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Organic Photovoltaics in European Greenhouses – Mapping Renewable Electricity Potential across Europe

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ABSTRACT

This study investigates the potential of organic photovoltaics (OPV) for integration into greenhouses across the European Union (EU) as a pathway to strengthen both energy and food security within the clean energy transition. The integration of renewable electricity generation with agricultural production in greenhouses employs a dual-use strategy for land and energy. As an emerging photovoltaic technology, OPV is explicitly relevant in this context, directly supporting the EU's goals for sustainable transformation and the clean energy transition.

The techno-economic feasibility of OPV greenhouses under varying deployment and performance scenarios is assessed. Depending on the assumptions made regarding coverage and efficiency, the annual electricity generation potential ranges from 14 TWh year⁻1 under conservative conditions to over 130 TWh year⁻1 in advanced cases.

The findings indicate that, even under scenarios characterized by low OPV coverage and lower power density, annual OPV electricity generation has the potential to reach or even surpass allocated annual greenhouse electricity demand in numerous EU regions on an annual-balance basis.

Under current high-cost assumptions, economic feasibility remains limited, with LCOE values ranging from 0.13 to 0.46 € kWh⁻1 across regions and module-capacity scenarios. Under industrial-scale manufacturing assumptions, LCOE decreases to 0.02–0.05 € kWh⁻1. Sensitivity analyses further show that degradation, lifetime, and financing assumptions affect absolute LCOE levels, while the relative advantage of higher module capacity and industrial-scale production remains robust.

These findings underscore the strategic relevance of OPV in supporting the EU's clean energy transition, energy and food security, and sustainable agricultural production.

Introduction

In 2022, for the first time, global agrifood systems emissions accounted for less than 30% of the total emissions. Nevertheless, the sector was responsible for almost one third of the total emissions [1]. Beyond direct emissions, unsustainable land use remains a key driver of ecosystem degradation and increases the vulnerability of ecosystems and human populations to climate change impacts.

In the context of a globally increasing population, efficient land use systems are imperative in order to ensure the sustainable use of limited natural resources while guaranteeing food security and expanding clean energy provision.

One way of resolving land use conflicts between food and energy production are Agriphotovoltaic (APV) systems that seek to achieve

Abbreviations: APV, Agriphotovoltaics; CAPEX, Capital expenditures; EU, European Union; GHG, Greenhouse gas; GHI, Global Horizontal Irradiance; GWp, Gigawatt peak; IPCC, Intergovernmental Panel on Climate Change; kWh, Kilowatt hours; kWp, Kilowatt peak; LCOE, Levelized Cost of Electricity; MW, Megawatt; MWh, Megawatt hours; NUTS, Nomenclature of territorial units for statistics; OPEX, Operational expenditures; OPV, Organic photovoltaics; PV, Photovoltaics; RESKit, Renewable Energy Simulation toolkit for Python; TWh, Terawatt hours; Wp, Watt peak; A_{GH}, Greenhouse area share; α, Azimuth; CR, Coverage ratio; C_t, Annual expenditures; D, Electricity demand; E_t, Annual electricity yield; i, Discount rate; n, System lifetime; ρ, Capacity density; RF, Roof factor; t, Tilt; Y, Capacity factor; PV_{occ}, Ground area occupied by OPV panels; P_{GWp}, Installable capacity potential; $P_{r,s}$, Electricity potential per NUTS-3 region r and scenario s; $P_{block,s}$, Electricity potential per greenhouse block and scenario s.

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renewable energy targets while conserving agricultural land.

A prospective APV system is the "PV greenhouse," which entails the integration of photovoltaics (PV) into greenhouse structures. This incorporation is particularly intriguing in light of the existing foundation of greenhouses, which facilitates the seamless integration of PV panels. Greenhouses enable more efficient land use due to significantly higher yields on a smaller area [2]. Conventional greenhouse cultivation is amongst the most energy-intensive methods of crop production [3], imposing costs of energy production to account for the largest share with up to 50% of the total production costs [4]. Given that, the power generated by PV panels can be directly utilized for agricultural activities within the greenhouse, fostering positive commercial outcomes, and can enhance the sustainability of greenhouses and thereby establish energy self-sufficient agricultural systems [5].

Current projections indicate that climate change could increase greenhouse energy consumption, as well as fuel prices. Fossil fuels remain the status quo of energy sources for greenhouses [6], resulting in elevated GHG emissions and costs [7].

In order to mitigate climate change, the need for energy-saving methods and the use of renewable energy sources is therefore a necessary development in greenhouses.

Recent years have seen an increasing trend towards the integration of Organic photovoltaics (OPV) technology in greenhouse applications [8], given rise to the innovative notion of an "OPV greenhouse." OPV are thin-film solar technologies based on solution-processable organic semiconductors that enable low-cost, lightweight, and flexible solar modules through scalable printing and coating techniques [9].

The European Union (EU) represents a highly relevant case for OPV deployment given the extensive greenhouse cultivation area [10], the economic importance of agriculture and ambitious climate and energy policy frameworks,

To date, research on PV and OPV greenhouse systems has largely focused on individual experimental systems, specific greenhouse types, or selected regions [11,12].

Existing studies provide important insights into technical feasibility [13], crop responses and micro climate effects [14,15], and module performance [16], but a comprehensive Europe-wide techno-economic assessment of OPV-integration in greenhouses is still lacking. In particular, no study has yet quantified the spatially differentiated OPV electricity generation potential of European greenhouses at regional scale while linking this potential to annual greenhouse electricity demand and levelized cost of electricity.

This study addresses this gap by providing a EU-wide techno-economic assessment of OPV integration in greenhouse systems. Specifically, it quantifies regional OPV electricity generation potential at NUTS-3 level, evaluates the annual-balance contribution of OPV generation to allocated greenhouse electricity demand, and assesses Levelized Cost of Electricity (LCOE) under current, upscaling, and industrial-scale OPV cost assumptions. The analysis further tests the robustness of the results through sensitivity analyses on module capacity, degradation, lifetime, and discount rate.

By addressing this research gap, this study aims to inform strategic discussions on the role of emerging photovoltaic technologies in sustainable agricultural and energy systems and highlights the strategic relevance of OPV technology for achieving European climate and energy objectives.

To achieve the research objective, the following analytical steps were undertaken:

1. *Quantify OPV Potential in the EU:* To calculate the overall OPV potential for European greenhouses under different technical scenarios and identify the most suitable regions based on the technical potential and greenhouse distribution.
2. *Evaluate Energy Impacts*: To analyze the annual-balance contribution potential of OPV generation to allocated greenhouse electricity demand at the local as well as the regional scale.
3. *Assess Economic Feasibility*: To calculate the LCOE under current, upscaling, and industrial-scale OPV cost scenarios, including sensitivity analyses for degradation, lifetime, and discount rate.

Background

Photovoltaic technologies in the greenhouse context

Greenhouse-integrated photovoltaic systems can be realized using a variety of photovoltaic technologies, each associated with distinct advantages and limitations. Conventional silicon (c-Si) photovoltaics, including rigid and flexible module variants, currently dominate global PV markets due to their high efficiencies, long lifetimes, and technological maturity and is the most common PV technology in greenhouse installations [17].

More recently, semi-transparent photovoltaic concepts including emerging PV technologies such as amorphous silicon, kesterite, chalcopyrite, cadmium telluride, dye-sensitized, organic and perovskite based systems have gained attention due to their potential to transmit photosynthetically active radiation while harvesting non-essential wavelengths [18]. While promising, these technologies remain at an early stage of development with unresolved challenges related to long-term stability, scalability, and environmental safety [17].

Within this broader technology landscape, OPV represents a complementary technology for specific greenhouse integration contexts. Its potential relevance arises from application-specific properties such as low weight, mechanical flexibility, and compatibility with structurally lightweight greenhouse typologies such as foil tunnels [19]. These characteristics may expand the range of greenhouse structures suitable for PV integration, particularly where rigid or heavy modules would require additional structural adaptation. At the same time, OPV remains less mature than c-Si PV and generally shows lower efficiencies and greater uncertainty regarding long-term operational stability.

Organic photovoltaics as greenhouse-integrated shading technology

In greenhouse applications, OPV modules can serve a dual function as energy-generating and shading elements. Several studies show that OPV shading can reduce canopy temperatures and modify the radiation environment without significantly affecting air temperature or humidity [20]. At the same time, OPV installations may introduce spatial heterogeneity in light distribution, particularly under direct solar radiation, depending on module layout and coverage [21]. The impact on crop performance is heterogeneous but generally indicates that OPV integration can maintain agricultural productivity under appropriate conditions. While reductions in total yield due to lower light availability have been observed in some cases, these effects are often limited to early growth stages. In later stages, no significant differences in yield, fruit number, or fruit mass were reported, and light use efficiency can even increase under OPV shading [14]. In some experiments, OPV shading resulted in comparable or even improved crop performance depending on environmental conditions and shading configurations [20].

A growing body of literature has investigated OPV integration in greenhouse systems, highlighting both technological challenges and application potential. From a technological perspective, OPV performance remains below that of conventional photovoltaics [13,16].

Beyond structural and functional advantages, a major limitation of OPV technology is its limited operational stability. Significant performance degradation has been observed under outdoor conditions, including rapid burn-in losses and short operational lifetimes. While recent developments report improved stability under greenhouse conditions [22], degradation remains strongly influenced by environmental factors such as irradiance and temperature [23].

Existing experimental and technology-focused studies provide the empirical foundation for assessing OPV greenhouse integration, but they remain limited in their ability to support large-scale regional techno-economic conclusions. Their main contribution lies in demonstrating technical feasibility, documenting field-performance limitations, and identifying potential crop and microclimatic responses under specific greenhouse and module configurations. However, they do not provide a harmonized basis for quantifying OPV electricity generation potential, annual-balance electricity demand contribution, or LCOE across European greenhouse regions. Table 1 therefore summarizes how the present study is positioned relative to existing research and clarifies the analytical scope of the assessment.

Methods

Study design and data

This study adopts a system-oriented perspective that evaluates large-scale technical potential and spatial integration of OPV greenhouses across the EU.

The methodological approach links spatial greenhouse mapping, OPV electricity generation modelling, annual-balance demand comparison, and LCOE analysis. The assessment is conducted at NUTS-3 level to capture regional differences in greenhouse distribution, solar irradiation, electricity demand, and economic performance.

The methodology is organized into three main analytical steps. First, the technical OPV electricity generation potential is estimated from spatial greenhouse data using the model RESKit for simulations under different capacity-density, rooftop occupancy, and roof-configuration assumptions. Second, the simulated annual OPV generation is compared with allocated greenhouse electricity demand as well as regional electricity demand to assess annual-balance demand contribution and electricity utilization, including a sensitivity analysis for demand allocation. Third, the financial implications are evaluated through an LCOE analysis that combines simulated electricity generation with CAPEX, OPEX, degradation and lifetime assumptions, and discount-rate scenarios.

The overall workflow is illustrated in Fig. 1.

OPV potential

The identification of greenhouse areas within the EU was conducted on the basis of the dataset provided by Tong et al.[1] [10]. All greenhouse surfaces identified in the EU were included in the analysis, regardless of their structural type, as the physical characteristics of OPV such as its low weight, flexibility, and adaptability make it suitable for a wide range of greenhouse designs, including foil tunnels and other lightweight constructions. The dataset only includes greenhouse areas that have been in place for more than one year, ensuring that only stable and long-term structures are considered.

The dataset consists of high-resolution images where each white pixel marks the location of a greenhouse with the approximate size of 3 m x 3 m[2]. We further divided the pixel grid into 20 x 20 blocks, where each block is assigned the location and the number of white pixels, i.e. the area of greenhouses in the block. This aggregation facilitates the analysis of OPV integration potential on a manageable spatial scale while preserving regional distribution patterns across Europe.

Production

The technical potential for OPV integration was estimated through simulations performed using the Renewable Energy Simulation toolkit for Python (RESKit) [25], which is a well-established model for conducting highly resolved and detailed technical analyses for renewable energy assessments [26,27].

The model under consideration is composed of hourly-resolved electricity generation simulations, which are predicated on weather data from ERA-5, which is a global atmospheric reanalysis developed by the Copernicus Climate Change Service [28] and the Global Solar Atlas [29]. The 10-year period from 2010 to 2019 was selected for analysis to calculate long-term annual average irradiation and corresponding annual OPV electricity generation. The period serves as the basis for deriving representative long-term annual irradiation conditions.

Because open RESKit simulations require a complete single-diode parameter set, we supplied a calibrated module-level set consistent with manufacturer Standard Testing Condition ratings. The corresponding values are reported in Appendix A.

In the potential calculation, $(Y_{\alpha,t,y})$ denotes the RESKit-derived capacity factor parameter in kWh kWp-1 year-1. It was obtained by simulating the annual electricity output of a standardized OPV system with a nominal capacity of 1 kWp. Thus, $(Y_{\alpha,t,y})$ describes the annual electricity generation per installed kWp for a specific azimuth (α), tilt angle (t), location, and simulation year (y). Higher values indicate more favorable irradiation and operating conditions for OPV electricity generation.

We applied values of 10%, 25%, and 40% of coverage of greenhouse rooftop area with opaque OPV modules to represent a realistic spectrum of integration levels. Research indicates that rates ranging from 10 to 40% are typically observed in APV studies and are indicative of potential suitable scenarios, contingent on factors such as crop type and geographical location [5,30–32]. The values that have been selected serve as representative scenario assumptions for a Europe-wide potential assessment and should therefore not be interpreted as crop- or location-specific option.

The upper bound of 40% was deliberately chosen to reflect a high yet still literature-based shading scenario, while acknowledging that such coverage levels may already induce significant changes in crop yield and product quality.

As this study focuses on the techno-economic potential of OPV systems, crop-specific responses to shading are not explicitly modelled but are implicitly reflected through the selected coverage constraints.

A_{GH} denotes the greenhouse ground area (m^2). ρ is the capacity density, derived from current OPV performance characteristics. Current industry standards indicate a peak performance value of 55 W per OPV module of an area of 0.872 m^2 [33]; resulting in a capacity of 0.063 kWp m-2. The record efficiency demonstrated in laboratory settings was confirmed to be 14.5% module efficiency [34], indicating a capacity of 0.145 kWp m-2. However, such values are not representative of large-area OPV modules due to well-known scaling challenges, including resistive losses, non-uniform coating, and encapsulation constraints.

We therefore use two capacity values in our analysis: (i) a state-of-the-art value reflecting currently achievable commercial module performance (0.063 kWp m^{-2}), and (ii) an upper-bound, forward-looking scenario based on laboratory-scale efficiencies to illustrate the potential future development of OPV technology (0.145 kWp m-2).

Additionally, we accounted for the effective roof-to-ground area ratio, hereafter termed roof factor. Because greenhouses have sloped roofs, the available module area exceeds the ground area projection. The roof factor (*RF*) is defined in Equation (1):

$$RF = \frac{1}{\cos(|t|)} \tag{1}$$

where *t* is tilt. This results in an average roof factor of approximately 1.009 in southern Europe and 1.027 in central/northern Europe, implying that the effective roof area is ∼ 1–3% larger than the ground area projection.

Based on research regarding greenhouse orientation, tilt and slope

[1] The authors acknowledge Planet Labs PBC for satellite data provision.

[2] When the Earth's surface is represented as a two-dimensional image (a pixel grid), curved areas are projected onto a flat plane, so a pixel does not correspond to the same real-world area everywhere. Consequently, calculations of greenhouse size from satellite data must account for these variations with latitude, which was done in further calculations.

Table 1
Positioning of own study in comparison to literature overview on OPV greenhouse assessments.

Study	Main focus	Scale	OPV greenhouse integration	Energy modelling	Economic assessment
[13]	electric behavior, radiometric and thermal properties of flexible semitransparent OPV modules	(local) Experimental greenhouse	Yes	Experimental output, module performance	/
[20]	electrical behavior, Microclimate, crop yield impact, physiological parameters	(local) Experimental greenhouses	Yes	Module performance, electricity generation	Yield performance
[23]	outdoor behavior of OPV panels on a polytunnel greenhouse roof	(local) Experimental greenhouses	Yes	Experimental output, module performance	/
[21]	effect of semitransparent flexible OPV modules on a greenhouse tunnel on spatial variability of radiation, air temperature and vapour pressure deficit	(local) Experimental greenhouses	Yes	Experimental output, energy balance components	/
[14]	Microclimate conditions and tomato crop growth and yield parameters for OPV shaded vs. non-shaded section	(local) Experimental greenhouse	Yes	Experimental output, OPV power production	Light use efficiency, yield performance
[16].	Development and application of practical methods to estimate solar irradiance on curved surfaces	(local) Experimental greenhouse	Yes	Experimental output, module performance	/
[24]	OPV performance on greenhouse structures	(local) Experimental greenhouse	Yes	Measured module performance	/
[22].	The Lab-to-Fab development electric behavior and stability of flexible semitransparent OPV modules	(fab) Experiment/ fabrication	No/ comparison only	Experimental output, module performance	/
Present study	Europe-wide OPV greenhouse potential and LCOE	(continental); Regional resolution for NUTS-3 level Europe-wide	Modelled	Spatial annual OPV generation and demand balance	LCOE and sensitivity analysis

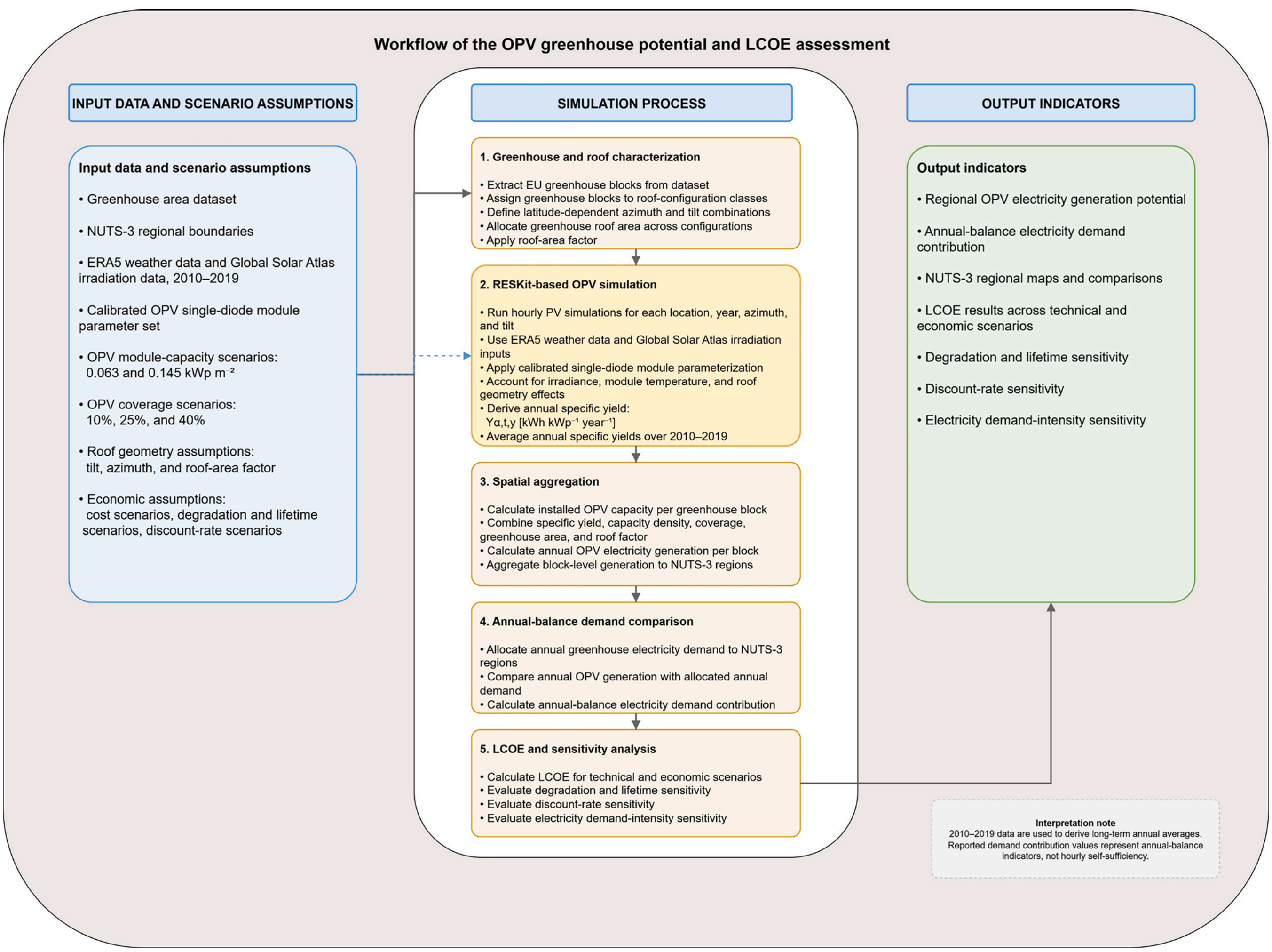

Fig. 1. Simulation workflow of OPV assessment.

[35–38], latitude-dependent roof orientations and tilt angles are applied to reflect typical European greenhouse designs and near-optimal PV irradiance conditions.

For regions below 40° N latitude, representing predominantly Mediterranean plastic greenhouses with shallow roof slopes, both east-facing and south-facing roofs are considered. East-facing roofs are assigned tilt angles of − 10°, 0°, and + 10°, while south-facing roofs use tilt angles of 0° and + 10°. For regions at or above 40° N latitude, south-facing roofs with tilt angles of 0°, 10°, and 20° are applied, reflecting the typical roof slopes of Venlo-type glasshouses common in Central and Northern Europe.

The total roof area in each region is distributed evenly across the respective tilt and orientation combinations. For sites below 40° N, one third of the area is assigned to each east-facing tilt and one half to each south-facing tilt. For sites at or above 40° N, the roof area is equally divided among the three south-facing tilt angles. An overview of the applied tilt and azimuth combinations is provided in Fig. 2.

Finally, we derive the total annual potential in kWh per location and scenario by multiplying the per-m^2 module yield with the occupied area and the applied roof-area factor, then summing over tilts within each azimuth, as presented in Eq. (2):

$$P_{block,s} = \sum_t \left[\underbrace{Y_{\alpha,t}}_{\text{kWh/kWp}} \times \underbrace{\rho}_{\text{kWp/m}^2} \times \underbrace{(PV_{\text{occ}} \cdot A_{\text{GH}} \cdot \text{share}_{\alpha,t})}_{\text{occupied ground area share}} \times RF \right], \quad (2)$$

where $P_{block,s}$ is the potential per greenhouse block per scenario s, Y is the capacity factor kWh/kWp, α is azimuth, t is tilt, ρ is the capacity density kWp/m^2, PV_{occ} is the occupancy fraction (10%, 25%, 40%), A_{GH} is the greenhouse ground area, and RF is the roof factor. The total potential was obtained by computing the average of the totals per azimuth for each combination of occupancy and capacity-density scenario, for every year from 2010 to 2019, and subsequently averaging across all simulation years.

Each aggregated greenhouse block was assigned to a Nomenclature of Territorial Units for Statistics level 3 (NUTS-3) region. This allows the estimation of electricity generation at the regional level and enables comparison with local electricity demand across Europe.

In the following, r denotes a NUTS-3 region and s denotes the considered OPV scenario (e.g., PV coverage level and efficiency assumption).

The total electricity generation potential of a region r under scenario s is calculated by summing the electricity potential of all greenhouse blocks located within that region (Eq. (3):

$$P_{r,s} = \sum_{block \in r} P_{\text{block,s}} \quad (3)$$

The NUTS-3 level provides a suitable balance between spatial resolution and data availability, ensuring comparability across European regions.

To improve transparency of the scenario design, the technical assumptions used for OPV electricity generation modelling are summarized in Table 2.

Electricity demand and utilization

Greenhouse electricity demand can vary substantially depending on greenhouse typology, climatic conditions, and the degree of technical equipment [4]. General, low-tech greenhouses are more frequently in the south of Europe while high-tech greenhouses greenhouses occur more in the north [39]. Low-tech Mediterranean greenhouse systems are often characterized by simple structures and limited active climate control [40–42], whereas high-tech glasshouses, particularly in

Table 2
Technical assumptions used for OPV electricity generation modelling.

Parameter	Scenario values	Interpretation / role in the analysis
Capacity density / implied module efficiency	0.063 kWp m^{-2} / approx. 6.3%; 0.145 kWp m^{-2} / approx. 14.5%	Current state OPV performance scenario Upper-bound OPV performance scenario
Rooftop occupancy ratio	10%, 25%, 40%	Representative OPV coverage levels of greenhouse rooftop area
Roof orientation and tilt	<40° N: east- and south-facing configurations; ≥40° N: south-facing configurations	Representative greenhouse roof configurations across European latitude zone
Weather and irradiation years	2010–2019	Used to derive long-term annual average electricity generation

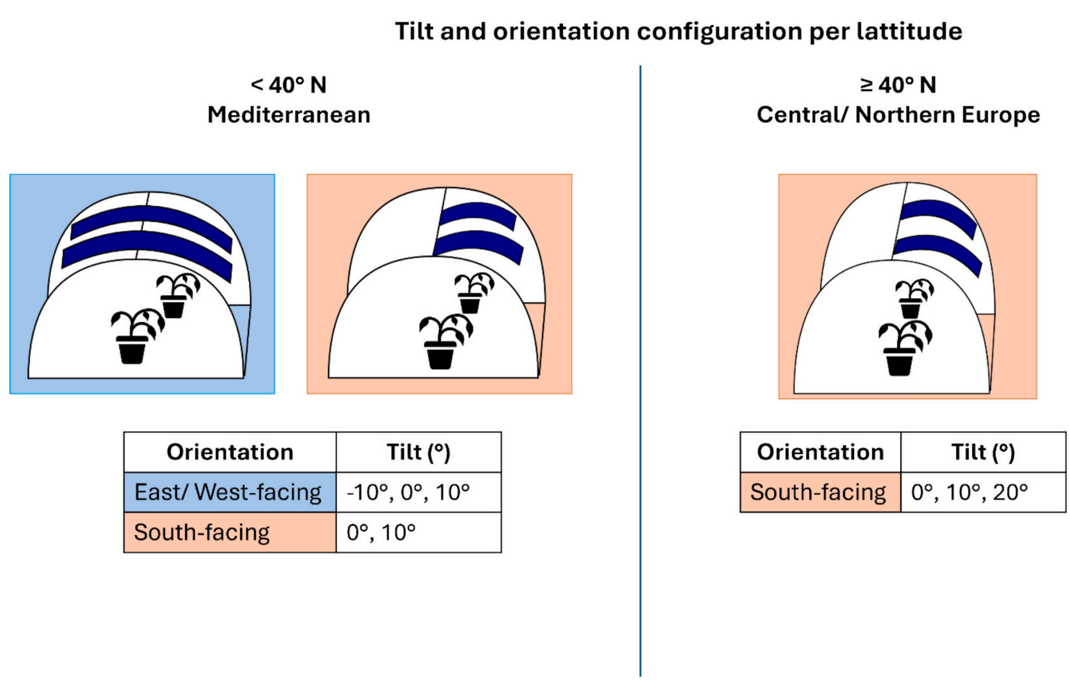

Fig. 2. Technical configurations for RESKit simulations.

northern Europe, may require substantially higher electricity inputs for ventilation, pumping, lighting, and climate regulation [43]. Conversely, exceptions can be observed, particularly in southern regions, where elevated energy demands have been recorded, often attributable to additional heating or other factors [39,44,45].

However, harmonized region-specific data on greenhouse typology, technical equipment, and electricity demand intensity are not available on European NUTS-3 scale. Therefore, this study applies a spatial allocation approach combined with a demand-intensity sensitivity analysis. This allows the potential contribution of OPV-integrated greenhouses to annual electricity demand reduction to be assessed while explicitly accounting for uncertainty in greenhouse electricity demand intensity. All comparisons between OPV generation and electricity demand are conducted on an annual-balance basis, using annual generation and annual demand values derived from the respective datasets.

In the baseline case, greenhouse electricity demand was estimated using an area-share-based allocation. Sectoral electricity demand data for households, public services, agriculture, and fisheries [46] were allocated to greenhouse locations within each NUTS-3 region based on the share of greenhouse-covered area. This enabled the estimation of electricity demand associated with greenhouse surfaces and the assessment of the extent to which annual OPV electricity generation could contribute to this allocated electricity demand.

To account for the heterogeneity of greenhouse typology and the uncertainty in electricity demand intensity, this initial analytical step was complemented by a demand-intensity sensitivity analysis. To this end, the baseline greenhouse electricity demand was scaled by factors of 0.5, 2, 5, and 10. The 0.5 × case is indicative of lower-demand greenhouse systems, the 2 × case reflects moderately higher demand intensity, and the 5 × and 10 × cases represent high-tech and extreme high-tech greenhouse scenarios, respectively. The original area-based allocation is regarded as the baseline case. The supplementary factors offer a dynamic range for assessing the sensitivity of the results to the uncertainty surrounding greenhouse demand intensity across NUTS-3 regions.

In the second step, OPV electricity production was compared with the total electricity demand of each NUTS-3 region across all major sectors, including households, industry, transport, agriculture, and services, to assess the contribution of OPV greenhouses to regional electricity supply.

For both analytical scales, a coverage rate (CR) was calculated as the ratio of OPV electricity production to electricity demand, capped at 100%. Regions with CR values ≥ 100% were considered to fully meet annual demands under the respective scenario (Eq. (4):

$$CR = min\left(\left(\frac{P_{r,s}}{D}x100\right); 100\right) \tag{4}$$

where $P_{r,s}$ denotes annual OPV electricity production in region r under scenario s, and D denotes the respective annual electricity demand. In the greenhouse-specific sensitivity analysis, D refers to the adjusted greenhouse electricity demand under the respective demand-intensity case.

Moreover, the greenhouse areas were compared with the total NUTS-3 area to ascertain the significance of greenhouses for the region and to contextualize this with the significance of potential electricity autonomy levels.

The annual-balance demand comparison focuses on regional electricity generation and demand contribution potential. Local grid-connection constraints, feed-in limits, curtailment, and connection costs are outside the model boundary. Accordingly, surplus OPV generation is treated as technically available electricity at the regional level.

Building upon these spatial and energy assessments, the subsequent section examines the financial implications of OPV integration by evaluating its techno-economic feasibility through the Levelized Cost of Electricity (LCOE).

Financial implications

LCOE

The economic feasibility of OPV greenhouse systems was evaluated using the LCOE, defined as the ratio of discounted lifetime expenditures to discounted lifetime electricity generation (Eq. (5):

$$\text{LCOE} = \frac{\sum_{t=0}^{n}\frac{C_t}{(1+i)^t}}{\sum_{t=1}^{n}\frac{E_t}{(1+i)^t}} \tag{5}$$

with C_t denoting annual expenditures [EUR], E_t the annual electricity generation [kWh], i the real discount rate, and n the system lifetime. The annual electricity generation E_t is obtained from the simulation results and aggregated at the regional NUTS-3 level. For each region, the configuration with the highest electricity yield (i.e., optimal azimuth) is selected.

Three cost scenarios were considered, all expressed in 2025 euros and recalculated for the two power densities used in our yield simulations (63 W m^{-2} and 145 W m^{-2}).

- A current “high-cost scenario”.
  Itis based on reported commercial module prices of 150 € m^{-}2, which corresponds to 2.38 € Wp^{-}1 at 63 W m^{-2} and 1.03 € Wp^{-}1 at 145 W m^{-2}.
- An “upscaling scenario” which reflects the “medium cost” scenario in a longer term.

It is based on Machui et al., who conducted a detailed cost analysis of roll-to-roll manufactured, fully printed and vacuum-free polymer solar cell modules, identifying key cost drivers and optimization pathways toward competitive production costs [47]. The scenario was inflated to 26 € m^{-2} (30.5% price change between 2014 and 2025) equal to 0.41 € Wp^{-}1 at 63 W m^{-}2and 0.18 € Wp^{-}1 at 145 W m^{-2},

- An industrial scenario, reflecting the “future low-cost” scenario.

It is based on Machui et al. and Lu et al. [8], was adjusted to 9.1 € m^{-}2 corresponding to 0.14 € Wp^{-}1 at 63 W m^{-2} and 0.06 € Wp^{-}1 at 145 W m^{-2},

Additional capital expenditures (CAPEX) components include inverters, electrical parts such as cables, and installation were estimated as a point of reference from APV CAPEX estimations [48] and were assumed to decrease with scale. Additional project-specific structural reinforcement costs were not explicitly included. This reflects the assumed use of lightweight and flexible OPV modules, for which integration is expected to require lower structural adaptation than conventional rigid PV systems.

It should be noted that higher prices for other investment components are required due to the necessity for greater spatial capacity per kilowatt peak, which in turn necessitates the use of additional materials. The full CAPEX breakdown is shown in Table 3 Panel A. For all scenarios, a system lifetime of 20 years, a real discount rate of 7%, and an annual operational expenditures (OPEX) of 1.5% of CAPEX were applied, which is in line with PV financial studies [49]. Performance degradation was set to 1% per year [50] which is in line with lifetime guarantees of current producers, warranting 80% of initial production after 20 years [51]. One inverter replacement was included after 10 years [48]. The applied cost scenarios and economic assumptions are provided in Table 3 Panel A-C.

For the main LCOE analysis, the roof configuration with the highest simulated annual electricity yield was selected from the considered latitude-dependent tilt and azimuth configuration set. This reflects the design assumption that OPV integration would be oriented towards the most productive available roof configuration when installed in practice.

Table 3
Economic and lifetime assumptions used in the LCOE analysis.

Panel A. CAPEX assumptions by OPV cost scenario

Scenario	Module costs (€ m^{-2})	Module costs (€ Wp^{-1}) 63 W m^{-2}	Module costs (€ Wp^{-1}) 145 W m^{-2}	Inverter (€ Wp^{-1})	Electrical (€ Wp^{-1})	Installation (€ Wp^{-1})	Total CAPEX (€ Wp^{-1}) 63 W m^{-2}	Total CAPEX (€ Wp^{-1}) 145 Wm^{-2}
OPV Current High	150	2.38	1.03	0.18	0.08	0.15	2.79	1.44
OPV Upscaling 100 MW	26	0.41	0.18	0.10	0.05	0.10	0.66	0.43
OPV Industrial 100 GW	9.1	0.14	0.06	0.06	0.03	0.05	0.38	0.20

Panel B. Financing and operating assumptions

Parameter	Values	Interpretation
Real discount rate	5%, 7%, 10%	Financing sensitivity; 7% used as baseline assumption
Annual OPEX	1.5% of CAPEX year^{-1}	Annual operating cost assumption used in the LCOE calculation

Panel C. Degradation and lifetime assumptions

Scenario	Initial loss	Annual degradation	Lifetime	Interpretation
Baseline	0%	1% p.a.	20 years	Warranty-oriented reference case
Moderate degradation	0%	2% p.a.	20 years	Higher long-term degradation
Conservative degradation	25%	2% p.a.	20 years	Early burn-in / field-performance loss and higher long-term degradation
Reduced lifetime stress case	0%	2% p.a.	15 years	Shorter OPV lifetime

Sensitivity analysis

Long-term operational stability represents a central uncertainty for OPV greenhouse applications. Field studies have shown that OPV systems can experience performance degradation under real-world conditions due to photo-oxidation, moisture ingress, UV exposure, temperature stress, mechanical stress, dust accumulation, and condensation, with reported losses varying substantially depending on environmental exposure, encapsulation quality, and installation design [23,52–56].

At the same time, recent developments in commercial OPV products and outdoor testing indicate progress in operational stability, including 20-year performance guarantees for commercially available OPV films [51] and recent outdoor module tests reporting extrapolated degradation rates below 2% per year under specific operating conditions [57].

Despite these developments, long-term field evidence for greenhouse-integrated OPV systems over multi-decadal operating periods remains limited. Greenhouse environments expose modules to installation-specific stressors such as elevated humidity, condensation, thermal variation, and mechanical constraints, which may affect degradation patterns differently from conventional outdoor PV applications. OPV stability was therefore represented through four degradation and lifetime scenarios in the LCOE analysis. As presented in 3.4.1, the baseline scenario assumes 1% annual degradation over a 20-year lifetime and serves as a warranty-oriented reference case. Based on the literature indications regarding burn-in losses and annual degradation [54,57], we developed further degradation scenarios: The moderate degradation scenario assumes 2% annual degradation over 20 years. The conservative degradation scenario combines a 25% initial performance loss with 2% annual degradation over 20 years. The reduced-lifetime stress case assumes 2% annual degradation over a 15-year lifetime. Together, these scenarios assess the robustness of the LCOE results under different long-term stability assumptions. An overview of the degradation scenarios is provided in Table 3 Panel C.

The economic assessment was conducted in real terms using a baseline discount rate of 7%. This value follows standardized LCOE comparison approaches and is consistent with the upper range of discount rate assumptions reported by the IEA for established utility-scale solar PV technologies [49]. Given the continental scope of this study, harmonized discount-rate assumptions were applied to ensure comparability across regions. Estimating country- or project-specific WACC values would require detailed assumptions on financing structures, debt and equity costs, taxation, ownership models, and project-specific risk profiles. These data are not consistently available for OPV greenhouse applications across Europe and would introduce an additional layer of uncertainty into the regional comparison. The 7% discount rate is therefore used as a harmonized real cost-of-capital assumption to ensure comparability across regions and scenarios. To assess the influence of financing assumptions on the LCOE results, additional sensitivity cases of 5% and 10% were included.

To improve transparency of the scenario design, the overall economic assumptions used for the LCOE analysis are summarized in Table 3.

Results

OPV potential of Europe – Production and capacity

EU

Based on Tong et al., the overall greenhouse surface for the European Union is 2075.65 km^2 of base area. If we apply the roof factor according to our applied latitude rule, we even estimate a “roof area” of 2115 km^2.

Fig. 3 illustrates the spatial distribution of OPV greenhouse potential across Europe, with pixel size representing greenhouse surface area and corresponding electricity production potential. Distinct hotspots are identified in coastal regions of Italy and Spain, as well as a major greenhouse cluster in the Netherlands. Further regions with substantial potential include France, Portugal, and Greece.

The analysis also reveals limitations in the underlying dataset, particularly in metropolitan areas, northern regions, and parts of Eastern Europe, where greenhouse coverage is likely underrepresented. The absence of valid pixel data results in a stripe-like pattern.

At the EU27 scale, the cumulative electricity yield increases from 14.3 TWh year^{-1} under 10% occupancy with 63 W m^{-2} modules to 131.5 TWh year^{-1} under 40% occupancy with 145 W m^{-2} modules (see Fig. 4). A relevant comparison emerges between the 10% occupancy, 145 W m^{-2} scenario (32.9 TWh year^{-1}) and the 25% occupancy, 63 W m^{-2} scenario (35.7 TWh year^{-1}), which deliver nearly identical yields despite the former requiring substantially less ground coverage. This demonstrates that efficiency improvements in OPV modules can offset lower land-use intensity, enabling comparable electricity generation without substantially increasing shading of greenhouses. The mixed-azimuth approach, where northern regions ($\geq$ 40°N) are simulated with south-facing modules (0° azimuth) and southern regions ($<$ 40°N) with east–west orientations (90° azimuth), consistently yields slightly higher potentials compared to uniform azimuth-0 assumptions. This comparison represents an orientation-parameter sensitivity within the predefined roof-

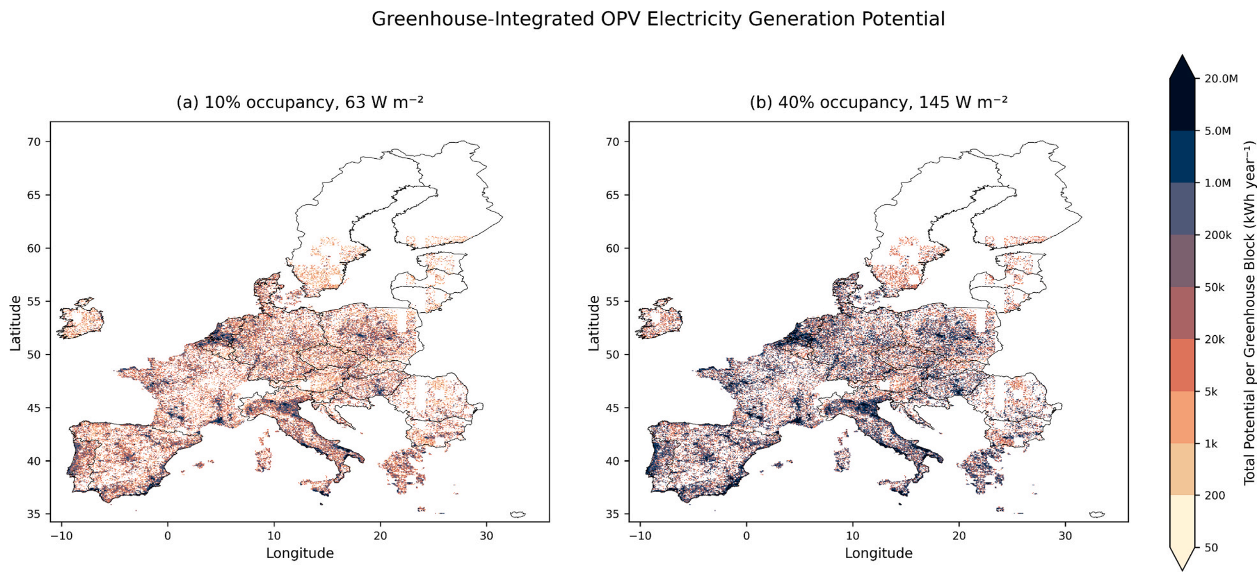

Fig. 3. OPV greenhouse potential map of Europe indicating hotspots and available data.

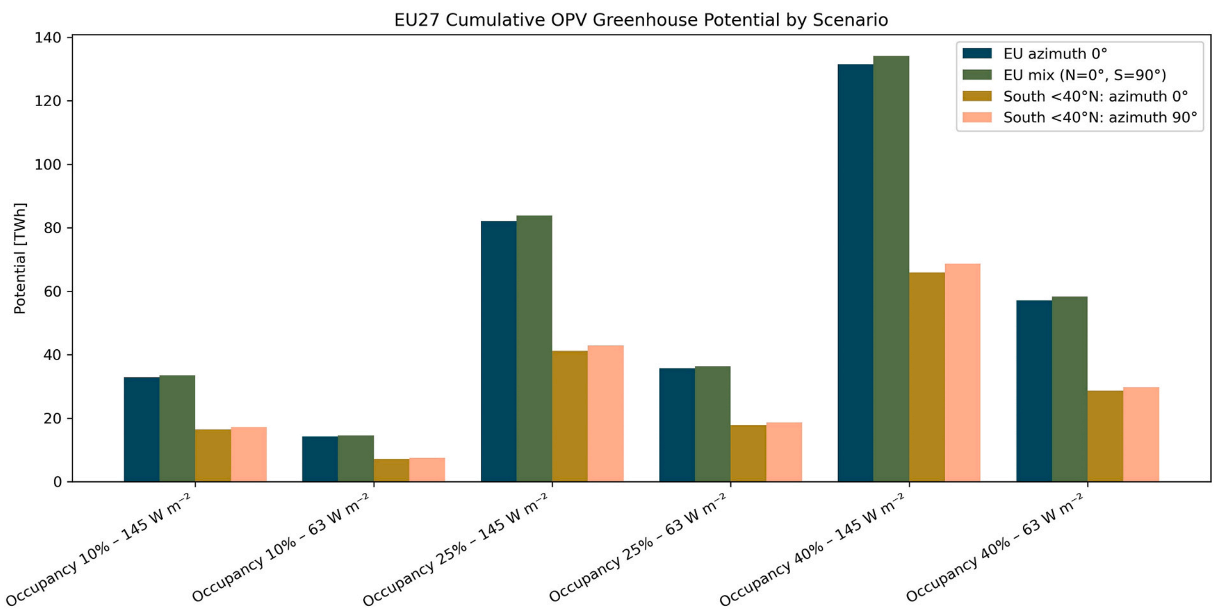

Fig. 4. Total production potential of OPV greenhouses across the EU.

configuration framework. When focusing exclusively on southern regions ($< 40^{\circ}$N), the comparison confirms that azimuth-90 scenarios outperform azimuth-0 configurations in all cases, with relative gains of around 3–4% depending on the scenario. Although the magnitude of this effect is moderate, it indicates that regional roof-orientation assumptions can influence estimated OPV potential and should therefore be considered in large-scale greenhouse PV assessments.

To date, no comparable large-scale assessments of greenhouse-integrated PV exist beyond Europe. The results therefore indicate that OPV greenhouses represent a largely untapped and space-efficient option for photovoltaic expansion.

The deployment scenario considered in this study assumes full technical availability across the identified greenhouse stock. The results therefore represent an upper-bound potential scenario and do not estimate expected market diffusion or actual adoption by greenhouse operators.

Furthermore, the results indicate the potential for one representative year. In the context of a longer lifetime, it is imperative to consider degradation rates, which would consequently result in a reduction of the overall figures. This was taken into consideration in the subsequent economic analysis.

Key regions

The regional analysis shows that the OPV greenhouse potential is highly concentrated:

Only 10 NUTS-3 regions account for the majority of the total potential (Fig. 5). Overall, greenhouse areas represent only a small fraction of land use across Europe. Only one region shows a significant greenhouse area, which is Delft en Westland (NL362), where greenhouses cover 29.1% of the regional area. In Almería (ES611), known as a greenhouse hotspot in Europe, the total greenhouse area accounts for 3.8% of the total regional surface. Most NUTS-3 regions have greenhouse shares below 1% of the total regional area.

This indicates that, despite high local concentrations, greenhouse-

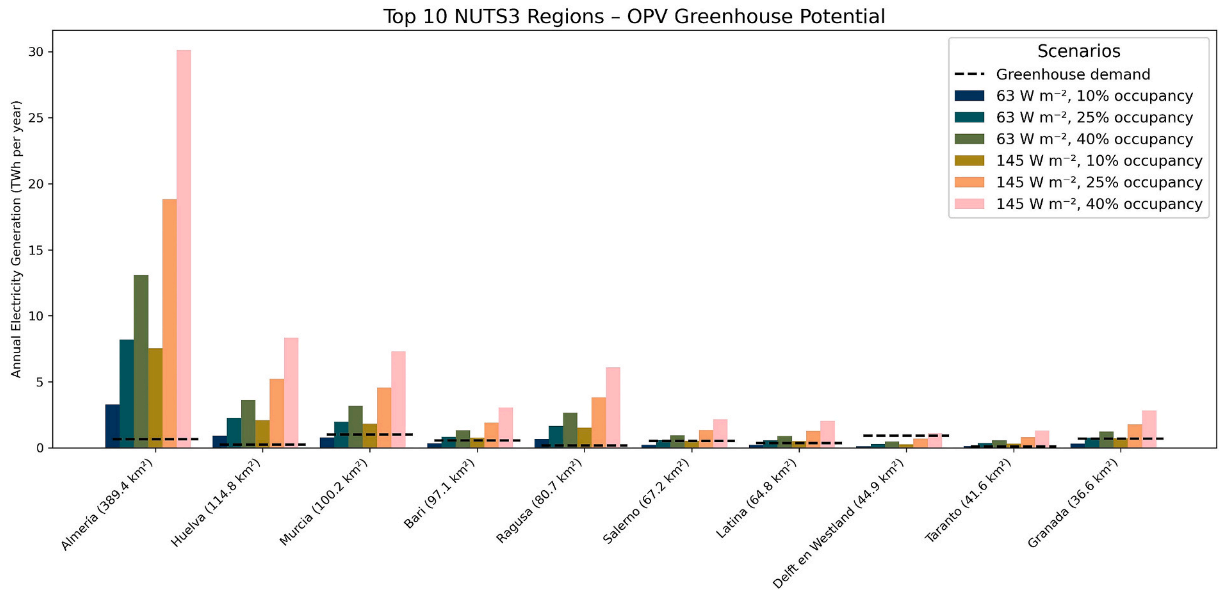

Fig. 5. Top 10 NUTS-3 Regions in the EU in terms of OPV production and greenhouse area.

based OPV deployment remains spatially limited at the continental scale.

The top ten NUTS-3 regions account for nearly half (1,037 km^2; 49.9%) of the total greenhouse area. The single largest cluster remains Almería in Spain, with almost 390 km^2 of greenhouse ground surface, followed by Huelva (115 km^2) and Murcia (100 km^2). The Dutch region Delft en Westland, although smaller in absolute terms (45 km^2), still stands out due to the very high relative share of greenhouses within its territory.

When translated into annual electricity generation, these regions also dominate OPV production potential, accounting for nearly 55% of the total production potential of the EU. Under high-efficiency scenarios (145 W m$^-$2 and 40% occupancy), Almería alone could exceed 30 TWh year$^-$1, accounting for 22% of the total European potential. Huelva and Murcia contribute between 5 and 9 TWh year$^-$1 annually depending on the scenario, while Italian provinces such as Bari, Ragusa, and Salerno each exceed 2–6 TWh year$^-$1. Even Delft en Westland, with its comparatively smaller surface area, reaches nearly 2 TWh year$^-$1, highlighting its strategic relevance due to the combination of high relative greenhouse share and substantial production capacity.

In most of these regions, the OPV potential is sufficient to fully cover annual demand on a balance basis of the local greenhouse electricity demand even under moderate assumptions (63 W m$^-$2 and 25% occupancy). This indicates that the large-scale deployment of OPV could have a transformative impact on the sector's energy autonomy, particularly in Mediterranean clusters such as southern Spain, Sicily, and horticultural hubs such as Delft en Westland.

These spatial patterns indicate where OPV deployment could be most effective from a regional planning perspective. To assess practical implications at the greenhouse level, the following analysis therefore examines the extent to which local electricity demand can be met under different OPV deployment scenarios. Regional electricity autonomy is a key indicator of the potential of OPV greenhouses to reduce reliance on external energy supply and support decentralized renewable generation. Accordingly, Section 4.2.1 presents a scenario-based assessment of the share of greenhouse-related electricity demand covered by on-site OPV production.

Electricity demand and utilization – Regional assessment

Annual balance contribution potential – Local level

The scenario analysis indicates that, under the assumed OPV deployment scenarios, annual OPV electricity generation could equal or exceed allocated local greenhouse electricity demand in a large share of NUTS-3 regions on an annual-balance basis (see Fig. 6).

Under the baseline area-based demand allocation, annual OPV electricity generation equals or exceeds allocated local greenhouse electricity demand in 1,074 of 1,117 NUTS-3 regions (96.2%) even in the lowest OPV deployment scenario of 10% occupancy and 63 W m$^-$2. At 25% occupancy, this share increases to more than 99% for both power density assumptions, while the highest deployment scenario of 40% occupancy and 145 W m$^-$2 reaches this annual-balance threshold in 1,116 regions (99.9%).

These results indicate that OPV integration is well suited to the relatively moderate electricity demand of greenhouse operations and can enhance sectoral energy autonomy even at low deployment levels. This enhances energy security, and avoids electricity transmission losses, which is particularly beneficial in rural or infrastructurally weak areas. In addition, on-site OPV generation can support increased electricity demand for supplemental lighting, helping to compensate for reduced natural light. The scenario-specific results are shown in Fig. 13 in Appendix B.

Greenhouse typology heterogeneity across Europe

To assess the effect of greenhouse electricity demand uncertainty, the area-based baseline demand allocation was complemented by a demand-intensity sensitivity analysis. In this analysis, the allocated greenhouse electricity demand was uniformly scaled across all NUTS-3 regions using multipliers of 0.5, 2, 5, and 10, while the original area-based allocation represents the 1 $\times$ baseline case. The results are interpreted as annual-balance contribution potentials, indicating whether annual OPV generation equals or exceeds allocated annual greenhouse electricity demand.

Fig. 7 shows that the share of NUTS-3 regions reaching $\geq$ 100% annual-balance contribution decreases with increasing demand intensity. This decline is most pronounced in the lowest OPV deployment scenario, while higher OPV occupancy and power density substantially reduce the sensitivity to increased electricity demand. Across the sensitivity range, the 10% occupancy and 63 W m$^-$2 scenario shows the strongest reduction in regional contribution potential. By contrast, the scenarios with 145 W m$^-$2 and higher occupancy levels remain considerably more robust, even under elevated demand multipliers. These results indicate that the original area-based allocation produces optimistic coverage estimates for high-demand greenhouse systems, while

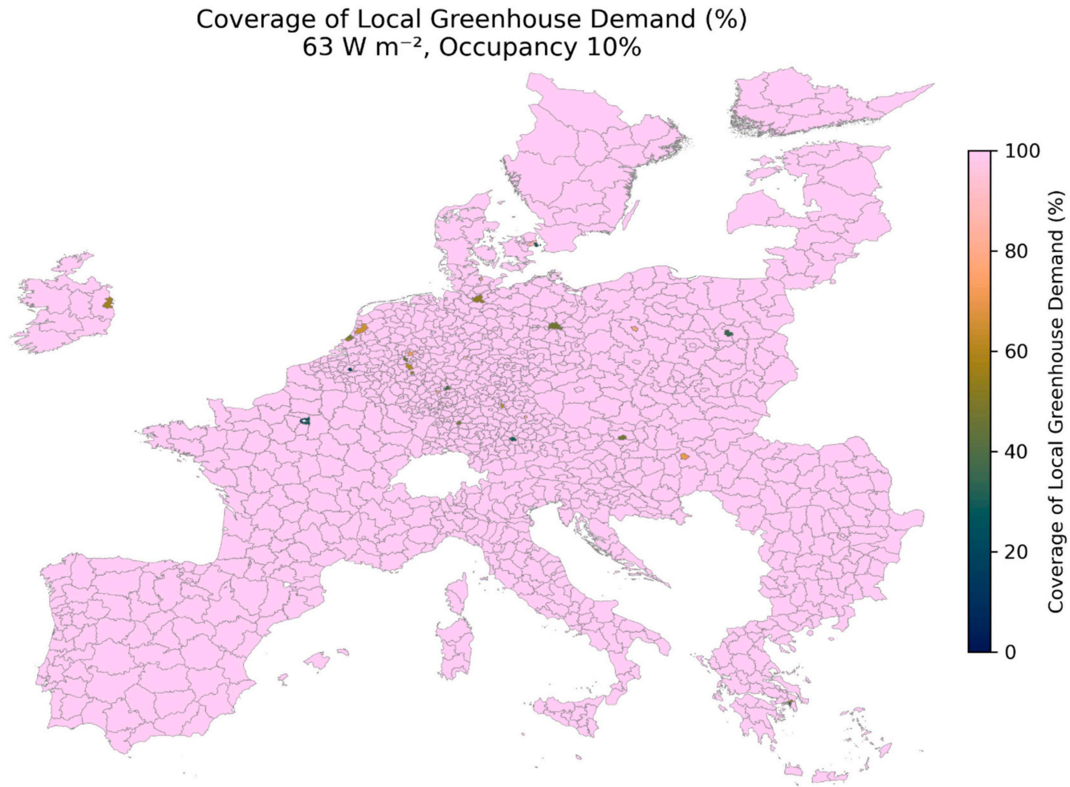

Fig. 6. Mapping the coverage of local greenhouse demand in the EU- lowest level of capacity density and occupancy.

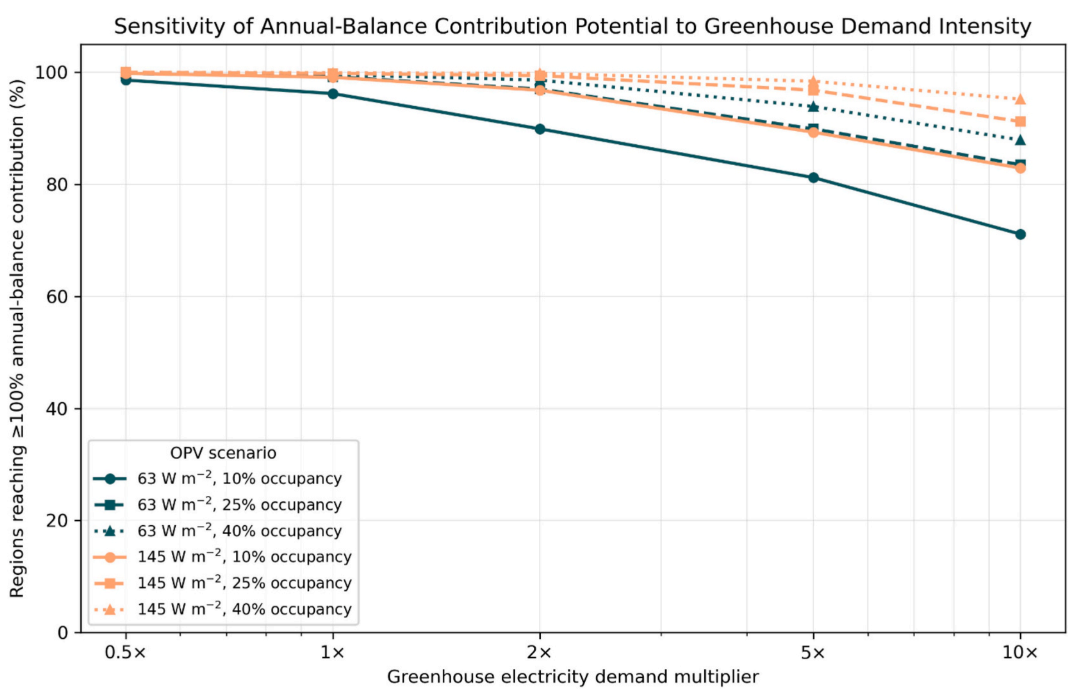

Fig. 7. Demand-intensity sensitivity across OPV deployment scenarios.

the overall contribution potential remains substantial under higher OPV deployment assumptions.

To further illustrate the spatial implications of greenhouse demand-intensity heterogeneity, an additional configuration-gradient scenario was calculated. In this scenario, NUTS-3 regions south of 40°N were retained under the baseline area-based demand allocation, while regions at or north of 40°N were assigned a 10-fold greenhouse electricity demand factor. Compared with the original baseline allocation, the share of regions reaching $\geq$ 100% annual-balance contribution decreased most strongly in the lowest OPV deployment scenario. For 10% occupancy and 63 W m^{-2}, the share declined from 96.15% to 71.80%, corresponding to 272 regions in which annual OPV generation no longer equals or exceeds allocated annual greenhouse electricity demand.

This spatial shift is illustrated in Fig. 8 for the lowest occupancy and power density scenario. Compared with the baseline allocation shown in Fig. 6, substantially more regions north of the 40°N latitude line fall below 100% annual-balance coverage under the configuration-gradient scenario. Nevertheless, most regions remain at or above this threshold even under this stress case. The effect becomes progressively smaller under higher OPV deployment assumptions. At 25% occupancy and 145 W m^{-2}, the share remains at 91.67%, while under the highest scenario of 40% occupancy and 145 W m^{-2}, 95.52% of all regions still reach $\geq$ 100% annual-balance contribution. These results indicate that the annual-balance contribution potential is sensitive to higher demand-intensity assumptions, especially in northern regions, while remaining substantial under higher OPV power density and occupancy scenarios.

Annual balance contribution potential – Overall NUTS-3 demand

In contrast to the high annual coverage of greenhouse electricity demand reported in the previous section, OPV installations contribute only modestly to total regional electricity demand (see Fig. 9). Across the entire sample of 1,117 NUTS-3 regions, the potential for coverage of total electricity demand increases in proportion to higher assumptions regarding OPV coverage rate and module efficiency.

Under the conservative scenario (10% coverage, 63 W m^{-2} module capacity), two regions (0.2%) achieve full demand coverage. This number increases to ten regions (0.9%) under a 25% coverage and 145 W m^{-2} scenario, and to 18 regions (1.6%) under the highest deployment assumption (40% coverage, 145 W m^{-2}). While full regional full annual demand coverage remains limited to a small number of regions, OPV can supply a substantial share of regional electricity demand in areas with dense greenhouse clusters and high solar irradiation, such as Almería and Huelva in southern Spain. The scenario-specific results are shown in Fig. 14 in Appendix B.

These findings highlight OPV greenhouses as a relevant technology for supporting regional energy autonomy and emission reduction in selected high-potential regions within the EU.

Building on the regional assessment of OPV potential, the following section evaluates its economic feasibility. While the technical analysis indicates substantial potential for renewable electricity generation and high annual coverage potential, realization depends on cost competitiveness. Therefore, the LCOE is assessed under different technological and scale assumptions.

LCOE

Baseline LCOE results under warranty-oriented degradation assumptions

The following LCOE results refer to the baseline degradation assumption of 1% annual degradation over a 20-year lifetime and a real discount rate of 7%.

The LCOE represents the ratio of the discounted lifetime costs of an energy-generating system to its discounted lifetime electricity output, expressed as a cost per unit of electricity produced (€ kWh^{-1}). It provides

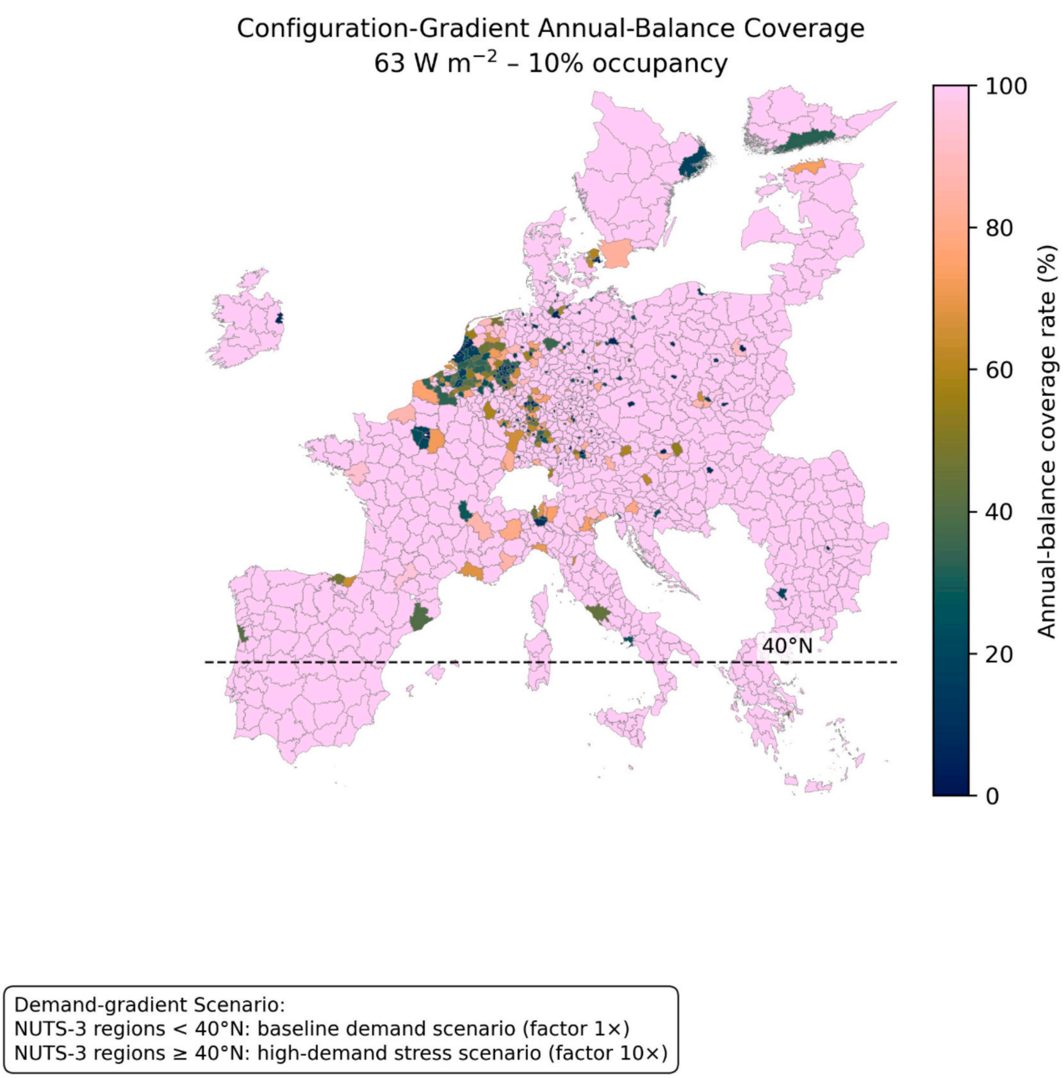

Fig. 8. Configuration-gradient annual-balance coverage of allocated greenhouse electricity demand under the lowest OPV deployment scenario.

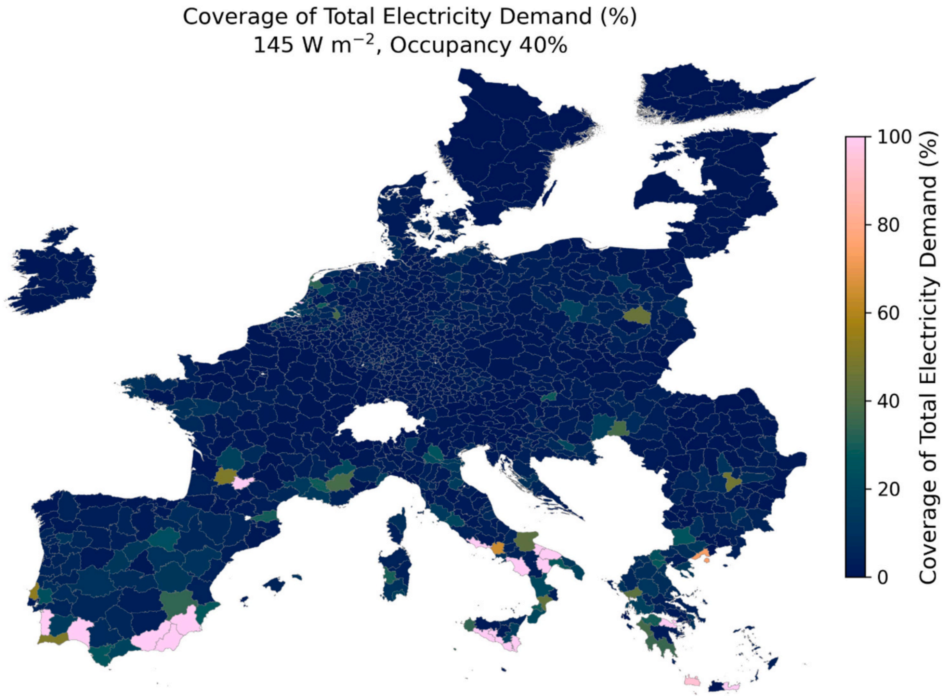

Fig. 9. Mapping the coverage of the total regional electricity demand in the EU- highest level of capacity density and occupancy.

a standardized metric to compare the economic performance of different energy technologies under varying assumptions of cost, efficiency, and lifetime [58,59]. In this study, the LCOE is used to evaluate the techno-economic feasibility of OPV-based greenhouse electricity generation across different cost and performance scenarios. The LCOE results indicate a wide range regarding the underlying cost scenario as well as assumed module capacity (see Fig. 10). For the high-cost case reflecting current market conditions, LCOE values range between 0.23 and 0.46 € kWh^{-1} at 63 Wm^{-2} and between 0.13 and 0.26 € kWh^{-1} at 145 W m^{-2}, with mean values of 0.38 and 0.20 € kWh^{-1}, respectively considering all NUTS-3 regions. Under an upscaling scenario at 100 MW production capacity, costs decline substantially, with LCOE values of 0.06–0.12 € kWh^{-1} for 63 W m^{-2} and 0.04–0.08 € kWh^{-1} for 145 W m^{-2}, averaging 0.09 and 0.06 € kWh^{-1}. The industrial-scale case at 100 GW capacity yields the lowest electricity costs, with regional values ranging from 0.03 to 0.05 € kWh^{-1} for 63 W m^{-2} and 0.02 to 0.04 € kWh^{-1} for 145 W m^{-2}, corresponding to mean values of 0.04 and 0.03 € kWh^{-1}. These results indicate that higher module efficiency systematically reduces LCOE significantly across all cost scenarios, while industrial-scale production reaches values below 0.05 € kWh^{-1} under favorable cost, stability, and financing assumptions. Regional variation remains significant: the lowest LCOE is observed in Southern Europe (Crete, EL421) with 0.019 € kWh^{-1} under the industrial high-efficiency scenario, while the highest values occur in Northern Europe (FI19B, Finland) at 0.49 € kWh^{-1} in the current high-cost, low-efficiency case. This underlines the strong influence of solar resource availability and

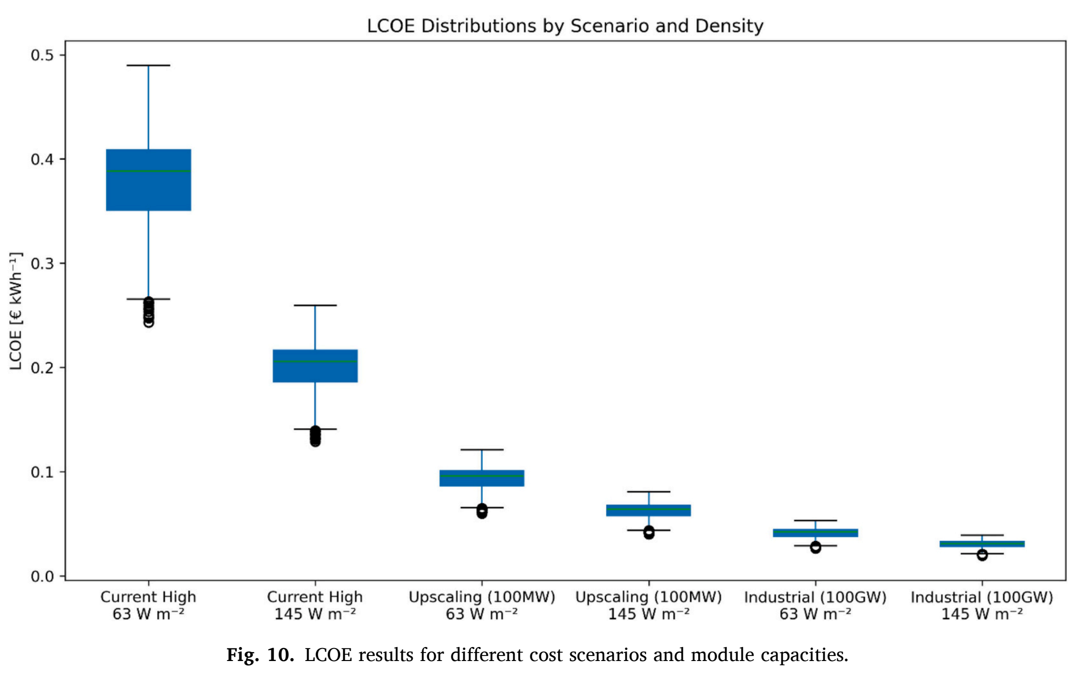

Fig. 10. LCOE results for different cost scenarios and module capacities.

geographical location on the competitiveness of OPV greenhouse electricity.

Sensitivity analysis – Degradation and lifetime assumptions

The degradation and lifetime sensitivity was evaluated under the baseline financing assumption to isolate the effect of OPV performance stability on LCOE. For the current high-cost scenario at 63 W m^{-2}, mean LCOE increases from 0.377 € kWh^{-1} under the warranty-oriented baseline degradation case to 0.539 € kWh^{-1} under the conservative degradation scenario combining a 25% initial performance loss with 2% annual degradation over 20 years. Across NUTS-3 regions, the corresponding LCOE range shifts from 0.243 to 0.490 € kWh^{-1} to 0.348–0.700 € kWh^{-1}. In the industrial-scale 100 GW scenario at 145 W m^{-2}, mean LCOE increases from 0.030 € kWh^{-1} under baseline degradation to 0.043 € kWh^{-1} under the conservative degradation scenario, with regional values shifting from 0.019 to 0.039 € kWh^{-1} to 0.028–0.056 € kWh^{-1}. The largest contrast is observed between the most favorable industrial-scale high-capacity case under baseline degradation in EL421, with 0.019 € kWh^{-1}, and the least favorable current high-cost, low-capacity case under conservative degradation in FI19B, with 0.700 € kWh^{-1}. This difference of 0.681 € kWh^{-1} highlights the combined importance of module cost reduction, power density, geographical irradiation conditions, and long-term operational stability. Fig. 11 illustrates the effect of the applied degradation scenarios for the two boundary cases of the analysis: the current high-cost scenario at 63 W m^{-2} and the future industrial-scale 100 GW scenario at 145 W m^{-2}. Although the relative

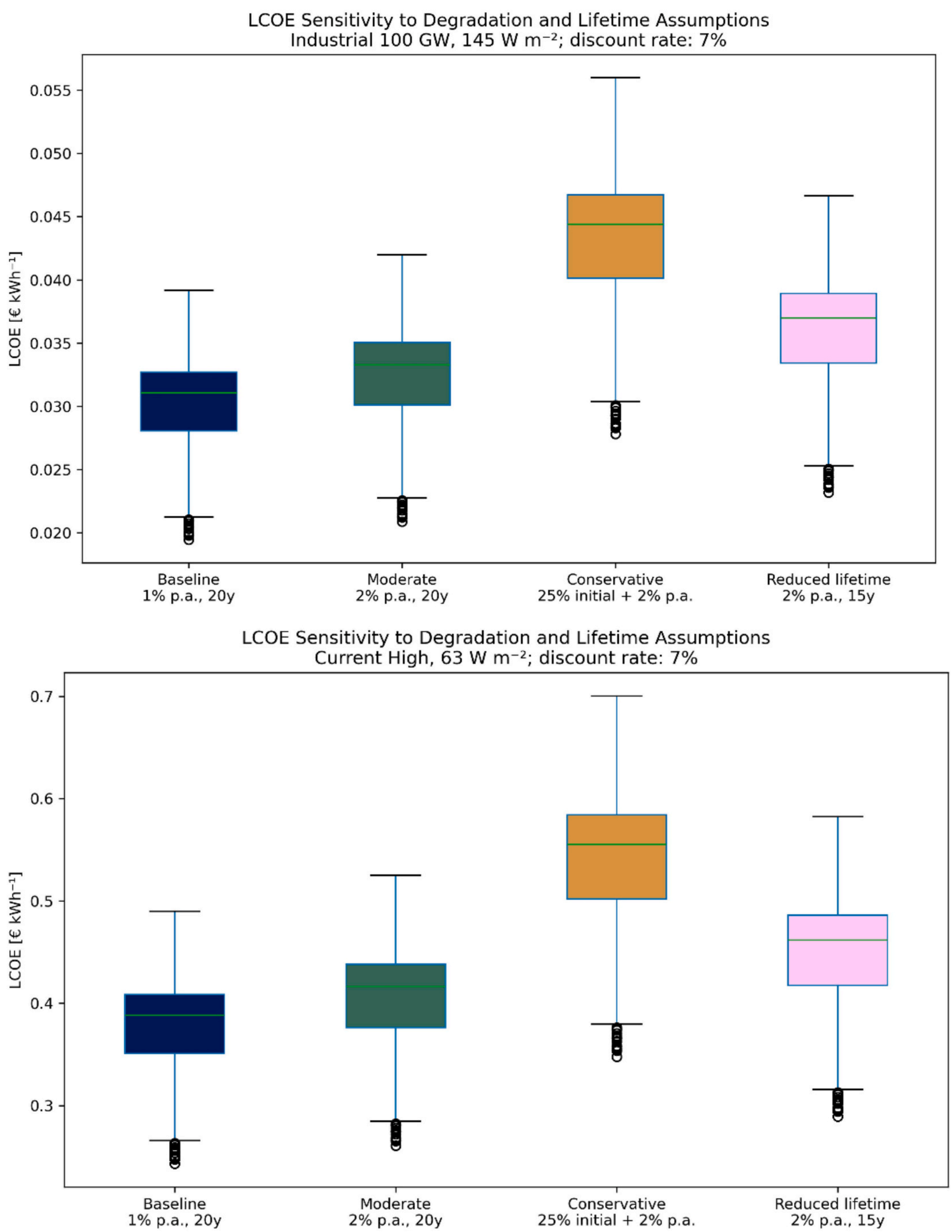

Fig. 11. LCOE sensitivity to degradation for future oriented industrial OPV scenario (top) and current state OPV scenario (bottom).

pattern across degradation scenarios is similar in both cases, the comparison shows the span of absolute LCOE impacts, ranging from the least favorable present-day configuration to the most favorable future industrial-scale case.

Sensitivity analysis – Discount rate assumptions

The discount-rate sensitivity was evaluated under the baseline degradation assumption of 1% annual degradation over a 20-year lifetime (Fig. 12). The results show that financing conditions affect absolute LCOE levels, particularly in the more capital-intensive current high-cost scenarios. For the current high-cost scenario at 63 W m⁻2, mean LCOE changes from 0.332 € kWh⁻1 at a 5% real discount rate to 0.377 € kWh⁻1 at 7% and 0.450 € kWh⁻1 at 10%. For the industrial-scale 100 GW scenario at 145 W m⁻2, the corresponding mean values are 0.027, 0.030, and 0.035 € kWh⁻1. The effect of the discount rate is more pronounced where initial CAPEX remains high, whereas industrial-scale cost reductions substantially reduce sensitivity to financing assumptions in absolute terms.

Limitations

The results of this study are based on a modelling approach and have not been experimentally validated at system level. While input parameters are derived from empirical literature and industry data, uncertainties remain regarding real-world performance under operational conditions. Therefore, the findings should be interpreted as indicative estimates of techno-economic potential rather than precise forecasts.

Published field measurements from OPV-integrated greenhouse systems are only partially comparable to the module-capacity scenarios employed in this study. The reason for this discrepancy is that existing experiments often utilize semi-transparent modules designed to balance electricity generation with light transmission and crop compatibility. This design trade-off contributes to lower reported electrical efficiencies, with scalable semi-transparent OPV modules reaching 4–6.2% and up to 7.8% [22], while practical field studies report values of approximately 0.8–3% reflecting scaling losses and real operating conditions [13,16]. Direct validation against existing OPV greenhouse experiments was therefore not feasible, as harmonized long-term operational datasets combining module performance, transparency, crop response, degradation, system design, electricity demand, and cost data at regional scale are currently unavailable.

While semi-transparency represents a distinctive potential advantage of OPV for greenhouse applications, this benefit is not included in the quantitative results of the present study. Its quantitative assessment would require crop-specific information on wavelength-selective light transmission, radiation distribution, greenhouse layout, and yield responses under different module designs. The analysis is consequently based on opaque OPV modules and does not quantify the agronomic effects of semi-transparent OPV configurations.

The analysis represents a technical upper-bound scenario in which OPV systems are assumed to be installed across the considered greenhouse stock. This suggests that the extent of OPV deployment may be regarded as overly optimistic. In practice, adoption will depend on greenhouse operators perceived usefulness of the technology, investment conditions, regulatory certainty, and potential effects on crop management. Evidence from the broader agrivoltaics literature shows that farmers' willingness to adopt agrivoltaics is strongly influenced by perceived usefulness, subjective norms, and innovativeness, while bureaucratic effort and regulatory uncertainty may act as relevant barriers [60]. Since empirical adoption rates for OPV greenhouse systems in Europe are currently unavailable, we do not impose an adoption-rate assumption and instead identify this as an important area for future stakeholder-based research.

One additional source of uncertainty of the study lies in its applied energy demand patterns. The analysis is based on annual electricity balances and therefore does not capture diurnal or seasonal mismatches between electricity generation and demand. While the results indicate high levels of annual electricity coverage, meaningful regional electricity autonomy would in practice require additional system components such as electricity storage or grid integration. The annual perspective was adopted due to the lack of harmonized, high-resolution regional case studies and the availability of electricity demand data

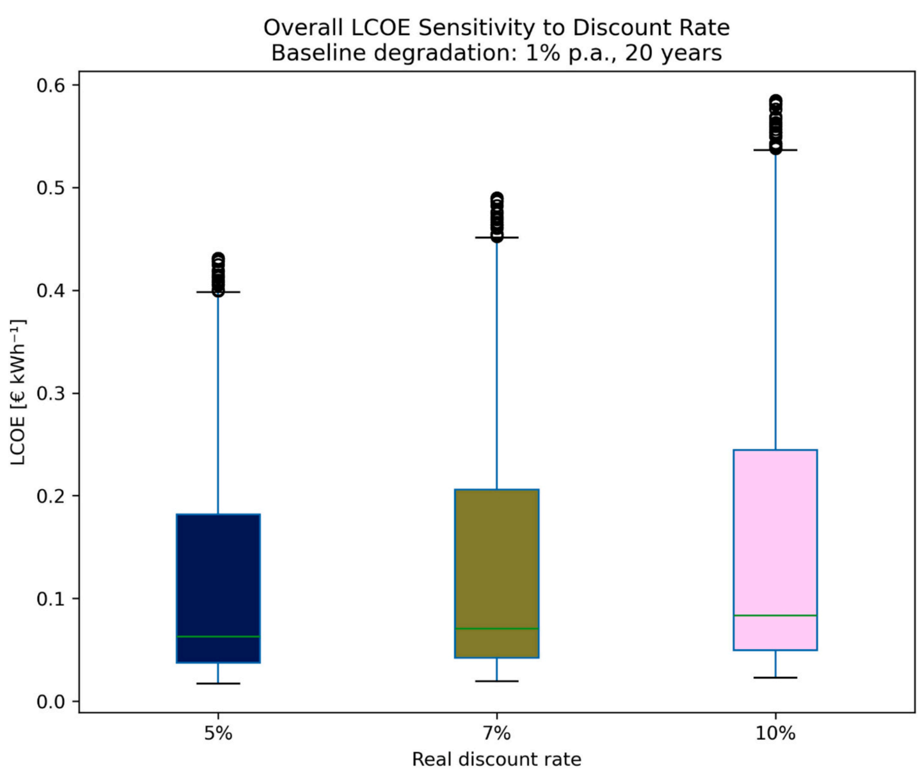

Fig. 12. LCOE sensitivity to discount rate.

primarily on an annual basis. The reported coverage rates should therefore be interpreted as annual-balance indicators under idealized balancing conditions.

By treating surplus OPV generation as technically available electricity at the regional level, while actual utilization or export depends on local grid infrastructure and available connection capacity, the consideration of grid integration remains limited. In regions with limited grid capacity, surplus electricity may require grid reinforcement, storage, demand-side flexibility, or curtailment. These requirements can increase project costs and may reduce economic feasibility, particularly in rural agricultural areas where grid infrastructure can be constrained.

The absence of structural reinforcement capital expenditures may be defined as another limitation. The necessity for reinforcement may be subject to variation due to factors including greenhouse type, structural condition, roof material, local wind and snow loads, and mounting concept. In instances where supplementary reinforcement is deemed necessary, the reported LCOE values may exhibit a tendency to underestimate the aggregate system costs.

For a limited number of NUTS-3 regions, no OPV potential could be calculated because no greenhouse area was identified in the underlying dataset. These gaps mainly occur in metropolitan areas, sparsely populated northern regions, and parts of Eastern Europe, where greenhouse cultivation is either absent or not represented in the available data. Accordingly, these regions appear without values in the spatial results, while the majority of NUTS-3 regions could be assessed consistently.

Lastly, this study does not explicitly model crop-specific yield and quality responses to reduced light availability. While shading effects are indirectly accounted for through constrained OPV coverage levels of 10%, 25%, and 40%, the actual impact on agricultural productivity may vary significantly depending on crop type, growth stage, greenhouse design, module layout, and local climatic conditions. The selected coverage levels therefore represent scenario assumptions and do not constitute an optimization of OPV integration for individual crops, regions, or greenhouse typologies due to lack of data on crop-specific light-response functions, local irradiation conditions, greenhouse design data, module transparency characteristics, electricity prices, crop values, and yield-loss estimates. The results should therefore be interpreted as techno-economic potential under simplified agricultural assumptions, while crop- and location-specific optimization remains an important subject for future research.

Discussion

This study assessed the system-level potential of integrating OPV into greenhouse structures across the European Union, focusing on technical electricity generation potential, contributions to greenhouse self-consumption, regional electricity demand, and indicative economic feasibility under different technological scenarios. The results indicate that OPV-integrated greenhouses could support the EU clean energy transition by enabling renewable electricity generation within existing agricultural infrastructure and without additional land consumption. At the greenhouse level, OPV systems can substantially contribute to cover annual electricity demand, while at the regional level they may form a relevant component of decentralized renewable energy strategies. These results should be interpreted as indicative annual system-level potential, given the annual temporal resolution of the analysis. Future oriented cost and efficiency scenarios provide favorable LCOEs while current cost estimates and efficiencies indicate high values.

Opportunities and challenges

The results of this study indicate that OPV greenhouse integration can provide a relevant complementary pathway for photovoltaic deployment in agricultural systems. Its potential lies in the use of existing greenhouse surfaces for electricity generation, thereby avoiding additional land consumption and enabling energy production directly at the site of agricultural demand. This application context is particularly relevant because greenhouse production is spatially concentrated, energy-intensive, and increasingly affected by electrification needs related to ventilation, cooling, supplemental lighting, and climate-control systems.

At the same time, OPV remains technologically less mature than conventional crystalline silicon photovoltaics. A key limitation is its lower power conversion efficiency compared with crystalline silicon PV, which typically reaches efficiencies of approximately 20–25% [61]. This limits the absolute electricity output of OPV systems relative to mature PV technologies. Long-term operational stability also remains a central challenge. Although commercial OPV products are associated with 20-year performance guarantees, scientific studies still identify stability and degradation as key uncertainties for long-term economic performance [62]. These limitations are reflected in the degradation and lifetime sensitivity analysis of this study.

The competitiveness of OPV greenhouse systems therefore needs to be interpreted relative to clearly defined benchmarks and deployment contexts. Under current high-cost assumptions, OPV remains substantially above established PV cost levels, with mean LCOE values of 0.38 € kWh^{-1} for 63 W m^{-2} and 0.20 € kWh^{-1} for 145 W m^{-2}. These values exceed recent benchmark values for global solar PV, which reached approximately 0.041 € kWh^{-1} after conversion from 0.044 USD kWh^{-1} [58], and are also above reported LCOE ranges for German utility-scale ground-mounted PV systems of 0.041–0.069 € kWh^{-1} and Agri-PV systems of 0.052–0.120 € kWh^{-1} [63]. Under industrial-scale OPV manufacturing assumptions, however, mean LCOE decreases to 0.04 € kWh^{-1} for 63 W m^{-2} and 0.03 € kWh^{-1} for 145 W m^{-2}. These values approach or fall within benchmark ranges reported for established and emerging PV technologies. For other thin-film technologies, for comparison, system-level cost modelling reports LCOE values of approximately 0.033–0.057 € kWh^{-1} for cadmium telluride, around 0.051 € kWh^{-1} for copper indium gallium selenide, and 0.035–0.039 € kWh^{-1} for perovskite/silicon tandem systems (exchange rate USD – EUR July 2026) under long-term stability assumptions [64]. OPV competitiveness is therefore conditional on manufacturing scale, module capacity density, long-term stability, and financing assumptions.

This interpretation is further supported by the scenario comparison between module capacity density and rooftop occupancy. Higher OPV capacity density can partly compensate for lower rooftop occupancy. A 10% occupancy scenario at 145 W m^{-2} provides a similar installed capacity per greenhouse area as a 25% occupancy scenario at 63 W m^{-2}. This suggests that future improvements in OPV module performance could reduce the need for high coverage levels and may ease potential trade-offs with crop light availability. Since crop-specific yield and quality responses are not explicitly modelled, this conclusion should be interpreted as a technical scenario result and does not represent crop-specific optimal coverage levels.

The relevance of OPV greenhouse integration should also be considered in relation to broader PV deployment options. Assuming conventional crystalline silicon PV modules, the technical PV potential for suitable rooftops, floating PV installations, and vertical bifacial PV along roads and railways in the EU has been estimated at 1,120 GWp, including 580 GWp from rooftops and 48.73 GWp from floating PV [65]. Against this background, OPV greenhouse integration represents a complementary sector-specific deployment option within the broader European PV landscape. Its value lies less in replacing established PV applications and more in expanding PV deployment to lightweight greenhouse structures and agricultural surfaces with specific integration constraints.

A further advantage of OPV is its potential compatibility with greenhouse-specific design requirements. Semi-transparent OPV modules may allow selective light transmission and electricity generation within the same system, which could support crop-compatible PV integration [19]. This potential advantage was not quantified in the present analysis because a European-wide assessment would require detailed spectral, agronomic, and greenhouse-design modelling. The present study therefore focuses on opaque OPV modules as a clearly defined technical reference case, while semi-transparent OPV remains an important direction for future research.

In the context of escalating demand for critical raw materials in clean energy technologies, OPV's independence from rare earth minerals and its compatibility with EU-made materials underscore its relevance [9]. The findings of this study offer a contribution to prevailing EU strategies aiming for innovation in technology including the Green New Deal and the Critical Raw Materials Act. Reducing critical raw materials and supporting sustainable agricultural systems is particular relevant in the EU, as demand for rare earth elements is anticipated to rise, particularly in the critical economic sector of renewable energy [66]. In addition, a revival of the European photovoltaic module production can be launched by scaling OPV greenhouse technologies.

From a system perspective, OPV greenhouses are most relevant as a multifunctional and application-specific PV pathway. Conventional PV technologies offer higher efficiencies, longer operational experience, and more mature supply chains. OPV contributes a different integration logic through low weight, mechanical flexibility, and potential suitability for lightweight greenhouse structures or retrofitting of existing facilities with limited structural modification. Context-specific advantages may include on-site renewable electricity generation, reduced pressure on land resources, and possible use in rural or structurally constrained agricultural settings.

The methodological framework developed in this study can also be applied to other regions with extensive greenhouse cultivation, such as China, which currently represents the global leader in greenhouse production area [10].

Research outlook

Further research on the greenhouse sector is particularly relevant, as the global greenhouse area continues to expand due to its capacity to ensure high-quality yields and extended growing seasons independent of external weather conditions [10]. This growth is accompanied by escalating energy demands [6] to ensure the maintenance of controlled environments throughout the year, emphasizing the need for the integration of clean and sustainable energy sources to meet future agricultural demands. On-site OPV generation can support increasing electricity demand in greenhouse systems, including supplemental lighting, ventilation, cooling, and electrified climate-control technologies. At the same time, low-cost on-site electricity may influence operational decisions and encourage additional electricity consumption. Such rebound effects are outside the scope of the present annual-balance assessment, which treats electricity demand as an exogenous input, and represent an important avenue for future research.

OPV technology may offer advantages due to resource-efficient production and favorable life-cycle performance. Life cycle assessment studies indicate substantially lower energy payback times and cumulative energy demand compared to conventional silicon-based photovoltaics [67]. Additional environmental benefits result from the use of non-chlorinated, environmentally friendly solvents [68], as well as the absence of toxic or critical raw materials [19,69], leading to reduced environmental impacts and a lower carbon footprint [8]. While environmental benefits of OPV are frequently highlighted in the literature, potential environmental risks related to polymer-based materials such as degradation products, microplastic release, and long-term behavior under greenhouse conditions remain insufficiently addressed. Environmental benefits and resource utilization therefore require more dedicated assessment.

System design plays a critical role in balancing energy generation and crop productivity. Module orientation and placement significantly influence electrical output and temporal generation patterns. For example, ridge-mounted configurations can maximize electricity yield, whereas east–west arrangements can reduce midday peaks and provide a more stable power output throughout the day [23]. The distribution of solar radiation beneath the panels, and consequently both electricity generation and crop yield, is also strongly influenced by the chosen mounting approach, as well as by structural parameters such as panel height, table spacing, and row arrangement [56,70]. Optimizing these factors is essential to maximize the combined benefits of energy production and agricultural performance. Future work should therefore include experimental validation through pilot projects and field-scale implementations of OPV-integrated greenhouses.

Additionally, future research should explicitly integrate crop-specific yield and quality responses to OPV-induced shading, enabling a more comprehensive assessment of trade-offs between electricity generation and agricultural productivity. In particular, coupling energy system modelling with agronomic models would allow for optimized system designs that balance both objectives.

Furthermore, seasonal dynamics of light availability and crop growth should be considered to better capture the temporal variability of both energy production and agricultural outcomes.

In consideration of the issue of self-consumption, the implementation of a battery energy storage system would constitute a promising avenue for research within the context of a local system. This is particularly salient given the system's potential to enhance both energy and economic efficiency. Studies have demonstrated that this approach can lead to a substantial enhancement in energy autonomy [71].

To support the establishment of effective policies and legal frameworks, socio-economic research is necessary to understand which investment conditions farmers are willing to accept in regard to the installation of OPV.

Conclusion

This study evaluates the technical and economic potential of integrating OPV into greenhouse structures across the EU. With a total greenhouse surface area of approximately 2,075 km^2, the sector provides a substantial and still expanding basis for decentralized renewable electricity generation [10]. Depending on deployment intensity and module performance, the estimated electricity generation potential ranges from 14.3 TWh $year^{-1}$ under conservative assumptions (10% occupancy, 63 W m^{-2}) up to 131.5 TWh $year^{-1}$ under more advanced scenarios (40% occupancy, 145 W m^{-2}), decreasing to approximately 11–105 TWh $year^{-1}$ under assumptions of significant performance losses.

At the regional level, OPV potential is highly concentrated, with the ten highest-potential NUTS-3 regions accounting for more than 55% of the total European OPV greenhouse potential. Across the annual-balance demand comparison, OPV systems can make a substantial contribution to greenhouse electricity demand. Even in the most conservative technical scenario, assuming 10% rooftop occupancy and 63 W m^{-2} module capacity, simulated annual OPV generation exceeds allocated annual greenhouse electricity demand in 1,074 of 1,117 NUTS-3 regions, corresponding to 96.2% of all regions. At 25% rooftop occupancy, this share increases to more than 99% across module-capacity assumptions, and in the highest technical scenario, assuming 40% rooftop occupancy and 145 W m^{-2}, annual-balance coverage is achieved in 1,116 regions, corresponding to 99.9%.

In contrast, the contribution to total regional electricity demand remains more limited and is concentrated in a small number of high-potential regions, primarily in Southern Europe. Higher occupancy levels must also be considered carefully, as increasing shading may negatively affect crop yields. Future developments in semi-transparent OPV modules may further improve the balance between electricity generation and crop light availability, although this aspect was not quantified in the present analysis.

From an economic perspective, the results underline the importance of technological progress and scaling effects. Under current high-cost assumptions, LCOE values range from 0.13 to 0.46 € kWh^{-1} across regions and module-capacity scenarios, with mean values of 0.38 € kWh^{-1} for 63 W m^{-2} and 0.20 € kWh^{-1} for 145 W m^{-2}. Under industrial-scale manufacturing assumptions, LCOE decreases to 0.02–0.05 € kWh^{-1}, corresponding to mean values of 0.04 and 0.03 € kWh^{-1} for 63 and 145 W m^{-2}, respectively. These values indicate that OPV systems can approach cost levels comparable to established and emerging PV technologies under favorable regional, stability, and financing conditions.

The sensitivity analyses show that degradation, lifetime, and discount-rate assumptions substantially affect absolute LCOE levels. In the current high-cost scenario at 63 W m^{-2}, mean LCOE increases from 0.377 € kWh^{-1} under baseline degradation to 0.539 € kWh^{-1} under the conservative degradation scenario, with regional values reaching up to 0.700 € kWh^{-1}. In the industrial-scale 100 GW scenario at 145 W m^{-2}, mean LCOE increases from 0.030 to 0.043 € kWh^{-1} under the same degradation assumptions. Discount-rate sensitivity shows a similar pattern: for the current high-cost scenario at 63 W m^{-2}, mean LCOE increases from 0.332 € kWh^{-1} at 5% to 0.450 € kWh^{-1} at 10%, while the industrial-scale 145 W m^{-2} scenario remains within 0.027–0.035 € kWh^{-1}. These results confirm that large-scale manufacturing and higher module capacity substantially improve economic performance, while long-term OPV stability remains critical for real-world feasibility.

These findings should be interpreted within the context of the study's key limitations. In particular, diurnal and seasonal load profiles, installation-specific environmental conditions, and crop-specific impacts are not explicitly modelled. These factors may significantly influence both system performance and economic outcomes under real-world conditions.

Overall, OPV integration in greenhouses represents a space-efficient and highly adaptable pathway for expanding solar capacity without requiring additional land. Its unique material properties, particularly semi-transparency and flexibility, position OPV as a promising technology at the interface of energy and agriculture. Future research should focus on empirical validation, crop-specific assessments, and improved modelling of demand, degradation and system performance under real operating conditions.

CRediT authorship contribution statement

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

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. . OPV module parameterization used in RESKit

RESKit simulations module-level parameter set according to manufacturer datasheet.

Parameter	Unit	Value used
Nominal operating cell temperature	°C	45
Module area	m^2	0.872
Short-circuit current at reference conditions	A	1.63
Open-circuit voltage at reference conditions	V	56.1
Current at maximum power point	A	1.32
Voltage at maximum power point	V	43.4

Appendix B. . Scenario-specific results

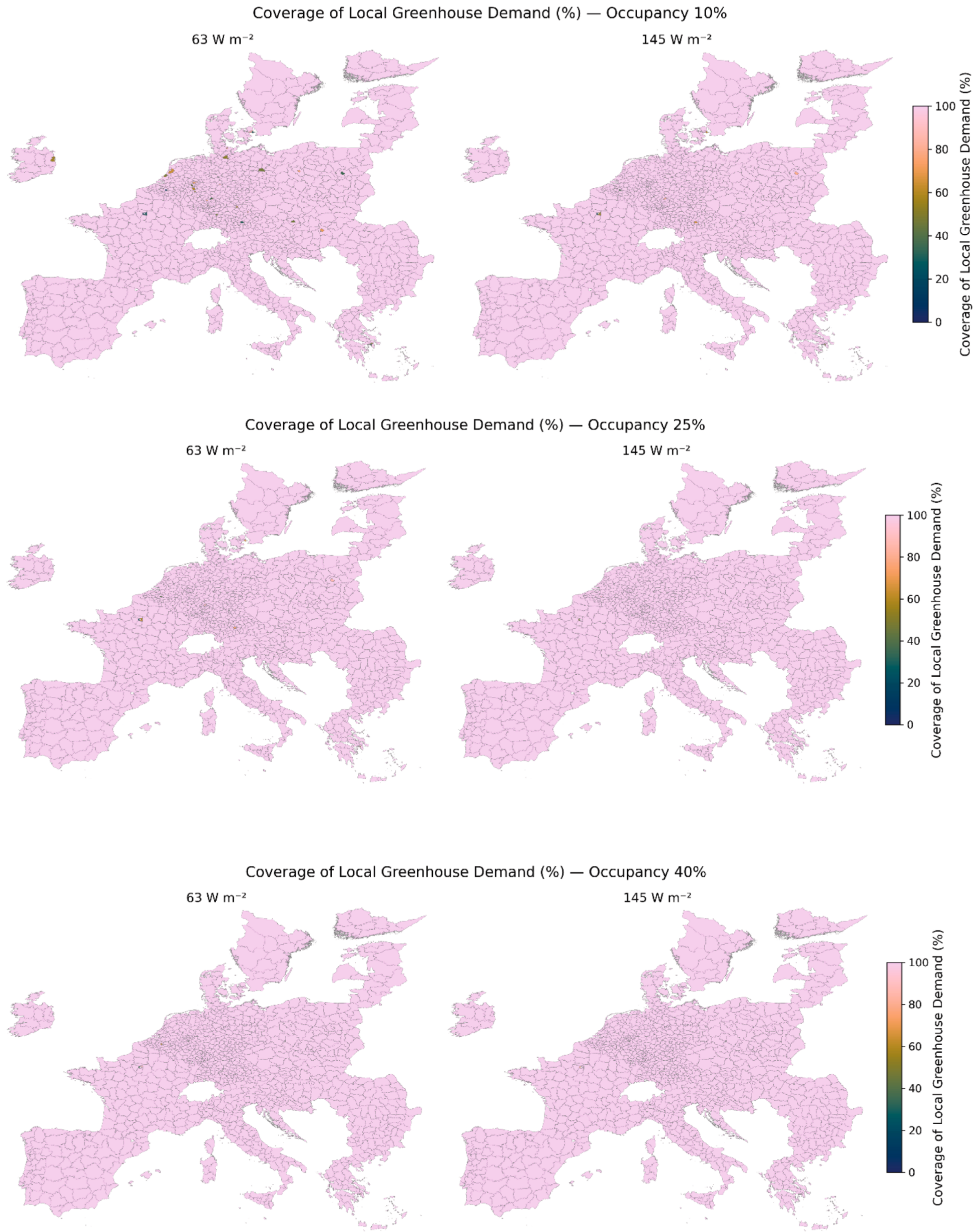

Fig. 13. Mapping the coverage of local greenhouse demand in the EU depending on capacity density and occupancy

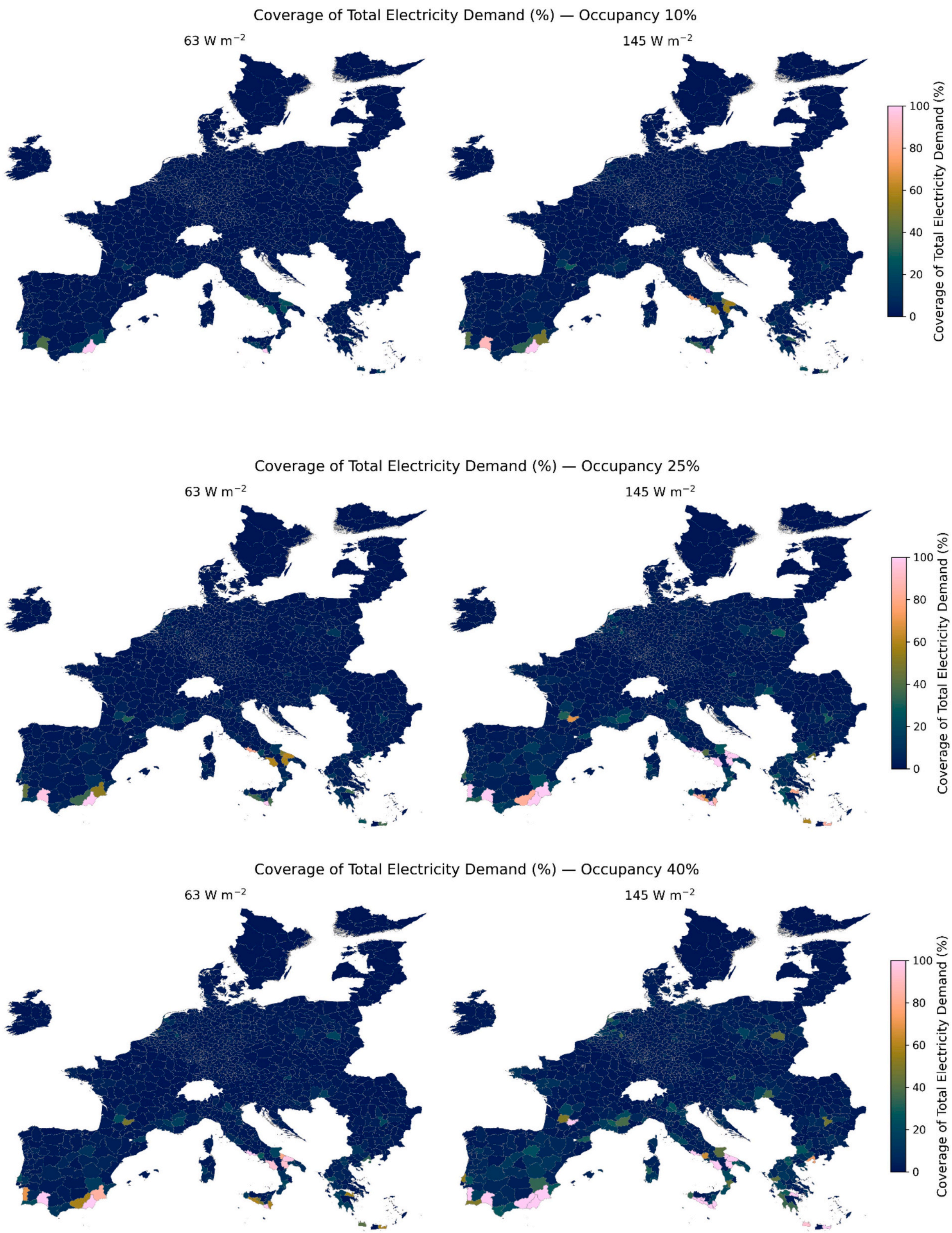

Fig. 14. Mapping the coverage of the total regional electricity demand in the EU depending on capacity density and occupancy

Data availability

Data will be made available on request.

References

[1] FAO, Greenhouse gas emissions from agrifood systems – Global, regional and country trends, 2000–2022, in FAOSTAT Analytical Brief, No. 94. 2024, FAO: Rome.

[2] Zhou D, et al. Towards delivering on the sustainable development goals in greenhouse production systems. Resour Conserv Recycl 2021;169:105379.
[3] La Notte L, et al. Hybrid and organic photovoltaics for greenhouse applications. Appl Energy 2020;278:115582.
[4] Golzar F, et al. A novel integrated framework to evaluate greenhouse energy demand and crop yield production. Renew Sustain Energy Rev 2018;96:487–501.
[5] Cossu M, et al. Agricultural sustainability estimation of the European photovoltaic greenhouses. Eur J Agron 2020;118:126074.
[6] Gorjian S, et al. A review on opportunities for implementation of solar energy technologies in agricultural greenhouses. J Clean Prod 2021;285:124807.
[7] Hassanien RHE, Li M, Dong Lin W. Advanced applications of solar energy in agricultural greenhouses. Renew Sustain Energy Rev 2016;54:989–1001.
[8] Lu L, et al. Comprehensive review on the application of inorganic and organic photovoltaics as greenhouse shading materials. Sustainable Energy Technol Assess 2022;52:102077.
[9] Azzopardi B, et al. Economic assessment of solar electricity production from organic-based photovoltaic modules in a domestic environment. Energ Environ Sci 2011;4(10):3741–53.
[10] Tong X, et al. Global area boom for greenhouse cultivation revealed by satellite mapping. Nat Food 2024;5(6):513–23.
[11] Schallenberg-Rodriguez J, Rodrigo-Bello J-J, Río-Gamero BD. Agrivoltaic: how much electricity could photovoltaic greenhouses supply? Energy Rep 2023;9: 5420–31.
[12] Toledo C, et al. Photovoltaic technology as a tool for ecosystem recovery: a case study for the Mar Menor coastal lagoon. Appl Energy 2024;356:122350.
[13] Friman Peretz M, et al. Testing organic photovoltaic modules for application as greenhouse cover or shading element. Biosyst Eng 2019;184:24–36.
[14] Waller R, et al. Semi-transparent organic photovoltaics applied as greenhouse shade for spring and summer tomato production in arid climate. Agronomy 2021; 11(6):1152.
[15] Cossu M, et al. Yield response and physiological adaptation of green bean to photovoltaic greenhouses. Front Plant Sci 2021;12.
[16] Waller R, et al. Evaluating the performance of flexible, semi-transparent large-area organic photovoltaic arrays deployed on a greenhouse. AgriEngineering 2022;4(4): 969–92.
[17] Emam Hassanien RH, et al. Review on photovoltaic greenhouses for sustainable food and energy production. Sol Energy 2025;302:114030.
[18] Lozbergs A, Vartukapteinis K, Kancevica L. A review on semi transparent solar panels application on greenhouse rooftops. Research for Rural Development 2024; 30:271–6.
[19] Song W, et al. Semi-transparent organic photovoltaics for agrivoltaic applications. Nano Energy 2023;116:108805.
[20] Friman-Peretz M, 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.
[21] Friman-Peretz M, 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.
[22] Tsao C-S, et al. Lab-to-Fab development and long-term greenhouse test of stable flexible semitransparent organic photovoltaic module. Mater Today Energy 2023; 36:101340.
[23] Magadley E, et al. Outdoor behaviour of organic photovoltaics on a greenhouse roof. Sustainable Energy Technol Assess 2020;37:100641.
[24] Magadley E, et al. Integrating organic photovoltaics (OPVs) into greenhouses: electrical performance and lifetimes of OPVs. Int J Sustain Energ 2022;41(8): 1005–20.
[25] Ryberg DS, et al. The future of European onshore wind energy potential: detailed distribution and simulation of advanced turbine designs. Energy 2019;182: 1222–38.
[26] Winkler C, et al. Participatory mapping of local green hydrogen cost-potentials in Sub-Saharan Africa. Int J Hydrogen Energy 2025;112:289–321.
[27] Winkler C, et al. High-Resolution rooftop photovoltaic potential assessment for a resilient energy system in Ukraine. Energy Convers Manage: X 2025;28:101242.
[28] Hersbach H, et al. ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS) 2018.
[29] Solargis, S., Global Solar Atlas 2.0. A free web-based application developed and operated by the company Solargis sro on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). See https://globalsolaratlas. info, 2023.
[30] Aroca-Delgado R, et al. Morphology, yield and quality of greenhouse tomato cultivation with flexible photovoltaic rooftop panels (Almería-Spain). Sci Hortic 2019;257:108768.
[31] Cossu M, et al. Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity. Appl Energy 2014;133:89–100.
[32] Laub M, et al. 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.
[33] Heliatek. Technical Datasheet: HeliaSol® 436-2000. 01.03.2026; Available from: https://www.heliatek.com/fileadmin/user_upload/pdf_documents/Datasheet_HeliaSol_436-2000_Website_EN.pdf.
[34] Basu R, et al. Large-area organic photovoltaic modules with 14.5% certified world record efficiency. Joule 2024;8(4):970–8.
[35] Valera, D., et al., Greenhouse Agriculture in Almeria. A comprehensive techno-economic analysis. 2016.
[36] Fernández-García MS, et al. Numerical simulation of multi-span greenhouse structures. Agriculture 2020;10(11):499.
[37] Maraveas C, et al. Agricultural greenhouses: resource management technologies and perspectives for zero greenhouse gas emissions. Agriculture 2023;13(7):1464.
[38] von Elsner B, et al. Review of structural and functional characteristics of greenhouses in european union countries, part ii: typical designs. J Agric Eng Res 2000;75(2):111–26.
[39] Paris B, 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.
[40] Bibbiani C, et al. Wood biomass as sustainable energy for greenhouses heating in Italy. Agric Agric Sci Procedia 2016;8:637–45.
[41] Yano A, Cossu M. Energy sustainable greenhouse crop cultivation using photovoltaic technologies. Renew Sustain Energy Rev 2019;109:116–37.
[42] Campiglia, et al. Energy balance of intensive vegetable cropping systems in central Italy. Acta Hortic 2007;747:185–91.
[43] Stanghellini, C., Baptista, F., Eriksson, E., Gilli, C., Giuffrida, F., Kempkes, F. L. K., Munoz, P., Stepowska, A., & Montero, J. I., Sensible use of primary energy in organic greenhouse production. 2016: BioGreenhouse.
[44] Baptista F, et al. Greenhouse energy consumption for tomato production in the Iberian Peninsula countries. Acta Hortic 2012;952:409–16.
[45] Tataraki K, et al. Cogeneration economics for greenhouses in europe. Energies 2020;13(13):3373.
[46] JRC, EU energy atlas - energy demand 2019. 2023, European Commission, Joint Research Centre (JRC).
[47] Machui F, et al. Cost analysis of roll-to-roll fabricated ITO free single and tandem organic solar modules based on data from manufacture. Energ Environ Sci 2014;7 (9):2792–802.
[48] Schindele S, et al. Implementation of agrophotovoltaics: techno-economic analysis of the price-performance ratio and its policy implications. Appl Energy 2020;265: 114737.
[49] IEA, Projected Costs of Generating Electricity 2020. 2020, Paris: International Energy Agency.
[50] Luo W, et al. Long-term outdoor study of an organic photovoltaic module for building integration. Prog Photovolt Res Appl 2024;32(7):481–91.
[51] Heliatek GmbH, Warranty Conditions for HeliaSol® Photovoltaic Modules (Version 1.3). 2021, Heliatek GmbH: Dresden, Germany.
[52] Krebs FC, et al. A round robin study of flexible large-area roll-to-roll processed polymer solar cell modules. Sol Energy Mater Sol Cells 2009;93(11):1968–77.
[53] Emmott CJM, et al. In-situ, long-term operational stability of organic photovoltaics for off-grid applications in Africa. Sol Energy Mater Sol Cells 2016;149:284–93.
[54] Soares GA, et al. Outdoor performance of organic photovoltaics at two different locations: a comparison of degradation and the effect of condensation. J Renewable Sustainable Energy 2020;12(6).
[55] Zhang Y, et al. Current status of outdoor lifetime testing of organic photovoltaics. Adv Sci (Weinh) 2018;5(8):1800434.
[56] Magadley E, et al. Organic photovoltaic modules integrated inside and outside a polytunnel roof. Renew Energy 2022;182:163–71.
[57] Liu S, et al. Analyzing the outdoor degradation behavior of organic solar modules in North China. J Mater Chem A 2024;12(24):14688–97.
[58] IRENA, Renewable power generation costs in 2023. 2024, International Renewable Energy Agency: Abu Dhabi.
[59] Short W, Packey DJ, Holt T. A manual for the economic evaluation of energy efficiency and renewable energy technologiesNREL/TP-462-5173. Golden CO: National Renewable Energy Laboratory; 1995.
[60] Wagner J, et al. Factors influencing the willingness to use agrivoltaics: a quantitative study among German farmers. Appl Energy 2024;361:122934.
[61] Green MA, et al. Solar cell efficiency tables (Version 63). Prog Photovolt Res Appl 2024;32(1):3–13.
[62] Kim SY, et al. Semitransparent organic and perovskite photovoltaics for agrivoltaic applications. Energy Adv 2025;4(1):37–54.
[63] Fraunhofer ISE, Study: Levelized Cost of Electricity – Renewable Energy Technologies. 2024, Fraunhofer Institute for Solar Energy Systems (ISE).
[64] Intal D, Ebong AU. Thin-film solar photovoltaics: trends and future directions. Renew Sustain Energy Rev 2026;226:116464.
[65] Kakoulaki G, et al. Communication on the potential of applied PV in the European Union: Rooftops, reservoirs, roads (R3). EPJ Photovolt 2024;15:2.
[66] IEA, IEA (2021), The Role of Critical Minerals in Clean Energy Transitions, IEA, Editor. 2021: Paris.
[67] Tsang MP, Sonnemann GW, Bassani DM. Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. Sol Energy Mater Sol Cells 2016;156: 37–48.
[68] Gärtner S, et al. Eco-friendly fabrication of 4% efficient organic solar cells from surfactant-free P3HT:ICBA nanoparticle dispersions. Adv Mater 2014;26(38): 6653–7.
[69] Colsmann A, Röhm H, Sprau C. Shining light on organic solar cells. Sol RRL 2020;4 (6):2000015.
[70] Sarr A, et al. A new approach for modelling photovoltaic panel configuration maximizing crop yield and photovoltaic array outputs in agrivoltaics systems. Energ Conver Manage 2024;309:118436.
[71] Gholami M, et al. Enhancing energy autonomy of greenhouses with semi-transparent photovoltaic systems through a comparative study of battery storage systems. Sci Rep 2025;15(1):2213.