The potential for Agrivoltaics in Orchards
Dual-use solar + tree fruit systems

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Fresno, California, February 9, 2026
69th Annual IFTA Conference and Tours

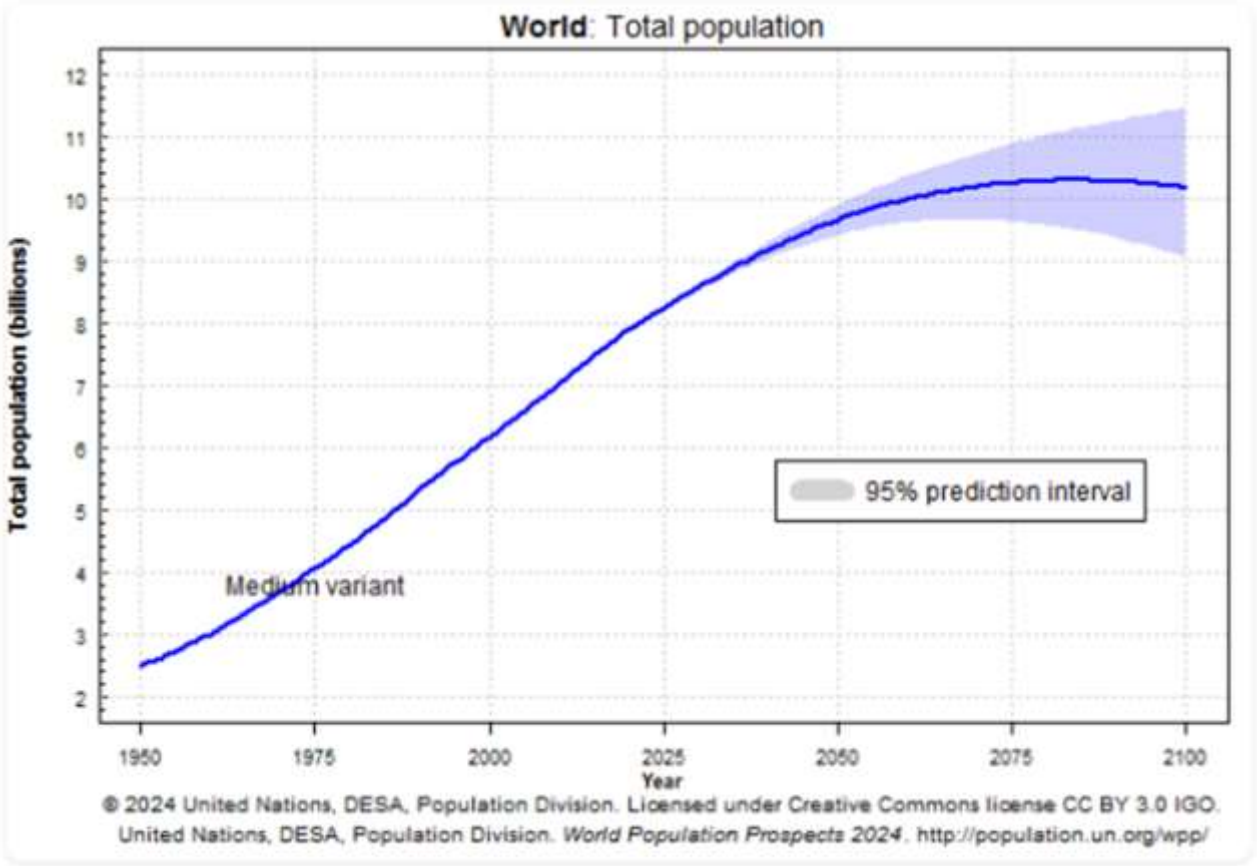




Population growth from now to 2050 implies:

- An increase of about **+1.2 billion people** between 2030 and 2050
- Roughly **15% more people** globally in only 20 years
- Strong pressure on:
  - **Food production**
  - **Water availability**
  - **Energy demand**
  - **Land resources**

  The global consumption of food has been on a rapid rise, reaching a staggering 2.5 billion metric tons in 2021 [Statista, 2022].

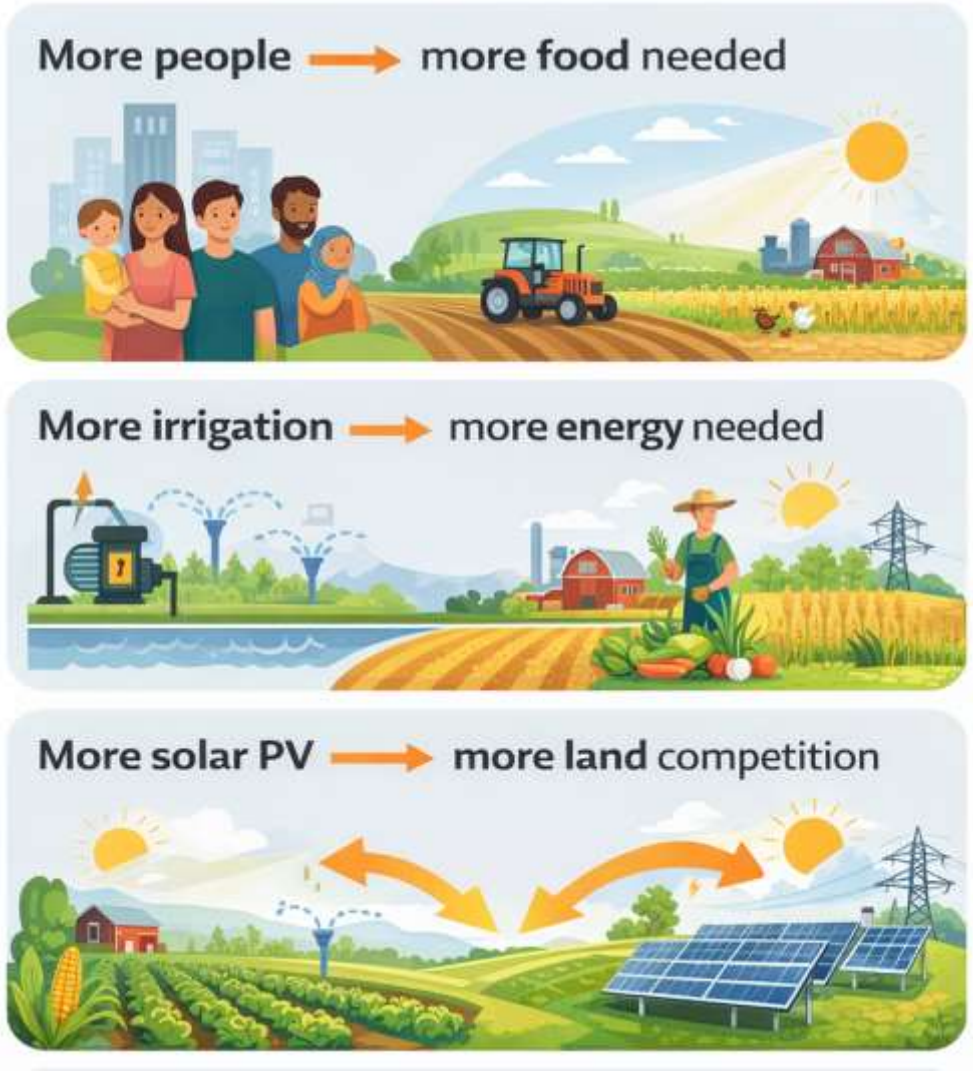


Sarr et al, 2023

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What is Agrivoltaics and why is it relevant?

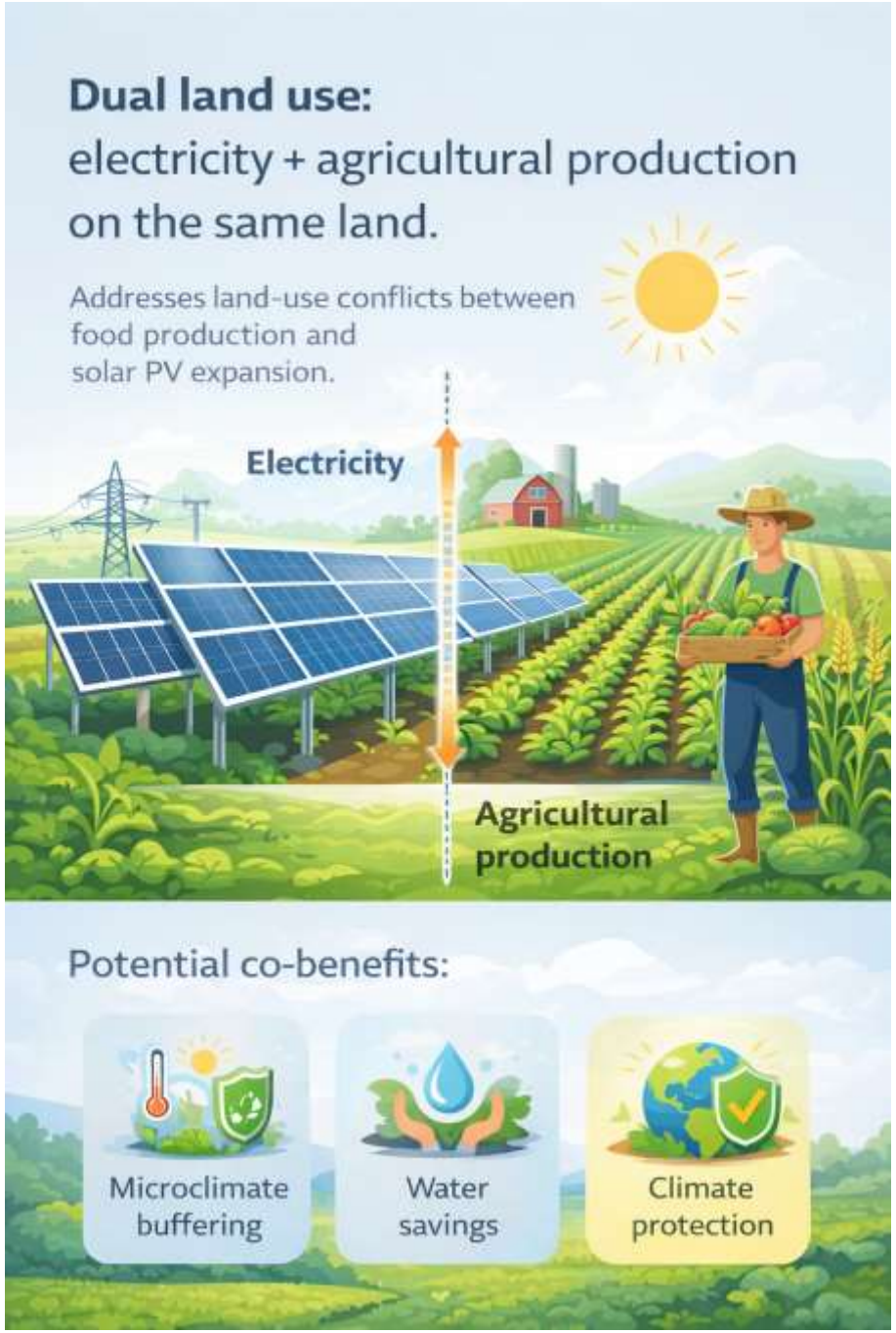
- **Co-locating photovoltaic (PV) energy production with agriculture on the same land**
- Goal: **increase total land productivity (food + energy) while supporting farm resilience**



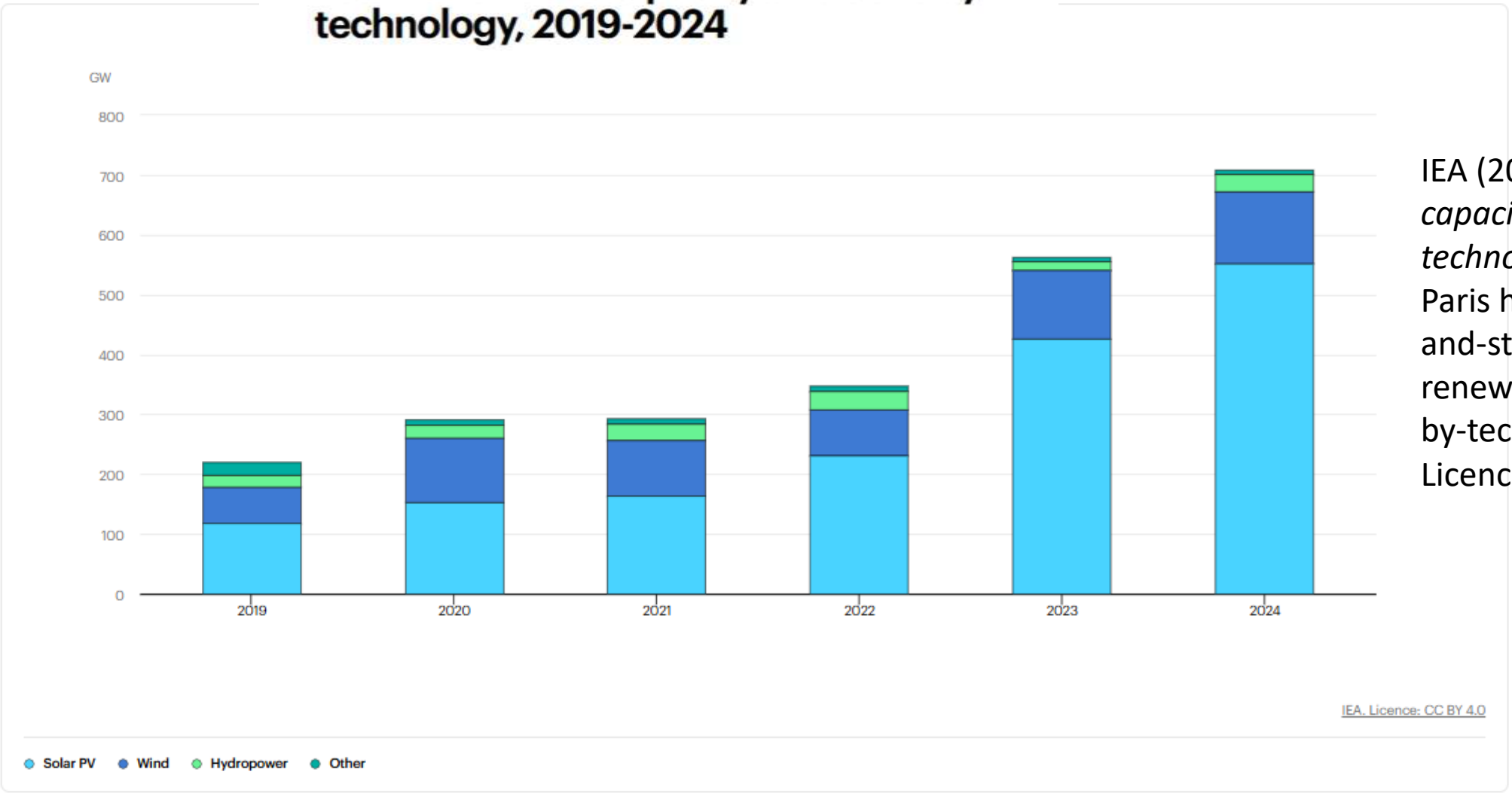
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Why Agrivoltaics?

- **Dual land use**: **electricity + agricultural production on the same land.**
- Addresses **land-use conflicts between food production and solar PV expansion**.
- **Potential co-benefits**: **microclimate buffering, water savings, climate protection.**



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IEA (2025), *Total renewable capacity additions by technology, 2019-2024*, IEA, Paris https://www.iea.org/data-and-statistics/charts/total-renewable-capacity-additions-by-technology-2019-2024, Licence: CC BY 4.0

https://www.iea.org/reports/global-energy-review-2025/electricity?utm_source

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Why Apple Production Needs Climate Adaptation

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Why Apple Production Needs Climate Adaptation: Heat Stress, Sunburn, and Hail - Part 1

•Climate scenarios project **~+1.5°C global warming by 2021–2040** (Masson-Delmotte et al., 2021).

•By **2100 in Mediterranean regions**, warming could reach **+4 to +5°C in spring–summer**, with **~20% less rainfall**, mainly in summer (Stocker et al., 2013).

•Among fruit trees, **almond and olive are relatively well adapted to hot/dry climates**, while **temperate fruit species are more vulnerable** to global warming.

•**Apples are highly sensitive to climate change, because most varieties were developed for temperate climates with mild summers and high humidity (Bouhier de l'Ecluse, 1983).**

•**Rising temperatures reduce fruit growth by lowering photosynthetic activity** (Herring et al., 2016).

•**Climate stress also reduces marketable yield, mainly due to sunburn** (Wünsche et al., 2001; Manja & Aoun, 2019) **and hail damage** (Mupambi et al., 2018).

Juillion et al., 2022

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Why Apple Production Needs Climate Adaptation: Heat Stress, Sunburn, and Hail - Part 2

- **Apple orchards** **already use multiple shading systems** (protective nets, overhead netting, partial/louvred netting, drape netting).

- They also **modify the orchard** **microclimate** (cooler/more temperate conditions).

- This influences **tree physiology, leaf morphology, and overall productivity**.



Juillion et al., 2022

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Why Apple Production Needs Climate Adaptation: Heat Stress, Sunburn, and Hail – Part 3

•In agrivoltaics (APV), **sunlight is shared** between PV panels and crops, so the **light available for photosynthesis is reduced**.

•Many important orchard crops—**olive, grape, apple, and pear**—are **C3 species** (Bongi et al., 1987), making them promising candidates for agrivoltaic systems.

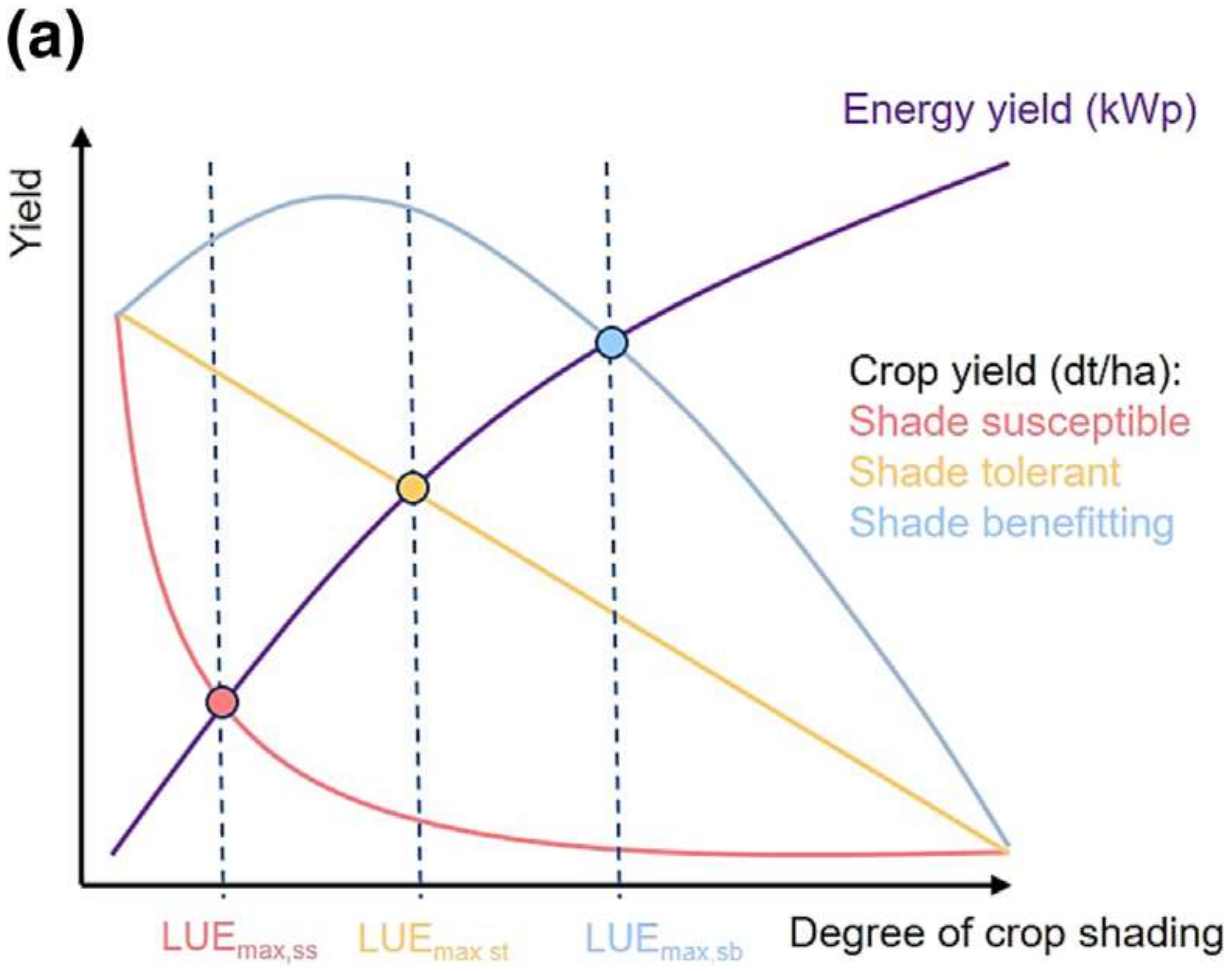
•**C3 plants** tend to reach photosynthesis saturation at **lower PAR**, meaning they are generally **more shade-tolerant** (Yin & Struik, 2009; Mahendra et al., 1974).

•Therefore, using **C3 crops can reduce the negative impact of PV shading and maintain efficient photosynthesis under APV.**

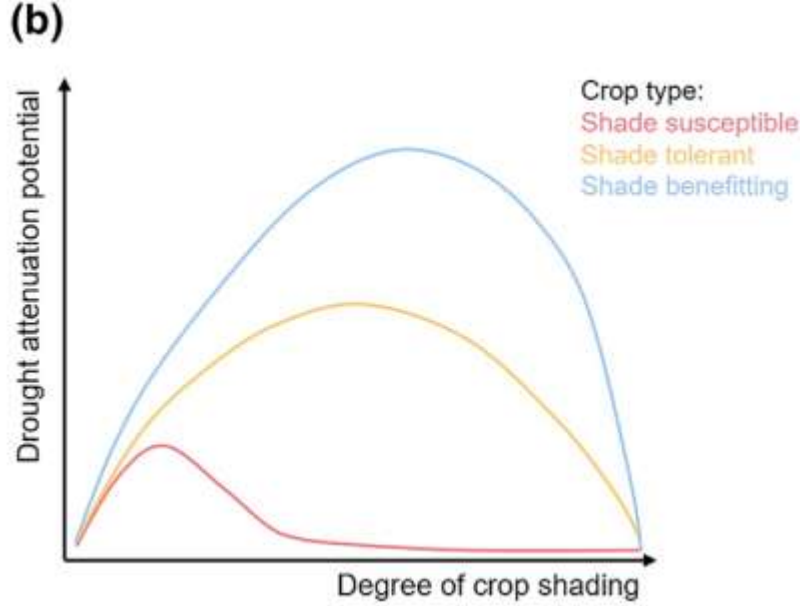
Juillion et al., 2022

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Light Trade-Offs and Crop Response



(Schweiger and Pataczek,2023)

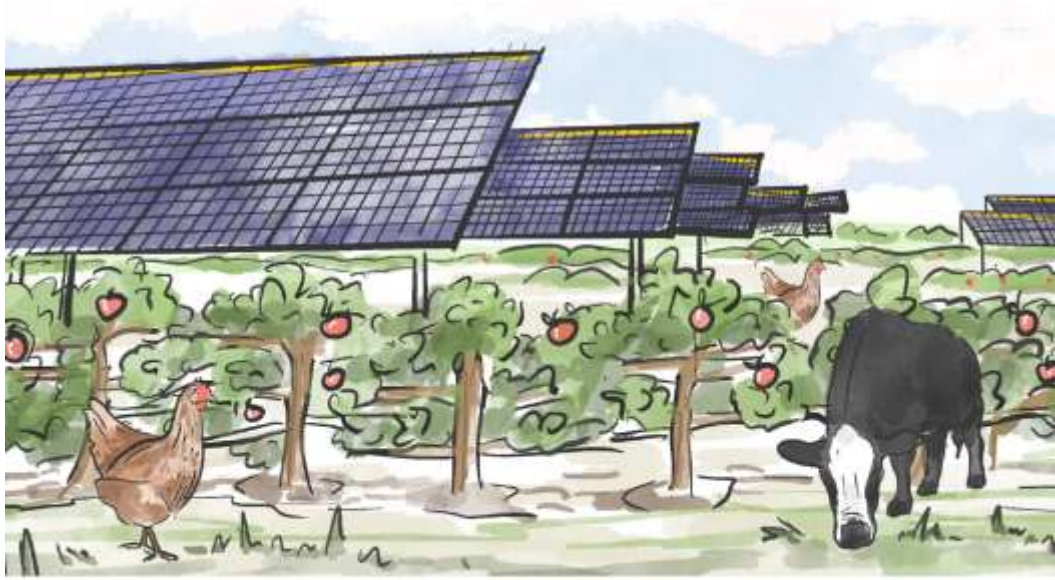


- Agrivoltaics balance **energy production** and **crop growth** using the same sunlight.
- Increasing PV density boosts electricity output but **increases crop shading**.
- **Shade-susceptible crops**
  - Perform poorly under the **dominant clear-sky / low-diffuse conditions**
  - Experience strong yield reductions under panels
  - Lower achievable **LUE_{max}**
- **Shade-tolerant crops**
  - Can exploit moderate diffuse light
  - Yield losses are smaller
  - Intermediate LUE
- **Shade-benefiting crops**
  - Benefit during periods with higher diffuse fractions
  - Gain from reduced heat and water stress
  - Highest potential LUE

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Why Agrivoltaics Matters in Washington?





Lambert, M. R., Candib, A., Wu, G., Tinianov, R., Schoenbachler, K., Robertson, J., Altadonna, N., Khan, M. R. A., Rajagopalan, K., Yourek, M., Shapiro, L. F., Kinzer, A., and C. Kruger. 2025.

Low hanging fruit for Washington's energy future? Agrivoltaic feasibility for agricultural and energy resilience in the Evergreen State. Report to the Washington Department of Commerce, Olympia, WA.

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Why Agrivoltaics Matters in Washington?

- **Washington has ambitious renewable energy goals requiring large-scale solar deployment.**
- **Challenge: build solar while minimizing impacts to farmland, natural land, and Indigenous rights.**
- **Agrivoltaics enables solar + continued farming, diversifying farmer revenue streams.**
- **204,000+ acres** were identified as hypothetically amenable to agrivoltaics within **1 mile of substations**.
- If fully built out, this could equal **20.5–41 GW** of solar capacity.

Lambert et al., 2025

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Orchards Are the Main Opportunity

In the realistic scenario:

- **Orchards represent ~50%** of all potential agrivoltaics acreage in Washington.
- Most orchard potential is in **central and eastern Washington**.

- Counties with the largest agrivoltaic potential include:
  - **Grant, Yakima, Benton**
- **Counties with >2,000 orchard acres within 1 mile of a substation include:**
  - **Grant, Chelan, Yakima, Douglas, Benton, Okanogan, Franklin, Walla Walla**

Lambert et al., 2025

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Why Orchards?

- **High-value perennial crop** → can justify elevated structures
- **Rows/trellis systems align naturally with PV canopy layouts**
- **Orchards already use overhead infrastructure** (nets, frost lines, trellis posts)
- **Increasing heat, sunburn, and hail** risk drives interest in protective shade

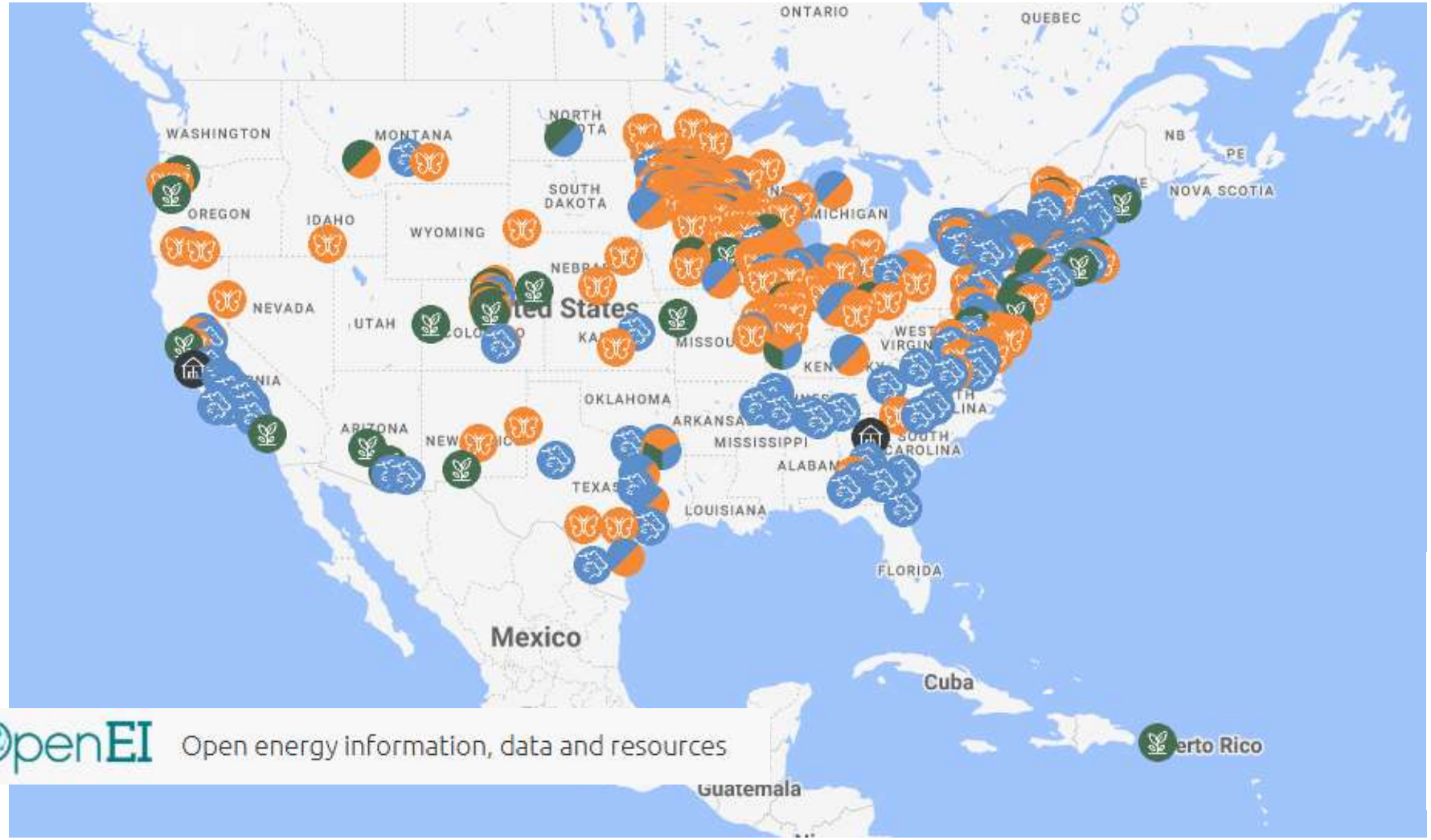


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Agrivoltaic System Situation in USA

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USA Agrivoltaics Map



Agrivoltaic Activities

- Crop Production
- Habitat
- Grazing
- Greenhouse

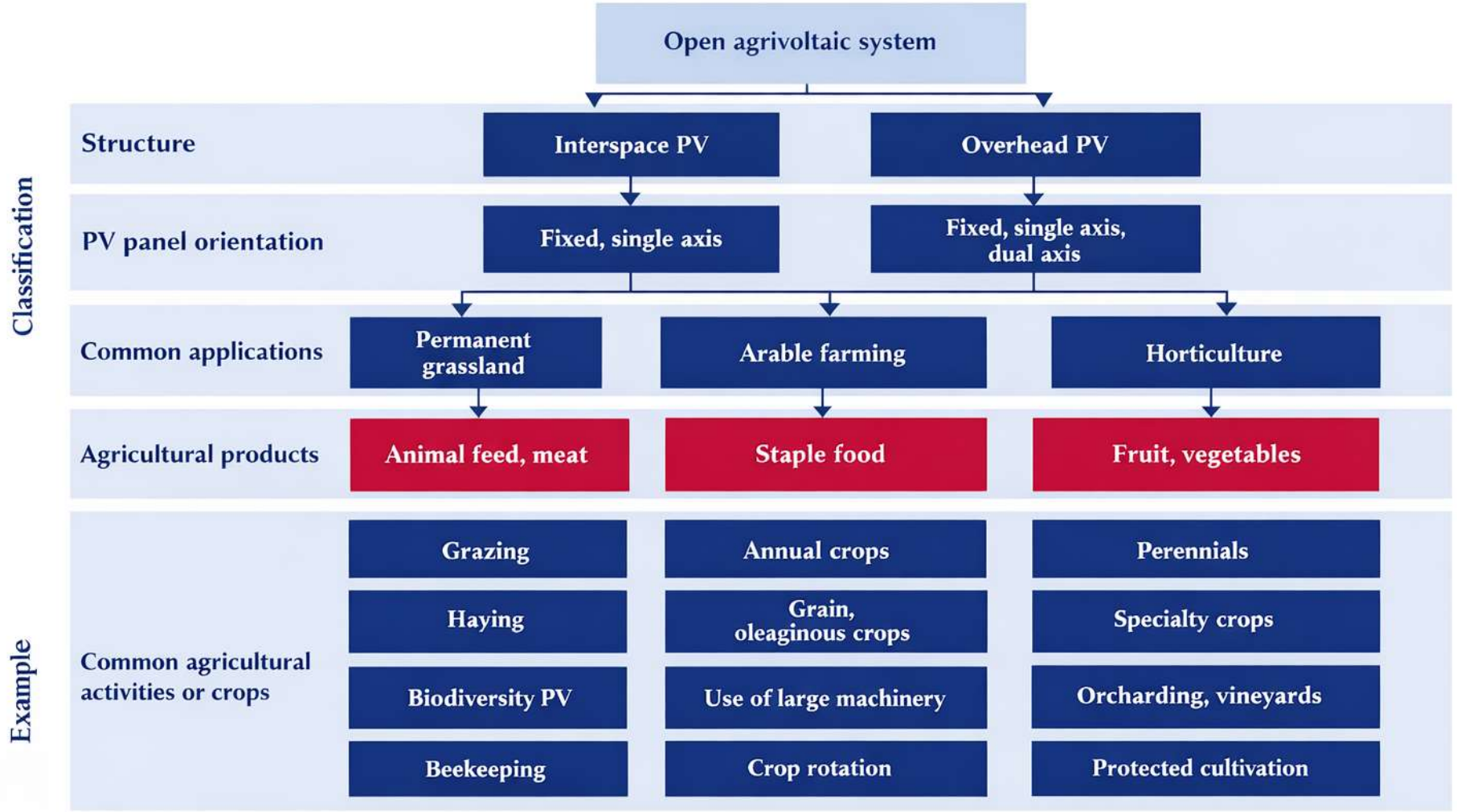
637
Sites

13679
Megawatts

84614
Acres

https://openei.org/wiki/InSPIRE/Agrivoltaics_Map

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Agrivoltaic System Types

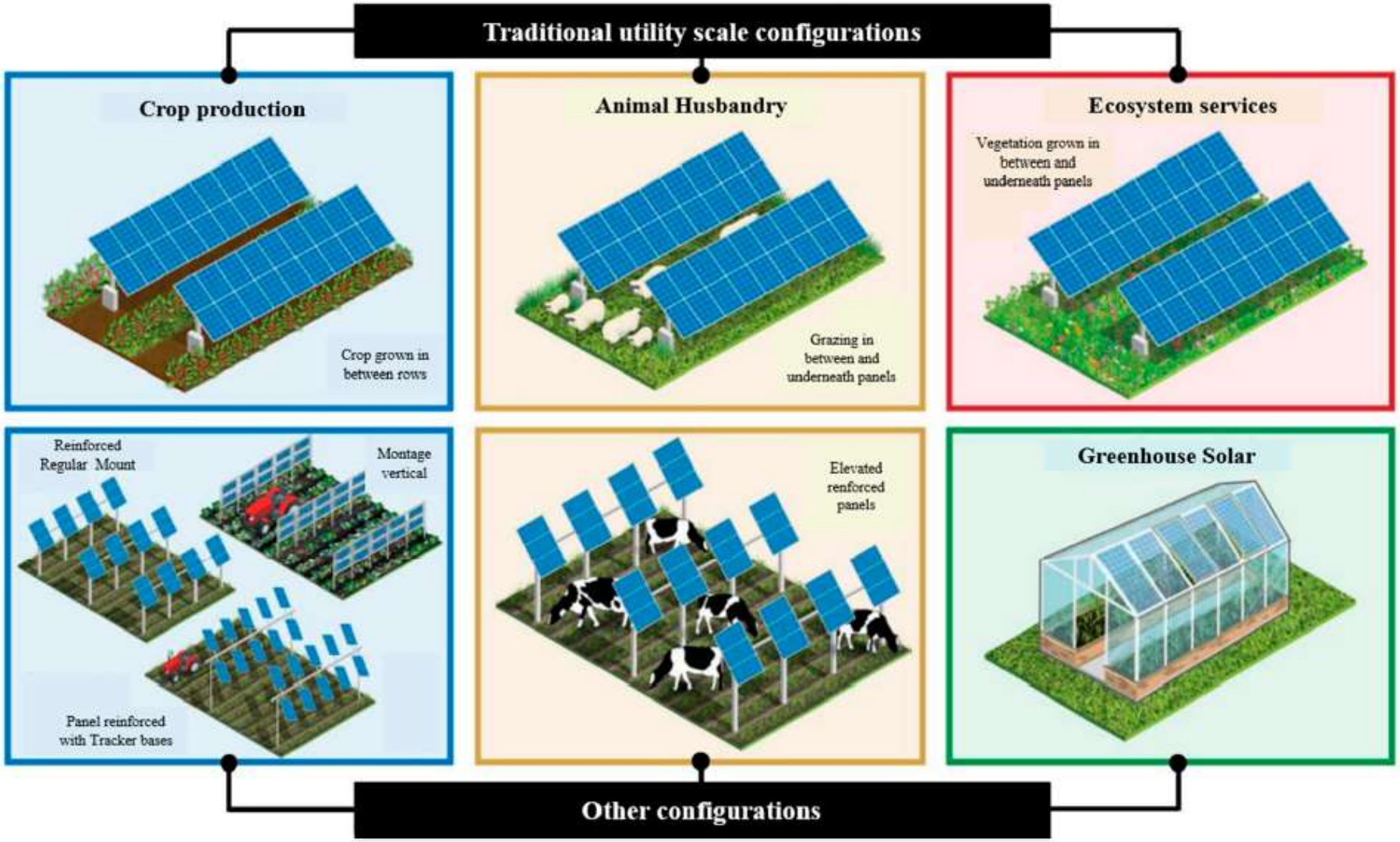


Figure 1. The different agrivoltaic systems [29].

Sarr et al, 2023

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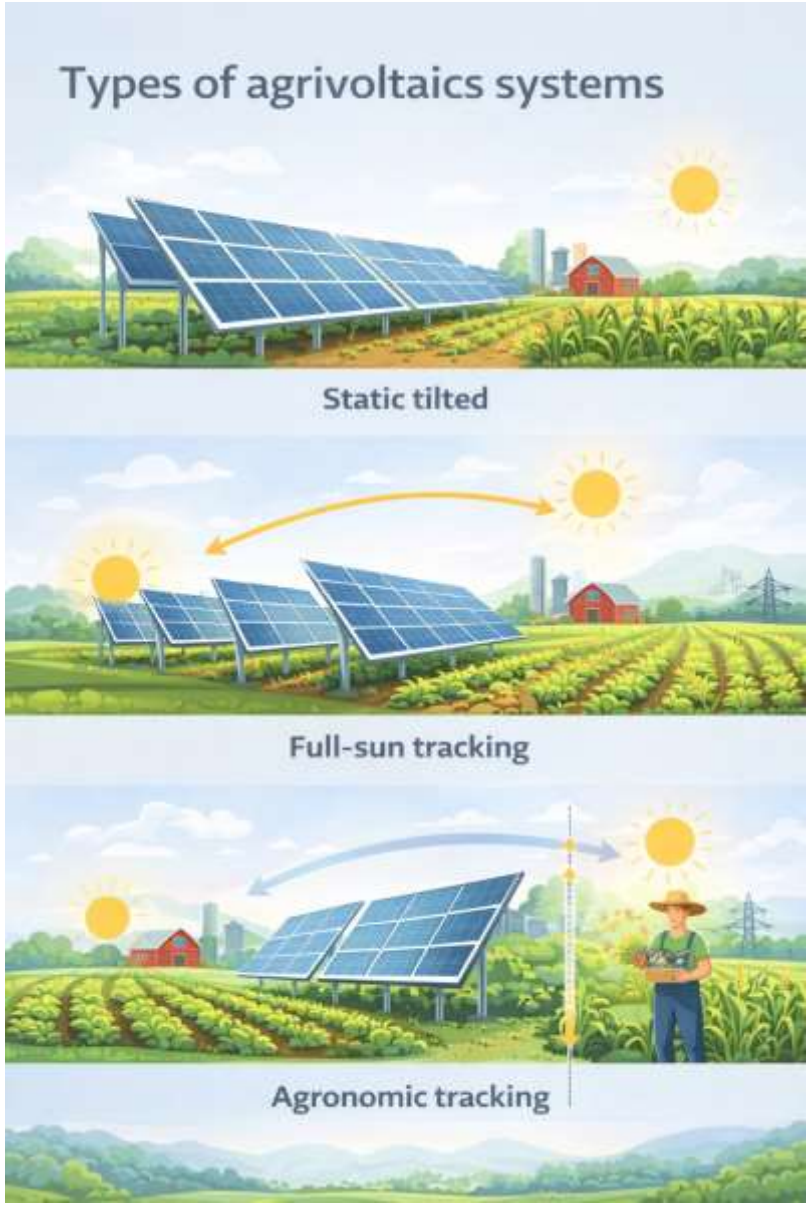
Agrivoltaics technologies

As the world seeks alternatives to fossil fuels, agrivoltaics offer a promising solution by integrating solar panels with farming practices.

Three key agrivoltaics setups:

- **static tilted,**
- **full-sun tracking,**
- **agronomic tracking**

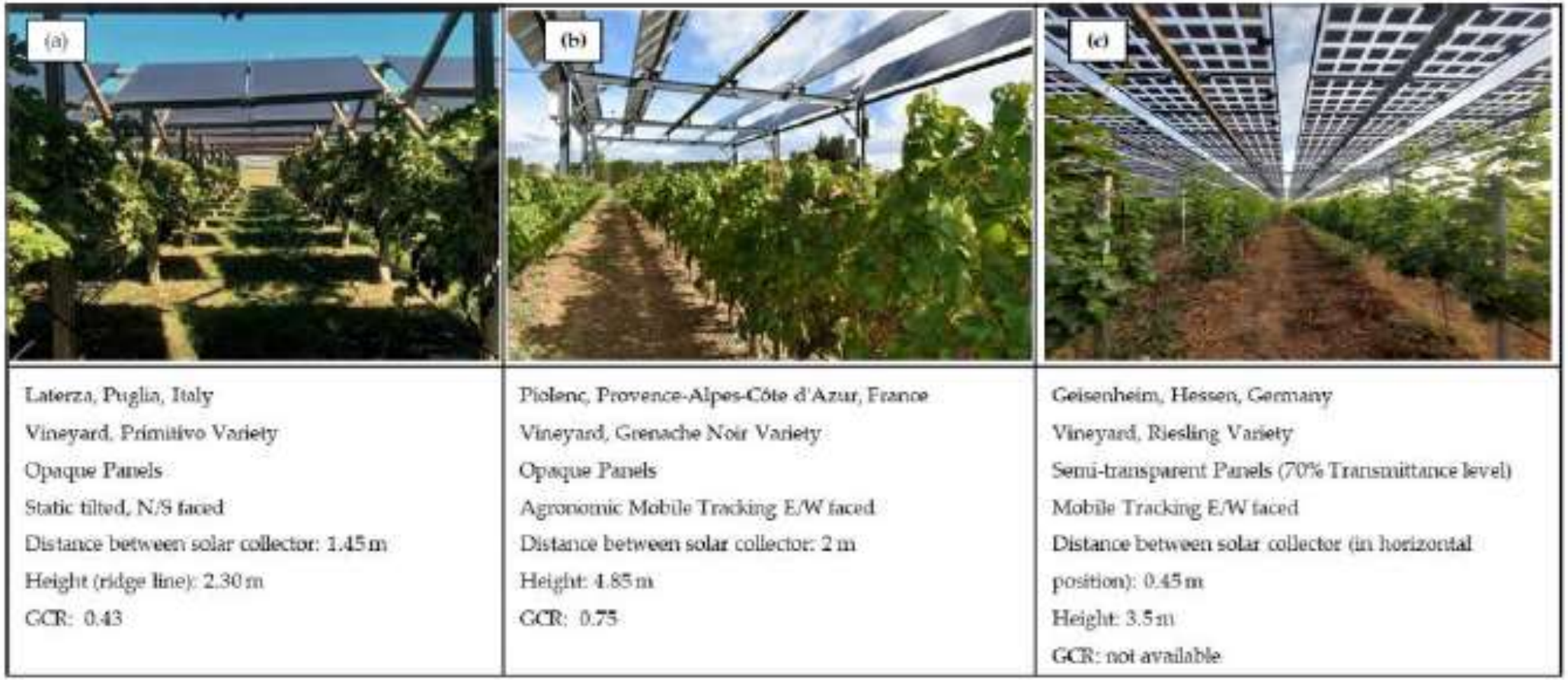
Optimizing both the electricity yield and the fruit productivity of some fruit crops.



Magarelli, Mazzeo & Ferrara (Agronomy 2024, 14, 722)

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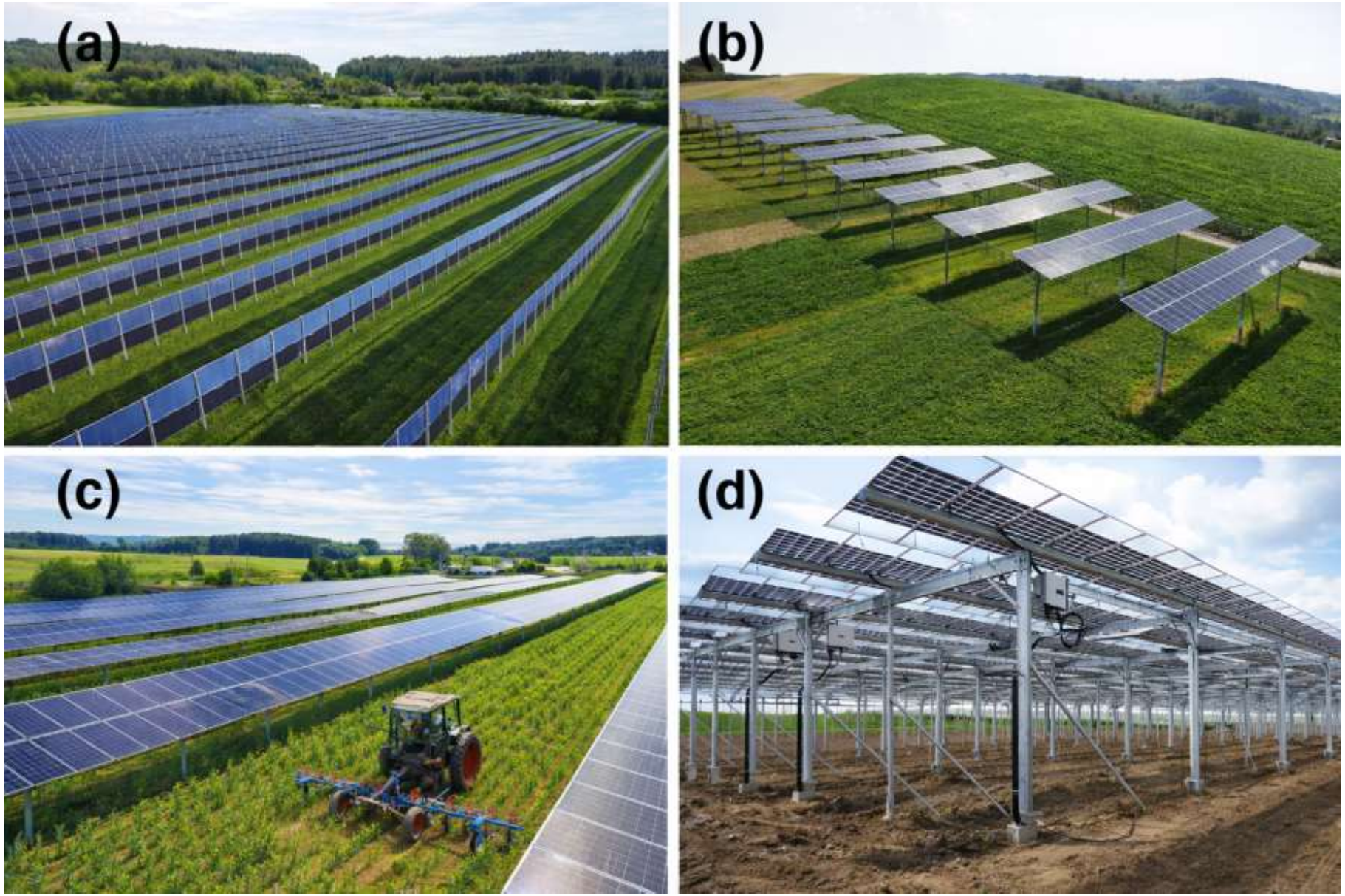
Static **Tracking panel** **Tracking panel**



Laterza, Puglia, Italy	Piolenc, Provence-Alpes-Côte d'Azur, France	Geisenheim, Hessen, Germany
Vineyard, Primitivo Variety	Vineyard, Grenache Noir Variety	Vineyard, Riesling Variety
Opaque Panels	Opaque Panels	Semi-transparent Panels (70% Transmittance level)
Static tilted, N/S faced	Agronomic Mobile Tracking E/W faced	Mobile Tracking E/W faced
Distance between solar collector: 1.45 m	Distance between solar collector: 2 m	Distance between solar collector (in horizontal position): 0.45 m
Height (ridge line): 2.30 m	Height: 4.85 m	Height: 3.5 m
GCR: 0.43	GCR: 0.75	GCR: not available

Figure 3. Three AV experimental sites with wine grape cultivation (a) . Static panels at height 2.30 m, ground coverage ratio (GCR) 0.43, and N/S oriented in Italy, (b) tracking panels at height 4.85 m, GCR 0.75, and E/W oriented in France, (c) tracking panels at height 3.50 m, GCR not available, and E/W oriented in Germany.

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Different types of agrivoltaic systems.

(a) Vertical system on grassland—farming between solar panels (Donaueschingen- Aasen, Germany, image credit: Next2Sun),

(b) System with clear height on arable land—farming under solar panels (Herdwangen-Schönach, Germany, image credit: BayWa r.e.),

(c) Ground level system on arable land—farming between solar panels (Althegnenberg, Germany, image credit: Matthias Baumgärtner Videofotografie/ÖKO-HAUS),

(d) System with clear height in orcharding—farming under solar panels (Ahrweiler, Germany, image credit: Fraunhofer ISE).

(Schweiger and Pataczek, 2023)

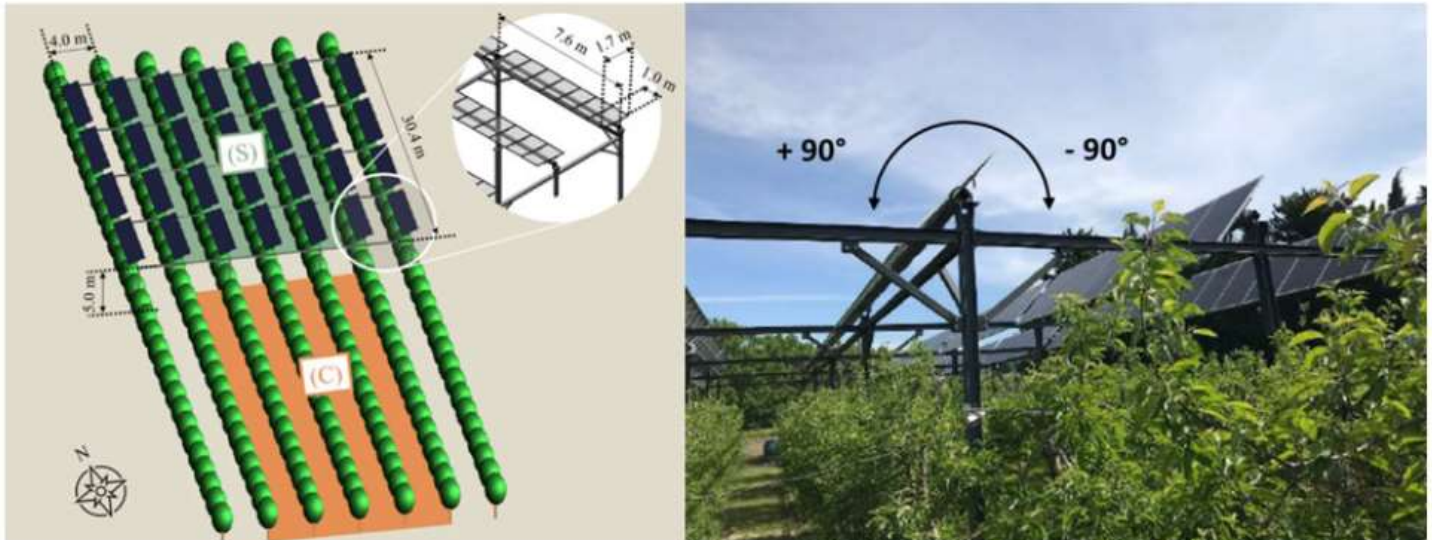
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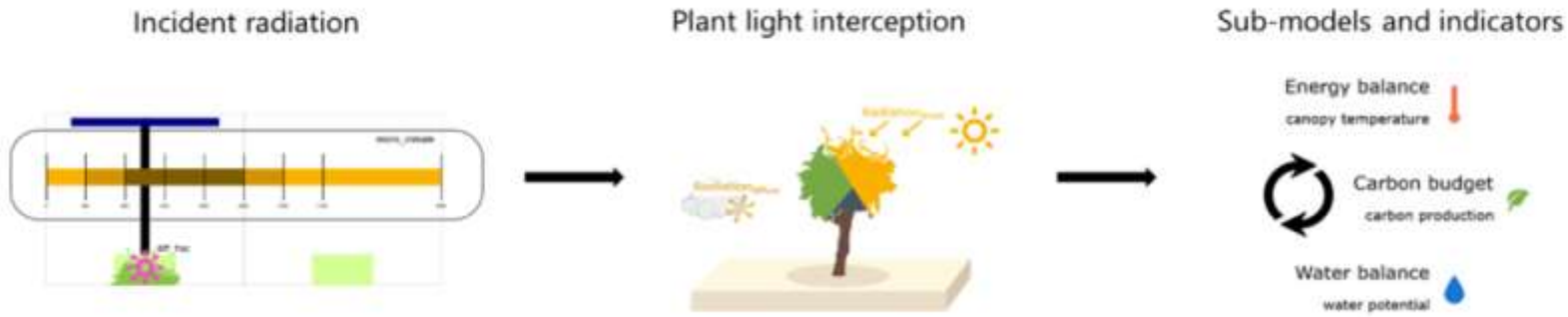
DAV system Sun'agri (FR)

DAV system is an orchard PV system with **rotating panels (±90°)** that can switch between **energy-optimized tracking** and **crop-optimized anti-tracking**, allowing **active microclimate + stress protection** while still generating electricity.

What is a DAV system? **A Dynamic Agrivoltaic System (DAV) is an agrivoltaic orchard system where PV panels are installed above the fruit tree sand the panels can rotate dynamically (not fixed) to control how much light reaches the orchard**

The key idea is: **Use PV panels not only for electricity, but also as an active "climate protection tool" for fruit trees.**





Lopez et al., 2023

Main Drivers of PV Energy Production

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Main Drivers of PV Energy Production

Electric output is strongly influenced by:

- **Solar radiation received**
- **Cell temperature** (high temperatures reduce power, cooler conditions improve efficiency)

Key geometric and environmental factors include:

- **Elevation height**
- **Tilt angle**
- **Spacing & density**
- **Azimuth angle**
- **Latitude and solar declination**
- **Shadow angles**
- **Zenith and hourly angles**
- **Vegetation under panels**

Sarr et al, 2023

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Panel Height: Evidence from Literature

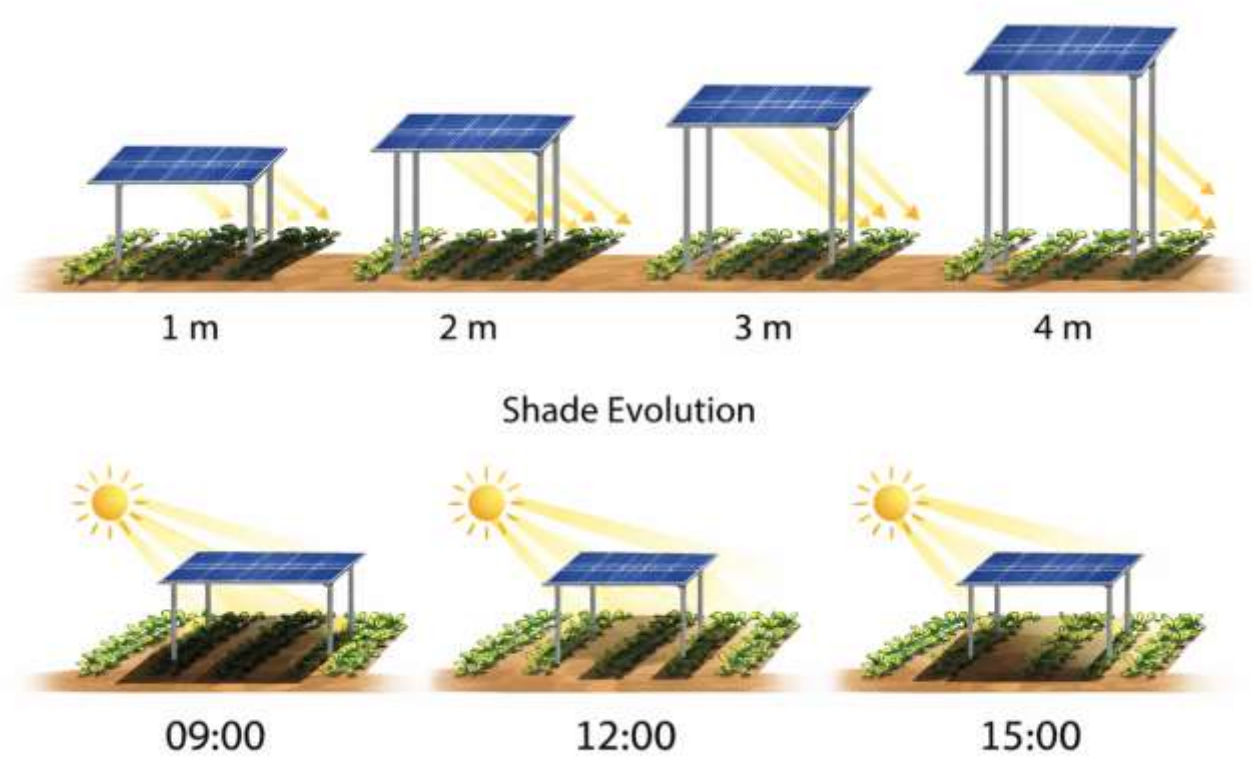
- **No universal optimal height**; depends on crop, machinery, climate, and economics.
- **Minimum practical heights**:

~1.8 m for vegetables;

~2.1 m for overhead systems;

~2.4 m is preferable for many crops.

- **Examples in literature**: 3 m (10 feet) (Japan), 4 m (13 feet) (Montpellier), 5 m (Germany), 3.3 m (11 feet) (USA), 5.2 m (17 feet) (Korea).



Height: governs machinery access, light distribution, and crop compatibility.

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Tilt, Orientation, and Tracking

Tracking increases flexibility for managing light under panels.

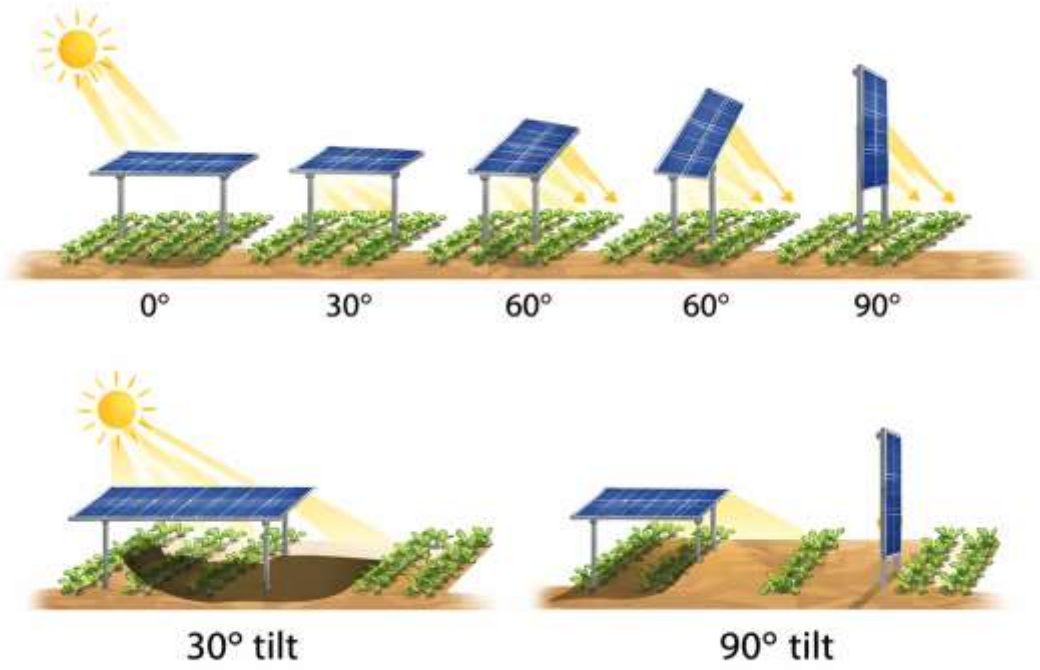
Single-axis: rotation around one axis (daily east–west or seasonal) like a door hinge.

- Shadow moves smoothly across crops
- More predictable light patterns

Dual-axis: combines azimuth (east–west) + tilt control (up/down elevation). Maximizes energy but has higher complexity.

- Can create more uneven light distribution
- Large arrays may produce strong shade patches

Tracking can also provide hail/radiation protection by changing panel orientation.



Tilt Angle	Panel Position
0°	Flat like a roof
30°	Standard inclined panel
60°	Very steep
80°	Almost vertical
90°	Perfectly vertical like a wall

- **Tilt & azimuth: determine energy yield and shading patterns.**

Mouhib et al., 2024

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Importance of Tilt and Orientation

- **Tilt angle** is the angle between the panel surface and horizontal ground.
  - Changing tilt changes the amount of solar radiation captured.
  - A common rule: tilt ≈ site latitude.
- **Azimuth angle** defines the compass direction of panel orientation:
  - 90° = East
  - 0° = South
  - –90° = West
  - 180° = North

Panels generally face:

- **South in the Northern Hemisphere**
- **North in the Southern Hemisphere**

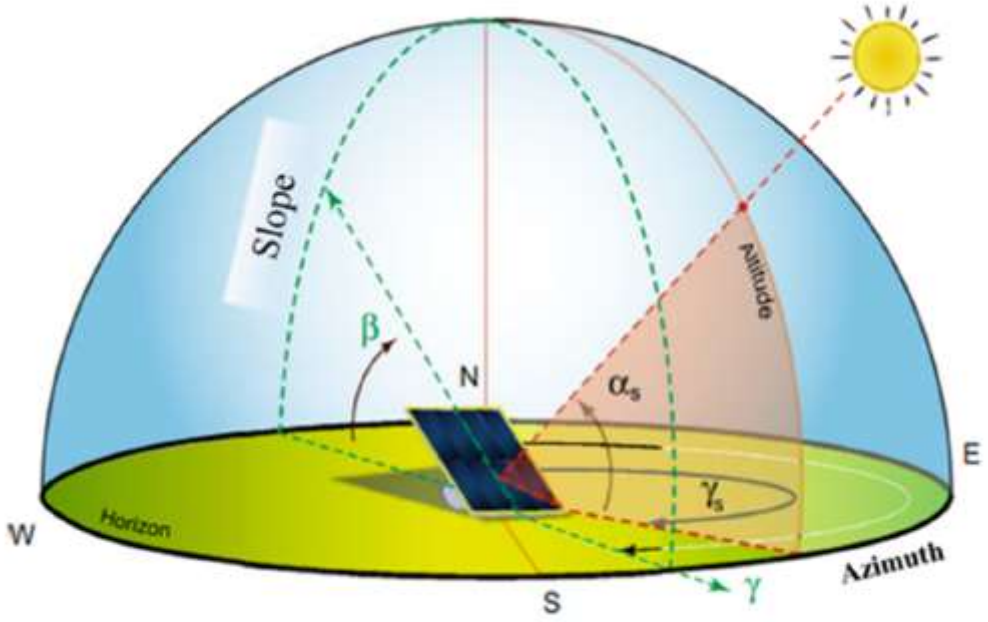


Figure 10. Factors affecting the performance of solar PV panels [87].

Sarr et al, 2023

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Additional Performance Factors

Other important influences include:

- **Albedo** (ground-reflected radiation)
- **Vertical shadow angle**
- **Declination and hourly angles**
- **Zenith angle**

These determine shading patterns and radiation reaching the panels.



Sarr et al, 2023

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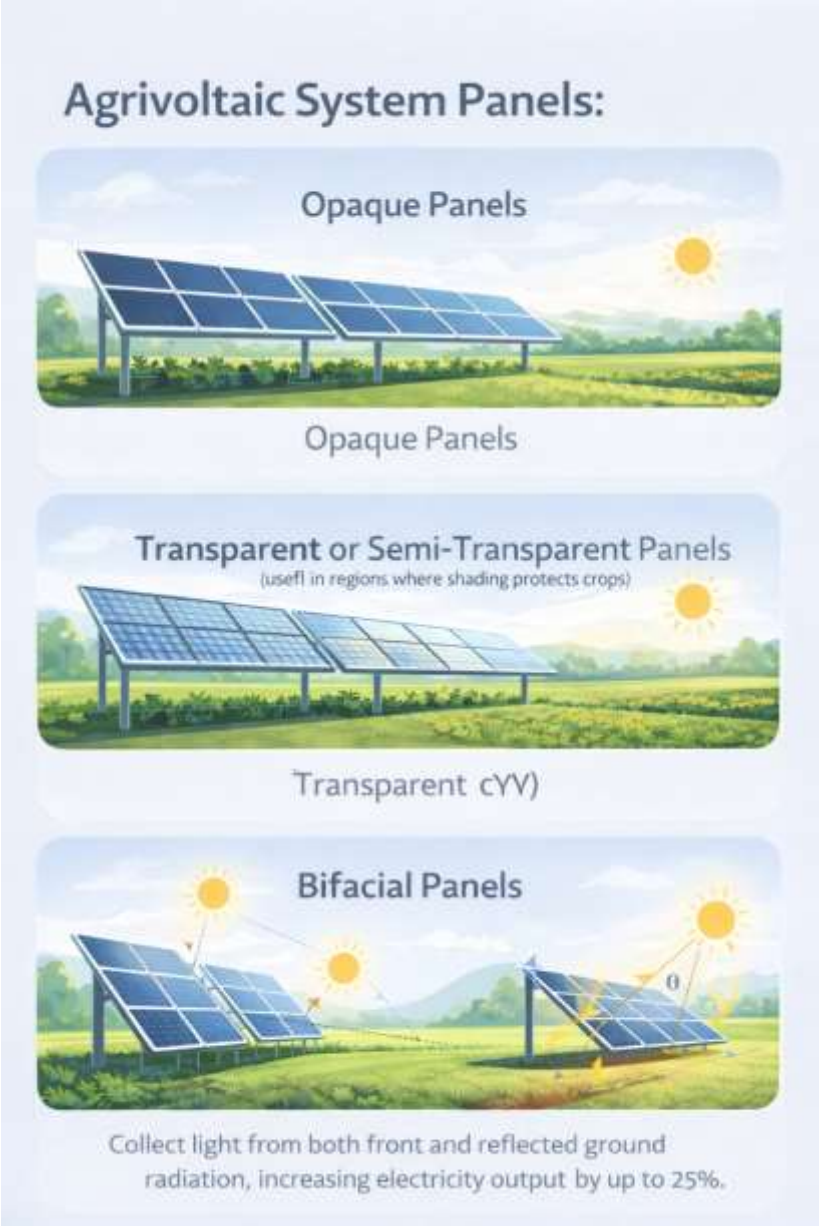
Solar cell Types

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PV Module Types Used in Agrivoltaics

Agrivoltaic systems may use:

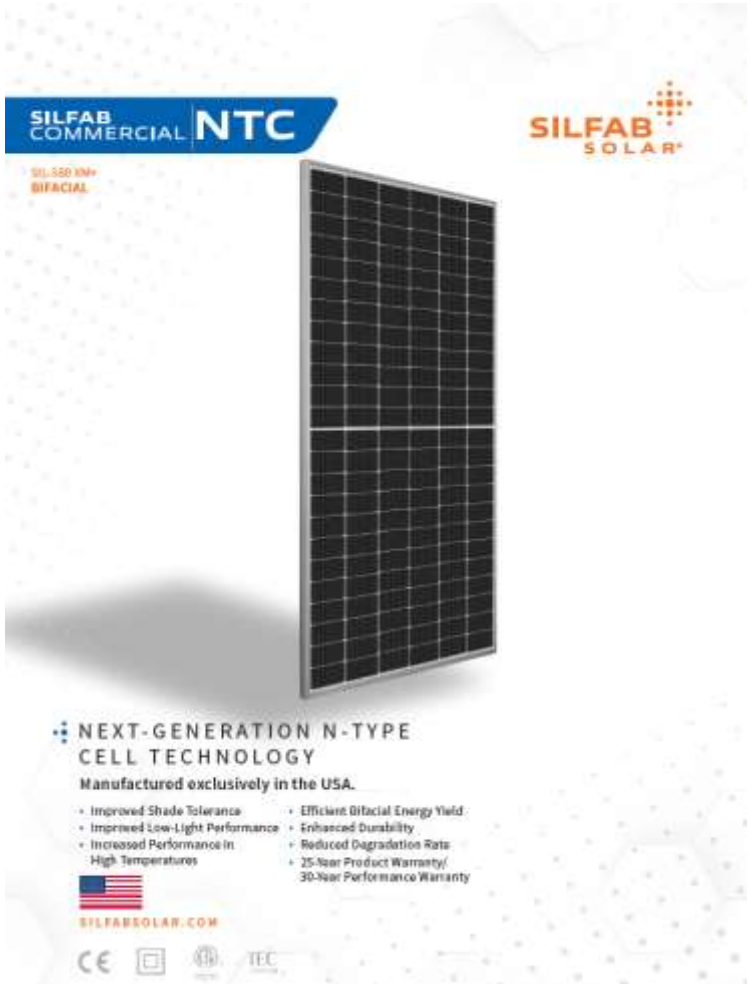
- **Opaque panels**
- **Transparent or semi-transparent panels** (useful in regions where shading protects crops)
- **Bifacial panels**, which collect light from both front and reflected ground radiation, increasing electricity output by up to **25%**.



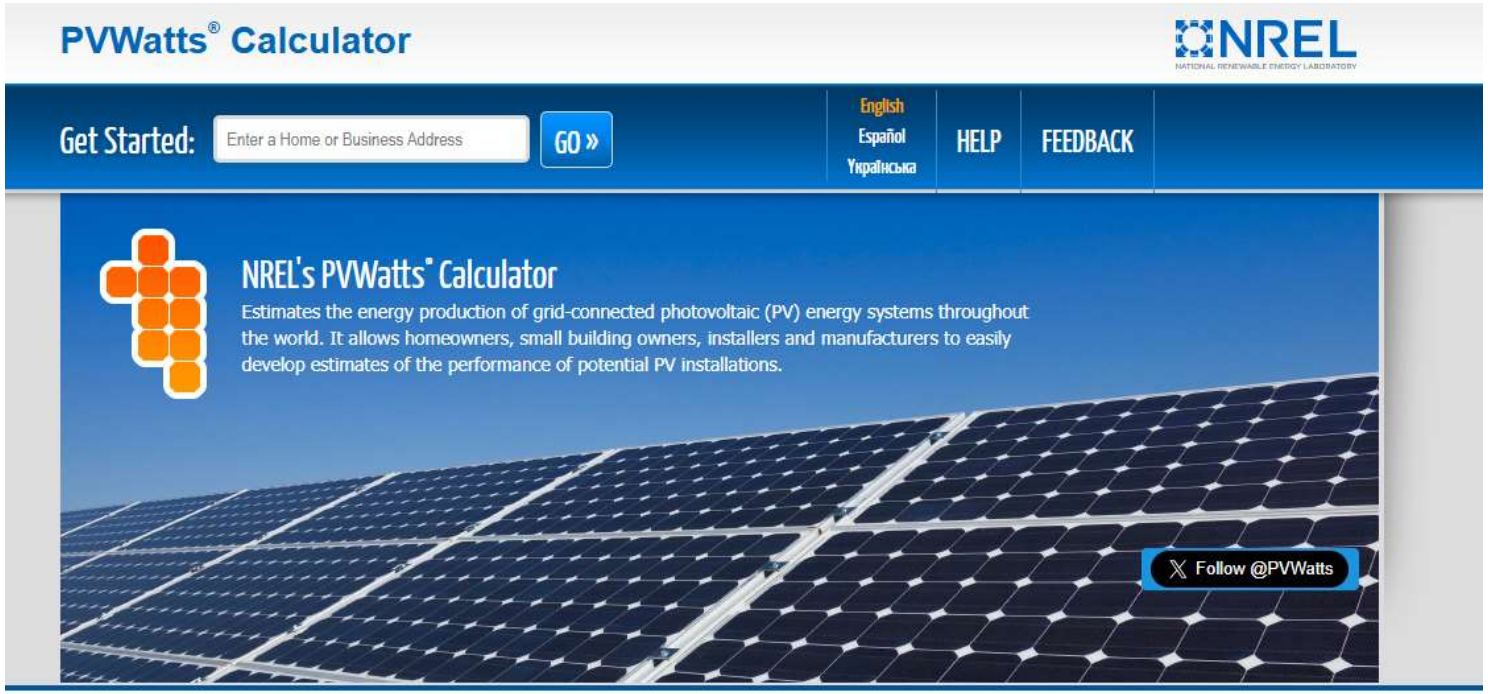
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Example PV module specifications



MECHANICAL PROPERTIES / COMPONENTS	METRIC	IMPERIAL
Module weight	28.5 kg ±0.2 kg	62.8 lbs ±0.4 lbs
Dimensions (H x L x D)	2278 mm x 1133 mm x 35 mm	89.7 in x 44.6 in x 1.4 in
Maximum surface load (wind/snow)*	2400 Pa rear load / 5400 Pa front load	50.1 lb/ft² rear load / 112.8 lb/ft² front load
Hail impact resistance	ø 25 mm at 83 km/h	ø 1 in at 51.6 mph
Cells	144 Half cells - N-Type Silicon solar cell 182 mm x 91 mm	144 Half cells - N-Type Silicon solar cell 7.16 in x 3.58 in
Glass	3.2 mm high transmittance, tempered, anti-reflective coating	0.126 in high transmittance, tempered, anti-reflective coating
Cables and connectors (refer to installation manual)	1350 mm, ø 5.7 mm, EVO2 from Staubli	53.1 in, ø 0.22 in (12 AWG), EVO2 from Staubli
Backsheet	High durability, superior hydrolysis and UV resistance, multi-layer dielectric film, transparent PV backsheet	
Frame	Anodized Aluminum (Silver)	
Junction Box	UL 3730 Certified, IEC 62790 Certified, IP68 rated, 3 diodes	



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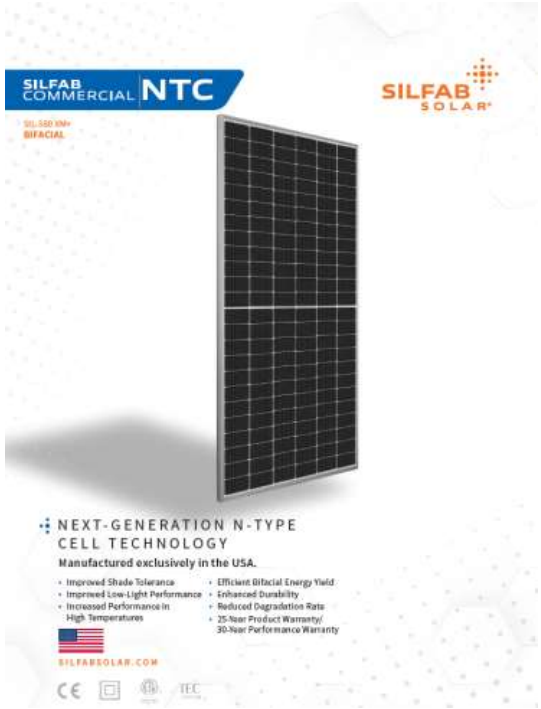
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Example PV module specifications



580 W module
Module size = **0.58 kW**
- **Low case:** 1,854 × 0.58 ≈ **1,075 kWh/year per module**
- **High case:** 2,228 × 0.58 ≈ **1,292 kWh/year per module**

Planning range for Wenatchee DAV (per SIL 580 bifacial module): ~1.1 to 1.3 MWh/year

That is:
- **1,100–1,300 kWh per year**
- about **3.0–3.6 kWh per day on average**

Household comparison
A typical U.S. home uses roughly **10,000–12,000 kWh/year**.
So **one module** could cover roughly:
~9–13% of one home's annual electricity

Orchard operations
Irrigation pumping (example)

If a pump uses 5 kW, then:1,200 kWh / 5 kW = 240 hours of pumping=

about 10 full days of pumping per year (24h/day)

or more realistically:30 days of pumping at ~8 hours/day

https://pvwatts.nrel.gov/?utm_source

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Land Use Efficiency Concepts

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Land Equivalent Ratio (LER)

- **Land Equivalent Ratio (LER) is** a widely used **index** in intercropping / agroforestry / agrivoltaics **to quantify how efficiently land is used when two (or more) products are produced together on the same land compared with producing them separately (monocultures).**

For a system with two components (e.g., crop A and crop B):

- $LER = \frac{Y_{A,\,mix}}{Y_{A,\,sole}} + \frac{Y_{B,\,mix}}{Y_{B,\,sole}}$

Where:

- $Y_{A,mix}$ **=yield of A in the mixed system (intercrop / agrivoltaic / alley crop, etc.)**
- $Y_{A,sole}$ **=yield of A grown alone (monoculture)**
- $Y_{B,mix}$ **=yield of B in the mixed system**
- $Y_{B,sole}$ **=yield of B grown alone**

Each term is called a partial LER:

- $LER_A = Y_{A,mix}/Y_{A,sole}$
- $LER_B = Y_{B,mix}/Y_{B,sole}$
- **Total LER = LER_A+LER_B**

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Land Use Efficiency: Example calculation

Suppose:

- Apples yield under agrivoltaics: **40 tons/ha**
- Apples yield in a standard orchard: **50 tons/ha**
- Energy yield under agrivoltaics: **300 MWh/ha**
- Energy yield in a standalone solar farm: **350 MWh/ha**
- $LER = \frac{40}{50} + \frac{300}{350} = 0.80 + 0.857 = 1.657$

LER = 1.66 → This means **1 ha of agrivoltaics produces the equivalent output of 1.66 ha** of separate apple + solar production (a strong land-use advantage).

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Microclimate

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Air Temperature Effects Under Agrivoltaics (APV)

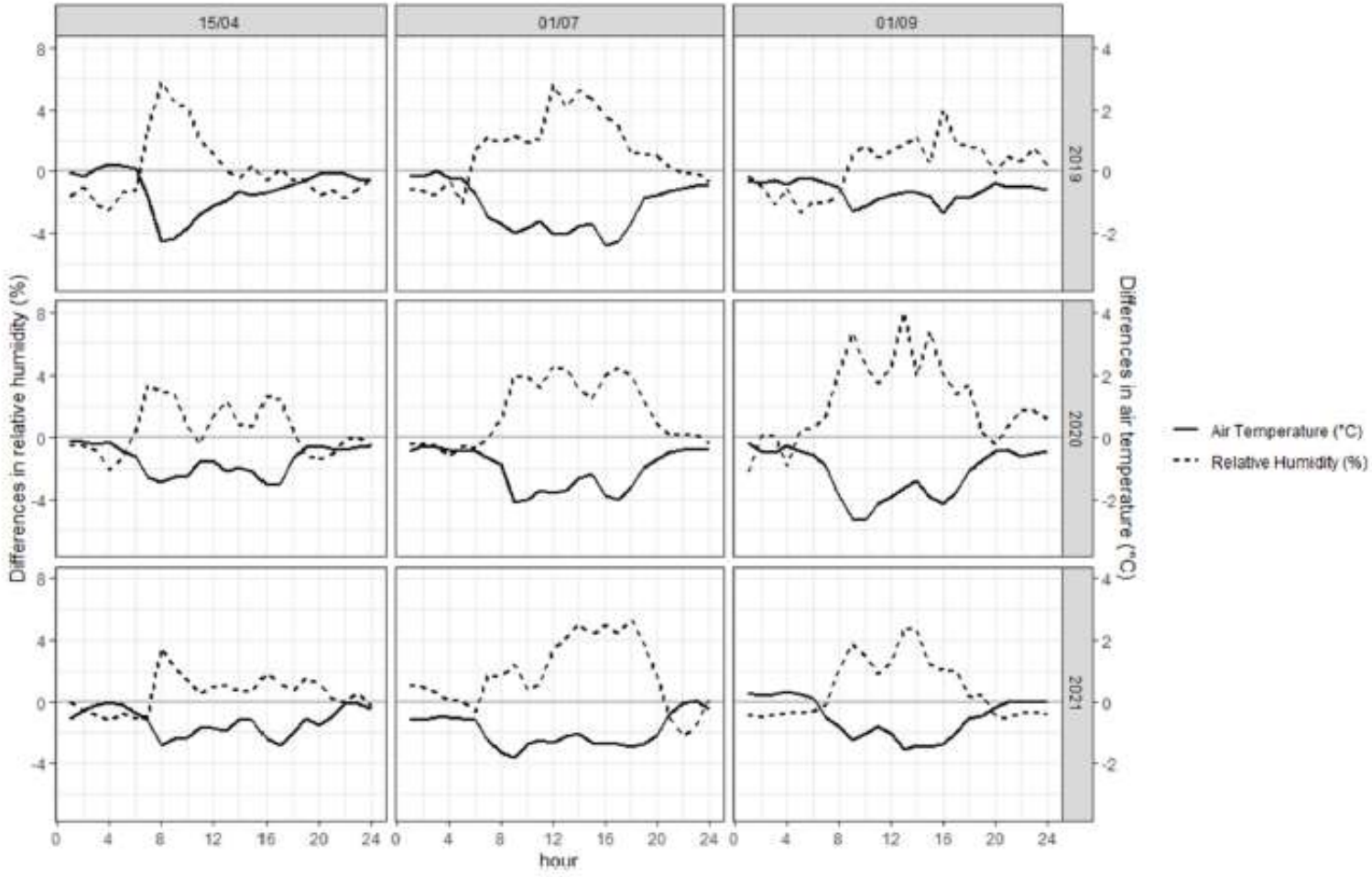


Fig. 3. Air temperature (°C) and relative humidity (%) differences between Shade and Control treatments (Shade – Control) for three clear sunny days, in 2019, 2020 and 2021 in La Pugère, Mallemort, South of France.

- Jullion et al. (apple trees, France) reported up **to ~4°C daytime difference, while nighttime conditions were similar** (often slightly cooler under PV).

Juillion et al., 2022

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Air Temperature and wind

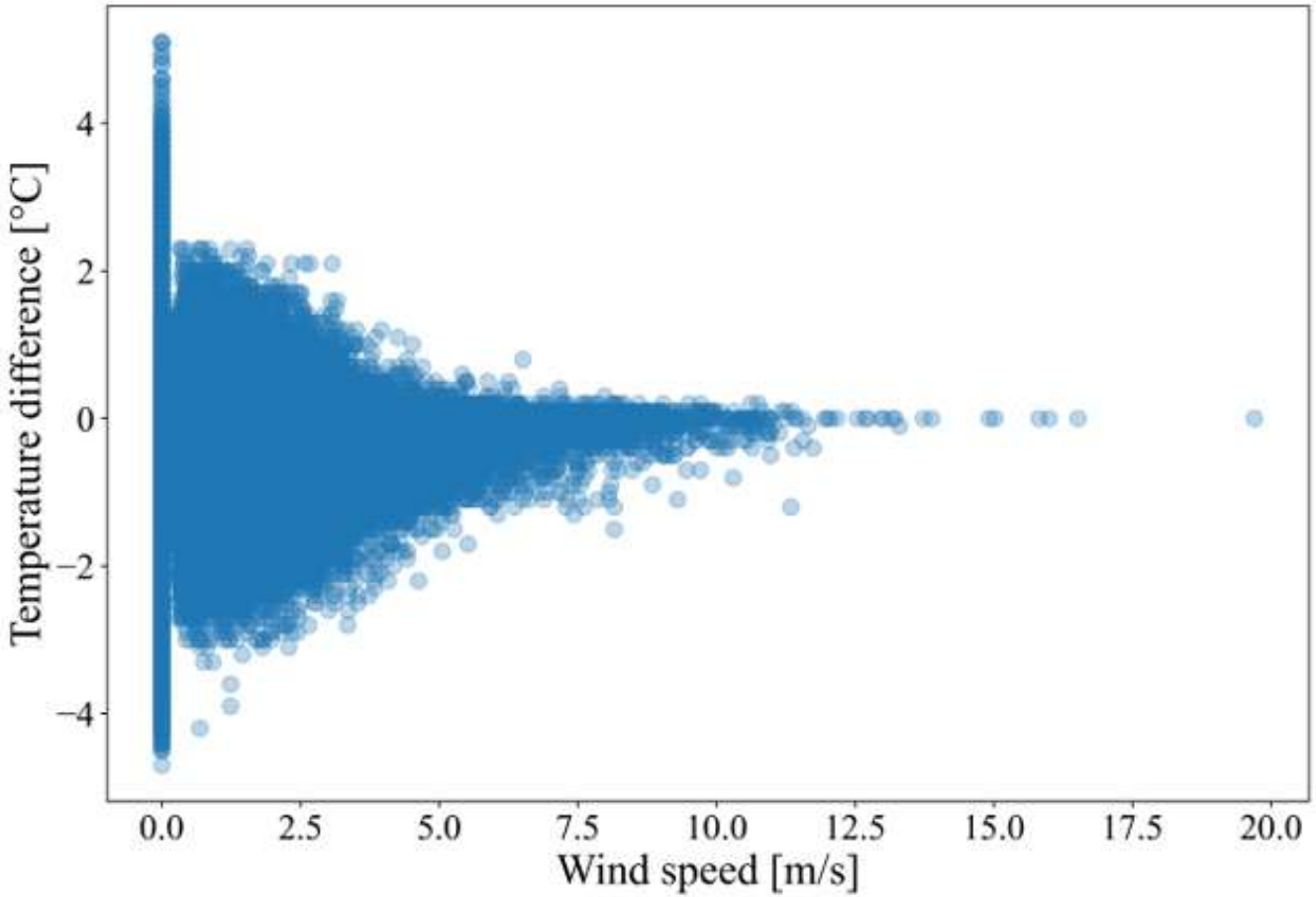
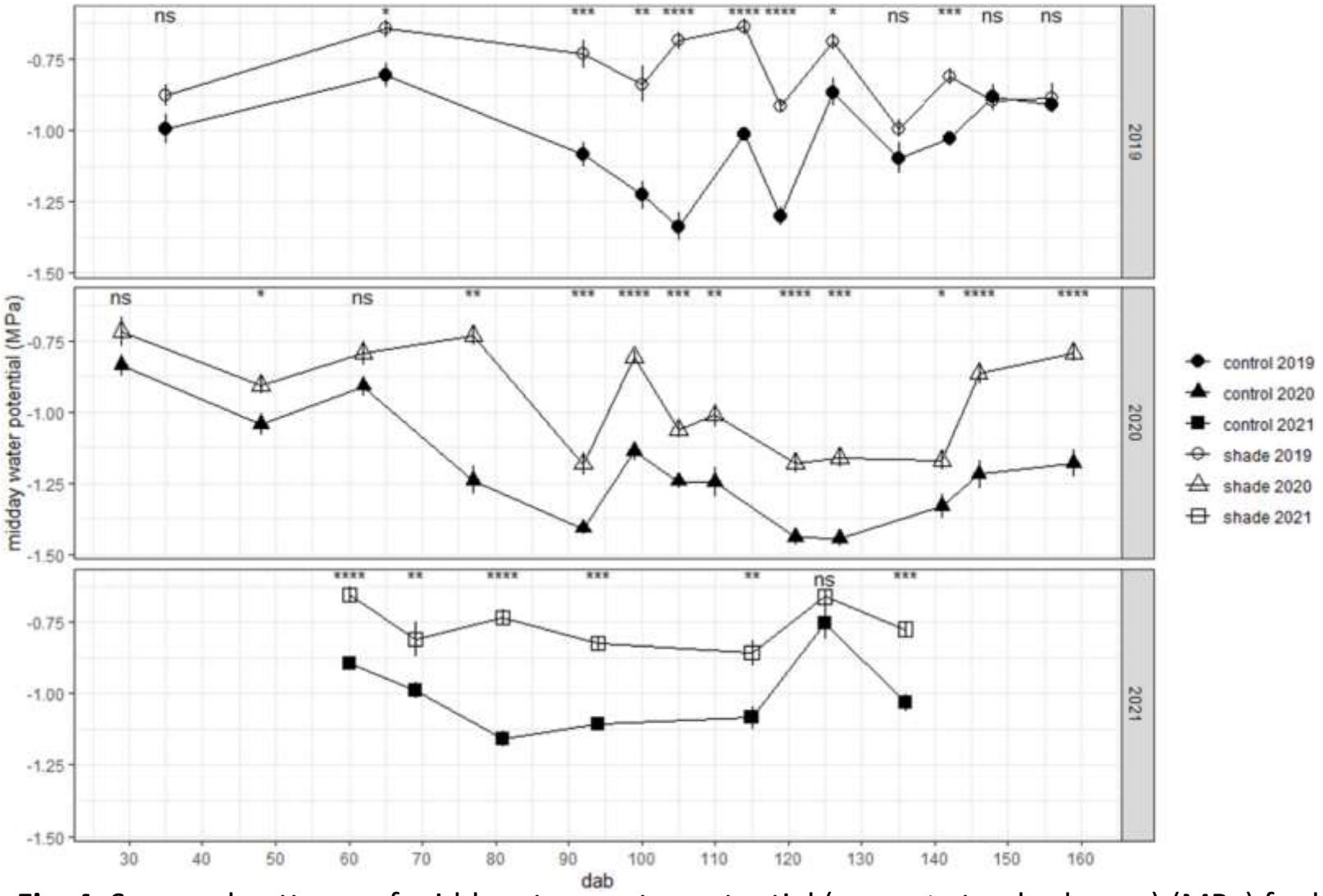


Fig. 20. Temperature difference between the reference and agrivoltaic area, depending on the wind speed. Largest differences are measured in wind-free conditions, resulting from a change in the soil/tree energy balance.

Willockx et al., 2024

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How Agrivoltaics Affects Drought



- Increased shading under panels can:
  - **increase soil water availability**
  - **reduce evaporative demand** (lower atmospheric drying power)
  - improve **plant water status**
  - and support **plant growth during drought periods**

Juillion et al., 2022

Fig. 4. Seasonal patterns of midday stem water potential (mean ± standard error) (MPa) for leaves of the Shade and Control groups during the 2019, 2020 and 2021 growing seasons (in day after bloom). Each point represents nine measurements (three leaves per tree) (ns: $P > 0.05$; *: $P \leq 0.05$;**: $P \leq 0.01$; ***: $P \leq 0.001$; ****: P

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Microclimate: soil effects

- **Soil temperature responses are inconsistent** (warming vs cooling) across sites/configurations.
- **Soil moisture often improves under panels**; runoff can create strong spatial heterogeneity.
- **Models predict reduced water consumption**, especially in arid/semi-arid contexts.

Magarelli, Mazzeo & Ferrara (Agronomy 2024, 14, 722)

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AGRIVOLTAICS RESULTS ON DIFFERENT CROPS

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Table 1. Scientific publications involving fruit species grown under agrivoltaic systems.

Fruit Crop Tested	Location	Type of Panels	Structure	Ground Coverage Ratio	Shading Rate (%)	Energy Production	Remarks		References
							Yield	Fruit Quality	
Apple	Mallemort, France	Single-axis horizontal, adaptive solar tracking	Opaque	0.43	42%	-	Yield reduction from 27 to 32%, alternate bearing reduction	Minimum standard reached, but lower sugar concentration	[48,58,65]
Pear	Bierbeek, Belgium	double-sided, static, inclined	Semitransparent	0.6	35%	950 kWh/kWp	A 16% yield reduction (estimation)	Similar quality (estimation)	[32]
Grape	Valpolicella, Italy	Static, tilted	Opaque	-	75%	-	Observed a decrease in yield, at least in two years	Total soluble solids were lower, reduction in both polyphenols and anthocyanins	[55]
Grape	Yeongheung, South Korea	Static, tilted	Opaque	-	<30%	-	Not significantly affected	Did not affect sugar content or anthocyanins, delay in skin coloration	[61]
Grape	Gyeongsan, South Korea	Static on umbrella-shaped facility, tilted	Opaque, bifacial, semitransparent	-	≤30%	Opaque: 25.2 MWh Bifacial: 21.6 MWh Semi-transparent: 25.7 MWh	Not available (berry weight and number not affected except for opaque type)	Similar sugar-content level, delay in coloration	[46]
Kiwifruit	Puijiang County, China	Static, tilted	Semitransparent	0.15; 0.25; 0.31	19%; 30.4%, 38%	-	Remarkable yield reduction	Fruit volume reduction	[56]
Cranberries	Massachusetts, USA	Fixed	Plywood sheet	-	29.3–41.5%	-	Significantly reduced yield	Significantly reduced fruit firmness and total soluble solids, skin color not affected	[54]

Magarelli, Mazzeo & Ferrara (Agronomy 2024, 14, 722)

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Yield impacts: main pattern

- **Low–moderate shading (~30%):** productivity often maintained or slightly affected (~5%).

- **Moderate to high shading (30–60%):** yield losses reported ~16–42% depending on crop and site.

- **High shading (>60%):** limited data; often associated with significant yield/quality penalties.

Magarelli, Mazzeo & Ferrara (Agronomy 2024, 14, 722)

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Fruit quality impacts

- **Higher shading (>30%) often reduces starch/sugar accumulation** and modifies sugar/acid balance.

- **Fruit skin coloration is sensitive**: delays of ~10 days reported in grapes under low shading.

- In some **regions, shaded fruit can be greener at harvest;** polyphenols/anthocyanins may decline.

Magarelli, Mazzeo & Ferrara (Agronomy 2024, 14, 722)

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Species snapshot: apple

- **Reported yield reduction ~27–32%** under ~42% shade (adaptive tracking).
- **Potential alternate-bearing** moderation via reduced floribundity.
- **Quality standards generally met, but sugar concentration can be lower.**

Magarelli, Mazzeo & Ferrara (Agronomy 2024, 14, 722)

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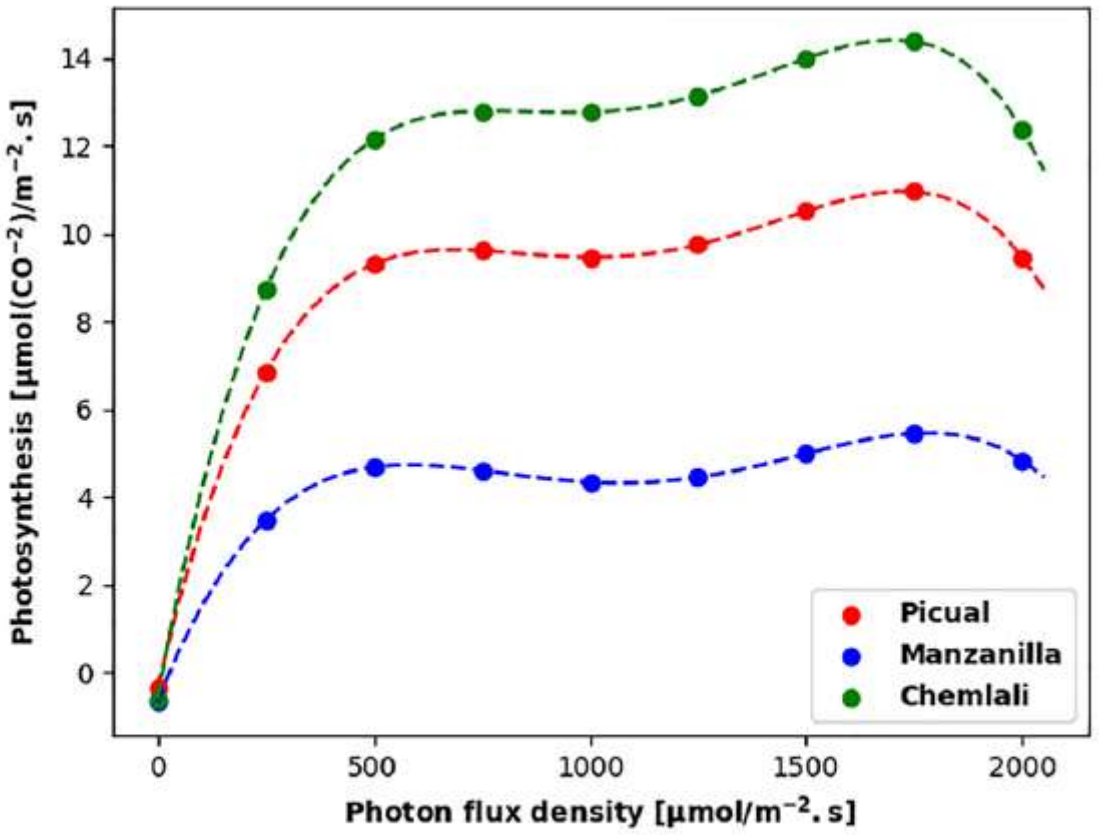


Fig. 5. Photosynthetic light response curves of three different olive tree varieties plotted against photosynthetic photon density.

- Manzanilla is more sensitive at moderate light levels (more shade) because it has a **lower light saturation point**

Applied Energy 359 (2024) 122660

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Enhancing land use: Integrating bifacial PV and olive trees in agrivoltaic systems

Elmehdi Mouhib [a,*], Álvaro Fernández-Solas [a], Pedro J. Pérez-Higueras [a], Ana M. Fernández-Ocaña [b], Leonardo Micheli [c], Florencia Almonacid [a], Eduardo F. Fernández [a]

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[b] Departamento de Biología Animal, Biología Vegetal y Ecología, Facultad de Ciencias Experimentales, University of Jaén, Las Lagunillas Campus, Jaén 23071, Spain
[c] Department of Astronautical, Electrical and Energy Engineering (DIAEE), Sapienza University of Rome, 00184 Rome, Italy

- The study optimizes agrivoltaic systems combining **bifacial photovoltaic panels with super-intensive olive orchards to maximize dual land productivity (electricity + crop yield).**
- **Three olive cultivars were analyzed: Picual, Manzanilla, and Chemlali,** showing similar response patterns to shading.
- Key **PV design parameters tested were tilt angle (0°–90°) and hub height (3.0–4.5 m),** constrained by agricultural machinery clearance.
- PV energy yield is maximized when tilt angle is close to site latitude (~38°), peaking around 37.77°.
- **Vertical PV panels (90° tilt) reduce PV energy output drastically,** by about 50% compared with optimal tilt.

Mouhib et al., 2024

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Pear Orchard Case Study (Willockx et al. 2024)

Applied Energy 353 (2024) 122166

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Design and evaluation of an agrivoltaic system for a pear orchard

Brecht Willockx [a,*], Thomas Reher [b], Cas Lavaert [a], Bert Herteleer [a], Bram Van de Poel [b,c], Jan Cappelle [a]

[a] Electrical Energy Systems and Applications (ELECTA) Ghent, KU Leuven, Gebroeders De Smetstraat 1, Ghent, 9000, Belgium
[b] Molecular Plant Hormone Physiology Lab, Division of Crop Biotechnics, Department of Biosystems, KU Leuven, Willem De Croylaan 42, Leuven, 3001, Belgium
[c] KU Leuven Plant Institute (LPI), University of Leuven, Arenbergpark 30, Leuven, 3001, Belgium



Fig. 3. Dimensions of the selected pear orchard with hail netting system. The pear trees are 2.4 m high, planted at 1 m distance. The interspace between the rows is 3.3 m and the hail netting system is 4.2 high.

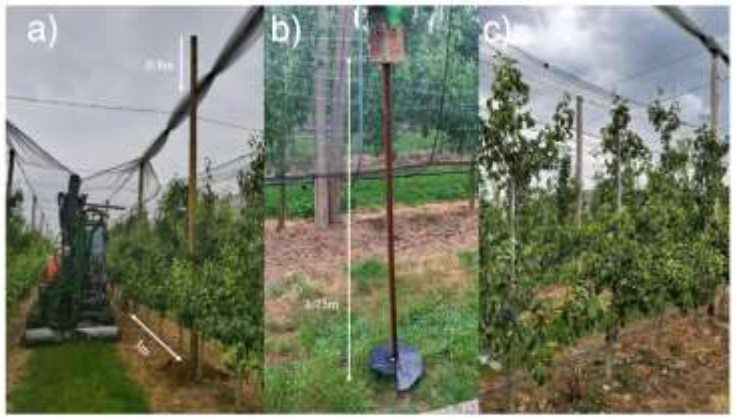


Fig. 5. First steps in the building process to reinforce the base structure. (a) additional wooden pillars are placed resulting in a maximum span of 3.3 m (b) helix ground anchors with (c) steel cables are placed for wind stability and uplifting.



Fig. 7. Last step in the building process: wind bracings are attached in both longitudinal and lateral direction (indicated with white arrows), with respect to the machinery dimensions.



Fig. 6. Next steps in the building process. (a) the aluminium upper-structure is placed, fixed at the wooden pillars with L-profiles. (b) the PV modules are placed on the triangles.



Fig. 8. Picture of the IMT Si-reference cell placed in the plane of array (POA).

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Pear: Light, Yield, and Quality 1

Key Results (Pear Orchard Agrivoltaics Study)

- **Remaining PAR under APV** was about **~65%** compared to the reference hail-net area.
- **Pear yield decreased by ~16.4%** (relative yield ≈ **84%**) mainly due to:
  - fewer fruits
  - slightly smaller fruit size
- **Fruit quality remained essentially unchanged**, including:
  - Brix (sugars)
  - firmness
  - color
  - storability

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PV Energy Performance

- **First-year PV production: ~12.74 MWh**
- **Specific yield: ~956 kWh/kWp**
- **Self-consumption: ~85%**

Pear: Light, Yield, and Quality 2

Land Use Efficiency (LER)

- The system achieved a **Land Equivalent Ratio (LER) ≈ 1.44**, indicating strong land-use efficiency.
- LER calculation logic:
  - crop relative yield: **84%**
  - PV relative yield: **60%** (from **40% transparency**)
  - **LER = 0.84 + 0.60 = 1.44**
- LER = **1.44** is considered high compared to other mixed land-use systems (e.g., agroforestry).

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Apple Orchard Case Study (Juillion et al. 2022)

- Daytime cooling under panels (up to ~3–4 °C) and increased RH.
- Reduced evaporative demand improved tree water status.
- Irrigation requirement reduced ~6–31% depending on year.

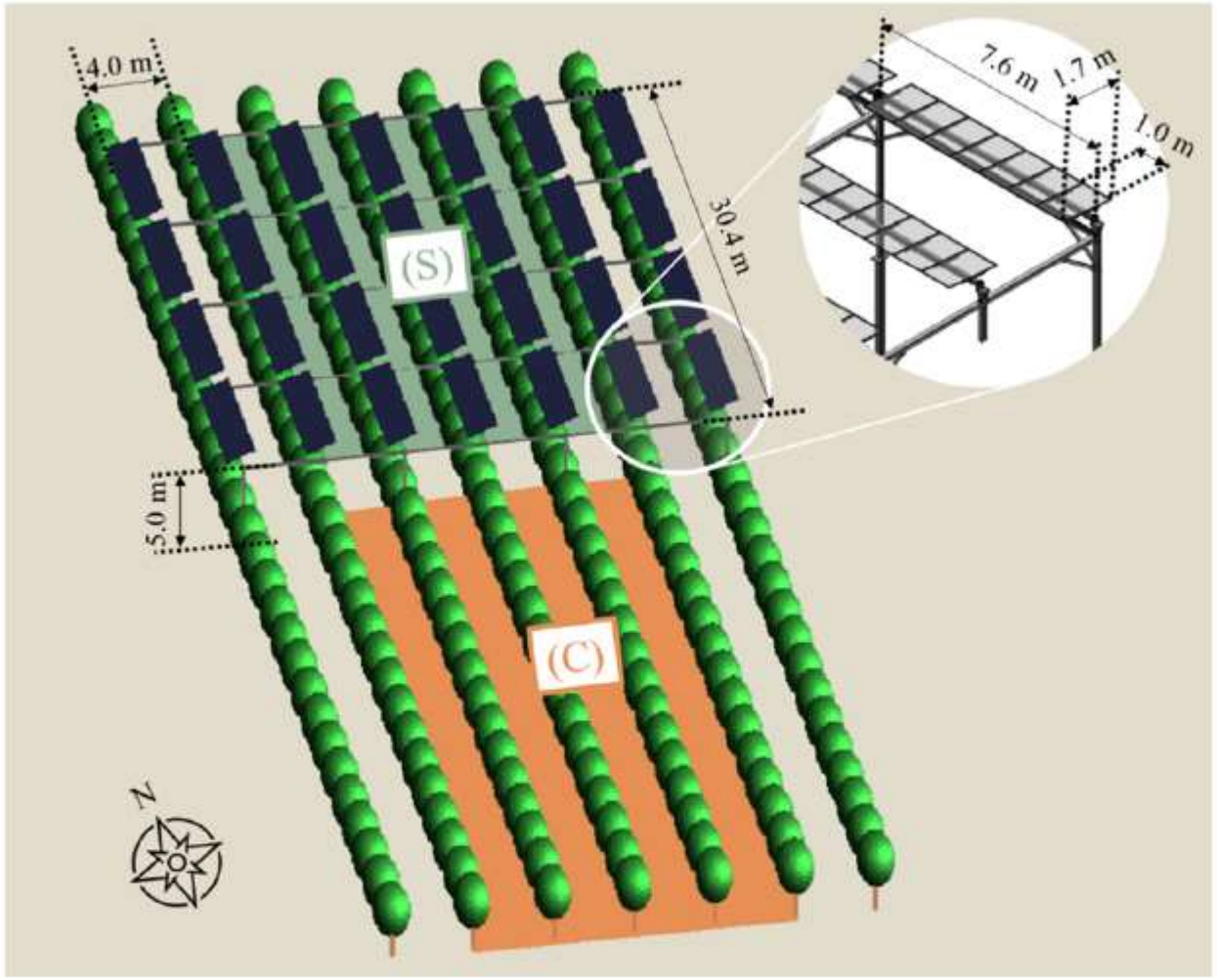


Fig. 1. Agrivoltaic system above 10-year-old 'Golden Delicious' orchard in the southeast of France (Mallemort, France: 43.74 °N; 5.125 °E) with two distinct plots: Shade (S) under photovoltaic panels and Control (C) without photovoltaic panels.


Scientia Horticulturae 306 (2022) 111434

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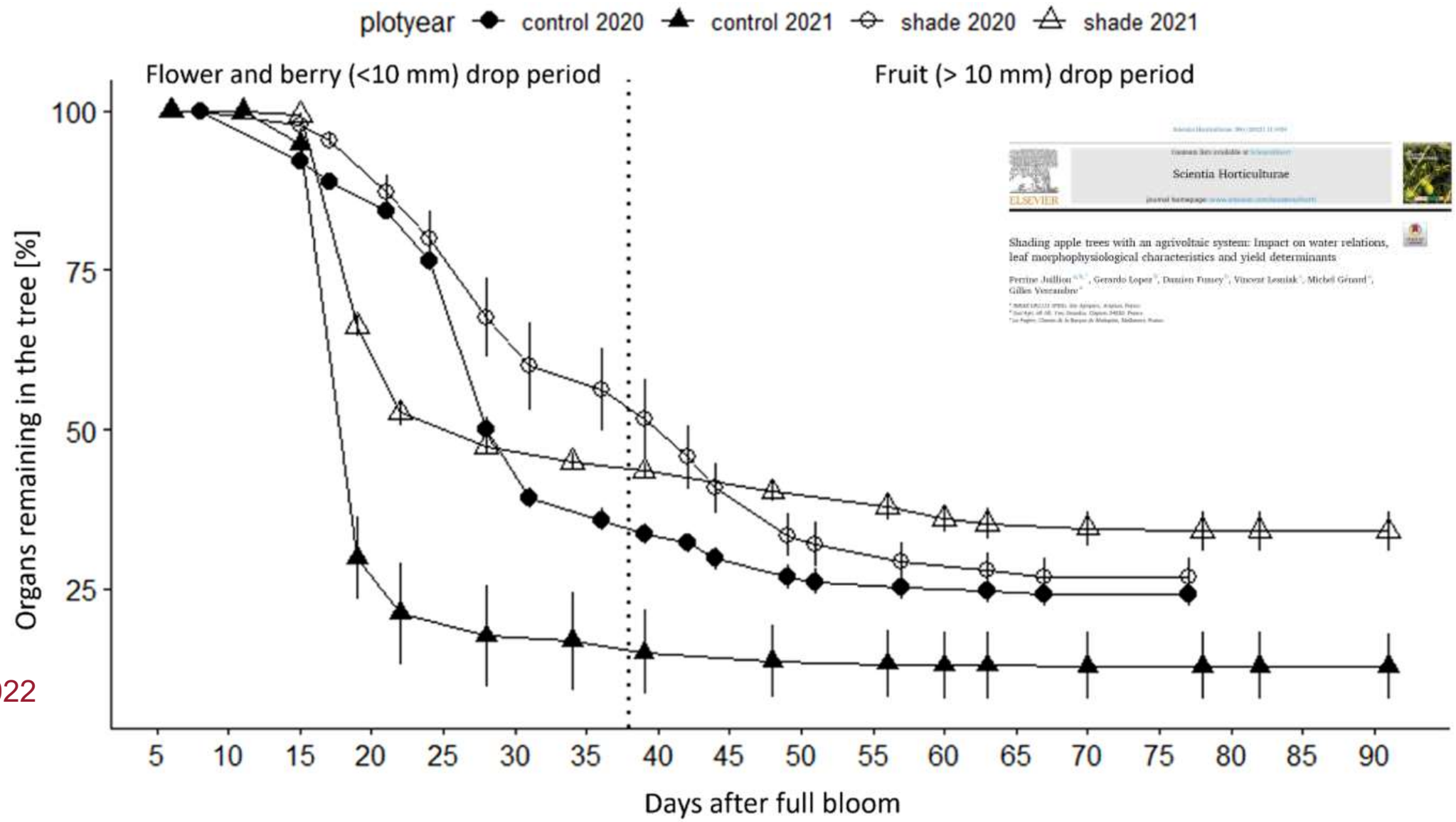
Shading apple trees with an agrivoltaic system: Impact on water relations, leaf morphophysiological characteristics and yield determinants

Perrine Juillion [a,b,*], Gerardo Lopez [b], Damien Fumey [b], Vincent Lesniak [c], Michel Génard [a], Gilles Vercambre [a]

[a] INRAE-UR1115 (PSH), Site Agroparc, Avignon, France
[b] San Agri, 60 All. Yves Saurdac, Clapiers 34830, France
[c] La Pugère, Chemin de la Barque de Malespine, Mallemort, France

Juillion et al., 2022

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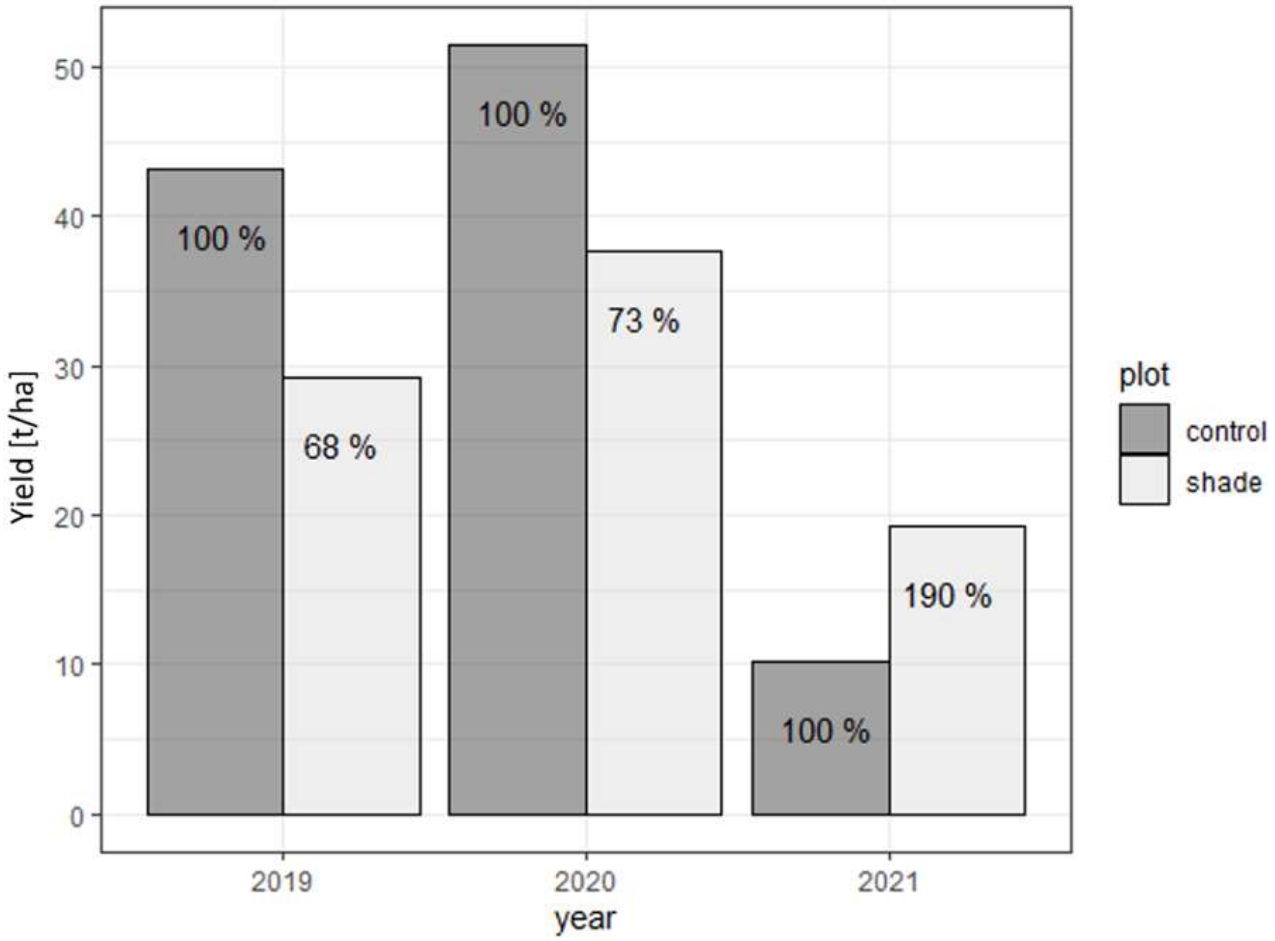
Scientia Horticulturae

Shading apple trees with an agrivoltaic system: Impact on water relations, leaf morphophysiological characteristics and yield determinants

Juillion et al., 2022

Fig. 9. Early season pattern of the percentage of fruit remaining on the tree relative to the initial flower number. Each value is the mean (± standard error) for six trees with representative floribundity in the S and C modalities during the 2020 and 2021 seasons. All trees presented medium floribundity except for C trees in 2021 that had low floribundity. The vertical dotted line (DAB = 38) separates the period of flower and fruitlet drop (diameter <10 mm) and fruit drop (diameter >10 mm).

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Scientia Horticulturae 306 (2022) 111454

Contents lists available at ScienceDirect

Scientia Horticulturae

journal homepage: www.elsevier.com/locate/scihorti

Shading apple trees with an agrivoltaic system: Impact on water relations, leaf morphophysiological characteristics and yield determinants

Perrine Juillion [a,b,*], Gerardo Lopez [b], Damien Fumey [b], Vincent Lesniak [c], Michel Génard [a], Gilles Vercambre [a]

[a] INRAE-UR1115 (PSH), Site Agroparc, Avignon, France
[b] San'Agri, 60 All. Yves Saourdin, Clapiers 34830, France
[c] La Pugère, Chemin de la Barque de Malegoine, Mollégès, France

Fig. 11. Yield (t/ha) at the orchard scale considering all trees on each shading treatment (*n* = 110 in S plot, *n* = 240 in C plot) in 2019, 2020 and 2021 harvests. Percentages indicate yield in the considered plot compared to the C plot. *P. Juillion et al.*

Juillion et al., 2022

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CONCLUSIONS

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Where AV orchards may perform best?

- **Semi-arid horticultural regions**: water savings + heat buffering can be high value.
- **Sites needing protection** from hail, heavy rain, and sunburn.
- **Shade-tolerant fruit species** or systems with strong quality premiums for climate protection.

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Risks & operational considerations

- **Higher humidity** and lower wind can increase disease pressure.
- **Permanent structures** can constrain machinery, pruning, harvest, and spray programs.
- **Water redistribution**/runoff may require redesigned irrigation scheduling and layout.

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Take-home messages

- **Agrivoltaics for fruit crops is promising but still data-limited. Expensive trials.**
- **Microclimate benefits exist, but shading intensity is the dominant risk driver.**
- A practical **~30% shading threshold is a useful starting point for orchard AV design**.

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THANK YOU FOR YOUR ATTENTION !!!

SUPPORTED BY THE WSU TREE FRUIT ENDOWMENT

November 4, 2025

Report: Blending solar power into farms shows promise

By Shawn Vestal, WSU News & Media Relations



A new report co-authored by WSU researchers concluded that Washington state could add solar panels to tens of thousands of acres of orchards and farms, making a significant dent in future energy needs without taking farmland out of production. (Photo by SunAgri)

Chad Kruger and Stefano Musacchi 2025-26-27

Chad Kruger, Associate Vice President for Research Advancement and Strategy, WSU Office of Research

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