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Review

Agrivoltaic Engineering and Layout Optimization Approaches in the Transition to Renewable Energy Technologies: A Review

Meagan Reasoner and **Aritra Ghosh** *

College of Engineering, Mathematics and Physical Sciences, Renewable Energy, University of Exeter, Exeter EX4 4PY, UK
* Correspondence: a.ghosh@exeter.ac.uk

Abstract: As more nations move towards net-zero emission goals by 2050, research into the coupling of photovoltaics (PV) and agriculture has increased into a new sector of agrivoltaics (AV). Measurement of the Land Equivalent Ratio (LER) has allowed researchers to develop methods for optimizing the agrivoltaic system. Studies on innovative engineering technologies related to photovoltaic tracking along with new generation PV cells were reviewed to determine the factors that influence optimization. This review also considered AV farm layouts and how different spacing, height, and density impact the shading under the panels. As panels block the light from hitting the plants, the photosynthetically active radiation (PAR) changes and alters plant growth. The shading, however, also creates micro-climates that have beneficial qualities in terms of water usage and PV efficiency. The overall review investigated the research of the last five years into AV optimization and the implications for future AV developments.

Keywords: agriculture; agrivoltaic; photovoltaic; renewable energy; land-use; sustainable integration; single-axis tracking; dual-axis tracking; crop yield

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Citation: Reasoner, M.; Ghosh, A. Agrivoltaic Engineering and Layout Optimization Approaches in the Transition to Renewable Energy Technologies: A Review. *Challenges* **2022**, *13*, 43. https://doi.org/10.3390/challe13020043

Academic Editor: Susan Prescott

Received: 7 June 2022
Accepted: 25 August 2022
Published: 1 September 2022

1. Introduction

As more nations sign on to the Paris Agreement and attempt to achieve net-zero emissions (NZEs) by 2050 [1], the utilization of renewable energy technologies (RETs) has increased. PVs are a major component of shifting energy production to RETs. This is mainly due to the low levelized cost of energy [2] in most regions compared to other RETs. However, with the increase in PV installation, there is a conflict with the United Nations' sustainability development goals pertaining to land restoration [3]. The goals reflect the sustainable use of lands to promote food security and nourishment through sustainable agriculture [4]. This potential conflict of land use has led to an increased interest in AVs. In the dual-land use concept that integrates PV and agriculture, first proposed by [5], the AV system allows for both land restoration and NZE goals to be reached simultaneously. The interest has grown exponentially within the past decade, as illustrated in Figure 1. It also shows the growth in installed PV electricity generation by GWh. This article reviewed new research in the field of AVs, with a focus on design optimization of the coupled system and the impacts on both crop growth and PV efficiency. The review included both in situ experiments and computer simulations. By focusing on recent studies, this review will provide researchers with an overview of the current state of the industry and help direct new avenues of future work. In addition, reviewing the optimization of the AV farms will also motivate growth in the industry globally.

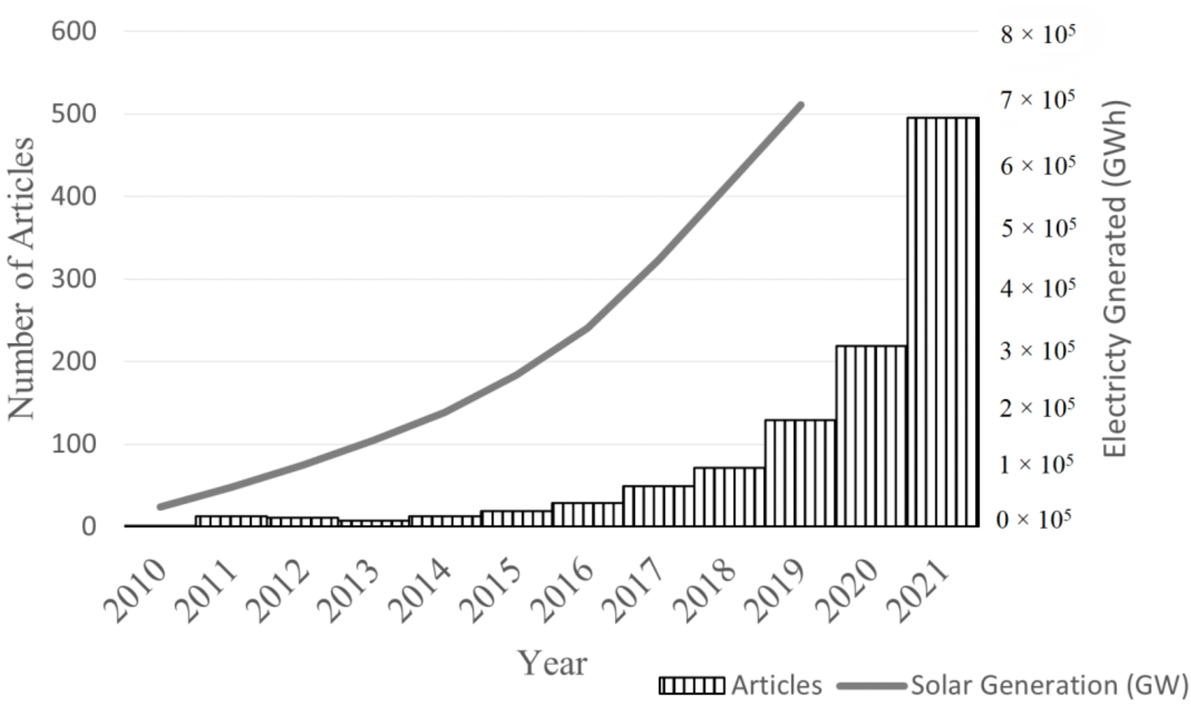


Figure 1. Increasing number of scholarly articles relating to AVs in the past 10 years. Sources: [6] All Rights Reserved.

1.1. Land Use Optimization

While the advancements in PV technologies have improved the overall power density [7], land requirements are still a major concern for utility-scale PV power plants. The recent study conducted by [7] determined that the power density ($\frac{MW_{DC}}{Acre}$) was 52% higher than the 2011 calculations for fixed-tilt plants and 42% higher for tracking plants. However, even with the vast improvements in power density, a small utility-scale solar system would require ~14.25 acres of land. This land requirement has helped drive the increase in *AV* research [8]. In a PV system, optimization is dependent on the tilt angle (θ), maximizing the solar irradiation on the panels [9], whereas the coupled system needs to account for inter-row shading to minimize the loss of photosynthetically active radiation (PAR) on the crops. This has led the way for optimization factors such as the land equivalent ratio (*LER*), which according to [10], is defined as

$$LER = \frac{Yield\ of\ Plants_{\ AV}}{Yield\ of\ Plants_{\ no\ AV}} + \frac{Electricity\ Yield_{\ AV}}{Electricity\ Yield_{\ no\ AV}} \quad (1)$$

to use as an economic parameter that considers both biomass and electricity yields. As shown in Figure 2, the LER compares the land utilization individually and combined in an *AV* system. The initial works of [5] considered module spacing as a key parameter in optimizing the *AV* system. Early works [11], based in Montpelier, France, analyzed the LER of a full-density and half-density *AV* set-up and compared the results to determine the impact of module shading on the overall system efficiency.

In addition to module spacing, modeling of different PV technologies, such as vertical bifacial solar modules [12,13] and single-axis tracking [14], were used as methods to optimize electricity generation. Experiments run by the University of Oregon [15,16] and by [17] examined in situ data on the effects of crops on the efficiency of PV modules. Several feasibility studies examined land availability [18] and different climates throughout Europe [19] to determine where an *AV* system would be most suitable. Studies looked into the impact of crops on the ambient temperature surrounding the solar system. Throughout this review, both numerical models and field tests were used to determine how *AV* systems contribute to the overall efficiency of the PV.

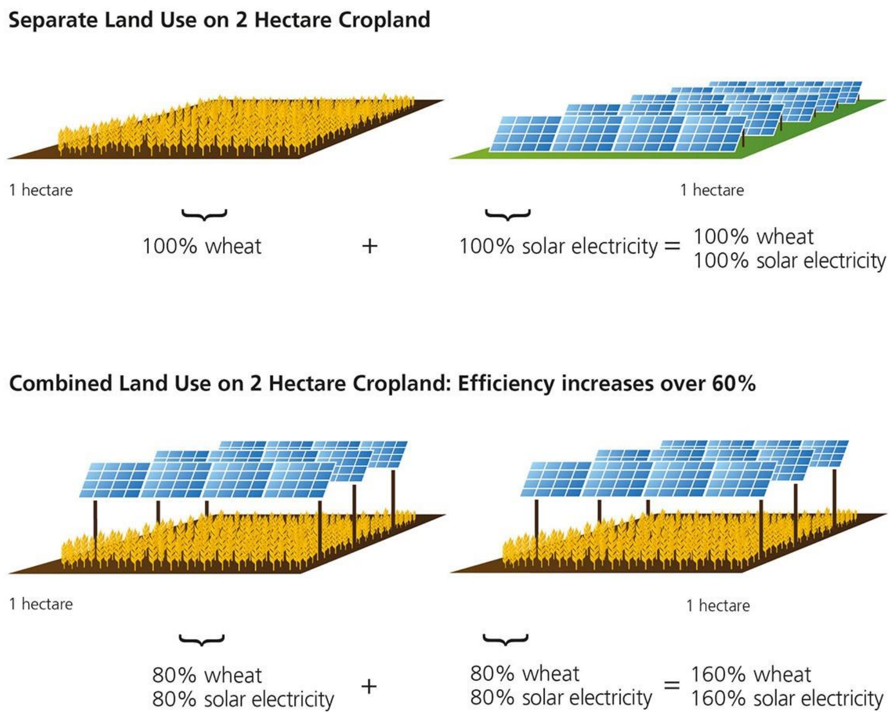


Figure 2. Comparison of land use for separate and combined agriculture and PV systems. Source: Reprinted with permission [20]. Copyright {2021}.

1.2. Mutually Beneficial Relationship

The optimization of an AV system requires an understanding of both the crops PAR, which is considered to be the entire visible light spectrum (400–700 nm) [21], and PV efficiency. Earlier studies analyzed the impacts of shading on crop yields (lettuce) [22] and the benefits of micro-climates created by under-panel crops [23]. These initial studies were limited in the variety of crop types and locations. However, with the growing need to move towards dual-land use options, numerous experimental and modeled studies were conducted in this region of interest. A substantial amount of current research revolves around identifying crops that would benefit from growing in an AV system. The determination of AV-compatible crops is vital to the success of a coupled system. Studies such as those conducted by [24,25] analyzed the irradiation under the PV modules and the overall effects on crop yields. Along with in situ experiments, researchers made use of simulation software for both PV electricity generation (PVSYST) and for crop modeling (STICS) to run optimization studies [9]. This review provides a comprehensive list of crops that were studied recently (post-2016) and how the shading from an AV system impacts crop yield.

2. Optimization Studies

As discussed in Section 1, the need to understand the coupled efficiency of an AV system can help move nations toward their NZE goals. The amount of solar irradiance that is converted into electricity is dependent on panel tracking [14,26,27], tilt and azimuth angle [25], and the PV used in the system [21,28,29]. Along with the electrical efficiency, the AV layout, including inter-module spacing [30] or density [31,32], PV transparency [33], and the water usage change due to panel shading [34,35] are all variables that must be considered when optimizing an AV system. Initial AV farms, such as the one in Montpelier, France, acted as proof of concept [11], and the first AV farm in Japan [36] allowed for different methods of optimization to be studied. The optimization of these systems can be divided by which component of the AV system it belongs to. Table 1 lists the different methods that were studied in the last five years.

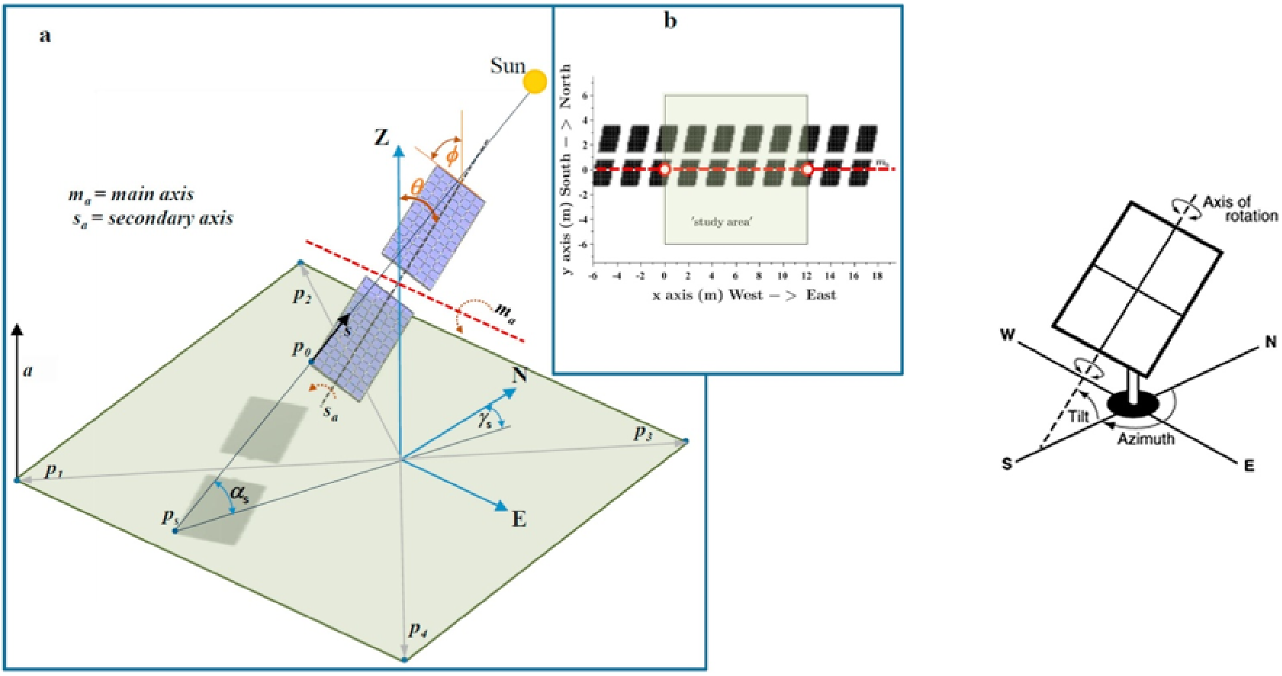
Table 1. Optimization methods modeled or field tested in the last 5 years.

	Engineering
Tracking	Dual Axis North/South West/East
PV	Bifacial Concentrated Thin Film Transparent Spectral Selective
	System Layout
Placement	Density Spacing Patterned (i.e., Checker-board) Height
Orientation	Vertical Panels Tilt Angle

2.1. Engineering Optimization

2.1.1. Tracking

A PV array is designed to maximize the amount of solar irradiance striking the PV. In an effort to improve electricity production, researchers engineered different methods of tracking the sunlight [37]. While the tracking control system may differ between an active and passive method, the tracking is relative to the axis of rotation. A single-axis tracking system, Figure 3B, can be rotated either about the North/South axis, as shown, or the East/West axis. However, the dual-axis tracking system (Figure 3A) is controlled to rotate both axes. The AV system solar tracking was studied for both the increased electrical output and the effective shading factor [27,38]. The study conducted by [31] modeled the effects of different systems in Lahore, Pakistan. The study compared the effects that N/S and E/W tracking had on the PAR for lettuce and tomato plants. The conclusion showed that a vertical E/W tracking orientation provided the best power output, while the fixed E/W allowed for the most useful PAR. This same conclusion was drawn by [27] for AV systems modeled in both California and Texas, USA. A 2018 study by Amaducci et al. on the dual axis tracking AV system Agrovoltaico© (Figure 3A) analyzed the impact of sun tacking on the shading and growth of biogas maize. The study investigated the LER for full tracking systems compared to fixed arrays. The study compared arrays with 10 panels and 32 panels, both fixed (F1 and F2) and tracking (ST1 and ST2) to full sunlight maize growth and a ground-based sun-tracking PV system. The analysis showed the LER as 1.31, 1.31, 2.04, and 1.74 for the ST1, FT1, ST2, and FT2, respectively. The dual tracking 32-panel system (ST2) generated the highest level of electricity, and all four systems were modeled to produce more bio yield compared to full spectrum light. The modeling of tracking from the [38] was validated with field observations of a rice paddy with AVs.



(**A**) Dual–axis: (a) perspective; (b) plane (**B**) Single–axis

Figure 3. Different options for PV array tracking. (**A**) source: [26], (**B**) source: [37].

2.1.2. PV Cell Type

Another area of engineering optimization that has been researched in the last five years centers around the PV cell. While silicon solar cells are the most commercially available [39], it has limitations in the AV market. The opaque characteristics of the silicon cells block the PAR from reaching the crops unless proper spacing is applied (Section 2.2). This led researchers to investigate the potential of using different generations of solar cells. Studies by [40] and [21] investigated the use of high-concentration PV as a method of optimizing crop and electrical output. A high concentration PV works by splitting the light into solar radiation and PAR for plant growth. Ref. [40] suggested the use of a bi-layer, as shown in Figure 4, to increase solar production and the ability to tune the spectral band that is transmitted, which is beneficial for agriculture. Ref. [41] studied the use of spectral separation with ultra-thin amorphous germanium (a-Ge:H) solar cells. Moreover, [42] experimented with semi-transparent PV cells and their effects on the growth of spinach and basil. While all studies showed viability in tuning the transmitted light for PAR, the electrical output efficiency typically does not reach above 5% [41].

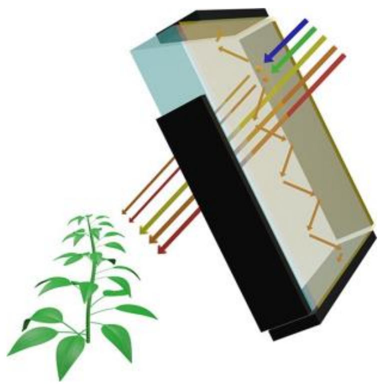


Figure 4. High Concentrator PV with diffused light used for plant growth; source: Reprinted with permission [40]. Copyright {2021}.

2.2. Layout Optimization

2.2.1. Placement

The most promising area of research in AV optimization in the last five years is in the placement of solar modules [25]. Since the first AV farm in Montpelier, France [11], ten new AV research facilities have been developed [43]. These facilities allow for the in situ data on different spacing and density methods; different layouts are shown in Figure 5. The AV system needs to be optimized for both power and agriculture. Research into spacing methods was conducted to determine if there is an optimal method to reduce shading with limited power loss. The cost of tracking panels is a limiting factor for many solar projects [44] and has led to different studies on AV farm layouts both at research facilities and modeled.

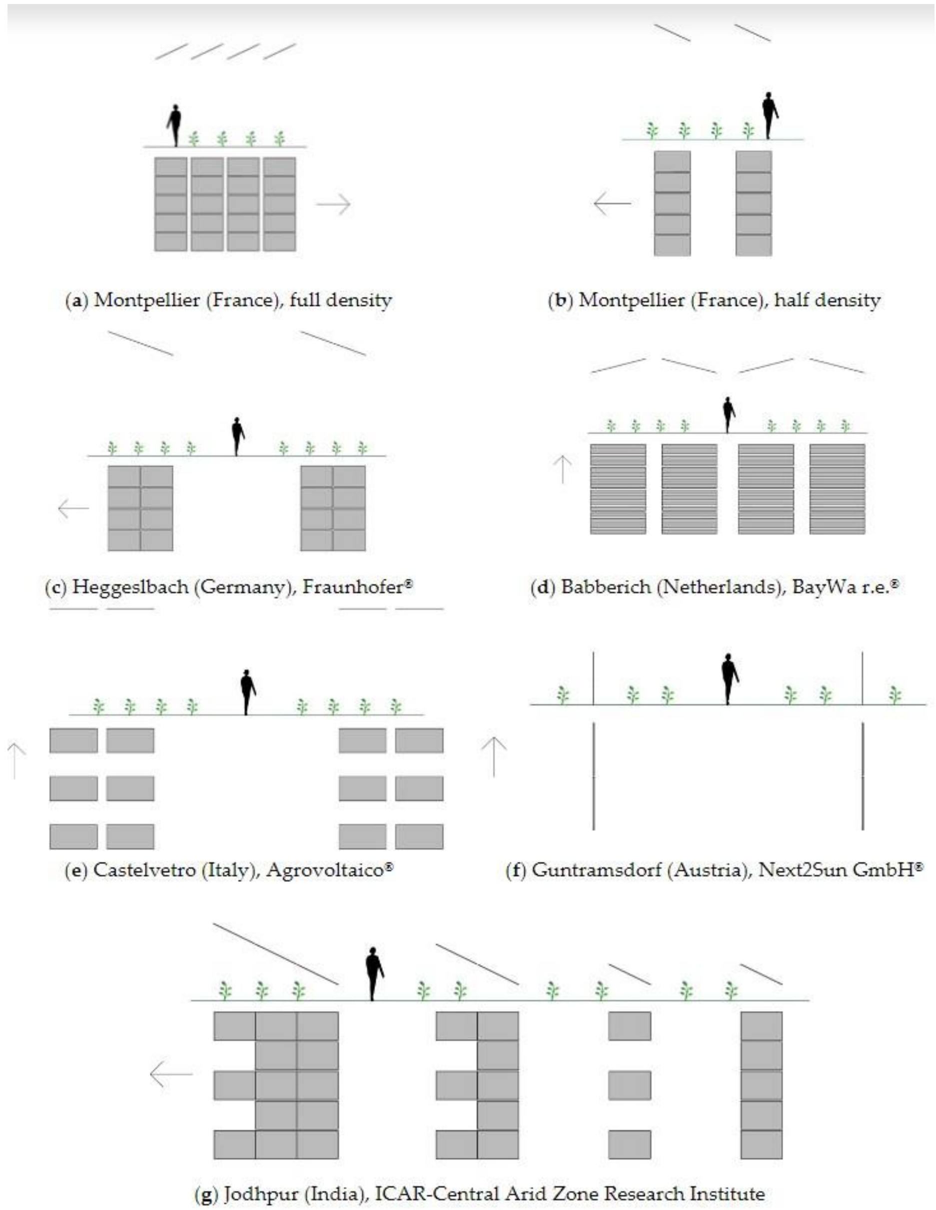


Figure 5. Different array patterns were studied in situ. Source: [43].

Table 2 provides a list of different panel placement methods that have been studied in the last five years. Ref. [45] reviewed different impacts of panel spacing, height [25], arrangement [27], and density [26,46] were other factors in AV system layouts.

Table 2. Comparison of different layout methods tested: IS—In situ, M—Model.

Testing Facility or Model Location	Method	Observations	Source
Montpelier, France	Density (IS)	Half density produced more than full density in summer only.	[46]
ICAR-Central Arid Reseach Insitute, India	Vertical and Spacing (IS)	PAR measured, and shading under PV was 18–58%.	[47]
Lahore, Pakistan	Spacing (M)	Inter-cropping increases production. Half density was ∼24% more productive.	[31]
	Vertical Bifacial Density	Spacial uniformity of sunlight better and increased LER.	[12]
Incheon, Korea	Height/Spacing (M)	2–3 m height saw the largest change. Spacing between panels, not just rows, decreased shading.	[25]
Fresno, Ca	Checkerboard Arrangement (M)	No significant shadow difference from 15 m × 15 m vs. 3 m × 3 m Checkerboard reduces irradiation losses by 6%.	[27]
R.E.M Tech Energy, Italy	Panel Density (M)	Higher density tracking saw increased maize yield. Non-tracking saw decrease in yield.	[26]
Västerås, Sweden	Bifacial Spacing (IS)	Optimal spacing for oats is 9.7 m. Optimal distance for potatoes is 9.7 m.	[48]

2.2.2. Orientation

Methods for optimization also included the orientation of the panels and the tilt angle. As shown in Figure 6, experiments were performed with vertical bifacial PV panels to measure shadow depth. This type of study was conducted in a variety of regions and both in situ and modeled. Table 2 lists some of the observations for the studies. Ref. [48], in particular, studied the optimization of an AV farm in terms of the LER and determined the optimum spacing of the bifacial panels to generate the highest amount of electricity without sacrificing plant growth. Studies such as those conducted by [25,31] researched the tilt angle of the panels to reduce shading while maintaining a high PV efficiency.

Figure 6. Bifacial vertical installation in Västerås, Sweden. Source: [48].

3. Potential Benefits of AV System

While AVs are seen as a method to reduce the land loss for traditional PV farms, research has shown that they can be both beneficial to crop growth [49] and PV efficiency [50]. The levels of PAR under the solar modules impact crop species in different ways. Understanding the PAR can be used to determine the most suitable crop to plant for each season [47]. Factors such as micro-climates and water requirements are also changed due to the set-up of each AV system [35]. Research into the benefits of plant growth from an AV farm will allow for better crop rotation and, ultimately, more efficient dual land use.

3.1. Crop Production

As installations of AV systems have increased in the last five years, the field of research has expanded into determining crops that are best suited for the coupled system. This review covered 23 studies that focused on the impact of PVs on the growth of different crops. The most common plants studied were lettuce, tomatoes, and wheat, covering four different countries and three states. The different studies were designed to make observations on different aspects of the AV systems. Figure 7 shows the set-up for a study on lettuce growth under two types of AV arrangements [24]. Some studies, such as those conducted by [49], investigated the relationship to crop production to the profitably of the AV farm, while other studies, such as the one conducted by [50], focused on crop yield. Table 3 reviews the different studies and notable observations.

Figure 7. Lettuce experiment conducted by [24].

Table 3. Impacts of AV on crop development in field tests.

Crop	Location	Observations	Source
Alfalfa	OR, USA	$2.623 per acre improvement	[49]
Basil	Italy	−15% in market yield +2.5% financial gain	[42]
Bok Choy	Thailand	Significant growth loss, ↑ panel efficiency	[51]
Canola	Spain	−20% yield	[52]
Carrots	Spain	−10% yield	[52]
Celeriac	Germany	+12% ('18) harvest yield, 1.76 LER	[53]
		−19% ('17) + 12% ('18) harvestable yield	[17]
Chiltepin Pepper	AK, USA	Production 3x greater, same water efficiency	[50]
Clover Grass	Germany	−8% ('17) − 5% ('18) harvest yield	[53]
Corn	Japan	+5% low density, −3% high density	[54]
Fava Bean	Spain	No change yield	[52]
Grapes	Korea	No growth difference, 10 delay for harvest	[55]
	India	∼same yield, 15x economic gains	[56]

Table 3. *Cont.*

Crop	Location	Observations	Source
Jalapeño	AZ, USA	Production equal with 157% water efficiency	[50]
Lettuce	Spain	Pattern Array: +68.8% (sp) + 87.6% (sum), Single Array: +15.3% (sp) + 16.4% (sum)	[24]
		LER:1.51 (sp), 1.57 (sum), 1.53 (fall)	[57]
Melon	Spain	−17% yield	[52]
Misai Kuciy	Malaysia	No yield change, +14.27% PV efficiency	[58]
Onion	Spain	6% decrease in crop yield	[52]
Potato	Germany	−10% ('17) + 11 ('18)% harvest yield, 1.76 LER	[53]
	Spain	23% decrease in crop yield	[52]
Rice	Japan	Shading limit range 27–39%	[59]
Soybeans	NC, USA	$2.473 per acre improvement	[49]
Spinach	Italy	−26% marketable yield, +35% financial gain	[42]
Strawberries	NC, USA	Increase from $656/acre to $2.162/acre	[49]
	OR, USA	Increase from $149/acre to $1.884/acre	
Tomato	AZ, USA	2x greater production 65% water efficiency	[50]
	OR, USA	Under Panel: −51%, Between Panel: −39%	[60]
	Spain	5% decrease in crop yield	[52]
Wheat	Germany	−19% ('17) + 3% ('18) harvest yield, 1.71 LER	[53]

Non-Commercial Crops

The studies reviewed also considered the use of AV for grazing grounds for different animals. An in situ study conducted in Oregon, USA, [61] determined that despite a reduction in herbage (38%), the AV produced higher quality; thus, spring lamb growth was not affected. In a modeled study regarding rabbits, Ref. [62] described how AV could also be used as a protective fence against predators while allowing the rabbits to graze on the grass under the panel, which has the potential to increase the revenue of a PV farm. The conclusion was reached by a reduction in operation and maintenance costs associated with grass mowing. Another new area of research for non-commercial crops is based on what is referred to as pollinators. Ref. [63] investigated the impact the solar canopy had on the bloom time of habitats for pollinating insects. They showed that the AV system increased the floral yield and delayed bloom time, which can help late-season pollinators.

3.2. Micro-Climates

The effects of a PV on the shaded area underneath tend to create a micro-climate. These micro-climates generally have lower soil and crop temperatures [23] and impact water requirements and PV efficiency. The panel layout, as discussed in Section 2.2.1, also impacts the micro-climate. Ref. [64] evaluated a Python model using a checkerboard panel placement. The method was not able to increase soil temperatures enough to prevent frost.

3.2.1. Water Usage

Several studies were conducted on the micro-climate that is created under AV systems. As indicated in Table 3, [50] monitored both crop yield but also water efficiency. The transpiration rate is slower under the PV due to the shading. This both lowers the soil temperature [35] and increases soil moisture [50], leading to a reduction in water usage. It was concluded by both [50,65] that hot arid climates would benefit from the creation of these AV micro-climates. The study by [52] saw a reduction in crop yield but also observed an increase in irrigation savings for all crops ranging from 9 to 14% savings. Another study in Oregon by [34] found a staggering 328% increase in water efficiency at their Rabbit Hills site (Figure 8) for areas observed under the AV system. This savings in water is yet another benefit that farmers would gain with an AV system.

Figure 8. Rabbit Hill site set-up for micro-climate observation Source: [34].

3.2.2. Increased PV Efficiency

There is a correlation between increasing temperatures and decreasing efficiencies of PV panels [66]. The micro-climates of the AV systems were shown to reduce ambient temperatures [67]. In a study conducted on Bok Choy in Thailand, it was demonstrated that while plant growth was reduced due to shading, the panel efficiency increased by ~1% [51]. While this increase is not a significant improvement over the life-cycle of the panels depending on the size of the array could lead to a surmountable amount of energy production.

4. Discussion

Agrivoltaics were demonstrated as a viable option for a dual-land use solution to the climate change crisis. Early systems such as those in Germany [11] and Japan [36] helped push research around the world. Countries such as the United States of America determined that an adaption of AVs can generate ~20% of domestic energy needs [68]. Research into the methods of optimization has shown the effects of shading on plant growth. In the majority of studies, the use of a half-density or patterned array allowed for higher production in plant growth. This was most often associated with the amount of PAR that the plants were able to receive throughout the day. The use of the LER has become a method of finding an optimal reduction in plant growth. There is an understanding that the shading from PV modules impacts the overall yield, but economically the coupling with electricity production should have an LER of greater than 1. Governmental policies are beginning to reflect the viability of coupling the two systems. In Japan, 80% of crop production must be maintained with the installation of PVs [59]. This is why optimization research plays a vital role in the installation of AV systems. In addition to governmental policies, social impact studies in Japan found support for the AV system among farmers, workers, and local residents [69], signaling that the industry can expect to see continued growth. Ref. [70] recently reported on a new vertical AV system sharing land use with livestock grazing. It was reported that Japan has over 200 MW grid-connected AV farms operational.

The engineering optimization of an AV farm has shown several areas of improvement. Most notably the tracking methods. The dual-axis tracking studies were shown to produce the highest electricity without sacrificing crop yields. However, these studies are limited, and the cost implications of a dual-axis system might be a limiting factor. When determining the feasibility of an AV system, economics plays a role in the decision process [71,72].

Simpler and most cost-effective tracking systems are more practical for small-scale AV farms. A South facing panel that is tracked along the East/West axis was shown to provide the best power production at a minimal loss to plant production. This was a result shared across a variety of studies conducted in different countries, both in situ and modeled.

Cost restrictions and efficiency are also factors when considering novel PV cells designed in an AV system. While spectral selective cells are capable of providing plants with the PAR spectrum required for photosynthesis, in the current phase of research, they only reach a 5% efficiency. This aspect of the cell would need to be improved if they were to be considered a viable option. The concentrated PV cells showed potential but would be better suited in a greenhouse application. There was research conducted in this field that was not covered in the scope of this review.

The optimization of the AV has the potential to be beneficial to both crop yields and PV efficiencies. Modeling studies that are then validated by in situ data are invaluable for the future of AV. They allow for crop rotation to be analyzed before implementation and can help boost the production of both crops and energy. Measurements of PAR under the AV system are another area that has shown value in crop rotation and placement. Collecting data on the PAR under the arrays allows farmers to select specific crops that thrive under those conditions. According to [73], the required PAR for crops varies and is considered when farmers are planted. By monitoring the PAR, crop rotation can be optimized to encourage the largest yields. This helps to prevent unnecessary crop loss and improve the overall efficiency of the entire system.

Micro-climates created under the arrays are another benefit that the coupled system provides. Hot arid regions, such as those studied in Arizona, USA [50], will see water usage decrease for the AV system. As climate change continues, the water supply will be closely monitored, and any method that allows for efficient water usage will need to be explored. As an established system, AV systems might begin to see more installations in water scarcity regions.

5. Conclusions

In the last five years, the agrivoltaic industry has begun to see exponential growth. A once novel concept, AV, has established its feasibility, and new research has shifted to optimizing the coupled system. The complexity of trying to boost energy production without sacrificing crop yields has led researchers to use the LER parameter to improve the dynamic system. Thus far, single-axis tracking along the East/West axis has produced the best results in a variety of regions around the world. The dual-axis, while effective, comes with a higher installation and operating cost and, at this time, would be considered less practical than small-scale farming. Increased costs and PV efficiency are other drawbacks of spectral selective cells in their current state. While their applications could be used in other sectors of AV, such as greenhouses, concentrators, and spectral selective PVs are still underdeveloped at this time. The inter-row spacing and height of the PV arrays were reviewed to determine the impact of shading on crop yields. Each region had different results, but overall having a lower density of panels allowed for more PAR to reach the crops and reduce shading loss. It was shown that understanding the PAR levels would improve crop growth by allowing for the best-suited crop to be planted. The creation of a micro-climate is both beneficial in terms of water usage but also has a positive impact on PV efficiency. Overall, agrivoltaics are considered a viable dual-land use option for the future to provide renewable energy and still allow for sustainable use to promote food security.

Author Contributions: Writing—original draft preparation, M.R.; review and editing, A.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors wish to the Environment and Sustainability Institute (ESI) and the College of Engineering, Mathematical and Physical Sciences (CEMPS) at the University of Exeter, Penryn Campus for allowing us to explore this topic and prepare this paper.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AV	agrivoltaic
LER	land equivalent ratio
NZE	net-zero emission
PAR	photosynthetically active radiation
PV	photovoltaic
RET	renewable energy technology
STICS	Simulateur mulTIdisciplinaire les Cultures Standard

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