

Review

Agrivoltaic Systems Design and Assessment: A Critical Review, and a Descriptive Model towards a Sustainable Landscape Vision (Three-Dimensional Agrivoltaic Patterns)

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Abstract: As an answer to the increasing demand for photovoltaics as a key element in the energy transition strategy of many countries—which entails land use issues, as well as concerns regarding landscape transformation, biodiversity, ecosystems and human well-being—new approaches and market segments have emerged that consider integrated perspectives. Among these, agrivoltaics is emerging as very promising for allowing benefits in the food–energy (and water) nexus. Demonstrative projects are developing worldwide, and experience with varied design solutions suitable for the scale up to commercial scale is being gathered based primarily on efficiency considerations; nevertheless, it is unquestionable that with the increase in the size, from the demonstration to the commercial scale, attention has to be paid to ecological impacts associated to specific design choices, and namely to those related to landscape transformation issues. This study reviews and analyzes the technological and spatial design options that have become available to date implementing a rigorous, comprehensive analysis based on the most updated knowledge in the field, and proposes a thorough methodology based on design and performance parameters that enable us to define the main attributes of the system from a trans-disciplinary perspective.

Keywords: agrivoltaics; land use; photovoltaic design assessment; landscape; PV greenhouse; PV pattern; integrated photovoltaics



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1. Introduction

Thanks to its modularity, decreasing cost, lifespan and efficiency improvements, photovoltaic (PV) technology is playing a key role in the transition to low-carbon economies.

Nowadays, however, land-based PV farms compete with food production for land allocation. Therefore, the number of innovative solutions for implementing PV while reducing the related land use are becoming increasingly relevant. Building integrated photovoltaics (BIPV) (use of existing building surfaces), floating PV (use of existing water surfaces) or agrivoltaic systems (APV) (double use of land for food and energy) are some of these new examples. They represent a strategic part of the future vision, with a huge potential driven by the growing shift towards renewable energy sources.

In recent years, agrivoltaic systems have been the subject of numerous studies due to their potential in the food–energy nexus. Demonstrative projects with new conceptual designs based on PV modules for covering open fields have shown promising results through optimizing light availability while reducing the need for irrigation and protecting from extreme weather phenomena. APV denotes sharing the sunlight for co-production of food and energy on the same piece of land; therefore, designs must overcome, as far as possible, physical constraints of covering crops with photovoltaic modules in order to alleviate the reduction in crop profitability. Some examples of the main issues related to the use of co-located PV on cropland and the solutions commonly proposed to solve them are shown in Table 1.

In parallel to the development of the new field-tested designs, the continuously scientific progress in PV has extended the range of design solutions by using different technologies which optimize the light absorption of the modules in different regions of the light spectrum, so that the light resource can be shared for both purposes: energy generation and crop growth. In this regard, success of experiences implementing PV in greenhouses (protected fields) has shown technical feasibility in real operating conditions. Just as Table 1 summarizes the main problems of integrating PV modules in open fields together with the solutions from two perspectives, design and technology, Table 2 shows them for greenhouses.

As can be seen, APV does not follow classical PV system design practices where parameters such as tilt and orientation angles are optimized to maximize electricity production choosing slopes close to the latitude and orientations facing the equator. Moving PV to include farm activities is an ongoing challenge since energy performance sometimes conflicts with optimal agricultural development and landscape preservation issues, and thus involves multiple design adaptations according to the local climate conditions, crop type, energy needs and landform. A new list of requirements must be addressed to ensure and understand the tight connection between energy, food production and space. This paper therefore aims to analyze the different design possibilities that focus on the energy performance of the PV system, extending to agriculture objectives and presenting an original contribution in the cognitive trans-disciplinary approach for describing and classifying the agrivoltaic system, which harmonizes different disciplinary issues in a unique vision, making room to consider landscape issues.

The article is organized as follows. Section 2 presents the research method to describe how the literature review was conducted. Section 3 gives an overview of the current design solutions and technologies used in agrivoltaic systems based on the literature and current practices. In Section 4, the new inclusive approach to describe an agrivoltaic system is presented and discussed. Finally, main conclusions are presented in Section 5.

Table 1. Barriers and solutions to implementation of agrivoltaics in open-field systems.

Topic	Design Related Solution	Technology Related Solution
Minimizing shadows on crops (biomass yield)	Optimal design: Distance between the arrays of modules (the stripes) Distance of the modules from the ground	Sun-tracking systems Semi-transparent PV modules (by spacing PV cells) Light-selective PV devices
Maximizing electric energy generation	Optimal planning: Avoiding shading losses from surrounding elements (structures, buildings, trees, inter-row shading of the PV modules should be minimized) Optimal design: Azimuth facing equator and tilt close to latitude	Highly efficient systems (e.g., sun-tracking systems) Highly efficiency modules or technologies (e.g., bifacial module technology)
Social acceptance (landscape dimension)	Optimal landscape design: Pattern of PV arrays aligned to the parcel Natural fences and low height structures to minimize visual disturbance Use of marginal areas Removable systems Optimal design: Different tilt, azimuth and height to reproduces the orography of the land New business models: Higher economic efficiency per land unit (farmer perspective) Benefits for local economy and employment (tourism, local recreation, etc.)	New materials for structure

Table 2. Technical barriers and solutions to implementation of agrivoltaics in greenhouses.

Topic	Design Related Solution	Technology Related Solution
Minimizing shadows on crops (biomass yield)	Different layouts to homogenize the distribution of the light inside the greenhouse Increase the gutter height of the greenhouse	Dynamic systems Semi-transparent PV modules (by spacing PV cells or using semi-transparent PV layers)
Minimizing the loss of PAR (Photosynthetically active radiation)	Use of colored layers	Spectral selective PV devices by selective focus different wavelengths of the solar spectrum on plants and modules Luminescent solar concentrator technology (LSC)
Maximizing electric energy generation	Optimal design for energy generation: Maximum energy intensity (dense pattern of the PV modules) with no shading effects on the modules Optimal positioning of the modules (tilt and azimuth angles of the roof)	Use of high efficiency PV systems, or high efficiency PV modules (such as bifacial modules)
Microclimatic issues (temperature and humidity conditions inside the greenhouse)	Ventilation (natural through vents) Orientation (sun direction along the year) Location (climate)	Highly efficient heating, ventilation and air conditioning systems Artificial light
Social acceptance	Designing the greenhouse for an optimal visual performance (e.g., high level of integration of the greenhouse in the landscape, and of the modules in the greenhouse envelope)	Appropriate choice of the PV technologies allowing for an increased visual performance (size, shape, color and texture)

2. Materials and Methods

A comprehensive review process was conducted by using Web of Science (WoS) (Clarivate Analytics, <https://apps.webofknowledge.com> (accessed on 7 December 2020)) and Scopus (Elsevier, <https://www.scopus.com> (accessed on 7 December 2020)). Peer-reviewed literature databases where highly cited documents written in English and published up to the date were consulted for the analysis. The following categories were considered: journal publication (article or review) and conference paper. The keywords for the search engines are listed as follows, including the different terminologies for the concept:

- “Agrophotovoltaics” (APV)—German research context
- “Agrivoltaics systems/array” (AVS/AVA)—French and US research context
- “Photovoltaic agriculture”—Chinese context
- “Solar sharing”—Japanese context
- “Photovoltaic or solar greenhouse” (PVG)
- “Agro-PV” or “agri-PV”

In addition to academic research papers, and in order to include the current research development of agrivoltaics systems, the search was extended to outstanding demonstration projects and commercial-scale plants from the industry and relevant international conferences in the field.

The academic papers were then reviewed to select those that follow the criteria of “dual functionality” of generating electricity and serve a specific and integral purpose. In this case, solutions which consider synergies between agriculture and photovoltaics.

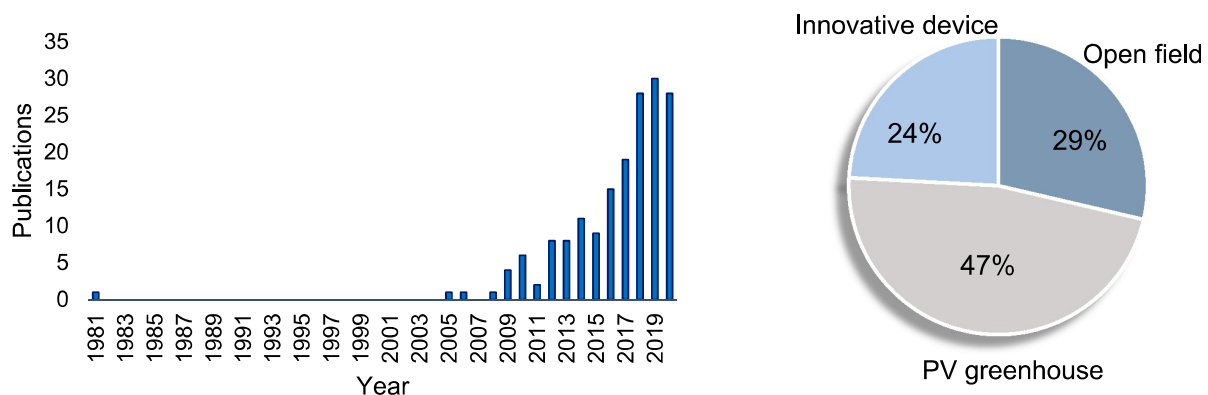
Therefore, PV systems that are in “co-existence” with agricultural land and prioritize farming activities were considered (It should be noted that publications which focus on key saving strategies and climate control technologies for greenhouses using PV technology were excluded in this research. We included only PV solutions which strategically were used to provide electricity without substantially affecting crop quality or yield).

In total, 195 academic papers were identified. Upon reviewing the detail information in the academic papers, there are three application areas that are being actively researched:

1. PV + open-field crops
2. PV + protected crops (photovoltaic greenhouses, PVGs)
3. PV technology with innovative solutions designed to optimize the light transmission (amount and spectral quality) increasing the compatibility between PV and agriculture.

Two scales are distinguished: the system scale (dynamic solutions) and the module scale (enhances light transmittance through PV devices).

The literature review shows the increase in studies related to the topic in recent years, as shown Figure 1a, while Figure 1b shows the special interest of the scientific community in PV systems applied to greenhouses.



(a) Number of relevant academic papers published yearly

(b) Publications by research areas

Figure 1. Literature review analysis.

3. State of Art

3.1. Current Design Solution and Technologies

The concept of a dual-use approach for both solar photovoltaic power as well as agricultural production was theoretically conceived by Goetzberger and Zastrow at the Fraunhofer Institute (Germany) in 1981 [1]. They proposed to elevate the structure (by about 2 m) and the distance between rows (about 3 times the height of the modules) to achieve uniform radiation on the ground while at the same time that allow the moving of mechanized agricultural equipment. In 2004, Japanese engineer Akira Nagashima developed the first agrivoltaic system (here referred to as “solar sharing”) using a structure similar to a garden pergola [2]. Nagashima designed diverse test fields with different shadowing rates based on the concept of the light saturation point of each crop (plants only employ a small percentage of incident sunlight (between 3% and 6% of total solar radiation) to accomplish their maximum rate of photosynthesis) with the idea of sharing the excess of solar radiation with PV systems to generate electricity. Graphical representations of both proposed solutions are presented in Figure 2.

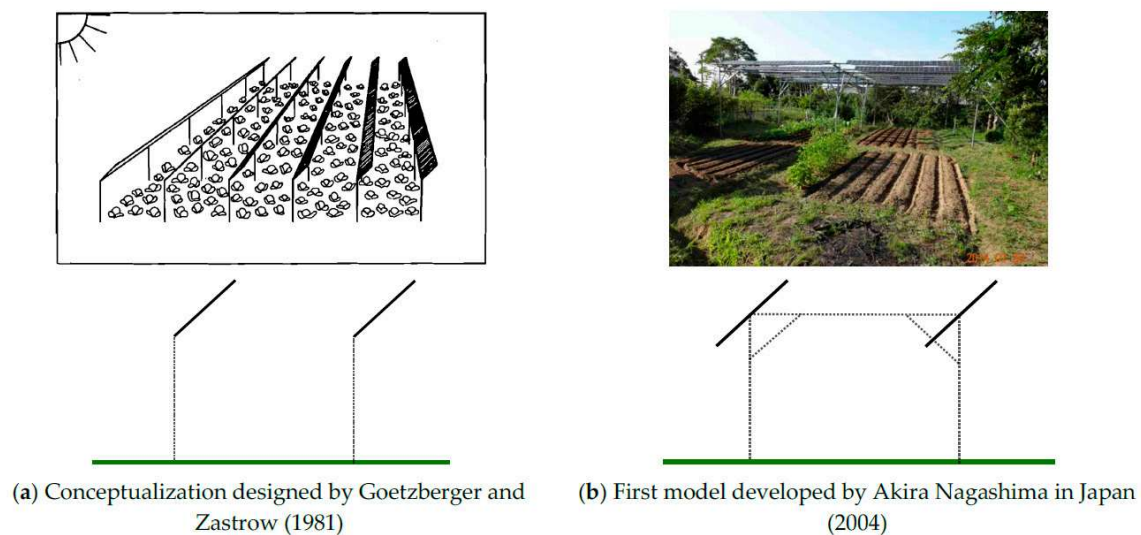


Figure 2. First models of agrivoltaic systems: co-located agriculture and solar photovoltaic (APV). © Goetzberger and Zastrow [1] (a), A. Nagashima [3] (b).

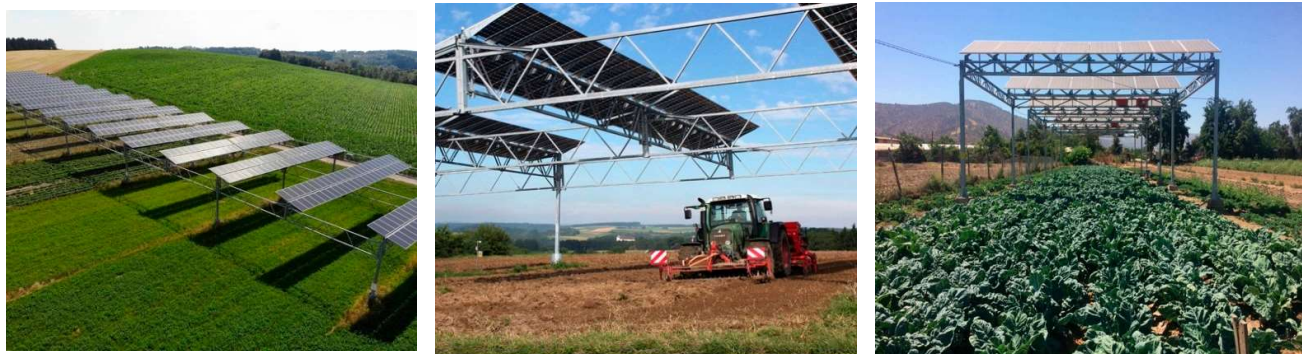
The first experimental pilot project, however, was installed in France, close to the southern city of Montpellier ($43^{\circ}65' N$, $3^{\circ}87' E$) in the spring of 2010. The prototype has mono-crystalline PV modules mounted at a height of 4 m above the ground (Figure 3a,b). Since the PV modules are opaque, the main issue is the effect of the shade created by PV on the plant growth. In order to evaluate the effect of the shadow by the PV, the prototype was split into different parts with two densities of solar modules: one called “full density”, with optimal spacing between rows for electricity production and which transmitted on average 50% of the incident radiation to the crop, and the second called “half density”, obtained by removing one PV strip out of two and which left on average 70% of incident radiation available to the crop, so that the effect of the shadow by the PV can be compared to each density, and to control plants under full sun conditions [4]. Additionally, to evaluate the advantages of solar-tracking technology, which allows the adjustment of the radiation level on crops, two independent single-axis tracking PV systems were added in 2014 [5] (Figure 3c). The experimental farm led to the exploration of the potential of the open-field agrivoltaic systems, giving rise to many scientific publications, from the effect of the rain distribution (PV–water nexus) [6,7] to the impact on microclimatic condition together with growth, morphology and yield in crops such as lettuce, cucumber and durum wheat [8–10].



(a) Structure 4 m above the ground (b) Mono-crystalline PV arrays (c) Single-axis sun tracking system

Figure 3. Experimental agrivoltaic system in Montpellier, France. © C. Dupraz.

In recent years, several research groups have implemented agrivoltaics demonstration projects around the world. In Germany, the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE) is at the forefront of APV research. A research pilot project was installed in 2016 near Lake Constance in southern Germany under the project APV-RESOLA [11]. This pilot research plant is used to examine the impacts of the technology with regard to aspects such as energy production, economic feasibility, crop production, social acceptance and technological design. It has a size of 0.3 ha and a capacity of 194 kWp. The solar modules are mounted on stilts with a vertical clearance of 5 m (Figure 4a,b). Moreover, in cooperation with their Chilean subsidiary Fraunhofer Center for Solar Energy Technologies (Fraunhofer CSET), three further pilot plants have been realized near Santiago de Chile to investigate the implementation of APV systems and its impact on field crops in regions with arid areas and high solar radiation (Figure 4c).



(a) Heggelsbach (Germany) (b) Heggelsbach (Germany) (c) Curacaví (Chile)

Figure 4. Experimental agrivoltaic systems installed by Fraunhofer ISE in Germany (a,b) and Chile (c). © Fraunhofer ISE.

The performance of the agrivoltaic systems in drylands is also under investigation by the Barron-Gafford research group in the USA [12]. A small-scale research plant was installed in Arizona at the Biosphere 2 Lab in August 2016. The research group focuses on common agricultural species for drylands such as peppers, jalapeños and cherry tomatoes [13]. The APV system is 3.3 m off the ground with a tilt of 32° and 1 m of spacing between each row of PV modules.

Research in the field continues to progress at a furious pace. Aside from these pilot projects, agrivoltaics have triggered much interest in the research community that explores the potential from different disciplinary perspectives and practical issues, such as the solar power potential by land cover type (croplands, grasslands and wetlands) [14], the water use efficiency in drylands [15] or groundwater stressed regions [16] (PV–water nexus), the

economic value of energy production coupled with shade tolerant crop production [17], the implementation in peri-urban agriculture areas [18] or the viability over shade-intolerant crops in specific geographical locations [19,20].

Although research in the field continues to progress, excitement around agrivoltaics remains high enough that commercialization is well underway. Globally, the installed capacity of the APV continues to climb. It is estimated that 2200 systems have been installed worldwide since 2014 (Japan is probably the country where the most agrivoltaic farms were installed, with over 1992 APV farms which produced about 0.8% of total PV energy in 2019), leading to a capacity of about 2.8 GW_p as of January 2020 [21]. From the results of the experimental farm in Montpellier, Sun'agri (FR) [22] was founded in cooperation with Sun'R group. In 2018, the first agrivoltaic field was built in the east Pyrenean region (France). This field has a capacity of 2.2 MW_p installed on 4.5 ha of vineyards (Figure 5a). Today, the company focuses on the development of large-scale demonstrator systems of dynamic agrivoltaic technology in orchards, grapes and market gardening. In Italy, together with the University of Piacenza, REM Tec [23] patented an agrivoltaic solar tracking system named Agrovoltaico®. It was examined for maize crop production by Amaducci et al. [24] while Agostini et al. assessed economic and environmental performance [25]. The first two Agrovoltaico systems were installed in 2012 in Castelvetro Piacentino (1.3 MW_p, Figure 5b) and Monticelli d'Ongina (3.2 MW_p) in the North of Italy covering an area of 7 ha and 20 ha, respectively. In the Dutch town of Babberich, BayWa r.e. company [26] has installed a 2.7 MW_p raspberry agri-PV farm, being the largest agrivoltaic system for fruit production in Europe (Figure 5c). Semi-transparent PV modules without frames are mounted above the crop with a semi-enclosed single-row system, protecting from weather phenomena, whilst providing better ventilation and reducing the use of pesticides, thereby improving biodiversity in the fields.



(a) Pionlec (France)

(b) Castelvetro (Italy)

(c) Babberich (Netherlands)

Figure 5. First demonstrator projects developed by the following companies: Sun'agri in France (a), REM Tec in Italy (b) and BayWa r.e. in the Netherlands (c). © Sun'agri (a), REM Tec (b), BayWa r.e. (c).

However, concepts that combine farming and energy production on the same site are not limited to stilted solar arrays (stripes) above crops. There are more design criteria with PV modules mounted on the ground (less than 2 m of clearance height). Low height mounting structures are then preferred because of their lower structure-related cost than stilted agrivoltaics and the microclimate, which is generated underneath the solar modules so that crops grow in between the rows of PV arrays or underneath the modules depending on the height of the plants and light requirements. Therefore, the area below modules may be exploited with shade-tolerant species, especially in hot arid climates. Some studies in this regard have already been carried out in India [27,28] and Malaysia [29–32] for testing species such as java tea, aloe vera or spinach (Figure 6), achieving higher crop yields for herbal plants while at the same time reducing the module temperature by 0.85%, which

may increase the annual energy production up to 2.8% [33], although with a potential risk of pest due the high moisture [30].

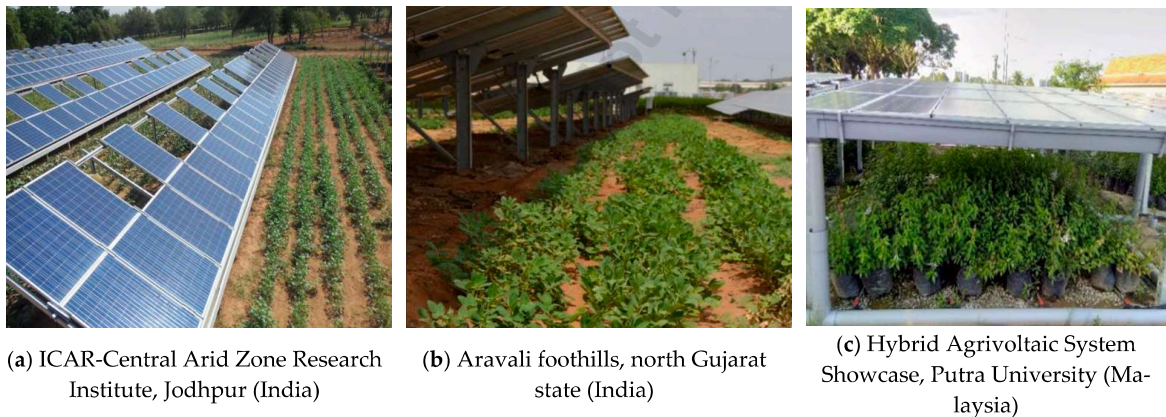


Figure 6. Research pilot plants with low height PV mounting system. © P. Santra (a), B. Patel (b), N.F. Othman (c).

Some projects have also reached the market. Agrinerjie® is the name of the systems created by Akou Energy [34] group to combine energy generation from PV and crop production, while considering landscape preservation issues. The first project which incorporates this concept was installed in the French tropical island of La Reunion. Two modules' stripes are deliberately spaced to allow cultivation of lemongrass between them. The ground has not been graded with the natural topography, as this helps to blend harmoniously into the landscape (Figure 7a). More ground-based projects are being developed with innovative design concepts. Thus, vertical installations with bifacial PV modules facing east and west and leaving the areas between the rows (about 10 m) for agriculture is the idea behind the Next2Sun company (GE) [35]. Projects with an installed capacity from 22 kW_p (Figure 7b) to 4.1 MW_p (Figure 7c) have already been developed in Austria and Germany for the cultivation of potatoes and hay and silage, respectively.

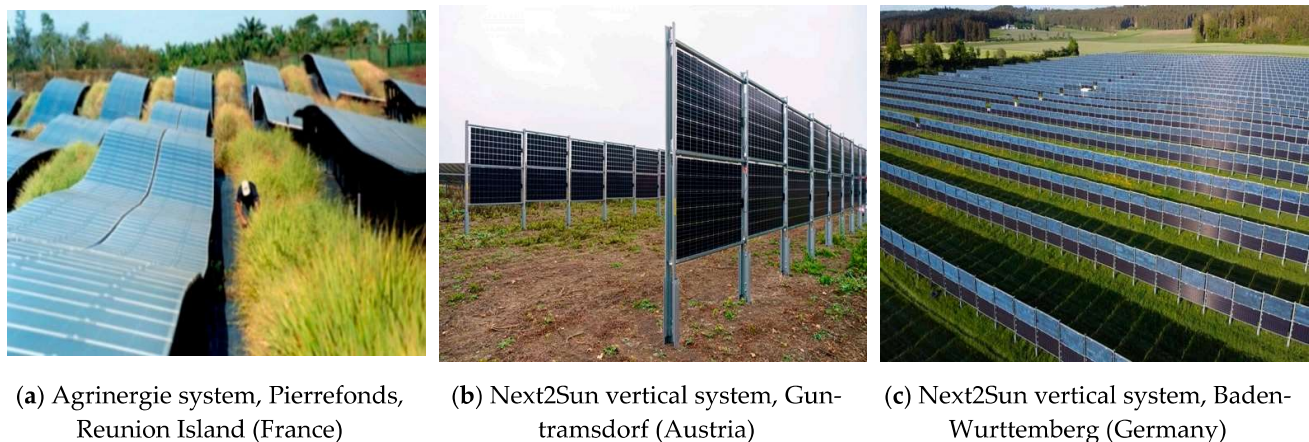


Figure 7. Commercial plants with ground-based PV mounting system. © Akuo Energy (a), Next2Sun GmbH (b,c).

Depending on the location, weather conditions and land availability, crops need to grow under climate control. In this case, the implementation of PV into agricultural settings is through integrating PV modules into the greenhouse's envelope, mainly the roof [36–41]. However, conventional opaque PV modules produce shade, thereby significantly affecting the microclimate inside the structure (air temperature, relative humidity, level of light and CO₂ concentration) and productivity [42–46]. To minimize this effect, one approach

is to use completely opaque PV modules that cover part of the greenhouse roof or PV modules with partial opaque sections that produce electricity (Figure 8a). In this way, the percentage of the greenhouse area covered by opaque PV modules is reduced in such a way that the light reaching the plants is sufficient for photosynthesis. Nevertheless, the solar irradiance is still distributed non-uniformly and varies seasonally. Therefore, it is necessary to find optimum arrangements of PV modules on the greenhouse roof in order to define the optimal conditions for plant cultivation. Checkerboard arrangement, for instance, has revealed better uniformity and consequently diminished the PV shading effects [47–52]. A recently published study—in which the yield estimations and the crop planning of 14 horticultural and floricultural crops inside four PV greenhouse (PVG) types, with coverage ratio ranging from 25% to 100%, is discussed—shows that all the considered species (including high light demanding crops) can be cultivated inside PVGs with 25% coverage ratio showing limited yield reductions (below 25%), but restrictions on growth and yield occurred when the coverage ratio raised from 50% to 100% [53]. More studies in literature, with diverse PV layouts in different roof geometries and covering ratios, seem to confirm that the relative density ratio of opaque PV modules should not exceed 50% (Table 3). This would provide a shading ratio that is compatible with greenhouse cultivation.

Table 3. Studies where yield reductions or quality of plants of different species are not affected significantly by the coverage of opaque PV modules integrated into the greenhouse’s roof.

% PV Roof	Plant	Reference
32%	Berry	[54]
26%	Strawberry	[55,56]
25%	Wild rocket	[57]
22%	Pepper	[58]
20%	Pepper	[59,60]
20%	Lettuce	[61–64]
20%	Flowers (<i>iberis</i> , <i>cyclamets</i> and <i>petunias</i>)	[65]
20%	Tomato	[66]
10%	Tomato	[67–70]

To further control the light delivered to the crops according to their needs, shading levels can be regulated dynamically. PV modules can rotate around fixed axes to adjust the degree of shading inside the greenhouse (Figure 8b). Sun-tracking mechanisms are then installed in the roof with PV rows used as slats of venetian blinds. The PV blind, oriented parallel to the roof, partially blocks intense sunlight penetration into the greenhouse and generates electricity, and perpendicular to the roof, the sunlight passes through the roof to crops below the PV modules. Already, some researchers have investigated the feasibility of using dynamic systems in greenhouses under different configurations:

- Opaque PV modules mounted above the greenhouse roof at different PV densities and layouts [71–73];
- Opaque PV modules integrated into the roof coupling with high reflective mirrors in order to allow for a better collection of reflective light (Figure 8b) [74–78];
- PV blinds installed underneath the greenhouse glass roof using semi-transparent PV technology [79–81].

Researchers also propose additional strategies for the application of dynamic mechanisms which allow control of the shading in an active way. Colantoni et al. [65] set up a rail system inside a PV greenhouse prototype, where two rows of semi-transparent glass-glass PV modules are installed. One row is fixed; the other one, mounted on top of the first, at about 25 cm distance, moves to control the shading dynamically. The modules translate over the fixed ones, and in combination with the others, enable a variation from 33% to 66% of light transmission by overlapping the transparent part of PV modules located above

with PV cells from the PV module placed below (and therefore configuration a dense or porous layout). In all these cases, the shading level is regulated by a threshold parameter, commonly the irradiance level, for the blind rotation or rail movement to adjust the ratio for electricity production and for plant cultivation.

Progress in PV technology has also provided additional possibilities for application in greenhouses. PV modules are not then conceived as partial shading systems where the spacing or coverage must be optimized since the annual solar radiation available inside a greenhouse may decrease with a ratio of 0.8% for each 1% of additional PV cover ratio [50]. The sunlight *quality* (direct vs. diffuse; availability of PAR) management inside the greenhouse is addressed by different innovative approaches: from using semi-transparent films [82,83], the use of new materials or techniques to transmit to the plant the diffuse component of the light [84] and devices based on spherical silicon micro-cells (1.2 mm of diameter) where the overlapping of the PV cells over the sun barely eclipses the plants [85,86] to sharing the solar spectrum through PV devices which generate electricity outside the PAR regions [87–90]. (Only a small portion of the sunlight is used for efficient plant growth. It is driven by two relative narrow wavelength regions: a red wavelength band around 660 nm and a blue wavelength band around 450 nm. Green light contributes less to photosynthesis due to the poor light absorption of chlorophyll in this region.)



(a) Fixed with different layouts

(b) Dynamic

(c) Innovative PV solution

Figure 8. Approaches to integrate PV into greenhouse's envelope. © A. Yano [47] (a), A. Marucci [75] (b), M. E. Loik [87] (c).

Recently, studies of combining concentrated photovoltaic (CPV) technology with special bended glass modules (an optimized dichroitic polymer film which allows the transmission of the blue light and red light for photosynthesis) has been reported with an efficiency of 6.8% [91–93]. Previous studies in the same line show efficiencies of about 3.3% by only reflecting the near infrared radiation (NIR) fraction [94–98]. CPV technology also allows the possibility to separate direct and diffuse light. Thus, systems that focus direct radiation through Fresnel lenses, transmitting the diffuse sunlight to the crops, have been analyzed to optimize their performance in recent years [99–104]. In fact, commercial production under this concept is already under way. Swiss startup Insolight [105] patented a system where optical lenses concentrate the direct sunlight onto tiny cells, which cover only 0.5% of the module surface. The cells are able to track the sun through horizontal movement of a few millimeters per day to keep the cells aligned with the light beam component [106].

Along the development of CPV technology, wavelength-selective PV systems which combine LSCs with PV have also attracted great interest from the scientific community. Luminescent dyes are embedded into a transparent matrix, trapping and guiding some of the incoming solar radiation at certain wavelengths and delivering to PV cells that are integrated into the module (Figure 8c). Designs to optimize this technology for APV applications have been developed by Corrado et al. [107] to field-test studies to explore

its performance and reliability [108]. Additional research shows the potential of this technology over species such as basil [109], tomato [87] and microalgae [110].

Customized PV modules to harness specific portions of the solar spectrum are also possible by using thin film semi-transparent devices. Thompson et al. [111] recently published a study where tinted semi-transparent solar modules (based on thin-film amorphous silicon technology) were tested for plant growth of basil and spinach. The results highlight that even with a loss in the yield production, this solution could appor a financial gain of up to 2.5% for basil and 35% for spinach. Another opportunity is offered by third-generation PV cells based on organic PV cells (OPV) or dye-sensitized solar cells (DSSC). Emmott et al. [112] demonstrated the potential of OPV devices in greenhouses modeling the impact on crop growth for a wide range of commercially available organic semiconductor materials. Ravishankar et al. [113,114] reported that there are benefits of integrating semi-transparent OPV to meet energy demand of greenhouses in warm and moderate climates, being a potential candidate to achieve net-zero energy greenhouses. Intensive research on OPV greenhouses currently focuses on developing new optimized devices that minimize the impact on crop yield [115–119], to evaluate performance in real operational conditions [120–124] and to study of the environmental impacts through the life cycle assessment (LCA) methodology [125–127]. Variation in color and transparency are characteristics that can be also achieved by DSSC technology being a potential candidate to be considered as a photo-selective covering for a greenhouse [128–134]. Despite the specific features of third-generation PV devices (flexibility, light weight, diverse colors and transparency degree, lower fabrication costs and environmental impact in comparison to silicon-based PV) and the new developments in the field, stability and efficiency are still critical factors which must be improved to promote them as an alternative to PV technologies consolidated at market levels.

3.2. Further agri-PV Integrated Applications

This paper focuses mainly on crop farming applications where significant adjustments to PV module infrastructure is needed, although other common approaches such as planting pollinators or livestock activities can also coexist along with PV, and they are beneficial to the overall ecological performance of APV. Benefits of integrating grazing livestock has been shown by Andrew, who analyzed the lamb growth and pasture production in Oregon (USA). The study reveals that grazing under PV can increase land productivity up to 200% as well as provide a more animal welfare and friendly environment [135]. In line with the study of Andrew, Maia et al. determined livestock shade preference, showing that animals spent more than 70% of their time under the shade from PV at irradiance values greater than 800 W/m² [136]. Agrivoltaics can benefit local biodiversity, creating a habitat for pollinators [137]. An ongoing study to quantify the potential is currently being carried out by the US Renewable Energy Laboratory (NREL) through the InSPIRE project [138]. The objective is studying pollinator-friendly solar in order to quantify the benefits and barriers of certain design approaches.

3.3. Relevant Design Parameters and Performance Metrics

3.3.1. Height of the Modules from the Ground

The height of the systems from the ground (space in between the modules and the ground surface) is an important design parameter since the use of higher structures, commonly associated with APV systems, can determine the homogeneity of the radiation availability under the PV modules, improve the connectivity and allow the use of high plants. The closer to the ground the modules are, the higher the heterogeneity of radiation over the crops in the same land unit is (without considering the effects on the surrounding areas).

However, there are also other implications when the modules are installed high on the ground. For instance, taller configurations may result in several public concerns or even rejection due to the negative impact (visibility is acknowledged as one of the

complex objective factors that contribute to the visual impact of PV [139]) on areas such as recreation and tourism [140–142]. The use of higher mounting structures not only have influence on social acceptance but would also significantly affect the cost of installation and the environmental impact. In the German context, the extra cost related to elevating the PV modules (mounting, installation and site preparation costs) is assumed to be more than double (increasing from 0.3 EUR/kW_p to 0.7 EUR/kW_p) compared to ground-mounted PV [143].

The height of the system also can be used as a parameter of sustainability. Higher emissions are related to larger size of the structure for elevating the modules. As the LCA study of Serrano et al. [144] shows, an integrated PV parking lot (222 kW_p) needs 72 t of steel, accounting for 82 t of CO₂ emissions, that, in comparison to the galvanized steel structure of a conventional PV mounted system, generates eight times more CO₂ emissions. In the case of PVG, the gutter height also is an important design parameter since it positively affects the cumulated global radiation inside the greenhouse; each additional 1 m of gutter height may increase by 3.8% the yearly global radiation on the PV greenhouse compared to the conventional one [50].

Thus, high APV systems can be beneficial for the plants, as they allow for better solar energy collection; nevertheless, literature also presents some concerns related to possible detrimental effects on the ecological performance of the system.

3.3.2. Spatial Configuration of PV and Type of Crops

A module's height and spacing may be adjusted to grow different types of crops depending on plant light, humidity, temperature and space requirements. In this way, zones for a successful growth can be identified. Thus, for ground-mounted PV installations combined with low-height crops, three different areas are detected (Figure 9): zone 1 with a low irradiance and high humidity level, zone 2 with regular light exposure and enough soil moisture and zone 3, which shows the highest irradiation and lowest humidity [145]. In the same way, APV for orchards or grapevines will need designs with tilt-mounted structures and PV modules placed at higher heights to allow tree growth and farm machinery to pass underneath.

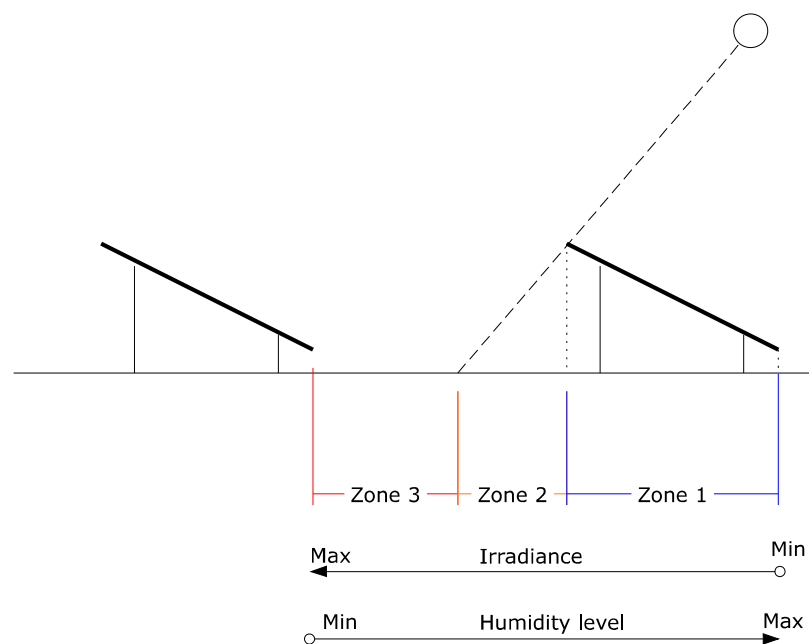


Figure 9. Ground-mounted PV and crop zones (adapted from [145]).

Quality aspects (size, fruit coloration, sugar content, etc.) can be affected by the passive influence of the PV modules even though there are no significant yield losses. Ureña et al. [68] shows that tomato cultivated under a PVG with 9.8% of PV covering area is affected negatively in terms of fruit size and color although there is not a significant impact on its yield and price. Bulgari et al. [146] also found a lower content of quality parameters for tomatoes with a configuration of 50% PV coverage besides lower yield by the high PV percentage coverage. Cho et al. [147] detected lower weight and sugar content in grapes cultivated in Korea than those of the control group, delaying the harvest time about 10 days, and the sugar-content level present almost the same level as that of the control site. Conversely, some species including strawberry show good response in terms of quality (with higher chlorophyll content) and yield in comparison to unshaded treatment [55]. Despite the studies mentioned above, there is a little information on the effects on quality parameters of the APV systems since they strongly depend on the season, crop type (with its own adapted strategy in terms of morphology, yield or quality parameters) and microclimatic conditions given by the technical implementation of PV. Therefore, crop selection method for agrivoltaic systems continues to be a key issue for the scientific community.

PV greenhouses are closed systems and should not be compared to open-field APV, where the effect of shading has no significant effect on air temperature or relative humidity. As covering ratio increases, the microclimate can play a negative role in the PV greenhouse yield production or quality of the plant, reducing the amount of solar radiation and thereby decreasing the air temperature and increasing the humidity. On the contrary, for open-field crops and open-field PV, soil temperature can significantly decrease, affecting the early phase of the plant growth [9].

Currently, the effectiveness of agrivoltaic systems, in terms of crop suitability, is analyzed based on the priority of the biomass yield, which is directly related to the potential benefit in terms of market value.

Dinesh and Pearce [17] show that if shade tolerant crops are used in APV, the crop yield losses are minimized and computed that, for lettuce production in the US context, the value of APV could reach over 30% when compared with conventional agriculture. In this sense, the correlation between plant light requirements (given by the light saturation point or, in other words, its degree of shade tolerance) and the percent of shade of the PV system define the selection of the crop.

Japan, where the most agrivoltaic systems are installed to date, has identified a list of the most important agrivoltaic crops suitable for the Japanese context through a repository collected by Chiba University, with more than 120 species cultivated under agrivoltaic farms along the country [148] providing a showcase of successful practices that have contributed to the consolidation of these systems in the country. Likewise, the Japanese Solar Sharing Network [149] provides a list of plants with advice on cultivation based on the crop's light saturation point.

Although there is a correlation between crop's shade tolerance and biomass yield, this seems to be only one of the multiple factors that define the effectiveness of the agri PV solution. There are studies that show that the performance of shade-intolerant crops with stilt-mounted PV structures present higher crop yields when compared to full sun conditions. Sekiyama and Nagashima [20] applied a stilt-mounted solution with two different configurations in terms of density to corn crop and found that the low-density configuration produces larger values of biomass than control by 5.6%. The findings carried out by the experiments on the Heggelbach farm in Germany show that seasonal temperature variations influence the total yield production of wheat, potato, celery and clover grass crops. Thus, in 2017, the production was reduced by -19% for wheat, -18% for potato, -19% for celery and -5% for clover grass, contrary to the production in 2018, characterized by a hot summer, changing to higher yields with $+3\%$, $+11\%$ and $+12\%$ for wheat, potato and celery, respectively, and scarcely affected clover grass with -8% under the same system configuration [150].

That is why further research is needed to define an accurate approach to classify the crop suitability in this context. Some authors suggest a classification composed of three categories: PLUS (+) for higher yields, ZERO (0) shows no influence and MINUS (−) is a negative effect [145]. Obergfell [151] evaluated the most important crops in Germany under this category. Based on field performance, the experiments carried out by the Barron-Gafford research group [13] classify the impact from the agrivoltaic system mounted in Arizona (USA) using this system with positive results on species such as basil (++), cabbage (+), carrots (++), chard (+), chiltepin peppers (+), lemon grass (+), lettuce (++), marigolds (+), sweet potatoes (++) and tomatoes (++); on the other hand, melon (0) and jalapeño (0) production was nearly equal between PV and full sun treatments.

Nevertheless, there is no general consensus to date on a standardized system that makes it possible to experimentally compare crop productivity under field conditions. The above proposed classification could help to identify suitable crop groups through the experience of different PV concepts in different operating conditions. However, in order to achieve a common frame of reference, it will be necessary to establish thresholds for crop yield reductions/increases to ensure that the dual use of the land unit enables the generation of electricity while maintaining active and productive agriculture. In this sense, farmers, who are the experts on their land, can define the tolerance of yield losses which can serve as reference to set the levels for the classification. For instance, based on the experience of the projects carried out in Germany, farmers reported they could tolerate crop yield losses up to 20% [152], which coincides with the guidelines of the Japanese Ministry of Agriculture, Forestry and Fishery (MAFF) for the implementation of PV systems on existing crop-producing farmlands.

3.3.3. Performance Metrics

Since the APV system is composed of PV modules and farmland, the impact of land use intensity on the energy performance of the system will determine an important part of the feasibility of the whole system's solution. In this sense, the land use energy intensity can be quantified by metrics which express the land area use per unit of energy generation (ha/kWh) and/or land area use per unit of capacity (ha/kW_p), whereas the performance can be expressed as unit of energy per unit of capacity over the course of a typical or actual year (kWh/kW_p/y), as commonly used for solar systems.

In order to assess the performance of the APV system, authors suggest using the indicator land equivalent ratio (LER) that leads to comparing the conventional approach (PV and farm set up separately) with the integrated solution on the same land area [4]. LER measures whether the combined value of agricultural yield and solar energy is equal or higher than it would be from the singular use of land. LER can be computed as:

$$\text{LER} = \frac{Y_{\text{agri-APV}}}{Y_{\text{agri}}} + \frac{Y_{\text{APV}}}{Y_{\text{PV}}} \quad (1)$$

where Y_{agri} stands for agricultural yield (kg/ha for instance) in a single use of land for farming and $Y_{\text{agri-APV}}$ refers to the yield under the agrivoltaic system for the same area. Y_{PV} refers to the electricity production under a standard PV system assumption, and Y_{APV} to the agrivoltaic system. Thus, LER values above 1 indicate that the integrated approach is more effective than separate crop production and PV for the same land area. (LER = 1.3 indicates that 30% additional area would be needed to produce the same amount of electricity and biomass on separate land areas.) However, caution must be taken in interpreting LER since it does not differentiate the yield of biomass over the energy. Higher LER can be obtained even if the crop yield represents only a small fraction of the system. For this reason, it is also important to describe performance characteristics such as morphology, yield and quality of the crop (as detailed in Section 3.3.2).

The impact of the PV design on agricultural production also can be quantified through the water usage efficiency (WUE) as proposed by Adeh et al. [153] and Marrou et al. [10].

WUE is then calculated as unit of biomass per unit of water used (commonly kg/m³) against the biomass produced in a control zone without the influence of PV:

$$WUE = \frac{WUE_{PV} - WUE_{control}}{WUE_{control}} \quad (2)$$

where WUE_{PV} refers to the water efficiency under PV panels.

The technical feasibility is strongly influenced by the design parameters of the PV system. Design criteria that consider a variation in azimuth and tilt angles of the modules to meet the light requirements for an optimal crop growth affect other parameters such as the land area occupation ratio (LAOR). (LAOR is the ratio between the area of the modules and the area of land that they occupy, expressed in percentage. When modules are tilted, there is a difference between the dimension of the height of the modules (that determines the height of the stripe) and one of their orthogonal projections on the ground (what we see in the pattern).) Nevertheless, considering that the average tilt angle of photovoltaic arrays is about 30°, the difference between these two values is neglectable (for modules 1.00 m high, the projection on ground is 1.06 m); for higher tilt angles, this difference increases) and thus, the normalized yearly energy generation and the land use intensity. Low tilt angles and larger row distance mean higher LAOR values which minimize the shading effect between rows, and enables enough radiation to allow the photosynthesis of the crop, but to the detriment of electricity generation. Therefore, finding the trade-off between energy and agricultural demands will require a careful analysis of the implications of selecting the design criteria. A frame of reference can be given by specific metrics, best known as key performance indicators (KPI), that are useful to analyze and compare existing facilities creating an analytical basis which helps the decision-making process, and hence the future development of these systems.

High LAOR values provide a high energy yield due to the amount of solar radiation that reaches solar modules, whereas the crop yield will be low. LER is a combination of PV and agriculture efficiency and comprises energy yield (unit of energy per unit of area on a yearly basis, or by time parameters that farmers can set according to the growing season) and agricultural yields, so the value also depends on local factors such as climate and crop under test. LER should only be used as reference for similar climatic conditions, PV system configuration and technology and crop. WUE is a useful parameter to assess the benefits of the food–energy–water nexus in drylands.

4. A Trans-Disciplinary Cognitive Framework for the Design and Assessment of Agrivoltaics

4.1. Innovative Three-Dimensional Patterns for Improved Ecological Performances

An agrivoltaic system is a complex system, being, at least, a spatial, an energy and an agronomic system. Its design and assessment must adhere to requirements set depending on the project's needs in order to meet desired performance quality objectives. Different dimensions of performance need to be taken into account. Moreover, the PV performance and the agri performance are in opposition, as solutions optimized for PV are detrimental to the sun caption of the plants (shading effects). This means that an optimization of the PV performance in general implies some negative effects on the "other" performance, the agri one.

It is crucial to understand what are the most influential parameters that can allow for an optimal design of the overall integrated performance of agrivoltaic system, considering the photovoltaic and the agri dimensions, and also some others, such as the effects on water and microclimate (already analyzed in literature) and new ones related to additional activities that may take place in the pore space of the APV pattern.

The analysis carried out so far demonstrates that the most influential design parameters are the pattern of the system and the height of the modules from the ground.

The following figures (Figures 10 and 11) show the state of art with designs for increasing the overall performance of the APV systems by varying the PV pattern (geometry

and density) and the modules' height (besides the technologies used for the PV systems and modules).

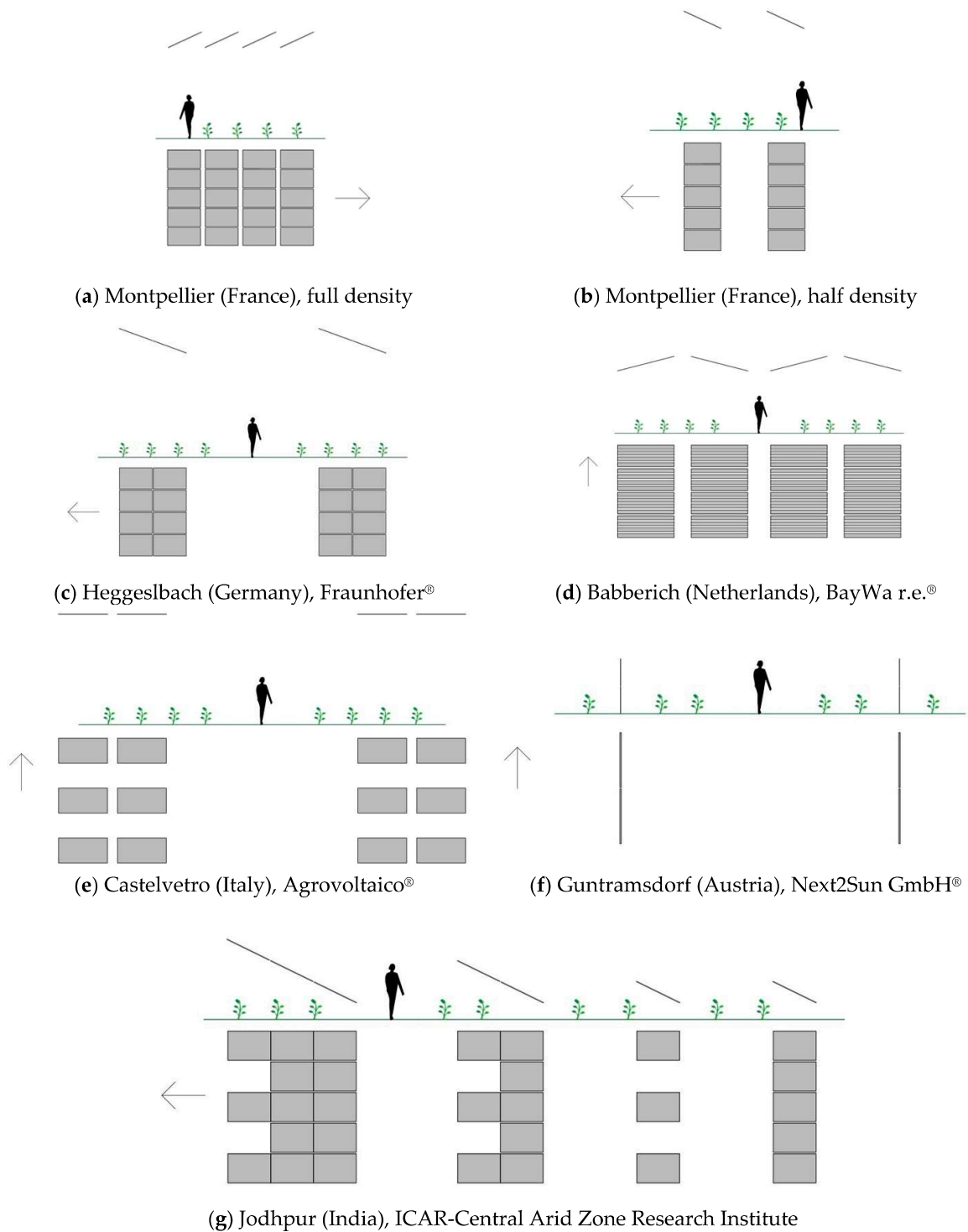


Figure 10. Different pattern solutions currently implemented or under investigation in open-field type APV systems. In the figures, the arrow is pointed north. The different solutions have an influence on irradiance and connectivity, as emphasized in Section 4.1, and different configurations create different pore zone types.

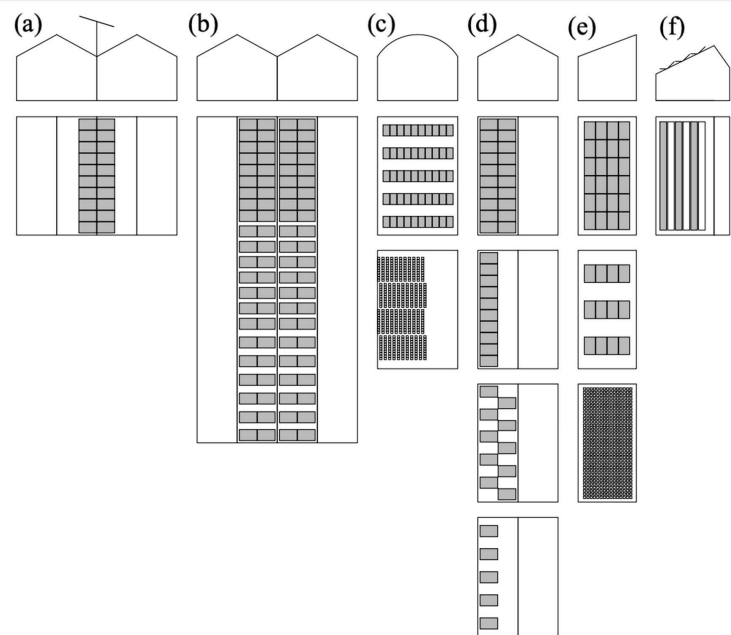


Figure 11. PV patterns in envelope integrated PV + protected crops systems (PV greenhouses). (a) Gable roof, dynamic system. (b) Gable roof fixed system, different densities 15%, 25% and 50% (adapted from [154]). (c) tunnel greenhouse, up: 37% PV density [122–124], down: checkerboard arrangement [51,155]. (d) Gable roof, one pitch covered 100% [43], 25% [47,48] checkerboard arrangement [47–52] and 20% [55,56]. (e) one pitch 100% and 32% covered [54] and semi-transparent glass PV modules (by spacing PV cells) 50% of light transmittance [65,84]. (f) Asymmetrical greenhouse, dynamic approach [74–78].

If the implications of different design choices related to the variation in the pattern (i.e., density) and in the height have been already emphasized, some new considerations are possible if APVs are understood as solar sharing systems, being part of a landscape.

For instance, the orientation of the pattern stripes (the PV modules), which until now mainly related to energy performance issues, can be varied so as to meet other objectives, such as the creation of pathways in designed areas of the landscape for people to walk on. The negative effects on the economical dimension related to the increased height of the modules from the ground have been proposed in literature. Nevertheless, in view of possible additional solar sharing options related to the APV, the perspective may change, as the structures of the APV can be seen as facilitating infrastructures (e.g., for the water collection, or for ground stabilizing elements).

Moreover, higher APV systems allow for better connectivity, and this is a relevant factor if additional functions related to animals and/or human activities are envisioned as further options for APV. Such new functions (or business models) might also generate beneficial effects for the economy (e.g., the use of APV areas as educational occasions for the local community).

For this reason, a “three-dimensional spatial approach” seems to be suitable for supporting design choices able to meet desired ecological quality objectives.

4.2. A New Landscape Oriented Descriptive Model

In light of all the features found in the literature, different disciplinary perspectives and related issues have to be considered in order to describe each system and identify diverse options and opportunities which correspond to performance quality objectives set by different stakeholders (farmers, PV industry, researchers, policy makers, local authorities). The study and development of APV systems requires, in fact, a truly trans-disciplinary ap-

proach, as their design and implementation entail agrarian, engineering, technological and energy issues, as well as landscape transformation and community acceptance ones. The existing knowledge should be addressed in a way that allows for the inclusion of current and future design issues and related ecological impacts. In this sense, some classifications have been presented, such as those of Willockx et al. [156] and Trommsdorff et al. [150] (this one mainly addresses first insights of how to design an open-field stilt-mounted type agrivoltaic system in the German context), but broader and more varied research questions must be addressed and discussed in a comprehensive methodological approach.

The background for the approach proposed here is the classification formulated by Scognamiglio [157] for the photovoltaic landscape, which builds a methodology for considering on ground PV as a part of the landscape, elaborating on fundamentals taken from the landscape ecology discipline. The descriptive methodology is based on the pattern-patch-matrix-corridor approach, as formalized by Forman [158], and then further elaborated for the specific needs of PV.

Based on research studies and commercial developments two main morphologies (to which multifaceted typologies are associated) were identified:

- On ground PV + open-field crops;
- Photovoltaic greenhouses (envelope integrated PV + protected crops).

Within the first category, two design approaches were detected in terms of installation height: stilt-mounted PV (elevating the solar infrastructure range from 2 to 5 m) and ground-mounted PV (Figure 12).

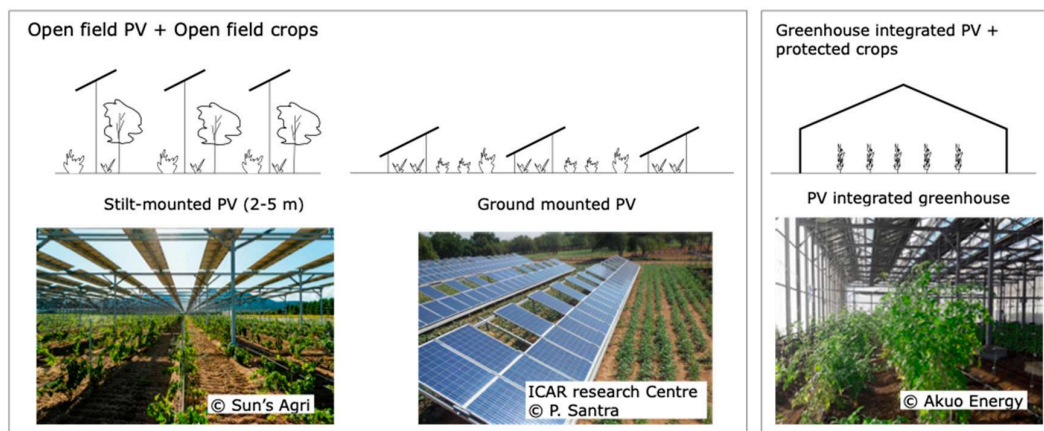


Figure 12. Agrivoltaic systems: typologies.

Thanks to the flexibility of the PV technology, integrated system configurations result in solutions that meet a complex set of objectives, wider than those carried out by the current PV design practices which only focus on prioritizing the energy generation at a given land area. A variety of spatial arrangements by modifying PV arrays' size, height and spacing in different patterns can be described according to a set of spatial parameters. In this context, energy and space features are strongly linked as a whole design approach where the spatial configuration of PV patterns within the existing parcellation defines the impact at landscape level. Therefore, the degree of porosity or density of the system becomes a relevant attribute to describe the pore (we define the pore as the space left by PV to host additional functions on the same land area) space (or the matrix) where the farming activity will be hosted. Moreover, the change of scale to include greenhouse applications can be covered by this approach through the analysis of the elements that comprise the envelope of the greenhouse and its configuration.

4.2.1. On Ground Photovoltaics + Open-Field Crops: The Agrivoltaic Pattern

Regarding the first family, the description assumes that the PV modules and the associated structures are the elements of partition of the space, whereas the crops are considered as a continuous in the considered area (matrix). The whole APV system is described as the APV pattern, so as to align the description to that of the landscape, and, i.e., the patch-corridor-matrix model [158].

The APV pattern is described as composed of photovoltaics and pore space (see Figure 13).

The PV system is considered in its multifaceted features, and it is described accordingly in terms of spatial features, energy features and engineering features. In this regard, Oudes and Stremke [159] have recently published a comparative study that analyzes solar landscapes by examining spatial properties, visibility, multifunctionality and temporality, showing the imperative need to build analytical frameworks for analyzing PV systems in a holistic manner, evaluating both individual properties and the system as a whole.

The spatial features are broken down into pattern and patch.

The pattern description gives an account of the spatial arrangement of the PV modules through the size (qualitatively: with large patches, with small patches; quantitatively: width, length, area); geometry (parallel stripes, checkboard, islands); type (continuous, dispersed, random); and density (porous, dense, LAOR). (In assessing as “porous” or “dense” a certain agrivoltaic pattern, here it is considered that about 40% of PV area/land area is usually standard for agrivoltaic systems.)

The patch corresponds to the single unit of a stripe configuring a pattern; that is, the PV module. It is therefore a repetition of PV modules, arranged along a line to form a stripe configuration. A patch is described in terms of transparency (opaque or semi-transparent/semi-translucent, and if semi-transparent or semi-translucent, the ratio between the PV and the total area is given in %); size (length, width, area); orientation (azimuth angle, tilt angle); color (qualitative assessment: name; quantitative assessment: RAL code, hue, saturation, brightness); borders (thick, fine); and height from the ground. (The assumption is considering the lowest side of the module for measuring the height from the ground.)

The energy features are broken down into nominal power, number of modules, density of power, land use energy intensity, normalized yearly energy generation and PV module technology. For each of these categories, appropriate metrics are considered.

The engineering features are broken down into system typology (fixed, sun-tracking one axis/two axis), modules supporting system (material, technology, weight) and foundations (material, technology, weight).

The “pore space” (what is in between the PV modules, and in between the PV modules and the ground) in the agrivoltaic pattern is described in terms of three-dimensional pattern features, crop features (type, homogeneity, plant’s height and seasonality) and energy features.

The three-dimensional pattern is an original descriptive expedient that the authors propose for characterizing an APV system from the performance point of view, based on the three-dimensional features of its pattern, referring to a unitary land area.

AGRIVOLTAIC PATTERN

1 PHOTOVOLTAICS

1.1 SPATIAL FEATURES

1.1.1 Pattern

1.1.1.1 Size

1.1.1.1.1 Qualitative assessment

1.1.1.1.1.1 With large patches

1.1.1.1.1.2 With small patches

Figure 13. *Cont.*

- 1.1.1.1.2 Quantitative assessment
 - 1.1.1.1.2.1 Width (m)
 - 1.1.1.1.2.2 Length (m)
 - 1.1.1.1.2.3 Area (m²)
- 1.1.1.2 Geometry
 - 1.1.1.2.1 Pararell stripes
 - 1.1.1.2.1.1 With uniform distancing
 - 1.1.1.2.1.2 With variable distancing
 - 1.1.1.2.2 Checkerboard
 - 1.1.1.2.3 Islands
 - 1.1.1.2.4 Others
- 1.1.1.3 Type
 - 1.1.1.3.1 Continuous
 - 1.1.1.3.2 Dispersed
 - 1.1.1.3.3 Random
- 1.1.1.4 Density
 - 1.1.1.4.1 Porous
 - 1.1.1.4.2 Dense
 - 1.1.1.4.3 LAOR (land area occupation ratio %)
- 1.1.2 Patch (The PV module)
 - 1.1.2.1 Transparency
 - 1.1.2.1.1 Opaque
 - 1.1.2.1.2 Semitransparent / semitranslucent
 - 1.1.2.1.2.1 PV area / total area (%)
 - 1.1.2.2 Size
 - 1.1.2.2.1 Width (m)
 - 1.1.2.2.2 Length (m)
 - 1.1.2.2.3 Area (m²)
 - 1.1.2.3 Orientation
 - 1.1.2.3.1 Azimuth angle (°)
 - 1.1.2.3.2 Tilt angle (°)
 - 1.1.2.4 Color
 - 1.1.2.4.1 Qualitative assessment
 - 1.1.2.4.1.1 Name
 - 1.1.2.4.2 Quantitative assessment
 - 1.1.2.4.2.1 HUE
 - 1.1.2.4.2.2 Brightness
 - 1.1.2.4.2.3 Saturation
 - 1.1.2.4.2.4 RAL code
 - 1.1.2.5 Borders
 - 1.1.2.5.1 Thick
 - 1.1.2.5.2 Fine

Figure 13. *Cont.*

- 1.1.2.5.3 Quantitative assessment
 - 1.1.2.5.3.1 Modules frame thickness (cm)
- 1.1.2.6 Height from the ground (cm)
 - *The assumption is considering the lowest side of the module for measuring the height from the ground
- 1.2 ENERGY FEATURES
 - 1.2.1 Nominal power (kW_e)
 - 1.2.2 Number of modules (n)
 - 1.2.3 Density of power (W/m²)
 - 1.2.4 Land use energy intensity (kWh/m²/y)
 - 1.2.5 Normalized yearly energy generation (kWh/kW_e/y)
 - 1.2.6 PV module technology
 - 1.2.6.1 monofacial
 - 1.2.6.2 bifacial
 - 1.2.7 PV layer technology
 - 1.2.7.1 PV active material
 - 1.2.7.1.1 Thin film
 - 1.2.7.1.2 amorphous Si
 - 1.2.7.1.3 CdTE
 - 1.2.7.1.4 CIGS
 - 1.2.7.2 Crystalline
 - 1.2.7.2.1 mono-crystalline
 - 1.2.7.2.2 poly-crystalline
 - 1.2.7.3 spectral selective film
- 1.3 ENGINEERING FEATURES
 - 1.3.1 System Typology
 - 1.3.1.1 Fixed
 - 1.3.1.2 Sun-tracking
 - 1.3.1.2.1 One axis
 - 1.3.1.2.2 Two axis
 - 1.3.2 Modules Supporting System
 - 1.3.2.1 Material
 - 1.3.2.2 Technology
 - 1.3.2.3 Weight (kg)
 - 1.3.3 Foundations
 - 1.3.3.1. Material
 - 1.3.3.2 Technology
 - 1.3.3.3 Weight (kg)
- 2 THE PORE SPACE
 - 2.1 THREE-DIMENSIONAL PATTERN FEATURES
 - 2.1.1 Average volume (m³)
 - 2.1.2 Area (m² or ha)
 - 2.1.3 Zone type (irradiation and connectivity)

- 2.1.3.1 High irradiation
 - 2.1.3.1.1 High connectivity
 - 2.1.3.1.2 Medium connectivity
 - 2.1.3.1.3 Low connectivity
- 2.1.3.2 Medium irradiation
 - 2.1.3.2.1 High connectivity
 - 2.1.3.2.2 Medium connectivity
 - 2.1.3.2.3 Low connectivity
- 2.1.3.3 Low irradiation
 - 2.1.3.3.1 High connectivity
 - 2.1.3.3.2 Medium connectivity
 - 2.1.3.3.3 Low connectivity
- 2.1.4 Crop density (crop area / pore area, %)
- 2.2 CROP FEATURES
 - 2.2.1 Crop type
 - 2.2.1.1 Fructifers
 - 2.2.1.2 Herbaceous / Arable crops
 - 2.2.1.3 Meadles & Pastures
 - 2.2.2 Crop homogeneity
 - 2.2.2.1 Monoculture
 - 2.2.2.2 Association
 - 2.2.3 Plants height
 - 2.2.3.1 Uniform
 - 2.3.3.1.1 Plants height (m)
 - 2.2.3.2 Nonuniform
 - 2.2.3.2.1 Maximum plants height (m)
 - 2.2.3.2.2 Minimum plants height (m)
 - 2.2.3.2.3 Average plants height (m)
 - 2.2.4 Seasonality
 - 2.2.4.1 12 months
 - 2.2.4.2 6 months
 - 2.2.4.2 3 months
- 2.3 ENERGY FEATURES
 - 2.3.1 Irradiance (W/m²)
 - 2.3.1.1 High
 - 2.3.1.2 Average
 - 2.3.1.3 Low
 - 2.3.2 Crop yield (kg/m²/y)

Figure 13. Comprehensive methodological approach to describe APV systems (on ground PV + open-field crops) from a trans-disciplinary perspective (preliminary qualitative assessment).

The features of the three-dimensional pattern are average volume, area, zone type (irradiation and connectivity) and crop density (crop area/total area %). The average volume considers the pore space area (total land area minus the area corresponding to the

projection of the PV modules on the ground) multiplied by the height of the modules from the ground (considering the lowest line of the modules) (see Figure 14).

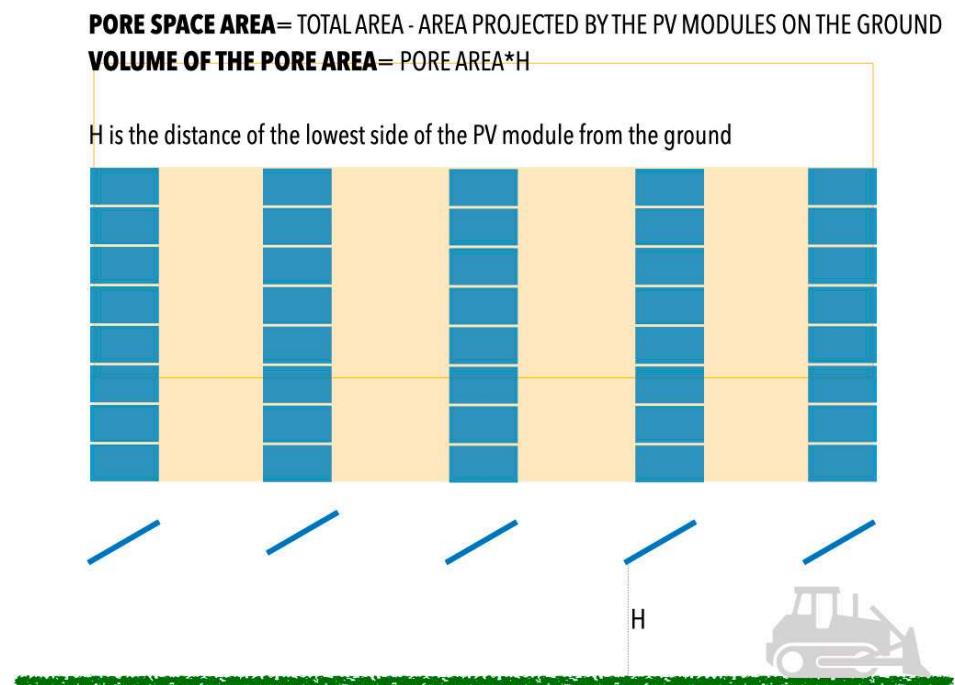


Figure 14. The three-dimensional pattern of the APV systems.

The zone type qualitatively describes irradiation and connectivity that characterize the pore area. Connectivity is defined as the degree to which the landscape facilitates or impedes movement among resource patches. There are zones with high, medium and low irradiation, and to these correspond high, medium and low connectivity.

Irradiation and connectivity basically depend on the degree of porosity of the PV pattern and on the height of the PV modules from the ground: the more porous the pattern, the higher the irradiance (and therefore the irradiation), whereas a high distance from the ground implies generally a higher connectivity and a lower irradiance.

Figure 15 shows the influence of module height on irradiance. Given a certain PV pattern and sun altitude, in fact, depending on the height of the modules from the ground, it is possible to see that the dynamically shaded area decreases with the increase in the height for the same area under the PV arrays. In Figure 15a, the color ranging from blue to orange provides a qualitative assessment of the height effect on the irradiance, and therefore on the irradiation. A quantitative assessment is more complex (a simple analysis is shown in Figure 15b) and requires a simulation effort, as the degree of irradiation depends on the dynamic shading on the ground.

Regarding the connectivity, Figure 16 shows that, given a certain PV pattern, the connectivity increases along with the increase in the height of the modules from the ground.

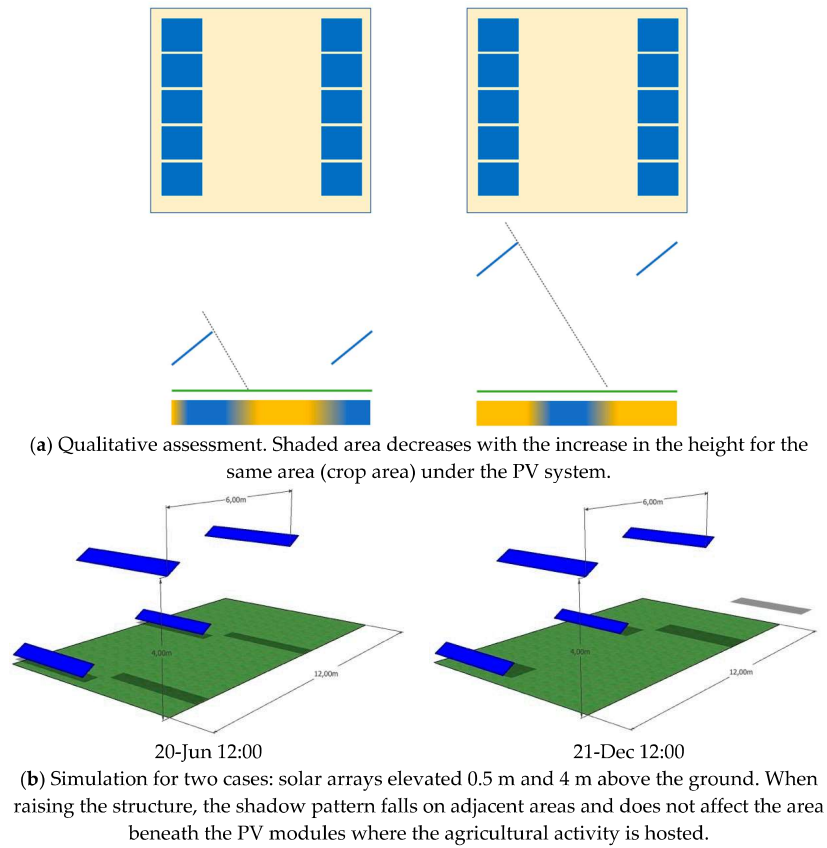


Figure 15. Irradiation vs. height of the photovoltaic modules on the ground.

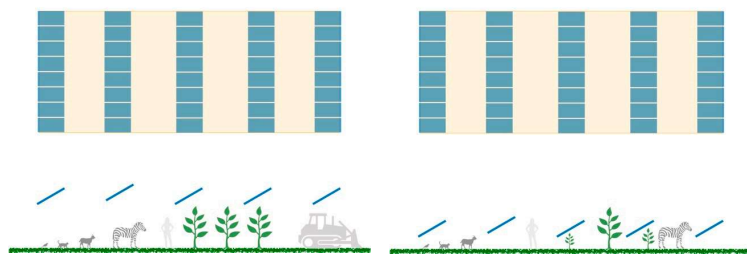


Figure 16. Photovoltaic pattern and connectivity.

Figure 17 shows how, given a certain land area, a porous pattern increases both the average irradiation on the crops and the connectivity.

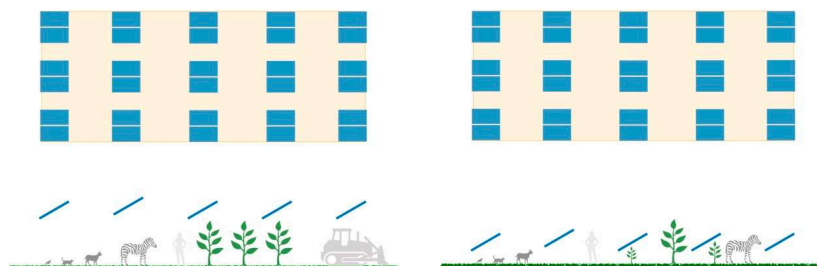


Figure 17. Porous pattern and connectivity.

Based on these considerations, zone types have been defined as high irradiation and high/medium/low connectivity, medium irradiation and high/medium/low connectivity and low irradiation and high/medium/low connectivity.

Then, the crop density is considered as the ratio between the crop area and the pore area (%).

The crop features are plant's height (uniform; nonuniform, and is uniform: height; if nonuniform maximum, minimum and average height); seasonality (12, 6 or 3 months).

The energy features are irradiance (classified as high, average, low) and crop yield.

Being aware of the complexity in describing vegetable organisms, we propose this preliminary classification as a starting point for creating a link between spatial features of the pore area and crop selection based on low to high irradiance needs of the plants—and also on additional animal or human activities that can take place in the pore area based on connectivity degree.

4.2.2. Greenhouses (Envelope Integrated PV + Protected Crops)

The greenhouses (envelope integrated PV + protected crops) are described, keeping into account the PV systems and the crop (see Figure 18). Technological systems for microclimate controlling and performance monitoring should be added for giving a complex account of the greenhouse functioning, but this is out of the scope of this paper.

PHOTOVOLTAIC GREENHOUSES

1 ENVELOPE

1.1 MORPHOLOGY (CROSS SECTION)

1.1.1 One pitch

1.1.1.1 Area (m²)

1.1.1.2 Height

1.1.1.2.1 Minimum (m)

1.1.1.2.2 Maximum (m)

1.1.1.3 Orientation

1.1.1.3.1 Azimuth angle (°)

1.1.1.3.2 Tilt angle (°)

1.1.1.4 Transparency

1.1.1.4.1 Opaque

1.1.1.4.2 Semitransparent / semitranslucent

1.1.1.4.2.1 PV area/total area (%)

1.1.2 Two pitches

1.1.2.1 Pitch 1

1.1.2.1.1 Area (m²)

1.1.2.1.2 Height

1.1.2.1.2.1 Minimum (m)

1.1.2.1.2.2 Maximum (m)

1.1.2.1.3 Orientation

1.1.2.1.3.1 Azimuth angle (°)

1.1.2.1.3.2 Tilt angle (°)

1.1.2.1.4 Transparency

1.1.2.1.4.1 Opaque

1.1.2.1.4.2 Semitransparent / semitranslucent

Figure 18. *Cont.*

- 1.1.2.1.4.2.1 PV area/total area (%)
- 1.1.2.2 Pitch 2
 - 1.1.2.2.1 Area (m²)
 - 1.1.2.2.2 Height
 - 1.1.2.2.2.1 Minimum (m)
 - 1.1.2.2.2.2 Maximum (m)
 - 1.1.2.2.3 Orientation
 - 1.1.2.2.3.1 Azimuth angle (°)
 - 1.1.2.2.3.2 Tilt angle (°)
 - 1.1.2.2.4 Transparency
 - 1.1.2.2.4.1 Opaque
 - 1.1.2.2.4.2 Semitransparent / semitranslucent
 - 1.1.2.2.4.2.1 PV area/total area (%)
- 1.2 MATERIAL
 - 1.2.1 Glass
 - 1.2.2 Others
 - 1.2.2.1 Plastic sheets
 - 1.2.2.2 Polycarbonate
- 1.3 DIMENSIONS
 - 1.3.1 Side 1 (m)
 - 1.3.2 Side 2 (m)
 - 1.3.3 Area (m²)
 - 1.3.4 Volume (m³)
- 2 PHOTOVOLTAICS**
 - 2.1 PV SYSTEM
 - 2.1.1 Spatial Features
 - 2.1.1.1 Area (m²)
 - 2.1.1.2 Transparence degree (%)
 - 2.1.2 Energy Features
 - 2.1.2.1 Nominal power (kW_v)
 - 2.1.2.2 Normalized yearly energy generation (kWh/kW_v/y)
 - 2.1.2.3 Density of power (kW_v/m²)
 - 2.1.3 Typology
 - 2.1.3.1 Fixed
 - 2.1.3.2 Dynamic
 - 2.1.3.2.1 Lamellas
 - 2.1.3.2.2 Sun-tracking
 - 2.2 PV MODULES
 - 2.2.1 Spatial Features
 - 2.2.1.1 Area (m²)
 - 2.2.1.2 Transparency
 - 2.2.1.2.1 Opaque

Figure 18. Cont.

- 2.2.1.2.2 Semitransparent / semitranslucent
- 2.2.1.2.3 Transparence degree (%)
- 2.2.1.3 Size
 - 2.2.1.3.1 Quantitative assessment
 - 2.2.1.3.1.1 Width (m)
 - 2.2.1.3.1.2 Length (m)
 - 2.2.1.3.1.3 Area (m²)
 - 2.2.1.4 Orientation
 - 2.2.1.4.1 Azimuth angle (°)
 - 2.2.1.4.2 Tilt angle (°)
 - 2.2.1.5 Color
 - 2.2.1.5.1 Qualitative assessment
 - 2.2.1.5.1.1 name
 - 2.2.1.5.2 Quantitative assessment
 - 2.2.1.5.2.1 HUE
 - 2.2.1.5.2.2 Brightness
 - 2.2.1.5.2.3 Saturation
 - 2.2.1.5.2.4 RAL code
 - 2.2.1.6 Borders
 - 2.2.1.6.1 Thick
 - 2.2.1.6.2 Fine
 - 2.2.1.6.3 Quantitative assessment
 - 2.2.1.6.3.1 Modules frame thickness (cm)
- 2.2.2 Energy Features
 - 2.2.2.1 Nominal power (kW_e)
 - 2.2.2.2 Efficiency (%)
- 2.2.3 Typology
 - 2.2.3.1 Module Technology
 - 2.2.3.1.1 Monofacial
 - 2.2.3.1.2 Bifacial
 - 2.2.3.1.3 Concentrating
 - 2.2.3.1.4 Spectral selective
 - 2.2.3.2 Layers and materials
 - 2.2.3.2.1 Front layer
 - 2.2.3.2.2 PV layer
 - 2.2.3.2.2.1 Standard
 - 2.2.3.2.2.1.1 Thin film PV active materials
 - 2.2.3.2.2.1.1.1 a-Si
 - 2.2.3.2.2.1.1.2 CIGS
 - 2.2.3.2.2.1.1.3 CdTe
 - 2.2.3.2.2.1.1.4 OPV
 - 2.2.3.2.2.1.1.5 Others

Figure 18. *Cont.*

- 2.2.3.2.2.1.2 Crystalline PV active materials
 - 2.2.3.2.2.1.2.1 Mono-crystalline Si
 - 2.2.3.2.2.1.2.2 Poly-crystalline Si
 - 2.2.3.2.2.2 Spectrum selective
 - 2.2.3.2.3 Back layer
 - 2.2.3.2.4 Additional layer
- 3 CROP**
- 3.1 SPATIAL FEATURES
 - 3.1.1 Area (m²)
 - 3.1.2 Density (crop area/patch area, %)
 - 3.1.3 Plants height (m)
 - 3.2 ENERGY FEATURES
 - 3.2.1 Yield (kg/m²/y)

Figure 18. Comprehensive methodological approach to describe APV systems (envelope integrated PV + protected crops) from a trans-disciplinary perspective (preliminary qualitative assessment).

The envelope is broken down in morphology, material and dimensions.

Morphology refers to the cross section of the greenhouse, and it is therefore broken down into one pitch, two pitches and curved. Each single pitch is described in terms of area, height (minimum and maximum, respectively), orientation (azimuth angle, tilt angle) and transparency (opaque, semi-transparent/semi-translucent).

For the envelope material, glass and others (plastic sheets, polycarbonate, etc.) are considered.

The dimensions are side 1, side 2, area and volume.

Photovoltaics is broken down in PV system and PV modules. For each of them, spatial features, energy features and typology are described.

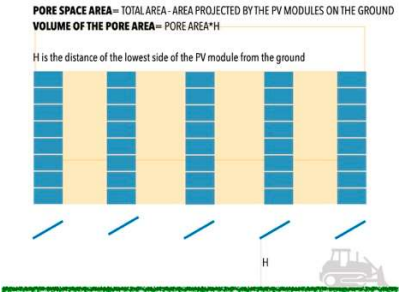
For the PV system, spatial features are area (m²) and transparency (%). Energy features are nominal power (kW_p), normalized yearly energy production (kWh/kW_p/y) and density of power (kW_p/m²). Typology is broken down into fixed and dynamic (lamellas and sun-tracking).

For the PV modules, the spatial features are area (m²) and transparency (opaque, semi-transparent/semi-translucent, transparency degree %). Energy features are nominal power (kW_p) and efficiency (W/m²). Typology is broken down into module technology (monofacial, bifacial, concentrating; spectral selective) and layers and materials (front layer, PV layer, back layer, additional layer). The PV layer is further broken into standard (thin film and crystalline technologies) and spectrum selective.

4.3. Three-Dimensional Agrivoltaic Patterns and Related Metrics

Starting from the considerations thus far, some first preliminary metrics related to the three-dimensional agrivoltaic pattern, useful for guiding and assessing the design of sustainable APV systems, can be advanced (see Table 4). It is worth noting that there is still room for exploring design possibilities of APV. This translates into a variety of possibilities for the PV greenhouses, both in terms of envelope and technologies; whereas in the case of the on-ground PV + open-field crops (agrivoltaic patterns), this translates into the design and assessment of new patterns, which may be characterized by low or high levels of “randomness”, both in terms of horizontal and vertical patterns of the PV modules (Figures 19 and 20), and leading, theoretically, to a kind of three-dimensional sparse mosaic or to the PV modules fading out in space (with possible new ecological significance).

Table 4. Three-dimensional APV pattern: definition and metrics.

Three-Dimensional Agrivoltaic Pattern: Main Metrics Involved		
<p>The three-dimensional agrivoltaic pattern (normalized “pore space”, being the pore space the space in between the PV modules and in between the PV modules and the ground) corresponds to certain spatial configuration of an APV system. It can be defined as a function of the volume of the pore space given a unitary land area and a unitary modules height (H). For instance: 1 ha and 1 m.</p> <p>The normalized pore space volume would then be: $100 \times 100 \times 1 = 10,000 \text{ m}^3$</p> <p>The density of the PV pattern influences the amount of the yearly irradiation, while specific pattern configurations (geometrical arrangement of the PV modules) influence the homogeneity of the irradiation on ground. The height of the PV modules from the ground influences the degree of connectivity (the degree to which the landscape facilitates or impedes movement among resource patches) of the system.</p>		
 <p>PORE SPACE AREA = TOTAL AREA - AREA PROJECTED BY THE PV MODULES ON THE GROUND VOLUME OF THE PORE AREA = PORE AREA * H H is the distance of the lowest side of the PV module from the ground</p>		
Three-Dimensional Pattern Spatial Attributes		
PV PATTERN	Density degree (PV area/ pore area)	%
	Geometry	Continuous/Dispersed/Random
	Number of crop zone types (depending on irradiance)	n
MODULES HEIGHT	H	m
PORE SPACE VOLUME	(Pore area—PV area projection on the ground) * H	m^3
(Site Depending) Solar Potential Parameters		
YEARLY IRRADIATION		$\text{kWh}/\text{m}^2/\text{y}$
SOLAR POTENTIAL	Yearly equivalent sun hours	n
(Three-Dimensional Pattern) Depending Solar Potential And Connectivity Parameters		
IRRADIANCE HOMOGENEITY DEGREE ON PV	Number ranging from 1 to 0 depending on whether the orientation of PV is homogeneous or not. No variation of tilt and azimuth is 1; no variation of azimuth, variation of tilt or variation of azimuth, no variation of tilt is 0.5; variation of azimuth and tilt is 0.	n (1; 0.5; 0)
IRRADIANCE HOMOGENEITY DEGREE ON CROPS	Number ranging from 1 to 0 depending on whether the geometrical pattern of PV is homogeneous (1), dispersed (0.5) or random (0).	n (1; 0.5; 0)
CROP TYPE ZONES	The crop selection depends on irradiance. If the irradiance is homogeneous, there is 1 zone type. If it is not there, are more. For standard patterns (parallel stripes with optimized distancing between the stripes), there are 2 (one underneath the PV modules, and the other in between the stripes of modules), but a more porous pattern may allow for a third zone with no shading.	n (1 or 2 or 3)
PV TYPE ZONES	Depending on how many different orientations of the PV modules are, the number of PV type zones can be determined.	n
CONNECTIVITY DEGREE (MATRIX PERMEABILITY)	Volume of the pore area/total area.	%
Nominal Power Parameters		
MODULES AREA		m^2
PV NOMINAL POWER		W_p
CROP AREA		m^2
Solar Conversion Efficiency Parameters		
MODULES EFFICIENCY		%
ENERGY DENSITY PARAMETERS		
PV DENSITY OF POWER		W/m^2
LAND USE ENERGY INTENSITY		$\text{kWh}/\text{m}^2/\text{y}$
PLANTS DENSITY OF MASS		Kg/m^2
Producibility Parameters (should be calculated based on yearly equivalent Sun hours)		
NORMALIZED PV PRODUCIBILITY		$\text{kWh}/\text{kW}_p/\text{y}$
PV YEARLY YIELD		MWh/y
CROPS YEARLY YIELD		q/y

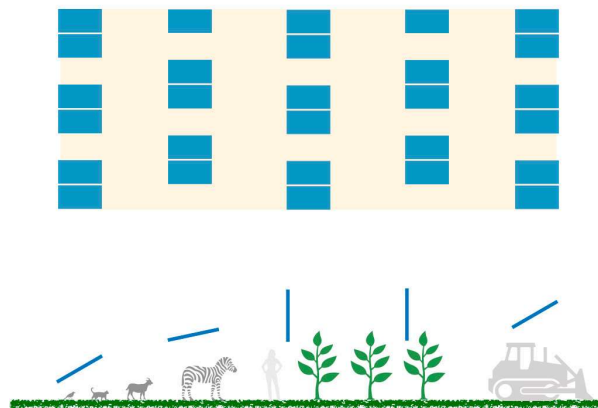


Figure 19. The design and assessment of agrivoltaics open new perspectives if the system is approached as a three-dimensional pattern characterized by a certain degree of randomness, both in the horizontal and vertical arrangement of the modules. The limit point is that PV modules fade out in space, with possible new related ecological performances.



Figure 20. Suggestion for a three-dimensional photovoltaic random pattern. Solar Drifts, designed by Balmori Associates. University of Buffalo, Buffalo Solar Park, NY, USA. Competition Finalist, 2010 [160].

5. Conclusions

The energy and engineering design optimization, the development of new technologies and the correct selection of plant species adapted to the PV system are the areas where the current research is actively focusing in APV systems. Along with the continuous research progress, the success of several international experiences through pilot projects which implement new design solutions and use different PV technologies (showing the technical potential in real working conditions) has triggered APV, and it has been met with great acceptance from the industry and interest from governments. It is in fact a significant potential contribution to meet climate challenges touching on food, energy, agriculture and rural policies [161,162]. Moreover, it is understood—i.e., by energy developers—as a possible driver for the implementation of large-scale PV installations and building-integrated agriculture [163], which without the APV function, would not be successful in the authorization process due to land use concerns.

A sharp increase is expected in terms of number of installations and capacity in the near future. Along this trend, new concerns regarding landscape and urban transformation issues are emerging as the implementation of APV might be mainly focused on the efficiency of the PV system (more profitable than agriculture), with insufficient attention on the correct synergy between energy and food production.

The landscape, as intended by the European Landscape Convention [164], is the correct dimension where issues can be faced in view of an improved ecological performance of the systems. The mere technical perspective must be overcome in favor of a more inclusive, sustainable one that considers new approaches for conceiving APV patterns. These may include, for instance, new community-oriented functions (e.g., educational or recreational) that can empower the use of APV as solar-sharing solutions (energy, agri, community).

The proposed framework, which describes the APV systems as three-dimensional landscape patterns, seeks to characterize them from a new inclusive design vision enabling

understanding of the tight connection between energy and space and making some room for other new considerations (i.e., landscape related). A set of parameters classified by category to define an APV system as a part of the landscape (pattern, patch, pore) including different disciplinary contents (photovoltaic technology, agronomy, engineering) has been formalized, guiding and assessing the design of agrivoltaic systems in view of desired quality objectives. Under this perspective, the need for new APV-related research emerges.

The study of ecosystem service trade-offs in the spatial planning and design for energy transition, to identify potential synergies and minimize trade-offs between renewable energy and other ecosystem services, has been already acknowledged as a key issue for avoiding conflicts between global and local perspectives [165].

Further specific actions towards the formalization of an appropriate cognitive framework for APV are a multidimensional performance matrix including heterogeneous performance indicators for assessing the overall ecosystem performance of the systems and the experimentation with new innovative patterns able to include community functions.

The development of new innovative systems (PV system technology) and components (photovoltaic devices technology) can enhance the energy performance of selected design options for APV greenhouse typology.

None of these perspectives can overlook a truly inter-disciplinary and even trans-disciplinary approach.

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Nomenclature

APV	Agrivoltaics
BIPV	Building integrated photovoltaics
CPV	Concentrated photovoltaics
DSSC	Dye-sensitized solar cell
KPI	Key performance indicator
LAOR	Land area occupation ratio
LCA	Life cycle assessment
LER	Land equivalent ratio
LSC	Luminescent solar concentrator
NIR	Near infrared radiation
OPV	Organic photovoltaics
PAR	Photosynthetically active radiation
PCE	Power conversion efficiency
PV	Photovoltaics
PVG	Photovoltaics greenhouses
WUE	Water usage efficiency

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