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Photovoltaic greenhouses in the European south: balancing energy generation and agricultural productivity - an economic analysis

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HIGHLIGHTS

- Greenhouse crop-yield responses to PV shading can strongly alter NPVs and outweigh energy-related revenues.
- Projected future OPV scenarios (14% efficiency) can approach present-day c-Si photovoltaics economic performance under high demand but remain more sensitive to system conditions.
- High electricity demand and self-consumption support small-scale greenhouse PV viability.
- Current-state OPV remains economically constrained across all evaluated scenarios.
- Economic feasibility depends on location, crop type, PV coverage and system design.

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ABSTRACT

This study evaluates the techno-economic feasibility of photovoltaic greenhouses in representative Mediterranean regions in Spain and Italy. A techno-economic model was developed to analyze the interaction between photovoltaic technology choice including present-day crystalline silicon PV (c-Si), current-state Organic Photovoltaics (OPV) modules with 63 $W\,m^{-2}$, and a projected future OPV scenario with 145 $W\,m^{-2}$, greenhouse electricity demand profiles, PV coverage levels, battery storage integration, remuneration schemes and crop yield responses to shading.

Without taking crop yields into account, results show that greenhouse electricity demand and the resulting self-consumption potential are the dominant drivers of economic performance. Under high-demand conditions several configurations become profitable, reaching net present values (NPVs) of up to 51,640€ in Bari and 22,176€ in Almería.

Abbreviations: APV, Agriphotovoltaics; B, Installed battery capacity; B*, Optimal battery capacity maximizing project NPV; BESS, Battery Energy Storage System; $Bill_0$, Annual electricity expenditure without PV system; $Bill_1$, Annual electricity expenditure after PV and battery implementation; $Bill_m^{imp}$, Monthly electricity import bill; BOS, Balance of System; CAPEX, Capital expenditures; CAPEXbat(B), Investment cost of battery storage depending on capacity B; CAPEXPV, Investment cost of the photovoltaic system; CFy(B), Annual energy-related cash flow in year y for battery capacity B; Ch_t, Electricity used for battery charging in hour t; c-Si, Crystalline silicon photovoltaic modules; C_m, Monthly compensation credit under net billing; D_t, Electricity demand of the greenhouse in hour t; Dis_t, Electricity discharged from the battery in hour t; Eexch, Exchanged electricity under the SSP scheme; Eexcess, Excess electricity exported beyond imports; Eexp, Total annual electricity exported to the grid; Eimp, Total annual electricity imported from the grid; EOV, Annual energy operating value; Exp_t, Electricity exported to the grid in hour t; Imp_t, Electricity imported from the grid in hour t; IOPV, Investment cost of the OPV system; IOPVmax, Maximum admissible OPV investment cost for which NPV = 0; kWh, Kilowatt hours; kWp, Kilowatt peak; m, Month index; MWh, MegaWatt hour; NPV(B), Net present value of the project for battery capacity B; OPEXy, Annual operating expenditures in year y; OPV, Organic photovoltaics; pimp, Retail electricity price for imported electricity; pt exp, Hourly market price for exported electricity; pmin, Guaranteed minimum export price under RID; pt zonal, Zonal electricity market price; PV, Photovoltaics; PV_t, Photovoltaic electricity generation in hour t; r, Real discount rate; REPy, Battery replacement cost in year y; RID, Ritiro Dedicato remuneration scheme; Rscheme, Remuneration obtained under the respective electricity compensation scheme; RSSP, Annual remuneration under the Scambio sul Posto scheme; SC_t, Electricity directly self-consumed in hour t; SOC_t, Battery state of charge in hour t; SSP, Scambio sul Posto remuneration scheme; t, Hourly time step; y, Project year index; α, Fixed compensation rate for exported electricity; ΔCRy, Change in crop revenues in year y due to shading effects; ηch, Battery charging efficiency; ηdis, Battery discharging efficiency; ϕ, Export fee applied to electricity exports.

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Under the optimistic OPV145 scenario, which combines a projected module output of 145 W m^{-2} with future upscaling-related cost reductions, NPVs reach values comparable to the present-day c-Si PV reference in selected high-demand configurations. Profitability declines under less favorable performance assumptions, with initial performance losses exerting a stronger economic effect than higher annual degradation rates.

The current-state OPV63 scenario, based on commercially oriented module cost assumptions and 63 W m^{-2} output, remains economically constrained across most configurations, although NPVs at low PV coverage indicate that moderate improvements in efficiency or costs could enable feasibility.

When crop yield impacts are incorporated, profitability becomes strongly crop-dependent. High-value crops such as strawberries are better able to offset PV investment costs, as the shading effect can enhance crop yields. Lower-value crops remain economically challenging. Sensitivity analysis indicates that, if the PV system alone does not achieve break-even, additional crop revenues of up to 4700€ year^{-1} in Bari and 6400€ year^{-1} in Almería are required to reach economic break-even. Conversely, economically viable configurations can withstand revenue losses of up to 3600€ year^{-1} and 1600€ year^{-1}, respectively.

Overall, the results demonstrate that photovoltaic greenhouse systems can become economically viable under favorable demand conditions, suitable crop selection and future OPV cost and performance improvements.

1. Introduction

Greenhouse cultivation plays a central role in high-value agricultural production in Europe, enabling controlled growing conditions and high yields per unit of land. However, these production systems are also characterized by substantial energy requirements. Energy is needed to maintain optimal growing conditions through heating, cooling, irrigation, ventilation and artificial lighting, making greenhouse cultivation one of the most energy-intensive forms of agriculture [1]. In many regions, fossil fuels remain the dominant energy source for greenhouse operations, resulting in high operational costs and considerable greenhouse gas emissions [2–4]. Improving the energy performance of greenhouse systems while maintaining agricultural productivity has therefore become a key challenge for sustainable horticultural production.

One approach to address this challenge is the integration of photovoltaic (PV) technologies into greenhouses. Such “PV Greenhouses” combine food and energy production within the same land area and represent a form of agriphotovoltaic (APV) system. By generating electricity directly at the site of consumption, they can improve land-use efficiency, support greenhouse operations, and reduce dependence on external energy supplies.

Among photovoltaic technologies used in PV greenhouses, organic photovoltaics (OPV) a thin-film polymer-based solar technology, have recently attracted particular interest for greenhouse integration [5].

OPV have been included in this study as they offer a distinct integration pathway for greenhouse applications. Their lightweight, flexible and potentially semi-transparent design [6–8] has the potential to facilitate integration into greenhouse covering materials or lightweight roof structures, particularly in plastic greenhouse systems with limited structural load capacity [9]. In this context, OPV modules can act as energy-generating shading elements while allowing part of the photosynthetically relevant radiation to reach the crop canopy. Previous greenhouse experiments have indicated that OPV shading can modify the radiation environment and crop microclimate, with crop responses depending on species, shading intensity and environmental conditions ([9,10]; Friman Peretz et al. [11,12]).

In contrast, conventional silicon-based photovoltaic modules, while technologically mature and highly efficient, are rigid and heavy, which may limit their compatibility with lightweight greenhouse constructions. From a system perspective, the practical integration advantages of OPV therefore need to be evaluated against the higher efficiencies and longer lifetimes of conventional silicon PV technologies.

Beyond integration advantages, OPV is relevant from a techno-economic perspective because scalable manufacturing pathways may reduce area-based module costs. Cost analyses indicate that solution-processed and roll-to-roll manufactured OPV modules could achieve low production costs and short energy payback times under large-scale manufacturing assumptions [13,14]. These potential advantages are accompanied by important practical limitations. OPV technologies still face challenges related to material stability, degradation and operational lifetime [15–17], especially under outdoor or greenhouse-relevant conditions such as elevated temperature, humidity and exposure to cleaning or agrochemical residues [18].

Therefore, OPV is represented through two distinct technology scenarios in this study: OPV63 as a current-state scenario with lower power density and higher module costs, and OPV145 as an optimistic future upscaling scenario reflecting potential improvements in power density and area-based manufacturing costs.

Beyond structural considerations, the integration of photovoltaic modules affects the greenhouse microclimate by introducing partial shading, which influences crop growth depending on crop species and climatic conditions [19,20]. Furthermore, greenhouse energy demand is strongly influenced by seasonal climatic conditions and crop cultivation cycles. In temperate regions, heating demand during winter can account for up to 85% of the total energy consumption and approximately 70% of operational costs [21,22]. These dynamics can create significant temporal mismatches between electricity production and energy demand. However, detailed hourly energy demand data for greenhouse systems are rarely available, making realistic system assessments challenging.

Given that electricity prices during periods of high PV generation are often significantly reduced, the economic performance of PV systems is strongly influenced by system configuration. In this context, the optimization of on-site electricity consumption and feed-in strategies, as well as the careful integration of battery storage, are key factors determining overall profitability [23].

Assessing the feasibility of PV-integrated greenhouse systems therefore requires analyzing the interaction between photovoltaic electricity production, greenhouse energy demand and potential impacts on crop production, while explicitly accounting for these dynamics at fine temporal resolutions.

A large share of greenhouse areas is located in southern European regions [24] and high solar irradiation levels. In particular, the regions of Almería (Spain) and Bari (Italy) represent relevant case studies due to their large greenhouse areas with around 390 and 100 km^2 respectively [25], dominated by plastic greenhouse structures and favorable solar resources.

This study therefore focuses on the economic feasibility of photovoltaic greenhouse systems under realistic operational conditions at representative locations in Almería and Bari. To enable a system-level assessment, synthetic hourly electricity demand profiles are developed and combined with PV electricity output profiles. The analysis evaluates different system configurations, including variations in photovoltaic technology, PV coverage levels, electricity demand needs, remuneration schemes, battery storage integration and potential economic effects on agricultural production. Photovoltaic technology is represented through three scenarios: conventional c-Si as the mature present-day reference

technology, OPV63 as a current-state OPV scenario with lower power density and higher module costs, and OPV145 as an optimistic future upscaling scenario reflecting potential improvements in power density and area-based manufacturing costs. The role of battery energy storage system (BESS) integration is examined to better capture the interaction between PV electricity output and on-site electricity consumption. The overarching research question of this study is therefore:

To what extent can the integration of photovoltaics in European greenhouse systems ensure economic profitability while maintaining agricultural productivity?

To address this question, the study follows three specific objectives:

1. *Technology comparison*: Evaluate the economic implications of integrating emerging OPV technologies compared to conventional silicon photovoltaic modules in greenhouse systems.
2. *Energy system interaction*: Analyze how greenhouse demand profiles, PV coverage levels and potential battery storage integration influence system performance and economic outcomes.
3. *Economic feasibility*: Assess the overall feasibility of photovoltaic greenhouses by considering investment costs, electricity remuneration schemes and potential impacts on agricultural revenues.

By combining technological, agricultural, and economic perspectives, the study aims to provide a comprehensive evaluation of the conditions under which photovoltaic greenhouse systems can become economically viable components of future sustainable agricultural systems.

2. Methods

This study provides a techno-economic modelling framework to assess the feasibility of APV greenhouse systems under different economic influences. The analysis focuses on two representative Mediterranean greenhouse regions, Bari, Italy (40.987269 lat; 16.938996 lon) and Almería, Spain (36.811389 lat; −2.595783 lon), which provide comparable solar irradiation potential while differing in policy frameworks and electricity market characteristics.

The methodological approach combines technical system simulation, scenario-based agronomic assumptions, and economic modelling for a 1000m^2 greenhouse. Energy generation, electricity demand, and potential crop yield effects are integrated into a comprehensive framework that evaluates system operation and project-level profitability under different technology, coverage, and policy scenarios.

The following sections describe the individual methodological components in detail.

2.1. PV electricity production potential

The technical potential for PV technology integration was estimated through simulations performed using the RESKit Python model [26], which is a well-established model for conducting highly resolved and detailed technical analyses for renewable energy assessments [27–31]. The production assessment and its technical assumptions and configurations is explained in detail in our previous study [25]. OPV integrated in the greenhouse was considered with two capacity values, 63 W m^{-2} for showing current technology status as well as 145 W m^{-2} to display projected technology advancement, as has been proven on a lab-scale [32].

For organic photovoltaics (OPV), two distinct technology maturity stages were considered. The first represents current-generation OPV technology (OPV63) with a power density of 63 W m^{-2} and reflects currently available commercial products. The second represents a prospective future-generation OPV scenario (OPV145) with a power density of 145 W m^{-2}.

Beyond the technical assumptions adopted in the previous study, this work additionally incorporates conventional silicon modules besides organic photovoltaic assuming a typical module power density of 230 W m^{-2} based on reported average conversion efficiencies ranging from 20 to 25% [33,34] to be able to compare the technologies regarding performance and costs.

Consequently, the three investigated PV configurations represent:

- a mature reference Crystalline silicon photovoltaic (c-Si) technology scenario
- a current-state OPV scenario (OPV63)
- and an exploratory future OPV cost-performance scenario (OPV145).

2.2. Simulation of hourly greenhouse demand

Generally, there are different status quo of greenhouses, ranging from low-tech greenhouses, more frequently in the south of Europe to high-tech greenhouses [2,35].

Empirical studies indicate extremely low specific energy consumption values of 2–6 kWh m^{-2} a^{-1} for unheated or naturally ventilated houses without electrical cooling systems [36–40]. Higher consumption levels are reported for greenhouse systems equipped with active heating, cooling, ventilation or climate-control technologies [41–43], while several studies indicate substantially higher electricity demands under intensive greenhouse management conditions[35,36,41,42,44]. For example, reported heating and cooling demands for tomato greenhouses in Almería can exceed 80 kWh m^{-2} a^{-1}, highlighting the relevance of active climate-control systems in Mediterranean production environments [45]. Consequently, the selected demand scenarios were intended to cover a broad range of greenhouse operation types, ranging from low-input systems to highly electrified and climate-controlled production systems.

However, most available studies report energy consumption only on an annual or monthly basis, limiting the availability of empirically derived hourly load profiles.

To estimate hourly energy demand of greenhouses in our target regions, a top-down and profile-based disaggregation approach was applied to construct representative 24 h energy profiles. The profiles integrate region-specific greenhouse energy consumption values with empirically derived annually, monthly, and seasonal end-use load profiles indicated in the literature.

Two reference studies were applied to construct two representative Mediterranean reference profiles that represent different technological status quo of greenhouses. The two profiles provide a wide range of energy consumption from 8 to 110 kWh m^{-2} a^{-1}, representing different technological advancements of greenhouses consistent with the range of sectoral averages indicated for the region [35,37,38,44]. Each profile consists of one representative 24 h day for each month, with hourly electricity demand expressed per greenhouse area in kWh m^{-2} h^{-1}. The representative monthly profiles were repeated for all days of the respective month to construct annual hourly demand time series.

The first profile is based on Campiotti et al. and represents a “low-energy greenhouse”. It reports daily and seasonal electrical energy consumption for a “typical” Mediterranean greenhouse by operational category (heating, cooling, ventilation, irrigation, control) [46]. Seasons were disaggregated to months and in a second step converted to kWh m^{-2} day^{-1}. 24 h profiles were built in accordance to heating peaks in the morning and the evening, cooling profiles peaking during the day, irrigation increasing during the day and other energy end uses equally disaggregated for the day. The cumulated annual electricity demand accounts for 8 kWh m^{-2} a^{-1}.

The second profile displays a higher energy consumption level due to heating requirements added. It is based on Cherkaoui et al. and provides monthly daytime and nighttime energy consumption data (kWh m^{-2} $month^{-1}$) for a polyethylene tunnel greenhouse operating under typical Mediterranean climatic conditions. The dataset differentiates heating and cooling demand under seasonal ventilation regimes for daytime and nighttime [47]. Using these values, a 12 h daytime / 12 h nighttime

disaggregation was applied, assigning the monthly totals to representative hourly distributions to capture diurnal temperature-driven dynamics. The cumulated annual electricity demand accounts for 110 kWh m^{-2} a^{-1}.

Since PV electricity can only directly offset electrical demand, the high-load scenario was interpreted as an electrified greenhouse energy system case. Thermal energy conventionally supplied by fossil fuels was not explicitly modeled.

Typical day profiles and their potential coverage by the technologies considered can be found in the Appendix (Figs. 13 and 14).

2.3. Agronomics

The following section outlines the methodology used to assess the agricultural economic component, including general crop statistics and associated prices, the applied economic evaluation approach, and the potential economic impacts of shading effects induced by the PV system.

2.3.1. Baseline agricultural income assessment

In APV systems, agricultural production remains the primary objective, while electricity generation represents an additional revenue stream. Therefore, the first step was to analyze which crops are typically grown in greenhouses in Almería and Bari. According to the national agricultural statistics, the most important crops are tomatoes, peppers, cucumbers, watermelons, courgettes, strawberries and eggplants (see Fig. 1). We obtained cultivations areas as well as yield assumptions based on these statistics in 2023 [49,50].

Given the wide variation of crops cultivated in the regional greenhouses and price fluctuations throughout the year, a baseline scenario was calculated for each crop in both regions on the reference area of 1000m2 from reported yields. Weekly prices $p_{c,r,w}$ were completed to a full annual series, and the three highest-price weeks $W^{*}_{c,r}$ were selected. This assumption is motivated by evidence that farmers' crop and production decisions respond to expected prices and market conditions [51,52], intended to reflect the potential for farmers to adjust harvest timing and sales strategies in response to price signals, thereby approximating upper-bound revenue conditions.

Assuming equal sales volumes across these weeks, annual revenue under ideal timing was calculated as

$$R^{(3)}_{c,r} = \sum_{w \in W^{*}_{c,r}} \left(\frac{Q_{c,r}}{3}\right) p_{c,r,w}. \quad (1)$$

c = crop

r = region.

$R^{(3)}_{c,r}$ = agronomic baseline revenue without PV-induced shading for crop (c) in region (r)

$W^{*}_{c,r}$ = set of the three weeks with the highest producer prices for crop (c) in region (r)

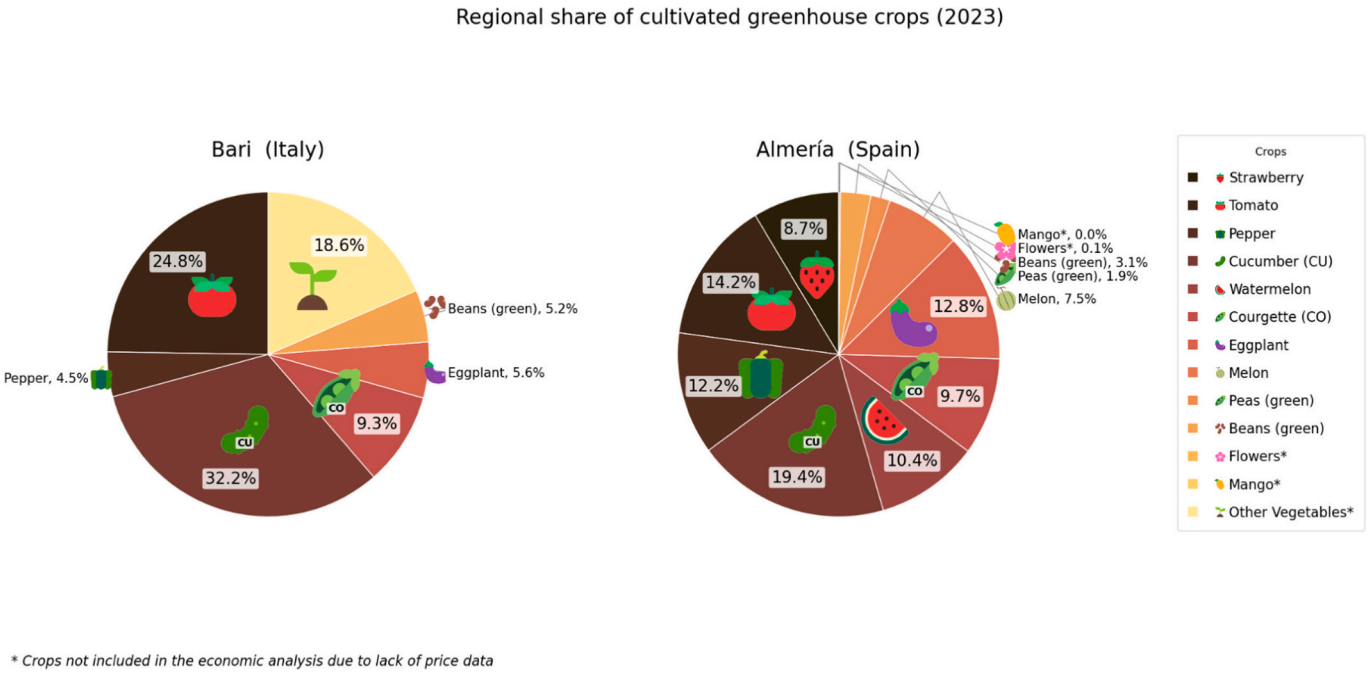
$p_{c,r,w}$ = weekly producer price of crop (c) in region (r) in week (w),

$Q_{c,r}$ = production quantity of crop (c) in region (r) on the reference area of 1000m2

The available crop data for greenhouse cultivation in the studied regions does not distinguish between greenhouse systems with different technological levels and associated energy demand profiles. To represent both low- and high-demand greenhouse systems, an economic differentiation was introduced via the energy balance. Only crops whose revenues on a cultivated area of 1000 m^2 could cover the respective annual energy costs were considered for the corresponding scenario. Annual electricity costs were calculated as $C_{r,d} = D_d \pi_r$, where D_d denotes annual electricity demand for the High and Low demand profiles described in section 3.2 and π_r the region-specific electricity price described in Section 3.4. Crops were assigned to mutually exclusive feasibility sets: high-demand crops satisfy $R^{(3)}_{c,r} \geq C_{r,\mathrm{High}}$, whereas low-demand crops satisfy $C_{r,\mathrm{Low}} \leq R^{(3)}_{c,r} < C_{r,\mathrm{High}}$. Consequently, each crop was assigned to only one demand category in each region and was therefore evaluated exclusively under either the high-demand or low-demand profile. Figs. 2 and 3 illustrate the resulting allocation of crops to the respective demand profiles in the regions.

2.3.2. Shading impact

To evaluate the potential impact of PV-induced shading on crop yields, a comprehensive literature review was conducted focusing on greenhouse crops cultivated in Southern Europe. Previous studies



* Crops not included in the economic analysis due to lack of price data

Fig. 1. Greenhouse crops and respective shares in Almería and Bari 2023 according to national statistics. Source: Istituto Nazionale di Statistica, Italy and Ministerio de Agricultura, Spain, 2024.

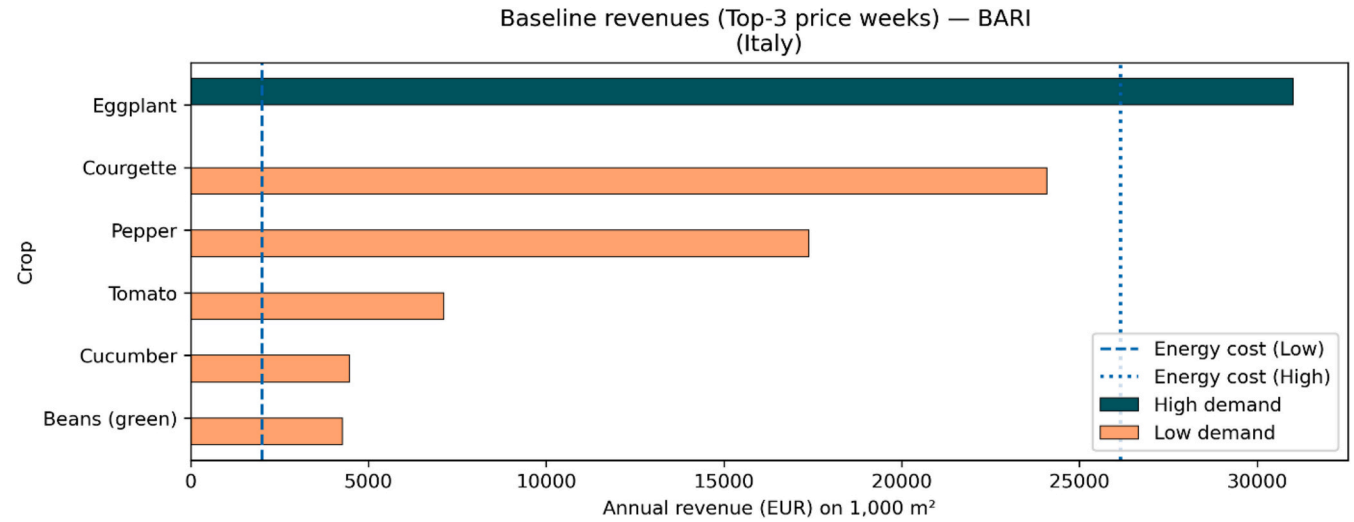


Fig. 2. Baseline crop revenues in Bari and allocation to low and high energy demand.

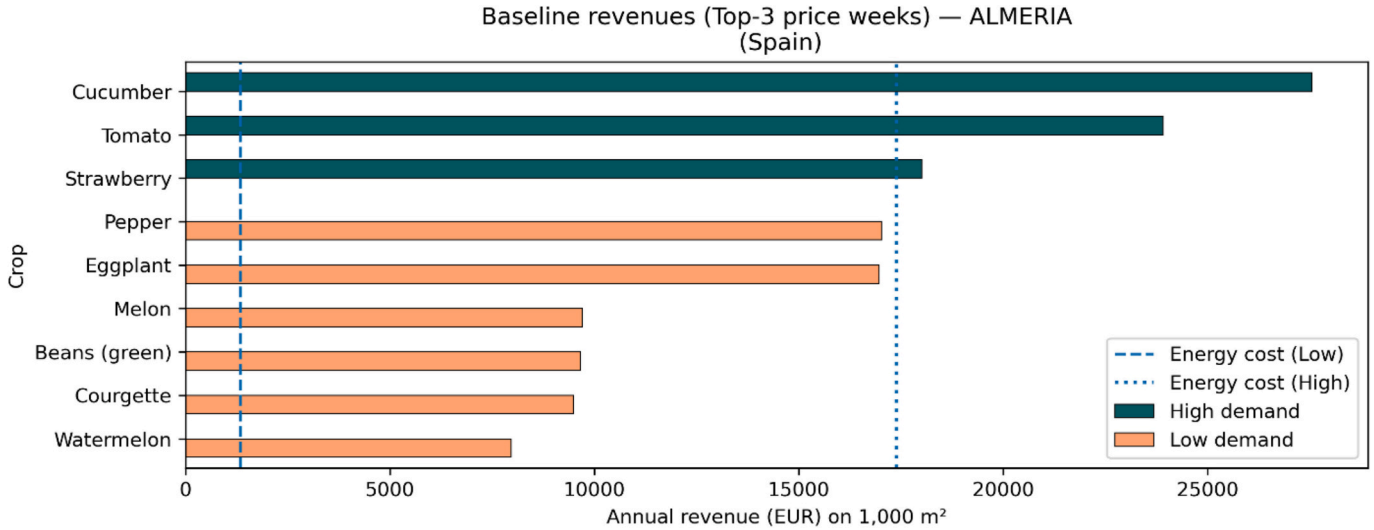


Fig. 3. Baseline crop revenues in Almería and allocation to low and high energy demand.

indicate that crop responses to shading depend strongly on crop type and shading intensity. Meta-analyses and synthesis studies generally show that moderate shading levels of approximately 10–25% are tolerated by many vegetable crops with limited yield reductions, while higher shading levels can lead to stronger productivity losses [53–55].

Experimental greenhouse studies in Southern Europe provide additional evidence of crop-specific responses. For example, experiments with PV coverage rates of 10% of the greenhouse area showed no significant impacts on tomato yield or plant quality [56,57]. Similarly, experiments with semitransparent organic photovoltaic filters reported no significant differences in lettuce growth compared to control treatments [58]. Other studies indicate that yield reductions can occur at higher shading levels. For instance, tomato production declines of approximately 12% and 26.8% were reported for PV coverage ratios of 25% and 50% respectively [59], while shading experiments using opaque panels at 15% coverage reported stronger yield reductions in some cases [60].

Further modelling studies for greenhouse systems in Southern Europe suggest that PV coverage ratios of around 25% are generally compatible with most crops, while higher coverage levels may remain feasible for crops with lower light demand [53]. Site-specific modelling for plastic greenhouses in Almería also indicates that PV coverage levels of up to approximately 44% could remain compatible with high-light-demand crops under certain seasonal conditions [20]. The results of the literature review are summarized in Fig. 4.

2.3.3. *Crop input parameters*

Based on these findings, three shading scenarios of 10%, 25% and 40% PV coverage were defined. Crops were grouped according to their light requirements into high-light demanding crops, fruity vegetables, leafy vegetables, grain legumes and berries, in accordance to [55]. For each crop category three yield response scenarios were defined (optimistic, conservative and pessimistic) relative to the baseline yield without shading. These scenarios represent the range of yield responses reported in the literature and allow the economic model to account for uncertainty in crop performance under PV shading. Categorizations and respective yield scenarios be found in the Appendix Section A.2 (Tables 2 & 3).

Crop revenue impacts were assumed constant over time, while variability is implicitly captured through the considered yield scenarios as presented in the Appendix Section A.2(Table 3), which reflect a range of potential production outcomes.

Crop prices were obtained from the EU Agri-Food Portal [61] and respective yield assumptions were based on national agricultural

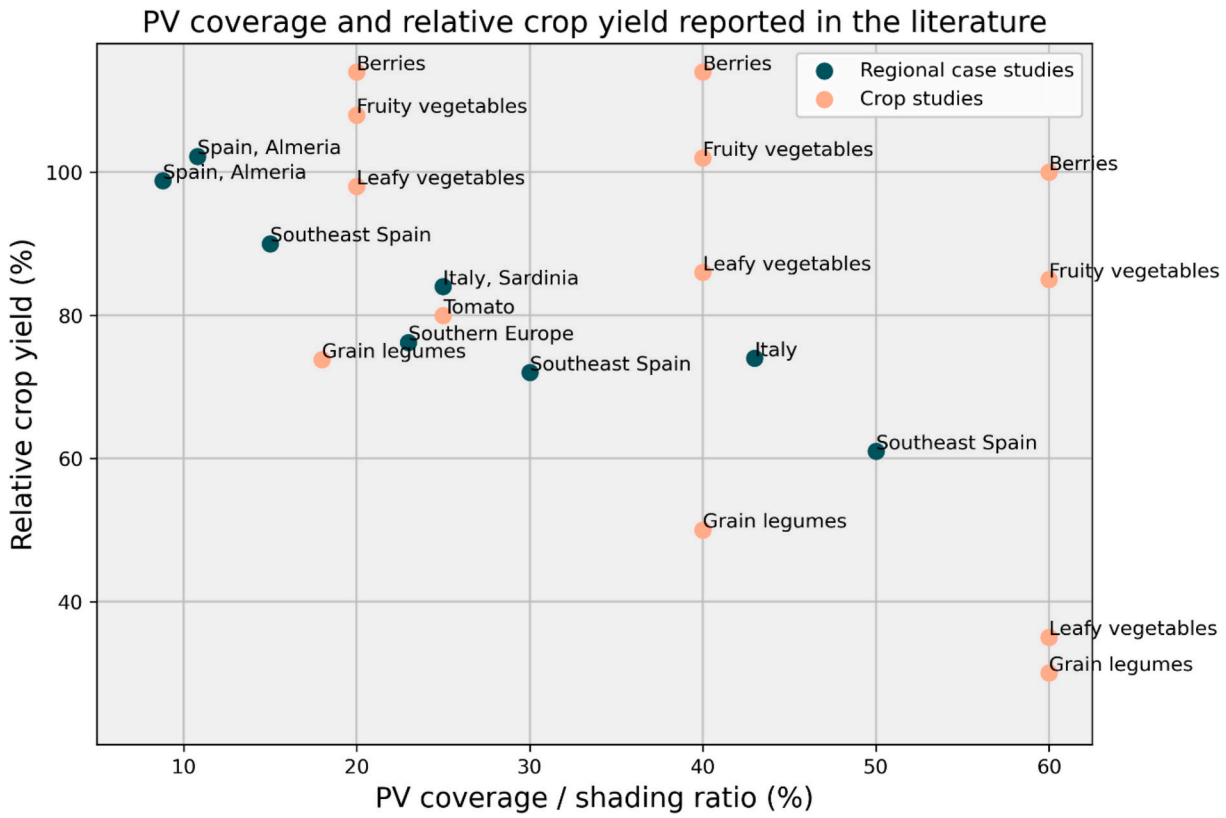


Fig. 4. Overview of shading impact on crop yield according to literature review.

statistics and are provided in the Appendix Section A.3 (Table 4).

2.4. Economic assumptions

2.4.1. PV and battery input parameters

Project NPV was evaluated over a lifetime of 25 years using a real discount rate of $r = 5\%$. Initial investment costs included photovoltaic and, if optimal battery capacity was >0, respective battery capital expenditures (CAPEX).

To ensure a consistent comparison across technologies, total CAPEX was conceptually separated into module costs and balance-of-system (BOS) costs. For c-Si, which represents the mature present-day reference technology, cost assumptions were based on the detailed component-level assessment of small-scale medium-height agrivoltaic systems [48] including modules, inverters, mounting structures, cabling, installation, permitting and project development costs.

For OPV, cost assumptions were derived from the OPV cost scenarios developed in Kierdorf et al. [25]. Current-generation OPV modules (63 W m^{-2}) were represented by commercial module costs of approximately 150 € m^{-2}, corresponding to 2.38 € Wp^{-1}. Future-generation OPV modules (145 W m^{-2}) were represented by an upscaling scenario used in a prior study based on the roll-to-roll manufacturing cost analysis by Machui et al. [14]. This scenario assumes module costs of approximately 26 € m^{-2}, corresponding to 0.18 € Wp^{-1} at a power density of 145 W m^{-2}.

The cost difference between OPV63 and OPV145 is therefore based on two combined assumptions: an increase in power density and a substantial reduction in area-based module manufacturing costs under future large-scale production. The OPV145 case should consequently be interpreted as an optimistic future OPV cost-performance scenario and does not reflect current commercial OPV market conditions.

For OPV systems, inverter, electrical component and installation cost assumptions were based on the OPV cost scenarios in Kierdorf, Lubjuhn, et al. (2025) [25]. The treatment of structural integration was adapted from the c-Si APV reference case by assuming reduced mounting and foundation requirements for OPV systems. This reflects the lightweight and flexible nature of OPV modules, which enables their potential integration into greenhouse cover structures and can reduce the need for additional supporting structures compared with conventional silicon-based APV systems [62].

The OPV145 scenario is compared with the present-day c-Si reference assumptions used in this study. Future improvements in c-Si module efficiency, module costs, lightweight designs and greenhouse-specific integration concepts were not explicitly modeled. The resulting technology-specific cost assumptions are summarized in Table 1.

Battery investment cost was set to 300 € kWh^{-1}, setting a medium range with regard to cost estimations for battery system costs [63]. Battery replacement was assumed after ten years at 80% of initial battery investment, reflecting anticipated cost declines, with no residual value considered for the replaced system. Battery charge and discharge efficiencies were both set to 95% Annual operating expenditures (OPEX) were assumed to equal 1.5% of initial CAPEX for both PV systems and battery storage.

Technology-specific degradation was applied to electricity-related cash flows. For OPV, annual degradation was assumed to be 1% as reported by manufacturers [25]. However, long-term field evidence for OPV systems remains limited compared to mature silicon PV technologies. The applied degradation rate should therefore be interpreted as an indicative modelling assumption rather than a validated long-term performance trajectory. Additional sensitivity analyses considering higher degradation rates were applied in Section 3.3.

For silicon photovoltaics, annual degradation was assumed to be 0.5%, consistent with degradation rates commonly reported for contemporary crystalline silicon PV systems and applied in the NREL Annual Technology Baseline [64].

Self-consumption was valued using average retail electricity prices for non-household consumers with annual demand between 500 MWh and 1999 MWh in [65] as a baseline, resulting in 0.236€ kWh^{-1} for Italy

Table 1
Technology-specific CAPEX assumptions used in the economic model.

Technology scenario	Technology status	Power density (Wm^{-2})	Module cost assumption	Module CAPEX (€Wp^{-1})	Treatment of non-module costs	Total CAPEX (€kWp^{-1})
c-Si	Mature present-day reference technology	230	Component-level APV cost assessment based on Böhm et al. [48]	0.20	Full APV system-cost reference including modules, inverters, mounting structures, cabling, installation, permitting and project development costs	970
OPV63	Current-state OPV scenario	63	Commercial OPV module costs of 150 € m^{-2} adopted from Kierdorf, et al. [25]	2.38	OPV cost scenario including inverters, electrical components and installation costs; structural requirements reduced due to lightweight greenhouse integration	3345
OPV145	Optimistic future OPV upscaling scenario	145	Upscaling scenario of 26 € m^{-2} adopted from Kierdorf, et al. [25], based on Machui et al. [14]	0.18	OPV upscaling cost scenario including inverters, electrical components and installation costs; structural requirements reduced due to lightweight greenhouse integration	940

and 0.157€ kWh^{-1} for Spain (Eurostat [65]). This approach reflects the economic value of avoided electricity purchases from the perspective of greenhouse operators and is consistent with the structure of the investigated self-consumption schemes. While it does not explicitly capture dynamic retail electricity tariffs or short-term wholesale market volatility, temporal electricity price variability is incorporated in the remuneration of exported electricity where applicable (e.g., direct selling and Ritiro Dedicato), through the use of hourly market prices.

2.4.2. Remuneration scheme

The remuneration schemes were selected as representative examples of different remuneration mechanisms that have been applied in practice. Their inclusion enables an assessment of how alternative regulatory designs influence the economic performance of greenhouse-integrated PV systems.

The modelling focused on those regulatory elements that directly affect annual energy-related cash flows: avoided electricity imports, remuneration of exported electricity and compensation limits.

For Spain, two self-consumption remuneration options were considered: net billing and direct selling. Under net billing, exported electricity generates monthly compensation credits that are deducted from the remaining electricity bill. The monthly credit is limited by the value of the remaining monthly import bill. Under direct selling, exported electricity is remunerated using the hourly day-ahead market price, reduced by an assumed export-related fee of 5%. In both cases, self-consumed PV electricity reduces electricity imports and is valued through avoided retail electricity purchases.

For Italy, two remuneration schemes were implemented: Scambio sul Posto (SSP) and Ritiro Dedicato (RID). SSP was represented as an annual net-metering proxy, in which annual imported and exported electricity volumes are offset. Offset electricity was valued at 0.12 € kWh^{-1} and surplus exported electricity at 0.06 € kWh^{-1}. RID was treated as the forward-looking remuneration scheme. Under RID, exported electricity is remunerated hourly at the higher value of the zonal electricity market price and the guaranteed minimum price, assumed here at 0.044 € kWh^{-1}.

The resulting scheme-specific annual operating values were transferred to the investment model as yearly energy-related cash flows. These cash flows capture avoided electricity imports, remuneration of exported electricity and scheme-specific compensation limits.

Detailed regulatory background and the mathematical implementation of each scheme are provided in the **Appendix** Section A.5.

2.5. Economic analysis

This section outlines the techno-economic framework, including system optimization, remuneration schemes, and key economic assumptions, as well as the determination of maximum admissible investment costs.

The analysis was conducted in two consecutive steps. First, a baseline techno-economic assessment excluding crop-yield impacts was performed to isolate the influence of energy-system design parameters and regulatory conditions on greenhouse PV profitability. In a second step, crop-yield impact scenarios were incorporated to evaluate integrated APV feasibility under holistic greenhouse operating conditions.

2.5.1. System optimization framework

The techno-economic assessment was based on an hourly dispatch optimization combined with an outer-loop investment model. For each combination of region, photovoltaic technology, coverage fraction, electricity demand level, and crop yield scenario, the battery capacity

B(0–25 kWh) that maximized project net present value (NPV) was selected. In each hour, generated electricity could be allocated to direct self-consumption, battery charging, or grid export (Eq. 2).

$$PV_t = SC_t + Ch_t + Exp_t. \tag{2}$$

With.
PV_t = PV electricity generation.
SC_t, = Direct self-consumption.
Ch_t= Battery charging r
Exp_t= Grid export

Electricity demand was met by direct self-consumption, battery discharge, and grid imports (Eq. 3).

$$D_t = SC_t + Dis_t + Imp_t. \tag{3}$$

With.
D_t = Electricity demand.
SC_t, = Direct self-consumption.
Ch_t= Battery charging r
Exp_t= Grid export

Battery operation was constrained by the state of charge (Eq. 4 & 5).

$$SOC_t = SOC_{t-1} + \eta_{\mathrm{ch}} Ch_t - \frac{Dis_t}{\eta_{\mathrm{dis}}}, \tag{4}$$

Given

$$0 \le SOC_t \le B, \tag{5}$$

With.
SOC_t = State of Charge.
$\eta_{\mathrm{ch}}/\eta_{\mathrm{dis}}$= Charging and discharging efficiency (95%).
Ch_t = Battery charging r.
Dis_t = Battery discharging.
B= Battery capacity (0–25 kWh).

The hourly dispatch problem maximizes annual energy operating value (EOV), with the exact objective depending on the remuneration scheme.

The annual energy operating value (EOV) can then be written in general form as

$$EOV = (Bill_0 - Bill_1) + R_{scheme},$$

$$EOV = (Bill_0 - Bill_1) + R_{scheme}, \tag{6}$$

with.

EOV= Annual energy operating value

$Bill_0$= Annual electricity expenditure without PV system

$Bill_1$= Annual electricity expenditure after PV and battery implementation

R_{scheme}= Remuneration obtained under the respective electricity compensation scheme

The term $(Bill_0 Bill_1)$ represents avoided electricity purchases and therefore captures the economic value of self-consumption.

In general, annual operating value was defined as relative to a no-PV reference scenario, in which all electricity is supplied from the grid. Eq. 7 denotes the annual electricity expenditure without the PV system, and Eq.8. the residual electricity expenditure after PV and battery implementation.

$$Bill_0 = p_{imp} \sum_t D_t \tag{7}$$

with.

$Bill_0$= Annual electricity expenditure without PV system

p_{imp}= Retail electricity price for imported electricity

D_t= Electricity demand

$$Bill_1 = p_{imp} \sum_t Imp_t \tag{8}$$

with. $Bill_1$= Annual electricity expenditure after PV and battery implementation

p_{imp}= Retail electricity price for imported electricity

Imp_t= Electricity imported from the grid in hour t

The EOV was transferred to the investment model as the yearly energy-related cash flow $CF_y(B)$. The economic analysis was carried out in two stages. In the first stage, only energy-related cash flows were considered without included crop cash flows. The energy-related NPV was calculated as presented in Eq. 9:

$$NPV(B) = -CAPEX_{PV} - CAPEX_{bat}(B) + \sum_{y=1}^{25} \frac{CF_y(B) - OPEX_y - REP_y}{(1+r)^y}, \tag{9}$$

With.

$NPV(B)$= Energy-related net present value for battery size B

$CAPEX_{PV}$ = Initial photovoltaic investment costs.

$CAPEX_{bat}(B)$= Initial battery investment costs for battery size B

$CF_y(B)$= Annual energy-related cash flow in year y for battery size B

$OPEX_y$= Annual operating expenditures in year y

REP_y= Battery replacement costs in year y for battery size B

r= Real discount rate

y= Project year

B= Battery size

The optimal battery size was therefore obtained from Eq. 10:

$$B^* = \text{argmax} NPV(B). \tag{10}$$

with.

B^*= Optimal battery size

Second, crop revenue impacts were included (ΔCR_y) to capture the APV trade-off between electricity revenues and yield impacts. The total APV-related NPV was calculated as presented in Eq. 11:

$$NPV_APV(B) = -CAPEX_{PV} - CAPEX_{bat}(B) + \sum_{y=1}^{25} \frac{CF_y(B) - OPEX_y - REP_y + \Delta CR_y}{(1+r)^y}, \tag{11}$$

with.

ΔCR_y= Annual change in crop revenue relative to the agronomic baseline without PV-induced shading

The agronomic baseline revenue itself was treated as the counterfactual agricultural production and was therefore not included as an additional cash inflow attributable to the PV investment. Only the change in crop revenue caused by the assumed PV-induced yield response was included in the total APV-related NPV.

2.5.2. Determination of maximum admissible PV investment costs

In addition to NPV maximization over battery capacity, the maximum admissible OPV investment cost was determined for each configuration. For this step, the annual energy operating value was first calculated from the hourly dispatch model without battery storage and without crop revenue effects. NPV was then expressed as a function of OPV investment cost I_{OPV},

$$NPV(I_{OPV}) = -I_{OPV} + \sum_{y=1}^{25} \frac{CF_y(I_{OPV}) - 0.015 I_{OPV}}{(1+r)^y}. \tag{12}$$

the break-even investment level was obtained by solving

$$NPV\left(I_{OPV}^{max}\right) = 0 \tag{13}$$

The root was identified numerically using interval expansion followed by bisection. The resulting value I_{OPV}^{max} represents the maximum admissible investment cost at which the respective OPV system remains economically viable under the modeled operating and market conditions.

The economic model was checked for internal consistency by verifying the energy balance between PV generation, self-consumption, imported electricity and exported electricity, as well as the application of remuneration schemes, investment costs and crop-related cash-flow adjustments. The economic assessment follows a scenario-based design to compare relative economic performance under defined technical, agronomic and regulatory assumptions.

2.5.3. OPV degradation and replacement

To assess the economic implications of uncertainty in long-term OPV performance, the application of degradation scenarios was conducted in accordance with prior developments [25]: Besides the reference case assuming 1% annual degradation, a higher-degradation case with 2% annual degradation, and a scenario combining a 25% initial performance loss with 1% annual degradation was implemented. All scenarios were evaluated over the common 25-year project horizon.

Additionally, to reflect uncertainty regarding OPV performance parameters with respect to lifetime, we applied two replacement cost scenarios. In the two sensitivity scenarios, full OPV module replacement is assumed after 15 and 10 years respectively, with replacement costs set at 80% of the initial module CAPEX, reflecting a conservative 20% cost reduction consistent with documented PV learning effects and projected declines in PV capital costs [64,66,67].

3. Results

In the following part, first, the results for the baseline techno-economic assessment excluding potential crop-yield impacts caused by PV-induced shading are presented. This initial step was intentionally designed to isolate the influence of energy-system parameters, self-consumption dynamics, and regulatory conditions on overall economic performance before integrating agronomic trade-offs. In a consecutive

step, the results with incorporated crop cash flows are presented.

3.1. Isolated energy-system profitability assessment with optimized BESS integration without crop cash flows

The NPV results provide an overview of the economic feasibility of the investigated APV greenhouse configurations under varying PV coverage levels, demand profiles, remuneration schemes, technologies, and battery integration options.

To focus the discussion on economically relevant configurations, only scenarios with clearly positive NPVs or values close to zero are presented in the main text. The full set of NPV results, including optimal battery capacities across all scenarios, is provided in the Appendix Section A.4 (Figs. 16 and 17). For simplification, PV technology categories are called OPV 63, OPV 145 and c-Si.

3.1.1. Overall trends

Across both locations, the demand profile emerges as the most influential parameter for baseline economic performance. Scenarios with high electricity demand consistently achieve substantially higher NPVs, which is clear due to the higher remuneration by retail prices. This increases the value of PV generation and reduces reliance on grid electricity purchases. In contrast, scenarios with low electricity demand show significantly lower NPVs and frequently approach or fall below the break-even threshold, particularly at higher PV coverage levels where surplus generation increases.

These results highlight that, independent of agronomic considerations, high self-consumption rates are a key prerequisite for favorable energy-economic greenhouse PV configurations.

3.1.2. Influence of PV technology

The technology selected also profoundly impacts baseline economic performance. In the majority of scenarios, c-Si modules have been shown to achieve the highest NPVs, primarily due to their high conversion efficiency and well-established cost structure (Fig. 5). From a purely energy-economic perspective excluding crop-yield impacts, c-Si therefore remains the strongest benchmark technology. However, the integration of c-Si modules into greenhouse systems can require dedicated mounting structures or building-integrated PV concepts. Due to their rigidity and comparatively higher weight, c-Si modules may require additional structural support, particularly when installed on existing greenhouse roofs. This can increase installation complexity and may limit retrofitting options.

OPV modules represent a different integration pathway due to their low weight, flexibility and potential semi-transparency. They may be integrated into greenhouse cover materials or applied as lightweight films on greenhouse roof structures, which can reduce structural mounting requirements compared with conventional silicon-based APV systems. These characteristics are reflected in the reduced structural integration requirements assumed for the OPV scenarios.

OPV modules with a projected output of 145 W show mixed but promising results. For identical system configurations, the resulting NPVs of OPV145 and crystalline silicon are often of comparable magnitude. For example, under high-demand conditions and 40% PV coverage NPVs reach approximately 22,176€ for OPV145 compared with approximately 11,610€ for c-Si in Almería, while in Bari both technologies reach values slightly above 50,000€. A similar pattern can be observed at 25% PV coverage, where both technologies achieve clearly positive NPVs of comparable magnitude.

These results indicate that future OPV improvements could become economically relevant in greenhouse applications, particularly in configurations where electricity demand is high and self-consumption remains strong, if higher power densities and substantial reductions in area-based module manufacturing costs are achieved. At the same time, the economic performance of OPV145 remains more sensitive to variations in demand levels and system configuration. The result should be interpreted as an exploratory indication of future OPV potential under fixed present-day c-Si reference assumptions.

In contrast, OPV modules with a nominal output of 63 W are not economically viable in any of the evaluated scenarios. Their lower efficiency combined with the assumed cost assumptions leads to negative NPVs across all coverage levels and demand profiles. However, at low PV coverage under high demand scenarios, NPVs reach values close to feasibility threshold (Bari: −2907€, Almería −8389€) compared with other configurations that remain far below −20,000€. This indicates that relatively small parameter changes such as lower investment costs, efficency increases, slightly higher electricity prices, or moderate yield improvements could improve the economic competitiveness of these configurations under integrated APV conditions.

Furthermore, beyond the economic feasibility considerations associated with current OPV module costs, it is important to recognize that even the OPV 63 scenario could already meet the greenhouse's annual electricity demand. Given that self-consumption generally offers greater economic benefits than electricity export by offsetting retail electricity purchases, this finding has important implications for the underlying business model. It suggests that maximizing electricity generation may be less economically significant than optimizing generation capacity to match on-site demand and maximize the value of self-consumed

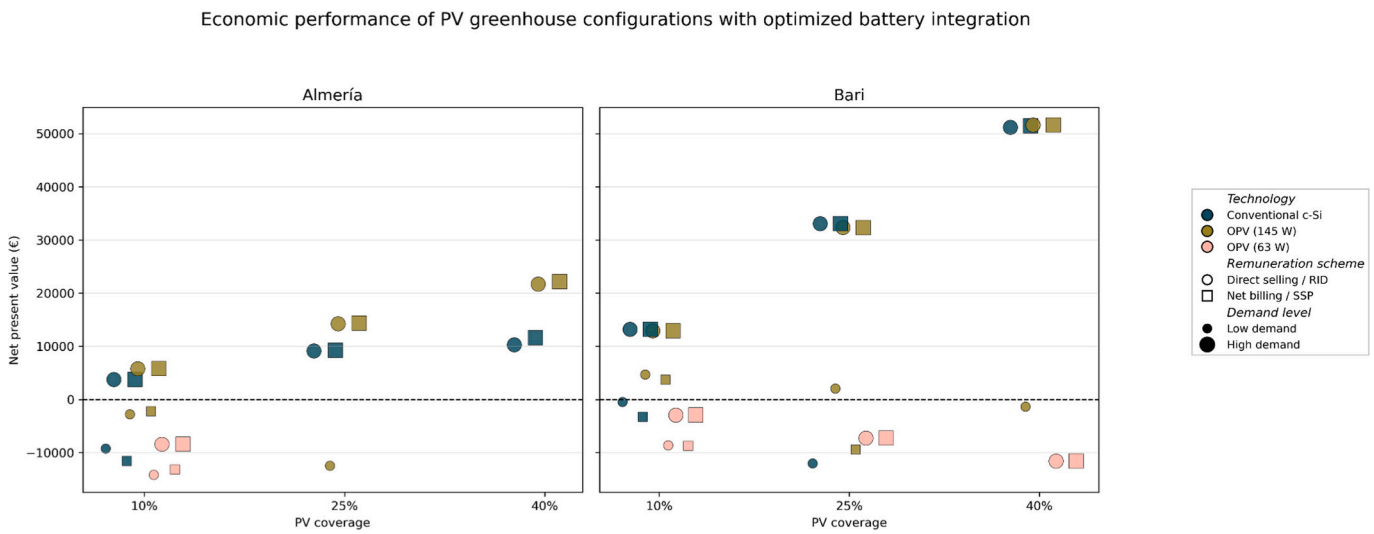


Fig. 5. Baseline techno-economic NPV results of greenhouse PV-BESS systems excluding crop-yield impacts.

electricity.

3.1.3. Influence of remuneration schemes

A general observation indicates that the discrepancies among the examined remuneration schemes are comparatively negligible in relation to the impact of demand profile, PV coverage, and technology. In both countries, the evaluated remuneration structures produce similar NPV levels in many cases, indicating that project profitability is driven primarily by self-consumption rather than by revenues from exported electricity. This underscores the pivotal role of demand structure and system sizing in the context of energy management.

However, as PV coverage increases and export volumes become more significant, some scheme-specific disparities become noticeable. In Bari, low-demand scenarios under the RID scheme demonstrate marginal superiority over SSP for advanced OPV configurations. Specifically, for OPV145, the results indicate economically favorable baseline scenarios at 25% PV coverage, and only slightly negative results at 40% PV coverage, whereas the corresponding SSP cases remain negative. In Almería, however, a slight deviation from this norm emerges. Specifically, net billing tends to yield higher NPVs at lower levels of PV coverage, while direct selling performs more favorably at higher coverage levels. While these variances do not modify the overall ranking of the primary drivers, they do underscore that the remuneration framework becomes more substantial once surplus electricity increases.

3.1.4. Comparison between locations

A comparison between the two locations reveals a significant contrast. While the potential for photovoltaic electricity generation in Almería is estimated to be approximately 15% higher than in Bari, due to more favorable solar irradiation conditions), this does not necessarily translate into enhanced overall economic performance. While profitable scenarios are observed in both regions, NPVs tend to be slightly lower in Almería, and a larger number of configurations remain close to the break-even threshold.

This finding indicates that greater solar resource availability does not necessarily guarantee superior economic performance. The profitability of these enterprises is significantly influenced by the interplay among generation, on-site demand, and the prevailing tariff and remuneration framework. Therefore, economic feasibility is determined not solely by the quantity of electricity produced, but also by the effectiveness with which this electricity can be utilized on-site and monetized under the prevailing regulatory conditions.

3.1.5. Role of battery storage

Battery profitability varies strongly across configurations (Fig. 6) and is mainly observed under low-demand conditions, where storage improves energy management by shifting PV generation to periods of use. This reduces losses from temporal mismatches between supply and demand.

The effect is most pronounced in Bari, with viable battery sizes of 8–11 kWh in low-demand scenarios, while in Almería only isolated cases with small capacities (~3 kWh) are economically viable.

Overall, this baseline assessment excluding crop-yield impacts indicates that self-consumption is the primary driver of favorable energy-economic system performance, while battery integration mainly becomes beneficial under conditions of limited direct electricity use. The extent to which these configurations remain favorable under realistic crop-yield impact conditions is evaluated in the subsequent analysis.

3.2. Feasibility with incorporated agricultural changes

When crop-related effects are incorporated into the economic

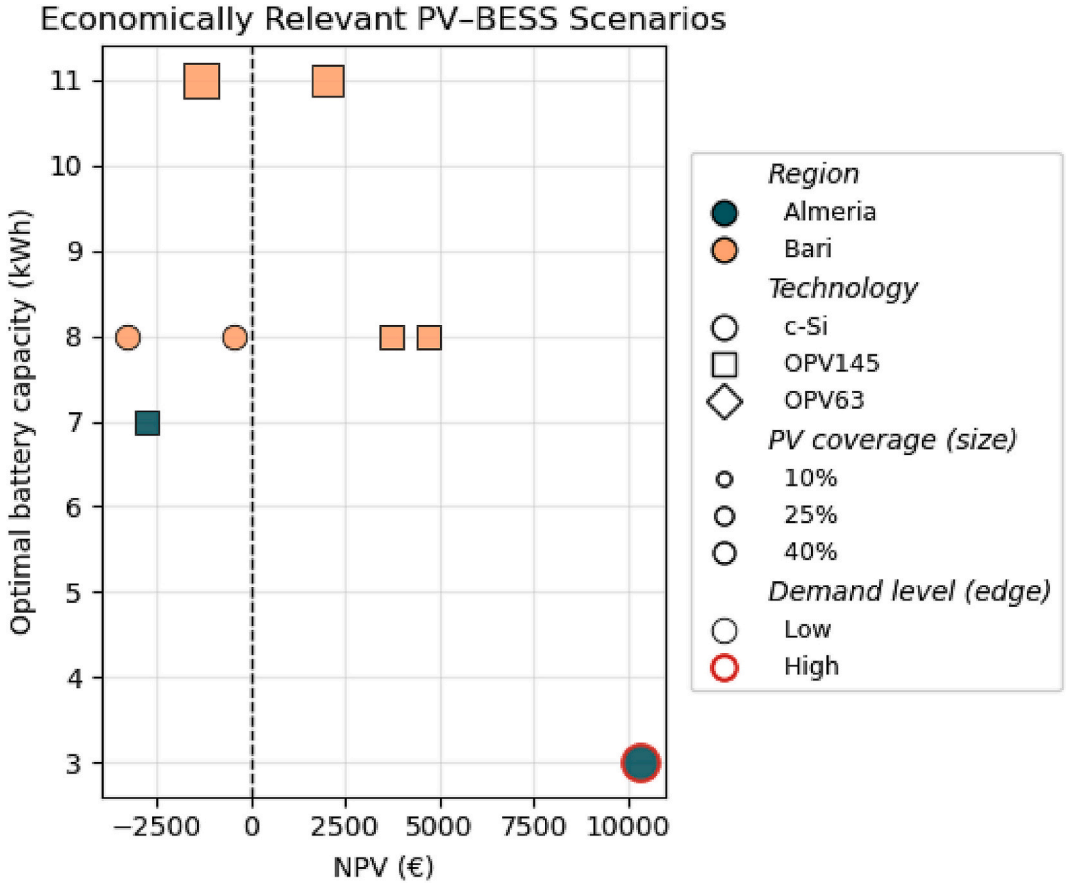


Fig. 6. Optimal battery capacities for (nearly) profitable scenarios.

assessment, the resulting profitability changes noticeably compared with the baseline evaluation that considers only electricity revenues. As illustrated in Fig. 7, the incorporation of crop responses has been demonstrated to affect the NPV, thereby demonstrating how the NPV changes with regard to PV coverage levels and indicating the range of the impact including all assumed yield scenarios.

Overall, the results show that agricultural impacts can significantly influence the economic outcome of APV greenhouse systems. This finding differs from several APV studies in open-field agriculture where crop impacts typically have a limited influence on overall profitability [48,68]. In greenhouse systems, crops generally achieve higher yields per unit area and have higher market values, meaning that even moderate yield changes can substantially affect the economic balance of the system.

In some scenarios, crop responses can improve economic performance. Such cases occur where moderate shading leads to beneficial crop responses, including yield increases that have occasionally been reported for certain berry crops under partial shading conditions. However, in most scenarios the inclusion of crop effects reduces profitability because shading may lead to yield reductions and therefore lower crop revenues.

The negative economic impact becomes more pronounced as PV coverage increases. Higher coverage levels lead to stronger shading of the greenhouse area and therefore increase the likelihood of yield reductions. In many cases, the additional revenue from electricity generation is not sufficient to compensate for agricultural losses. As a result, NPVs decrease compared with the baseline evaluation that only considers electricity revenues.

3.2.1. Regional comparison

The economic implications of crop responses differ between the two case study regions.

In Almería, only a limited number of crop and technology combinations remain economically attractive once crop effects are incorporated. While most crops exhibit negative NPVs across the majority of evaluated scenarios, strawberry cultivation represents a notable exception. Under favorable assumptions, individual strawberry configurations achieve NPVs of more than 40,000 €, indicating that the combination of comparatively high crop revenues and positive crop responses can offset APV investment costs. In contrast, crops such as cucumber, pepper and eggplant remain economically challenging, with crop-related impacts substantially reducing profitability. Fig. 7 shows that tomato and cucumber systems experience ΔNPV reductions of up to approximately 50,000 € and 78,000 €, respectively, while even strawberries can experience NPV reductions exceeding 60,000 € under conservative and pessimistic assumptions at higher PV coverage levels.

In Bari, the overall economic outlook is comparatively more favorable, reflecting higher electricity prices and larger economic benefits from PV self-consumption. Several crop configurations approach or exceed economic break-even under favorable assumptions. However, Fig. 7 demonstrates that crop responses remain an important determinant of profitability. While tomato and cucumber exhibit comparatively moderate ΔNPV reductions, crops such as pepper, courgette and eggplant show substantially larger economic impacts. In the most pessimistic scenarios, eggplant experiences ΔNPV reductions exceeding 200,000 €, highlighting the strong sensitivity of economic outcomes to crop-specific yield responses.

Overall, the results indicate that crop responses can substantially alter economic outcomes in both regions and that crop composition and crop-specific responses to PV-induced shading significantly affect the overall feasibility.

3.3. Sensitivity analysis

The sensitivity analysis was conducted to assess the robustness of the economic results with respect to future OPV investment costs and crop-related revenue effects. First, break-even CAPEX thresholds were calculated for OPV systems to determine the maximum investment cost at which OPV configurations would reach economic feasibility to analyze how strongly the viability of OPV depends on future cost reductions and performance improvements. Second, break-even crop revenue adjustments were calculated to assess how additional crop revenue would be required to compensate negative NPVs, or how much crop revenue loss could be tolerated while maintaining economic feasibility. Together, both analyses provide threshold values that help interpret the economic robustness of the evaluated greenhouse PV configurations beyond the specific baseline assumptions.

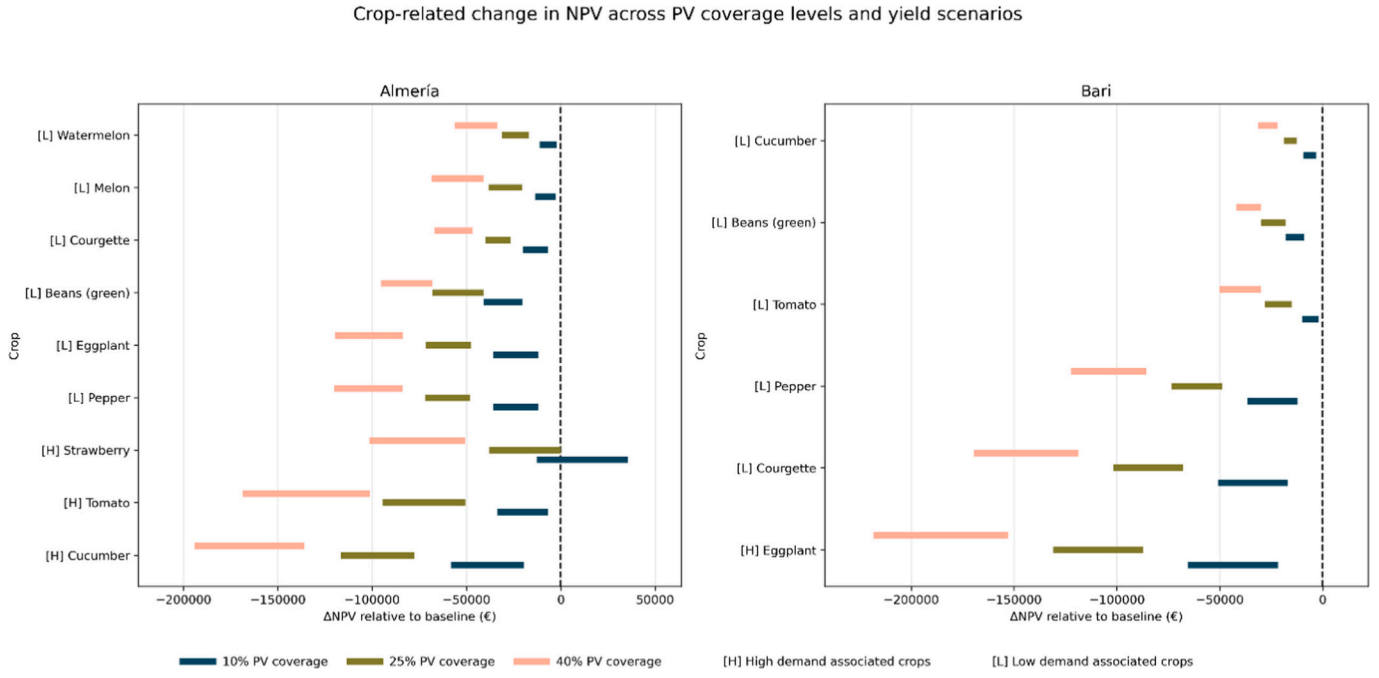


Fig. 7. NPV change including economic crop impact compared to baseline scenario without crops across all PV technology scenarios.

3.3.1. Organic PV

Fig. 8 presents the distribution of maximum permissible CAPEX for OPV systems across all scenarios, defined as the investment level yielding a net present value of zero. Profitability therefore requires actual investment costs to remain below these thresholds.

For current OPV technology, the assumed CAPEX exceeds all break-even values, confirming its lack of economic viability under present conditions, consistent with the preceding analysis. In contrast, the improved OPV 145 scenario shows substantially higher break-even CAPEX values, with the median already exceeding the assumed investment costs, indicating that several scenarios could become economically feasible under moderate technological progress.

For comparison, CAPEX for silicon-based Agri-PV systems of similar scale are reported in the range of 970–1475€ kWp^{-1} [48], which overlaps with or remains below the break-even thresholds observed for OPV 145. This highlights that OPV could become competitive with established silicon systems if projected improvements in efficiency and cost are realized.

Overall, while current OPV systems are not yet economically viable, moderate cost reductions and performance gains could significantly enhance their competitiveness. In particular, integration into low-cost greenhouse structures (e.g., foil tunnels) may further reduce installation complexity and system costs, as no additional substructure is required. It should be noted that these CAPEX thresholds do not account for potential crop-related effects on economic performance.

3.3.2. Break-even analysis of crop revenue adjustments

A sensitivity analysis was conducted to evaluate the influence of agricultural and operational uncertainties on system viability. A break-even crop impact analysis was used to determine the maximum reduction in crop-related revenues that can be tolerated while maintaining a non-negative NPV.

The break-even crop revenue analysis quantifies the magnitude of agricultural revenue changes required to achieve minimum economic viability, indicated by NPV = 0. Fig. 9 illustrates the corresponding yearly crop revenue adjustments for investigated scenarios. Positive values indicate additional required crop revenue to compensate negative NPVs, whereas negative values indicate tolerable yield losses that would still be offset by the additional PV income streams.

This analysis differs conceptually from the previous section, which evaluated the economic outcomes under specific crop yield assumptions. The break-even analysis does not assume particular crop responses to shading but instead determines the revenue adjustment necessary to reach economic feasibility. It therefore provides a sensitivity-based threshold analysis that indicates how robust or fragile the economic viability of the APV greenhouse system is with respect to crop performance.

The results obtain that crops with higher market values and consequently higher baseline revenues, such as strawberries or tomatoes, provide greater economic flexibility and are therefore more capable of compensating for PV investment costs. Conversely, crops with lower revenues would require unrealistically large yield increases to reach economic break-even under APV conditions.

Across the investigated scenarios, the required crop revenue increases for economically unprofitable configurations range from a few hundred euros up to approximately 4700€ $year^{-1}$ in Bari and 6400€ $year^{-1}$ in Almería. Relative to typical baseline crop revenues, these gains correspond to roughly 5–30% of annual crop revenue, depending on the crop considered (see Fig. 10). For crops with high baseline revenues such increases may be achievable through yield improvements or price variation. For lower revenue crops, however, the required gains represent a substantial share of annual revenue and therefore appear less

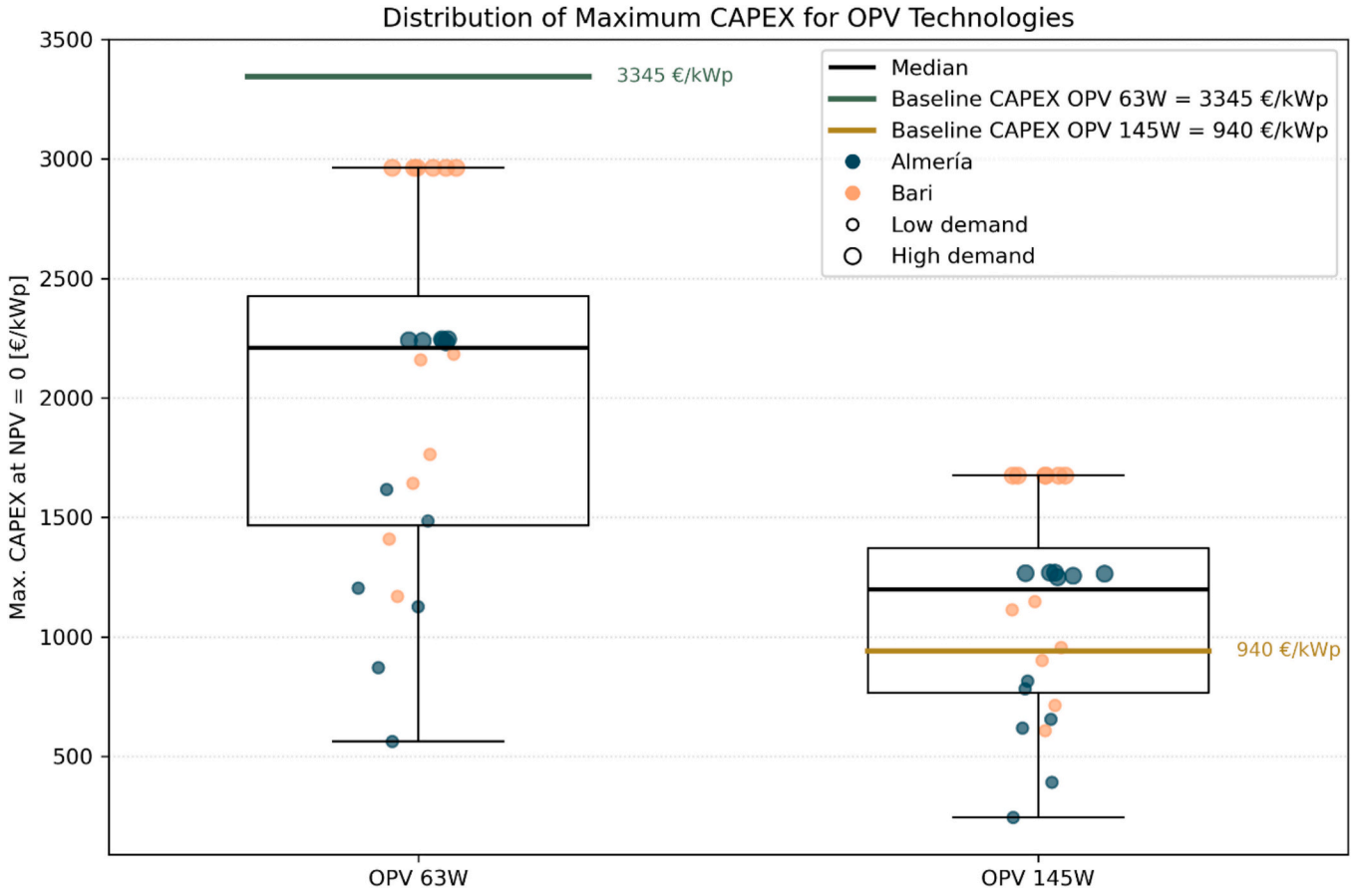


Fig. 8. Maximum costs per kWp for OPV feasibility threshold.

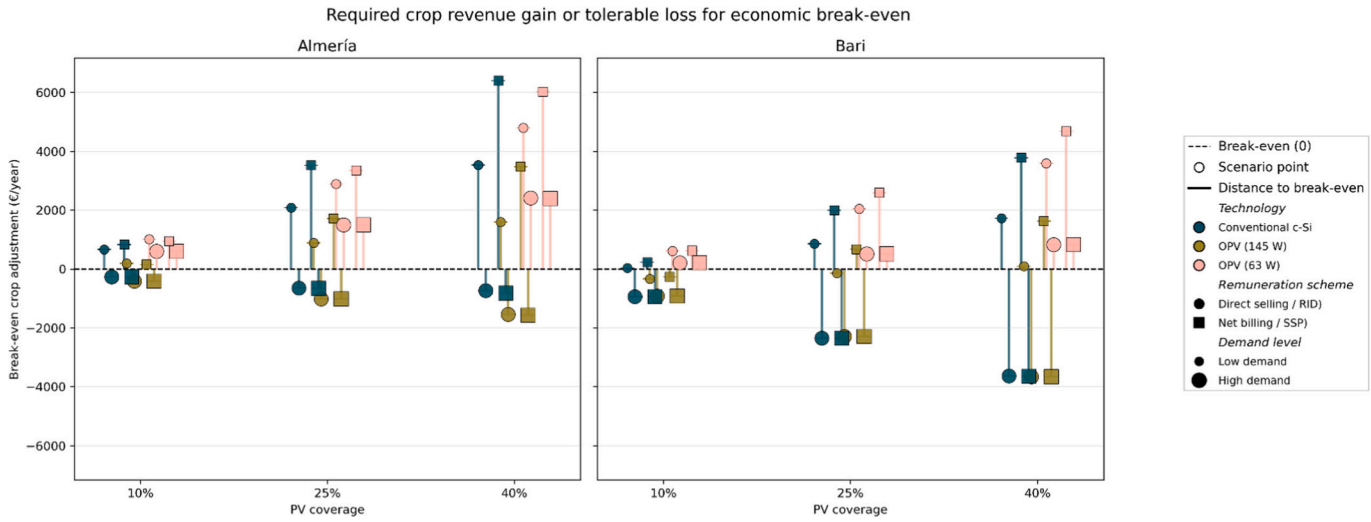


Fig. 9. Additional crop revenue required per year for reaching feasibility threshold.

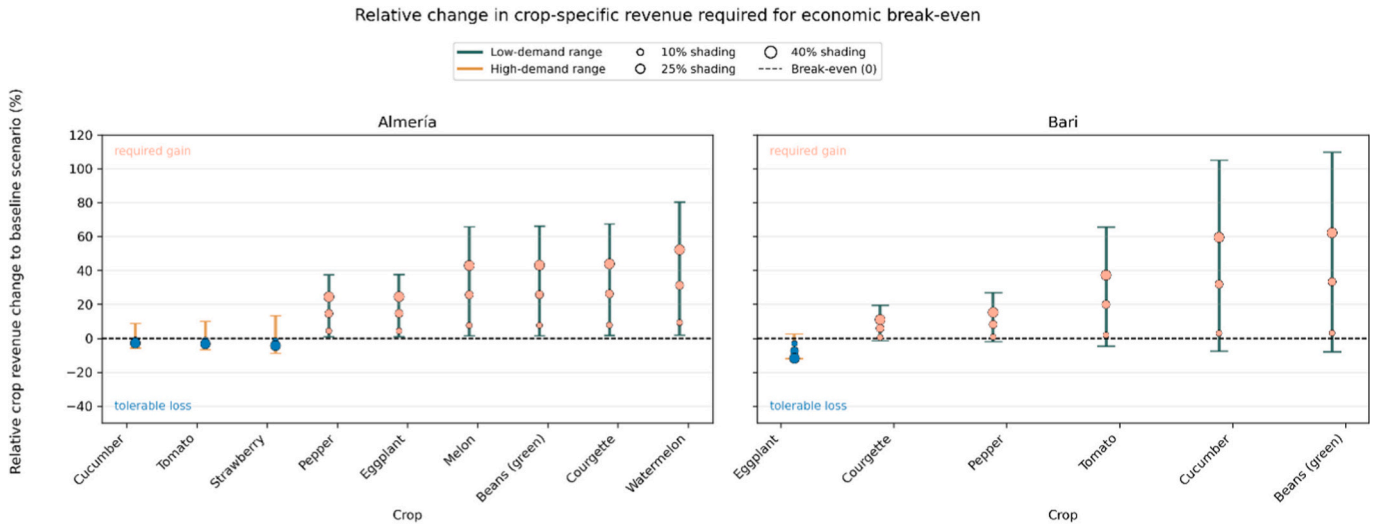


Fig. 10. Required crop specific revenue change to reach yield feasibility threshold.

realistic.

Conversely, economically viable PV configurations can tolerate crop revenue losses of up to approximately 3700€ year^{-1} in Bari and 1600€ year^{-1} in Almería. For most crops this corresponds to approximately 10–20% of baseline crop revenue, indicating that moderate shading-induced yield reductions could be economically acceptable in these cases.

Overall, the feasibility of APV greenhouse systems depends strongly on the underlying crop. High-value crops with larger baseline revenues provide greater flexibility to absorb shading-related revenue losses or offset negative NPVs. In contrast, lower-value crops would require comparatively large revenue increases to achieve economic breakeven.

When these results are compared with the expected yield responses under different shading levels, an important pattern emerges. The tolerable crop revenue losses estimated by the break-even analysis partly overlap with yield reductions expected under low to moderate shading levels of approximately 10–25% for many crop categories. This suggests that moderate shading impacts could remain economically acceptable in several configurations. Under higher shading levels of approximately 40%, however, pessimistic yield assumptions often exceed the tolerable revenue loss thresholds. In these cases, shading-sensitive crops face a substantially increased risk of economic infeasibility.

3.3.3. *Degradation sensitivity*

The degradation sensitivity analysis showed a substantially stronger economic impact of the assumed initial performance loss than of higher continuous annual degradation. For OPV145, increasing annual degradation from 1% to 2% reduced NPV by 1190€–7550€ across the Spanish configurations and by 2020€–10,070€ across the Italian configurations. Without crop-revenue effects, all six profitable Spanish reference configurations remained profitable, while one of nine profitable Italian configurations fell below the NPV break-even threshold.

Assuming a 25% initial performance loss resulted in larger NPV reductions, ranging from 3450€–22,060€ in Spain and 5540€–29,420€ in Italy, indicating that material stability is of fundamental importance. Under this scenario, one of six profitable Spanish configurations and three of nine profitable Italian configurations became unprofitable.

Since crop-revenue effects remain constant across the degradation scenarios, the degradation-related NPV changes were equivalent when crop revenues were included. However, the resulting profitability response differed due to changes in the initial economic position of individual configurations. Under 2% annual degradation, all six profitable Spanish configurations remained profitable, while three of four

profitable Italian configurations became unprofitable. Under the 25% initial-loss scenario, all six profitable Spanish configurations remained profitable, while all four profitable Italian configurations fell below the NPV break-even threshold.

For OPV63, the degradation sensitivities reduced NPV across the evaluated configurations but did not change the profitability classification in either country, with or without crop-revenue effects. Fig. 11 shows the respective changes in profitability within the OPV145 scenario.

3.3.4. Replacement sensitivity

The module-replacement scenarios had a comparatively limited effect on the economic viability of OPV145. Replacement after 10 years changed NPV by between an increase of 375€ and a reduction of 4117€ across the Spanish and Italian configurations, while replacement after 15 years resulted in changes ranging from an increase of 748€ to a reduction of 3159€. Without crop-revenue effects, all six profitable Spanish and all nine profitable Italian reference configurations remained profitable under both replacement scenarios.

Since crop-revenue effects remain constant across the replacement scenarios, the replacement-related NPV changes were equivalent when crop revenues were included. All six profitable Spanish and all four profitable Italian reference configurations also remained profitable under both replacement scenarios. In some Italian configurations, the restored module performance slightly exceeded the discounted replacement expenditure, resulting in a small increase in NPV.

For OPV63, replacement resulted in substantially larger NPV reductions, ranging from 6000€ to 27,290€ after 10 years and from 4616€ to 21,314€ after 15 years. The profitability classification remained unchanged under both replacement scenarios. None of the OPV63 configurations without crop-revenue effects were profitable, while the two profitable Spanish configurations with crop-revenue effects remained profitable.

3.4. Limitations

Several limitations should be considered when interpreting the results of this analysis.

The primary objective of this study is to rely on validated energy demand profiles for economic analysis, as opposed to simulating them without real measured data. It becomes overall evident that high-resolution energy demand profiles of case studies are lacking. Consequently, we provided two profiles representing different levels of load profiles. A limitation concerns the interpretation of the high-load scenario. While greenhouse energy demand is often reported in kWh regardless of the underlying energy carrier, elevated demand levels may in practice include substantial thermal loads that are commonly supplied by fossil fuels. Since PV electricity can only directly offset electrical demand, the high-load scenario should therefore be interpreted as representing an electrified greenhouse configuration rather than a conventional fossil-based heating system. Consequently, the economic value of self-consumed PV electricity depends strongly on the displaced energy carrier: if PV generation replaces grid electricity purchases, avoided costs correspond to non-household electricity tariffs, whereas the substitution of fossil fuels used for thermal energy supply would result in substantially lower economic benefits due to the lower price of natural gas compared to electricity.

Furthermore, future analyses could investigate the impact of dynamic retail electricity tariffs and increasing electricity market volatility on greenhouse APV profitability.

Crop responses to partial shading depend strongly on crop type, local climatic conditions, and cultivation practices. Consequently, the crop-related component introduces considerable variability into the economic assessment of APV systems and should therefore be interpreted with caution. This also relates to the assumed crop prices as actual harvest timing is constrained by crop physiology, production cycles, labor availability and market access. Therefore, the resulting crop revenues should be interpreted as upper-bound estimates under favorable marketing conditions rather than as expected average revenues.

Other agronomic effects of greenhouse-integrated PV systems, such as changes in irrigation demand, microclimate conditions, or water consumption, were not included in the economic assessment. These factors could influence both costs and revenues and therefore affect the overall economic performance of APV systems. For example, the impact of the transmittance by the respective greenhouse material is crucial when considering light impacts [69]. Also, the distribution of radiation under the panels is significantly influenced by factors such as height of the panels, spacing between tables and rows of tables [70]. Nonetheless, owing to the scarcity of studies that differentiate between the shading impact of PV panels or panel simulations and transmittance impacts on crop yields, this value was not incorporated into the analysis but yield scenarios were developed based on reported findings regarding crop yields under shading patterns.

The semitransparent PV scenario was not included due to insufficient data on module efficiencies and the resulting economic performance. However, the “no crop impact” scenario presented in Fig. 5 (first part of

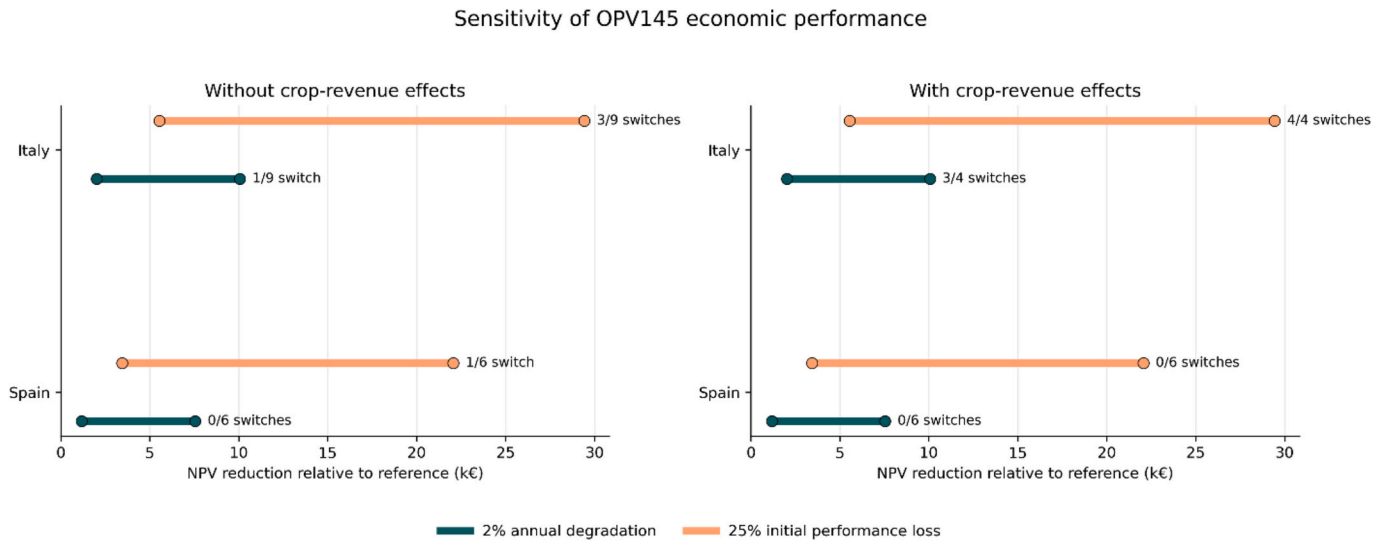


Fig. 11. NPV changes after applied degradation scenarios.

the analysis) may serve as a proxy for such a case, potentially representing conditions at the lower efficiency range of OPV as an indicative assumption.

Finally, the results depend on several economic assumptions, including the electricity prices used to value self-consumed energy, applied discount rate, battery and PV CAPEX as well as crop prices. Variations in these parameters could significantly affect the calculated NPVs and break-even investment thresholds. Consequently, the findings should be interpreted as indicative for the assumed framework conditions rather than universally applicable economic outcomes.

4. Discussion

This study explores the integration of PV greenhouses in representative locations in Spain and Italy with the aim to explore economic profitability under the aspect of PV technologies, demand profiles, battery integration, remuneration schemes and crop yield scenarios. The focus was on the incremental usage of the PV greenhouse so to compare added values by PV Battery system with potential yield changes for crops. Results obtain that feasibility is highly dependent on demand profiles due to higher remuneration compared to export remuneration. Advances in OPV demonstrate comparable outcomes to conventional silicon when configured identically, suggesting a potentially transformative technological advancement. Potential effects on crop revenues show significant impact on feasibility.

4.1. Significance of PV greenhouses for the European south

The potential for the implementation of photovoltaic greenhouses in Europe is significant, particularly in the southern regions [25]. Besides the potential of producing clean energy, reducing costs and replacing fossil energy sources, the economic advantages of the PV greenhouse concept may also allow exploration of new production schemes. In Almería, foil tunnels are often unoccupied during summer months due to excessive irradiation; exceeding the optimum levels for cultivation [20]. Consequently, the addition of PV could either enhance production periods during summer months or just generate income even in the absence of greenhouse production.

In addition, PV greenhouses have associated environmental benefits and the potential to enhance the sustainability of greenhouses by a reduction in nitrate fertilizer usage and water consumption [71], which is particularly relevant in the context of water stress in agriculture in the European south.

4.2. OPV – opportunities and challenges

The OPV greenhouse offers numerous opportunities, constituting a fruitful APV concept.

The system's viability is attributed to its capacity for enhanced synergy effects, attributable to the pre-existing sub construction and the lightweight and flexible nature of the OPV modules, which facilitate their seamless integration. Consequently, the OPV greenhouse offers distinct technical advantages with the potential to translate into economic benefits. Additionally, OPV can be made semi-transparent, thereby overcoming permanent shadow [72]. The ability to match wavelengths with plant photoreceptors fosters enhanced productivity, thereby ensuring sustainable resource utilization and food security [8].

Experimental studies have shown that semi-transparent OPV installations showed either no significant differences in fresh weight and chlorophyll content of lettuce grown [58] or even increased yields for pepper [73]. Such results highlight that photovoltaic integration can influence greenhouse microclimates in ways that may mitigate heat stress and improve growing conditions, particularly in high-irradiation regions [5].

These findings are broadly consistent with the economic results of the present study, which indicate that greenhouse-integrated PV systems can remain economically viable under moderate crop-yield impacts and may benefit from crop-specific responses to shading.

Although the current-state OPV63 scenario remains economically constrained under the assumed investment costs, it provides an important system-design insight. Its lower electricity output can be better aligned with on-site greenhouse electricity demand than higher-output PV configurations as can be seen in Fig. 12, thereby reducing the risk of export-oriented oversizing. Since self-consumed electricity generally provides higher economic value than exported electricity in the evaluated remuneration schemes, this shifts the interpretation of OPV from maximum electricity generation toward demand-oriented self-supply. Under future cost reductions, OPV could therefore become particularly relevant for greenhouse business models that prioritize on-site electricity use and lightweight integration over export revenues.

Furthermore, empirical studies indicate that OPV integration can reduce canopy temperatures and alter the radiation environment without significantly affecting air temperature or humidity [9]. Although reductions in yield may occur during early growth stages, overall productivity is generally maintained, with comparable yields and, in some cases, increased light use efficiency under OPV shading [9,12].

A significant reduction in water evaporation was demonstrated through the use of a glass covered with a polymer multilayer film in a novel APV technique [74]. This suggests that technologies such as OPV could assist in overcoming challenges related to water scarcity, emphasizing the synergistic effects within the concept of an OPV greenhouse as an Agri PV system.

However, challenges such as immaturity, limited data on long-term energy harvesting performance [72], lower device efficiency, and shorter module lifetime [14] pose significant drawbacks. Even though the wavelength-selective absorption spectra of OPVs hold promise for enhancing productivity and environmental sustainability in agricultural settings, yet current materials absorb excessive light, limiting competitiveness with conventional greenhouses [75].

A further challenge pertains to the discrepancy in lifespans, with OPV modules projected to have a minimum operational lifespan of 20 years, though this is comparatively lower for specially engineered foil tunnels. The conducted sensitivity analysis indicated that module replacement after 10 or 15 years had only a limited effect on OPV145 profitability under the assumed replacement costs, although this result depends strongly on future module-cost reductions and the extent to which performance can be restored after replacement. For OPV63, replacement caused substantially larger NPV losses due to its higher module-specific CAPEX, highlighting the continued importance of cost reductions for long-term economic viability.

The integration of OPV in greenhouse systems remains constrained by comparatively low efficiencies and limited operational stability. Field applications exhibit substantially lower efficiencies than those achieved under laboratory conditions [76–78]. In addition, performance degradation under outdoor conditions, driven by irradiance and temperature, represents a significant limitation [79]. The sensitivity analysis showed that increasing annual degradation from 1% to 2% had a moderate effect on the economic viability of OPV145, whereas a 25% initial performance loss resulted in substantially stronger NPV reductions and more frequent losses of profitability.

Greenhouse-specific operating conditions, including elevated temperatures, humidity, cleaning procedures, and potential exposure to fertilizers or pesticides, may further affect long-term module durability and maintenance requirements. Additionally, the integration of PV and greenhouse technologies may present challenges related to ease of use and optimization. Investigations have demonstrated an increased lifetime of OPV modules that were inside the polytunnel greenhouse [18], though this may result in a reduced power production.

Consequently, the economic results of the OPV scenarios should be interpreted with caution, as uncertainty regarding long-term degradation and operational lifetime may lead to an overestimation of

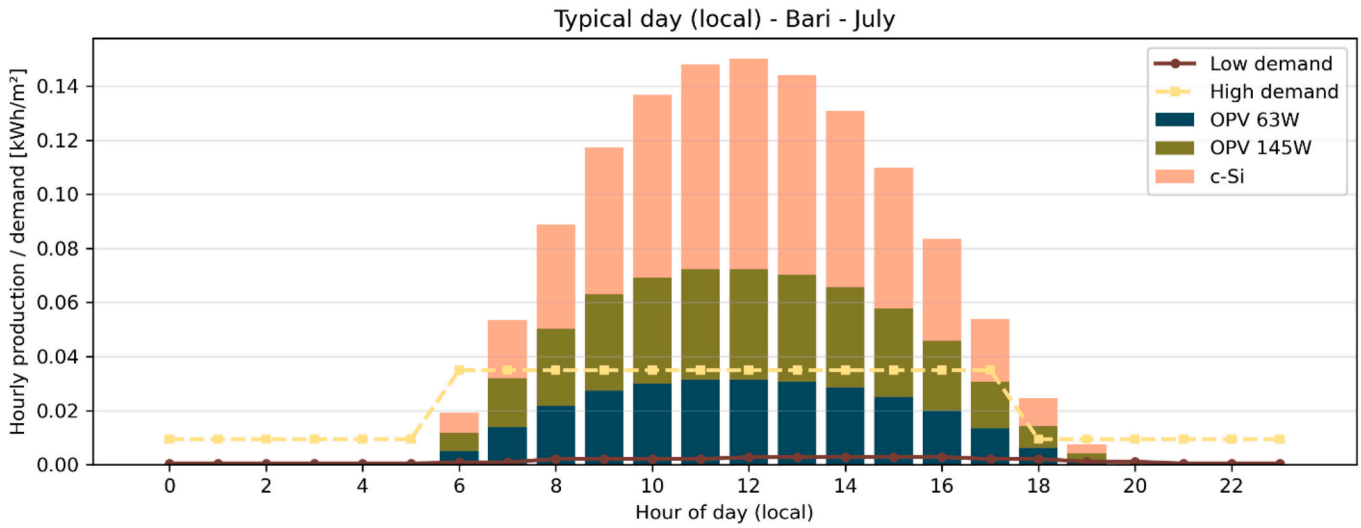


Fig. 12. Representative summer day in Bari regarding load profile and PV production.

achievable NPVs and profitability under real operating conditions. The sensitivity analysis confirms that less favorable performance assumptions can substantially reduce economic returns and, in some configurations, alter the profitability classification.

Concurrently, lightweight silicon-based photovoltaic technologies offer higher efficiencies and greater durability, thereby intensifying competitive pressure and potentially reducing the standalone advantages of OPV in PV-integrated greenhouse applications [80].

4.3. Cost reductions and economies of scale

The model uses a 1000 m^2 greenhouse as a representative reference unit. While commercial greenhouse operations in Southern Europe often operate larger areas (e.g., 10,000 m^2 or more, [43]), techno-economic results scale approximately linearly with area for PV systems. Therefore, the results can be proportionally extrapolated while Economies of scale may reduce system costs in larger installations, which may even further improve economic viability. As seen in other APV feasibility studies, potential within scaling is huge with 40% in CAPEX and 60% OPEX when scaling from 1 to 80 ha [48]. The effect for OPV greenhouses could potentially be even bigger, first, due to less equipment needed such as steel for construction and second, the cost of components is comparatively low, suggesting a substantial reduction in costs with increased production [14,81]. Additionally, the utilization of polymers as the fundamental materials of OPV Modules eliminates the reliance on rare materials that could potentially lead to dependencies from foreign sources.

Second, Alternative deployment models, such as cooperative installations in which multiple greenhouse operators jointly operate a larger PV system, could benefit from economies of scale and lower specific investment costs. Such configurations would likely follow a different economic structure and could lead to improved feasibility compared with the individual system configurations analyzed here.

5. Conclusion

This study assessed the economic feasibility of photovoltaic greenhouse systems by analyzing PV technology choice, the interaction between greenhouse energy demand and PV system design, and the overall economic feasibility when considering electricity revenues and potential crop impacts.

First, regarding the technology comparison, future prognosed OPV systems (145 W m^{-2}) systems reach comparable economic outcomes compared to current state silicon PV systems under identical configurations. Current market status of OPV (63 W m^{-2}) remains economically unfeasible in most scenarios, although NPVs at low PV coverage rates indicate that moderate parameter improvements could enable economic feasibility.

The results further indicate that high and low electricity demand needs strongly affect economic viability by shaping the self-consumption potential of greenhouse PV systems. Greenhouses with higher electricity demand needs can use a larger share of the generated PV electricity on site, which increases the value of avoided electricity imports and improves economic performance.

Higher PV coverage improves economic performance only when electricity demand is sufficiently high to absorb the additional generation. Battery storage becomes economically relevant mainly in low-demand scenarios where it helps shift PV electricity to periods of use and reduces export losses.

The overall economic feasibility of photovoltaic greenhouses depends strongly on local and project specific conditions such as electricity prices, remuneration frameworks and crop revenues. While positive NPVs are achievable under favorable demand conditions, crop yield impacts can significantly influence economic outcomes. High-value crops provide greater flexibility to offset PV investment costs, whereas lower-value crops require larger yield improvements to maintain economic feasibility.

The inclusion of crop responses underscores the strong influence of agricultural performance on the economic viability of PV greenhouse systems. Due to higher yields and crop values, even moderate yield changes can significantly affect NPVs. While beneficial shading effects may improve profitability in specific cases, crop impacts generally reduce economic performance, particularly at higher PV coverage levels above 25%. This highlights that economic feasibility depends not only on energy-related factors but also on crop-specific responses to shading, requiring integrated system design.

CRediT authorship contribution statement

Chantal Kierdorf: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Sebastian Lubjuhn:** Writing – review & editing, Supervision, Formal analysis. **Matthias Meier-Grüll:** Writing – review & editing, Supervision, Resources, Conceptualization. **Sandra Venghaus:** Writing – review & editing, Supervision, Resources, Conceptualization.

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

During the preparation of this work the authors used DeepL and ChatGPT to improve academic language. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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

A.1. Load profiles

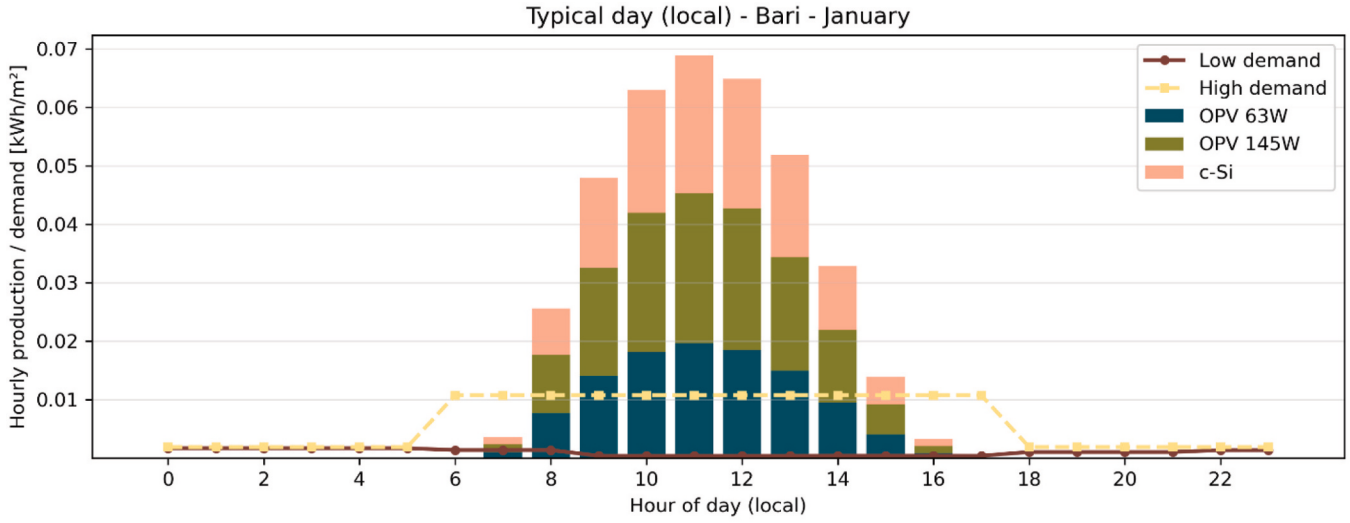

Fig. 13. Representative winter day Bari regarding load profile and PV production.

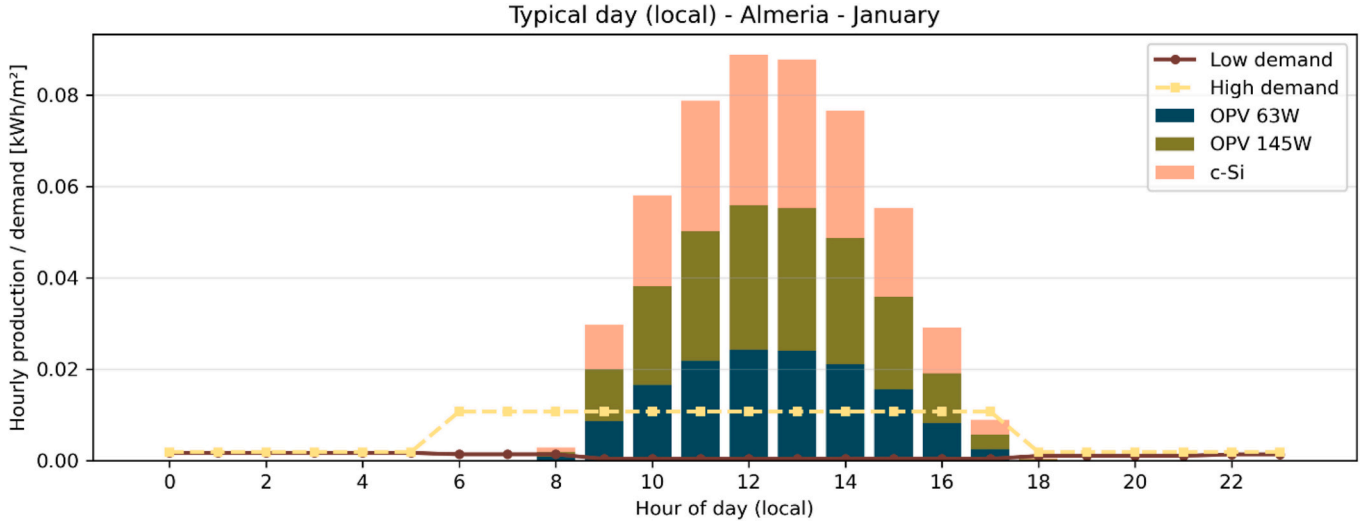

Fig. 14. Representative winter day Almería regarding load profile and PV production.

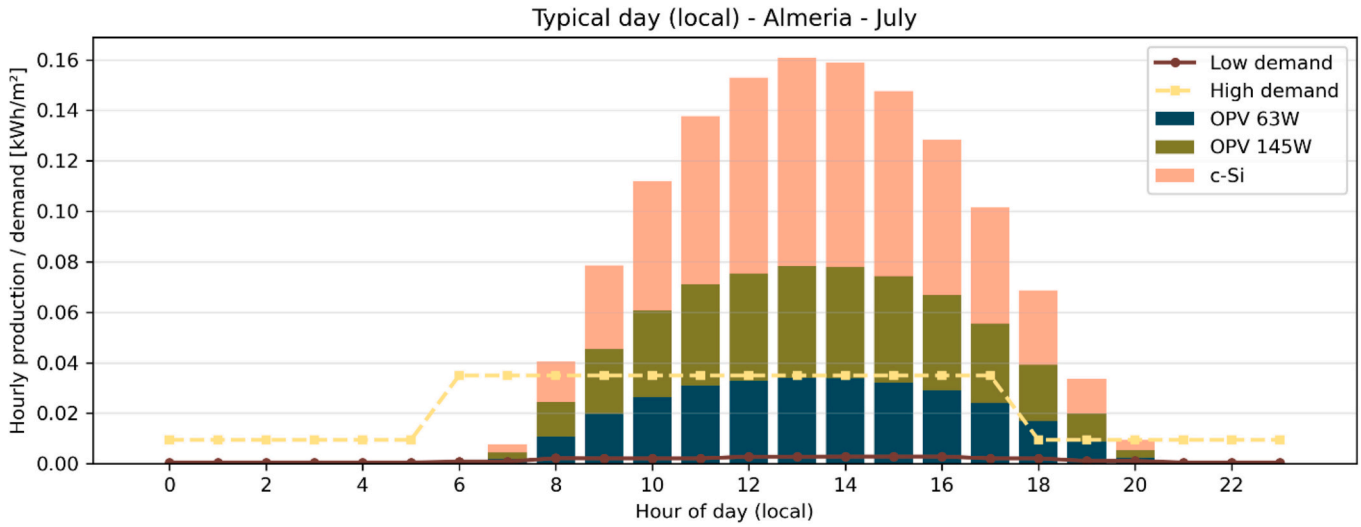

Fig. 15. Representative summer day Almería regarding load profile and PV production.

A.2. Crop categorizations and applied crop yield scenarios

Table 2
crop categorizations according to [55].

Crop Categorization	Crops
High-Light Demanding Crops	Tomato, Watermelon, Melon
Fruity Vegetables	Cucumber, Courgette, Eggplant, Pepper, Mango
Leafy Vegetables	Lettuce, Spinach, Chicory, Celery, Carrot
Grain Legumes	Peas, Beans
Berries	Strawberry, Blueberry, Raspberry

Table 3
relative crop yield with PV Shading impact compared to baseline based on literature findings.

Shading (%)	Yield scenario	High-Light Demanding Crops	Fruity Vegetables	Leafy Vegetables	Grain Legumes	Berries
10% Shading	Optimistic	98	95	98	85	114
	Conservative	95	90	95	75	100
	Pessimistic	90	85	90	70	95
25% Shading	Optimistic	85	80	86	70	100
	Conservative	75	72	80	60	90
	Pessimistic	72	70	75	50	85
40% Shading	Optimistic	70	65	70	50	80
	Conservative	61	61	60	40	75
	Pessimistic	50	50	50	30	60

A.3. yield and crop price data

Table 4
crop prices obtained from EU agri data prices dashboard and yield statistics obtained from national agricultural statistics from Spain and Italy in 2023. Source: Istituto Nazionale di Statistica, Italy and Ministerio de Agricultura, Spain, 2024.

Member State	Product	Price (€/100 kg)	yields (kg/ha)
Italy	beans	219.761333	14,800
	carrots	79.4125	–
	courgettes	168.616038	100,000
	cucumbers	114.060943	25,000
	egg plants, aubergines	126.474528	101,100
	lettuces	120.589623	–
	melons	121.66875	0

(*continued on next page*)

Table 4 (*continued*)

Member State	Product	Price (€/100 kg)	yields (kg/ha)
	peppers	176.606226	57,000
	strawberries	308.081818	0
	tomatoes	275.066981	24,500
	tomatoes	188.661895	24,500
	tomatoes	141.277949	24,500
	water melons	50.3882353	0
	spinach	91.3425	–
	radish	66.41	–
	celery	76.3466667	–
	peas (green)	277.375	0
	chicoree	80.225	–
Spain	beans	320.082075	18,900
	carrots	60.165283	–
	courgettes	76.3781132	60,100
	cucumbers	88.7924528	120,100
	egg plants, aubergines	82.4928302	79,000
	lettuces	92.960566	–
	melons	92.8576	46,100
	peppers	140.047547	75,300
	strawberries	238.76	53,500
	tomatoes	169.527703	87,800
	water melons	68.155	64,000
	peas	235.73	12,000
	papaya	132.9	–
	mango	117.3	0
	avocado	175.6	–

A.4. General Results of NPVS of first stage analysis excluding crops

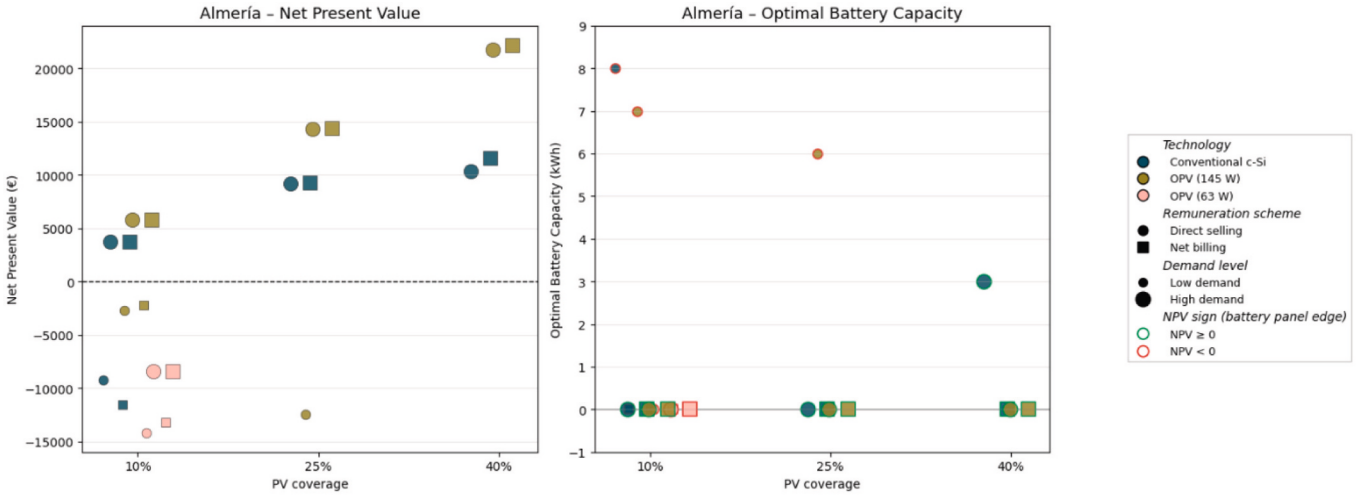

Fig. 16. Overall results of NPVs and optimal battery capacity Almería.

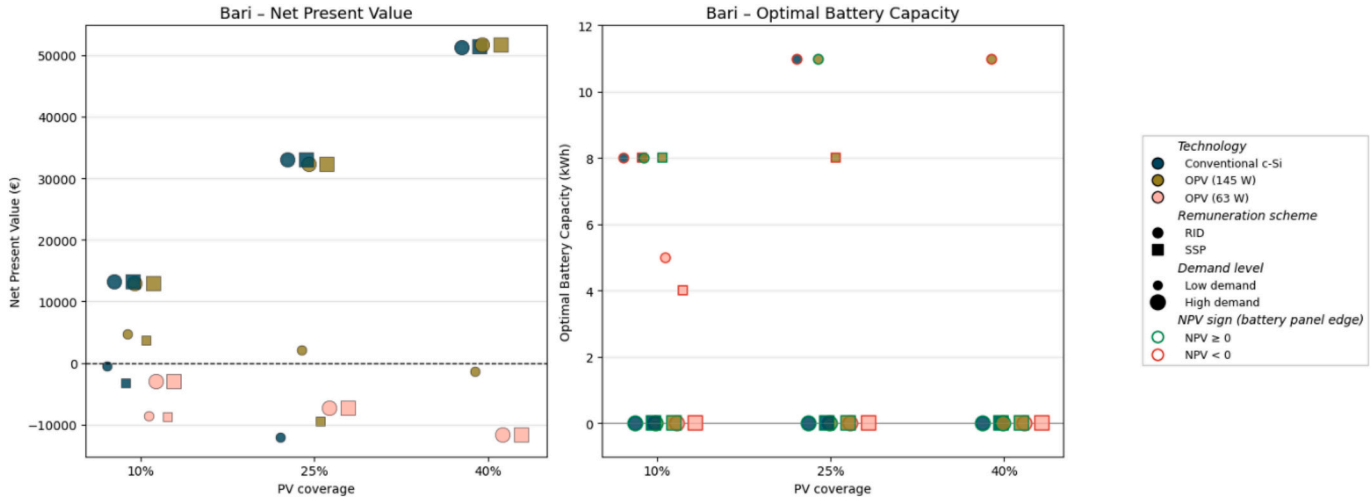

Fig. 17. Overall results of NPVs and optimal battery capacity Bari.

A.5. Regulatory background and remuneration scheme implementation

Spain

Spain has no particular remuneration or support scheme for APVs, besides a recent update in the national common agriculture policy, which now qualifies APVs systems for agricultural subsidies. Only in Catalonia, a technical guideline was issued to support the development of criteria for APV systems [82]. Spain's current self-consumption framework was established through two major regulations (RD-L 15/2018 [83]; RD 244/2019 [11]), which repealed previous "sun tax" provisions [84] and introduced a modernized regime for distributed renewable generation. This regulation considerably reduced administrative barriers and enhanced overall profitability [85]. A new surplus compensation scheme was developed with two modalities, net billing and direct selling.

Under net billing, installations up to 100 kWp can sell their electricity surplus to the retailer. The electricity exported is compensated through credits that are deducted from the monthly electricity bill. The maximum compensation is limited to the economic value of the monthly electricity bill. No administrative formalities or additional taxes apply.

For net billing, exports were not remunerated directly. Instead, monthly compensation credits C_m were introduced, constrained by.

$C_m \leq \alpha \sum_{t \in m} Exp_t$ and

$$C_m \leq Bill_m^{\text{imp}}$$

where α is the fixed compensation rate and $Bill_m^{\text{imp}}$ the remaining monthly import bill. The objective maximized annual credits net of import expenditure, and annual operating value was calculated as avoided retail purchases plus total compensation credits.

The new legal framework has led to a significant increase of PV power capacities across Spain. However, results still indicate a limitation of feasibility of self-consumption installations [86].

Alternatively, under direct selling, surplus electricity is remunerated based on the wholesale electricity market price. Installations must be registered as generation facilities and are subject to taxes and grid access charges.

Under direct selling, the annual energy operating value (EOV) is defined as

$$EOV = \sum_t \left((1-\varphi) p_t^{\text{exp}} Exp_t - p^{\text{imp}} Imp_t \right)$$

where p_t^{exp} is the hourly day-ahead market price and p^{imp} the retail electricity price. An export fee of $\varphi = 0.05$ was assumed, displaying grid fees. Relative to the no-PV baseline, annual cash flow was calculated as avoided electricity expenditure plus export revenues.

Italy

Italy's renewable energy strategy, outlined in the National Integrated Energy and Climate Plan (PNIEC 2021–2030), targets a 30% share of renewables in total final energy consumption and 55% in electricity by 2030 [87,88]. To advance these goals, the government established successive incentive decrees (Decreti FER – Fonti Energetiche Rinnovabili) which provided competitive support mechanisms and long-term market integration pathways for renewable electricity technologies. These decrees are designed to guide capacity expansion and system integration. However, there are no federal remuneration schemes for small scale systems included [89].

Recently, Italy has advances its support for APV systems including funding options for CAPEX up to 40% and supported funding schemes [90]. In addition, ground mounted PV on agricultural land has been prohibited, consequently, APVs earning more interest. However, greenhouses does not seem to qualify as supported APV systems [91].

The "scambio sul posto" (SSP) scheme constituted the main regulatory framework for small PV systems in Italy until its phase-out at the end of 2025. It operated as a virtual net-metering mechanism, with annual compensation based on the minimum of grid injections and withdrawals. In 2023, compensation typically ranged from 0.10 to 0.16€ kWh^{-1}, while surplus electricity was remunerated at approximately 0.06–0.13€ kWh^{-1} [89]. For this study, average values of 0.12 kWh^{-1} for exchanged energy and 0.06€ kWh^{-1} for excess electricity were assumed. The scheme was discontinued due to declining PV costs and a policy shift toward market-oriented, self-consumption-based mechanisms.

As an alternative, the "ritiro dedicato" (RID) mechanism allows excess generation to be directly sold to the grid at market-based prices. Under the RID framework, electricity not consumed on-site is remunerated through a guaranteed minimum price which amounted to 4.4 ct kWh^{-1} in 2023 [92].

When the market price exceeds this threshold, the producer receives the market price; otherwise, the GSE provides a balancing annual payment to cover the difference.

To adequately represent the regulatory environment, both SSP and RID are implemented in the present model. However, RID is treated as the forward-looking remuneration scheme and is therefore fully incorporated in the long-term analysis, independent of potential future adjustments to the guaranteed minimum price.

For Italy, SSP was modeled as an annual net-metering proxy. At the end of the year, total exports E_{exp} and imports E_{imp} were aggregated and split into exchanged and excess electricity,

$$E_{\text{exch}} = \min\left(E_{\text{exp}}, E_{\text{imp}}\right), E_{\text{excess}} = \max\left(E_{\text{exp}} - E_{\text{imp}}, 0\right).$$

Annual SSP remuneration was then given by

$R_{\text{SSP}} = 0.12E_{\text{exch}} + 0.06E_{\text{excess}}$, so that the annual cash flow equaled avoided electricity purchases plus R_{SSP}.

Under Ritiro Dedicato, exports were remunerated hourly at the higher of the zonal market price and the guaranteed minimum price $p^{\min}$. Export remuneration was therefore

$$R_{\text{RID}} = \sum_t \max\left(p_t^{\text{zonal}} p^{\min}\right) Exp_t.$$

Data availability

Data will be made available on request.

References

[1] La Notte L, Giordano L, Calabrò E, Bedini R, Colla G, Puglisi G, et al. Hybrid and organic photovoltaics for greenhouse applications. Appl Energy 2020;278:115582. https://doi.org/10.1016/j.apenergy.2020.115582.

[2] Golzar F, Heeren N, Hellweg S, Roshandel R. A novel integrated framework to evaluate greenhouse energy demand and crop yield production. Renew Sust Energ Rev 2018;96:487–501. https://doi.org/10.1016/j.rser.2018.06.046.

[3] Gorjian S, Calise F, Kant K, Ahamed MS, Copertaro B, Najafi G, et al. A review on opportunities for implementation of solar energy technologies in agricultural greenhouses. J Clean Prod 2021;285:124807. https://doi.org/10.1016/j.jclepro.2020.124807.

[4] Hassanien RHE, Li M, Dong Lin W. Advanced applications of solar energy in agricultural greenhouses. Renew Sust Energ Rev 2016;54:989–1001. https://doi.org/10.1016/j.rser.2015.10.095.

[5] Lu L, Effendy Ya'acob M, Shamsul Anuar M, Nazim Mohtar M. Comprehensive review on the application of inorganic and organic photovoltaics as greenhouse shading materials. Sustain Energy Techn and Assess 2022;52:102077. https://doi.org/10.1016/j.seta.2022.102077.

[6] Azzopardi B, Emmott CJM, Urbina A, Krebs FC, Mutale J, Nelson J. Economic assessment of solar electricity production from organic-based photovoltaic modules in a domestic environment. Energy Environ Sci 2011;4(10):3741–53. https://doi.org/10.1039/C1EE01766G.

[7] Colsmann A, Röhm H, Sprau C. Shining light on organic solar cells. Sol RRL 2020;4(6):2000015. https://doi.org/10.1002/solr.202000015.

[8] Song W, Ge J, Xie L, Chen Z, Ye Q, Sun D, et al. Semi-transparent organic photovoltaics for agrivoltaic applications. Nano Energy 2023;116:108805. https://doi.org/10.1016/j.nanoen.2023.108805.

[9] Friman-Peretz M, Ozer S, Geoola F, Magadley E, Yehia I, Levi A, et al. Microclimate and crop performance in a tunnel greenhouse shaded by organic photovoltaic modules – comparison with conventional shaded and unshaded tunnels. Biosyst Eng 2020;197:12–31. https://doi.org/10.1016/j.biosystemseng.2020.06.007.

[10] Friman-Peretz M, Ozer S, Levi A, Magadley E, Yehia I, Geoola F, et al. Energy partitioning and spatial variability of air temperature, VPD and radiation in a greenhouse tunnel shaded by semitransparent organic PV modules. Sol Energy 2021;220:578–89. https://doi.org/10.1016/j.solener.2021.03.050.

[11] Real Decreto 244/2019, de 5 de abril, por el que se regulan las condiciones administrativas, técnicas y económicas del autoconsumo de energía eléctrica. https://www.boe.es/buscar/doc.php?id=BOE-A-2019-5089; 2019.

[12] Waller R, Kacira M, Magadley E, Teitel M, Yehia I. Semi-transparent organic photovoltaics applied as greenhouse shade for spring and summer tomato production in arid climate. Agronomy (Basel) 2021;11(6):1152. https://doi.org/10.3390/agronomy11061152.

[13] Lee B, Lahann L, Li Y, Forrest SR. Cost estimates of production scale semitransparent organic photovoltaic modules for building integrated photovoltaics. Sustainable Energy Fuels 2020;4(11):5765–72. https://doi.org/10.1039/D0SE00910E.

[14] Machui F, Hösel M, Li N, Spyropoulos GD, Ameri T, Søndergaard RR, et al. Cost analysis of roll-to-roll fabricated ITO free single and tandem organic solar modules based on data from manufacture. Energy Environ Sci 2014;7(9):2792–802. https://doi.org/10.1039/C4EE01222D.

[15] Choi Y, Kim D, Ryu SU, Kim H, Kim S, Kim M, et al. Stability of organic photovoltaics: from root causes to advanced analytical techniques. Adv Energy Mater 2026;16(3):2501340. https://doi.org/10.1002/aenm.202501340.

[16] Mateker WR, McGehee MD. Progress in understanding degradation mechanisms and improving stability in organic photovoltaics. Adv Mater 2017;29(10):1603940. https://doi.org/10.1002/adma.201603940.

[17] Wachsmuth J, Distler A, Deribew D, Salvador M, Brabec CJ, Egelhaaf H-J. Overcoming moisture-induced degradation in organic solar cells. Adv Eng Mater 2023;25(16):2300595. https://doi.org/10.1002/adem.202300595.

[18] Magadley E, Kabha R, Dakka M, Teitel M, Friman-Peretz M, Kacira M, et al. Organic photovoltaic modules integrated inside and outside a polytunnel roof. Renew Energy 2022;182:163–71. https://doi.org/10.1016/j.renene.2021.10.012.

[19] Esmaeli H, Roshandel R. Optimal design for solar greenhouses based on climate conditions. Renew Energy 2020;145:1255–65. https://doi.org/10.1016/j.renene.2019.06.090.

[20] Hanrieder N, Kujawa A, Seychelles AB, Blanco M, Carballo J, Wilbert S. Estimation of maximum photovoltaic cover ratios in greenhouses based on global irradiance data. Appl Energy 2024;365:123232. https://doi.org/10.1016/j.apenergy.2024.123232.

[21] Acosta-Silva YdJ, Torres-Pacheco I, Matsumoto Y, Toledano-Ayala M, Soto-Zarazúa GM, Zelaya-Ángel O, et al. Applications of solar and wind renewable energy in agriculture: a review. Sci Prog 2019;102(2):127–40. https://doi.org/10.1177/0036850419832696.

[22] Costantino A, Comba L, Sicardi G, Bariani M, Fabrizio E. Energy performance and climate control in mechanically ventilated greenhouses: a dynamic modelling-based assessment and investigation. Appl Energy 2021;288:116583. https://doi.org/10.1016/j.apenergy.2021.116583.

[23] Migliari L, Cocco D. Cost-effectiveness of photovoltaic-battery systems for self-supply across various market and load conditions. J Energy Storage 2025;135:118240. https://doi.org/10.1016/j.est.2025.118240.

[24] Tong X, Zhang X, Fensholt R, Jensen PRD, Li S, Larsen MN, et al. Global area boom for greenhouse cultivation revealed by satellite mapping. Nat Food 2024;5(6):513–23. https://doi.org/10.1038/s43016-024-00985-0.

[25] Kierdorf C, Lubjuhn S, Meier-Grüll M, Venghaus S. Organic photovoltaics in European greenhouses – mapping renewable electricity potential across Europe. Energy Convers Manage: X 2026;31:102162. https://doi.org/10.1016/j.ecmx.2026.102162.

[26] Ryberg DS, Caglayan DG, Schmitt S, Linßen J, Stolten D, Robinius M. The future of European onshore wind energy potential: detailed distribution and simulation of advanced turbine designs. Energy 2019;182:1222–38. https://doi.org/10.1016/j.energy.2019.06.052.

[27] Chen S, Goergen K, Hendricks Franssen H-J, Winkler C, Poll S, Houssoukri Zounogo Wahabou Y, et al. Higher onshore wind energy potentials revealed by kilometer-scale atmospheric modeling. Geophys Res Lett 2024;51(19):e2024GL110122. https://doi.org/10.1029/2024GL110122.

[28] Ishmam S, Heinrichs H, Winkler C, Bayat B, Lahnaoui A, Agbo S, et al. Mapping local green hydrogen cost-potentials by a multidisciplinary approach. Int J Hydrog Energy 2024;87:1155–70. https://doi.org/10.1016/j.ijhydene.2024.08.501.

[29] McKenna R, Pfenninger S, Heinrichs H, Schmidt J, Staffell I, Bauer C, et al. High-resolution large-scale onshore wind energy assessments: a review of potential definitions, methodologies and future research needs. Renew Energy 2022;182:659–84. https://doi.org/10.1016/j.renene.2021.10.027.

[30] Winkler C, Dabrock K, Kapustyan S, Hart C, Heinrichs H, Weinand JM, et al. High-resolution rooftop photovoltaic potential assessment for a resilient energy system in Ukraine. Energy Convers Manage: X 2025;28:101242. https://doi.org/10.1016/j.ecmx.2025.101242.

[31] Winkler C, Heinrichs H, Ishmam S, Bayat B, Lahnaoui A, Agbo S, et al. Participatory mapping of local green hydrogen cost-potentials in sub-Saharan Africa. Int J Hydrog Energy 2025;112:289–321. https://doi.org/10.1016/j.ijhydene.2025.02.015.

[32] Basu R, Gumpert F, Lohbreier J, Morin P-O, Vohra V, Liu Y, et al. Large-area organic photovoltaic modules with 14.5% certified world record efficiency. Joule 2024;8(4):970–8. https://doi.org/10.1016/j.joule.2024.02.016.

[33] Fraunhofer ISE. Photovoltaics report. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf; 2025.
[34] Green MA, Dunlop ED, Yoshita M, Kopidakis N, Bothe K, Siefer G, et al. Solar cell efficiency tables (version 63). Prog Photovolt Res Appl 2024;32(1):3–13. https://doi.org/10.1002/pip.3750.
[35] Paris B, Vandorou F, Balafoutis AT, Vaiopoulos K, Kyriakarakos G, Manolakos D, et al. Energy use in greenhouses in the EU: a review recommending energy efficiency measures and renewable energy sources adoption. Appl Sci 2022;12(10):5150.
[36] Alonso AM, Guzmán GJ. Comparison of the efficiency and use of energy in organic and conventional farming in Spanish agricultural systems. J Sustain Agric 2010;34(3):312–38. https://doi.org/10.1080/10440041003613362.
[37] Bibbiani C, Fantozzi F, Gargari C, Campiotti CA, Schettini E, Vox G. Wood biomass as sustainable energy for greenhouses heating in Italy. Agriculture and Agricultural Science Procedia 2016;8:637–45. https://doi.org/10.1016/j.aaspro.2016.02.086.
[38] Campiglia, Colla G, Roberto M, Rouphael Y, Marucci A. Energy balance of intensive vegetable cropping systems in Central Italy. Acta Hortic 2007;747:185–91. https://doi.org/10.17660/ActaHortic.2007.747.20.
[39] Kittas C, Katsoulas N, Bartzanas T. Greenhouse climate control in Mediterranean greenhouses. ISSN2173-7568. Cuadernos de Estudios Agroalimentarios; 2012. p. 89–114.
[40] Yano A, Cossu M. Energy sustainable greenhouse crop cultivation using photovoltaic technologies. Renew Sust Energ Rev 2019;109:116–37. https://doi.org/10.1016/j.rser.2019.04.026.
[41] Baptista F, Silva AT, Gracia LM, Correa-Guimaraes A, Meneses JF. Greenhouse energy consumption for tomato production in the Iberian Peninsula countries. Acta Hortic 2012;952:409–16. https://doi.org/10.17660/ActaHortic.2012.952.51.
[42] Tataraki K, Giannini E, Kavvadias K, Maroulis Z. Cogeneration economics for greenhouses in Europe. Energies (Basel) 2020;13(13):3373. https://doi.org/10.3390/en13133373.
[43] Valera D, Belmonte L, Molina-Aiz F, López A. Greenhouse agriculture in Almeria. [A comprehensive techno-economic analysis], ISBN 978-84-95531-75-9.
[44] Nikolaou G, Neocleous D, Christou A, Polycarpou P, Kitta E, Katsoulas N. Energy and water related parameters in tomato and cucumber greenhouse crops in semiarid Mediterranean regions. A review, part I: increasing energy efficiency. Horticulturae 2021;7(12):521.
[45] Prieto J, Ajnannadhif RM, Fernández-del Olmo P, Coronas A. Integration of a heating and cooling system driven by solar thermal energy and biomass for a greenhouse in Mediterranean climates. Appl Therm Eng 2023;221:119928. https://doi.org/10.1016/j.applthermaleng.2022.119928.
[46] C. Campiotti, F. Dondi, A. Genovese, G. Alonzo, V. Catanese, L. Incrocci, Photovoltaic as sustainable energy for greenhouse and closed plant production system 2008 ActaHortic., 2406-6168 https://doi.org/10.17660/ActaHortic.2008.797.53.
[47] Cherkaoui M, Mouhat O, Rougui M, Oukmi H. Developing a passive energy consumption reduction solution. E3S Web Conf, 601, 00043. 2025. https://doi.org/10.1051/e3sconf/202560100043.
[48] Böhm J, de Witte T, Offermann F, Latacz-Lohmann U. Preserving agricultural land with agrivoltaic – but at what cost? An economic analysis of different agrivoltaic systems in Germany. Land Use Policy 2026;164:107966. https://doi.org/10.1016/j.landusepol.2026.107966.
[49] Istituto Nazionale di Statistica (ISTAT). Coltivazioni – superfici e produzioni agricole per tipo di coltura. 2024. https://esploradati.istat.it/databrowser/#/en/dw/categories/IT1,Z1000AGR,1.0/AGR_CRP/DCSP_COLTIVAZIONI/IT1,101_1015_DF_DCSP_COLTIVAZIONI_2,1.0.
[50] Ministerio de Agricultura, Pesca y Alimentación (MAPA). Encuesta sobre superficies y rendimientos de cultivos (ESYRCE). 2024. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/.
[51] Hao W, Cao Y, Hu X, Zhang Z, Cai M, Zhou H, et al. Analysis of the impact of price incentives and precipitation fluctuations on maize planting area and yield [original research]. Front Sustain Food Syst 2025;9. https://doi.org/10.3389/fsufs.2025.1587677.
[52] Tang J, Ma M, Razzaq A. Market signals vs. policy incentives: an empirical analysis of rapeseed acreage decisions under uncertainty [original research]. Front Sustain Food Syst 2026;10. https://doi.org/10.3389/fsufs.2026.1758440.
[53] Cossu M, Yano A, Solinas S, Deligios PA, Tiloca MT, Cossu A, et al. Agricultural sustainability estimation of the European photovoltaic greenhouses. Eur J Agron 2020;118:126074. https://doi.org/10.1016/j.eja.2020.126074.
[54] Dupraz C. Assessment of the ground coverage ratio of agrivoltaic systems as a proxy for potential crop productivity. Agrofor Syst 2023. https://doi.org/10.1007/s10457-023-00906-3.
[55] Laub M, Pataczek L, Feuerbacher A, Zikeli S, Högy P. Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis. Agron Sustain Dev 2022;42(3):51. https://doi.org/10.1007/s13593-022-00783-7.
[56] Aroca-Delgado R, Pérez-Alonso J, Callejón-Ferre Á-J, Díaz-Pérez M. Morphology, yield and quality of greenhouse tomato cultivation with flexible photovoltaic rooftop panels (Almería-Spain). Sci Hortic 2019;257:108768. https://doi.org/10.1016/j.scienta.2019.108768.
[57] Ureña-Sánchez R, Callejon-Ferre ÁJ, Pérez-Alonso J, Carreño-Ortega A. Greenhouse tomato production with electricity generation by roof-mounted flexible solar panels. Sci Agric 2012;69:233–9. https://doi.org/10.1590/S0103-90162012000400001.
[58] Ravishankar E, Charles M, Xiong Y, Henry R, Swift J, Rech J, et al. Balancing crop production and energy harvesting in organic solar-powered greenhouses. Cell Rep Phys Sci 2021;2(3):100381. https://doi.org/10.1016/j.xcrp.2021.100381.
[59] Ghaffarpour Z, Fakhroleslam M, Amidpour M. Calculation of energy consumption, tomato yield, and electricity generation in a PV-integrated greenhouse with different solar panels configuration. Renew Energy 2024;229:120723. https://doi.org/10.1016/j.renene.2024.120723.
[60] López-Díaz G, Carreño-Ortega A, Fatnassi H, Poncet C, Díaz-Pérez M. The effect of different levels of shading in a photovoltaic greenhouse with a north–south orientation. Appl Sci 2020;10(3):882.
[61] European Commission – Directorate-General for Agriculture and Rural Development. EU Fruit and Vegetable Prices Dashboard. 2024. https://agridata.ec.europa.eu/extensions/DashboardFruitandVeg/FruitandVegetablePrices.html.
[62] Trommsdorff M, Gruber S, Keinath T, Hopf M, Hermann C, Schönberger F, et al. Agrivoltaics: opportunities for agriculture and the energy transition -a guideline for Germany. Fraunhofer Institute for Solar Energy Systems ISE; 2022.
[63] Bielewski M, Pfrang A, Bobba S, Kronberga A, Georgakaki A, Letout S, et al. Clean energy technology observatory: batteries for energy storage in the European Union – 2022 status report on technology development, trends, value chains and markets. Luxembourg: Publications Office of the European Union; 2022. https://doi.org/10.2760/808352.
[64] Mirletz B, Vimmerstedt L, Stehly T, Stright D, Cohen S, Cole W, et al. 2024 annual technology baseline (ATB) cost and performance data for electricity generation technologies (National Renewable Energy Laboratory (NREL). 2024. https://doi.org/10.25984/2377191.
[65] Eurostat. Electricity prices for non-household consumers. Retrieved 1.10.2025 from, https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_204__custom_14045578/default/table; 2023.
[66] Fraunhofer ISE. Photovoltaics report. https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf; 2026.
[67] IEA. Trends in photovoltaic applications 2024 [IEA PVPS Task 1 Report] (978–3–907281-68-0). https://iea-pvps.org/wp-content/uploads/2024/10/IEA-PVPS-Task-1-Trends-Report-2024.pdf; 2024.
[68] Kierdorf C, Schlüter S, Meier-Grüll M, Venghaus S. Agriphotovoltaics as a profitable land use approach for regions in transformation? - an economic analysis and technical validation of suitable concepts. Sustainable Prod Consumption 2025;54:115–28. https://doi.org/10.1016/j.spc.2025.01.001.
[69] Schallenberg-Rodriguez J, Rodrigo-Bello J-J, Río-Gamero BD. Agrivoltaic: how much electricity could photovoltaic greenhouses supply? Energy Rep 2023;9:5420–31. https://doi.org/10.1016/j.egyr.2023.04.374.
[70] Sarr A, Soro YM, Tossa AK, Diop L. A new approach for modelling photovoltaic panel configuration maximizing crop yield and photovoltaic array outputs in agrivoltaics systems. Energy Convers Manag 2024;309:118436. https://doi.org/10.1016/j.enconman.2024.118436.
[71] Toledo C, Ramos-Escudero A, Serrano-Luján L, Urbina A. Photovoltaic technology as a tool for ecosystem recovery: a case study for the mar Menor coastal lagoon. Appl Energy 2024;356:122350. https://doi.org/10.1016/j.apenergy.2023.122350.
[72] Feroze S, Distler A, Forberich K, Ahmed Channa I, Doll B, Brabec CJ, et al. Comparative analysis of outdoor energy harvest of organic and silicon solar modules for applications in BIPV systems. Sol Energy 2023;263:111894. https://doi.org/10.1016/j.solener.2023.111894.
[73] Zisis C, Pechlivani EM, Tsimikli S, Mekeridis E, Laskarakis A, Logothetidis S. Organic photovoltaics on greenhouse rooftops: effects on plant growth. Mater Today Proc 2019;19:65–72. https://doi.org/10.1016/j.matpr.2019.07.658.
[74] Ali Abaker Omer A, Li M, Liu W, Liu X, Zheng J, Zhang F, et al. Water evaporation reduction using sunlight splitting technology. Agronomy 2022;12(5):1067. https://doi.org/10.3390/agronomy12051067.
[75] Hollingsworth JA, Ravishankar E, O'Connor B, Johnson JX, DeCarolis JF. Environmental and economic impacts of solar-powered integrated greenhouses. J Ind Ecol 2020;24(1):234–47. https://doi.org/10.1111/jiec.12934.
[76] Friman Peretz M, Geoola F, Yehia I, Ozer S, Levi A, Magadley E, et al. Testing organic photovoltaic modules for application as greenhouse cover or shading element. Biosyst Eng 2019;184:24–36. https://doi.org/10.1016/j.biosystemseng.2019.05.003.
[77] Tsao C-S, Chuang C-M, Cha H-C, Huang Y-Y, Sung Y-M, Chung T-Y, et al. Lab-to-fab development and long-term greenhouse test of stable flexible semitransparent organic photovoltaic module. Materials Today Energy 2023;36:101340. https://doi.org/10.1016/j.mtener.2023.101340.
[78] Waller R, Kacira M, Magadley E, Teitel M, Yehia I. Evaluating the performance of flexible, semi-transparent large-area organic photovoltaic arrays deployed on a greenhouse. Agri Engineering 2022;4(4):969–92. https://doi.org/10.3390/agriengineering4040062.
[79] Magadley E, Teitel M, Peretz MF, Kacira M, Yehia I. Outdoor behaviour of organic photovoltaics on a greenhouse roof. Sustain Energy Techn and Assess 2020;37:100641. https://doi.org/10.1016/j.seta.2020.100641.
[80] Fraunhofer ISE. Agri-Photovoltaik in Kombination mit Witterungsschutz. 2025. https://www.ise.fraunhofer.de/de/presse-und-medien/presseinformationen/2025/agri-photovoltaik-in-kombination-mit-witterungsschutz.html.
[81] Gambhir A, Sandwell P, Nelson J. The future costs of OPV – a bottom-up model of material and manufacturing costs with uncertainty analysis. Sol Energy Mater Sol Cells 2016;156:49–58. https://doi.org/10.1016/j.solmat.2016.05.056.
[82] Tomasi S, Pellegrini C, Gaspari F, Vitale S, Macarulla Martí M, Gras A, et al. Agrivoltaics as a win-win for rural regions? Energy and environmental justice perspectives across Italy, Spain, Belgium, and the Netherlands. Energy Res Soc Sci 2025;129:104369. https://doi.org/10.1016/j.erss.2025.104369.
[83] Real Decreto-ley 15/2018, de 5 de octubre, de medidas urgentes para la transición energética y la protección de los consumidores. https://www.boe.es/buscar/doc.php?id=BOE-A-2018-13593; 2018.

[84] Silveira B, dos Melo Santos ME, Maia FJF, Basso AP, Singh JN, Costa HKDM. Incentives for photovoltaic energy generation: a comparative analysis of policies in Spain, Germany, and Brazil. Energ Strat Rev 2024;54:101415. https://doi.org/10.1016/j.esr.2024.101415.
[85] López Prol J, Steininger KW. Photovoltaic self-consumption is now profitable in Spain: effects of the new regulation on prosumers' internal rate of return. Energy Policy 2020;146:111793. https://doi.org/10.1016/j.enpol.2020.111793.
[86] Dasí-Crespo D, Roldán-Blay C, Escrivá-Escrivá G, Roldán-Porta C. Evaluation of the Spanish regulation on self-consumption photovoltaic installations. A case study based on a rural municipality in Spain. Renew Energy 2023;204:788–802. https://doi.org/10.1016/j.renene.2023.01.055.
[87] Colasante A, D'Adamo I, Morone P. What drives the solar energy transition? The effect of policies, incentives and behavior in a cross-country comparison. Energy Res Soc Sci 2022;85:102405. https://doi.org/10.1016/j.erss.2021.102405.
[88] Esposito L, Romagnoli G. Overview of policy and market dynamics for the deployment of renewable energy sources in Italy: current status and future prospects. Heliyon 2023;9(7):e17406. https://doi.org/10.1016/j.heliyon.2023.e17406.
[89] Südtiroler Bauernbund. Leitfaden photovoltaik. https://www.sbb.it/public/fileadmin/user_upload/Innovation/Hauptseite_Energie/INNOPhotovoltaik/231101_Photovoltaik_Leitfaden_Photovoltaik.pdf; 2023.
[90] Ministero dell"Ambiente e della Sicurezza Energetica. Decreto recante criteri e modalità per incentivare la realizzazione di sistemi agrivoltaici. Roma: Ministero dell'Ambiente e della Sicurezza Energetica; 2023.
[91] Tedioli F. Advanced agrivoltaics in Italy: innovation, sustainability, and regulation for the future of rural energy. Visegrad Journal on Bioeconomy and Sustainable Development 2025;14(1):31–48. https://doi.org/10.2478/vjbsd-2025-0005.
[92] Südtiroler Bauernbund. Merkblatt photovoltaik. https://www.sbb.it/public/fileadmin/user_upload/Innovation/Hauptseite_Energie/INNOPhotovoltaik/2302_Merkblatt_Photovoltaik.pdf; 2023.