2024, the shading impact was larger during its first half, with peak DLI reductions larger than 60 %. Throughout the cycle, the shading factor experienced an upward trend, being the plants in their final growth stage affected by shading factors of about 0.8 (i.e. a DLI reduction of 20 %). In the spring-summer 2025 cycle, more constant daily shading factors were registered, with a median value of 0.51. It is also of interest to analyze this relative DLI reduction along with the

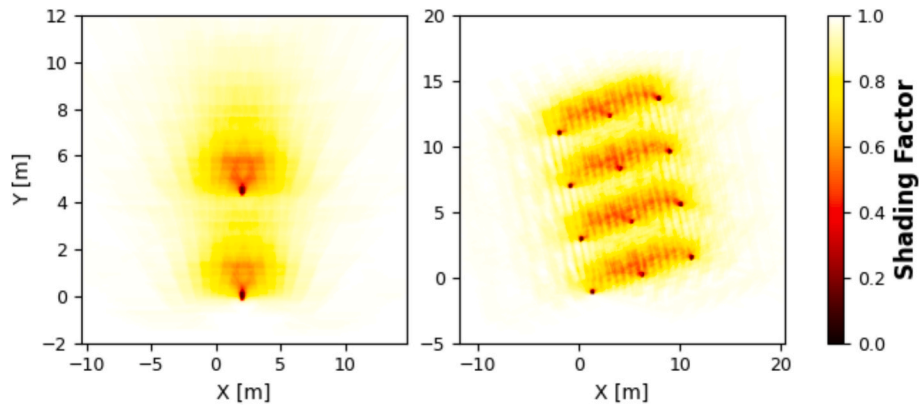


Fig. 2. Accumulated spatial shading factor patterns at the Seville site (left) and the Laujar site (right).

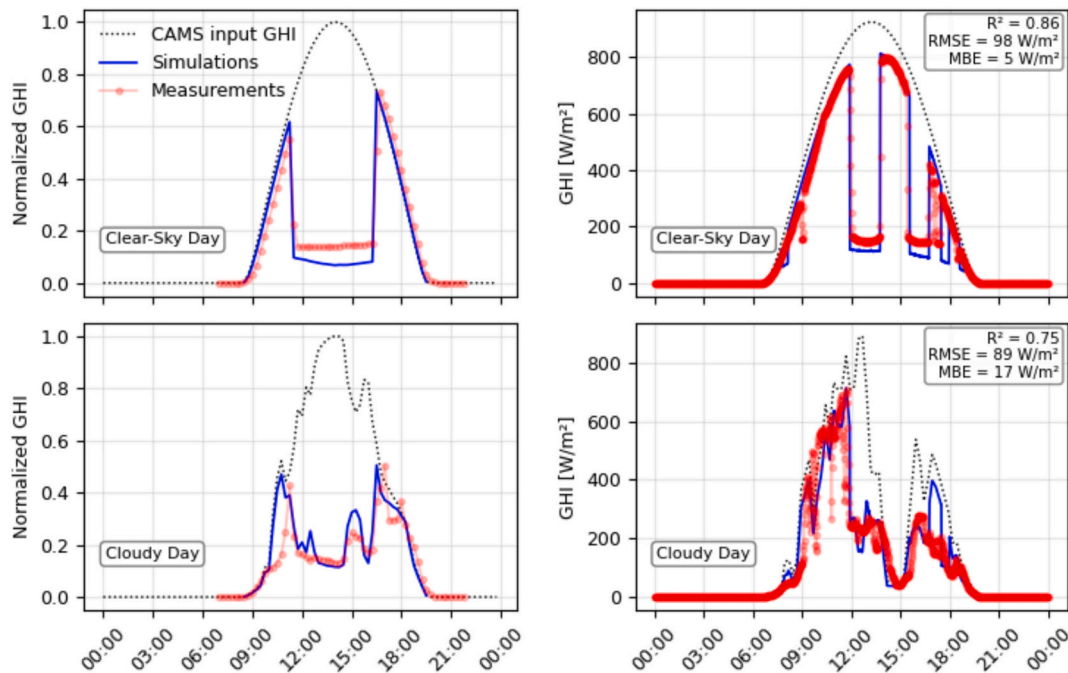


Fig. 3. Comparison between simulated and measured irradiance at representative monitoring locations for both sites (left column – Seville; right column – Laujar). Daily irradiance profiles are shown for a clear-sky day (top) and a cloudy day (bottom). The dotted grey line represents GHI from CAMS [57], while the blue and red lines correspond to simulated and measured irradiance, respectively. At the Laujar site, simulated and measured GHI values are directly comparable, and quantitative performance metrics are included. At the Seville site, measured PAR data were used instead of GHI; therefore, both datasets were normalized to enable comparison of temporal irradiance dynamics. Simulation time resolution was reduced to 15 min (Seville) and 1 min (Laujar) to match measurement granularity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

absolute DLI values, being these, in the APV plot, close to $30 \text{ mol m}^{-2} \text{ day}^{-1}$ in the spring-summer cycle and between 10 and $20 \text{ mol m}^{-2} \text{ day}^{-1}$ in the fall cycle. Although previous studies did not specifically identify clear optimal DLI values for outdoor lettuce cultivation, experimental works [72,73] suggested that increasing DLI can promote lettuce growth, but this depends on the combination of instantaneous PAR radiation and photoperiod. With that in mind, DLI values above $40 \text{ mol m}^{-2} \text{ day}^{-1}$ can become harmful to plants; and values between 30 and $40 \text{ mol m}^{-2} \text{ day}^{-1}$ can be considered optimal during spring cycles with longer daytime durations. The DLI range between 15 and $30 \text{ mol m}^{-2} \text{ day}^{-1}$ can be classified as acceptable for promoting lettuce growth.

Fig. 5 represents the DLI evolution at the Laujar site during the 2025 crop cycle. It can be seen how the APV system mitigated the effect on excessive DLI values. According to established guidelines, the optimal DLI for grapevines ranges from 20 to $30 \text{ mol m}^{-2} \text{ day}^{-1}$ [74]. Notably, DLI values consistently exceeded $20 \text{ mol m}^{-2} \text{ day}^{-1}$ in both the APV and

control zones, except on very cloudy days, throughout the crop cycle (March to August). During the berry growth-ripening stage, which happened between mid-June and late August, the DLI in the APV zone remained close to the upper threshold, with DLI values slightly exceeding $30 \text{ mol m}^{-2} \text{ day}^{-1}$. The shading factor fluctuated around 0.6 (i.e. a DLI reduction of 40 % compared to the control zone) during the whole period, with a median value of 0.57.

3.2. Microclimate analysis

The effects of the APV systems on the microclimate at both sites were analyzed by comparing the air temperature (T) and relative humidity (RH) measurements taken below the panels in the APV plots and at the unshaded control plots, differentiating between daytime and nighttime.

Fig. 6 shows the differences in T (top row plots) and RH (bottom row plots) over the two lettuce cycles at the Seville site. In both cycles (fall

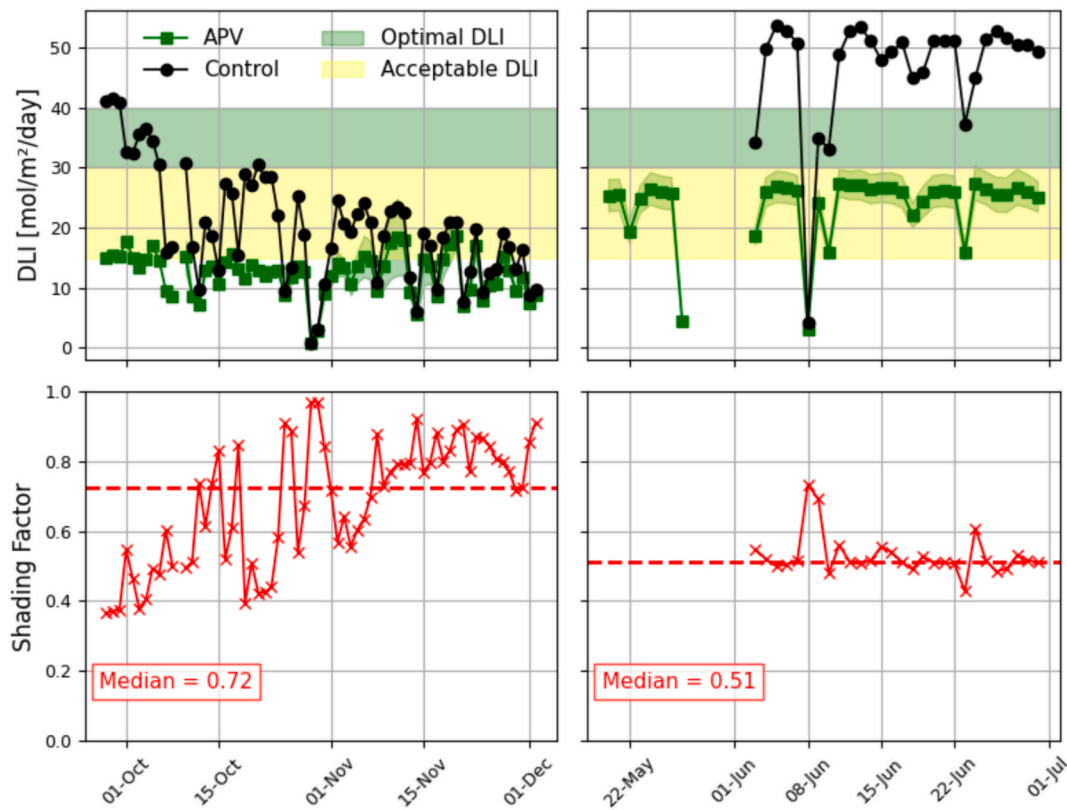


Fig. 4. DLI profiles (top plots) and shading factor (bottom plots) at the Seville site over the two experimental lettuce crop cycles (left column – fall 2024; right column – spring-summer 2025 cycle). The shaded area surrounding the green line in the top plots indicates the measurement range (i.e., the minimum–maximum values) recorded by the different sensors within the APV zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

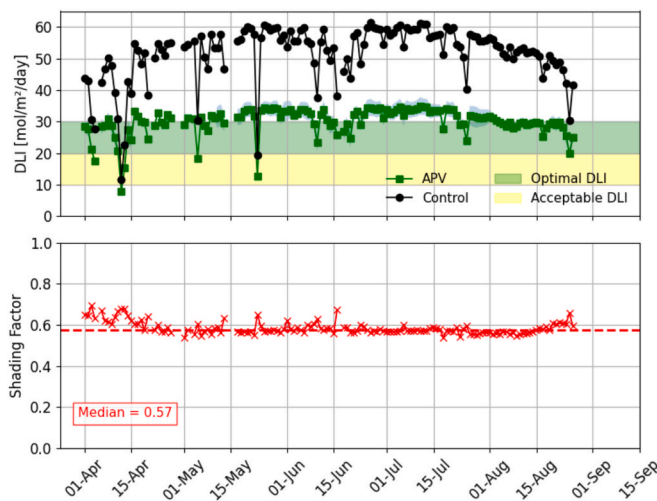


Fig. 5. DLI profile (top plot) and shading factor evolution (bottom plot) at the Laujar site for the crop cycle from 30 March 2025 to 26 August 2025. The shaded area surrounding the green line in the top plots indicates the measurement range (i.e., the minimum–maximum values) recorded by the different sensors within the APV zones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2024 and spring-summer 2025), lower temperatures were recorded below the panels during the daytime, with peak differences ranging from -0.6°C to -0.9°C . Specifically, during the spring-summer 2025 cycle, mean temperatures were up to 0.9°C lower, with instantaneous differences reaching up to 2°C in the early afternoon on days when mean

daytime temperatures exceeded 30°C . In contrast, during the fall cycle, temperature differences were on average about 0.3°C lower. During nighttime, similar temperature values were observed in both the APV and control plots for the spring-summer 2025 cycle. In contrast, the fall 2024 cycle showed slightly higher temperatures (up to 0.5°C) below the panels, particularly in its second half. With regard to RH differences, lower values (up to -4% and -2% in the 2024 and 2025 cycles, respectively) were recorded in the APV plots, with larger differences during nighttime. These disparities in RH increased throughout the fall 2024 cycle reaching values about -4% , while they remained almost steady during the spring-summer 2025 cycle. It should be also noted that despite lower daytime temperatures in the APV area, actual vapor pressure was also reduced by values up to 0.1 kPa relative to the control, indicating lower atmospheric moisture content below the panels (see Fig. S3 in the Supplementary Information). Consequently, the reduction in moisture content outweighed the RH increase expected from cooling, resulting in lower daytime-average RH.

A similar pattern was observed at the Laujar site, as shown in Fig. 7. Regarding T, compared to the Seville site, it was clearer that values were lower during the daytime, peaking at -0.8°C in mid-July, and higher during the nighttime, fluctuating around $+0.5^{\circ}\text{C}$. For RH, daytime values were similar to those measured in the plot without panels, with a slightly increased of RH below the panels at the end of the cycle. Conversely, lower nighttime RH values, reaching up to -4.2 pp in the second half of May, with a pattern similar to the RH values of the Seville site, were found. The difference between both locations in the daytime RH pattern suggested an effect of plant development considering different irrigation practices at both sites. The Laujar site was not irrigated and the light increase in daytime RH at the end of the cycle may indicate a moderation of plant water stress because of the decrease in radiation and T. This could improve plant transpiration due to a lowered

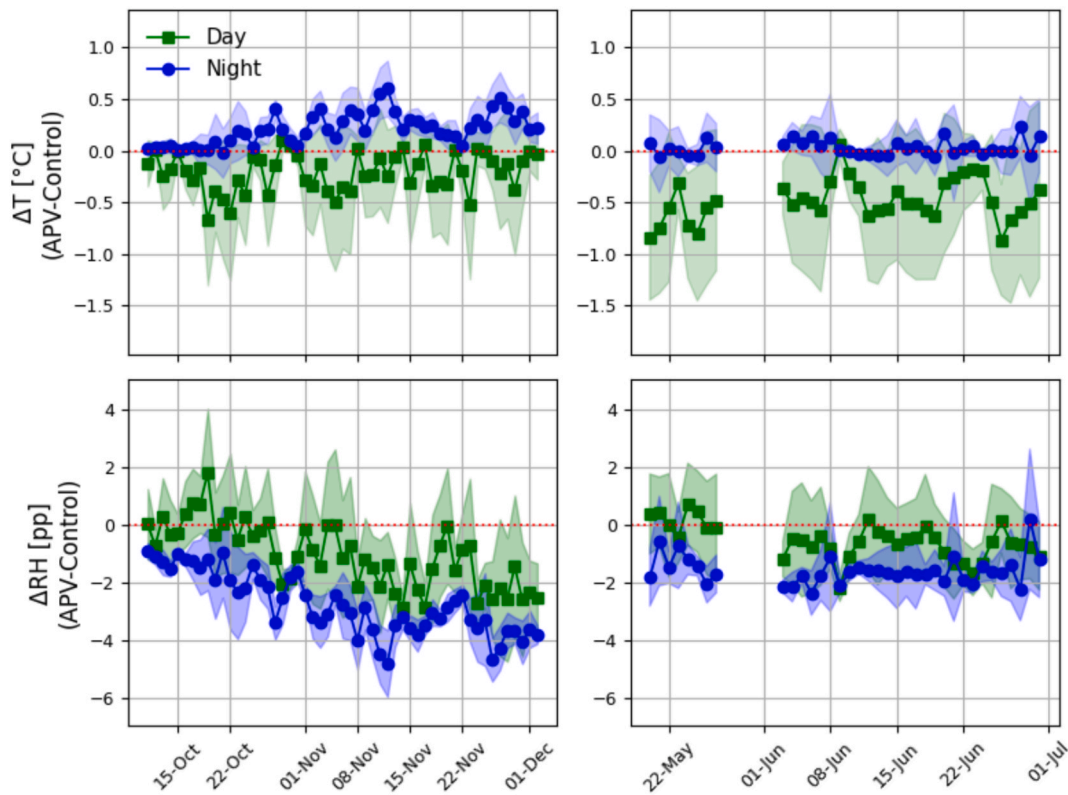


Fig. 6. Shading effects on T (top plots) and RH (bottom plots) at the Seville site over the two experimental lettuce crop cycles (left column – fall 2024; right column – spring-summer 2025 cycle). The graphs represent the difference in both parameters between the APV and the control plots. The shaded areas surrounding the lines represent the standard deviation around the mean values (lines). The displayed values are based on measurements collected from three plots for each treatment (APV and control).

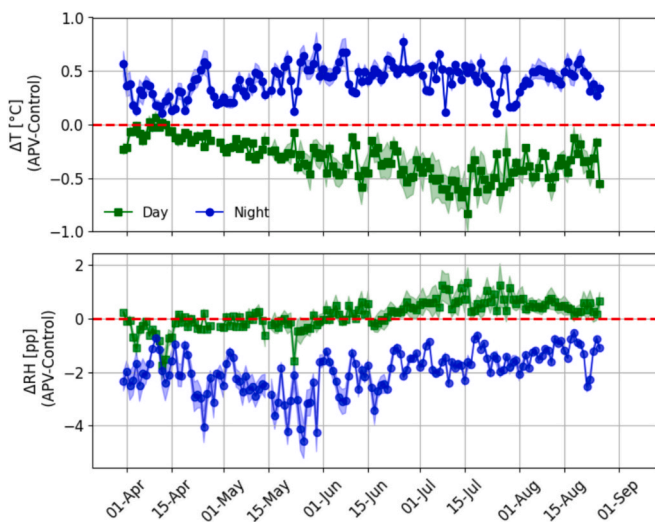


Fig. 7. Shading effects on T (top plot) and RH (bottom plot) at the Laujar site for the crop cycle from 30 March 2025 to 26 August 2025. The graphs represent the difference in both parameters between the APV and the control plot. The shaded areas surrounding the lines represent the standard deviation around the mean values (lines). The displayed values are based on measurements collected from a control zone and three different measurement locations in the APV zone.

atmospheric evaporative demand in the last stage of the crop cycle, resulting in a slightly increased RH during daytime. At the Seville site with deficit irrigation, the decrease of RH below panels is likely related with combined effects of water limitation and altered canopy development. The lettuce plants in the APV plots were deficit irrigated and such

conditions could induce an increase in water stress, leading to reduced stomatal conductance and decreased plant transpiration rates, thereby decreasing RH during daytime. However, lettuce cultivation also experienced a strong reduction in radiation during the fall 2024 cycle, which likely affected leaf growth and gas exchange, and may further reduced canopy transpiration during daytime. This effect is consistent with the differences in tomato leaves gas exchange reported by Shao et al. [75], which they attributed to limiting conditions of development between leaves in the upper and lower canopy layers. This combination of constraints could explain the observed RH reduction during daytime in Seville.

3.3. Energy assessment

Energy performance assessments were conducted through simulations to get estimations of final PV energy yield, expected PR values and factors of losses. The simulations were validated with actual energy yield data.

Fig. 8 and Fig. 9 present the monthly summary simulation results for the PV performance assessments at both sites since the deployment of the PV systems. The plots in the first row show the accumulated monthly radiation received by the modules, specifically the POA radiation. It is worth noting that for the Laujar site, this value corresponds to the sum of the front and rear POA radiation. Both locations exhibit a similar trend, with the highest radiation values observed during the summer months. The plots in the second row display the monthly average T and wind speed, which align with the characteristics of a hot-summer Mediterranean climate. The third row presents the factors of losses, with higher losses observed at the Seville site compared to those simulated at Laujar. Notably, the combined angular and spectral losses peaked at the end of spring in both years, while temperature and soiling losses reached their

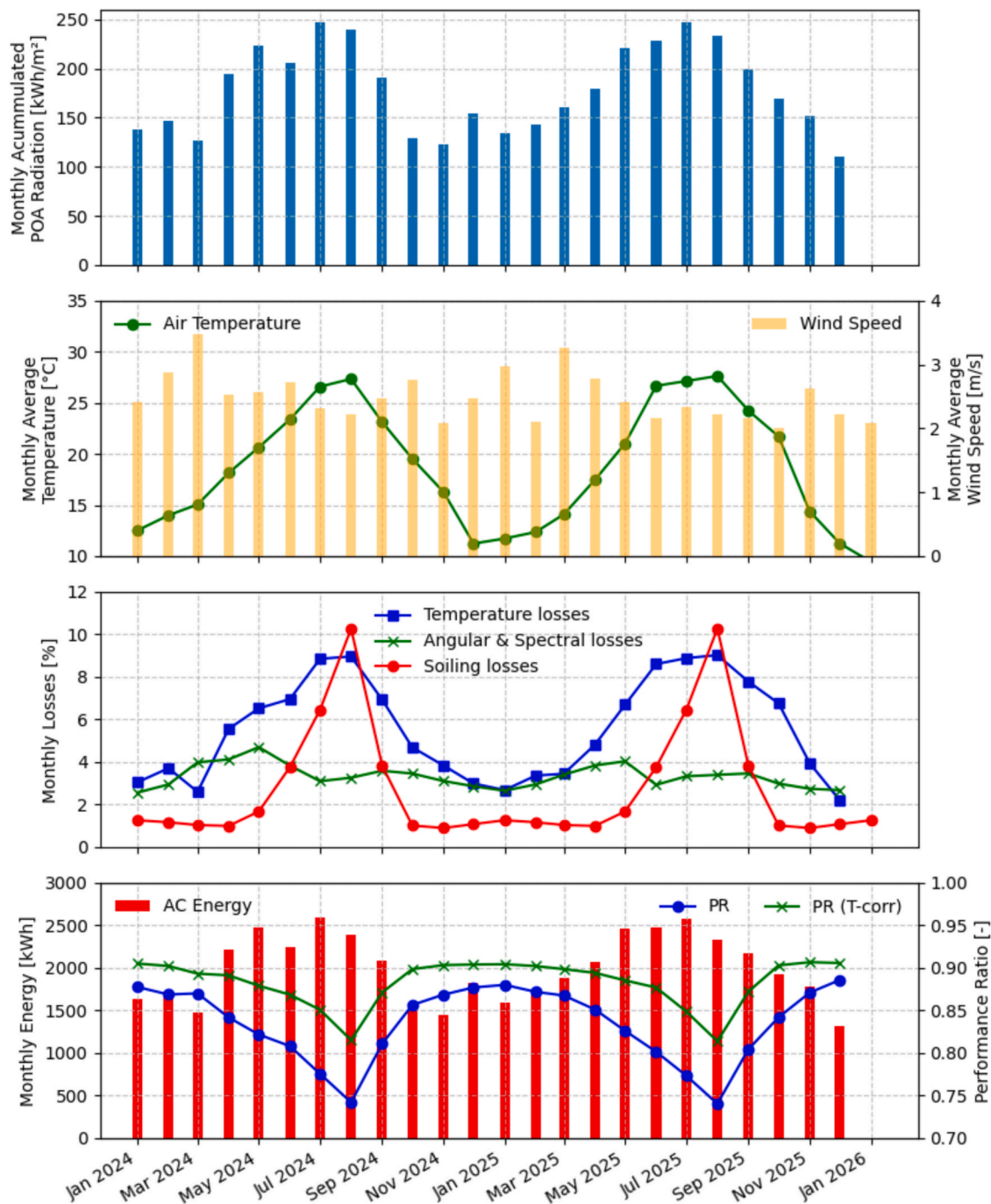


Fig. 8. Monthly summary simulation results for the PV performance assessments at the Seville site. The values of all the plots are / were calculated using reanalysis data from CAMS [57] and ERA5 [52].

highest values during the summer months, with soiling losses exceeding 10 % in August and temperature losses of approximately 9 %. These high soiling loss values during summer can be attributed to the long dry spells that prevented PV modules from being naturally cleaned. The relatively large tilt (50°) of the panels at the Seville site contributed to higher angular losses compared to those typically found in conventional large-scale fixed-tilt PV systems, which optimize the tilt to maximize energy production throughout the year. At the Laujar site, only the temperature losses followed the same trend as at the Seville site, with angular, spectral and soiling losses below 4 %. These losses have a direct impact on the PR, as shown in the plots on the bottom row. At the Seville site, the PR dropped significantly between April and August, mainly affected by both temperature and soiling losses, with a minimum value of 0.75 at

the end of the summer in both years. Interestingly, the highest PR at this site was obtained in December 2024, which was also the month with the lowest radiation. Conversely, at Laujar, the PR was mainly affected by temperature, as demonstrated by the almost flat profile of the temperature-corrected PR, with a minimum PR value in August 2025 of 0.83.

Fig. 10 and Fig. 11 present a comparison of the actual and simulated monthly energy yields at the Seville and Laujar sites, respectively. To enable a comprehensive evaluation of energy use and associated economic performance, the analyses considered all available data collected since PV system commissioning, including periods outside the crop cycles. For error calculations, only common timestamps with available measured data were used, which explains the differences between the

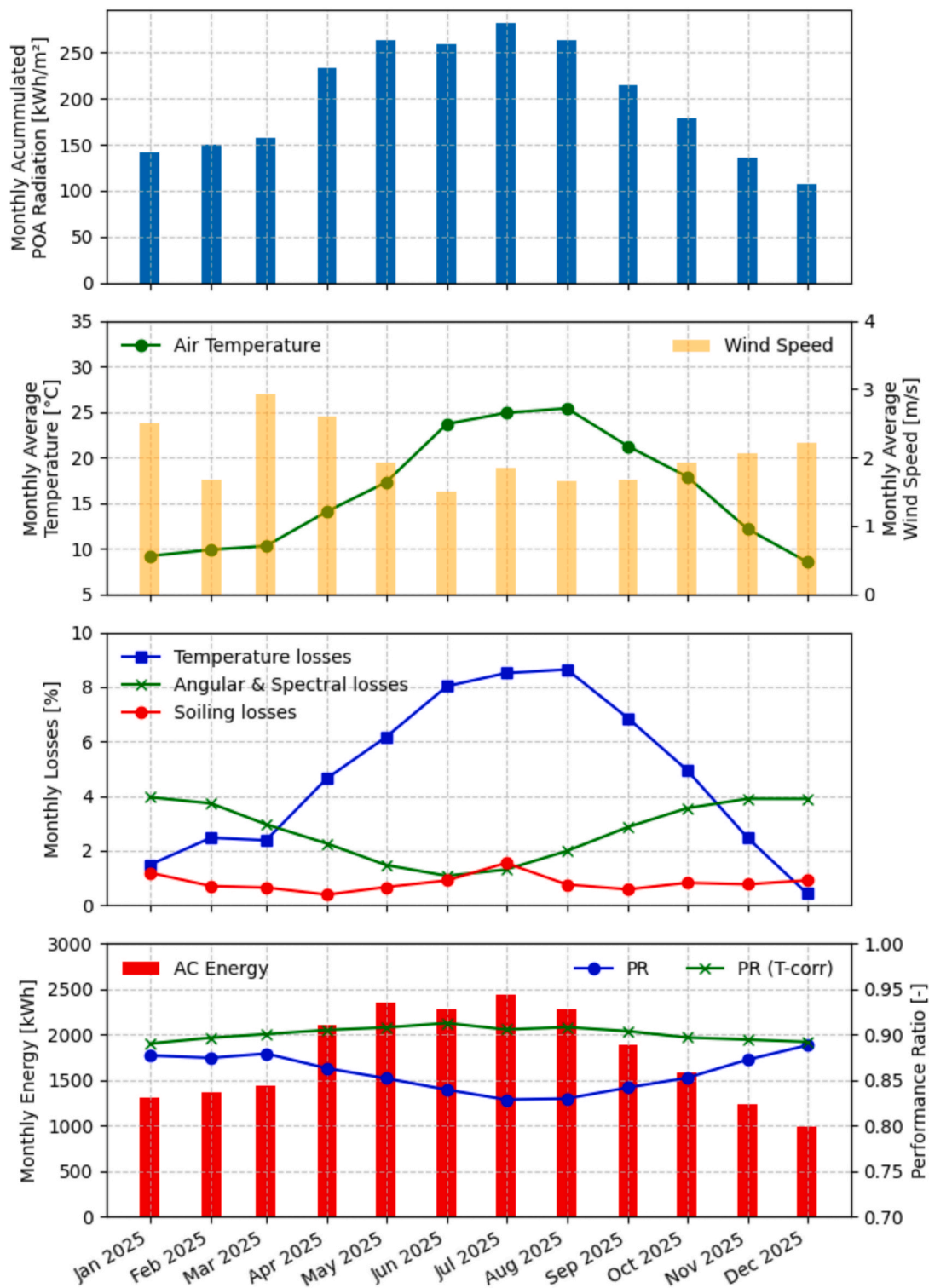


Fig. 9. Monthly summary simulation results for the PV performance assessments at the Laujar site. The values of all the plots are / were calculated using reanalysis data from CAMS [57] and ERA5 [52].

simulation values in the bottom plot of Fig. 8 and those in Fig. 10. At the Seville site (Fig. 10), the simulations overestimated the measurements during all the period, with the exception of February 2024, leading to a R^2 of 0.77, an MBE of 186 kWh (nMBE of 11.4 %) and a RMSE of 220 kWh (nRMSE of 13.4 %). To investigate potential causes of this overestimation, a sensitivity analysis was conducted by varying the fixed derate factor representing other losses, including mismatch and wiring losses. Increasing this factor from 2 % to 10 % reduced the MBE (nMBE)

and RMSE (nRMSE) to 44.5 kWh (2.7 %) and 115.4 kWh (7.1 %), respectively, suggesting that higher residual electrical losses than those initially assumed may have contributed to the deviations between simulations and measurements. Also, it should be noted that the deviation in September 2024, with a relative difference of 55 %, was due to the malfunctioning of the inverters due to construction works nearby that caused frequent and prolonged disconnections.

At the Laujar site (Fig. 11), in addition to comparing the

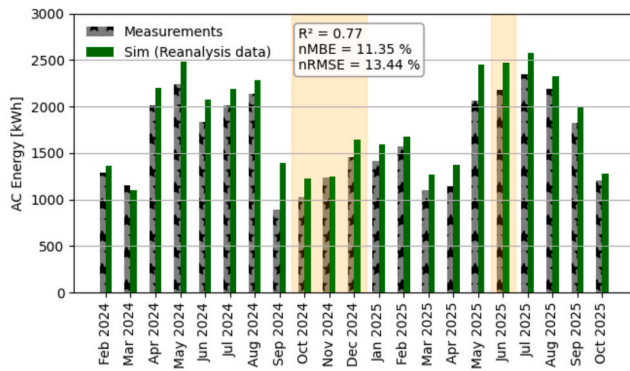


Fig. 10. Comparison of simulated and actual monthly energy production at the Seville site. The shaded orange areas indicate the crop cycle periods in 2024 and 2025. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

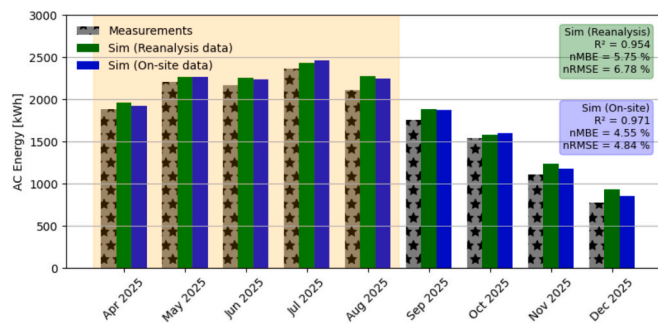


Fig. 11. Comparison of simulated and actual monthly energy production at the Laujar site. The shaded orange area indicates the crop cycle period. Data for February and March 2025 are not shown because rear-side irradiance sensors were unavailable prior to their installation on March 19, 2025. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

measurements with the simulations that rely on reanalysis data (green bars), on-site measured POA irradiance, including front- and rear-side irradiance measured by reference cells, module temperature and soiling data were used to estimate the energy yield (blue bars). The inclusion of measured rear-side irradiance was particularly important for the bifacial system, as it enabled a more accurate representation of bifacial gain and contributed to reducing uncertainties associated with rear-side irradiance modelling based on reanalysis data. It can be seen that the use of on-site measured data contributed to reducing the error between the simulations and the measurements. The use of reanalysis inputs derived in R^2 , nMBE and nRMSE values of 0.95, 5.8 % and 6.8 %, respectively. However, by employing on-site measured data, these nMBE and nRMSE errors dropped to 4.5 % and 4.8 %, respectively, while the R^2 reached a value of 0.97. It is worth noting that the largest deviations occurred in December, which was the month with the lowest radiation, resulting in overestimations of 20.8 % and 9.8 % when using reanalysis and on-site measured inputs, respectively. In August, the errors were higher than 7.5 % (reanalysis) and 6 % (on-site measured data) due to a potential underestimation of soiling losses.

3.3.1. Energy self-consumption and economic implications

In addition to total energy production, the on-site self-consumption was evaluated for the Laujar site. Fig. 12 represents the accumulated monthly consumption alongside PV generation. It can be observed that consumption was notably lower than generation for most months of the year (February - July 2025 and November - December 2025), with monthly consumption ranging from 12 % to 36 % of the corresponding

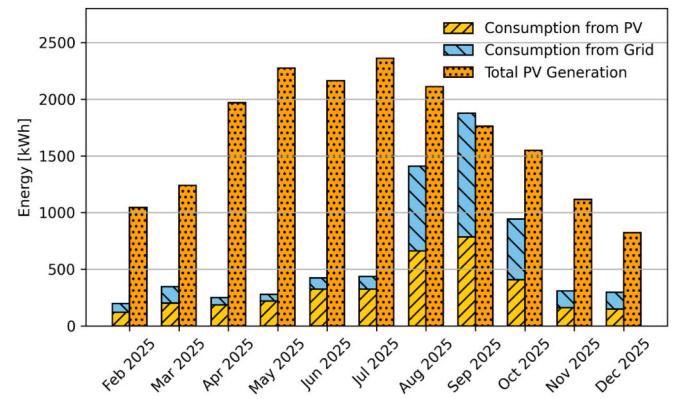


Fig. 12. Monthly energy consumption and PV generation profiles at the Laujar site.

PV generation. In contrast, after harvest (from mid-August to mid-October), consumption increased notably due to the operation of machinery for the wine's fermentation processes, with monthly values higher than 1000 kWh and even exceeding total PV generation in September. Fig. 12 also shows which fractions of the consumption were covered by the PV system or by the grid. Grid supply was always required because no storage system was available to provide electricity during nighttime.

To better understand the efficiency of on-site PV energy use and the winery's independence from the grid, two key metrics were calculated: (i) the self-consumption ratio (SCR), which represents the fraction of PV generation directly consumed on-site, with a value of 1 (100 %) indicating that all PV energy is self-consumed without export to the grid; and (ii) the self-sufficiency ratio (SSR), which represents the fraction of the facility's electricity demand met by PV generation, with a value of 1 (100 %) indicating full independence from the grid. The monthly values of SCR and SSR were derived using equations (15) and (16), respectively.

$$SCR [\%] = \frac{PV \text{ energy generation self} - \text{consumed on-site}}{Total \text{ PV energy generation}} \cdot 100 \quad (15)$$

$$SSR [\%] = \frac{PV \text{ energy generation self} - \text{consumed on-site}}{Electricity \text{ demand}} \cdot 100 \quad (16)$$

Fig. 13 summarizes the monthly SCR and SSR for the Laujar system, along with the corresponding energy costs without and with PV and the resulting monthly savings. For the economic calculations, only energy-

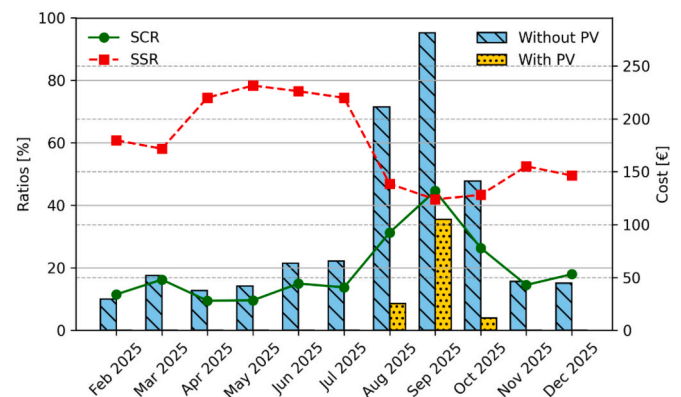


Fig. 13. Monthly evaluation of SCR and SSR indicators, along with energy costs without and with the APV installation at the Laujar site. The economic values report only energy-related costs (before taxes), not the total electricity bill. Calculations assume a fixed electricity purchase price of 15 c€/kWh and surplus PV revenue of 6 c€/kWh.

related costs before taxes were evaluated. They were based on the net-billing mechanism [76] and considered representative current price values offered by Spanish electricity retailers to households: a fixed electricity purchase price of 15 c€/kWh and a surplus PV revenue of 6 c€/kWh [77].

SCR was notably lower, with values below 20 % during months without post-harvesting activities, which coincided with periods of low electricity consumption. SCR peaked in September 2025, which was the month with the highest electricity demand, reaching over 44.6 % of PV generation being self-consumed on-site at the winery. For the SSR, the three lowest values (below 50 %) were registered between August and October 2025, coinciding with months of highest electricity demand. On the other hand, higher SSR values (above 70 %) were recorded during months with low consumption and high PV generation (April–July 2025). A joint evaluation of SCR and SSR values suggest that, although the APV system significantly reduced reliance on the electricity grid, achieving monthly values between 41.9 % and 78.4 %, there was still potential to further optimize self-consumption. The conservative values of PV energy use efficiency confirmed this aspect, as the maximum self-consumption reached only 44.6 % in the month of peak electricity demand.

Regarding economic savings, the calculations are based on the conditions established by the Spanish net-billing self-consumption scheme. Under this scheme, surplus electricity exported to the grid is compensated through bill credits, with compensation capped at the monthly electricity bill value, therefore preventing negative electricity costs. The APV installation eliminated energy-related costs in most months, as revenues from surplus PV energy exported to the grid fully offset any costs, except in August, September, and October 2025, when consumption was higher. Even so, savings of up to 186 € were possible in August 2025. As previously noted, optimizing energy use could increase these savings. A first step would be aligning daily consumption patterns with the PV generation profile. Fig. S4 and Fig. S5 in the [Supplementary Information](#) show consumption and PV generation profiles for two days with differing demand levels. On high-demand days, grid consumption could be significantly reduced by measures such as adjusting consumption patterns, integrating storage units to use surplus energy during nighttime, or employing smart APV tracking. Additionally, alternative business models from electricity retailers (e.g., virtual batteries) could also allow using previous months' surplus generation to further compensate demand [78]. It should be noted that the presented analysis focuses exclusively on the potential savings in electricity expenditures resulting from self-consumption of energy generated by the APV system, while installation and investment costs are not considered and would require a separate assessment beyond the scope of this study.

While this analysis provides a simplified economic perspective, it highlights the potential for APV systems to reduce operational energy costs, leading to significantly lower electricity bills in the case of small farmers. When combined with crop production benefits, local energy use can improve overall system viability. A recent economic assessment about APV in Germany [79] provided a more critical perspective on APV system costs. However, it should be highlighted that bifacial and smart tracking APV configurations may offer additional value by shifting PV generation toward periods with higher electricity prices in future energy systems, and by enabling smart tracking strategies that better align electricity supply with demand.

3.4. Crop assessment

In this subsection, the agronomic performance at both APV sites is evaluated by analyzing the indicators described in [Section 2.3.2](#).

At the Seville site, lettuce was grown under two irrigation treatments: a conventional control and a RDI strategy. This complemented the experimental comparison between the APV plots and the control unshaded ones. Fig. 14 shows the applied water, which is the total irrigation depth delivered to crops, calculated by dividing the volume of

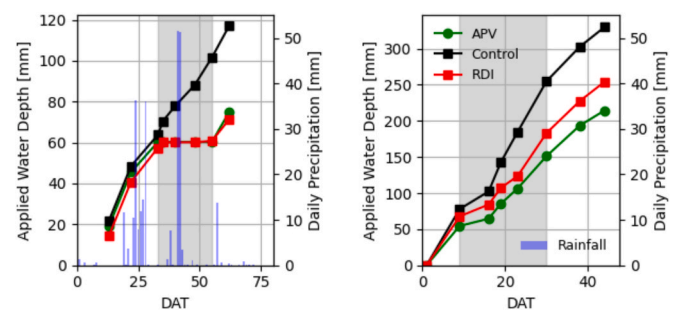


Fig. 14. Seasonal irrigation patterns at the Seville site over the two experimental crop cycles (left – fall 2024; right – spring-summer 2025 cycle). Treatments are: Control (black line, square markers), APV (green line, circle markers), and RDI (red line, square markers). Each data point represents the mean of three replicate plots per treatment. The vertical blue bars represent daily precipitation (right y-axis). Grey shading indicates the period of irrigation restriction when RDI plants received 50 % of the standard irrigation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

water by the irrigated area, and considering that 1 L/m² is equal to 1 mm, in each crop cycle and treatment. Because precipitation and evaporative demand differed notably between cycles, without any rain events during the spring-summer cycle, the total applied water also varied. The applied water in the fall 2024 cycle ranged between 71 and 117 mm, whereas the spring-summer 2025 experiment demanded considerably more irrigation, ranging from 214 to 330 mm. In both cycles the control plots received the greatest amount of water, while the RDI and APV treatments were irrigated less. The RDI approach led to water savings of 39 % (both RDI and APV) in the fall 2024 cycle, and between 22 % (RDI) and 35 % (APV) in the spring-summer 2025 cycle. In both cases, the savings occurred mainly during the phase of slow dry-weight accumulation, which corresponds to the period of water stress imposed by the RDI strategy, which began 33 and 9 days after transplanting (DAT) in the fall 2024 and spring-summer 2025 cycles, respectively.

As indicated in [Table 5](#), some differences in lettuce yield and quality were observed among the three different treatments, including clear seasonal effects between both cycles: yields in the fall 2024 cycle were higher than in the spring-summer 2025 one, reflecting the more favorable temperature and radiation conditions of the cooler season for lettuce growth. Across both cycles the control plots consistently gave the highest yields, while the APV treatment recorded the lowest yield in fall 2024 (–25 % relative to control and –18 % relative to the RDI treatment). In the spring-summer 2025 cycle the performance gap narrowed, with APV only 9.6 % below the control and the RDI treatment yielding 10 % less than APV. A similar trend was observed for the number of leaves, a key quality indicator: in fall 2024, APV produced about 10 % fewer leaves than RDI, whereas in spring-summer 2025, APV outperformed the other treatments, delivering 18 % more leaves than RDI and 4 % more than the control. However, it should be noted that plant weight in the APV plots was slightly lower than in the control (see [Fig. S7](#) in the [Supplementary Information](#)), which explains the reduced final yield of the APV treatment compared to the control in the spring-summer 2025 cycle. Additional analyses about other plant growth parameters (soil cover ([Fig. S6](#)) and leaf conductance ([Fig. S8](#))) can be found in the [Supplementary Information](#).

These results can be explained by the different light conditions between cycles (see [Fig. 4](#)): in spring-summer 2025, with higher radiation, the shading provided by the APV system mitigated water stress and excessive irradiance [72], enhancing leaf development; in fall 2024, however, the DLI under the APV panels dropped to values below the optimal range [73] (15–30 mol m^{–2} day^{–1}) and 28 % lower than the average DLI recorded in the unshaded plots, with a mean value of 23.8 mol m^{–2} day^{–1}.

Table 5

Yield quantity and quality, and irrigation water productivity as affected by applied irrigation at the Seville site during two experimental crop cycles (mean $\pm$ standard deviation).

	Yield (t ha ⁻¹)		Number of leaves per plant (no. plant ⁻¹)		Irrigation water applied (mm)		Irrigation water productivity (kg m ⁻³)	
	Fall 2024	Spring – Summer 2025	Fall 2024	Spring – Summer 2025	Fall 2024	Spring – Summer 2025	Fall 2024	Spring – Summer 2025
APV	23.7 $\pm$ 1.4	20.6 $\pm$ 3.1	67.2 $\pm$ 2.7	36.4 $\pm$ 2.6	74.9 $\pm$ 4.4	214.3 $\pm$ 7.3	22.5 $\pm$ 1.1	9.7 $\pm$ 1.6
RDI	28.8 $\pm$ 4.1	18.7 $\pm$ 2.1	75.1 $\pm$ 6.3	30.8 $\pm$ 1.9	71.3 $\pm$ 7.3	254.1 $\pm$ 16.4	29.6 $\pm$ 1.4	7.4 $\pm$ 0.9
Control	31.5 $\pm$ 1.1	22.8 $\pm$ 1.5	73.8 $\pm$ 3.9	34.8 $\pm$ 0.9	117.1 $\pm$ 2.1	329.8 $\pm$ 9	21.0 $\pm$ 0.4	7.0 $\pm$ 0.6

The use of irrigation and water productivity also showed differences between cycles. As above mentioned, both RDI and APV treatments reduced the amount of water applied. RDI of lettuce is rarely reported because the crop is highly sensitive to water stress. Previous works showed that a 25 % reduction in irrigation can be achieved without yield loss, whereas larger restrictions can lead to yield declines [80,81], which actually align with our experimental results. Water productivity was about three times higher in the fall 2024 cycle than in the spring-summer 2025 cycle. In fall 2024, the RDI treatment yielded the greatest water productivity, with a 40 % increase relative to the control; whereas in spring-summer 2025 the APV treatment performed best, returning a 38 % gain over the control. Because the volumes of water applied were similar for RDI and APV, the contrasting productivity results indicate that different factors limited performance in each cycle: low radiation constrained growth in fall 2024, while water stress was the dominant limitation in spring-summer 2025. Additionally, Table S1 (see Supplementary Information) shows the best-fit linear correlations between plant growth indicators (plant weight and soil cover) and environmental-related parameters (DLI and T). The associated discussion of the results is also included in the Supplementary Information.

Fig. 15 shows the comparison of the 2025 grape harvest at the Laujar site between the control and the APV zones. We should note that the timing and duration of phenological stages (budburst, flowering, veraison, and ripening) were identical in the control and APV plots, with the same recorded dates for each stage: budburst occurred on 30 March 2025, flowering on 2 June 2025, veraison on 27 July 2025, and full ripening on 24 August 2025. Regarding yield, the difference between APV and control plots was found to be less than 2 %. It should be highlighted that the average yield in the area (lower than 1.4 t ha⁻¹) was severely affected by a prolonged drought in fall 2024. However, a comparison of the physical and chemical ripening parameters of the grapes revealed that those grown under the PV modules were smaller, but had a higher sugar content, lower acidity, and increased pH. These findings suggest that the smaller berries may have compensated for the

reduced carbon assimilation due to shading by concentrating sugars and acids, highlighting a potential adaptation mechanism in response to the altered microclimate created by the PV modules and evaluated in Section 3.2.

4. Challenges and lessons learned

Although the deployment and monitoring of these 2 APV installations in southern Spain provided valuable information about the crossed-impacts between PV modules and crops, the study has also helped to identify several key challenges. System's design and construction was the first challenge encountered. In Spain, the APV market is still in a very early stage of development and most of the developers do not count with previous experience in the design and construction of APV installations. This can lead to systems' configuration that are not fully adapted to the requirements of crops and the need to conduct agricultural activities below and in between the structures [82]. The Seville site clearly illustrates this issue with the use of deep concrete foundations, that contributed to the loss of part of cultivation area. In addition, the concentrated arrangement of the opaque panels without spacing between them led to a heavily non-uniform distribution of the shadows throughout the days. This can lead to heterogeneous impacts on the growth of the crops placed on the surroundings.

The lack of integrated models customized for APV installations [8,45] is also strongly related to the previous challenge of system's design. Most commercially available PV performance models are designed for conventional ground-mounted or rooftop installations and do not account for the shading effects of crops, elevated mounting structures, or the microclimate interactions between panels and crops in APV setups. This shortcoming limits accurate performance assessment and highlights the need for developing customized modeling approaches for APV systems. Specifically, the estimation of soiling losses is particularly challenging. Existing models do not consider particularities, such as sticky pollen particulates that rain cannot efficiently remove, the impact of agricultural management and the increase risk of bird droppings that cause non-uniform soiling losses across the system [83–85]. This latter aspect does not only apply to soiling modelling, but also to soiling monitoring devices, which cannot capture this heterogeneous distribution of the soiling impact.

The optimization of monitoring systems is another critical lesson. At both analyzed APV sites, the sensors were connected via wired systems to dataloggers, resulting in complex installations, incompatibilities with agricultural activities and limited flexibility for scaling. To address this issue, a wireless sensor network (LoRaWAN) is being now implemented at the Seville site to enable flexible deployment and efficient long-range data transmission with reduced wiring complexity.

Finally, despite being essential to maximize the benefits of APV installations, energy use under real-world conditions was not comprehensively evaluated during the design phase of either site. At the Laujar site, less than 20 % of the annual generated energy in 2025, most of them concentrated in the weeks following the harvest, was self-consumed by the winery machinery, with the surplus fed into the grid and compensated at a low feed-in tariff. This remarks the importance of coupling PV energy production with real energy demand in APV setups, which can allow for accurate evaluations of economic viability, potentially leading to more optimized designs, including the use of smart tracking systems

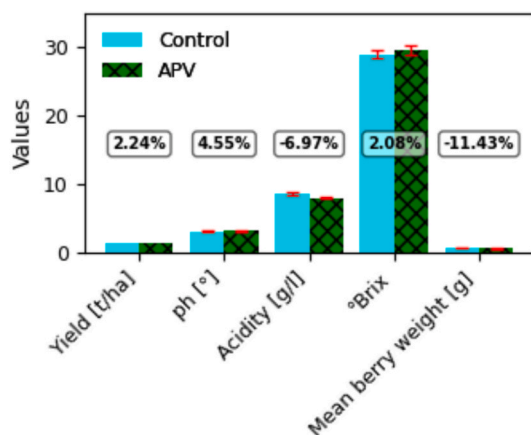


Fig. 15. Grape yield and quality indicators at the Laujar site in 2025. Blue and green bars show mean values for each treatment, while red error bars indicate standard deviations. The text boxes indicate the relative difference (APV vs. control) for each parameter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the integration of energy storage, and even to the selection of a more profitable business model.

5. Conclusions

This study provides a comprehensive assessment of two different elevated APV installations in Southern Spain (Seville and Laujar). The methodology presented and the results demonstrate the potential of APV to mitigate the impact of excessive radiation and extreme temperature values on crops, while generating clean energy that can be used on-site by farmers. This contributes to both the support of rural economy and the synergistic and sustainable integration of PV energy systems. The discussed challenges and their associated recommendations are expected to be implemented by the APV community in future installations or research works.

The integrated simulation and field validation used to assess APV performance not only provided insights into the overall operation of the case studies, but also demonstrated the suitability of accurate simulations to complement field data. Regarding performance assessment, one of the main findings was the impact of APV systems on reducing radiation at crop level, with DLI reductions ranging between 20 % and 50 %, depending on the location within the APV plots. Shading simulations improved the representation of spatial radiation distribution and were successfully compared against in-situ sensor measurements. Another key outcome was the positive microclimatic effect observed in APV plots, with lower temperatures (up to -0.9°C) recorded during daytime below the panels. The energy analyses demonstrated that through a proper design and operation of the system, this can operate with high PR values throughout the year (PR higher than 0.8), minimizing losses unrelated to temperature. In addition, the results confirmed that energy generation can be reliably estimated using reanalysis data, with relatively low errors (RMSE of 6.8 % for the Laujar demonstrator). Crop evaluations indicated that the presence of PV modules not only mitigated light and heat stress but also resulted in slightly higher yields (+2.2 % grape yield at the Laujar site) or in potential water savings for lettuce at the Seville site. It should be noted that the impact of PV modules on the plant environment influenced agronomic performance differently depending on the crop and growth cycle considered. In particular, the environmental conditions below the panels varied between locations, as reflected in RH data, suggesting that the effects of the APV system are crop- and growth cycle-dependent. In addition, it should be highlighted that the results of this study showed that APV systems can have a great potential to improve water productivity and reduce irrigation needs with minimal negative impact when compared with a strategy of deficit irrigation in conventional open field unshaded conditions. Further works are required to improve the knowledge about the response to DLI of different crops, cycles and cultivars to improve design criteria of APV systems. Finally, the self-consumption assessment for the Laujar site indicated that APV systems can reduce electricity-related costs through on-site PV generation, highlighting the importance of optimizing energy self-consumption strategies, such as aligning demand with PV production or integrating storage solutions, to further enhance the profitability of APV installations.

Overall, this work contributes new field-based evidence from two elevated APV systems. By combining irradiance assessment, microclimate analysis, and crop and energy performance evaluations within a single framework, the study provides important insights about methodological approaches for the design and evaluation of APV systems. Also, the difficulties and challenges presented in this study, related to the design and construction of APV systems, modelling and optimization, the standardization of monitoring criteria, and the assessment of economic viability, are intended to pave the way for joint efforts and new developments in the field. Additional research is needed to develop integrated modelling platforms for APV and to implement technical solutions, such as smart tracking systems and rainwater management strategies, that can enhance both profitability and sustainability of the

systems. Economic viability should be assessed under a wide range of climatic conditions, crop types, and socio-economic contexts. Finally, multi-year performance evaluations of different APV configurations across diverse crops and climates are required to ensure continuous progress based on real-world and field-derived data.

CRediT authorship contribution statement

Álvaro Fernández Solas: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Natalie Hanrieder:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition. **Anna Kujawa:** Writing – review & editing, Visualization, Validation, Software, Methodology. **Marta Sánchez-Piñero:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **María José Martín-Palomo:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis. **Mireia Corell:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Alfonso Moriana:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used the model OpenAI GPT OSS 120B included in ChatAI (<https://academiccloud.de/services/chatai/>), which is a secure cloud service for German universities and research centers, to improve spelling, grammar, clarity, and general editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.solar.2026.114845>.

[org/10.1016/j.solener.2026.114845](https://doi.org/10.1016/j.solener.2026.114845).

Data availability

Data will be made available on request.

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