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AIoT for Cascade Hydroponic Greenhouses with Solar Energy Harvesting and Water Regeneration System

# D2.1-Survey of advances in agrovoltaic infrastructure in greenhouses

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# 1 Introduction

The increasing demand for sustainable agricultural practices and clean energy sources has led to the emergence of integrated systems that combine food production with renewable energy generation. Among these, agrivoltaics (also known as agrophotovoltaics) has become a promising approach, enabling the dual use of land for both agriculture and solar energy harvesting. This concept is particularly relevant in contexts where land availability is limited or where agricultural productivity must coexist with environmental goals such as reducing greenhouse gas emissions and improving energy resilience.

Greenhouses are a key application area for agrivoltaic systems, offering controlled environments where crops can be grown efficiently. Integrating photovoltaic infrastructure into greenhouse designs not only allows for the continued production of high-value crops, but also enables the generation of electricity on-site. This dual functionality enhances the sustainability and economic viability of agricultural operations. In many cases, the energy produced is sufficient to meet the internal demands of the greenhouse, such as lighting, heating, cooling, and irrigation systems, contributing to energy self-sufficiency. In optimal scenarios, surplus electricity can even be fed into the grid, providing an additional revenue stream for farmers and greenhouse operators.

Furthermore, the implementation of agrivoltaic systems in greenhouses requires careful consideration of factors such as light transmission, crop species compatibility, structural design, and energy conversion efficiency. Recent technological advances have focused on developing semi-transparent photovoltaic materials, dynamic shading systems, and integrated control algorithms that balance energy generation with optimal plant growth conditions. These innovations aim to minimize the trade-offs between shading from solar panels and the light requirements of crops, which vary significantly between species and growth stages.

One of the main challenges in agrivoltaic greenhouse design lies in optimizing the spatial and spectral distribution of sunlight. While photovoltaic panels convert solar radiation into electricity, they also reduce the amount of light available to crops beneath them. This can be mitigated through the use of semi-transparent or spectrally selective panels that filter specific wavelengths of light, allowing the rest to pass through to the plants. Additionally, dynamic or movable panel systems can adjust their position based on real-time environmental conditions or plant needs, thereby maximizing both crop yield and energy output throughout the day and across seasons.

Another critical aspect is the integration of digital technologies and control systems. Precision agriculture tools, including sensors, data analytics platforms, and artificial intelligence algorithms, can be employed to monitor and adjust environmental variables such as temperature, humidity, $CO_2$ levels, and light intensity. These systems can be linked to photovoltaic power management systems, enabling adaptive strategies that prioritize either crop health or energy production depending on operational goals and real-time conditions. The development of digital twins (virtual replicas of the physical greenhouse environment) further enhances decision-making by simulating outcomes of

different configurations and control strategies before implementation.

The potential benefits of agrivoltaic greenhouses extend beyond energy efficiency and crop productivity. From an environmental perspective, these systems contribute to the decarbonization of agriculture by reducing reliance on fossil fuels and lowering the carbon footprint of food production. Economically, they offer opportunities for diversification of income sources, particularly in rural areas facing economic challenges. Socially, they support the transition toward more sustainable and resilient food systems, which is critical in the face of climate change, resource scarcity, and population growth.

Despite these advantages, the widespread adoption of agrivoltaic systems in greenhouses faces several barriers. Initial capital investment for photovoltaic infrastructure and control systems can be substantial, requiring financial support mechanisms or public-private partnerships. Additionally, there is a need for interdisciplinary collaboration between agronomists, engineers, architects, and energy specialists to ensure that system designs are tailored to local conditions and specific crop requirements. Regulatory frameworks and policy incentives also play a pivotal role in promoting or hindering the deployment of such technologies, and must evolve to reflect the integrated nature of these systems.

In the context of this project, the focus is on the development and evaluation of a parametrized digital twin for an agrivoltaic greenhouse. This digital representation will be used to simulate various configurations, assess energy balances, and analyze the impact of different photovoltaic technologies on crop growth and greenhouse performance. By leveraging computational tools and real-world data, the aim is to provide actionable insights that support the design and operation of optimized agrivoltaic greenhouses.

This report presents a comprehensive survey of recent advances in agrivoltaic infrastructure applied to greenhouse systems. The aim is to provide a clear overview of the progress made to date, highlight existing challenges, and propose directions for future research and development in this emerging interdisciplinary field.

# 2 Methodology

This section describes the methodology used to conduct the systematic literature survey on agrivoltaic infrastructures in greenhouses. The process was carried out according to established practice in systematic reviews and includes the definition of research questions, the inclusion and exclusion criteria, the search strategy, and the data extraction procedure. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to ensure transparency and reproducibility.

## 2.1 Research questions

The main goal of this survey is to identify and analyze all advances in agrivoltaic infrastructures implemented in greenhouses, as well as to extract valuable information from open-field agrivoltaic studies relevant for greenhouse applications. The research

questions guiding this study are as follows:

- RQ1. What are the main types of greenhouses used in agrivoltaics?
- RQ2. What photovoltaic technologies and panel configurations are most commonly used in agrivoltaics?
- RQ3. What crops are grown in agrivoltais systems?
- RQ4. What regulatory, technical, or legal frameworks are used for the design and implementation of agrivoltaic systems?

These questions aim to synthesize key aspect of agrivoltaics integration in protected cultivation systems and support future development if energy-agriculture synergy greenhouses.

## 2.2 Inclusion and exclusion criteria.

The review included only peer-reviewed journal articles published in English between 2010 and 2025. The selected publications addressed real implementations or simulation-based studies on agrivoltaic systems. Although the main focus was on greenhouse applications, studies on open-field agrivoltaics were also considered, provided they contributed relevant data on panel types, configurations, or system performance that could be extrapolated to greenhouse contexts.

Exclusion criteria include:

- Conference papers or non-peer-review sources.
- Articles not available in full text.
- Studies not related to agrivoltaic applications.
- Duplicated entries across databases.

A total of 187 articles were initially identified. After duplicate removal and abstract screening, 139 articles were assessed. A total of 24 were discarded during full-text evaluation, leading to a final dataset of 115 eligible articles.

## 2.3 Data sources and search strategy.

The literature search was conducted manually using three major academic databases: Google Scholar, Scopus and Web of Science.

The search string was designed to capture the relevant domain and combined keywords such as: "agrophotovoltaic" OR "agrivoltaic" OR "pv greenhouse" OR "photovoltaic greenhouse".

The search period covered the last 15 years, from 2010 to 2025.

## 2.4 Article selection and review protocol.

Figure 1 shows the PRISMA flow diagram used to structure the article selection process. Of the 187 documents retrieved. 73 where from Google Scholar, 46 from Scopus and 68 from Web of Science; 48 duplicates were removed. After abstract screening, 139 articles remained, of which 24 were excluded following a full text review. The final corpus included 115 scientific articles relevant to agrivoltaics systems.

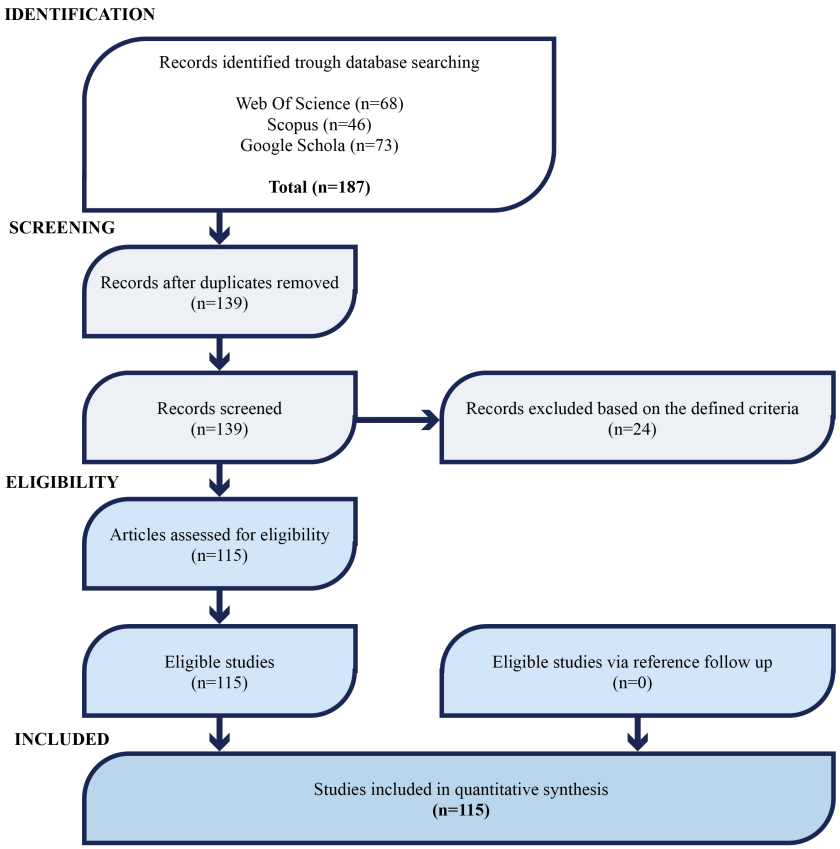


Figure 1: PRISMA flow diagram

## 2.5 Data extraction process

The data extraction process was defined to align with the research questions. For each selected article, the following attributes were recorded:

- Title, authors and year of publication.
- Country or location of the agrivoltaic system
- Type of greenhouse system (e.g., tunnel, Venlo-type, semi-closed, retrofit).

- Configuration of the photovoltaic installation (e.g., roof-integration, fixed or tracking systems).
- Type of photovoltaic modules (e.g., mono-crystalline, bifacial, semitransparent).
- Crops grown beneath the photovoltaic structure.
- Referenced policies or regulations including local or national frameworks.

The extracted data were organized into a structured dataset that allowed for the generation of analytical visualizations, including the number of eligible papers published per year and the geographical distribution of publications per country, as shown in Figures 2 and 3. As can be seen, most of the related papers were published in 2024.Furthermore, the graph illustrates the growing interest in agrivoltaics, as the number of publications has been steadily increasing. China and Italy are the countries with the highest number of published papers on agrivoltaics, followed by Spain and Japan.

# 3 Types of photovoltaic greenhouses

The reviewed literature includes a broad variety of photovoltaic greenhouse (PVG) and agrivoltaic system (AVS) typologies, categorized according to structure type, PV integration method, and installation environment (greenhouse or open field). This section details these findings.

Regarding PV greenhouse types and structures, the following main types have been identified:

- **Fixed PV Greenhouses:** Include Venlo-type, multi-span, Gothic-arch, tunnel, single-span, gable roof, pitched roof, mono-pitched, and quonset greenhouses.
- **Dynamic PV Greenhouses:** Several articles describe PV modules with adjustable tilt or dynamic internal shading systems (e.g., venetian blinds).
- **Semi-transparent PV Greenhouses:** Integration of semi-transparent OPV, STPV, and perovskite panels is frequent, both as static and dynamic installations.
- **Modular and Experimental Prototypes:** Some articles focus on experimental mini-greenhouses or modular structures (e.g., NZEB designs, raceway greenhouses for microalgae).
- **Chinese Solar Greenhouses (CSG):** Arched, east-west oriented, and passive solar-based structures are frequently described (non-PV in some cases).
- **Polytunnels:** Common in studies using semi-transparent or OPV modules, sometimes installed inside the structure above the crop canopy.

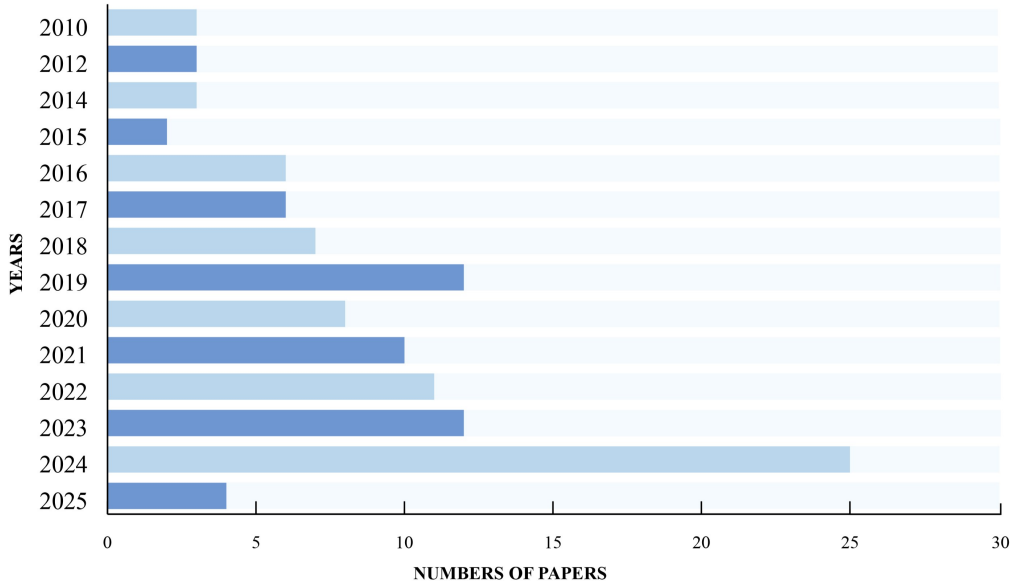


Figure 2: Number of eligible papers published each year

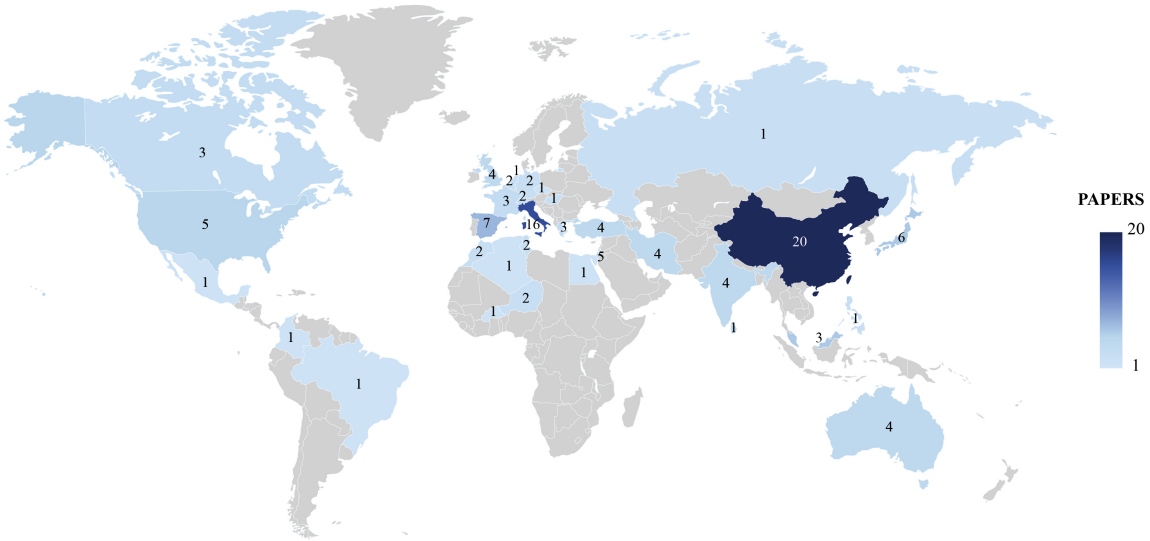


Figure 3: Number of published papers presenting agrivoltaic systems per country.

There are also different types of photovoltaic Integration:

- **Roof-Mounted Panels** The most common integration, often with checkerboard, straight-line, or crisscross layouts. Includes both opaque and semi-transparent panels.
- **Internal Shading Systems:** Some studies feature PV modules installed internally as shading elements (e.g., venetian blinds or above canopy installations).
- **Dynamic Tracking Systems:** Both single-axis and two-axis sun-tracking mechanisms are described (mostly in simulation studies or open-field AVS).
- **Building-Integrated PV (BIPV):** Described particularly in smart or hybrid greenhouse models.
- **PV/Thermal Systems (PVT, CPVT):** Photovoltaic-thermal hybrid integration is discussed in multiple review papers.

Regarding the agrivoltaic systems in open fields, the following varieties have been identified:

- **Elevated Structures:** AVS mounted 2–3.6 m above the ground, used for crops like kiwifruit, wheat, maize, and others.
- **Tracker-Based Systems:** Include 2-axis sun-tracking AVS systems (e.g., Italy's Po Valley).
- **Inter-row PV Placement:** Ground-mounted AVS with rows of panels between crop lines.
- **Integrated with Animal Husbandry:** At least one study includes rabbit production within an AVS.
- **Mixed-use Systems:** Some installations combine open-field and greenhouse integration (e.g., Sardinia installation).

The technologies in these types of systems include include OPV, STPV, BIPV, PVT, CPVT, Fresnel lenses, LSCs, and mirror-based shading systems.

It is also important to mention that some of the reviewed articles included reviews and also simulation studies. In review articles many references are systematic or thematic reviews describing multiple systems without detailing specific case studies. Conversely, simulation-based studies focused on modeling PVG performance, including microclimate impact, energy balance, or control strategies (e.g., fuzzy logic).

Lastly, the thorough description of the information regarding the types of photovoltaic greenhouses for each reviewed paper is provided in Table 1

Table 1: Types of photovoltaic greenhouses in the reviewed works.

| **Reference** | **Observations** |
|---|---|
| [1] | Tunnel greenhouse with a curved shape. The study focuses on a prototype of a photovoltaic (PV) greenhouse tunnel. Not an open-field agrivoltaic system |
| [2] | The article does not describe a specific photovoltaic greenhouse installation. It mentions various agrivoltaic installations, including: Open-field agrivoltaics, greenhouse-integrated photovoltaic systems, different solar PV module technologies used in agrivoltaics. Some reviewed studies focus on greenhouse PV systems, but no singular case study is detailed. |
| [3] | No specific photovoltaic greenhouse is described in the article. The article classifies agrivoltaic (AV) systems into: Open-field agrivoltaics, Overhead agrivoltaics, Vertical bifacial agrivoltaics, and PV greenhouses. Greenhouse agrivoltaics are mentioned, but not detailed as a specific case study. |
| [4] | The study examines two types of greenhouses with photovoltaic (PV) panels on their roofs: Asymmetric greenhouse (1 hectare, six asymmetrical modules), Venlo greenhouse (1 hectare, 10 Venlo-type modules). Not an open-field agrivoltaic system. |
| [5] | Prototype photovoltaic greenhouse with fixed horizontal PV panels. The system allows for passive variation of shading by exploiting the natural change in the elevation angle of the sun's rays. Not an open-field agrivoltaic system. |
| [6] | Prototype photovoltaic greenhouse with variable shading via rotating PV panels. The system allows dynamic adjustment of shading to optimize both energy production and agricultural productivity. Not an open-field agrivoltaic system. |
| [7] | The article does not describe a specific PV greenhouse. It reviews various agrivoltaic setups, including: Open-field agrivoltaics, animal-integrated agrivoltaics, and solar greenhouses. Discusses semi-transparent, opaque, and transparent PV modules mounted on greenhouse roofs. |
| [8] | The article does not describe a specific photovoltaic greenhouse installation. It classifies agrivoltaic systems into: Open-field agrivoltaics (ground-mounted, pergolas, elevated structures), greenhouse-integrated agrivoltaics (semi-transparent PV, rooftop PV on greenhouses), and animal-integrated agrivoltaics (livestock grazing under PV structures) Vertical agrivoltaic systems. Mentions various greenhouse PV applications but no specific case study is detailed. |
| [9] | The article does not describe a specific photovoltaic greenhouse but reviews multiple solar greenhouse technologies, including: Passive solar greenhouses (PSGs), greenhouse-integrated photovoltaic (GHIPV) systems, greenhouse-integrated photovoltaic-thermal (GHIPVT) systems, greenhouse-integrated solar thermal collectors, and solar greenhouses with thermal energy storage (TES) |
| [10] | The article discusses greenhouse environments and their optimisation, including photovoltaic integration. It mentions agrivoltaic systems but does not specify the exact type of photovoltaic greenhouse. |
| [11] | Greenhouse-integrated photovoltaic (GHIPV) system using semitransparent organic solar cells (OSCs). Designed to achieve Net Zero Energy (NZE) greenhouses. Not an open-field agrivoltaic system. |
| [12] | Greenhouse-integrated photovoltaic (GHIPV) systems. Describes passive and active solar greenhouses: Passive solar greenhouses – Utilize greenhouse materials and design for solar heating; Active solar greenhouses – Incorporate photovoltaic panels (PVs), solar thermal collectors, and hybrid systems. |

| Reference | Observations |
|---|---|
| [13] | The article does not describe a specific photovoltaic greenhouse but reviews multiple strategies for zero-emission, zero-energy greenhouses. Key greenhouse technologies discussed: Greenhouse-integrated photovoltaic (GHIPV) systems, smart greenhouses with IoT and AI-based energy optimization, renewable energy-powered greenhouses (solar, geothermal, wind), and thermal energy storage (TES) integrated greenhouses. No open-field agrivoltaic systems (such as ground-mounted, pergolas, or canopies) are discussed. |
| [14] | The study evaluates four PVG types with different photovoltaic cover ratios (PVR): Gable roof (PVR: 25%) – Half of the south-facing roof covered with PV panels. Gable roof (PVR: 50%) – Entire south-facing roof covered with PV panels. Venlo-type (PVR: 60%) – Asymmetric roof with a wider south-facing PV-covered side. Mono-pitched roof (PVR: 100%) – Entire south-facing roof covered with PV panels. |
| [15] | Chinese Solar Greenhouses (CSGs) integrated with dynamic agrivoltaic systems. The study describes a large-scale agrivoltaic project incorporating dynamic photovoltaic tracking technology into CSGs. Two configurations of dynamic photovoltaic tracking are evaluated: Solar Tracking (ST) – maximizes electricity generation. Reverse Tracking (RT) – minimizes shading effects on crops. Not an open-field agrivoltaic installation. |
| [16] | Photovoltaic greenhouses (PVGs) with envelope-integrated PV and protected crops. Describes both static and dynamic roof-mounted systems. Does not focus on open-field agrivoltaics like canopies or elevated pergolas (except in comparative contexts). |
| [17] | Closed AVS (Agrivoltaic Systems): PV greenhouses with integrated or semi-transparent PV roofs. Open AVS: Ground-mounted systems with elevated or fixed PV modules. Multiple AVS types were discussed, including: PV greenhouses (fully closed structures), and elevated open-field PV arrays for horticulture. No applications yet for cereal crops or vertical AVS in West Africa |
| [18] | General Classification: Closed Agrivoltaic Systems– PV modules installed on greenhouses; Open Agrivoltaic Systems – PV modules elevated or ground-mounted in open fields. The article focuses primarily on open agrivoltaic systems. Greenhouse applications are only briefly referenced. |
| [19] | Type: Open-field agrivoltaic system. Mounting type: Elevated structure (not a closed greenhouse). No greenhouse infrastructure is used — crop cultivation occurs under PV panels on open agricultural land. |
| [20] | This is a review article, describing multiple types: Stilt-mounted PV arrays (n = 33), greenhouse-mounted PV arrays (n = 15), and interspersed PV arrays (n = 2) |
| [21] | Type: Agrivoltaic system in open field. Structure: Panels elevated above soybean crops. No greenhouse structure was used |
| [22] | Not a traditional greenhouse. The article discusses agrophotovoltaic (APV) systems primarily as elevated field installations (i.e., solar panels elevated above open-field crops). Types include: Elevated structures with ground clearance of 2–5 meters, solar tracking structures, and some pilot greenhouse integrations are referenced (e.g., Li et al. 2018), but not the focus. |
| [23] | Even-span type greenhouse. Greenhouse structure with East–West orientation and four construction units. Only two construction units are utilized in the study. |
| [24] | Pitched-roof greenhouse. (Not an open-field agrivoltaic installation) |

| Reference | Observations |
|---|---|
| [25] | Not specifically greenhouse-type structures, but various agrivoltaic installations, some with elevated structures, including: Elevated structures (3m and 8m height), pilot projects with integration into aquaponics or agroecological farming, and agricultural installations with crops grown underneath panels. Installations Mentioned: Ecolume Project (Ibimirim - PE), Pankará Village (Itacuruba - PE), CCampo Cooperative (Santarém - PA), UFAL Pilot Project (Alagoas - AL), and Fotovoltaica UFSC R&D Agrivoltaic Project (Florianópolis - SC) |
| [26] | Dynamic photovoltaic greenhouse with adjustable panels (Not an open-field agrivoltaic installation) |
| [27] | The article refers to general greenhouse applications using PV technology and does not focus on a single specific greenhouse type. However, it includes examples of roof-mounted flexible PV panels and PV-powered climate control systems. |
| [28] | Not a specific greenhouse installation. The article analyzes materials intended for use in semi-transparent photovoltaic greenhouses, particularly focusing on glass-glass (GG) and glass-transparent backsheet (GTB) modules. |
| [29] | The article analyzes four types of commercial photovoltaic greenhouses. All installations are located in open fields, used for greenhouse cultivation, and feature fixed PV arrays on roofs: Type 1: Mono-pitched roof, 100% PV cover ratio, entire roof is PV-covered, and most profitable in energy but least suitable for crops. Type 2: Venlo-type greenhouse, 60% PV cover ratio, asymmetric roof, taller south wall, covered with glass, and tall gutter height (4.5 m) to allow more light. Type 3: Gable roof,50% PV cover ratio, only south-facing roof fully covered with PV modules, covered with plastic cladding, and common and relatively inexpensive. Type 4: Gable roof, 25% PV cover ratio, only upper half of south-facing roof is PV-covered, and considered most agriculturally sustainable of the four |
| [30] | Not explicitly specified as a conventional photovoltaic greenhouse structure. The study refers to indoor horticulture environments where artificial lighting is used, and a portable polycrystalline silicon photovoltaic module is employed for indoor energy harvesting. |
| [31] | Not a greenhouse. The article focuses on agrivoltaic installations in open fields. Type: Ground-mounted agrivoltaic systems |
| [32] | PV-integrated greenhouse with uneven-span structure, roof-mounted solar panels. It is not an open-field agrivoltaic system. |
| [33] | Type 1: Asymmetric greenhouse. Type 2: Venlo-type greenhouse. Both are roof-integrated photovoltaic greenhouses, constructed with glass and simulated under controlled CFD models. |
| [34] | Photovoltaic greenhouse integrated with ecological agriculture. (Not specified if it's on the ground, pergolas, or canopies—focuses on rooftop PV modules integrated with greenhouse structure) |
| [35] | Mono-span greenhouse. Covered with polyethylene plastic. PV panels integrated on 50% of the roof (south-facing) |
| [36] | This is a review article summarizing various types. The described types include: Semi-transparent photovoltaic greenhouses, dynamic photovoltaic greenhouses, greenhouses with flexible panels, tunnel-type greenhouses, and greenhouses with photovoltaic roofs (glass or plastic). The article also references agrivoltaic systems in open fields: Ground-based agrivoltaics and Canopies and elevated structures (e.g., systems proposed by Dupraz et al. and Valle et al.) |
| [37] | Type: Venlo-type greenhouse (glass greenhouse). Structure: Three ridges in a single span, PV panels mounted on south-facing roof only. Location climate: Severe cold region. Other installations mentioned: Not applicable. |

| Reference | Observations |
|---|---|
| [38] | Multiple types are reviewed: PV Greenhouses (explicitly mentioned among fixed AVS types), ground-mounted AVS, stilt-mounted PV modules, rooftop PV AVS, vertical bifacial PV systems, semi-transparent modules, agrivoltaic canopies and tracker-based systems. |
| [39] | Multiple types are discussed. Greenhouses with: Fixed PV modules (straight-line, checkerboard, crisscross); Dynamic PV systems (manual and automatic); Semi-transparent, flexible, and OPV roof structures; Agrivoltaic systems described are all integrated into greenhouse roofs. Open-field systems are not the focus. |
| [40] | Prototype of a dynamic photovoltaic greenhouse with a south-facing asymmetric cross-section and adjustable tilt PV modules. Not in open fields. Not a pergola/canopy. Fully enclosed greenhouse structure made of iron and glass. |
| [41] | Not a traditional greenhouse, but an agrivoltaic installation over a kiwifruit orchard using a roof structure. Structure: Elevated steel structure with translucent PV panels and plastic polycarbonate sheets installed at 3.0 m above the ground. |
| [42] | Single-span Gothic-arch style greenhouse. (Not explicitly classified beyond this description) |
| [43] | Photovoltaic greenhouse with organic photovoltaic modules (OPV) installed inside the structure at gutter height above the crop canopy. Not an open field agrivoltaic installation. |
| [44] | Greenhouse with venetian-blind-type semi-transparent PV modules installed inside the structure. Not a traditional greenhouse PV roof installation; instead, it is a dynamic internal shading system. |
| [45] | Multiple types of greenhouses are described, including: Plastic greenhouses, glass greenhouses, high tunnels (considered as simple plastic greenhouses), and Chinese solar greenhouses with north-wall thermal storage. The article is a review and does not focus on a single installation. |
| [46] | Multi-tunnel greenhouse with semitransparent organic photovoltaic (OPV) modules integrated in the roof. Note: This is not an open field agrivoltaic installation. |
| [47] | Not specifically a single greenhouse; the article is a review of multiple systems and types, including: Venlo-type greenhouses, greenhouses with solar panels on roofs and sides, ,and installations with transparent and semi-transparent PV modules. No open-field agrivoltaic systems are the focus. |
| [48] | High-technology Venlo-type agrophotovoltaic greenhouse. |
| [49] | Plastic greenhouses typical of the Almería region (also called "Almería-type" or "raspa y amagado"). These are closed structures. Some comparisons are also made with gable roof and Venlo greenhouses from other studies. No installations in open fields are described in this article. |
| [50] | Standard greenhouse structure with integrated photovoltaic panels on the roof. It is not specified as a commercial type like Venlo or Tunnel. It is not an agrivoltaic open field installation. |
| [51] | Polytunnel greenhouse with internal installation of PV modules (Not a traditional rooftop PV; modules installed inside the greenhouse above plant canopy) |
| [52] | Not specified This article is a review of various greenhouse design strategies and cooling technologies, including photovoltaic integration, but does not describe a specific installation. |
| [53] | Various types described including: Pitched roof greenhouses, gothic-arch roof greenhouses, venlo-type greenhouses, quonset greenhouses, terraced greenhouses, and mono-pitched and gable structures. Note: Specific categorization for all greenhouses not always specified. |

| Reference | Observations |
|---|---|
| [54] | Photovoltaic cooling greenhouse (Static structure with semi-transparent insect screen and rooftop solar panels) |
| [55] | Multiple types are mentioned as part of the broader concept of AV (agrivoltaic) systems. Greenhouse-integrated systems are considered "closed systems" within AV classifications. The article focuses on both: Open AV systems – overhead structures, rows between crops. Closed AV systems – integrated into greenhouse roofs or walls. |
| [56] | Multi-span greenhouse and plastic tunnel greenhouses; specific types include: PV greenhouses with integrated photovoltaic roofs and solar thermal greenhouses using collectors and thermal storage. Also mentions large-scale demonstration and industrial installations. |
| [57] | Not a greenhouse. Agrivoltaic installation in open fields — ground-mounted system integrating rabbit production. |
| [58] | Three types of PV greenhouses are described: PV plastic greenhouse, PV glass greenhouse, and PV multi-span greenhouse. |
| [59] | Tunnel greenhouse with semi-transparent organic photovoltaic (OPV) modules integrated on the roof. Not specified as a general PV greenhouse type beyond tunnel form. |
| [60] | Dynamic photovoltaic greenhouse. Roof-mounted PV panels with sun-tracking functionality. Simulated installations (no physical experimental installation described) |
| [61] | Mini PV greenhouse, static structure with semi-transparent roof-mounted modules. Prototype designed as a Nearly Zero Energy Building (NZEB) for Mediterranean climates. |
| [62] | Modular greenhouse. Experimental setup using active and passive optical glass rasters. Six modules with different configurations, including growing areas and technological compartments. |
| [63] | Multiple APV configurations including greenhouse-type APV, interspace, and elevated systems: Greenhouse-integrated APV: semi-transparent PV, opaque PV, organic solar cells, luminescent solar concentrators (LSC). Other systems include: elevated structures, vertical bifacial PVs, single-axis tracking arrays. |
| [64] | Raceway-based greenhouse with photovoltaic integration. Not a classical horticultural greenhouse, but an industrial-scale greenhouse for microalgae production, combining CIGS PV panels and raceway cultivation. Integration type: static rooftop PV coverage over raceways inside greenhouses. |
| [65] | Raceway-based greenhouse with photovoltaic integration. Not a classical horticultural greenhouse, but an industrial-scale greenhouse for microalgae production, combining CIGS PV panels and raceway cultivation. Integration type: static rooftop PV coverage over raceways inside greenhouses. |
| [66] | Chinese Solar Greenhouse (CSG). Not a photovoltaic-integrated greenhouse. Focus is on solar energy passive optimization (no PV panels used). Described structure: arched steel skeleton covered with transparent polyolefin film (0.15 mm) |
| [67] | Polytunnel greenhouse with integrated semi-transparent organic photovoltaics (OPV). Static installation. Panels distributed on a curved roof. Comparison with a control greenhouse without OPV panels. |
| [68] | "Raspa y Amagado" type plastic greenhouse. Integrated with thin-film photovoltaic modules on the roof. Divided into three zones: two PV-integrated (T1 and T2), one control (T0). |

| Reference | Observations |
|---|---|
| [69] | Simulated solar greenhouse with integrated photovoltaic roof. Fully enclosed greenhouse structure. Designed to provide energy for internal systems (air-conditioning, irrigation, ventilation, etc.) while supporting agricultural cultivation |
| [70] | East–west oriented glass greenhouse. Roof-integrated PV panels. Area: 230.4 $m^2$. Used for simulation and experimental validation. PV coverage: 25% of total roof area. |
| [71] | Canarian greenhouse, North–South oriented. Structure: plastic greenhouse with polyethylene cover. Integration: opaque photovoltaic panels covering 40% of roof area. Format: checkerboard panel distribution |
| [72] | Chinese Solar Greenhouse (CSG). Passive design with three insulated walls and one transparent south-facing roof. Structures include south-slope-integrated PV, and systems with PV on the north wall. |
| [73] | PV Agricultural Greenhouse. Two types illustrated: Panels mounted directly on the greenhouse roof and Panels mounted above the greenhouse structure. Description includes use of transparent and semi-transparent PV modules to balance light needs for crops |
| [74] | Double-pitched photovoltaic greenhouse. Designed for island application with food and energy co-production. Structural system reinforced for cyclone resistance. Called "Agrinergie 5" project. |
| [75] | Greenhouses with Organic Photovoltaic (OPV) integration. Mostly theoretical and review-based. Real-world references mentioned but no detailed installation case described. |
| [76] | Semi-transparent photovoltaic (STPV) greenhouses and agrivoltaic installations in both greenhouses and open fields. Includes arched greenhouses, tunnel-type greenhouses, rooftop-integrated systems, and foil-shaded greenhouses |
| [77] | Not a single case study but a review article that includes: Greenhouses with roof-mounted PV panels, closed greenhouses, semi-closed greenhouses, and plant factories (indoor farms with artificial lighting). Note: Agrivoltaic systems in open fields are not covered in this article. |
| [78] | Multiple types described, as this is a review article: Conventional greenhouses with roof-integrated PV panels, greenhouses with photovoltaic thermal (PVT) and concentrated PVT (CPVT) systems, retrofit PV structures on existing greenhouses, semi-transparent PV integration on roofs, and greenhouses with solar concentrators and thermal storage. |
| [79] | Not specified. The article does not focus on photovoltaic greenhouses specifically. It is a general review of solar photovoltaic (PV) technologies and applications. |
| [80] | Plastic greenhouse with multi-span structure and polycarbonate walls, used for hydroponic tomato cultivation. Includes comparison with conventional soil cultivation ("enarenado"). |
| [81] | The article is a review. It discusses various greenhouse systems retrofitted or integrated with PV and PV/T technologies, including: Greenhouses with conventional PV modules, greenhouses with semi-transparent PV modules, greenhouses with photovoltaic/thermal (PV/T) and concentrated photovoltaic/thermal (CPV/T) systems, and greenhouses with Fresnel lens-based concentrators No specific architectural greenhouse type is described (e.g., tunnel, gothic, Venlo). |
| [82] | Single-span arched Chinese solar greenhouse (CSG) with a length of 16 m, width of 8 m, and height of 5 m. Not a traditional photovoltaic installation. The study focuses on a solar radiation fuzzy adaptive control system, not on direct photovoltaic power generation or panel integration. |

| Reference | Observations |
|---|---|
| [83] | Chinese Solar Greenhouse (CSG). Single-slope structure, with the front roof as the only lighting surface and opaque envelope structures on the other sides. |
| [84] | Not applicable. This is a bibliometric and science mapping study. It analyzes trends in greenhouse engineering publications over four decades (1981–2021), including PV greenhouses among broader themes, but does not describe a specific installation or structure. |
| [85] | Not specified. The article refers generally to the integration of photovoltaic systems in greenhouses, with examples such as solar greenhouses with PV roofs, BIPV systems, and integrated NIR filter solar cooling systems, but does not detail structural types (e.g., tunnel, Venlo, etc.). |
| [86] | Multiple types are mentioned, including: Greenhouses with conventional PV panels on the roof (partial coverage), greenhouses with semi-transparent PV modules, and greenhouses with checkerboard and straight-line PV panel arrangements Not all installations are real; some are simulation-based. One real-world installation is a small-scale APV system with tomato cultivation. |
| [87] | General discussion of greenhouses integrating semitransparent organic photovoltaics (ST-OPVs) and semitransparent perovskite photovoltaics (ST-PPVs). Specific greenhouse architectural types not identified (e.g., Venlo, tunnel). Examples include both experimental greenhouses and commercial ones with various cover ratios. |
| [88] | General references to greenhouses using semi-transparent organic photovoltaic (ST-OPV) panels. Greenhouse types include plastic-covered traditional greenhouses and conceptual net-zero energy greenhouses. Specific structural types (e.g., Venlo, tunnel) are not mentioned. |
| [89] | East–west oriented, single-span Gothic-arch style greenhouse. One greenhouse used as PV-integrated test unit; another identical greenhouse used as control. |
| [90] | Multiple greenhouse-integrated PV systems, with installations including: Straight-line and checkerboard PV arrays, greenhouses with semi-transparent and opaque PV panels, and various ground-mounted agrivoltaic systems. |
| [91] | Venlo-type greenhouse, two-span metal structure, with plastic cover. The structure was segmented into zones with variable shading (15%, 30%, 50%, and 0% as control). |
| [92] | Various types are reviewed, with focus on greenhouses integrated with shared-structure building-integrated photovoltaics (BIPVs), and those using smart covers with semitransparent PV materials. Specific installations are not detailed; the review is focused on materials and system types rather than case studies. |
| [93] | Agrivoltaic installation in open field. Elevated structure (3.6 m height above ground) |
| [94] | Multiple types are reviewed. Includes greenhouses with integrated semi-transparent photovoltaics (BIPV), photovoltaic thermal systems (PV/T), and hybrid solar greenhouses. Some installations are referenced with closed-system or automated microclimate control. |
| [95] | Not specified. The article provides a general review of solar energy applications, including solar use in greenhouses, but does not focus on a particular greenhouse or agrivoltaic installation. |

| Reference | Observations |
|---|---|
| [96] | Multiple agrivoltaic system configurations are described; the article does not describe traditional closed greenhouses but open-field agrivoltaic systems, some integrated with greenhouses (e.g., Sardinia).<br>If it is an agrivoltaic installation in open fields: Yes, includes elevated structures, two-axis trackers, and vertically or horizontally spaced modules. Types of instalation mentioned: Oregon State University (USA) – Fixed east-west oriented strips; Po Valley (Italy) – 2-axis sun-tracking, elevated structure; Sardinia (Italy)– Integrated with greenhouses (mono-pitched roof); Junagadh (India) – Agricultural-energy centric AVS model; Selangor (Malaysia)– Large-scale solar farm with grass planting (indirect AVS use). |
| [97] | A commercial east–west oriented greenhouse for horticulture with 50% of the roof area covered by photovoltaic modules. |
| [98] | Miniature smart greenhouse (controlled environment for research and nursery-scale applications). |
| [99] | Chinese solar greenhouse (CSG). Photovoltaic system not described for electricity generation — The study focuses on thermal energy collection via a water heat accumulator, not on electricity-producing PV panels. |
| [100] | Multiple types including: Venlo, gable roof, mono-pitch, gothic-arch, flat arch, tunnel, quonset, and Chinese solar greenhouse. Some installations are dynamic agrivoltaic greenhouses using mirrors or blind-blade systems. Some others are open-field agrivoltaic systems using concentrating Fresnel or parabolic systems. |
| [101] | Multiple types are referenced. This is a review article and not based on a single installation. Types include: Stand-alone greenhouses (Quonset, modified arch, vinery, uneven span, even span), gutter-connected greenhouses, PV-integrated greenhouses with static panels, Greenhouses with dynamic photovoltaic shading systems. No specific greenhouse structure is the focus, as it is a literature review. |
| [102] | Greenhouse high tunnel (polyethylene-covered) with semi-transparent OPV modules used as partial roof cover/shading elements. Not a fully integrated PV greenhouse. |
| [103] | Not specified as a commercial greenhouse installation. Experimental trials conducted under controlled conditions using plexiglass boxes and greenhouses. The configuration represents indoor agrivoltaic applications in controlled environments rather than full-scale greenhouses. |
| [104] | Both passive and active solar greenhouses are described. Passive systems are east-west oriented to maximize winter solar gain. Active greenhouses integrate PV, PVT, or thermal collectors.<br>Agrivoltaic installation in open fields (if any): Yes, multiple agrivoltaic systems are described, with PV modules elevated 2 meters above ground in wheat, maize, rice, potato, and clover-grass fields, including fixed and dual-axis tracking systems.<br>Installations mentioned: Passive solar greenhouses and active solar greenhouses. Agrivoltaic systems in wheat, maize, rice, potato, clover-grass fields in Germany, Italy, France, Japan, China, Chile |
| [105] | Five types of integrated photovoltaic greenhouses (PVGs) are described: Terraced PVGs, doubled film-column PVGs, part-shaded spring PVGs, part-shaded winter PVGs, and bricked winter PVGs. These are greenhouse-integrated systems (not open-field agrivoltaics). |
| [106] | Traditional greenhouses with integrated opaque crystalline silicon solar cells (CSCs) and novel applications of semi-transparent Dye-Sensitized solar Cells (DSCs). Not a field agrivoltaic installation. |

| Reference | Observations |
|---|---|
| [107] | Single stand-alone mushroom greenhouse with gable roof. Not a typical agrivoltaic installation in open fields. Integrated with PV modules directly on the building roof. |
| [108] | The article includes both open field agrivoltaic systems (on stilts and ground-mounted) and a greenhouse with photovoltaic panels on the roof. The greenhouse configuration is briefly mentioned as a solution for land-limited areas like islands. Installations: Ground-mounted agrivoltaic system, stilt-mounted agrivoltaic system, PV-integrated greenhouse (partial roof coverage). |
| [109] | Mediterranean greenhouse with semi-transparent photovoltaic film integrated on the covering structure. |
| [110] | General PV greenhouses. Chinese Solar Greenhouses (CSG). Venlo-type PV greenhouses. Greenhouse tunnels. Some installations have dynamic or semi-transparent PV systems. |
| [111] | Greenhouse with photovoltaic blind system (SPBS) mounted above the roof, in checkerboard array. Type specified: Flat-arch greenhouse. |
| [112] | Greenhouse with integrated semi-transparent photovoltaic (STPV) panels and hybrid energy storage (Battery Energy Storage System - BESS, and Hydrogen storage). |
| [113] | Not a greenhouse. The study is based on agrivoltaic installations in open fields using vertical free-swinging structures. |
| [114] | Not specified. The paper is a review article covering multiple agrivoltaic systems, including both greenhouse-integrated and open-field types. Installations discussed include: Greenhouse rooftops, elevated open-field systems, systems with livestock grazing, and vertical and tracking installations. |

# 4 Configuration of the Photovoltaic Installation

This section details the types of photovoltaic installation configurations present in current agrivoltaic systems for greenhouses.

Regarding the distribution of solar panels, photovoltaic panels in greenhouses and agrivoltaic structures are primarily installed on the roofs or coverings of greenhouses, employing various patterns such as straight-line arrays, checkerboard layouts, grid patterns, and asymmetric or elevated fixed structures. Some studies report integration into facades, double glazing, or plastic covers, as well as flexible roll-to-roll modules for modular and dynamic applications. Panels are also mounted on shared structures, auxiliary containers, pergolas, or elevated frameworks that allow for cultivation or livestock underneath.

Regarding module types and solar tracking, static modules predominate; however, a significant number of studies include single-axis and dual-axis solar tracking systems, especially in concentrated photovoltaic thermal (CPVT) applications and dynamic agrivoltaic setups. Systems with adjustable tilt angles, rotatable panels for optimal solar incidence, and freely swinging modules influenced by wind have been documented. Some research discusses tracking technologies without direct greenhouse applications. Semi-transparent photovoltaic (STPV) technologies are also common, enabling combined electrical generation and light transmission suitable for crop growth.

The most frequent panel orientations are south-facing, though east-west and north-south alignments are also used depending on location and system goals. Optimized tilt angles typically range between 10° and 70°, with common inclinations around 20°–30° for pitched roofs and horizontal arrangements for flexible modules. Several studies explore dynamic monthly or seasonal tilt adjustments to maximize energy production or shading control. In some cases, orientations and inclinations are not explicitly specified but assumed to be location-optimized.

Lastly, several specific configurations and applications were identified:

- Partial roof coverage ranging from 10% to 60% with regular or irregular patterns to balance energy generation and crop yield.
- Semitransparent modules integrated into films or glazing to enable selective light transmission alongside electricity production.
- Narrow photovoltaic strips with variable spacing to optimize solar radiation management and minimize shading effects on crops.
- Dynamic shading systems that adjust module or screen orientation to improve microclimate and energy efficiency.
- Elevated panel installations allowing cultivation or livestock grazing beneath, integrating agriculture and photovoltaics.
- Integrated energy management systems within greenhouses, including external panels powering sensors and control units.

The detailed findings for each reviewed article are provided in Table 2.

Table 2: Configurations of photovoltaic greenhouse installations in the reviewed works.

| **Reference** | **Observations** |
|---|---|
| [1] | Distribution of Solar Panels: Installed in a checkerboard arrangement on the tunnel greenhouse roof. Static or Solar Trackers: Static (Fixed) Panels, no mention of solar tracking. Orientation of Solar Modules: East-West (EW) orientation. |
| [2] | The article does not focus on a specific installation configuration. Instead, it reviews various studies on: Panel distribution in open fields and greenhouses, Tracking vs. fixed panels, orientation of PV modules, and different agrivoltaic configurations (vertical bifacial panels, semi-transparent PVs, concentrated PVs) |
| [3] | The article does not describe a single photovoltaic greenhouse configuration. Instead, it reviews various configurations used in agrivoltaics, including: Fixed PV panels, single-axis and dual-axis tracking PV panels, east-West (E-W) vertical bifacial panels Overhead agrivoltaic systems (elevated structures) Greenhouse PV setups are mentioned, including: Semi-transparent PV modules for better light transmission. Checkerboard patterns to improve crop growth and light distribution. |

| Reference | Observations |
|---|---|
| [4] | Distribution of Solar Panels: PV panels are installed on the roof of the greenhouses. Two different arrangements of PV panels were tested: Straight-line arrangement Checkerboard arrangement (improved spatial light distribution). Static or Solar Trackers: Static (fixed) panels, no mention of tracking systems. Orientation of Solar Modules: Not explicitly stated, but shading and sunlight distribution were analyzed. |
| [5] | Distribution of Solar Panels: Fixed horizontal PV panels positioned on the roof pitch of the greenhouse, the design allows for passive variation in shading throughout the year, mirrors are used to recover reflected solar energy. Static or Solar Trackers: Static (fixed) PV panels, no solar tracking system. Orientation of Solar Modules: East-West (E-W) oriented greenhouse with south-facing roof pitch optimized for PV production. Inclination angle of PV panels: 33°. Natural variation in solar shading throughout the year, ranging from 39.4% in December to 72.6% in June. |
| [6] | Distribution of Solar Panels: PV panels are installed on the south-facing roof pitch, mirrors are used to recover reflected solar energy, panels rotate to adjust shading according to external weather conditions and crop light needs. Static or Solar Trackers: Rotating PV panels, manually operated in the prototype but designed for automation. Orientation of Solar Modules: South-facing roof pitch with an inclination of 33°. Maximum shading variation from 0° to 78°. |
| [7] | Distribution of Solar Panels: Panels are mounted on greenhouse rooftops or integrated into structures.Static or Solar Trackers: Not specified in detail, but mentions both fixed and tracking systems in various studies. Orientation of Solar Modules: Not detailed, but mentions optimization techniques such as tilting angles and shading control. |
| [8] | The article does not describe a single photovoltaic greenhouse configuration. It discusses multiple configurations, including: Fixed-axis PV panels, single-axis and dual-axis tracking systems, semi-transparent PV panels mounted on greenhouses, East-West (E-W) and South-facing panel orientations, and agrivoltaic systems with adjustable panel density to control shading. |
| [9] | The review does not describe a single configuration but discusses multiple setups, including: PV modules mounted on greenhouse roofs, bifacial PV and semi-transparent PV panels for optimized light transmission, PV panels with sun trackers for dynamic shading and improved efficiency, checkerboard and straight-line arrangements for PV panels, and combination of PV and thermal energy storage (TES) systems for optimized heating and energy efficiency. |
| [10] | The article discusses the integration of photovoltaic systems in greenhouse environments. Mentions flexible PV panels as a renewable energy source. No explicit details on panel distribution, tracking, or orientation. |
| [11] | Distribution of Solar Panels: Semitransparent OSCs integrated into the greenhouse roof. Replaces traditional shading cloths while generating electricity. Static or Solar Trackers: Fixed OSC panels (static), no tracking system. Orientation of Solar Modules: North-South greenhouse orientation. Roof tilt angle: 27°. |

| Reference | Observations |
|---|---|
| [12] | Distribution of Solar Panels: Mounted on greenhouse roofs (checkerboard or straight-line arrangements), Integrated flexible thin-film PV modules covering 9.8% of the roof area (Spain case study), and PV arrays mounted inside Gothic-arch style greenhouse roofs (Japan case study). Static or Solar Trackers: Most systems use fixed PV modules, some studies discuss PV panels with two-axis tracking for optimization. Orientation of Solar Modules: East-West orientation in winter climates for maximum solar gain. North-South greenhouse orientation for even light distribution. |
| [13] | No specific installation or configuration is detailed. Discusses multiple renewable energy integration strategies: Photovoltaic (PV) panels on greenhouse roofs Smart glass and intelligent shading systems Combination of PV with geothermal and wind energy AI-driven energy management systems to optimize PV efficiency. |
| [14] | Distribution of Solar Panels: Installed on greenhouse roofs in varying coverage percentages (25% to 100%). Static or Solar Trackers: Fixed/static PV panels (no tracking system). Orientation of Solar Modules: South-facing roof orientation in East-West oriented greenhouses. |
| [15] | Distribution of Solar Panels: PV modules mounted on single-axis tracking structures in front of the greenhouses. Integrated into the roof and adjacent land areas. Static or Solar Trackers: Single-axis dynamic tracking systems: Solar Tracking (ST): Adjusts PV panels for maximum sunlight capture. Reverse Tracking (RT): Adjusts PV panels to minimize shading on crops. Orientation of Solar Modules: East-West tracking axis, with adjustable tilt angles from -60° to +60°. |
| [16] | Distribution: PV panels integrated on greenhouse roofs, using: Checkerboard arrangements, fixed rows, PV slats with adjustable angles, and dynamic blinds or movable modules. Module Movement: Both static and dynamic systems are described. Dynamic systems use venetian blind-type trackers, rails, or roof-integrated rotation. Orientation: Designed based on local solar paths; no uniform standard orientation given. Dynamic systems allow variable orientation to optimize PAR transmission. |
| [17] | Distribution of Solar Panels: Closed AVS – PV panels integrated into the roof of greenhouses (Benin, Nigeria). Open AVS – PV modules elevated 2–6 m above ground; includes checkerboard and full-density layouts. Static or Solar Trackers: Fixed/static PV modules in all installations mentioned. No dynamic tracking systems were reported in these West African AVS. Orientation of Solar Modules: Orientation not explicitly specified, but implied to be standard fixed systems aligned with solar exposure in respective countries. |
| [18] | Distribution of Solar Panels: Elevated systems– Modules installed at heights between 1.8 m and 5.42 m above crops; Inter-row systems– Modules arranged with crops planted between rows; Vertical systems– Bifacial PV modules mounted vertically (east–west or north–south). Static or Trackers: Both static and dynamic systems described. Fixed installations and single-axis and dual-axis solar trackers (adjust tilt and orientation). Tested orientations: Tilt angles 18° to 32°. Azimuth angles: Site-specific, oriented south (northern hemisphere) or north (southern hemisphere). Vertical mounting: east–west and north–south orientations. Spacing Between rows ranged from 0.71 m to 9.5 m. Between modules in same row ranged from 0.2 m to 6.4 m. |
| [19] | Distribution of Solar Panels: Panels are elevated with Panel height of 2.77 m (lower side) and 3.99 m (upper side). Distance between panels of 4.5 m. Centre-to-centre pole spacing of 6.7 m. Fixed (static) mounting system. No solar trackers used. Panels are tilted at 23°. South-facing orientation. |

| Reference | Observations |
|---|---|
| [20] | Varied distribution of Solar Panels: Fixed on greenhouses (replacing part of the greenhouse cover), elevated (stilt-mounted) above crops, and interspersed between rows. Static panels: most common (n = 45). Dynamic panels: used in 3 stilt-mounted systems. Spectrum-selective panels: used in 1 stilt-mounted and 1 greenhouse-mounted system. Orientation not explicitly standardized, as the paper is a meta-analysis of multiple configurations. |
| [21] | The distribution of Solar Panels is 10 panels (1.2 m × 0.6 m), arranged in 2 rows for each unit, in an area of 2 × 3 m per installation, Installed on ground stakes with a tilt angle of 36°. The height 0.9 m (lowest) to 2.3 m (highest) above ground and the orientation is North–South. The distance between installations 7 m (to prevent cross-shading). Static panels were used (no solar tracking). |
| [22] | Distribution: Elevated modules on stilts or poles. Spacing to allow sunlight to reach crops and farm machinery to pass. Module movement: Both static and mobile (solar tracking) configurations are described. Research into 1-axis solar tracking systems and diurnal light management modes. Orientation: South-west orientation mentioned (e.g., Heggelbach site). Panel tilt angles between 20–25° depending on location. Some facilities used bifacial modules to capture reflected radiation. |
| [23] | Distribution of the solar panels: Panels are integrated on the southern inclined section of the roof of the greenhouse. Module movement: Static modules (no solar tracking). Orientation of the solar modules: Fixed on the south-facing sloped roof. |
| [24] | Distribution of solar panels on the greenhouse structure: PV modules installed on the south-oriented roof of each span of the greenhouse, covering 50% of the roof area. Modules are: Static (no solar trackers mentioned). Orientation of the solar modules: South-oriented roof; the greenhouse itself has East–West (E–W) orientation. |
| [25] | Ecolume: Distribution of 10 PV static modules in fixed position. Pankará Village: Elevated 3 meters above ground, Static modules. CCampo: Static modules mounted for agroecological use. UFAL: Static modules elevated 8 meters above ground. Fotovoltaica UFSC R&D: Bifacial modules (fixed, standard tracking, optimized tracking), spaced-cell bifacial modules, and tracking systems with spectrally selective PV technology. The orientation varies (tracking systems included). |
| [26] | Distribution of solar panels on the greenhouse structure: 24 photovoltaic panels installed on the south-facing roof pitch of an asymmetrical, small-scale prototype greenhouse. Modules: Dynamic – Rotatable along the longitudinal axis to adapt shading to solar angles and crop needs. Orientation: East–West (E–W) for the structure and south-facing photovoltaic surface orientation, with a pitch angle of 33° (south), 51° (north). The simulated panel angles are horizontal position and rotational steps of 10°. |
| [27] | Ureña-Sánchez et al. (Spain): Flexible static solar panels installed on two parts of the roof. A roof coverage of 9.8%. Energy production of 2766 kWh. There was no effect on tomato yield or market price. Al-Shamiry et al. (Tropical greenhouse – unspecified location): Hybrid PV system with 48 PV panels (18.75 W each), inverter, charge controller, and battery bank (12 batteries). The daily energy production is 2.8 kWh, with a daily consumption of 2.6 kWh, a 92.86% of supply is covered. Yano et al. (Japan): PV-powered Amorphous silicon (a-Si) climate control (side-vent controller) module with an area of 0.78 $m^2$, a max power of 32 W, battery of 28 Ah at 12 V, and ventilation control based on temperature (20–25°C range). |

| Reference | Observations |
|---|---|
| [28] | Distribution of solar panels on greenhouse structure not specified; the study does not focus on physical installations but rather material properties. |
| [29] | Distribution of the solar panels on the greenhouse structure: Static modules mounted on the roof. Type 4 also evaluated using a checkerboard pattern for more uniform light distribution. The orientation of the solar modules is East-West (E-W) orientation, which is most common in installations. Simulations also tested North-South (N-S) orientation, which improved light distribution but slightly reduced energy yield. |
| [30] | Distribution of the solar panels on the greenhouse structure: Not specified on a greenhouse structure; the PV module is placed horizontally 10 cm below programmable LED lamps to simulate indoor horticulture conditions. Static modules without mention of solar tracking systems. Orientation of the solar modules: Horizontal orientation under indoor lighting during tests. Lighting configurations tested (6 total): White + Blue, White + Red, White + Far-red, Blue + Red + Far-red, Blue + Red (1), Blue + Red (2). |
| [31] | Distribution of panels: Ground-based, self-supporting structures; crystalline-silicon PV modules. Modules: Static (fixed-tilt). Orientation: South-facing (typical in the Northern Hemisphere). Configurations described: Full-density PV system: Designed for maximum energy generation, with optimal row spacing. Half-density PV system: One PV strip removed to increase light availability for crops. |
| [32] | Distribution: Solar panels installed on both north and south sloped roofs of the greenhouse. Modules: Static (no trackers used). Orientation: East–West greenhouse orientation; south roof has a tilt of 25°. Arrangements analyzed: Straight line, symmetric checkerboard, and asymmetric checkerboard. Most suitable configuration found: Asymmetric checkerboard layout based on light distribution analysis. |
| [33] | Distribution of solar panels on the greenhouse structure: Roof-mounted panels; on Asymmetric type, PVs are on the roof side without openings; on Venlo type, fewer PVs allow more openings. Whether the modules are static or have solar trackers: Static (no solar tracking). Orientation of the solar modules: Orientation is integrated into greenhouse roof; simulations include scenarios with north-south and east-west prevailing wind directions. Coverage ratio: Asymmetric greenhouse–PV panels cover ∼60% of the roof; Venlo greenhouse – PV panels cover ∼50% of the roof. |
| [34] | Distribution of the solar panels on the greenhouse structure: On the roof of the greenhouse. |
| [35] | Distribution of the solar panels: Mounted in a straight-line format on 50% of the south-oriented roof of the greenhouse. Modules static or with trackers: Static (fixed installation). Orientation of the solar modules: South-facing roof with a slope of 33°. |
| [36] | Distribution of solar panels: Various configurations are cited: chessboard, longitudinal axis tracking, fully roof-covered, and partial roof coverage. Modules static or tracking: Both are discussed. Some installations use dynamic (tracking) systems, while others use static modules. Orientation of modules: Configurations vary (north-south, east-west, varying tilt angles). Specific mention of optimal tilt angles (e.g., 20° vs. 28°) for energy efficiency in Japan. |

| Reference | Observations |
|---|---|
| [37] | Distribution of panels: Mounted on the south-facing roof of the Venlo-type greenhouse. Static modules (no mention of solar trackers). Variable roof angles analyzed: south-facing roof = 10° to 70°and north-facing roof = 10° to 70°. Best configuration (optimal case): south-facing roof = 40°, north-facing roof = 10°. Shading rate ¡ 25%. Power generation = 35.8 MWh/year. Specific production = 1404 kWh/kWp/year. |
| [38] | Distribution: Panels installed on rooftops, stilt-mounted, and on elevated structures over crop rows; configurations include straight-line, checkerboard, and various densities. Mobility: Both static and dynamic (solar tracking) modules are discussed. Tracking systems include single-axis and dual-axis designs. Orientation: South-facing fixed panels (e.g., 26° tilt), East-West and North-South layouts, vertical bifacial setups. |
| [39] | Distribution of the solar panels on the greenhouse structure: Straight-line formation, Checkerboard formation, Crisscross pattern, Full roof coverage, Partial roof coverage with OPV (22%–49%), Dynamic shading systems with rotating PV modules. Modules are either static or use solar trackers: Static for most cases, Dynamic systems with motorized adjustment also discussed. Orientation of the solar modules: North–South and East–West orientations tested. Orientation affects solar uniformity and electricity production. |
| [40] | Distribution of solar panels: South-facing roof surface of the greenhouse. Modules: 24 polycrystalline photovoltaic panels arranged in 3 strings of 8 panels each. Movement: Modules can rotate along their longitudinal axis manually. Orientation: Adjustable; tested under multiple shading configurations (0% to 78%), with tilt angles set according to sun position. Panels equipped with mirrors: 24 highly reflective aluminum mirrors (98%) to recover reflected solar radiation. |
| [41] | Distribution of the solar panels: On the south-oriented roof of an elevated structure above the orchard. Static or with trackers: Static modules. Orientation of solar modules: South-oriented at 16° tilt (simulated optimal was 28°). Multiple configurations: Three shading levels tested: T1 for 19.0% roof coverage, T2 for 30.4% roof coverage and T3 for 38.0% roof coverage. |
| [42] | Distribution of the solar panels on the greenhouse structure: Mounted inside the south roof of an east–west oriented single-span greenhouse. Modules static or with solar trackers: Static modules. Orientation of the solar modules: South-facing, inside-roof mounted. PVs array: Inclined at 25° (straight-line formation). PVc array: Checkerboard formation with 20° inclination for higher modules and 26° for lower modules. Configurations: PVs array (2007): Straight-line aligned along the east–west axis. PVc array (2008): Checkerboard pattern to improve light distribution. |
| [43] | Distribution of the solar panels on the greenhouse structure: Installed horizontally at gutter height (3 m), in five long narrow strips aligned north-south to avoid continuous shading. Static modules. Orientation of the solar modules: Horizontal orientation along north-south direction. Number of configurations: Two configurations based on spectral type of OPV: one with red modules and one with blue modules. |
| [44] | Distribution of the solar panels on the greenhouse structure: Installed inside the greenhouse, mounted under a sloped east-facing glass roof (26.5° inclination). Modules static or with solar trackers: Dynamic rotation (motorized blind rotation system controlled by irradiance levels). Orientation of the solar modules: Adjustable between 0° (parallel to roof) and 90° (perpendicular to roof), controlled based on light intensity. |

| Reference | Observations |
|---|---|
| [45] | Distribution of the solar panels on the greenhouse structure: PV panels are installed in various configurations including entire or partial roof coverage, next to greenhouses on the ground, integrated within shading systems. Whether the modules are static or have solar trackers: Most installations are static. Some experimental systems use movable or adjustable shading devices (e.g., blinds). Orientation of the solar modules: North–South and East–West orientations are described. Configuration depends on local climate and PV optimization strategy. |
| [46] | Distribution of the solar panels on the greenhouse structure: Modules are integrated on the roof in 8 different configurations with varying coverage percentages (33%, 66%, 100%) and on different roof slope segments (10°, 30°, 45°). Static modules. Orientation of the solar modules: North–South oriented greenhouse with roof slopes at 10°, 30°, and 45°. Configurations (ID codes and coverage): 1OPV10, 1OPV30, 1OPV45 with 33% coverage at respective roof slopes, 2OPV10_30, 2OPV10_45, 2OPV30_45 with 66% coverage with combinations of roof slopes, 3OPV with 100% coverage, and REF with 0% (reference case, no OPV). |
| [47] | Distribution of panels: PV modules installed on roofs, sides, or inner roof (with straight-line or checkerboard pattern). Modules static or tracking: Modules described are static. Orientation: Optimal orientation depends on latitude; South-facing or E-W directions are common. Specific azimuth angle recommendations are based on simulations and case studies. |
| [48] | Distribution of the solar panels on the greenhouse structure: Panels installed on the north-facing roof surfaces. Static modules. Orientation of the solar modules: North-facing in the southern hemisphere (Australia). |
| [49] | Distribution of solar panels: Not tested in-situ but analyzed theoretically. Shading distribution modeled based on known radiation simulations and literature-based regression models. Some references to checkerboard vs linear patterns in comparative studies. Modules static or trackers: Static (tracker use not mentioned in the methodology). Orientation of solar modules: Both East-West and North-South orientations were evaluated. |
| [50] | Distribution of the solar panels on the greenhouse structure: 66 solar panels installed on 50% of the southern face of an asymmetric roof (south-facing surface larger to maximize solar capture). The panels are arranged in 6 horizontal rows, with gaps between each to ensure uniform radiation inside the greenhouse. Static modules. Orientation of the solar modules: South-oriented, on a 38.4° inclined roof (latitude of İzmir). |
| [51] | Distribution of the solar panels: Mounted inside the greenhouse under the roof cover, above the plant canopy at about 3 meters height. Type of modules (tracking/static): Static. Orientation of the solar modules: Not specified explicitly, but modules installed above canopy level, with some tilt (e.g., westward tilt in OPV noted) |
| [52] | Only one configuration is illustrated hypothetically: A rotating photovoltaic panel system combined with highly reflective mirrors for shading in a greenhouse (cited from Marucci & Cappuccini, 2016). Orientation: Panels dynamically adjusted, no fixed orientation mentioned. Modules: Mechanically driven (rotating), used as part of shading system. Distribution: Positioned above the greenhouse as part of a mobile shading structure. |

| Reference | Observations |
|---|---|
| [53] | Distribution of solar panels: Various configurations: straight-line, checkerboard, and dynamic systems. Modules static or trackers: Mostly static, one case of rotating (sun-tracking) modules. Orientation: East-west and north-south orientations used, depending on installation. |
| [54] | Distribution of the solar panels on the greenhouse structure: Installed on the roof of the greenhouse. Whether the modules are static or have solar trackers: Static modules. Orientation of the solar modules: Not explicitly specified. |
| [55] | Distribution: PV panels mounted over crops, between rows, or integrated into greenhouses. Modules: Fixed and tracking systems (single-axis and dual-axis) are both mentioned. Orientation: Varies depending on system; tilt optimization discussed in models. |
| [56] | Distribution of the solar panels: Roof-mounted, particularly on multi-span structures and individual solar greenhouses. Static or trackers: Static modules. Orientation of the solar modules: Not explicitly detailed; one example mentions a roof installation angle of 35° in Xinjiang. |
| [57] | Distribution of the solar panels on the greenhouse structure: Ground-mounted system across a 5-acre pasture. Whether the modules are static or have solar trackers: Static modules. Orientation of the solar modules: Not explicitly stated. |
| [58] | Distribution of the solar panels on the greenhouse structure: Panels are installed on the roof structures. In plastic greenhouses, additional support frames are required due to low load-bearing capacity. In glass and multi-span greenhouses, panels are directly mounted on the structure. Static modules. Orientation of the solar modules not specified directly. Installation ratio simulation: Simulated installation ratios from 0% to 60% of rooftop area in 5% increments. A real case is based on 30% PV coverage. |
| [59] | Distribution: OPV modules covered 37% of the roof area arranged in strips (1 m wide, 6.4 m long) with 1 m spacing between strips, across the arch of the tunnel roof. Tracking: Static modules (no solar trackers). Orientation: Modules aligned across the arch-shaped tunnel roof, facing upward, installed on the polyethylene cover. |
| [60] | Distribution of solar panels: Panels mounted on the south-facing gable roof. Three types of layouts: HDPV 1 (High-density: full south roof coverage), LDPV 1 (Low-density: partial south roof), LDPV 2 (Lower-density: sparse layout). Dynamic sun-tracking system with rotating PV modules around a fixed axis. Four tracking positions modeled: closed (parallel to the roof), quasi-perpendicular (max irradiance incidence), no-shading (no shadow on neighboring modules), and open (parallel to sunlight). Orientation: East–West orientation, with south-facing roof. |
| [61] | Distribution of solar panels: Integrated on the 30° inclined slope of a double-pitch roof (facing South-West). Solar tracking: No solar trackers; modules are static. Orientation: South–West facing (30° slope), opposite slope faces North–East (60° slope). |
| [62] | Distribution of solar panels: Integrated into the roof and facades of six greenhouse modules. Specific modules include: Reflective insulated glass raster (passive), concentration collectors with linear Fresnel lenses and PV/PT absorbers, water-cooled hybrid photovoltaic absorbers, flat vacuum thermal collectors (non-PV), and facade-mounted solar collectors. Solar tracking using absorbers under Fresnel lenses are movable, adapting to solar angle. Orientation: Roof slope orientation for optimal solar gain: south-facing, slope 30–45°. Facade collectors adjusted for oblique solar incidence. |

| Reference | Observations |
|---|---|
| [63] | Distribution of solar panels: Roof-integrated for greenhouses, elevated arrays (e.g., 4 m height in Germany and Japan), interspaced arrays for open field farming, and vertical bifacial and single-axis tracking arrays. Solar tracking: Static and dynamic configurations. Examples include: Single-axis horizontal tracking (Belgium, Italy), free-swinging bifacial systems (Canada), and static vertical bifacial modules (Sweden). Orientation: East–West, South–North, and azimuth-specific angles (e.g., 52.5° azimuth in Germany). |
| [64] | Distribution of solar panels: Installed on greenhouse roofs at variable coverage rates (0%–90%). Each greenhouse comprises 5 raceway ponds. Modules static or trackers: Static modules only; no sun-tracking. Orientation: Not explicitly specified; assumed fixed horizontal layout on greenhouse roof. Number of scenarios: 10 scenarios tested: PV coverage from 0% to 90% in 10% increments. |
| [65] | Distribution of the solar panels: Full roof coverage allowed (PVR 0–100%), variable by crop type and transparency factor. Static STPV modules; no solar tracking. Orientation: Not specified, assumed horizontal or standard rooftop mount in simulation. There are two scenarios with different configurations: (I) STPV only, (II) STPV + BESS. PVR tested across transparency factors from 0.337 to 0.671. |
| [66] | Not applicable – the greenhouse does not use photovoltaic modules. |
| [67] | Distribution of the solar panels on the greenhouse structure: 10 strips of OPV panels mounted across the arch of the polytunnel greenhouse roof, panels spaced 1 m apart, fixed with ETFE-foil adhesive. 3 specific panels monitored: A2 with 21° tilt and facing West, A6 with 11° tilt and near-horizontal– top of roof, facing East–, and A9 with 27° tilt and facing East. Static modules only; no sun-tracking. Orientation of the solar modules: Mixed orientation (East, West, and top of the arched roof). Greenhouse itself oriented North–South. |
| [68] | Distribution of the solar panels on the greenhouse structure: Roof-integrated PV modules covering 9.79% of the total roof surface. T1: 12 individual strips (checkerboard configuration), T2: 6 paired strips. Modules static or with trackers: Static modules without tracking. Orientation of the solar modules: Modules followed the existing tilting angles of the greenhouse roof. Not changed or reoriented. |
| [69] | Distribution of the solar panels on the greenhouse structure: Integrated into the roof, particularly on the southern slope, covering a portion of the surface. Placement creates shading, particularly affecting southern side crops. Modules static or with trackers: Static PV modules; no tracking involved. Orientation of the solar modules: Oriented southward, as per standard solar optimization for Italy. |
| [70] | Distribution of the solar panels on the greenhouse structure: Mounted on the roof and tested in three layouts, being La– Straight-line layout (36 panels), Lb – Crisscross layout, and Lc– Checkerboard layout. Static modules. Orientation of the solar modules: East–West greenhouse orientation. Panels aligned with the roof inclination, not actively oriented. |
| [71] | Distribution of the solar panels: 132 opaque PV panels mounted in checkerboard format on the roof. Panels fixed at a 10° tilt angle, located 3 cm above plastic roof cover for airflow. Modules static or with trackers: Static modules. Orientation of the solar modules: Fixed 10° tilt, aligned with the North–South greenhouse orientation. |

| Reference | Observations |
|---|---|
| [72] | Distribution of the solar panels on the greenhouse structure: Mounted on south slope or north wall of the greenhouse. Configurations studied include: Compact rows, checkerboard pattern, east–west stripes, north–south stripes, dual-glass PV arrays. Modules static or with trackers: Static modules only. Orientation of the solar modules: South-facing roof integration (main orientation). Both east–west and north–south module alignment studied. |
| [73] | Distribution of the solar panels on the greenhouse structure: Panels placed on or above the greenhouse roof. Used to allow natural light entry while generating electricity. Static modules. Orientation of the solar modules: Not explicitly stated; assumed to align with roof slope or standard solar orientation in China. |
| [74] | Distribution of the solar panels on the greenhouse structure: PV modules mounted on the north-facing roof slopes only. Installed on 13 greenhouse structures totaling 1.4 MWp. Checkerboard or partial roof coverage not mentioned; full slope coverage on one side. Modules static or with trackers: Static modules; fixed installation at 15° tilt. Orientation of the solar modules: North-facing slope only (due to southern hemisphere location). |
| [75] | Distribution of the solar panels on the greenhouse structure: OPV modules integrated into greenhouse structures, in some studies positioned on roofs or façades. Generally assumed to replace conventional cladding or shading elements. Modules static or with trackers: Static modules only. |
| [76] | Distribution of the solar panels on the greenhouse structure: Roof-mounted configurations, checkerboard patterns, full coverage, segmented patterns, and integration with shading foils. Modules static or with trackers: Mostly static, with mention of dynamic Venetian-blind-type and micro-tracking systems. Orientation of the solar modules: South-facing, east-west, roof integrated; varies by installation. |
| [77] | Distribution of solar panels: Mounted on the roof of greenhouses as a shading strategy. Modules static or with solar trackers: Static modules only (no trackers mentioned). Orientation of solar modules: Not explicitly specified; presumed fixed horizontal or roof-angle mounted. Configurations described: Full roof coverage (reduced light transmission to 33%). Checkerboard layouts. Semi-transparent modules and flexible PV. |
| [78] | Distribution of solar panels: Roof-integrated, checkerboard pattern, straight-line arrangement, fresnel lens integration. Modules static or with solar trackers: Both static and trackers are mentioned, and single-axis and dual-axis tracking referenced in CPVT applications. Orientation of the solar modules: Not explicitly standardized; varies per case. Optimized tilt angles referenced in simulation studies. |
| [79] | Distribution of the solar panels on the greenhouse structure: Not specified. Whether the modules are static or have solar trackers: The article discusses both fixed and sun-tracking systems, but not in the context of greenhouses. Orientation of the solar modules: Not specified. |
| [80] | Distribution of the solar panels on the greenhouse structure: Installed on the roof of the container housing the reverse osmosis system. Static modules (no trackers). Orientation of the solar modules: South-facing, installed at a 30° inclination. Configurations: Only one configuration described. |

| Reference | Observations |
|---|---|
| [81] | Distribution of the solar panels on the greenhouse structure: Typically on the roof; one installation describes modules integrated into double glazing or facade panels. Static installations and dual-axis solar trackers used with Fresnel lens concentrators (e.g., South Korea). Orientation of the solar modules: Not consistently specified; assumed optimal for each location. Static conventional PV on roof, dual-axis tracking CPV/T with Fresnel lenses, semi-transparent PV glazing in facades, and water- and air-cooled PV/T modules. |
| [82] | Distribution of the solar panels on the greenhouse structure: Not applicable. The article does not describe photovoltaic panels but a control system responding to solar radiation input. Configurations: Curtain Rolling Machine (CRM) and film Rolling Machine (FRM). Controlled by fuzzy logic algorithm based on environmental inputs. |
| [83] | Distribution of the solar panels on the greenhouse structure: Grid Photovoltaic (GPV) panels installed on the front roof of the greenhouse. Static configuration (no tracking system). Orientation of the solar modules: Installed on a south-facing inclined roof (typical of CSGs); specific azimuth not detailed. Configurations: Narrow photovoltaic strips (approx. 9 mm width) arranged with varying gaps to form a grid pattern. Strip intervals tested from 1 mm to 20 cm to evaluate shading effects. |
| [84] | Distribution of the solar panels on the greenhouse structure: Not specified. Whether the modules are static or have solar trackers: Not specified. Orientation of the solar modules: Not specified. Configurations: Various configurations discussed in referenced studies but not detailed. |
| [85] | Distribution of the solar panels on the greenhouse structure: PV panels mentioned as integrated on roofs; no specific distribution detailed. Orientation of the solar modules: Not specified. Configuration: Rooftop solar PV, solar air pre-heaters, solar water heaters, and NIR-filtered PV cooling systems. |
| [86] | Distribution of the solar panels on the greenhouse structure: On the top surface of greenhouses or over field crops in APV setups. Includes checkerboard and straight-line patterns. Static installations and sun-tracking (one-axis and two-axis) systems. Orientation of the solar modules: Not always specified; in one experiment, modules are tilted at 32° (Nagpur case). Configuration: Static rooftop PV modules and sun-tracking PV modules. Dynamic tilt modules with reflective mirrors (greenhouse APV). |
| [87] | Distribution of the solar panels on the greenhouse structure: Integrated into rooftop structures, with variable coverage ratios (e.g., 20–37%). Static systems (no solar tracking mentioned). Configurations: ST-OPV covering 37% of rooftop, red and blue OPV configurations covering 27% of ground area (Germany), and ST-PPV with tunable thickness for AVT control. |
| [88] | Distribution of the solar panels on the greenhouse structure: Integrated into the roof or plastic covering of greenhouses. Designed for flexible roll-to-roll replacement. Static installation (no tracking mechanisms mentioned). Configuration: Uniform ST-OPV panel coverage of greenhouses, integration into plastic films for modular and flexible use, and simulated checkerboard patterns using inorganic panels also referenced for comparison. |

| Reference | Observations |
|---|---|
| [89] | Distribution of the solar panels on the greenhouse structure: PV modules mounted on the inner surface of the plastic film roof, facing south. Static modules (no tracking system). Orientation of the solar modules: Facing the southern sky with tilt angles 25° for the straight-line array (PVs), 20° and 26° for the checkerboard array (PVc; 15 upper and 15 lower modules). Configurations: PVs array with 30 modules in a straight line (Nov 2006–Oct 2007). |
| [90] | Distribution of the solar panels on the greenhouse structure: PV panels arranged in straight-line or checkerboard patterns on greenhouse roofs. Both static and sun-tracking PV modules are discussed. Orientation of the solar modules: Various orientations, including east–west and north–south roof configurations, depending on the site and study. Configurations: Static checkerboard (10–50% coverage), straight-line arrays (10–60% coverage), and elevated sun-tracking structures (4 m above ground in open field APV systems). |
| [91] | Distribution of the solar panels on the greenhouse structure: Panels mounted on the rooftop, simulating different shading configurations. Static modules. Configuration: Four rooftop configurations with shadings of 15% coverage, 30% coverage, 50% coverage, and 0% (unshaded control). |
| [92] | Distribution of the solar panels on the greenhouse structure: Shared structure designs with panels on the roof or integrated into greenhouse cladding. Static modules. Configuration: Discusses shared structure, adjacent systems (less preferred), and intelligent PV cover materials. |
| [93] | Distribution of the solar panels on the greenhouse structure: Panels elevated on a fixed structure over a 175 $m^2$ area, spaced with 3 m between rows. Static panels (no tracking systems used). Orientation of the solar modules: South-facing (azimuth 180°). Configuration: 8 tilt angle models tested, being M1– Annual optimum tilt (31.33°), M2– Tilt equal to latitude (39.93°), M3– Horizontal (0°), M4– Vertical (90°), and M5–M8 – Seasonal average tilt angles (winter to autumn). |
| [94] | Distribution of solar panels: Roof-mounted (e.g., checkerboard and asymmetric patterns), semi-transparent or partially covered roofs (e.g., 10–25% PV coverage commonly mentioned). Static modules. Orientation of the solar modules: South-facing in some case studies (e.g., Tehran); east-west orientations also referenced. |
| [95] | Distribution of solar panels on greenhouse structure: Not specified for greenhouses. Solar trackers are discussed in general; no specific application to greenhouses. |
| [96] | Distribution on structure: Elevated panels, spaced rows (e.g., 6 m in Oregon, 5–10 m in Montpellier studies), panels integrated on greenhouse roofs (mono-pitched), straight and checkboard patterns for greenhouse studies. Static or trackers: Static (USA, Sardinia) and 2-axis sun tracking (Italy). Orientation: East–West, North–South, and tilting angles up to 30° or adjusted by trackers. |
| [97] | Distribution of the solar panels: South-oriented roofs of each of the two spans of the greenhouse were completely covered with photovoltaic modules. 144 multi-crystalline silicon PV modules were used, covering 50% of the roof area. Modules static or with solar trackers: Static modules. Orientation of the solar modules: South-oriented, mounted on a pitched roof with a 22° slope. |
| [98] | Distribution of solar panels on the greenhouse structure: One 24-V, 100-W poly-crystalline silicon solar panel installed externally and wired to the greenhouse power and sensor systems. Modules static or with solar trackers: Static module. |

| Reference | Observations |
|---|---|
| [99] | There is no photovoltaic (electricity-generating) installation described in this article. The study focuses on thermal energy collection using PE and iron collectors, located under the north roof of the greenhouse. The collectors are static. Not oriented for solar optimization — the focus is on internal thermal convection and retention, not solar orientation. |
| [100] | Distribution of solar panels: Roof-integrated (in various configurations: straight-line, checkerboard, etc.), dynamic blade systems, and mounted on north walls. Static modules or solar trackers: Both static and dynamic systems are described. Dynamic systems include solar tracking and adjustable blade systems. Orientation of the modules: Varied (North-South, East-West). Dynamic systems adjust orientation based on solar angle. |
| [101] | Several configurations are reviewed. Distribution: Mounted on greenhouse roofs in both fixed and movable (dynamic) arrangements. Static vs. Solar Trackers: Both static and dynamic systems are discussed. Orientation of the solar modules: East–West orientation is generally preferred based on multiple studies. Specific azimuth optimization (e.g., 6° SW in Northern China, 37° in Bayburt, Turkey). |
| [102] | Distribution of the solar panels: OPV modules placed on top of the greenhouse polyethylene roof cover (partial coverage). Modules: Static (no trackers). Orientation: Various angles tested (0°, 22°, 41°, 46°) in both lengthwise and widthwise orientations. |
| [103] | Distribution of panels: PV films placed horizontally and at 30° tilt over plexiglass boxes used as growth environments. Static or with trackers: Static (no tracking systems used). Orientation: Both horizontal (0°) and tilted at 30° (angular orientation). Not oriented directionally (N-S or E-W) in standard PV sense, but tested in various light conditions (sunlight and artificial light). |
| [104] | Distribution of panels: Panels installed on greenhouse roofs (semi-transparent), or elevated 2 m above open fields for agrivoltaic systems. Static or tracking: Both fixed and solar tracking configurations are discussed. Orientation of modules: Passive greenhouses oriented East–West. Roof-mounted systems oriented South or based on shading optimization (checkerboard patterns also mentioned). |
| [105] | Distribution: PV modules are installed on the top brackets above greenhouses. For doubled film-column PVGs, modules are installed directly above the greenhouse roof. For terraced PVGs, modules are semi-transparent, placed on the sunny rooftop side with space left for sunlight. Static or trackers: All modules are static. Orientation: Not explicitly specified in degrees or direction; design aims to maximize solar radiation reception depending on structure. |
| [106] | Opaque PVs (CSCs): Positioned on greenhouse roofs, partial coverage (up to 30%, though ¡10% is optimal for crops like tomatoes). DSCs: Semi-transparent, integrated into greenhouse glazing. Allow selective light transmission. Static modules. No mention of trackers. Orientation: Not explicitly specified, though conventional greenhouse roof integration is assumed. |
| [107] | Distribution: PV modules were mounted on the southwest roof of a gable-roofed structure, covering 20% of the roof area. Tracking: Modules are static (no tracking system). Orientation: South-facing roof with 30° tilt angle. Alternative configurations: PVsyst simulations were used to test different tilt angles (20° to 60°) for energy generation comparison. |

| Reference | Observations |
|---|---|
| [108] | Ground-mounted: Panels 1 m above the ground, spaced 6 m apart, stilt-mounted panels 4 m above the ground with two variants, being full density (FD) – Four arrays spaced 3.2 m apart, and half density (HD)– Two arrays spaced 6.4 m apart. Greenhouse PV integration: PV modules cover part of the roof. All modules are static. Orientation: Tilted at 25°, fixed angle. |
| [109] | Distribution of the solar panels on the greenhouse structure: Flexible, semi-transparent photovoltaic films used as a greenhouse cover or shading element. Static modules. |
| [110] | Roof-mounted PV modules (partial or full coverage). Checkerboard pattern. Tessellated or linear arrangements. East-west and north-south oriented roofs. PV panels integrated or applied as roof elements. Dynamic photovoltaic systems (rotatable panels). Static or trackers: Both static and dynamic modules are mentioned. Some systems use rotatable panels for optimal tilt. Orientation: East-west and North-south. Roof tilt angles from 10° to 70° explored for optimization. |
| [111] | Distribution: PV panels in checkerboard arrays, 1 meter above the greenhouse roof. Modules: Dynamic, with adjustable angles (rotate on longitudinal axis). Orientation: Variable orientation based on months; angles from 128° to 180° for shading, 218° to 270° for unshading. Shading system replaces thermal screen. |
| [112] | Distribution of the solar panels on the greenhouse structure: Fixed on greenhouse roof (STPV area up to 27,200 $m^2$ in some scenarios). Modules: Static. Orientation of the solar modules: Not explicitly specified, but irradiance data from Qatar was used. |
| [113] | Distribution of the solar panels: Vertical rack with three layers of bifacial solar modules. Static or solar trackers: Modules are not fixed; they swing freely with wind-induced tilt (free-swinging). Orientation of solar modules: Orientation (azimuth) optimized to 260° in London, Ontario. The tilt varies dynamically based on wind speed and direction. |
| [114] | PV panel installation heights: 2–5 meters to allow cultivation or livestock below. Roof-mounted systems on greenhouses. Some configurations include single-row PV arrays for comparison. Some systems use static panels, others use tracking systems. Orientation details are not consistently specified, as the review compiles many studies. |

# 5 Type of photovoltaic models used

This section evaluates the types of photovoltaic models used in the reviewed works. From conventional opaque module installations to semi-transparent ones integrated into greenhouses, including bifacial panels and solar trackers. Modules are often combined to optimize overall electricity production and plant growth conditions, carefully balancing shading, light transmission, and energy efficiency.

The main photovoltaic technologies that have been identified are:

- **Crystalline Silicon:** Monocrystalline and polycrystalline silicon modules are the most common, with typical efficiencies ranging from 15% to 25%. Used in opaque, semi-transparent, and bifacial modules.
- **Amorphous Silicon and Thin-Film Technologies:** Includes CIGS, CdTe,

and amorphous silicon with lower efficiencies (5–20%) but advantages such as flexibility and lighter weight.

- **Organic and Polymer-Based Cells (OPV, STPV):** Known for semi-transparency, flexibility, and lightness, with efficiencies between 3% and 20%. Suitable for integration into greenhouses and buildings.
- **Concentrator and Advanced Technologies:** CPV (Concentrated PV), LSC (Luminescent Solar Concentrators), quantum dot cells, perovskites, and other emerging technologies with varying efficiencies, some theoretically reaching 28–38%.

Regarding the efficiencies and performance of the photovoltic panels used in agrivoltaics, the following key points were found:

- Nominal efficiencies range from 3–5% for OPV to over 25% for high-end monocrystalline silicon and multi-junction modules.
- Actual field efficiencies vary due to temperature, annual degradation ($\sim$0.5–1%), and environmental conditions.
- Semi-transparent panels balance light transmission and power output, with visible light transmittance typically between 10% and 50%, to optimize both electricity generation and crop lighting needs.

These photovoltaic panels are made of different materials including glass (double glass, tempered glass), polymers (PMMA, EVA, ETFE), and plastic substrates for flexible and semi-transparent modules. The panels also have spectral control coatings that block UV and NIR wavelengths while allowing PAR light transmission, essential for crop growth. There are also specific materials depending on technology, like CdTe and CIGS in thin-films, organic materials in OPV, and multilayer/concentrator materials for advanced cells.

The detailed information gathered from the reviewed articles are provided in Table 3.

Table 3: Types of photovoltaic models used in the reviewed works.

| **Reference** | **Observations** |
|---|---|
| [1] | Technology: Monocrystalline silicon cells. Efficiency: 18% efficiency. Manufacturing Materials: Monocrystalline silicon cells embedded in a high-resistance polymer. Module Specifications: Dimensions: 1.116 m $\times$ 0.165 m, thickness of 2 mm. Flexible and semi-transparent PV panels. |
| [2] | The article reviews multiple studies, mentioning different PV technologies, including: Monocrystalline silicon Bifacial PV modules, Organic photovoltaic (OPV), Semi-transparent PVs, Concentrated PVs (CPV). Efficiency varies depending on technology, but no specific efficiency values for a single installation are provided. |

| Reference | Observations |
|---|---|
| [3] | The review covers multiple PV technologies used in agrivoltaic systems: Monocrystalline silicon (c-Si), Bifacial PV modules, Thin-film PV technologies (CdTe, CIGS, amorphous silicon), Organic PV (OPV), Dye-sensitized solar cells (DSSC), Perovskite solar cells (PSC), Luminescent solar concentrators (LSC), Concentrated PV (CPV). Efficiency values vary but are not detailed for a single installation. Semi-transparent PVs are highlighted as suitable for greenhouses. |
| [4] | Technology: Monocrystalline photovoltaic solar panels. Efficiency: Not explicitly stated. Manufacturing Materials: Glass panels were used in the structure. Multiple Technologies: No additional photovoltaic technologies were mentioned. |
| [5] | Technology: Not explicitly mentioned; however, monocrystalline silicon technology is implied. Efficiency: Not specified in the document. Manufacturing Materials: Standard photovoltaic materials with glass covers. Multiple Technologies: No mention of bifacial or advanced PV technologies. |
| [6] | Technology: Not explicitly mentioned; monocrystalline silicon PVs are likely. Efficiency: PV energy production efficiency: Maximum 4.9%. Manufacturing Materials: Standard glass-covered photovoltaic modules. Multiple Technologies: No mention of bifacial or alternative PV technologies. |
| [7] | The review mentions various PV technologies, including: Monocrystalline silicon. Bifacial solar panels, Semi-transparent PVs, Organic photovoltaic (OPV) panels, Dye-sensitized solar cells (DSSC), Luminescent solar concentrators (LSC). Efficiency and materials are not detailed for a single installation. |
| [8] | The review mentions multiple PV technologies, including: Monocrystalline silicon, Bifacial PV modules, Thin-film technologies (CdTe, CIGS), Organic photovoltaic (OPV), Dye-sensitized solar cells (DSSC), Luminescent solar concentrators (LSC). No single efficiency value is provided, as different studies are reviewed. Semi-transparent PVs are highlighted for greenhouse applications. |
| [9] | The article reviews various PV technologies, including: Monocrystalline silicon, Bifacial PV panels, Semi-transparent PV Organic photovoltaic (OPV), Dye-sensitized solar cells (DSSC), Luminescent solar concentrators (LSC), Photovoltaic-thermal (PVT) modules, Flat-plate collectors (FPC) and evacuated tube collectors (ETC). Efficiency values vary depending on the study reviewed but are not specified for a single installation. |
| [10] | Mentions the use of flexible photovoltaic panels in greenhouse structures. Does not provide details on technology (monocrystalline, bifacial, etc.), efficiency, or manufacturing materials. |
| [11] | Technology: Semitransparent Organic Solar Cells (OSCs). Efficiency: Opaque OSCs: 11%-12% efficiency. Semitransparent OSCs: 9.5%-10% efficiency. Manufacturing Materials: ITO (Indium Tin Oxide) electrodes, ZnO electron transport layer, $MoO_3$ hole transport layer, Encapsulation with glass for durability. Multiple Technologies Combined: Dielectric Bragg reflector coatings to reduce infrared (IR) radiation losses. |
| [12] | Technology: Flexible thin-film PV modules. Semitransparent PV modules for optimizing light transmission. Hybrid PV/T (Photovoltaic-Thermal) collectors. Efficiency: No specific module efficiency mentioned. Some references to bifacial and semitransparent PVs for improved energy yield. Manufacturing Materials: Thin-film PV technology (flexible and lightweight). Hybrid PV/T modules include thermal absorbers for heat recovery. |

| Reference | Observations |
|---|---|
| [13] | No specific PV module technology or efficiency is provided. Discusses different PV technologies in general: Monocrystalline and polycrystalline silicon PV, flexible thin-film PV, semitransparent photovoltaic glass, bifacial solar panels. Highlights hybrid photovoltaic-thermal (PV/T) collectors as a promising technology. |
| [14] | Technology: Opaque multicrystalline silicon PV panels. Efficiency: Not explicitly mentioned. Manufacturing Materials: Polyvinyl chloride (PVC) cladding for gable-roof PVGs. Glass cladding for Venlo-type PVG. |
| [15] | Technology: Bifacial photovoltaic modules (dual-sided energy capture). Efficiency: No specific efficiency values are mentioned. Manufacturing Materials: Double-glass frameless bifacial PV modules. Model: BNDMJ60H(S)375-395-N-TOPCON (Raytech New Energy Materials Co., Ltd., China). Multiple Technologies Combined: Bifacial technology to capture reflected and scattered light. |
| [16] | Technologies Mentioned: Opaque monocrystalline silicon, semi-transparent PV modules, spectrally selective PV modules (targeting specific light wavelengths), bifacial PV modules, thin-film amorphous silicon, organic photovoltaic (OPV), dye-sensitized solar cells (DSSC), luminescent solar concentrators (LSC), concentrated photovoltaic (CPV). Efficiency: Specific efficiency values not provided. Some technologies noted for low efficiency but high PAR transmission compatibility. Manufacturing Materials: Describes glass-glass modules, polymer layers, microcell silicon, and dichroic films. Multiple technologies combined: Descriptions include hybrid systems combining tracking + spectral filtering or CPV + LSC. |
| [17] | Technology Monocrystalline modules (in open AVS). Semi-transparent PV modules (in closed AVS/greenhouses). Bifacial modules also mentioned in comparative studies. Efficiency: Not specified for any module type in the document. Manufacturing Materials: Glass-glass and polymer-based materials implied in semi-transparent PV applications. Multiple Technologies Combined: Different configurations include opaque and semi-transparent modules in the same AVS networks (e.g., Nigeria). |
| [18] | Technology Monocrystalline and polycrystalline (1st generation). Thin-film (2nd generation, including CdTe). Organic, dye-sensitized, and perovskite solar cells (3rd generation). Tandem and polymer–nanoparticle composite cells (4th generation). Bifacial modules: Frequently used, especially in vertical installations. Efficiency Monocrystalline/polycrystalline: 18–27%. CdTe thin film: Up to 22.6%. Organic/perovskite: 21%+. Tandem cells: Mentioned for their high potential (GaAs + Si). Manufacturing Materials: Glass–glass, polymer-based encapsulation, thin-film heterojunctions, and nanoparticle composites. Combined Technologies: Opaque and semi-transparent modules, bifacial modules, and spectrally selective PV options discussed. |
| [19] | Technology PV modules with 390 Wp rating each (specific technology not stated, but standard mono or polycrystalline implied). Efficiency not explicitly mentioned. Manufacturing Materials: Galvanized iron (GI) pipe for structural support, reinforced cement concrete (RCC) for foundation. Module material type not detailed |
| [20] | Technology Mixed, including: Standard PV panels (majority), Semi-transparent PVs, Spectrum-separating PVs, Organic PVs in some greenhouse examples. Efficiency not consistently reported across all studies. Manufacturing Materials not specified in most studies; some mention semi-transparent or tinted panels. |

| Reference | Observations |
|---|---|
| [21] | Two types og technology: Traditional monocrystalline silicon panels (TPM) – 0% transmittance and semitransparent panels (SPM) – 40% light transmittance, neutral spectrum (no wavelength selectivity). Efficiency not specified numerically in terms of module efficiency. Manufacturing Materials: Semitransparent panels: 3.2 mm CdTe + 0.4 mm EVA. |
| [22] | Technologies: Monofacial and Bifacial (e.g., at Heggelbach site). Mention of semi-transparent and wavelength-selective modules in other referenced studies. Efficiency: Not numerically specified for all modules, but some mentions of performance improvement strategies (e.g., bifacial gain). Manufacturing materials not explicitly stated. |
| [23] | Technology: Bifacial monocrystalline semi-transparent photovoltaic modules. Efficiency of the modules not explicitly stated in numerical terms. Manufacturing materials: Solar cells encapsulated between two glass sheets, Module specifications: Length 2.089 m, Width 1.033 m, Thickness 5.5 mm, Solar cells per unit 80, Cell dimensions 166 mm × 83 mm, Active surface per module: 1.1 $m^2$, Total surface per module: ∼2.12 $m^2$. Theoretical shading per module: ∼51.9% |
| [24] | Technology: Multicrystalline silicon PV modules (REC 235PE, REC Solar, USA). Efficiency of the modules: Not explicitly mentioned in percentage. Manufacturing materials: Standard multicrystalline silicon; no additional details provided. PV area and power: Total PV area: 475 $m^2$ (238 $m^2$ per span). Total active cell area: 420 $m^2$. Installed power: 68 kWp. |
| [25] | Ecolume: Not specified. Pankará Village: Not specified. Campo: Not specified. UFAL: Not specified. Fotovoltaica UFSC R&D: Bifacial modules, Spaced-cell bifacial modules, Spectrally selective photovoltaic technology. Efficiency and manufacturing materials are not specified for any of the modules. |
| [26] | Technology: Not specified in terms of exact technology (e.g., monocrystalline, bifacial). Efficiency of the modules not provided. Manufacturing materials not specified. Complementary elements: 24 highly reflective aluminum mirrors installed to recover solar radiation otherwise lost due to panel inclination. |
| [27] | Amorphous silicon (a-Si). Flexible solar panels (type not specified). CZTSe and CZTS (quaternary materials proposed for low-cost thin-film solar cells). Others discussed: Crystalline silicon, CdTe, CIS, CIGS. Efficiency and materials vary depending on the technology: Thin-film efficiency up to 11% (CZTSe), Theoretical efficiency up to 32.2% for CZTS, Triple-junction III–V cells may reach 40%+ (theoretical 50%) but with high cost. |
| [28] | Technology: Crystalline silicon (c-Si), specifically semi-transparent c-Si modules. Efficiency of the modules not specified. Manufacturing materials: Structural layout tested: Glass / Encapsulant / Encapsulant / Back cover (glass or transparent backsheet). 18 samples with combinations of: Encapsulants: EVA (Ethylene Vinyl Acetate), POE (Polyolefin Elastomer), TPO (Thermoplastic Polyolefin); Back covers: Rear glass or transparent polymer backsheet. Multiple encapsulant types tested with both rear glass and transparent backsheets. |
| [29] | PV Types for Greenhouse Types 1, 2, 3: Model REC 235 PE, Multi-crystalline silicon technology, efficiency 14.2%, active cell area 1.46 $m^2$; PV Type for Greenhouse Type 4, Model Qcells S 205, Mono-crystalline silicon technology, efficiency 15.2%, active cell area: 1.17 $m^2$. Manufacturing Materials not explicitly detailed beyond silicon base and crystalline structure. |
| [30] | Polycrystalline silicon technology. The efficiency of the modules ranges between 5.43% and 6.28%, depending on lighting spectrum. Manufacturing materials: Polycrystalline silicon; BP Solar MSX-005F modules. |

| Reference | Observations |
|---|---|
| [31] | Technology: Crystalline-silicon PV modules. Efficiency: Not explicitly stated. Manufacturing materials: Not detailed beyond crystalline-silicon. Multiple technologies: No. |
| [32] | Technology: Monocrystalline silicon (YGL 60 Cell Series, 295W from Yingli Solar). Efficiency: Not directly stated, but typical STC data from datasheet was used. Materials: Silicon-based; glass covered; standard commercial modules. Other configurations analyzed: Semi-transparent silicon-based panels (47% transparency) and semi-transparent organic PV modules were mentioned for comparison in literature but not applied in the main modeling. |
| [33] | Technology: Not explicitly specified (assumed standard opaque crystalline modules). Efficiency: Not stated. Manufacturing materials: Panels considered opaque to solar radiation (0% transmission). Glass cladding has 80% light transmission. Combined technologies: No. |
| [34] | Technology: Not explicitly stated in detail for the specific project. Efficiency of the modules: Not specified. Manufacturing materials: Photovoltaic glass is mentioned (in general, for integration into roof materials). |
| [35] | Technology: Polycrystalline photovoltaic panels. Efficiency: Not explicitly stated. Manufacturing materials: Mentioned as polycrystalline; emissivity $\epsilon = 0.9$, absorptivity $\alpha = 0.1$, reflectivity r = 0. |
| [36] | Technology: Monocrystalline, Semi-transparent modules, Flexible panels, Spherical microcells, Organic photovoltaic cells. Efficiency of modules: Not always specified numerically; emphasis is placed on transparency and balance with crop needs. Manufacturing materials: Includes semi-transparent materials, organic photonic crystals, and flexible solar films. |
| [37] | Technology: Not explicitly specified (assumed conventional crystalline silicon based on context). Efficiency: Conversion efficiency under standard conditions noted ($\eta$r), but exact module efficiency not specified. Manufacturing materials: Not explicitly mentioned. |
| [38] | Technologies: Monocrystalline, Polycrystalline, Bifacial, Semi-transparent (STPV), Organic Photovoltaics (OPV), Dye-sensitized solar cells, Concentrator PV (CPV). Efficiency: Not uniformly specified, but bifacial panels noted to have 20% more energy yield. Materials: Silicon (Si), CdTe, CIGS, GaAs, amorphous silicon. |
| [39] | Technology: Amorphous silicon (a-Si), Monocrystalline silicon (mono-Si), Polycrystalline silicon (poly-Si), Multicrystalline silicon, Organic photovoltaics (OPV), Dye-Sensitized Solar Cells (DSSC), HIT (heterojunction with intrinsic thin-layer). Efficiency of the modules: OPV: $\leq$10% (typical). Monocrystalline, polycrystalline: higher but not always specified. Manufacturing materials: In OPV common active layer materials include: P3HT:PCBM (transmittance 8–19.4%), PTB7-Th:IEICO-4F (PCE 10%, AVT 30%), FTAZ:IT-M, other blends targeting NIR absorption. Others: standard c-Si, CdTe, CIGS, DSSC-based technologies. |
| [40] | Technology: Polycrystalline. Efficiency: Not explicitly stated, but reference is made to typical silicon panel efficiencies of 17–18%. Manufacturing materials: Not specified in detail, but standard polycrystalline silicon; mirrors made of aluminum. Model: SYM 30P-7V, Sunenergy (Zollino, Lecce, Italy). |
| [41] | Technology: Thin-film amorphous silicon. Efficiency: Not directly provided, but transmission rate was 19%. Manufacturing materials: Transparent zinc oxide back conductive layer. Clear front glass coated with Fluorine Tin Oxide. |

| Reference | Observations |
|---|---|
| [42] | Technology: Thin-film amorphous-silicon (a-Si). Efficiency of the modules: 7% nominal module efficiency. Manufacturing materials: Ethylene-tetrafluoroethylene laminated soft modules, no metallic frame. Note on installation: Installed inside the roof to avoid damage from weather, affecting conversion efficiency slightly. |
| [43] | Technology: Organic photovoltaic (OPV) modules. Efficiency of the modules: Not directly measured in this study; referenced values from similar modules ranged from 1% to 3% PCE (from Subramaniam et al., 2020). Manufacturing materials: Semi-transparent polymer-based materials (specific spectral characteristics for red and blue light transmission). Multiple technologies combined: No combination; two types of OPV modules used independently in different greenhouses. |
| [44] | Technology: Bifacial, semi-transparent micro-spherical monocrystalline silicon PV cells (Sphelar® technology). Efficiency of the modules: Average measured module efficiency $\approx$ 1.0–1.2% (low due to experimental nature and system shading). Manufacturing materials: 3.8 mm glass / 3.0 mm resin with embedded microcells / 3.8 mm glass structure. Cells are 1.2 mm in diameter, embedded in transparent resin, arranged at 18.9 cells/cm$^2$. |
| [45] | Technology: Crystalline Silicon (c-Si, including poly- and mono-). Amorphous Silicon (a-Si), Perovskite, Dye-sensitized, Organic Photovoltaics (OPV), Microspherical solar cells. Efficiency of the modules: Crystalline Si: up to 26.7%, Amorphous Si: around 10.2%, Perovskite: around 19.7%, Dye-sensitized: around 11.9%, organic: around 11.2%. Manufacturing materials: Semiconductors, inorganic and organic molecules, depending on the module type. |
| [46] | Technology: Organic Photovoltaic (OPV) modules, flexible and semitransparent (OPV1 and OPV2 types). Efficiency of the modules: OPV1: 3.5% and OPV2: 3.0%. Manufacturing materials: Roll-to-Roll printed OPVs from ASCA; materials based on flexible organic layers. Transparency and Color: OPV1: AVT 17.79%, CCT 6014K (pale greyish tint); OPV2: AVT 21.8%, CCT 3213K (pale reddish tint). |
| [47] | Technologies mentioned: Monocrystalline silicon, Polycrystalline silicon, Organic photovoltaic (OPV), Semi-transparent modules, Dye-sensitized solar cells (DSC), Perovskite solar cells. Efficiency of OSC (organic solar cells) approx. 8.25%. General efficiency ranges not always specified. Manufacturing materials: Polycarbonate, glass, polyethylene (LDPE, HDPE, LLDPE), PVC. |
| [48] | Technology: Semitransparent Organic Solar Cells (STSCs) using PTB7-Th:IEICO-4F as the active layer. Efficiency of the modules: 9.4% power conversion efficiency. Manufacturing materials: Active layer: PTB7-Th:IEICO-4F. Electron transport layer: ZnO. Hole transport layer: $MoO_3$. Encapsulation: Transparent conductive materials. Comparison system: Silicon (Si) photovoltaic modules with 21% efficiency were used for comparison. |
| [49] | Technology: Not specified for the simulated theoretical case study. However, literature references include crystalline silicon, thin-film, and flexible PV modules. Efficiency of the modules: Not specified in the article. Manufacturing materials: Not specified. Multiple technologies: Not used in the model; the article discusses data derived from various studies that included different technologies, but these are not part of the core methodology. |
| [50] | Technology: Monocrystalline (Sanyo HIP-200BA3 HIT). Efficiency of the modules: 17%. Manufacturing materials: HIT (Heterojunction with Intrinsic Thin-layer) structure — hybrid monocrystalline silicon and thin-film technology. |

| Reference | Observations |
|---|---|
| [51] | Three types: Glass-encapsulated silicon PV modules (bifacial monoSi). Technology: Monocrystalline silicon, bifacial. Efficiency: 22.5%. Material: Glass encapsulation. Light transmission: 23%; Plastic-encapsulated silicon PV modules (bifacial monoSi): Technology: Monocrystalline silicon, bifacial. Efficiency: 22.5%. Material: ETFE plastic encapsulation. Light transmission: 23%; OPV (organic photovoltaic) modules: Technology: Organic photovoltaics. Efficiency: 4.5% (2.8% operational). Material: PBTZT-stat-BDTT-8 based in blue with stripy layout. Light transmittance in PAR range: 21.4%. |
| [52] | Technology: Not specified in detail; reference to general use of photovoltaic panels. Efficiency: Not provided. Manufacturing materials: Not specified. |
| [53] | Multiple technologies: Monocrystalline silicon: efficiency up to 19.8%. Polycrystalline silicon: efficiency around 14.2%. Amorphous silicon (a-Si) thin film: efficiency around 5.8%. Semi-transparent monocrystalline (e.g., spherical micro-solar cells): efficiency between 0.6%–4.5%. Heterojunction with intrinsic thin layer (HIT). Organic solar cells (OSCs). Dye-sensitized solar cells (DSSCs). Perovskite solar cells (PSCs). Manufacturing materials: Varied based on technology, including indium tin oxide, polycarbonate, polymethyl methacrylate, LDPE, etc. |
| [54] | Technology: Not explicitly stated, but likely standard monocrystalline or polycrystalline given context and power ratings. Efficiency of the modules: Not specified. Manufacturing materials: Not specified. System specifications: 12 PV modules of 260W each (total 3120W), with 4 batteries of 200Ah. |
| [55] | Technology: Monofacial, bifacial, semi-transparent, semi-scenic, organic (OPV), concentrator (CPV), photoelectrochromic. Efficiency: General efficiency for bifacial noted as 80%; OPV around 10%. Materials: Bifacial and monofacial panels: standard silicon-based. OPV: flexible, organic materials. Photoelectrochromic: tungsten oxide and graphene quantum dots. |
| [56] | Technology: Polycrystalline silicon, semi-transparent photovoltaic modules (including micro-spherical cells), amorphous silicon, and organic photovoltaics (OPV) are discussed. Efficiency of the modules: Efficiency examples not numerically stated for all; CPC–PV/TE hybrid system mentioned with efficiency up to 20.06%. Manufacturing materials: Includes polycrystalline silicon, amorphous silicon, CIGS thin films, and organic photovoltaic materials. |
| [57] | Technology: Multicrystalline silicon (mc-Si) photovoltaic modules. Efficiency of the modules: Not explicitly stated. Manufacturing materials: Included in Ecoinvent dataset; modeled with balance of system components (mounting, inverter, electric installation). |
| [58] | Technology: Polycrystalline silicon PV modules. Efficiency of the modules: Initial generation capacity: 100 $W/m^2$. Degradation rate: 3% in the first year, 0.8% annually afterward. Manufacturing materials: Not detailed beyond polycrystalline silicon. |
| [59] | Technology: Organic Photovoltaics (OPV). Efficiency: Not explicitly stated; referenced literature suggests potential efficiency up to 16% under lab conditions. Manufacturing materials: Not detailed; OPV modules manufactured by OPVIUS (Germany); semi-transparent and flexible. |

| Reference | Observations |
|---|---|
| [60] | The distribution of solar panels in panels mounted on the south-facing gable roof. Three types of layouts: HDPV 1 (High-density, full south roof coverage), LDPV 1 (Low-density, partial south roof), LDPV 2 (Lower-density, sparse layout). Sun-tracking system: dynamic system with rotating PV modules around a fixed axis. Four tracking positions modeled: Closed (parallel to the roof), Quasi-perpendicular (max irradiance incidence), No-shading (no shadow on neighboring modules), Open (parallel to sunlight). Orientation: East–West orientation, with south-facing roof. |
| [61] | Technology: Monocrystalline silicon (monoC–Si), Semi-transparent (12% transparency). Efficiency: 15.96%. Manufacturing Materials: Model Ferrania Solis Clear AP 60-265, Cell size: 156 mm × 156 mm, 60 cells/module. |
| [62] | Technology: Monocrystalline silicon (for PV/PT hybrid collectors), Photo-thermal (PT) collectors, Passive optical rasters based on total internal reflection. Efficiency: For concentration collectors (PV/PT) it starts at 28% (20 °C inlet), decrease to 15–10% (50 °C inlet) and for facade collectors it is from 38% to 0% (20–40 °C inlet). Manufacturing Materials: Glass Fresnel lenses, manufactured via continuous melting technology and reflective rasters integrated in double glazing. Modules: width 750 mm × length 2000 mm. |
| [63] | Technology: Monocrystalline silicon, Polycrystalline silicon, Thin-film CdTe, Organic PV (semi-transparent, PTB7-Th: IEICO-4F), Bifacial PV, Concentrated PV (CPV), Luminescent Solar Concentrators (LSC). Efficiency (examples from cases): Organic PV with 9.4% efficiency, 24.6% visible light transmittance; CPV (concentrator) with system 6.8% higher efficiency than standard PV; Si-based standard PV with typically 15–20%. Materials: Glass–glass bifacial modules, PMMA-based covers for spectral splitting, $Ta_2O_5$, $TiO_2$, $SiO_2$ for polymer film concentrators. |
| [64] | Technology: CIGS (Copper Indium Gallium Diselenide) thin-film technology. Efficiency of the modules: 15% (conservative assumption). Manufacturing materials: Vapor-deposited CIGS layers on glass substrate, encapsulated with a second glass pane. Module size: 1.2 m × 0.6 m, weight: 12.6 kg. |
| [65] | Technology: Semi-Transparent Photovoltaic (STPV) panels, Not specified if crystalline, organic, or thin-film—general STPV category used. Efficiency of the modules: Adjusted by transparency and environmental conditions, Panel degradation: 0.5%–1% annually, BESS efficiency loss  2% annually. Manufacturing materials: Not detailed beyond transparency characteristics (10%–40% STPV used for simulations). Example transmissivity coefficients: 0.671, 0.597, 0.522, 0.448, 0.337. |
| [66] | Not applicable – no PV modules are used in the greenhouse analyzed in the article. |
| [67] | Technology: Organic Photovoltaics (OPV), Semi-transparent, flexible, polymer-based modules (PBTZT-stat-BDTT-8). Efficiency of the modules: Rated 3.3% at STC. Measured daily averages of 0.58–0.82%, max 1.10% (morning peak). Manufacturing materials: Flexible modules (Opvius, Germany), Substrate Polyethylene-based with a thickness of 0.6 mm, dimensions of 800 mm × 1000 mm, active area of 655 mm × 855 mm, and encapsulated with ETFE-foil tape. Comparison panel: Polycrystalline Si-PV module (Bluesun Solar, China), rated at 45 W, 10.5% average efficiency. |
| [68] | Technology: Amorphous silicon (a-Si) thin-film. Efficiency of the modules: Nominal 5.8%, Overall system efficiency 4.7%, performance ratio 0.739–0.892 depending on month. Manufacturing materials of evaporated silicon on polymeric substrates. Each module is 3.399 × 0.461 $m^2$ with 92 W nominal power. Manufacturer: Fuji Electric Systems Co., Ltd., Japan. |

| Reference | Observations |
|---|---|
| [69] | Technology: Not explicitly detailed; standard opaque photovoltaic modules assumed. Efficiency of the modules: Not stated directly; performance analysis focuses on temperature impact on PV efficiency. Manufacturing materials: Not specified; however, integration challenges with non-transparent modules discussed. Mentions new modules with transparent parts between cells being developed (under patent at the time), but not used in the simulations due to lack of certification. |
| [70] | Technology: Multicrystalline silicon PV modules. Efficiency of the modules: Not explicitly given; efficiency behavior simulated using temperature-dependent models. Decrease in performance at higher cell temperatures. Manufacturing materials: the PV layers include Front glass, Upper EVA, ARC (Anti-Reflective Coating), PV cell, Back EVA, Tedlar-based backsheet. Module Details per Layout: La: LDK_DS_660P, 189 W max power; Lb: 90 W panels; Lc: 21 W panels. |
| [71] | Technology: Flexible opaque photovoltaic panels. Efficiency of the modules: 19%. Manufacturing materials: Model MX-FLEX Protect; Dimensions 1000 × 500 × 3 mm; Weight 1.7 kg. Electrical specs: 100 Wp, Voc: 23.4 V, Vmp: 19.8 V, Icc: 5.4 A. |
| [72] | Technology: Amorphous silicon thin-film, Monocrystalline silicon, Polycrystalline silicon, Dual-glass assembly with polysilicon, Organic photovoltaics (OPV) also discussed theoretically. Efficiency of the modules: Amorphous silicon 5–9%, Monocrystalline 13–18%, Polycrystalline 12–16%, Dual-glass's efficiency improved by 4% over regular modules. Manufacturing materials: Glass + EVA + silicon (for dual-glass), Transparent and semi-transparent coatings for spectrum tuning, Thin-film cells laser scribed for transmittance. Light transmittance tailored between 10%–41%. Modules selectively block UV/NIR while transmitting PAR. |
| [73] | Technology: Transparent and semi-transparent PV modules, Thin-film and crystalline silicon types implied. Efficiency of the modules: Not numerically specified. Manufacturing materials: Not specified in detail. Mention of flexible and selective plastic films for spectral optimization. Integration with LEDs for night lighting. Allows anti-seasonal production and heating in winter. |
| [74] | Technology: Monocrystalline silicon PV modules. Efficiency of the modules: Not explicitly stated; implied typical monocrystalline module performance. Manufacturing materials: 4368 modules, each rated at 320 Wp. Modules likely framed glass-on-glass or glass-backsheet type (not detailed). Inverters: 2 × 400 kW, 1 × 500 kW. |
| [75] | Technology: Organic Photovoltaic (OPV) modules; References to semi-transparent, flexible, lightweight OPV cells; Comparisons with Si-based, dye-sensitised, perovskite, quantum dot modules. Efficiency of the modules: Not numerically specified in the article. Manufacturing materials: OPVs do not require frames. installed on wood or plastic structures; Specific references to polymer-based layers, organic dyes, semi-transparent flexible laminates. Multiple technologies: Article discusses OPV, Si-based, CdTe, CIGS, dye-sensitised, and quantum-dot PV technologies in context. |
| [76] | Technologies: Crystalline silicon (c-Si), amorphous silicon (a-Si), organic photovoltaic (OPV), dye-sensitized solar cells (DSSC), perovskite, concentrating PV (CPV), luminescent solar concentrators (LSC). Efficiency: Ranges from 0.4% (LSC) to 12.7% (tandem pero, DSSC up to 9.2%, OPV 4–7.75%, and CPV up to 28.2%. Manufacturing materials: Glass-glass modules, dye-sensitized layers, polymer solar cells, spherical microcells (Sphelar®), amorphous silicon thin-film, quantum dots. The article explores comparative performance of multiple PV technologies used in STPV systems. |

| Reference | Observations |
|---|---|
| [77] | Technologies: Opaque PV panels, Semi-transparent PV, Spherical microcell PV (solar transmissivity 73%). Efficiency: Not quantified numerically in this article. Manufacturing materials: Not detailed; references to flexible PV and spherical microcells. Combinations: Mention of combined shading and energy production using semi-transparent PVs. |
| [78] | Technologies: Monocrystalline silicon (mono-cSi), Multicrystalline silicon (multi-cSi), Amorphous silicon (a-Si), Semi-transparent modules, Flexible thin film, Spherical microcells, PVT and CPVT collectors. Efficiency: Varies; some values include PV conversion 4.5% to 11.3%, CPVT thermal up to 65%, and total energy (electric + thermal) up to 160 kWh/m$^2$/year. Manufacturing materials: Not detailed; refers generally to crystalline silicon types and Fresnel lenses in CPVTs. Combinations: Several integrations PV + heat pump, PV + underground storage, PV + LEDs. |
| [79] | The article reviews various technologies: Crystalline silicon (mono- and poly-crystalline), GaAs (Gallium Arsenide), Amorphous silicon, CdTe, CIS/CIGS, Organic/polymer-based, Dye-sensitized cells, Hybrid cells (organic-inorganic). Efficiency of the modules: Reported efficiencies vary by technology: Crystalline Si up to 25.6%, CIGS up to 20.5%, CdTe up to 21.0%, Organic: ∼11%, and Dye-sensitized up to 11.9%. Manufacturing materials: Include silicon (crystalline and amorphous), CdTe, CIGS, polymers, organic compounds, etc. |
| [80] | Technology: Not explicitly mentioned (likely monocrystalline, typical for such setups, but not specified in the article). Efficiency of the modules: Not specified. Manufacturing materials: Not specified. Combination of technologies: Not mentioned. Multiple installations with different technologies: Not mentioned. |
| [81] | Technology: Monocrystalline (m-Si), Polycrystalline (p-Si), Amorphous silicon (a-Si), CIGS, CdTe, Organic thin-film, Multi-junction (e.g., InGaP/GaAs/InGaAs). Efficiency of the modules (ranges from Table 2): c-Si ∼25%, a-Si ∼10%, CIGS ∼20.5%, CdTe ∼21%, and multi-junction up to ∼38%. Manufacturing materials: Crystalline silicon, amorphous silicon, chalcogenides, polymers, and III–V compounds. PV/T and CPV/T systems combine electricity and heat generation. |
| [82] | Technology: Not applicable. Efficiency of the modules: Not applicable. Manufacturing materials: Not applicable. Combination of technologies: Not applicable. Multiple installations with different technologies: Not applicable. |
| [83] | Technology: Described as GPV (grid-type photovoltaic panels); specific cell type not mentioned. Efficiency of the modules: Not specified. Manufacturing materials: Not specified. |
| [84] | Technology: General references to photovoltaic systems (PV, CPV, PV/T); specific technologies not detailed. Efficiency of the modules: Not specified. Manufacturing materials: Not specified. If multiple technologies are combined: Mentioned (e.g., PV/T, CPV/T) but no details provided. If more than one installation with different technologies: Not applicable. |
| [85] | Technology: General references to solar PV and solar cooling; no mention of module types (monocrystalline, polycrystalline, etc.). Efficiency of the modules: Not specified. Manufacturing materials: Not specified. If multiple technologies are combined, list them all: Mentions possible combination with phase change material storage, solar air/water heating, and thermal curtains. If more than one installation with different technologies, mention each one: Not applicable. |

| Reference | Observations |
|---|---|
| [86] | Technology: Monocrystalline (used in simulations and some field trials). Polycrystalline (e.g., 7.2 kW plant in India), Semi-transparent modules (for greenhouses), Bifacial modules (mentioned in simulations). Efficiency of the modules: Not explicitly stated; temperature coefficient of -0.442%/°C given for a Tata Power 250W module. Manufacturing materials: Not specified. If multiple technologies are combined, list them all: Semi-transparent PV, bifacial, monofacial modules depending on configuration. If more than one installation with different technologies, mention each one: Yes, the article includes multiple case studies with various module types and configurations. |
| [87] | Technology: Semitransparent Organic Photovoltaics (ST-OPVs), Semitransparent Perovskite Photovoltaics (ST-PPVs), Some mentions of dye-sensitized and amorphous silicon technologies in other case studies. Efficiency of the modules: OPV up to 20%, PPV over 26% (theoretical and lab-scale), Example LUE values of ST-PPVs achieved up to 5.7%. Manufacturing materials: OPVs with various organic donor/acceptor blends (e.g., PM6:Y6, PTB7-Th-based combinations), PPVs with Metal halide perovskites such as CsFA and MA-based compositions. No hybrid installations described; each study refers to a single technology per case. Multiple studies referenced with different module technologies and AVT values. |
| [88] | Technology: Semi-transparent Organic Photovoltaics (ST-OPV). Efficiency of the modules: Lab-scale PCEs up to 13.1%, AVT (Average Visible Transmittance) up to 50.05%, LUE (Light Utilization Efficiency) up to 5.01%. Manufacturing materials: Organic semiconductors including polymer donors and non-fullerene acceptors (e.g., Y6-series, ITIC-series). Not combined with other PV technologies, but various donor:acceptor combinations are analyzed. Numerous ST-OPV blends analyzed in simulations; no physical installations reported by the authors. |
| [89] | Technology: Amorphous-silicon (a-Si). Efficiency of the modules: 7% nominal module efficiency. Manufacturing materials: Photoactive cell laminated in 1 mm thick ethylene-tetrafluoroethylene (ETFE) plastic. Same module technology used for both array configurations. |
| [90] | Technology: Monocrystalline silicon, Polycrystalline silicon, Semi-transparent building-integrated PV (BIPV), Organic photovoltaics (OPV). Efficiency of the modules: Specific efficiencies not consistently reported; energy outputs vary (e.g., 8.25 kWh/m$^2$/year in Spain, 637 kWh/year in China greenhouse). Manufacturing materials: Not detailed for each study, though OPVs include P3HT:PCBM photoactive layers. Detailed comparisons between OPV, BIPV, semi-transparent and opaque PV modules were provided. |
| [91] | Technology: Opaque PV panels. Efficiency of the modules: Not specified in this article. Manufacturing materials: Not specified; the panels are treated as opaque elements ($\tau$m = 0). Only opaque panels considered. The same panel type was used with different coverage ratios. |

| Reference | Observations |
|---|---|
| [92] | Technology: Semitransparent organic solar cells (OSCs), Pb-based quantum dots (QDs), Pb-free halide perovskites, Copper-doped InP/ZnSe quantum dots, Dye-sensitized solar cells (DSSCs), Amorphous tungsten oxide ($WO_3$), Building-integrated photovoltaics (BIPVs). Efficiency of the modules: OSCs up to 17.5%, Pb-QDs: ∼9%, Pb-halide perovskites up to 26%, DSSCs ∼8%, Semitransparent polymer solar cells 7.7%, LSCs with QDs ∼3.4%. Manufacturing materials: Organic semiconductors, Pb-based and Pb-free QDs, polymers, $WO_3$ films, metal oxides, carbon allotropes (graphene, fullerenes), and nanostructured elements. Technologies are evaluated separately and comparatively within the review.No physical installations are presented; rather, multiple technologies are discussed in terms of potential use. |
| [93] | Technology: Standard crystalline silicon (∼19%), Premium crystalline silicon (∼21%), and thin film (∼18%). Efficiency of the modules: Standard ∼19%, premium ∼21%, and thin film: ∼18%. Manufacturing materials: Crystalline silicon (standard, premium) and thin film (material not specified but noted for red spectrum responsiveness). Simulated performance under each of the eight tilt configurations. |
| [94] | Technology: Monocrystalline silicon, semi-transparent BIPV, organic solar cells (OSC), linear Fresnel lenses, PV/T systems. Efficiency of the modules: Ranges from ∼11.2% to 67% combined thermal and electrical in hybrid systems. Manufacturing materials: OSCs with green-light selective layers, encapsulated glass silicon, hybrid CPV elements. |
| [95] | Technology: Monocrystalline silicon, polycrystalline silicon, amorphous silicon, microcrystalline silicon, cadmium telluride, copper indium diselenide. Efficiency of modules: Not specified numerically for greenhouse applications; general trends discussed (some hybrid systems report thermal + electrical efficiency above 50%). Manufacturing materials: Various semiconductors including silicon-based and thin-film technologies. |
| [96] | Technology: Polycrystalline (Italy, USA), Monocrystalline (assumed but not explicitly detailed), Semitransparent photovoltaic (STPV) and bifacial (reviewed as promising), Opaque PV (conventional). Efficiency of the modules: Not numerically specified. Manufacturing materials: Not detailed per case; general references to crystalline silicon, STPV modules. Comparative discussion between opaque and STPV; also bifacial technology mentioned. |
| [97] | Technology: Multi-crystalline silicon. Efficiency of the modules: 14.2% (under standard test conditions). Manufacturing materials: Standard multi-crystalline silicon (e.g., 60-cell REC 235PE modules). Other technical data: Peak rated power of the PV system: 68 kWp. Total PV area: 475 $m^2$ (active cell area: 420 $m^2$). |
| [98] | Technology: Polycrystalline silicon (poly-Si). Efficiency of the modules: Not numerically stated. Manufacturing materials: Polycrystalline silicon solar panel. Other relevant components: 75 Ah battery storage, DC-DC buck converters (24V to 12V and 5V for system operation), MPPT charge controller. Energy monitoring via voltage and current sensors. |
| [99] | Not applicable — This article does not include photovoltaic modules (monocrystalline, bifacial, etc.). |

| Reference | Observations |
|---|---|
| [100] | Technologies: Polycrystalline silicon, Monocrystalline silicon, Amorphous silicon, Organic Photovoltaic (OPV), Dye-Sensitized Solar Cells (DSSC), Triple-junction cells (in CPV/T systems). Efficiency: Polycrystalline ∼14–15.2%, Monocrystalline up to 19.8%, Amorphous ∼7–9.8%, OPV ∼4% (commercial), reported 3–11.6 kWh/$m^2$-year generation, CPV/T up to 144 kWh/$m^2$-year electric and 180 kWh/$m^2$-year thermal. Materials: Silicon-based (poly, mono, amorphous), organic materials, Dye-sensitized (DSSC), and concentrator-based reflective materials (Fresnel mirrors, aluminum). |
| [101] | Technology: Monocrystalline silicon, semi-transparent crystalline silicon, organic photovoltaics, luminescent solar concentrators, and hybrid PV/T (photovoltaic/thermal) modules. Efficiency: Varies by module type; detailed figures provided in Table 5 for PV/T. Manufacturing materials: Conventional materials like polycarbonate, glass, polyethylene. Advanced materials including: Micro-nano photonic structures, $TiO_2$ mixed with LDPE, Five-layer polyethylene, and Polycarbonate and glass spectral variations. |
| [102] | Technology: Organic Photovoltaic (OPV), semi-transparent and flexible. Two types tested: Module A (OPVIUS, Germany) and Module B (InfinityPV, Denmark). Efficiency: Module A – ∼2.3% (manufacturer data), actual measured conversion efficiency ∼0.8%; Module B – ∼4% (manufacturer data). Manufacturing materials: Polymer-based organic semiconductors. Specific materials: poly(3-hexylthiophene) (P3HT) as donor and phenyl-C61-butyric acid methyl ester (PCBM) as acceptor. Encapsulation: Laminated thin transparent plastic film. No silicon-based panels used in this study. |
| [103] | Technology: Semi-transparent, spectrally selective thin-film silicon pseudo-modules (non-electrically active, but optically accurate). Efficiency: Not directly stated; modules are not electrically functional, designed for light filtering/transmittance studies. Manufacturing materials: a-Si:H (amorphous silicon), AZO (Al-doped ZnO), Ag (Silver), and glass substrate. Layer stack: AZO/a-Si:H/Ag/AZO/Ag/AZO. Overall thickness: 0.7 $\mu$m. |
| [104] | Technologies: Monocrystalline silicon, semi-transparent PV modules, spherical silicon microcells, organic solar cells (OSCs), and PVT hybrid collectors. Efficiency: Specific values mentioned: 18% for monocrystalline, 4.5% and 1.6% for semi-transparent modules with spherical cells. Manufacturing materials: Silicon (mono-Si), spherical silicon microcells, organic materials, polycarbonate sheets (greenhouse covering). |
| [105] | Technology: Polycrystalline silicon double-glazed PV modules. Efficiency: Not directly specified. Manufacturing materials: Double-glazed (glass-glass encapsulation). |
| [106] | Technology: Crystalline silicon solar cells (opaque), Dye-Sensitized solar Cells (DSCs, semi-transparent). Efficiency: Not specified numerically. Manufacturing materials: $TiO_2$-coated glass with dyes and electrolytes. |
| [107] | Technologies: Mono PERC PV (Monocrystalline Passivated Emitter Rear Contact), Mono BPERC PV (Monocrystalline Bifacial PERC). Efficiency: Mono PERC 18.8%, Mono BPERC: 18.5%. Manufacturing materials: Modules – 72-cell configuration (6 × 12), each 365 Wp. Installed with 0.08 m air gap for ventilation. Combined use: 6 Mono PERC PV modules (3 on roof, 3 outside) and 6 Mono BPERC PV modules (all outside the building). |
| [108] | Technology: Monocrystalline silicon (Trina Solar TSM300-P14A). Efficiency: Ranges from 12.75% to 14.93% depending on configuration. Manufacturing materials: Not explicitly detailed beyond silicon-based PV. |

| Reference | Observations |
|---|---|
| [109] | Technology: Innovative flexible photovoltaic films (experimental), polymer-based. Efficiency of the modules: Not explicitly quantified; however, it is stated that efficiency does not exceed 10%. Manufacturing materials: Polyvinyl butyral (PVB) lamination, PET/ITO substrates, and conducting polymer Pedot-PSS. |
| [110] | Technology: Monocrystalline silicon, Bifacial silicon, Semi-transparent organic photovoltaic (OPV), Spectral selective thin films, Dye-sensitized solar cells, Electrochromic glass, Quantum dot PV (Cu-doped InP/ZnSe), and spherical microcells. Efficiency of the modules: OPV showed 15% less PAR reduction with 12% higher cucumber yield. Semi-transparent silicon PV with 68% transparency used. Some materials (e.g., ITO/Ag layers) show ¿95% visible transmittance and 90% infrared reflectance. Manufacturing materials: Glass encapsulated silicon, plastic encapsulated silicon, ITO (indium tin oxide) coatings, Nanofluid spectral separators, and photoselective covers for NIR reflection and visible transmission. |
| [111] | Technology: Polycrystalline silicon modules (Model YGE 60 Cell 40 mm YL260P-29b). Efficiency: 15.9%. Manufacturing materials: Not explicitly specified, but typical for this model (glass + EVA + silicon + polymer backsheet). |
| [112] | Technology: Semi-transparent photovoltaic (STPV). Efficiency of the modules: 7% ($\eta$PV = 0.07). Manufacturing materials: Not detailed, but panels mentioned as semi-transparent, clear solar glass possibly used. |
| [113] | Technology: Bifacial. Efficiency: Not explicitly stated. Manufacturing materials: Mono crystalline silicon (Heliene 72M-400 G1 Bifacial used in simulations). Rear side energy generation adjusted by a bifaciality factor of 0.65. |
| [114] | The article refers to various technologies across studies: Monocrystalline silicon, Organic photovoltaics (OPV), Dye-sensitized solar cells (DSSC), and thin-film technologies. Efficiencies vary (e.g., OPV modules with 2.1% efficiency mentioned). Semitransparent panels are discussed in greenhouse applications (transparency up to 68%). |

# 6 Crops present in the installation

This section details the types of crops suitable for agrivoltaic systems, with a special emphasis on agrivoltaic greenhouses. The most Commonly Reported Crops include:

- **Vegetables:** *Tomato* (*Solanum lycopersicum*) is by far the most frequently cited crop, including multiple varieties (e.g., Daniela, Pristyla, Ramyle, Racymo, Shiren). Other common vegetables include: *cucumber, lettuce, bell pepper, eggplant, zucchini, pumpkin, broccoli, onion, garlic, spinach, chili pepper, celery, radish, mustard, cabbage, arugula.*

- **Fruits:** *Strawberry* is frequently mentioned, along with *raspberry, blackberry, blueberry, guava, watermelon, melon, grape, apple, pear, kiwi, passion fruit, goldenberry, granadilla.*

- **Cereals and Grains:** Crops such as *wheat* (spring, winter, and durum), *corn (Zea mays)*, *rice*, *millet*, *oats*, and *rye* are discussed, mostly in land-use simulations or yield equivalency (LER) studies.

- **Legumes and Oilseeds:** *Soybean, mung bean, red bean, peanut, sesame.*
- **Herbs and Medicinal Plants:** *Basil, mint, tulsi, gotu kola, coriander, wild garlic, aloe vera, tea tree, cassia, turmeric, ginger, vetiver.*
- **Flowers and Ornamentals:** *Rose, poinsettia, kalanchoe, chrysanthemum, dracaena, cyclamen, ficus, orchids, petunia, salvia, marigold, violet.*
- **Others:** *Microalgae* (e.g., *Chlorella vulgaris, Arthrospira platensis, Chlorococcum sp., Desmodesmus sp.*), *fungi* (e.g., *Pleurotus ostreatus*), and rare or high-value crops are also considered.

It is also important to consider the light needs of the crops to determine if they are suitable for agrivoltaic systems. Some studies have classified crops based on Daily Light Integral (DLI) requirements:

- **Low-light (<10 mol/m²/day):** Dracaena, Kalanchoe, Poinsettia.
- **Medium-light (10–20 mol/m²/day):** Ficus, Asparagus, Spinach, Basil, Strawberry, Lettuce, Chrysanthemum, Rose.
- **High-light (>20 mol/m²/day):** Cucumber, Sweet Pepper, Tomato.
- **Shade-tolerant crops:** (e.g., leafy greens, mushrooms, ornamentals) are preferred under high PV coverage or opaque modules. Simulations often recommend crop rotation or seasonal species adjustment for optimal productivity.

There are also other key aspects to consider regarding the changes in the form of growing crops under photovoltaic panels. Many studies investigate PV coverage, light spectra, and microclimate modification, often without live crop trials. However, others include detailed field setups with crop density, irrigation, and orientation. Some works used simulations and modeling to research these changes. Crops like tomato, lettuce, and cucumber are often used as proxies in spectral and thermal modeling. Some studies suggest seasonal rotation of crops(e.g., Chlorococcum sp. in winter and Desmodesmus sp. in summer). There are also some studies that regarded special systems such as vertical farming and multi-layered cultivation are discussed, especially for combining shade-tolerant and light-demanding species.

The detailed assessment of each reviewed paper is probided in Table 4.

Table 4: Types crops used in the reviewed works.

| Reference | Observations |
|---|---|
| [1] | The article does not specify the crops present inside the PV greenhouse. |

| Reference | Observations |
|---|---|
| [2] | The article does not focus on a specific photovoltaic greenhouse with crops. However, it reviews studies that mention: Greenhouse crops Open-field agrivoltaic crops Pasture-based agrivoltaic systems (e.g., sheep grazing) Some reviewed studies discuss shade-tolerant crops and crop yield under PV shading, but without detailing a specific installation. |
| [3] | The article does not describe a single PV greenhouse with specific crops. It reviews different studies, analyzing: Shade-tolerant crops Crop yield under agrivoltaic shading Crop-specific light requirements Some studies in the review mention: Tomatoes grown under organic PV (OPV) greenhouses Lettuce, maize, and wheat in agrivoltaic conditions Shade-adapted crops benefiting from agrivoltaic shading Berry crops under PV systems (e.g., raspberries, blueberries) |
| [4] | Tomato crops (modeled as two-meter-high plants arranged in rows). |
| [5] | The article includes a theoretical analysis of plant solar radiation needs, but no specific crops were cultivated in the experimental prototype. The study considers the minimum and maximum light requirements for various plant species: Tomato (Lycopersicon esculentum) Cucumber (Cucumis sativus) Lettuce (Lactuca sativa) Carnation (Dianthus caryophyllus) Strawberry (Fragaria x ananassa) Ornamental plants (e.g., geranium, rose, chrysanthemum, poinsettia) The study calculates shading levels necessary for optimal crop growth. |
| [6] | No real crops were cultivated, but the study modeled solar radiation requirements for various crops, including: Tomato (Lycopersicon esculentum) Lettuce (Lactuca sativa) Cucumber (Cucumis sativus) Strawberry (Fragaria × ananassa) Carnation (Dianthus caryophyllus) Various ornamental plants (geranium, rose, chrysanthemum, poinsettia) The study used simulation models to determine how the shading adjustments affect these crops. |
| [7] | No specific crops are described, but the article reviews: Tomatoes, lettuce, cucumbers, strawberries, and ornamental plants in agrivoltaic systems. Shade-tolerant crops that benefit from agrivoltaic shading. Crop yield variations due to shading in different agrivoltaic setups. |
| [8] | No specific greenhouse crop trials are described. The review discusses crops studied in agrivoltaic research, including: Tomatoes, lettuce, cucumbers, strawberries, and ornamental plants Shade-tolerant crops like spinach, kale, and mustard greens Pasture crops for livestock grazing Analyzes crop yield changes due to shading under PV panels. |
| [9] | No specific crops are described, but the article discusses: Tomatoes, lettuce, cucumbers, strawberries, and ornamental plants in solar greenhouses. Shade-tolerant crops that benefit from agrivoltaic shading. The effect of PV shading on crop yields and microclimate conditions. |
| [10] | The study discusses crop production in greenhouses but does not specify particular crops in the photovoltaic greenhouse system. |
| [11] | No real crops were cultivated. Simulation modeled greenhouse conditions for tomatoes as a reference crop. Greenhouse temperature and humidity settings based on optimal tomato cultivation: Daytime temperature: 21°C–28°C Nighttime temperature: 17°C–18°C Relative humidity: 60%–80% The study considers how light transmittance affects plant growth but does not include experimental crop trials. |
| [12] | No specific crops cultivated in experimental trials. Review discusses crops commonly found in agrivoltaic systems, such as: Tomatoes, lettuce, spinach, onions, and ornamental plants. Floriculture crops under PV-powered lighting. Shade-tolerant crops recommended for PV greenhouses. |

| Reference | Observations |
|---|---|
| [13] | No specific crops are described. The article discusses the impact of energy-efficient greenhouse technologies on crop yield. Mentions that shade-tolerant crops are suitable for PV-integrated greenhouses. |
| [14] | The study evaluated the yield of 14 crops in different PVG types (horticultural and floricultural crops). High-light demanding crops (DLI ¿ 30 mol/$m_2$/day): Tomato, cucumber, sweet pepper. Medium-light demanding crops (DLI 10-20 mol/$m_2$/day): Asparagus, basil, lettuce, strawberry, spinach. Florals: Chrysanthemum, rose, ficus. Low-light demanding crops (DLI 5-10 mol/$m_2$/day): Ornamentals: Dracaena, kalanchoe, poinsettia. Findings: PVG with 25% PVR: Suitable for all crops, including high-light-demanding crops, with yield reductions below 25%. PVG with 50% PVR: Acceptable for medium-light crops; high-light crops suffered yield reductions of up to 39%. PVG with 60% PVR: Acceptable only for low-light crops. PVG with 100% PVR: Suitable only for shade-tolerant ornamental crops. |
| [15] | Lettuce (C3 crop): Grown in experimental greenhouses. Grew better under ST conditions due to its low light saturation point. Tomato (C3 crop): Grew better under RT conditions, as it requires more light. Chili Pepper (C3 crop): No significant yield difference between ST and RT. Millet (C4 crop): Higher net photosynthetic rate under RT. Spring Wheat (C3 crop): No significant photosynthetic differences between ST and RT. Crop rotation strategy tested for optimizing APV system efficiency: Tomato, chili pepper, strawberry, eggplant, cucumber, watermelon. Dynamic PV tracking strategies adjusted seasonally based on crop growth stage. |
| [16] | This is a review article, but it cites studies that investigated crops including: Tomato, Lettuce, Spinach, Basil, Wild rocket, Strawberry, Pepper, Flowers (Iberis, Cyclamens, Petunias) Crop responses vary by PV coverage ratio (e.g., ¡25% PV coverage maintains yields for light-demanding crops). |
| [17] | General Categories Horticultural crops (used in most AVS applications)<br>Specific crops not detailed for all projects, but:<br>Cabbage reported to thrive under shading in southern Benin (Guinea climate zone)<br>Tomato reported to underperform under greenhouse AVS compared to open fields<br>Crops Not Present No AVS applied to cereal crops like maize, millet, sorghum. |
| [18] | This is a review article, so it compiles results from many global studies. Listed crops include: Lettuce, Cucumber, Durum wheat, Chili (Capsicum annuum var. glabriusculum), Tomato (Solanum lycopersicum var. cerasiforme), Maize, Oats, Potatoes, Grapes, Fruit trees, Grass and forage crops. |
| [19] | Rice: Boro, Aman, and Aus varieties. Vegetables: Cabbage, baby watermelon, cauliflower, cucumber. The system supports year-round cultivation without crop type restrictions. |
| [20] | Vegetables (majority): Lettuce (Lactuca sativa L.), Tomato (Solanum lycopersicum L.), Sweet pepper, spinach, basil, onion, garlic, wild rocket, cabbage, broccoli, celeriac. Cereals: Maize, rice, wheat, rye. Legumes and oilseeds: Soybean, red bean, mung bean, sesame, green beans. Fruits: Grapes, strawberries, apples, kiwifruit, raspberries, blackberries. |
| [21] | Soybean (Zhonghuang-13 variety). |

| Reference | Observations |
|---|---|
| [22] | Crops listed by site: Heggelbach, Germany: Winter wheat, clover grass, celeriac, potato. Montpellier, France: Lettuce, cucumber, French bean, durum wheat. Santiago de Chile: Broccoli, cauliflower, kale, potato, pumpkin. Chiba Prefecture, Japan: Cabbage, cucumber, eggplant, peanut, tomato, taro, yam. Italy (Rem Tec projects): Winter wheat, maize, tomato, watermelon. China (Tonking projects): Rice. Arizona, USA: Cabbage, chard, kale, tomato, onion. |
| [23] | Strawberries (mentioned as a crop used in previous related research within the same setup). Additional crops are not explicitly listed for this specific experimental run. |
| [24] | No specific crops were cultivated during this study. However, previous references suggest usage for tomatoes, basil, cucumber, Welsh onion, and ornamental/nursery crops in similar structures. |
| [25] | Ecolume 17 types of vegetables (not individually listed): Fish (aquaponics system), Chickens (eggs), Umbu seedlings (native plant for reforestation). Pankará Village: Watermelon, General vegetables (400 $m^2$ garden). Campo: Bell peppers, Kale, Cilantro, Scallions. UFAL: Sugarcane. Fotovoltaica UFSC R&D. Crops not specified yet (to be determined in trials). |
| [26] | No specific crops are cultivated or analyzed in this study. The analysis focuses on shading behavior, not agronomic performance. |
| [27] | Tomatoes (Ureña-Sánchez et al.). Freshwater production and general crop cultivation in a solar-wind desalination greenhouse (Mahmoudi et al.). General vegetable crops implied in protected agriculture systems (not individually listed). |
| [28] | No specific crops tested in this study. However, referenced crops benefiting from diffuse light include: Tomato, Cucumber, Lettuce, Roses, Blueberries, Sweet peppers, Eggplants. |
| [29] | Real crop trials mentioned: Tomato, Lettuce, Basil, Cucumber, Cherry tomato, Poinsettia, Welsh onion, Microalgae (experimental). The article also discusses crop physiology under shade, yield losses, and growth adaptation strategies. |
| [30] | No specific crops are mentioned in the installation. The article focuses on sensor operation and PV performance under artificial horticultural light spectra, not on plant growth results. |
| [31] | Specific crops: Soybean, Groundnut (peanut), Maize, Rapeseed, Rice, Wheat. Vegetables (mentioned in broader analysis). |
| [32] | Specific crop: Tomato (modeled using the TOMGRO model). |
| [33] | Specific crop: Tomato (mature plants, 2 meters tall, arranged in spaced rows). |
| [34] | Not specifically listed; general mention of "modern agricultural planting," "vegetables," and "ecological agriculture" (Fujitsu Xintian factory farm example in Japan includes vegetables). |
| [35] | Specific crop: Tomato (Lycopersicon esculentum). |
| [36] | Specific crops: Tomato, Lettuce, Pepper, Spinach, Broccoli, Melon, Arugula, Flowers (in floriculture greenhouse), Welsh onion. General crops: Mentioned generally in contexts of compatible agriculture. |
| [37] | No actual cultivation reported (simulation-based study). Crop suitability analyzed: Based on Daily Light Integral (DLI), the greenhouse is suitable for: Medium light demanding crops: Asparagus, Basil, Lettuce, Strawberry, Spinach, Chrysanthemum, Rose, Ficus. Low light demanding crops: Dracaena, Kalanchoe, Poinsettia. High light demanding crops (e.g., Tomato, Cucumber, Sweet Pepper): Not suitable due to lower winter solar radiation in Harbin. |

| Reference | Observations |
|---|---|
| [38] | Specific crops mentioned: Turmeric, Ginger, Bottle gourd, Lady finger, Tomato, Eggplant, Pumpkin, Green chili, Bitter gourd, Cucumber, Long beans, Cabbage, Kiwifruit, Zucchini, Sweet potato, Luffa, Broccoli, Maize, Winter wheat, Brinjal, Mung bean, Moth bean, Snap melon, Spinach, Cumin, Chickpea, Apple, Pear trees, Lettuce, Cucumber, Durum wheat, Aubergine, Rice, Soybean, Onion, Garlic, Rye, Italian ryegrass, Barley, Maize, Java tea, Potato, Chiltepin pepper, Jalapeno, Tomato, Basil, Aloe vera, Cassia angustifolia, Convolvulus pluricaulis, Capsicum annuum, Solanum lycopersicum. |
| [39] | Lettuce, Tomato, Strawberry, Pepper, Welsh onion, Cucumber, Mushroom. General evaluation of crop physiology under shading (photosynthesis, leaf area, etc.). |
| [40] | No crops were cultivated during the experiment. The study focused purely on energy and shading performance under clear sky conditions. |
| [41] | Specific crop: Kiwifruit (Actinidia chinensis deliciosa, cv. Jin Yan). |
| [42] | Welsh onion (Allium fistulosum L.) |
| [43] | Specific crops: Tomato (Solanum lycopersicum), cultivar: Maggie. |
| [44] | None. No crops were cultivated during the test period; the floor was concrete. |
| [45] | General crops and some specifics are mentioned: Tomato, Cucumber, Lettuce, Basil, Eggplants, Peppers, Paprika, Strawberries, Cotton (in intercropping or multiple-use greenhouses). |
| [46] | Tomatoes. |
| [47] | Crops present in the installation: Lettuce, Basil. General crop references include leafy greens and other vegetables (no exhaustive list of species). |
| [48] | Specific crop: Tomato. |
| [49] | High-light-demanding crops, specifically: tomato, cucumber, sweet pepper, eggplant, melon. |
| [50] | Tomato, Cucumber, Lettuce. |
| [51] | Specific crop: cucumber (cv. Megastar). |
| [52] | The review does not describe specific installations, but mentions some crops from referenced studies: Gerbera Jassemini, Tomato, Pepper, Cucumber, Melon. |
| [53] | Tomato, cucumber, lettuce, rocket, peppers, flowers, Welsh onion, tea tree, edible mushrooms, microalgae, general vegetables. |
| [54] | Tomatoes (Solanum lycopersicum), variety F1 Mongal. |
| [55] | Multiple crops are mentioned in experiments and referenced studies: General crops: wheat, maize, rice, forage clover, sugar beet, lettuce, tomato, basil, chicory. Specific crops mentioned: tomato, lettuce, chicory, basil, grape, maize, celery, potato, bok choy, jalapeño, peppers, cucumber, olives, winegrape, pear, apple, broccoli, chiltepin. |
| [56] | General crops and specific crops mentioned include: Rice, lettuce, peppers, cucumbers, tomatoes, flowers, chrysanthemums, Chinese kale, Chinese herbs (Ganoderma lucidum, Dendrobium officinale), cherry tomato, leaf lettuce, muskmelon, and others. |
| [57] | No crops. The agricultural production involves livestock — rabbits (pasture-fed). |
| [58] | Specific crop used for yield comparison: Tomato. |
| [59] | Tomatoes – specifically “Magnolia” (2018), “Shunit” (2019). |
| [60] | No specific crops were physically cultivated. Study focuses on simulation of irradiance and energy production. The target plane is 0.5 m above the ground, representing generic greenhouse-grown crops. |

| Reference | Observations |
|---|---|
| [61] | No specific crops grown yet. Future usage includes laboratory applications and limited crop area (1–2 $m^2$). Article suggests suitability for basil, pepper, cucumber, melon, eggplant (common Mediterranean crops with medium thermal requirements). |
| [62] | No specific crops mentioned. The greenhouse was mainly used for experimental energy performance evaluations. |
| [63] | Shade-intolerant crops: Corn, tomato, pumpkin, cabbage, cucumber, rice, watermelon, turnip. Shade-tolerant crops: Lettuce, parsley, kale, spinach, collard greens, taro, yam, sweet potatoes. Moderate/light tolerant: Beans, carrots, onions, cauliflower, green peppers. Low light: Mushrooms. Specific APV test crops: Lettuce, rice, alfalfa, grapes, potato, oats, sugar beet, wheat, celery, clover, celeriac, grass. Livestock included: Sheep, lamb, emu, rabbit (e.g., meat and grazing applications). |
| [64] | Microalgae species: Chlorococcum sp., Desmodesmus sp. Seasonal rotation: Chlorococcum sp. used in cooler months. Desmodesmus sp. used in warmer months. Selection based on productivity simulations under varying PV coverage. |
| [65] | Low light crops (DLI ¡ 10 mol/$m^2$/day): Dracaena, Kalanchoe, Poinsettia. Medium light crops (DLI 10–20 mol/$m^2$/day): Ficus, Asparagus, Spinach, Basil, Strawberry, Chrysanthemum, Rose, Lettuce. High light crops (DLI ¿ 20 mol/$m^2$/day): Cucumber, Sweet Pepper, Tomato. |
| [66] | Tomatoes (used as example crop for thermal/light needs). Reference to leafy vegetables for potential future modeling. |
| [67] | Not specified; experimental setup focused on panel performance. Greenhouse cover implied as suitable for Mediterranean crops based on shading and cooling effects. |
| [68] | Tomato (Solanum lycopersicum L.) cv Daniela. |
| [69] | Not specified. The study focuses on simulation of greenhouse climate conditions suitable for general agricultural crops. Importance of maintaining illuminance and temperature levels for year-round cultivation highlighted. |
| [70] | Vriesea poelmannii (ornamental flower). Planted in pots on concrete slabs. Crop height: 0.6 m above ground. |
| [71] | Tomato (Solanum lycopersicum, cultivar: Pristyla). Density: 0.7 plants/$m^2$. Grown in pots (40 pots × 3 plants/pot), 4 rows, 10 pots per row. Orientation: rows aligned North–South, drip irrigation system. |
| [72] | Tomato, Lettuce, Cucumber (used in spectral response modeling and field tests). Mushrooms (in low-light rear zones of the greenhouses). |
| [73] | General references to: Organic agricultural products. Rare and expensive seedlings. High-value crops. Specific crops not listed. |
| [74] | Passion fruit, tomato, taro, chili pepper. New experimental crops include: strawberry, guava, raspberry, cape gooseberry, giant granadilla, vanilla. |
| [75] | Tomato, lettuce, cucumber, basil, pepper, strawberry, guava, raspberry, medicinal plants. Referenced in OPV greenhouse literature and experimental modelling studies. |
| [76] | Lettuce, tomato, basil, spinach, pear, raspberry, blueberry, strawberry, guava, wild garlic, cucumber, water spinach, medicinal plants. Specific results reported for: tomato, lettuce, basil, spinach, pear, cucumber. |
| [77] | Crops discussed or tested in various cooling and PV integration studies include: Tomato, lettuce, cucumber, rose, sweet pepper, ornamental plants. |
| [78] | Various crops cited across referenced studies: Tomato, Welsh onion, strawberry, lettuce (Lactuca sativa), radicchio, valerianella, chrysanthemums, salvia, orchids, edamame, lemongrass, pepper (Piper). |

| Reference | Observations |
|---|---|
| [79] | Not applicable. No mention of crops or agricultural implementation within greenhouses. |
| [80] | Tomato (Solanum lycopersicum L.), varieties: Ramyle, Racymo. |
| [81] | Only general crop references: Tomatoes, Cucumber, Blueberries, Welsh onion. Generic references to vegetable crops Specific varieties not detailed. |
| [82] | Tomato seedlings (general reference). |
| [83] | No crops were present during the simulation; the greenhouse was empty during tests. Design considerations were made for crop lighting needs, but no specific crops were planted. |
| [84] | Tomato, cucumber, sweet pepper, zucchini, lettuce, melon, squash, eggplant, strawberry (mentioned as commonly cultivated crops in greenhouses, not linked to specific PV systems). |
| [85] | General crops referenced for analysis of light and $CO_2$ needs: Cold-tolerant crops. Generic mention of tomato, leafy vegetables. No specific crops associated with photovoltaic systems. |
| [86] | Tomato (in experimental setup at Nagpur, India). Chiltepin pepper, Jalapeño, Cherry tomato (in referenced studies). Lettuce, cucumber, wheat, corn. Shade-tolerant medicinal crops like aloe vera, mint, tulsi, and gotu kola. Horticultural crops: spinach, beets, peas, mustard greens, potatoes, radish, coriander, garlic. (All separated and listed in Tables 2 and 3 of the article.) |
| [87] | Various greenhouse crops cited across case studies, including: Tomato, cucumber, lettuce, basil, spinach, strawberry, wild strawberry, blueberry, sweet pepper, dracaena, kalanchoe, poinsettia, raspberry (Crops separated and reported as per context in each study.) |
| [88] | Crops discussed or referenced in case studies include: Tomato, lettuce, cucumber, shade-tolerant plants (general), berries, grapevines, vegetables, grassland crops. Note: No specific crop trial was conducted by the authors. |
| [89] | No crops present during experiments. Focus was on irradiance distribution and electrical generation only. |
| [90] | Tomato, lettuce, cucumber, pepper, strawberry, wild strawberry, blackberry, red raspberry, onion, rocket, spinach, maize, potato, jalapeño, celeriac, winter wheat. |
| [91] | The study focuses on radiation and evapotranspiration simulation; crops are not cultivated during the experiment. However, referenced crops from related works include tomato, cucumber, sweet pepper, and general greenhouse vegetables. |
| [92] | Referenced crops for PV greenhouse compatibility include: tomato, cucumber, sweet pepper, celery, mushrooms, tea tree, broccoli, floricultural species. |
| [93] | The study is simulation-based, but LER (Land Equivalent Ratio) was applied for: Turmeric, olive, winter cabbage, kiwifruit, corn, lettuce, bok choy |
| [94] | Tomato (extensively covered), cucumber, lettuce, wheat, green beans, Welsh onions, poinsettia (floriculture), flowers. |
| [95] | Not specified. Greenhouse use is discussed conceptually but without reference to specific crops. |
| [96] | Semi-arid pasture (Oregon State University). Maize (Zea mays L.) in Italy. General agriculture under experimental setups. Specific crops not listed for many sites, but crop productivity analysis is discussed. |
| [97] | Specific crop: Tomato (Solanum lycopersicum L., cv. Shiren) – cherry tomato variety. Cultivated in two cycles using hydroponics and coconut fiber substrate. |
| [98] | Specific crops: Capsicum annuum L. (ornamental pepper), Solanum lycopersicum (cherry tomato). |

| Reference | Observations |
|---|---|
| [99] | No crops were present during the experiment. (Deliberate choice to avoid interference in thermal performance evaluation). |
| [100] | Tomato, Cucumber, Sweet Pepper, Microalgae, Lettuce, Strawberry, Welsh Onion, Rose, Pepper. |
| [101] | This is a review summarizing multiple studies. The following crops are mentioned: Tomato, Sweet pepper, Lettuce, Rose, Marigold, Violet, Chili pepper, Lemon verbena, Triticum, Vetiver, Paprika, Eggplant, Coriander, Cherry tomato, Salicornia, Melon, Mango, Phalaenopsis. |
| [102] | Tomato. |
| [103] | Crops present in the installation: Lactuca sativa (lettuce), Ocimum basilicum (basil), Solanum lycopersicum (tomato), Chlorella vulgaris (microalga), Arthrospira platensis (microalga). |
| [104] | Tomato, lettuce, French bean, durum wheat, clover grass, celeriac, potato, maize, winter wheat, rice, cucumber, eggplant, peanut, pumpkin, cabbage (varieties). |
| [105] | Tea trees, Edible mushrooms, Tomatoes, Broccoli, Off-season vegetables, Potted vegetables, Celery. |
| [106] | Specific crops: Lettuce, Tomato, Radish, Passion fruit, French beans, Cucumber, Wheat. Crops under validation in DSCs installations: Ornamental plants (e.g., rose bushes) |
| [107] | Specific crop: Pleurotus ostreatus (Oyster mushroom). |
| [108] | Lettuce (Lactuca sativa). Discussed as a shade-tolerant crop; no other crops implemented in trials but others are suggested for future study (e.g., arugula, kale, chard, alfalfa, cassava, sweet potato) |
| [109] | Eggplant (Solanum melongena). |
| [110] | Cucumber, Basil, Tomato, Lettuce, Rose. General: leafy greens, shade-tolerant and light-demanding crops, vertical farming layers. |
| [111] | Specific crop: Rose (Rosa sp.). |
| [112] | Lettuce (for Qatar-specific case of year-round production). |
| [113] | Not specified. The study is focused on the technical and energy performance modeling of the racking system, not on specific crop integration. |
| [114] | Mentioned crops across various installations include: Grape, Apple, Pear, Tomato, Cucumber, Sweet pepper, Chiltepin pepper, Cherry tomato, Potatoes, Celeriac, Winter wheat, Grass clover, Lettuce, Corn, Pepper (Capsicum annuum). |

# 7 Regulations, Specifications, Decrees, or Laws Applied

This section details the information gathered on regulations, specifications, decrees and laws that affect agrivoltaic systems.

Most of the reviewed articles do not explicitly mention specific legal frameworks, regulations, or decrees related to photovoltaic greenhouse installations or agrivoltaic systems. Instead, the focus tends to be on environmental impact assessments, techno-economic feasibility, agronomic performance, and technological design.

Some works refer to general environmental or energy policies, such as the UK's 2008 target of 80% greenhouse gas (GHG) reduction by 2050 [78, 81], or the European Green Deal and Renewable Energy Directive (RED II) aiming to increase PV capacity and

reduce emissions [93].

A few standards relevant to energy efficiency and building performance are occasionally cited, including ASHRAE 90.1 (2016), ASHRAE 189.1 (2014), the Canadian National Energy Code for Buildings (NECB 2011) [85], and ISO standards related to Life Cycle Assessment (LCA) [80].

National or regional specific regulations are rare but notable:

- Italy imposes restrictions on PV greenhouse installations, such as limits on PV coverage (max 50% of greenhouse area), energy income vs. agricultural income balance, and suitability declarations [97].
- China's Shandong province provided feed-in tariffs and tax exemptions to support PV electricity sales in agricultural contexts [105].
- France and Germany have implemented financial support and economic assessments for agrivoltaic systems [114].
- Other mentioned frameworks include European standards for greenhouse structures (EN 13031-1:2001) [109], ASTM standards for transmissivity measurement [102], and national recovery programs supporting energy transition projects in Italy [103].

Many studies emphasize the need for policy development and social impact assessments but do not specify existing laws [96]. Lastly, several articles simply report no applicable regulations or focus purely on technical, environmental, or economic evaluations without legal context.

The detailed information gathered from each reviewed paper is provided in Table 5.

Table 5: Regulations mentioned in the reviewed works.

| **Reference** | **Observations** |
|---|---|
| [1] | Italian Decree of the President of the Republic No. 412 (August 26, 1993), concerning rules for designing, installing, and maintaining thermal installations in buildings to contain energy consumption. Regulations in Italy that ban PV installations on agricultural soils since 2013, promoting their use on existing structures like greenhouses. |
| [2] | The review discusses general policies and regulations affecting agrivoltaics, including: Land-use conflicts and policies promoting agrivoltaic installations. National regulations supporting dual-use solar farms. Challenges in policy frameworks for agrivoltaics worldwide. Specific regulatory frameworks in China and the USA. No single regulation is provided for a particular greenhouse project. |
| [3] | The article discusses agrivoltaic policy trends but does not focus on a single regulation. Land-use policies for agrivoltaics in various countries are covered. Energy and agriculture regulations worldwide are reviewed, including: Agrivoltaic incentives in France, China, and Italy. Land-use conflicts and dual-use policies. The need for agrivoltaic regulations supporting food-energy co-production. |
| [4] | Not specified. The study focuses on microclimate modeling rather than policy or regulations. |

| Reference | Observations |
|---|---|
| [5] | No specific legal framework is mentioned. The article discusses the importance of optimizing solar radiation for plant growth but does not reference national or international agrivoltaic regulations. |
| [6] | No specific legal framework is mentioned. The study focuses on optimizing shading rather than compliance with specific regulations. |
| [7] | The article reviews agrivoltaic policies and regulations, including: Incentives in France, China, and Italy for agrivoltaic projects. Land-use policies for agrivoltaics in different countries. The need for standardized regulations to integrate agrivoltaics with agriculture and energy production. |
| [8] | The article reviews policy trends but does not focus on a single regulation. Discusses agrivoltaic incentives and regulations in: France, China, Italy, Japan, Germany, and the USA. Land-use policies and subsidies supporting agrivoltaic adoption. The need for agrivoltaic-specific regulations to ensure food-energy coexistence. |
| [9] | The article discusses global policy trends but does not focus on a single regulation. Mentions agrivoltaic incentives and regulations in: France, China, Italy, Japan, Germany, and the USA. Policies supporting agrivoltaics as a dual-use technology. The need for standardized regulations to integrate agrivoltaics with agriculture and energy production. |
| [10] | No specific regulations or laws are mentioned in the document regarding photovoltaic greenhouse installations. |
| [11] | No specific regulations or policies mentioned. The study focuses on energy modeling rather than legal frameworks. |
| [12] | No specific policies or legal frameworks mentioned. Discusses economic feasibility and payback periods in different countries. Estimated payback time for PV-integrated greenhouses in Spain: $\sim$18 years. |
| [13] | No specific laws or regulations are provided. The article discusses global efforts to achieve zero-carbon agriculture in line with: The Paris Agreement Sustainability goals for greenhouse gas reduction The role of IoT and AI in meeting energy efficiency targets. |
| [14] | European and national regulations in Italy and France prohibit ground-mounted PV systems in agricultural areas. Some Italian regulations require that crop income must be equal to or higher than the income from PV electricity. |
| [15] | China's land-use policies pose challenges for large-scale APV deployment on arable land. CSGs (Chinese Solar Greenhouses) provide an alternative for integrating agrivoltaics without occupying farmland. China's carbon neutrality goals (2060) and renewable energy policies encourage the adoption of APV. |
| [16] | Refers to: Japanese Ministry of Agriculture guidelines allowing up to 20% yield loss tolerance in APV farms. German farmer thresholds for acceptable yield losses (also $\sim$20%). Mentions the importance of landscape integration regulations but no specific national laws are cited in detail. |
| [17] | No formal national regulations mentioned specific to AVS. Reference to international energy development policies and support from international agencies (e.g., GIZ, BMZ, USAID, BMBF). Emphasis on the need for integrated policy frameworks for successful AVS deployment. |
| [18] | The article does not mention specific regulations or national decrees. Policy discussion is general, referencing the need for supportive frameworks and the impact of land use efficiency (LER). |

| Reference | Observations |
|---|---|
| [19] | Bangladesh Energy Regulatory Commission Law (2003): Sets bulk electricity rate for solar power fed to the grid (5.29 BDT/kWh in this case). No greenhouse-specific regulations or decrees are cited. |
| [20] | Mention of Swiss policy: Agrivoltaics were not licensable until July 2022 in Switzerland. No specific international regulation referenced. |
| [21] | No national or regional regulations explicitly mentioned. |
| [22] | Reference to patent EP 2811819 B1 (Fraunhofer ISE) for APV system design. No specific national laws or government decrees explicitly detailed in the article. |
| [23] | No specific regulations, laws, or decrees are mentioned in the document. The project is funded by the Rural Development Programme 2014–2020 of the Region of Western Greece, specifically under: Sub-measure 16.1–16.2 "Establishment and operation of Operational Groups of the European Innovation Partnership for agricultural productivity and sustainability". |
| [24] | No specific laws or regulations mentioned in the article. |
| [25] | Brazilian Law 14,300 (2022): Legal framework for distributed micro and mini-generation (MMGD) and the Electricity Compensation System (SCEE). REN 482/2012: Earlier regulation enabling distributed generation. Regulatory mechanisms allow net metering but compensate only ∼70% of tariff value (excluding TUSD Fio B). No specific national guidelines for agrivoltaic systems yet. Distributed generation seen as most applicable for small-scale/family farmers. Business models explored: self-consumption, shared generation, cooperative models. |
| [26] | No specific regulations or legal frameworks are mentioned in the article. |
| [27] | No specific national regulations or decrees are mentioned. The article discusses the need for incentives and subsidies for renewable energy integration in agriculture. Emphasizes policy support and barriers to adoption (e.g., cost, access to grid, financing). |
| [28] | ASTM D1003 (for haze measurements). NEN 2675+C1:2018 (for Hortiscatter measurement standard). IEC 61215 (for UV aging/reliability tests). |
| [29] | Italy: "Conto Energia" incentive program (2007–2014). |
| [30] | The LED light simulator complies with IEC 60904-9 standards for solar simulator spectral emission. |
| [31] | In several provinces, regulations require PV components deployed on farmland to be elevated at least 2 meters above ground to allow for cultivation underneath. National-scale analysis considers reclamation policies and land use classifications post-2014. |
| [32] | ANSI/ASAE EP406.4 standard is referenced for ventilation area design (15–25% ventilator area to floor area). |
| [33] | Not explicitly mentioned; refers to ADEME 2007 energy price report as context for increasing energy-saving interest. |
| [34] | No specific regulations or decrees mentioned. However, government-led projects like the "National golden solar energy photovoltaic eco-agricultural demonstration project" are referenced. |
| [35] | Not specifically mentioned in terms of legal framework, regulations, or decrees. |
| [36] | Not explicitly mentioned. The article focuses on experimental and review data, not legal frameworks. |
| [37] | No specific national or regional laws mentioned. Simulation standards referenced include: PVsyst software data. China Photovoltaic Industry Association energy consumption standard (1.52 kWh/Wp). Financial and environmental payback period modeling based on standard economic formulas. |

| Reference | Observations |
|---|---|
| [38] | No specific legal or regulatory frameworks are mentioned in this review. However, policies and lack of incentives are listed as challenges in adoption. |
| [39] | Not specified in the article. |
| [40] | Italy's Feed-in Tariff regulation (Decree 5 July 2012): Installations integrated into greenhouse structures are eligible for a feed-in tariff halfway between rooftop and ground-mounted PV systems.Incentive rate mentioned: €0.327 per kWh produced. |
| [41] | Not specified in the article. |
| [42] | Not specified. |
| [43] | Not mentioned. |
| [44] | Not mentioned in the article. |
| [45] | Not specified in terms of specific regulations or laws. The article focuses on technical, environmental, and agricultural parameters rather than regulatory frameworks. |
| [46] | Heating temperature references based on FAO recommendations (20°C day / 16°C night). Thermal transmittance calculated according to UNE-EN 673. |
| [47] | Not specifically mentioned in the article. |
| [48] | Not mentioned in the article. |
| [49] | No specific regulations or laws are referenced for the installation itself. The article does mention EU's Common Agricultural Policy (CAP) support structures and their relevance to greenhouse-based horticulture. |
| [50] | The article mentions Turkish regulations regarding unlicensed electricity generation, particularly regarding net metering and grid feed-in tariffs. |
| [51] | Not specified. |
| [52] | Not mentioned in the article. |
| [53] | Environmental regulations influencing the maximum PV covering ratio to avoid affecting crop growth (specific legal texts not cited). |
| [54] | The crop variety was used under national and international legislations, with permissions aligned with IUCN policy. |
| [55] | The article references specific legal frameworks in: Japan: Legalized AV since 2013, prioritizing agriculture, setting maximum 20% reduction in crop yields, specific minimum installation heights, and removable PV structures. South Korea: Agricultural Land Law restricts AV systems; ongoing legislative reforms aim to allow 100 kW production per farmer and offer financial incentives. Also mentions the lack of harmonized EU-level regulation and policy gaps across countries. |
| [56] | "Golden Sun" incentive policy for photovoltaic development. National Energy Administration (NEA) 2014 policy: PV greenhouse projects under 20 MW and low-medium voltage (¡35 kV) can be treated as distributed PV but benefit from ground-mounted feed-in tariffs. Mention of coordination issues across NEA, MOA, NDRC for standardization. |
| [57] | ISO 14040 and ISO 14044 standards were followed for Life Cycle Assessment methodology. |
| [58] | EN 15978 standard for life cycle assessment. ISO 14040 "Life Cycle Assessment–Principles and Framework". |
| [59] | Not mentioned in the article. |
| [60] | Reference to European and national legislation requiring farmers to provide proof of agricultural income to qualify for incentive tariffs (page 426). No specific regulation or law cited by name or number. |

| Reference | Observations |
|---|---|
| [61] | Italian legislation UNI 1264-1: illuminance level for labs (500 lx). Italian DPR 74/2013: building indoor temperature requirements. ASHRAE Standard 55:2013. EN 15251:2008: indoor environmental input parameters. |
| [62] | EN ISO 12975-1:2006 (Thermal solar systems and components – General requirements). |
| [63] | Germany: PV must be above 2.1 m ($\leq$10% land loss) or under 2.1 m ($\leq$15% loss). Crop yield must be $\geq$66% of reference yield over the past three years. Japan: Minimum 80% rice yield required for APV approval. France: Shading from PV must not exceed 27–39% for certain rice fields. |
| [64] | ISO 14040:2006 for Life Cycle Assessment (LCA). SimaPro v8.3 software used for modeling. ReCiPe 2008 v1.3 for impact categories assessment. |
| [65] | Feed-in Tariffs (FiTs): Simulated scenarios with fixed compensation rates (e.g., \$0.30–\$0.45/kWh). Investment Tax Credits (ITC): Considered to reduce upfront capital costs. Accelerated Depreciation: Modeled to simulate early-year tax advantages. No specific country-level decree or law name cited. |
| [66] | China's Central Document No. 1 (2023): Policy supporting transformation of old vegetable facilities. Structural and safety standards assessed via finite element analysis and load combination design. |
| [67] | ISOS-O-2 outdoor testing protocol followed. No national legal decrees or incentive programs mentioned. |
| [68] | Not explicitly listed, but the system is grid-connected. Complies with Spanish feed-in tariff eligibility for renewable electricity generation. Supported by: Junta de Andalucía (Consejería de Innovación, Ciencia y Empresa). Ministerio de Ciencia e Innovación de España FEDER funds (EU). |
| [69] | DM 19.02.2007 (Italy): Government decree supporting photovoltaic deployment with feed-in tariffs. GSE (Gestore dei Servizi Energetici): Italian authority for recognizing incentives. Under "Conto Energia": Solar greenhouses fall into "Totally Integrated" PV category, receiving higher tariffs. Conditions: PV modules must be architecturally integrated, serving as functional elements of the structure (roof). |
| [70] | Not explicitly listed, but model supports year-round simulation using: EnergyPlus weather data. Simulation via Ecotect and Daysim. Methodology aligned with validated standards (Perez all-weather sky model). |
| [71] | Not explicitly listed. Funded/supported by INRA Agadir and CNRST Morocco |
| [72] | No specific Chinese laws cited directly, but policy context includes: Photovoltaic poverty relief policy. Distributed PV demonstration projects. Incentives from National Energy Bureau. Italian regulation cited for comparison: roof PV coverage must not exceed 50% |
| [73] | Multiple national policies cited supporting PV agriculture in China: Renewable Energy Law of the People's Republic of China (2005). Twelfth Five-Year Plan for Solar PV Industry (2012). State Council's opinion on promoting PV industry (2013). "PV poverty alleviation project" – NEA and SCPAO (2014). Multiple subsidy policies and grid-connection facilitation policies listed (2013–2014). |
| [74] | French land use regulation: prohibits ground-mounted PV systems in agricultural zones; only agricultural-purpose structures permitted. No specific decree/law cited, but project aligns with national agricultural land use and renewable energy integration laws. |
| [75] | None specified. Emphasis is on environmental impact analysis (Life Cycle Assessment) rather than regulatory frameworks. |

| Reference | Observations |
|---|---|
| [76] | No specific legal frameworks or regulations mentioned by name; emphasis is on techno-economic, environmental, and agronomic viability rather than legal compliance. |
| [77] | None explicitly mentioned in the article. |
| [78] | Mention of UK policy (2008): Target of 80% reduction in GHG emissions by 2050. No other specific legal frameworks or regulations detailed. |
| [79] | No legal or regulatory frameworks specific to installations are mentioned. |
| [80] | BOE (2000): Commercial quality standard for marketable tomato (size ¿35 mm, no disease or deformation). ISO 14040:2006 and ISO 14044:2006 standards used for Life Cycle Assessment (LCA). EU classification of Almería as a nitrate vulnerable zone is noted. |
| [81] | Mention of UK 2008 GHG reduction target (80% by 2050). ISO standards (implied in LCA methodology). No local or greenhouse-specific building regulations cited. |
| [82] | Temperature regulation for tomato seedlings (ideal: 25 °C, range: 23–29 °C). No legal or institutional standards are cited. |
| [83] | None explicitly mentioned in terms of legal or regulatory frameworks. |
| [84] | No specific regulations, laws, or decrees mentioned in the context of photovoltaic greenhouses. |
| [85] | Referenced standards: ASHRAE 90.1 (2016), ASHRAE 189.1 (2014), National Energy Code for Buildings (NECB) Canada (2011) These relate to insulation, HVAC, and building energy standards. |
| [86] | No specific national or international regulations cited. Focus is on simulation results, experimental design, and energy outputs. |
| [87] | No specific regulations or laws mentioned. |
| [88] | No legal or regulatory frameworks are mentioned. |
| [89] | None mentioned. |
| [90] | No specific laws or decrees cited; discussion is centered on performance, environmental effects, and economic feasibility. |
| [91] | None specified in the article. |
| [92] | No specific laws or regulations cited. The focus is on technological and economic viability. |
| [93] | Mentions EU Renewable Energy Directive (RED II) and the European Green Deal goals (21–22 GW of PV/year to reduce GHG emissions by 55%). |
| [94] | Not explicitly stated; emphasis is on technological design and performance evaluation. |
| [95] | Not mentioned. |
| [96] | Discussion on policy needs and recommendations (e.g., sector-wide social impact scoping, SSIS). No explicit decree or law cited by name. |
| [97] | The study references Italian national and regional restrictions on PV greenhouses: Agricultural income must equal or exceed energy revenue if PV power exceeds 200 kWp. PV coverage must not exceed 50% of the total greenhouse area. Suitability of crops and techniques must be declared and demonstrated. |
| [98] | No formal laws or governmental regulations cited; designed for experimental nursery-scale applications and smart farming promotion. |
| [99] | Not mentioned. |
| [100] | Not explicitly mentioned in the reviewed text. |
| [101] | Not specifically mentioned in this review article. |
| [102] | ASTM E 424-71 (2015) used partially as a standard for transmissivity measurement method. |

| Reference | Observations |
|---|---|
| [103] | Supported under Italy's National Recovery and Resilience Plan (NRRP) - Project title "Network 4 Energy Sustainable Transition – NEST", code PE0000021. Funded by Italian Ministry of Environment and Energy Security and MUR (Ministero dell'Università e della Ricerca). |
| [104] | Not specifically mentioned. |
| [105] | Subsidy of CNY 1.2/kWh granted in Shandong province (local feed-in tariff policy, 2013–2015). Tax exemptions: agricultural product processing and sales are tax-free; PV electricity sales enjoy VAT and income tax exemptions or reductions (first 3 years full exemption, next 3 years 50% reduction). |
| [106] | No specific legislation cited, but general mention of Eurostat monitoring and legislative pressure for energy reduction in greenhouse agriculture. |
| [107] | Not specified in the article. |
| [108] | No specific regulations, decrees, or laws mentioned in the article. |
| [109] | EN 13031-1:2001 — European standard for greenhouse structures. |
| [110] | Public programs in Europe encouraged PV greenhouse implementation (no specific laws or decrees cited). |
| [111] | No specific legal framework or regulation mentioned in the document. |
| [112] | Not explicitly mentioned. |
| [113] | The design complies with Canadian building code. Open-source design methodology and licensing (GNU General Public License). |
| [114] | France was the first to implement an AV financial support scheme (2017). Germany has specific CAPEX and OPEX comparisons for AV vs. ground-mounted PV. Economic metrics used: LCOE (Levelized Cost of Electricity), CAPEX, OPEX. |

# 8 Conclusion

This report has provided a detailed survey on the state of the art of agrivoltaic technologies in greenhouses. It has covered the various types of agrivoltaic greenhouses, configurations of photovoltaic installations, types of PV panel models, crop species cultivated, and the regulatory frameworks referenced in the literature. The analysis reveals that, while technical and environmental aspects have garnered significant interest in recent years, resulting in an increasing number of studies, there remains a notable lack of unified legal and regulatory standards specifically tailored to agrivoltaic greenhouse systems. This gap underscores the need for future policy development to support the sustainable and scalable implementation of these technologies. Overall, the integration of photovoltaic systems in greenhouse agriculture holds great potential to enhance energy efficiency and crop productivity, provided that technological innovation is accompanied by coherent regulatory support.

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