DATA-DRIVEN ANALYSIS OF CROP YIELD IN A CONTROLLED AGRIVOLTAIC INSTALLATION

Michela Costa[1,2,*], Davide Sgambato[2]

1 – CNR Institute of Science and Technology for Sustainable Science and Mobility (STEMS),
Via Marconi, 4, 80125, Naples, ITALY
2 - DG Twin S.r.l, c/o Campania NewSteel, Via Coroglio, 57, 80124, Naples, ITALY
*michela.costa-@stems.cnr,it, michela.costa@dgtwin.it

ABSTRACT: Agrivoltaics (APV) offer a promising solution to mitigate land-use competition between photovoltaic energy generation and agriculture, although the design requires a careful balancing of energy yield, crop productivity, regulatory constraints and economic profitability. This study presents a policy-aware, data-driven multi-objective optimization framework for APV system design, integrating experimentally validated crop yield responses, solar radiation and shading models with photovoltaic performance evaluation.
A real APV micro-plant equipped with agronomic sensors was used to experimentally derive crop yield response curves, enabling the validation and specialization of relationships previously obtained from meta-analytical studies. These functions were embedded into an integrated model of APV to finally perform a multi-objective optimization simultaneously maximizing agricultural yield and electrical energy production under Italian regulatory constraints.
The framework was applied to a 1 ha case study at the latitude of Naples (Italy), with 40% PV coverage and 2.5 m inter-row spacing. Panel tilt and installation height were considered as decision variables. The optimal configuration, identified using the utopia-point criterion, features a 50° tilt angle, achieving a 12.27% increase in total agricultural yield and producing 1009.6 MWh/y of electricity. An economic assessment results in a simple payback period of 11.8 years, reduced to 7.08 years when public incentives are considered.

1 INTRODUCTION

The increasing deployment of renewable energy systems, together with the growing demand for agricultural production, has intensified competition for land resources worldwide. This challenge is particularly evident in regions where high solar potential overlaps with fertile agricultural areas. Agrivoltaics, also referred to as agrophotovoltaics (APV), constitutes an integrated solution allowing photovoltaic electricity generation and agricultural production to coexist on the same land surface. The foundational concept of agrivoltaics was first formalized by Dupraz et al. [1], who demonstrated that appropriately designed PV installations can enable dual land use without necessarily compromising agricultural productivity.

The relevance of agrivoltaics has increased significantly in the context of climate change. Rising air temperatures, more frequent heatwaves and prolonged drought events are already reducing crop yields and are often determining increasing irrigation demand in many parts of the world or uncontrollable floods. Zhao et al. [2] showed that global crop yields are highly sensitive to temperature increase, even under moderate warming scenarios, while Lesk et al. [3] highlighted that extreme heat and drought events have already caused substantial yield losses at the global scale, underscoring the urgency of climate-adaptive agricultural strategies.

Partial shading provided by photovoltaic modules was identified as a potential mechanism to mitigate some of these climate-related stresses. Barron-Gafford et al. [4] experimentally demonstrated that APV reduce canopy temperature and evapotranspiration while maintaining or even increasing crop productivity in arid environments. Similarly, Marrou et al. [5] showed that modified radiation regimes under PV panels can alter crop microclimate in ways that are beneficial for plant growth, depending on crop type and environmental conditions.

A comprehensive and systematic synthesis of research on APV was recently provided by Campana et al. [6], who frame agrivoltaics as complex socio-technical systems rather than simple superpositions of agriculture and photovoltaics. Their review highlights that agrivoltaic performance emerges from interactions among solar radiation physics, microclimate dynamics, crop physiology, system geometry and socio-economic drivers. Evaluating APV requires integrated indicators that simultaneously account for agricultural yield, energy production, land-use efficiency, economic performance.

One of the central findings of the literature concerns the crop-specific response to shading. Laub et al. [7] conducted a large meta-analysis showing that crops can be classified into shade-benefitting, shade-tolerant and shade-sensitive categories, depending on how yield responds to reduced solar radiation. This classification was confirmed by field experiments on horticultural crops, where moderate shading was shown to improve yield and quality for selected species, such as tomatoes and leafy vegetables [8]. In contrast, cereal crops and other light-demanding species often exhibit yield reductions when shading exceeds crop-specific thresholds. The agronomic implications of these findings are substantial. Weselek et al. [9] emphasized that the temporal distribution of shading during the day and across the growing season plays a critical role in determining crop response, beyond the simple magnitude of radiation reduction.

From an engineering perspective, APV systems impose additional constraints on photovoltaic design. Valle et al. [10] showed that increasing panel height and row spacing can significantly modify shading patterns on the ground, directly affecting both crop performance and land-use efficiency. Schindele et al. [11] further demonstrated that system geometry strongly influences the trade-off between energy yield and agricultural productivity, highlighting the need for site-specific optimization.

Accurate modeling of solar radiation and shading dynamics is therefore a key requirement for agrivoltaic analysis. Perez et al. [12] developed foundational models for separating direct and diffuse radiation components, which remain widely used in solar energy applications. They also highlighted the importance of accounting for anisotropic diffuse radiation when evaluating PV performance under complex shading conditions. These modeling advances are directly applicable to APV, where shadows are unavoidably introduced on crops and dynamically evolve throughout the day.

Beyond technical performance, agrivoltaics were shown to deliver broader environmental and socio-economic benefits. At the policy level, the European Commission has explicitly recognized agrivoltaics as a strategic tool to support both renewable energy deployment and sustainable agriculture within the EU Solar Strategy [13].

Despite these advances, several knowledge gaps remain. Wolfert et al. [14] highlighted that the integration of real-time sensing and data-driven control strategies is still limited in agricultural energy systems, despite their strong potential for performance optimization.

Within this context, the present work aims to provide experimental evidence from a controlled micro-scale agrivoltaic installation. By combining high-resolution environmental monitoring with image-based assessment of crop development, the study delivers quantitative insights into crop responses under different shading configurations. The collected experimental data are subsequently used as inputs for a multi-objective optimization analysis, aimed at identifying the agrivoltaic system configuration optimally balancing the trade-off between agricultural productivity and energy generation. This approach is consistent with the emerging concepts of data-driven and adaptive APV, which are increasingly recognized as a key research frontier in the field [6].

2 MATERIALS AND METHODS

2.1 Solar radiation model

The solar radiation numerical model is implemented in MATLAB and is based on refs. [15] [16] [17]. These are used to describe the global solar radiation (G_{TR}), as:

$$G_{TR} = B_{TR} + D_{TR} + G_{RR} \quad [\text{W/m}^2] \quad (1)$$

where B_{TR}, D_{TR}, G_{RR} are the component of the global radiation, namely the direct radiation on the surface, the diffuse radiation on the surface and the ground reflected radiation.

2.2 Photovoltaic and shading model

The developed model of the PV, also written in MATLAB, is based on a well-established formulation that describes the power produced by the PV based on the area of the PV (A_{PV}), the global radiation (G_{TR}), described in the previous paragraph, and the efficiency of the PV (η_{PV}).

$$P_{pv} = \eta_{PV} \cdot A_{PV} \cdot G_{TR} \quad (2)$$

2.3 Shading model

The shading model represents a core element of the agrivoltaic framework, as it governs the spatial and temporal distribution of solar radiation reaching the cultivated surface. Unlike conventional photovoltaic installations, where shading is typically avoided due to its negative impact on energy production, agrivoltaic systems are deliberately designed to introduce partial shading. In this context, in fact, shading acts as a controllable design parameter that directly affects the local microclimate, plant physiological processes, and, ultimately, agricultural yield. Consequently, an accurate representation of the shadow geometry generated by the photovoltaic modules, as well as its temporal evolution over daily and seasonal cycles, is required. The projected shadow length of the photovoltaic panels is evaluated using expression (3)

$$L_{shadow} = \frac{H_{panel}}{\tan(\alpha)} \quad (3)$$

In this formulation, H_{panel} denotes the height of the photovoltaic panel, while α represents the solar altitude angle. The adopted approach [18] allows the shadow projection on the agricultural surface to be described by accounting for the apparent motion of the sun during the day and for seasonal variations in solar declination. The relative orientation between the photovoltaic modules and the solar direction makes it possible to identify the instantaneous position of the shadow with respect to the panel rows, as well as the extent of the partially shaded area, which is governed by the module geometry and tilt angle. The impact of shadow projection is quantified through two dimensionless coefficients, reported in equations (4) and (5), which respectively modify the beam radiation (BTR) and the diffuse radiation (DTR) components.

$$f_B = \frac{A_S}{A_G} \quad (4)$$

$$f_D = \frac{\iint f_B \cdot R \cdot \cos(AOI) \cdot \cos(\alpha) \, d\alpha \, dAOI}{\iint R \cdot \cos(AOI) \cdot \cos(\alpha) \, d\alpha \, dAOI} \quad (5)$$

In equation (4), A_S denotes the shaded area, while A_G represents the total ground area covered by the photovoltaic installation. In equation (5), R refers to the sky radiance contribution. Both dimensionless coefficients vary between 0 and 1, where a value of 0 indicates the absence of shading and a value of 1 corresponds to complete shading of the underlying surface. As a result, the beam and diffuse radiation components are accordingly adjusted as follows:

$$BTR_S = BTR \cdot (1 - f_B) \quad (6)$$
$$DTR_S = DTR \cdot (1 - f_D) \quad (7)$$

2.4 Crop yield model

The estimation of agricultural yield in agrivoltaic systems can be addressed through different modelling approaches. One widely adopted method relies on meta-analyses of experimental studies, which correlate crop yield variations with reductions in available solar radiation induced by photovoltaic shading. A notable example is

the meta-analysis conducted by Laub et al. [7], in which crops are classified into three main categories: shade-benefitting, shade-tolerant, and shade-sensitive, based on their yield response to decreasing radiation levels.
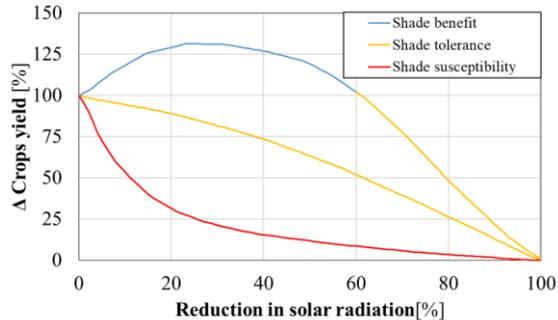

Figure 1. Crops yield vs. reduction in solar radiation: The curves in the graph represent the tolerance of crops to shading effects (from[7] with minor revision).

The upper curve (blue) represents crops that can benefit from the shading effect as long as the shading does not exceed 60%. Beyond this threshold, these crops experience a lower tolerance to the shading effect, as shown by the orange part of the curve. The second curve, also in orange, is positioned in the middle and represents crops with moderate tolerance to shading. The last curve, shown in red, represents crops that do not benefit from the shading effect.

In the present work, the meta-analysis by Laub et al. was used as a reference framework to describe the general behavior of crops under shading conditions. Building on this consolidated literature basis, an experimental micro-scale agrivoltaic installation was developed to validate and specialize the crop yield response for some given crop species.

The agrivoltaic micro-plant, as shown in Figure 2, consists of six raised cultivation boxes, divided into two groups. Each group includes three boxes characterized by different shading configurations induced by photovoltaic panels:

- Box 1: covered by a 100 W photovoltaic panel, providing almost complete shading of the soil;
- Box 2: without photovoltaic panels, representing a conventional open-field agricultural condition.
- Box 3: equipped with four 5 W photovoltaic panels mounted at the four corners, resulting in partial shading.

To support environmental monitoring of the agrivoltaic system, a multifunctional weather station was installed, consisting of a set of sensors designed to measure key meteorological and agronomic parameters. The data acquisition system includes:

- rain gauge.
- air temperature and relative humidity sensor.
- anemometer for wind speed and direction.
- barometer for atmospheric pressure.
- solar radiation sensor.
- PAR sensors for photosynthetically active radiation.
- soil temperature and moisture sensors.

All sensors and devices of the weather station are powered by a 20 W polycrystalline silicon photovoltaic panel coupled with a 17 Ah battery storage system, ensuring continuous operation even in the absence of solar irradiance. Energy management and data acquisition are handled by a control unit (microcontroller), which coordinates sensor readings and enables real-time data transmission to a remote server, allowing visualization through a mobile application or a web-based interface.

Figure 2. Micro-scale agrivoltaic installation and meteorological monitoring system

As an example, one of the measurements acquired by the meteorological station is reported in Figure 3, which shows the evolution of ambient air temperature during the monitoring period.
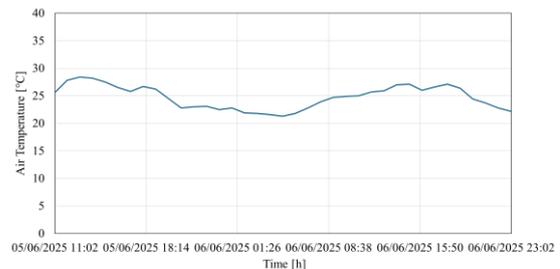

Figure 3. Temporal evolution of ambient air temperature measured by the meteorological station

Strawberry and zucchini were selected and cultivated in May under controlled agrivoltaic conditions, allowing crop-specific yield response curves to be derived directly from experimental data, as shown in Figure 4.

Figure 4. Representative image of zucchini plants cultivated under the agrivoltaic micro-plant in the partially shaded configuration.

A dedicated image-based algorithm for the evaluation of green canopy coverage was used as a proxy for vegetative growth.
Figures 5 and 6 show the weekly evolution of the green cover percentage for strawberries and zucchini, used as an indicator of plant growth.
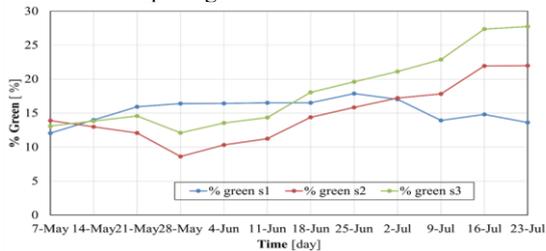

Figure 5. Weekly evolution of green cover percentage – Strawberries
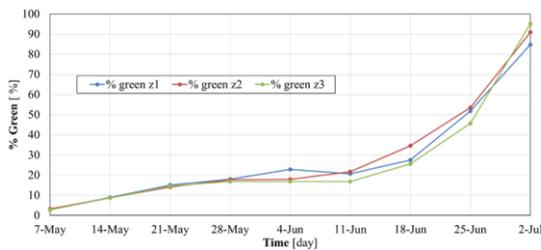

Figure 6. Weekly green cover percentage – Zucchini

Among the strawberry box configurations, F3 (partially shaded) exhibited the highest green cover percentage, thus representing an optimal balance between incident solar radiation and protection from excessive heat.
In the case of zucchini, additional considerations are required. Up to June 4, configuration Z1 (fully shaded) showed the highest green cover. However, after this date, Z1 developed a powdery mildew infection, likely promoted by microclimatic conditions characterized by high humidity and low solar radiation. Unlike strawberries, zucchini monitoring was interrupted on July 2, as extreme summer temperatures caused premature plant desiccation, making further data acquisition unreliable due to crop deterioration.
Based on the obtained results, for both analyzed crops the partially shaded configuration ensured the highest agricultural yield, benefiting from the protective effect of photovoltaic panels, which contributed to mitigating increasingly frequent extreme climatic events associated with climate change. In support of these findings, Figures 7 and 8 report the daily evolution of soil surface moisture and soil temperature.
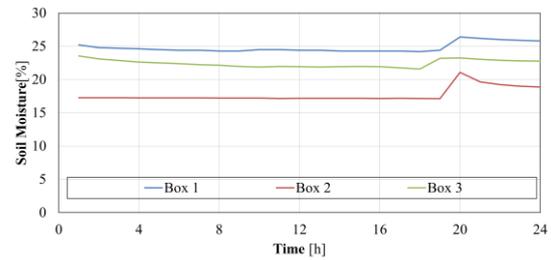

Figure 7. Daily soil moisture trends under the three shading configurations
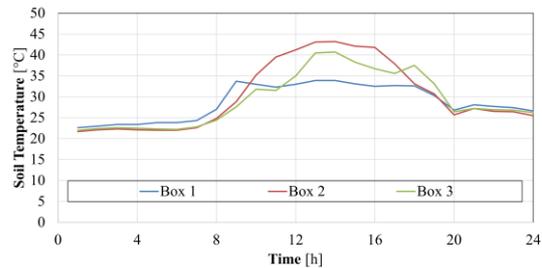

Figure 8. Daily soil surface temperature trends under the three shading configurations

These graphs highlight how the different shading configurations significantly influenced the microclimate of the three experimental boxes:

- Box 1 (full coverage with photovoltaic panel): The soil surface temperature was on average lower than in the other boxes, due to complete shading that limited direct solar irradiance. However, this condition also reduced evaporation, resulting in persistently high soil moisture levels. While this configuration provided protection against extreme heat, it promoted excessively humid microclimatic conditions, which in practice are associated with the development of fungal diseases, such as the powdery mildew observed in zucchini.

- Box 2 (no photovoltaic panels, conventional agronomic control):
  In this configuration, soil surface temperature reached the highest values, significantly exceeding those recorded in the other boxes during the central hours of the day. Similarly, soil moisture remained consistently lower than in the other two configurations, promoting water stress conditions. This exposed crops to increased summer thermal stress, with a consequent risk of premature desiccation, as effectively observed in more sensitive crops.

- Box 3 (partial coverage with four panels installed at the corners):
  The intermediate configuration exhibited an optimal balance: soil temperatures did not reach the high peaks observed in Box 2, nor did they remain as low as in Box 1, allowing for regular crop development. Likewise, soil moisture was maintained at intermediate levels, sufficient to prevent water stress without creating conditions favorable to fungal

diseases. This balanced microclimate resulted in a higher green cover percentage and, consequently, superior agricultural yield.

Overall, the data confirm that the partial shading provided by Box 3 represented the most favorable condition for vegetative development. This configuration enabled:

- mitigation of thermal peaks, preventing damage from excessive temperatures.
- maintenance of adequate soil moisture, reducing both desiccation risk and fungal infection susceptibility.
- improved balancing of light and water resources, with positive effects on crop productivity.

These results reinforce the hypothesis that agrivoltaic configurations with partial shading can offer significant agronomic benefits, particularly under conditions of increasing climatic stress.

By correlating the experimentally measured reduction in photosynthetically active radiation (PAR) with the temporal evolution of canopy coverage, crop-specific yield responses were reconstructed for strawberries and zucchinis, as shown in the following Figure 9.
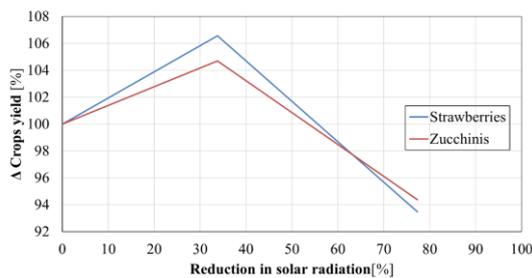
Figure 9. Crop yield variation for strawberries and zucchinis as a function of solar radiation reduction, experimentally measured in the micro-scale agrivoltaic installation

The resulting trends are consistent with the qualitative classification proposed by Laub et al., while exhibiting quantitative differences that reflect crop physiology, local climatic conditions and system geometry. This approach enables the specialization of literature-based yield models into experimentally calibrated functions, subsequently integrated into the numerical optimization framework.

3 MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK AND RESULTS

A multi-objective optimization framework was developed to maximize both agricultural yield and electrical energy production of a real scale agrivoltaic (APV) system. The case study refers to an agrivoltaic installation located at the latitude of Naples (Italy), with a total land availability of 1 ha. According to the Italian agrivoltaic regulation, the photovoltaic surface is limited to a maximum of 40% of the agricultural field, resulting in 4,000 m² of installed PV modules [19]. Additional regulatory constraints require a minimum inter-row spacing of 2.5 m between adjacent PV rows to allow the passage of agricultural machinery; this spacing was fixed at its minimum allowable value to maximize land-use efficiency [19].

The decision variables of the optimization problem are:

- the tilt angle of the PV modules, varying from 0° to 90° with a step of 10°;
- the minimum panel height above ground, varying between 2.1 m, corresponding to the regulatory lower bound, and 4.1 m, representative of elevated agrivoltaic structures [19].

The objective functions are defined as:

1. maximization of annual electrical energy production;
2. maximization of total agricultural yield, computed as the cumulative variation of crop yields over the entire agricultural cycle.

A representative crop rotation was defined based on typical Mediterranean agricultural practices: romaine lettuce (January–February), zucchini (March–June), tomato (July–October), and lettuce (November–December).

Electrical energy production, shading effects, and crop yield variations were calculated using the models described in Section 2 (Materials and Methods). In particular, for zucchini, crop yield response was quantified using experimental field data, while for lettuce and tomato the yield–radiation relationships were adopted from the meta-analysis by Laub et al.

The optimization process generated 50 feasible configurations, each corresponding to a unique combination of tilt angle and panel height. The optimal solution was identified using a Pareto-front analysis (Figure 10), adopting the utopia-point criterion to balance the trade-off between the two objectives.
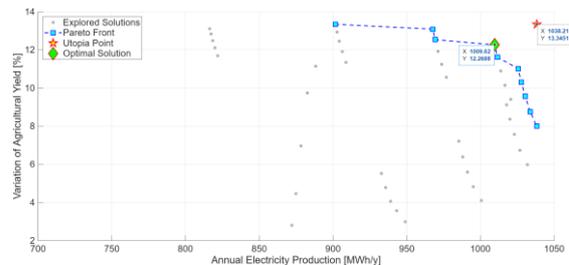
Figure 10. Pareto front of the bi-objective optimization

The selected optimal configuration corresponds to a tilt angle of 50° and a minimum panel height of 4.1 m, yielding an annual electrical energy production of 1009.62 MWh/y and a total agricultural yield increase of +12.27%, computed as the sum of yield variations across the four crops.

This result clearly highlights the intrinsic trade-off between energy and agriculture: while the energy-optimal tilt in Naples would be approximately 30°, and the agriculture-optimal configuration would tend towards vertical panels (≈90°), the optimized solution represents a balanced compromise between the two objectives.

Based on the total crop yield increase, an incremental agricultural revenue of €48,301/y was estimated. All the produced electricity was assumed to be sold to the national grid at the tariff defined by the Italian agrivoltaic

regulation, equal to 93 €/MWh [19].

Considering a total investment cost of €1,088,560, including PV modules, agronomic sensors required by regulation, inverters, supporting structures, and annual maintenance, the resulting annual revenues amount to €92,195, leading to a simple payback period (SPB) of 11.8 years. When accounting for the 40% non-repayable public incentive provided by the Italian agrivoltaic framework [19], the SPB is reduced to 7.08 years. It should be noted that this payback analysis represents a conservative worst-case scenario, as it assumes that all electricity is sold to the grid. In practical applications, partial or full on-site self-consumption would significantly improve economic performance, as it would offset electricity purchases from the national grid at prices considerably higher than the selling tariff, typically in the order of 250 €/MWh.

4 DISCUSSIONS

The results of the multi-objective optimization highlight the intrinsic trade-off that characterizes APV system design, where photovoltaic energy production and agricultural productivity compete for the same radiative resource. The Pareto-based analysis confirms that configurations optimized exclusively for energy yield or crop performance lead to suboptimal outcomes when evaluated from a land-use efficiency perspective.

The optimal configuration identified in this study, characterized by a PV tilt angle of 50°, represents a meaningful compromise solution between these competing objectives. From an energy standpoint, this tilt deviates from the conventional energy-optimal configuration for Southern Italy (≈30°), leading to a moderate reduction in annual PV yield. Conversely, from an agronomic perspective, the selected tilt avoids excessive shading. The selected solution, therefore, embodies the agrivoltaics design philosophy, in which neither energy nor agriculture is prioritized unilaterally.

The experimental validation of crop yield response plays a central role in strengthening the reliability of the optimization framework. While the meta-analysis by Laub et al. [7] provides a robust general classification of crop sensitivity to shading, the experimentally derived yield curves for strawberries and zucchinis reveal quantitative deviations that reflect local climatic conditions, crop-specific physiology, and system geometry. These differences demonstrate that literature-based yield functions, if used without local calibration, may lead to biased optimization outcomes. The integration of micro-scale experimental data into the numerical framework, therefore, represents a significant advancement toward site-specific and crop-oriented agrivoltaic design.

Although the experimental validation is conducted at the micro-scale, the measured crop yield responses are integrated into a hectare-scale optimization framework through physically based radiation and shading models. This multi-scale coupling allows experimental observations to inform system-level design decisions while preserving consistency with geometric and regulatory constraints.

From an economic perspective, the results confirm that APV can achieve competitive payback periods even under conservative assumptions. The estimated simple payback period of 11.8 years, reduced to 7.08 years when accounting for public incentives, is consistent with recent techno-economic assessments of innovative agrivoltaic installations. Importantly, the assumption of full electricity export to the grid represents a worst-case scenario. In real-world applications, partial self-consumption would substantially improve economic performance by offsetting electricity purchases at retail prices significantly higher than feed-in tariffs.

Finally, the regulatory constraints imposed by the Italian agrivoltaic framework emerge not merely as boundary conditions but as fundamental design drivers. Constraints on PV surface coverage, minimum panel height and inter-row spacing directly shape the feasible solution space, reinforcing the necessity of policy-aware optimization approaches. The proposed methodology demonstrates how regulatory requirements can be systematically embedded within the design process rather than treated as ex-post limitations.

5 CONCLUSIONS

The present work focuses on a data-driven and policy-aware framework for the optimization of agrivoltaic systems, integrating experimental crop yield measurements, solar radiation and shading models, photovoltaic performance evaluation and multi-objective optimization. By experimentally validating and refining literature-based crop yield response functions, the study bridges the gap between meta-analytical knowledge and site-specific agrivoltaic system design.

The results demonstrate that Pareto-based optimization approaches enable APV configurations to simultaneously enhance agricultural productivity and maintain high levels of energy generation. For the considered case at the latitude of Naples, the identified optimal configuration achieves a total agricultural yield increase of 12.27% while producing more than 1 GWh/y of electrical energy, confirming the effectiveness of balanced design strategies.

The economic analysis highlights the financial viability of agrivoltaic systems under current regulatory frameworks, particularly when public incentives and self-consumption strategies are considered. While the presented payback analysis assumes full electricity export to the grid, this conservative scenario underestimates the potential benefits achievable in real-world applications.

The proposed framework is inherently replicable and transferable to different geographical locations, crop portfolios and regulatory contexts, provided that site-specific climatic data and experimental crop response measurements are available. Future developments will focus on extending the experimental dataset across multiple growing seasons and on investigating adaptive control strategies to further enhance agrivoltaic system resilience and performance.

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