Journal of Renewable and Sustainable Energy

REVIEW ARTICLE | APRIL 12 2024

Agrivoltaic system success: A review of parameters that matter FREE

Naseem Ali

J. Renewable Sustainable Energy 16, 022703 (2024)
https://doi.org/10.1063/5.0197775

Journal of Renewable and Sustainable Energy | REVIEW | pubs.aip.org/aip/rse

Agrivoltaic system success: A review of parameters that matter

Cite as: J. Renewable Sustainable Energy **16**, 022703 (2024); doi: 10.1063/5.0197775
Submitted: 14 January 2024 · Accepted: 26 March 2024 ·
Published Online: 12 April 2024

View Online Export Citation CrossMark

Naseem Ali[a)]

AFFILIATIONS

Institute of Fluid Mechanics, Karlsruhe Institute of Technology, Kaiserstr. 10, 76131 Karlsruhe, Germany and Institute of Coastal Systems, Helmholtz-Zentrum Hereon, Max-Planck-Str. 1, 21502 Geesthacht, Germany

[a)]Author to whom correspondence should be addressed: naseem.ali@hereon.de

ABSTRACT

Solar energy is a rapidly growing sector, and agrivoltaic farms are playing an increasingly important role in meeting the world's energy needs. However, as the size and complexity of these farms increase, so do the challenges associated with managing them efficiently. This article presents a comprehensive review of the fundamental parameters that underpin agrivoltaic systems. Focusing on the latest research, this review examines the challenges and opportunities intrinsic to the implementation of agrivoltaic energy systems, paying particular attention to the various parameters that contribute to their performance. These parameters encompass a range of factors such as heat islands, shading factors, and surface energy budget. The review underscores the importance of considering a diverse array of parameters when developing agrivoltaic energy systems to optimize their efficiency and effectiveness.

I. INTRODUCTION

Solar energy stands as an abundant and renewable source of clean energy, poised to play a pivotal role in addressing global energy demands. A significant milestone in renewable energy was achieved in 2022 when global photovoltaic installations surpassed a capacity of 1 terawatt (TW).[1] Despite notable growth and cost reductions, photovoltaics (PV) accounted for a mere 4% to 5% of global electricity generation in 2022. Urgent actions are imperative to curtail greenhouse gas emissions and meet future energy needs. Projections indicate ambitious yet attainable targets of 50 to 65 TW by 2050, necessitating substantial contributions from manufacturing and research sectors.[2–4] Sustaining PV's historical growth rates is essential to achieve the 75 TW goal by 2050.[1] The PV industry has exhibited consistent growth over the past five decades, markedly increasing its share in electricity generation and setting impressive records, underscoring its potential for a sustainable energy future.

Agrivoltaic systems represent distinct entities within the domain of solar energy utilization, delineated by their respective scales and intended applications. Specifically, agrivoltaic farm denotes an expansive, high-capacity solar power generation infrastructure meticulously designed to supply electricity to the utility grid or cater to substantial power consumers. Its primary function involves localized electricity generation for on-site consumption and occasionally feeding surplus power back into the grid. The popularity of solar farms is on the rise due to the decreasing cost of solar energy.[5] However, efficiently managing these large-scale installations of solar panels poses challenges as their size and complexity escalate. Within this article, a comprehensive review of the latest literature is provided encompassing crucial parameters governing agrivoltaic systems, emphasizing the formidable challenges and promising opportunities inherent in their implementation.

Devising effective strategies to meet energy demands necessitates a comprehensive understanding of the intricate and interdependent interactions between the atmosphere and the Earth's surface.[6–10] The complex and chaotic nature of the atmospheric system, akin to the butterfly effect expounded by Edward Lorenz,[11] underscores profound interconnectivity. A pivotal determinant of agrivoltaic farm efficiency is the atmospheric boundary layer (ABL), representing the lowest stratum of the Earth's atmosphere where air movement is influenced by terrain and variables such as temperature, pressure, and humidity. The ABL exerts a profound influence on wind velocity and direction, solar radiation distribution, and air temperature and moisture content. Its impacts on agrivoltaic farm efficiency are multifaceted; during the daytime, the ABL often exhibits turbulence, leading to fluctuations in wind parameters.[12] These irregular variations influence solar panel temperatures, regulating heat exchange between panels and ambient air.[13,14] Elevated temperatures can reduce solar panel efficiency,[6] increase the risk of thermal damage, and contribute to the formation of heat islands. Figure 1 provides an overview of potential flow dynamics pertinent to an agrivoltaic farm.

In summary, this review emphasizes the importance of considering various parameters when designing agrivoltaic energy systems to

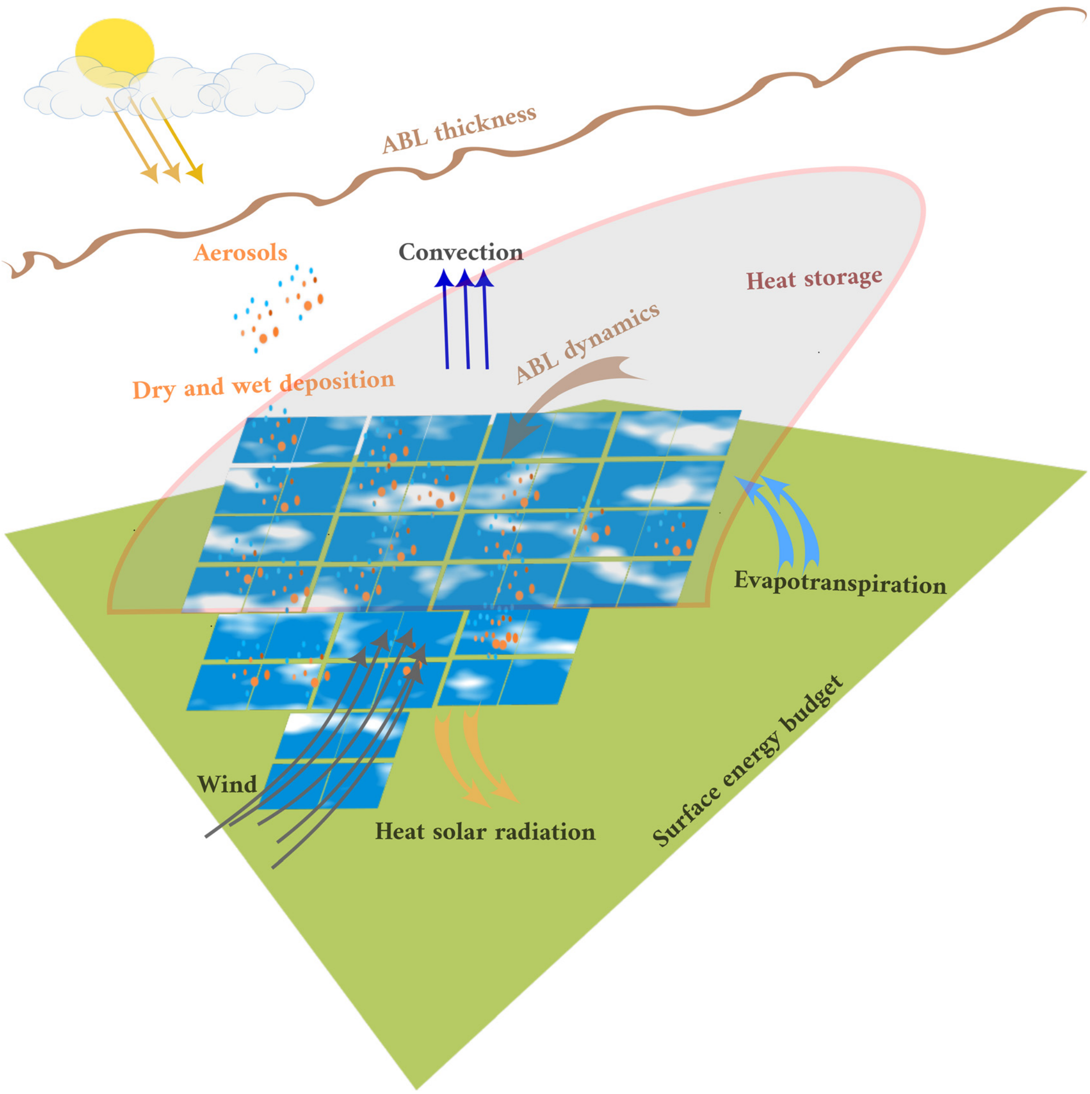

FIG. 1. Illustration of an agrivoltaic farm system, highlighting the pivotal mechanisms that determine its efficiency and output.

optimize their efficiency. The manuscript follows a structured framework outlined as follows: Sec. II delves into solar energy meteorology, focusing on the heat island phenomenon. Section III introduces the theoretical foundations and inherent challenges associated with the agrivoltaic paradigm. Section IV undertakes a comprehensive discussion to meticulously examine the significant parameters that necessitate a holistic approach to agrivoltaic system design. Finally, Sec. V presents the key findings derived from this literature review in the concluding remarks.

II. PV HEAT ISLAND PHENOMENON

This section aims to investigate how vast solar parks might affect boundary layer meteorology. The researchers aim to test the idea that these solar setups can significantly alter the meteorological traits of the boundary layer. This disturbance likely arises from changes in the surface's energy balance and the creation of substantial secondary air movements, potentially leading to the emergence of what's termed a photovoltaic heat island (PVHI). Solar panels' elevated temperatures may trigger strong convective cells and air movements in the surrounding atmosphere, thereby changing the local climate conditions. Being able to predict how much cooling a specific area can experience before setting up new solar parks would be highly beneficial in ensuring the system operates efficiently. However, understanding the impact of large solar farms is currently limited due to insufficient research. Most studies have focused on adjusting surface reflectivity in numerical models to simulate the impact of solar canopies. Despite the simplicity of these methods, available data suggest notable changes in temperatures close to the surface.

Taha[15] conducted an analysis focused on assessing how the deployment of solar photovoltaic systems could impact atmospheric conditions in the Los Angeles region. The findings indicate that widespread adoption of solar PV has no detrimental effects on air temperature or the urban heat island effect. In fact, it can contribute to cooling the urban environment by up to 0.2 °C. Even in hypothetical scenarios featuring extensive use of highly reflective surfaces (cool cities) and densely packed urban solar PV arrays, any potential warming effects are minimal, likely less than 0.1 °C. However, it is improbable that such extreme scenarios would actually materialize. In a distinct investigation, Fthenakis and Yu[16] developed computational simulation capabilities to scrutinize the influence of expansive solar photovoltaic farms on the local microclimate. This was achieved by simulating air velocity, turbulence, and energy flow fields. The researchers conducted three-dimensional simulations on a 1 MW segment of a solar farm in North America and compared the outcomes with measured wind and temperature data collected from the entire solar farm. Their analyses unveiled that the average yearly air temperatures in the center of the PV field can escalate by up to 1.9 °C above ambient temperatures. Furthermore, this thermal energy dissipates into the environment at altitudes spanning from 5 to 18 m. Notably, the thermal energy rapidly attenuates with increasing distance from the solar farm, with air temperatures nearing ambient levels at approximately 300 m from the perimeter of the installation. An assessment of 18 months of data established that the solar array undergoes effective cooling during nighttime, diminishing the likelihood of a heat island effect.[16] An experimental study conducted by Barron-Gafford *et al.*[17] unveiled that solar canopies, typically encountered in modest-sized solar plants (around 1 MW and less than 1 km in size), can elevate local air temperatures by approximately 3–4 °C during nighttime compared to the adjacent wilderness. This observation substantiates the hypothesis that solar farms can engender photovoltaic heat islands akin to those observed in urban canopies.

Solar panels reaching high temperatures, significantly exceeding the surrounding environment, may create strong convective cells and airflow within large solar parks. However, the precise extent and effects of these dynamics remain uncertain. Large solar installations, altering local surfaces, could influence atmospheric airflow akin to vegetated or urban areas. Broadbent *et al.*[18] found that significant photovoltaic farms can decrease daytime local temperatures by several degrees Celsius due to panel shading and underlying vegetation cooling. Conversely, at night, these panels may slightly increase temperatures by re-emitting trapped longwave radiation. The PV farms also alter the local energy balance by reducing incoming solar radiation and increasing the energy available for evapotranspiration and heat flux. Effects vary based on farm size, layout, weather, and ground cover. Adeh *et al.*[19] suggested the benefits of placing solar PV parks on agricultural lands. They found plant evapotranspiration could cool PV modules, enhancing overall energy output. Shading from modules might also boost agricultural productivity. To counter solar PV thermal effects, strategies include reducing heat at the cell level or improving heat dissipation. Pham *et al.*[20] compared the thermal effects of PV and reflective shade structures to an unshaded asphalt surface in Phoenix, AZ. The results show that during the day, the PV structure increases sensible heat flux by 80% compared to the unshaded surface, while the reflective shade reduces it by 50%. Both shades exhibit a slight cooling effect at night. Despite improved thermal comfort under both shades compared to the unshaded surface, the reflective shade performs better, with a 12 K lower mean radiant temperature under peak radiation.

In a recent study, Zhang and Xu[21] examined 23 major photovoltaic power plants globally and found a significant daily mean surface temperature reduction of 0.53 °C within these areas. Daytime cooling was more pronounced at 0.81 °C compared to 0.24 °C at night. The study noted that cooling rates correlated with power plant capacity: −0.32 °C/TWh for daily mean, −0.48 °C/TWh for daytime, and −0.14 °C/TWh for nighttime temperatures. Additionally, surface albedo changes due to PV plant construction lowered surface albedo but increased effective albedo (surface albedo combined with electricity conversion), emphasizing the role of solar energy conversion in surface cooling. The research identified correlations between the nighttime cooling effects of PV power plants and geographical factors like latitude, elevation, temperature, precipitation, solar radiation, and vegetation index. It explores heat island phenomena, secondary flow dynamics,[22] advection, dispersive fluxes,[23,24] and the heterogeneity effect.[25,26] The authors suggest that specific solar farm setups can either enhance or impede convective heat transfer between panels and the atmosphere, impacting the heat island effect.[27]

In an agrivoltaic configuration, crops exhibit the capacity to mitigate urban heat island effects by 0.5–4 °C through the process of evapotranspiration.[28] Brown *et al.*[29] examined the impact of rooftop PV panels on building energy demand and the urban climate. It involves direct surface temperature measurements and whole-building energy simulations for typical residential and retail structures. The results show that while PV panels can reduce cooling energy demand, their installation on highly reflective ("white") rooftops may lead to unintended consequences. In summer, the cooling energy penalty due to reduced outgoing longwave radiation can range from 4.9% to 11.2% of PV electricity generation. Additionally, adding PV to a white roof significantly increases daytime sensible heat flux, highlighting the need for careful consideration in PV deployment for building designers and urban planners. Sun'Agri,[30] a French agricultural technology firm, has demonstrated that their agrivoltaic system deployed in the transitional Mediterranean climate of Durance Valley, France, resulted in a reduction of ambient temperatures by 2–4 °C and alleviated water stress on crops by 63%. Similarly, in Singapore, the impact of evapotranspiration from green roof vegetation on photovoltaic module temperatures has been observed to decrease temperatures by 1–4 °C, contingent upon cloud cover density.[31] Teng *et al.*[32] showed that agrivoltaic systems optimize rooftop space by integrating urban farming with solar PV, improving microclimatic conditions and lowering PV operating temperatures. The microclimate ENVI-met simulations revealed average temperature reductions of 2.83 °C and 0.71 °C with crops beneath PV arrays on sunny and cloudy days, respectively. This correlates with PV efficiency gains of 1.13%–1.42% and 0.28%–0.35% on sunny and cloudy days respectively. Physical prototype data suggested evaporative cooling by crops lowered ambient temperatures, resulting in the agrivoltaic system generating 3.05%–3.2% more energy compared to a control system without crops. Table I provides a comprehensive overview of research endeavors examining the impact of solar farms on the microclimate at regional scales.

The correlation between the PV heat island effect and agrivoltaics necessitates exploring how the latter may serve as a remedial measure or mitigating element for the former. This association underscores the potential of agrivoltaics not solely in the generation of sustainable energy but also in providing ecological and agricultural advantages by mitigating the localized thermal elevation linked to solar panel

TABLE I. Summary of investigations on solar photovoltaic farms' influence on local microclimate.

Study	Key findings
Taha[15]	LA's solar PV deployment does not worsen air temperature or urban heat islands; it can cool by up to 0.2 °C.
Fthenakis and Yu[16]	1.9 °C increase in center air temperatures. Thermal energy dissipates 5–18 m high.
Barron-Gafford *et al.*[17]	PV increases daytime heat flux by 80%, while the reflective shade reduces it by 50%. Both shades cool slightly at night.
Pham *et al.*[20]	Solar canopies raise nighttime temperatures by 3–4 °C.
Adeh *et al.*[19]	PV farms cool daytime temperatures but elevate nighttime temperatures. Placement on agricultural lands benefits from cooling and shading.
Zhang and Xu[21]	Significant daily mean surface temperature reduction, more pronounced during daytime. Surface albedo changes affect surface cooling.
Qiu *et al.*[28]	Agrivoltaic configurations mitigate urban heat island effects by 0.5–4 °C through evapotranspiration.
Sun'Agri[30]	Agrivoltaic systems in Mediterranean climates reduce ambient temperatures by 2–4 °C and alleviate water stress on crops by 63%.
Hendarti[31]	Evapotranspiration from green roof vegetation decreases photovoltaic module temperatures by 1–4 °C in Singapore.
Brown *et al.*[29]	Findings reveal a potential cooling energy penalty of 4.9%–11.2% of PV generation in summer. Adding PV to white rooftops increases daytime sensible heat flux significantly.
Teng *et al.*[32]	Agrivoltaic systems optimize rooftop space, improve microclimatic conditions, and lower PV operating temperatures. Average temperature reductions of 2.83 °C and 0.71 °C on sunny and cloudy days, respectively.

installations. Strategically integrating vegetation or crops within solar panel arrays in agrivoltaic systems effectively mitigates localized thermal elevation associated with traditional solar farms. This approach optimizes land use, enhances biodiversity, diminishes water evaporation, and provides avenues for boosting agricultural productivity, concurrently generating renewable energy.

III. AGRIVOLTAIC SYSTEM: CONCEPTS AND CHALLENGES

Agrivoltaic systems merge solar farms, comprising solar panels, with agricultural setups to leverage mutual benefits.[33,34] This integration strategically controls sunlight reaching crops, optimizing water usage efficiency. Concurrently, evapotranspiration from the crops cools solar panels, enhancing their power efficiency and lifespan. This symbiotic approach aims to address the pressing food–water–energy nexus in contemporary times. Implementing photovoltaic systems on agricultural lands offers reduces heat and insolation stress and enhances water usage efficiency. To comprehend the dynamic interaction between photovoltaic and agricultural systems, detailed models must be developed. These models need to encompass shading and cooling effects on solar panels,[19] coupled with comprehensive soil–plant–atmosphere continuum models.[35] These integrative models will couple sensible and evaporative heat fluxes with soil moisture and solar panel temperature, enabling predictions of diverse photovoltaic setups on soil moisture, crop water usage, and yield.

As shown in Fig. 2, the surface energy budget of an agro-ecosystem encompasses a complex interplay of radiative and non-radiative fluxes, crucial for understanding ecosystem dynamics and agricultural productivity. The surface energy budget denotes the equilibrium between incoming and outgoing radiative and non-radiative fluxes at the Earth's surface, encompassing a complex interplay of energy transfer mechanisms. Incoming shortwave solar radiation, governed by solar geometry and atmospheric transparency, undergoes absorption and reflection at the surface, contributing to surface heating. A portion of this absorbed energy is re-emitted as longwave radiation, dictated by surface temperature and emissivity characteristics. The resulting net radiation flux R_n constitutes a key driver of surface energy exchange. Sensible heat flux H, arising from vertical temperature gradients between the surface and overlying air masses, facilitates convective heat transfer. Concurrently, latent heat flux LE accounts for the energy consumed or released during phase changes, notably through evaporation and condensation processes, significantly impacting surface moisture dynamics. Ground heat flux G_0, influenced by subsurface thermal properties and surface cover characteristics, governs heat transfer into or out of the ground. Comprehensive understanding of the surface energy budget is pivotal for elucidating climatic feedback mechanisms, assessing land-atmosphere interactions, and quantifying the impacts of anthropogenic perturbations, including land use modifications and the proliferation of agrivoltaic infrastructures. The water fluxes and storage within plants constitute a dynamic process crucial for their physiological functioning and ecosystem hydrology. Water uptake occurs primarily through roots via osmotic processes driven by soil water potential gradients. Once absorbed, water is transported upward through the xylem, facilitated by transpirational pull generated by leaf stomata. This upward transport, driven by cohesive and adhesive forces, enables the delivery of water to aerial plant parts for metabolic processes and transpiration. Concurrently, water loss through transpiration, regulated by stomatal conductance and influenced by environmental factors such as temperature, humidity, and light intensity, plays a pivotal role in plant water balance and carbon assimilation. Additionally, water is stored within various plant compartments, including roots, stems, and leaves, in forms such as cell vacuoles and intercellular spaces. This stored water serves as a reservoir for maintaining turgor pressure, facilitating cell expansion, and buffering against fluctuations in soil moisture availability.

The primary aims of the system are multifaceted, encompassing the maintenance of optimal temperature ranges conducive to maximizing crop yield, and the attainment of light levels proximate to the

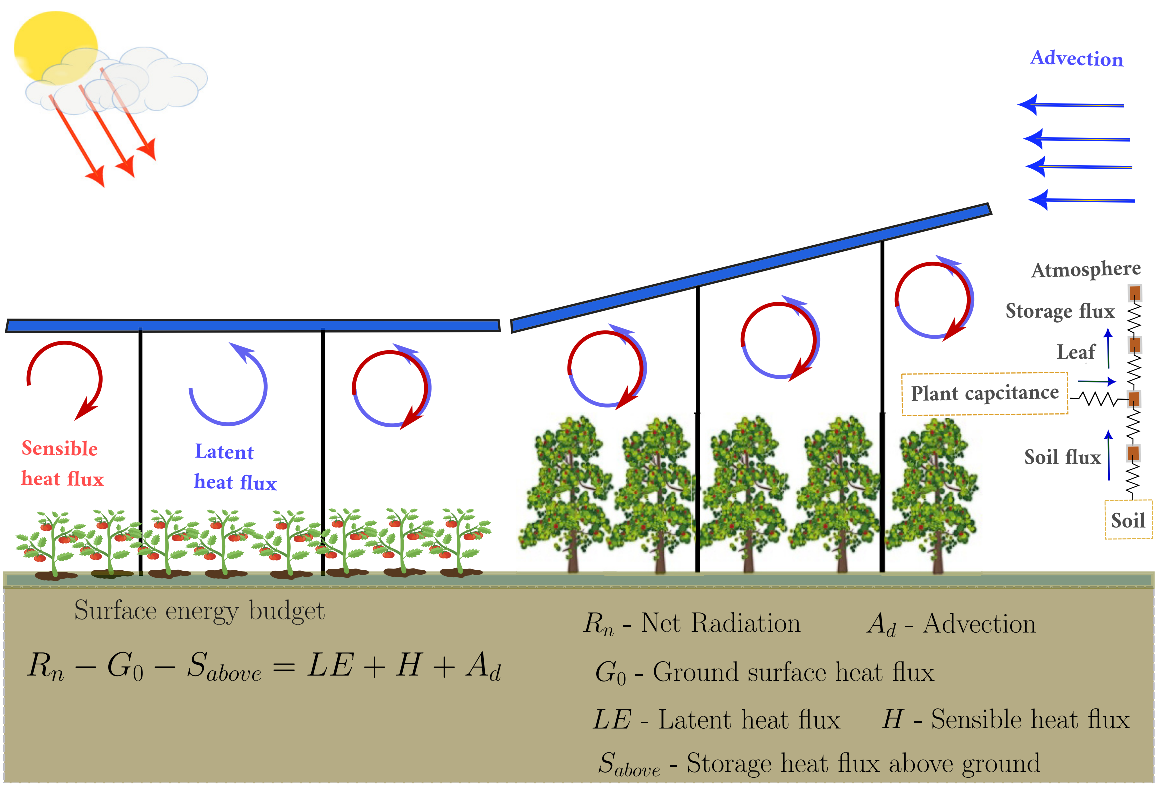

FIG. 2. Illustration of an agrivoltaic system and integrating model representation for fluxes and storage of water within the plants.

light saturation point, see Fig. 3, thereby ensuring high power production while preserving crop yields, and the mitigation of soil and crop water loss to minimize irrigation needs and water stress.[34,36] Given that these objectives fluctuate throughout the day and the growing season, it is incumbent upon us to concentrate on a solar panel array that can accommodate ever-changing environmental conditions and facilitate crop management and soil preparation during different seasons. Anticipated outcomes include the amplification of productivity and the alleviation of water stress for cool-season crops via the reduction of temperatures and insolation. However, these results are inextricably linked to the specific characteristics of the photovoltaic system, such as height, orientation, and surrounding environmental conditions.[35]

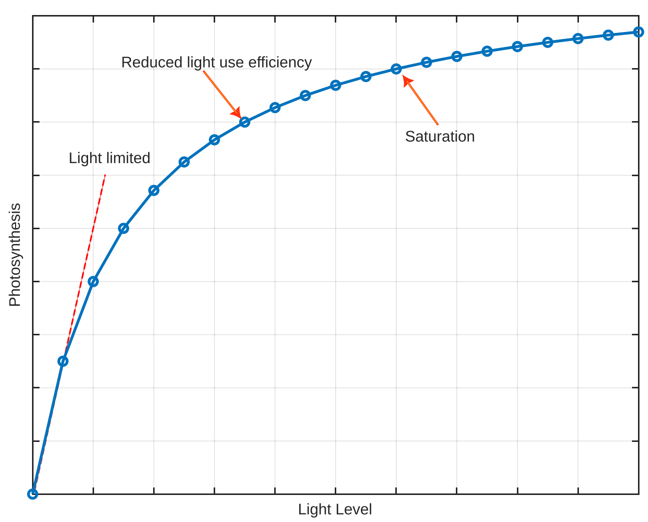

FIG. 3. Photosynthesis light response curve. The photosynthesis light response curve depicts how the rate of photosynthesis initially rises with increasing light intensity but eventually levels off due to factors like enzyme saturation.

Attaining the system's ideal operating temperature involves improving the convective heat transfer coefficient to efficiently eliminate or disperse the heat generated within the system. An increase in energy harvesting efficiency hinges on maintaining the solar module temperature close to ambient levels. It anticipates that crops, through evapotranspiration, will enhance thermal diffusivity, aiding in cooling. Evapotranspiration, the combined process of water evaporation and plant transpiration, indirectly influences soil thermal properties, thereby impacting thermal diffusivity. Changes in soil moisture due to evapotranspiration alter thermal conductivity and diffusivity. Heat transfer during evapotranspiration affects soil temperature distribution, influencing its thermal characteristics. Vegetation, impacting microclimates, indirectly modifies soil thermal properties, thereby affecting thermal diffusivity. Understanding these interactions is crucial in fields like agriculture and environmental science where soil thermal behavior plays a vital role.

While proposed agrivoltaic systems effectively reduce soil and crop temperatures, they may reduce solar radiation intensity on crops. This reduction can positively impact crop and soil temperatures, thereby improving crop water use efficiency, increasing soil moisture content, and alleviating crop water stress. Improved moisture levels prevent "bolting," a phenomenon caused by warm temperatures and water stress, resulting in poor-quality harvests.[37] Effective temperature control is crucial during the seedling phase, where lower temperatures can hinder growth, and higher temperatures can lead to accelerated bolting and inferior harvests. Employing crop shading techniques in agrivoltaic systems can mitigate photoinhibition caused by excessive light exposure. Therefore, decreasing the loss of soil moisture due to evapotranspiration is directly correlated with temperature. Table II presents a summary of the average effects of a 1% decrease in light level on the yield of crops.

Agrivoltaic systems encounter challenges related to light competition between solar panels and crops. Analyzing crop light-response curves is crucial, as yield shows linear increments until a saturation point, beyond which photoinhibition may cause a decline.[43] Evidence suggests certain crops optimize productivity under solar radiation levels lower than typical maximum intensities,[43,44] indicating the potential for harnessing solar radiation without compromising yields. Another concern is increased disease risk due to heightened humidity levels. Understanding crop responses to stress scenarios—focusing on physiological aspects like tree hydraulics, gas exchange, carbon allocation, growth, and stress recovery—is essential.[45] Evaluating stress severity and timing in crops is crucial for comprehending agrivoltaic system effects. Hartzell *et al.*[46] elucidated plant mechanisms addressing hydraulic stress, dependent on stress frequency, intensity, evaporative demand fluctuations, soil moisture variations driven by seasonal climate shifts, and rainfall events' sustained impacts.[47,48] Plants have evolved coping strategies, such as transpiration—a process of moving water from the soil through the plant and into the atmosphere, following water potential gradients. Water flow across soil, plant xylem, stomata, and atmosphere depends on hydraulic conductance and potential gradients. Transpiration, often modeled using steady-state water balance assumptions, correlates with plant conductance and water potential gradients.

The work of Chopard *et al.*[49] has led to the creation of a sophisticated decision support tool that assists in evaluating the health of crops grown under solar panels. This system comprises an integration of three critical indicators—predawn water potential, canopy temperature, and carbon production—to provide a comprehensive assessment of crop status. The system is thoughtfully designed to account for the intricate interplay between crops and their environment, taking into consideration factors such as panel orientation and crop growth stages. In addition, this advanced decision support system is equipped with the capability to provide valuable recommendations on optimal agricultural practices based on changes in solar panel configuration. The findings of Smith *et al.*[50] offer compelling evidence supporting the integration of PV with diverse plant species to create multifaceted agrivoltaic systems. Such systems possess the potential to revolutionize traditional farm design by facilitating the implementation of efficient and customized agricultural practices that can adapt to various spatial, agricultural, and environmental limitations. In a recent investigation, Williams *et al.*[51] scrutinized the influence of agrivoltaic design elements on the microclimate and surface temperature of solar PV modules within a solar farm. Employing computational fluid dynamics, the researchers developed a microclimate model, validated by experimental data. Their assessment focused on panel height, ground albedo, and evapotranspiration effects at a solar PV site. The study revealed that elevating an agrivoltaic farm to 4 m height and cultivating soybeans underneath effectively reduced solar module temperatures by up to 10 °C, compared to a farm at a mere 0.5 m height over barren soil. These findings underscore the significance of panel height and ground conditions in agrivoltaic farm cooling. They demonstrate the potential of agrivoltaic systems in addressing the global food-energy crisis by enhancing solar PV conversion efficiency while concurrently promoting agricultural production on the same land.

TABLE II. Typical impact resulting from a 1% reduction in light intensity on crop yield.[38–42] Each botanical specimen exhibits a distinct requirement for light intensity, quantified through the metric of daily light integral (DLI). Familiarizing oneself with the DLI of a given plant is imperative for ensuring optimal growth and productivity.

Group of crops	Crop	Daily light integral (mol/m^2/day)	Yield reduction	Remarks
Soil-grown vegetables	Lettuce	14–16	0.8%	Similar effects observed on both fresh and dry weight.
	Radish	12–18	1%	Pronounced impact on tuber growth compared to shoot growth. The shoot/tuber ratio increases under reduced light conditions.
Fruit vegetables	Cucumber	20–30	0.7%–1%	Diminished dry-matter percentage in fruit under low light. Impact on fruit fresh weight is less than on fruit dry weight.
	Tomato	22–30	0.7%–1%	More pronounced effect on fruit fresh weight than on plant dry weight.
Cut flowers	Rose	18–22	0.8%–1%	Light intensity influences both the number and weight of shoots. Effects are comparatively reduced in summer compared to winter.
	Sweet pepper	20–30	0.8%–1%	
Flowering pot plants	Poinsettia	4–8	0.5%–0.7%	Quality parameters take precedence over biomass
	Kalanchoe	9–30	0.8%–1%	
Non-flowering pot plants	Ficus benjamina	6–12	0.65%	Comparable effects on both fresh and dry weight. Adequate light during winter months crucial to prevent leaf abscission.

IV. AGRIVOLTAIC SYSTEM: DESIGN DETERMINANTS

In conceptualizing solar energy systems, particularly within agrivoltaic systems, a trio of pivotal parameters necessitates comprehensive contemplation. These parameters encompass the shading coefficient, the surface energy equilibrium, and the estimation of solar insolation. In the forthcoming sections, the paramount facets inherent to these discerning parameters will be discussed.

A. Surface energy budget

The surface energy budget and evapotranspiration are fundamental concepts in studying the Earth's hydrological and energy cycles, as they are closely interrelated. The former refers to the balance between the incoming and outgoing energy fluxes at the Earth's surface, while the latter describes the process of water transformation into water vapor and its release into the atmosphere. These complex processes are modulated by a myriad of interacting factors, including atmospheric temperature, humidity, wind speed, vegetation cover, and incoming solar radiation. Solar panels, upon installation, absorb solar radiation, potentially altering energy available for evapotranspiration and impacting water resources and ecosystems.[52] Additionally, they can change surface reflectivity, influencing temperature, atmospheric circulation, and surface processes.[53] The effects depend on regional climate, vegetation, and solar panel design and placement.[54]

Various methods exist to model the surface energy budget and estimate evapotranspiration, each tailored to specific research inquiries and data availability, see Table III. Land surface models (LSMs) integrated into larger climate models assess land-atmosphere interactions and analyze the impacts of climate change on the Earth's water and energy cycles.[55] The Penman–Monteith model, a widely used approach,[56] estimates evapotranspiration by incorporating empirical equations with weather data to consider both aerodynamic and energy components across diverse land surfaces, encompassing natural and agricultural ecosystems. An alternative, the Priestley–Taylor model,[57] simplifies evapotranspiration estimation based on net radiation and surface air temperature, providing adequate soil moisture and well-watered vegetation. The Shuttleworth–Wallace model[58] simulates surface energy budget and evapotranspiration by considering the transfer of energy and water vapor through a resistive surface air layer, incorporating variables like vegetation cover and soil moisture. The simplified surface energy balance (SSEB) model[59] utilizes satellite data of surface temperature and vegetation index to estimate evapotranspiration over extensive regions, beneficial for irrigation management and water resource planning. The Hargreaves–Samani model[60] estimates evapotranspiration using air temperature and extraterrestrial radiation, providing a simpler estimation for areas with limited input parameters, although with reduced accuracy compared to more complex models. Similarly, the Turc model[61] estimates evapotranspiration using mean air temperature, sunshine hours, and latitude, suitable for areas with limited data, albeit with less accuracy compared to complex models. The Blaney–Criddle method[62] estimates evapotranspiration using mean daily air temperature and monthly mean percentage of daylight hours, offering simplicity and utility in data-scarce regions, yet with limitations in accuracy compared to other complex models.

B. Shading factor

In designing an agrivoltaic system, an essential aspect to consider is the shading factor emanating from the solar panels on the crops beneath. The degree of shading, expressed as a percentage, caused by solar panels can significantly impact crop growth and yield. To calculate the shading factor, one can conduct a shading analysis using either computer modeling software or physical measurements. Optimal shading factors depend on various factors such as the panel orientation, tilt angle, height above the crops, and crop type.[63,64] Typically, a shading factor of approximately 30% is considered ideal for most crops.[65] Striking the perfect balance between maximizing solar panel energy production and minimizing shading on crops is crucial in achieving optimal results in an agrivoltaic system. Hence, a modern control adjusting the panel orientation and tilt angle, as well as the height above the crops, can help regulate the shading factor and attain the desired balance. In agrivoltaic systems, shading analysis

TABLE III. Models for surface energy budget and evapotranspiration.

Model	Input parameters	Application
Land surface models (LSMs)[55]	Heat and moisture exchange, solar radiation, surface, and atmospheric conditions.	Comprehensive understanding and simulation of the Earth's water and energy cycles.
Penman–Monteith model[56]	Weather data, aerodynamic, and energy components.	Suitable for various land surfaces, including natural and agricultural ecosystems.
Priestley–Taylor model[57]	Net radiation, air temperature, soil moisture, and vegetation condition.	Simpler model, limited to well-watered conditions.
Shuttleworth–Wallace model[58]	Variables representing resistive layer, vegetation cover, and soil moisture.	Incorporates resistive layer concept, useful for varying vegetation and soil conditions.
Simplified surface energy balance (SSEB) model[59]	Surface temperature, vegetation index, and remote sensing data.	Ideal for large-scale applications like irrigation management and water resource planning.
Hargreaves–Samani model[60]	Air temperature and extraterrestrial radiation.	Simple model, suitable for areas with limited data.
Turc model[61]	Mean air temperature, sunshine hours, and latitude.	Basic weather data are sufficient, accuracy limited compared to complex models.
Blaney–Criddle method[62]	Mean daily air temperature and monthly mean percentage of daylight hours.	Requires limited data inputs, accuracy is less compared to complex models.

traditionally involves physical measurements like sun path diagrams, solarimeters for solar irradiance, shadow analysis, and on-site observations of solar panels and crops. However, these methods are time-consuming and require specialized equipment.

Computer modeling software provides a more efficient and comprehensive analysis by considering parameters such as location, panel orientation, size, and surrounding object positions. A multitude of advanced computer modeling software programs exist for carrying out shading analysis in agrivoltaic systems, which utilize intricate algorithms and mathematical models to simulate the shading impacts of solar panels on crops. Notable among them are PVsyst,[66] HelioScope,[67] SAM,[68] and PVSOL.[69] Table IV provides a summary overview of the application of shading modeling.

Pioneering work by Bany and Appelbaum[70] developed an algorithm assessing shading impact on a solar collector field throughout a day, informing field design considerations. They found that shading on a collector depends on collector height, row length, inter-collector spacing, and location latitude. Their equations account for different solar collector types and insolation levels: direct, diffuse, and global irradiance. Cascone *et al.*[71] devised a complex calculation method to determine shading factors under intricate conditions. This tool evaluates shading factors for various surfaces, considering diverse window shapes and external elements like obstructions and vegetation. It simulates different sky conditions and time frames, providing instantaneous, daily average, or monthly average shading factor values. This sophisticated approach enhances accuracy in assessing solar heat gains as well as improving energy assessment model performance and efficiency.

Moreover, recent literature has presented several studies that delve into the modeling and analysis of photovoltaic systems and their performance under shading conditions as well as their impact on crop yield. In a systematic review by Dinesh and Pearce,[53] theoretical and experimental investigations on agrivoltaics were examined, analyzing potential crop yields and solar power output relative to incoming solar radiation. The study focused on fixed tilt agrivoltaic farms, optimizing photovoltaic tilt angles to maximize solar power output, with pitch determined by crop spacing for harvesting. A comparative analysis between PV power output and crop yields in different agrivoltaic configurations and conventional monocrop farms was conducted, evaluating economic viability and providing insights for future dual-use farm development. For instance, Gilman *et al.*[72] comprehensively describes the widely used SAM PV model, which considers the electrical and thermal characteristics of the PV system and accounts for shading and soiling effects. The model's algorithms and parameters are presented in detail, along with validation results against experimental data. Meanwhile, Meanwhile, Prilliman *et al.*[73] conducted an empirical study on the effects of shading on PV modules' performance, which involved measuring the modules' power output under varying shading conditions. They developed a model based on the experimental data to predict shaded module performance accurately. Toledo and Scognamiglio[74] conducted a rigorous analysis of technological and spatial design options, proposing a comprehensive methodology based on design and performance parameters, facilitating system attribute definition from a trans-disciplinary perspective. Discussing a theoretical framework for agrivoltaic system design, Trommsdorff *et al.*[75] covered crop classification, light distribution simulation, and row distance considerations, introducing the light energy ratio (LER) concept. The study reported conclusive agrivoltaic system design and key empirical findings from the initial two years of operation, emphasizing PV performance and land use efficiency.

Furthermore, Campana *et al.*[76] introduced an optimization model that optimizes the performance of vertically mounted agrivoltaic systems with bifacial PV modules. This model comprises three sub-models: solar radiation and shading, photovoltaics, and crop yield. The multi-objective optimization model allows for trade-off exploration between various agrivoltaic performance indicators. Their results highlight the significant impact of bifacial module row distance on the distribution of photosynthetically active radiation, which directly affects crop yield. In addition, Zainali *et al.*[35] developed mathematical models that precisely calculate shading factors for three different agrivoltaic system configurations. These models accurately estimate the shaded beam and diffuse shaded horizontal irradiance at ground level, which is crucial in assessing the agrivoltaic systems' impact on crop yield. Reasoner and Ghosh[77] reviewed agrivoltaic farm layouts, evaluating the influence of spacing, height, and density configurations on shading beneath panels. The study concluded that panel-induced shading alters photosynthetically active radiation (PAR), thereby not only affecting plant growth but also creating microclimates with advantageous properties for water usage and PV efficiency. Mouhib *et al.*[78] reviewed the current state of bifacial technology, covering distinctions from conventional monofacial cells and exploring modeling methods predicting bifacial photovoltaic (bPV) system performance. The review highlighted significant applications, including dual land use for energy and food production (agrivoltaics), placement on water surfaces (aquavoltaics), and vertical applications as solar fences, acoustic barriers, or building-integrated photovoltaic modules.

C. Partial shading

Despite advancements in improving photovoltaic system efficiency, various environmental factors, including soil accumulation, salt, avian excrement, and snow on PV module surfaces, hinder their

TABLE IV. Advanced computer modeling software for shading analysis.

Software	Description
PVsyst[66]	Widely used program for designing and simulating solar energy systems. Incorporates shading analysis considering parameters such as geographical location, orientation, tilt angle, panel size, and surrounding object positions.
HelioScope[67]	Web-based software utilizing 3D modeling and satellite imagery for detailed site modeling. Generates comprehensive reports and proposals for system design.
SAM[68]	Simulates the performance of various renewable energy systems including solar, wind, geothermal, and biomass.
PVSOL[69]	Utilizes a 3D model of the site to simulate shading effects from surrounding vegetation and objects on solar panels. Generates detailed reports and proposals for system design.

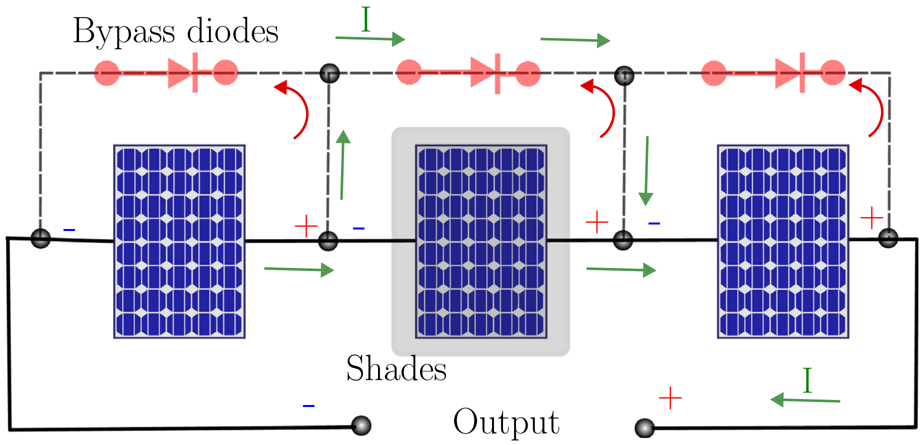

FIG. 4. Illustration of a solar PV system with bypass diode protections.

optimal functionality.[79] These introduce physical and chemical interactions like the formation of hot spots.[80] Shading-induced soiling on PV modules is broadly categorized as "soft" shading, caused by airborne pollutants, and more severe "hard" shading, resulting from solid material accumulation obstructing sunlight transmission.[81] Soft shading reduces electrical current generation but does not affect voltage output. Conversely, hard shading's impact depends on whether the entire module or a subset of cells is shaded. Partial shading leads to reduced electricity generation with a decrease in voltage output. Dust buildup significantly affects total energy output across daily, monthly, seasonal, and annual timeframes.[82] Soiling accumulation characterization relies on dust properties and local environmental characteristics.[80,83] Certain soil patches, like leaves on specific cells rather than the entire module, can substantially impact PV performance.[84] Moreover, partial shading has become a significant concern in photovoltaic systems due to uneven irradiation on modules.[85] This issue, often caused by adjacent buildings, leads to an annual average reduction in the production of about 20%, predominantly due to inherent resistors in solar cells.[86] Manufacturers address this by integrating "bypass diodes" (Fig. 4), which prevent energy dissipation through internal resistors in photovoltaic material.[86] Power electronic converters are crucial in optimizing solar energy utilization. Designing PV systems with deep discharge lead-acid batteries for "off-grid" setups or synchronizing with an "on-grid" network is vital.[86] Algorithms like maximum power point trackers (MPPT) play a pivotal role in ensuring efficient PV panel operation under various conditions.[85] Series-connected PV cells must harmonize their characteristics to avoid operating point disparities, which lead to substantial losses and potential physical damage.[85,87] Integrating bypass diodes mitigates partial shading issues but leads to energy loss in shaded panels.[88,89] Recent studies have explored strategies like smart bypass diodes and metal–oxide–semiconductor field-effect transistor (MOSFET) replacements to reduce hotspot formation and power losses.[90,91] Field tests are crucial for evaluating real-world PV system performance, emphasizing the role of bypass diodes despite potential failures.[92] Integrating artificial intelligence enhances fault detection and system performance prediction but requires consideration of unforeseen scenarios.[93]

V. CONCLUSION

The review paper highlights the potential benefits of understanding the dynamics of agrivoltaic farms. The heat island effect is crucial determinants that significantly impact the agrivoltaic farm's overall performance. Implementing agrivoltaic systems and shading factors offers promising opportunities to boost the solar farm's efficiency by mitigating the adverse effects of the heat island phenomenon and optimizing the usage of available land. Additionally, to guarantee that the solar farm operates sustainably and efficiently, a thorough assessment of its surface energy budget is imperative. In light of these findings, ongoing research and development in this domain are pivotal to the long-term viability and success of the renewable energy industry.

Agrivoltaics, the integration of agriculture and solar energy production, has shown promise but still presents several research gaps requiring further exploration. These gaps encompass critical aspects like optimizing crop selection and placement within photovoltaic arrays to maximize electricity generation and crop yields. Understanding the potential impacts of climate change on sustaining crop yields and energy production in agrivoltaic systems is crucial. Additionally, evaluating the economic feasibility of these systems while considering benefits such as increased crop yields and reduced land use remains an area that requires more in-depth study. Designing and optimizing agrivoltaic setups for various regions and crops to assess their costs and benefits are essential. Finally, investigating social acceptance among farmers and local communities is vital, considering the potential changes these systems might bring to traditional farming practices and land use. Closing these research gaps will significantly contribute to the effective implementation and success of agrivoltaic industry.

ACKNOWLEDGMENTS

N.A. acknowledges the Helmholtz Information and Data Science Academy (HIDA) for providing financial support enabling a short-term research stay at Karlsruhe Institute of Technology Campus Alpin in Garmisch-Partenkrichen.

AUTHOR DECLARATIONS

Conflict of Interest

The author has no conflicts to disclose.

Author Contributions

Naseem Ali: Conceptualization (equal); Formal analysis (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

[1]N. M. Haegel, P. Verlinden, M. Victoria, P. Altermatt, H. Atwater, T. Barnes, C. Breyer, C. Case, S. De Wolf, C. Deline *et al.*, "Photovoltaics at multi-terawatt scale: Waiting is not an option," Science **380**, 39–42 (2023).
[2]E. Pursiheimo, H. Holttinen, and T. Koljonen, "Inter-sectoral effects of high renewable energy share in global energy system," Renewable Energy **136**, 1119–1129 (2019).
[3]D. Bogdanov, M. Ram, A. Aghahosseini, A. Gulagi, A. S. Oyewo, M. Child, U. Caldera, K. Sadovskaia, J. Farfan, L. D. S. N. S. Barbosa *et al.*, "Low-cost renewable electricity as the key driver of the global energy transition towards sustainability," Energy **227**, 120467 (2021).
[4]J. C. Goldschmidt, L. Wagner, R. Pietzcker, and L. Friedrich, "Technological learning for resource efficient terawatt scale photovoltaics," Energy Environ. Sci. **14**, 5147–5160 (2021).
[5]R. Vignesh, D. Feldman, J. Desai, and R. U. S. Margolis, U.S. Solar photovoltaic system and energy storage cost benchmarks: Q1 2021, Technical Report, NREL, 2021.
[6]A. Glick, N. Ali, J. Bossuyt, M. Calaf, and R. B. Cal, "Utility-scale solar PV performance enhancements through system-level modifications," Sci. Rep. **10**, 10505 (2020).
[7]A. Glick, N. Ali, J. Bossuyt, G. Recktenwald, M. Calaf, and R. B. Cal, "Infinite photovoltaic solar arrays: Considering flux of momentum and heat transfer," Renewable Energy **156**, 791–803 (2020).
[8]A. Glick, S. E. Smith, N. Ali, J. Bossuyt, G. Recktenwald, M. Calaf, and R. B. Cal, "Influence of flow direction and turbulence intensity on heat transfer of utility-scale photovoltaic solar farms," Sol. Energy **207**, 173–182 (2020).
[9]S. E. Smith, A. Glick, J. Ali, N. Bossuyt, J. McNeal, G. Recktenwald, M. Calaf, and R. B. Cal, "Configuration effects on flow dynamics and convective behavior in large-scale solar arrays," in *47th IEEE Photovoltaic Specialists Conference (PVSC)* (IEEE, 2020), pp. 2195–2196.
[10]S. E. Smith, B. J. Stanislawski, B. K. Eng, N. Ali, T. J. Silverman, M. Calaf, and R. B. Cal, "Viewing convection as a solar farm phenomenon broadens modern power predictions for solar photovoltaics," J. Renewable Sustainable Energy **14**, 063502 (2022).
[11]E. Lorenz, "The butterfly effect," World Sci. Ser. Nonlinear Sci., Ser. A **39**, 91–94 (2000).
[12]N. Ali, N. Hamilton, M. Calaf, and R. B. Cal, "Turbulence kinetic energy budget and conditional sampling of momentum, scalar, and intermittency fluxes in thermally stratified wind farms," J. Turbul. **20**, 32–63 (2019).
[13]I. Y. Hussain and N. Ali, "Natural convection heat transfer from a plane wall to thermally stratified environment," J. Eng. **18**, 223–238 (2012).
[14]N. Ali and I. Y. Hussain, "Two-dimensional natural convection heat transfer from a heated plate immersed in a thermally stratified medium: Numerical and experimental study," Int. J. Comput. Appl. **179**, 1–8 (2017).
[15]H. Taha, "The potential for air-temperature impact from large-scale deployment of solar photovoltaic arrays in urban areas," Sol. Energy **91**, 358–367 (2013).
[16]V. Fthenakis and Y. Yu, "Analysis of the potential for a heat island effect in large solar farms," in *IEEE 39th Photovoltaic Specialists Conference (PVSC)* (IEEE, 2013), pp. 3362–3366.
[17]G. A. Barron-Gafford, R. L. Minor, N. A. Allen, A. D. Cronin, A. E. Brooks, and M. A. Pavao-Zuckerman, "The photovoltaic heat island effect: Larger solar power plants increase local temperatures," Sci. Rep. **6**, 35070 (2016).
[18]A. M. Broadbent, E. S. Krayenhoff, M. Georgescu, and D. J. Sailor, "The observed effects of utility-scale photovoltaics on near-surface air temperature and energy balance," J. Appl. Meteorol. Climatol. **58**, 989–1006 (2019).
[19]E. H. Adeh, S. P. Good, M. Calaf, and C. W. Higgins, "Solar PV power potential is greatest over croplands," Sci. Rep. **9**, 11442 (2019).
[20]J. V. Pham, A. Baniassadi, K. E. Brown, J. Heusinger, and D. J. Sailor, "Comparing photovoltaic and reflective shade surfaces in the urban environment: Effects on surface sensible heat flux and pedestrian thermal comfort," Urban Clim. **29**, 100500 (2019).
[21]X. Zhang and M. Xu, "Assessing the effects of photovoltaic powerplants on surface temperature using remote sensing techniques," Remote Sens. **12**, 1825 (2020).
[22]B. Viggiano, J. Bossuyt, N. Ali, J. Meyers, and R. B. Cal, "Secondary motions above a staggered multi-scale rough wall," J. Fluid Mech. **941**, R1 (2022).
[23]M. R. Raupach and R. H. Shaw, "Averaging procedures for flow within vegetation canopies," Boundary-Layer Meteorol. **22**, 79–90 (1982).
[24]T. Morrison, E. R. Pardyjak, M. Mauder, and M. Calaf, "The heat-flux imbalance: The role of advection and dispersive fluxes on heat transport over thermally heterogeneous terrain," Boundary-Layer Meteorol. **183**, 227–247 (2022).
[25]E. Bou-Zeid, W. Anderson, G. G. Katul, and L. Mahrt, "The persistent challenge of surface heterogeneity in boundary-layer meteorology: A review," Boundary-Layer Meteorol. **177**, 227–245 (2020).
[26]B. J. Butterworth, A. R. Desai, D. Durden, H. Kadum, D. LaLuzerne, M. Mauder, S. Metzger, S. Paleri, and L. Wanner, "Characterizing energy balance closure over a heterogeneous ecosystem using multi-tower eddy covariance," Front. Earth Sci. **11**, 1251138 (2024).
[27]B. Stanislawski, F. Margairaz, R. B. Cal, and M. Calaf, "Potential of module arrangements to enhance convective cooling in solar photovoltaic arrays," Renewable Energy **157**, 851–858 (2020).
[28]G.-Y. Qiu, H.-Y. Li, Q.-T. Zhang, C. Wan, X.-J. Liang, and X.-Z. Li, "Effects of evapotranspiration on mitigation of urban temperature by vegetation and urban agriculture," J. Integr. Agric. **12**, 1307–1315 (2013).
[29]K. E. Brown, A. Baniassadi, J. V. Pham, D. J. Sailor, and P. E. Phelan, "Effects of rooftop photovoltaics on building cooling demand and sensible heat flux into the environment for an installation on a white roof," J. Eng. Sustainable Build. Cities **1**, 021001 (2020).
[30]Sun'Agri, The la pugère experimental station, Available online, 2021. https://sunagri.fr/en/project/the-la-pugere-experimental-station/; accessed 13 September 2021.
[31]R. Hendarti, "The influence of the evapotranspiration process of green roof tops on PV modules in the tropics," Ph.D. thesis, National University of Singapore, 2013.
[32]J. W. C. Teng, C. B. Soh, S. C. Devihosur, R. H. S. Tay, and S. K. Jusuf, "Effects of agrivoltaic systems on the surrounding rooftop microclimate," Sustainability **14**, 7089 (2022).
[33]M. Trommsdorff, S. Gruber, T. Keinath, M. Kopf, C. Hermann, F. Schönberger, P. Högy, S. Zikeli, A. Ehmann, A. Weselek *et al.*, Agrivoltaics: Opportunities for agriculture and the energy transition, Fraunhofer Institute for Solar Energy Systems ISE, Breisgau, Germany, 2020.
[34]S. Gorjian, E. Bousi, Ö. E. Özdemir, M. Trommsdorff, N. M. Kumar, A. Anand, K. Kant, and S. S. Chopra, "Progress and challenges of crop production and electricity generation in agrivoltaic systems using semi-transparent photovoltaic technology," Renewable Sustainable Energy Rev. **158**, 112126 (2022).
[35]S. Zainali, S. M. Lu, B. Stridh, A. Avelin, S. Amaducci, M. Colauzzi, and P. E. Campana, "Direct and diffuse shading factors modelling for the most representative agrivoltaic system layouts," Appl. Energy **339**, 120981 (2023).
[36]N. C. Giri, R. C. M. R. N. Shaw, S. Poonia, M. Bajaj, and Y. Belkhier, "Agriphotovoltaic system to improve land productivity and revenue of farmer," in *IEEE Global Conference on Computing, Power and Communication Technologies (GlobConPT)* (IEEE, 2022), pp. 1–5.
[37]J. D. Robert, W. Brian, and L. H. Richard, "Dynamic relationships between field temperatures and romaine lettuce yield and head quality," Sci. Hortic. **120**, 452–459 (2009).
[38]L. M. Mortensen and S. O. Grimstad, "The effect of lighting period and photon flux density on growth of six foliage plants," Sci. Hortic. **41**, 337–342 (1990).
[39]K. E. Cockshull, C. J. Graves, and C. R. J. Cave, "The influence of shading on yield of glasshouse tomatoes," J. Hortic. Sci. **67**, 11–24 (1992).
[40]L. F. M. Marcelis, "Fruit growth and biomass allocation to the fruits in cucumber. 2. Effect of irradiance," Sci. Hortic. **54**, 123–130 (1993).

[41]H. R. Gislerod and L. M. Mortensen, "Effect of light intensity on growth and quality of cut roses," in *III International Symposium on Artificial Lighting in Horticulture* (International Society for Horticultural Science, 1994), Vol. 418, pp. 25–32.

[42]L. F. M. Marcelis, A. G. M. Broekhuijsen, E. Meinen, E. M. F. M. Nijs, and M. G. M. Raaphorst, "Quantification of the growth response to light quantity of greenhouse grown crops," in *V International Symposium on Artificial Lighting in Horticulture* (International Society for Horticultural Science, 2005), Vol. 711, pp. 97–104.

[43]F. Weiguo, L. Pingping, W. Yanyou, and T. Jianjian, "Effects of different light intensities on anti-oxidative enzyme activity, quality and biomass in lettuce," Hortic. Sci. **39**, 129–134 (2012).

[44]A. Wahid, S. Gelani, M. Ashraf, and M. R. Foolad, "Heat tolerance in plants: An overview," Environ. Exp. Bot. **61**, 199–223 (2007).

[45]N. K. Ruehr, R. Grote, S. Mayr, and A. Arneth, "Beyond the extreme: Recovery of carbon and water relations in woody plants following heat and drought stress," Tree Physiol. **39**, 1285–1299 (2019).

[46]S. Hartzell, M. S. Bartlett, and A. Porporato, "The role of plant water storage and hydraulic strategies in relation to soil moisture availability," Plant Soil **419**, 503–521 (2017).

[47]E. Daly, A. Porporato, and I. Rodriguez-Iturbe, "Coupled dynamics of photosynthesis, transpiration, and soil water balance. Part I: Upscaling from hourly to daily level," J. Hydrometeorol. **5**, 546–558 (2004).

[48]S. Hartzell, "Ecohydrology of photosynthesis," in *Dryland Ecohydrology* (Springer, 2019), pp. 101–120.

[49]J. Chopard, A. Bisson, G. Lopez, S. Persello, C. Richert, and D. Fumey, "Development of a decision support system to evaluate crop performance under dynamic solar panels," in *AIP Conference Proceedings* (AIP Publishing LLC, 2021), Vol. 2361, p. 050001.

[50]S. E. Smith, B. Viggiano, N. Ali, T. J. Silverman, M. Obligado, M. Calaf, and R. B. Cal, "Increased panel height enhances cooling for photovoltaic solar farms," Appl. Energy **325**, 119819 (2022).

[51]H. J. Williams, K. Hashad, H. Wang, and K. M. Zhang, "The potential for agrivoltaics to enhance solar farm cooling," Appl. Energy **332**, 120478 (2023).

[52]Y. Elamri, B. Cheviron, J.-M. Lopez, C. Dejean, and G. Belaud, "Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces," Agric. Water Manage. **208**, 440–453 (2018).

[53]H. Dinesh and J. M. Pearce, "The potential of agrivoltaic systems," Renewable Sustainable Energy Rev. **54**, 299–308 (2016).

[54]R. J. Randle-Boggis, E. Lara, J. Onyango, E. J. Temu, and S. E. Hartley, "Agrivoltaics in east Africa: Opportunities and challenges," in *AIP Conference Proceedings* (AIP Publishing LLC, 2021), Vol. 2361, p. 090001.

[55]J. M. Warren, P. J. Hanson, C. M. Iversen, J. Kumar, A. P. Walker, and S. D. Wullschleger, "Root structural and functional dynamics in terrestrial biosphere models–evaluation and recommendations," New Phytol. **205**, 59–78 (2015).

[56]L. Zotarelli, M. D. Dukes, C. C. Romero, K. W. Migliaccio, and K. T. Morgan, "Step by step calculation of the Penman–Monteith evapotranspiration (FAO-56 method)," Institute of Food and Agricultural Sciences, University of Florida, 2010.

[57]A. L. Flint and S. W. Childs, "Use of the Priestley–Taylor evaporation equation for soil water limited conditions in a small forest clearcut," Agric. Meteorol. **56**, 247–260 (1991).

[58]D. I. Stannard, "Comparison of Penman–Monteith, Shuttleworth–Wallace, And modified Priestley–Taylor evapotranspiration models for wildland vegetation in semiarid rangeland," Water Resour. Res. **29**, 1379–1392, https://doi.org/10.1029/93WR00333 (1993).

[59]G. B. Senay, M. E. Budde, and J. P. Verdin, "Enhancing the simplified surface energy balance (SSEB) approach for estimating landscape ET: Validation with the METRIC model," Agric. Water Manage. **98**, 606–618 (2011).

[60]G. H. Hargreaves and Z. A. Samani, "Estimating potential evapotranspiration," J. Irrig. Drain. Div. **108**, 225–230 (1982).

[61]L. Turc, "Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date," Ann. Agron. **12**, 13–49 (1961).

[62]R. G. Allen and W. O. Pruitt, "Rational use of the FAO Blaney–Criddle formula," J. Irrig. Drain. Eng. **112**, 139–155 (1986).

[63]M. H. Riaz, H. Imran, R. Younas, M. A. Alam, and N. Z. Butt, "Module technology for agrivoltaics: Vertical bifacial versus tilted monofacial farms," IEEE J. Photovoltaics **11**, 469–477 (2021).

[64]M. A. Al Mamun, P. Dargusch, D. Wadley, N. A. Zulkarnain, and A. A. Aziz, "A review of research on agrivoltaic systems," Renewable Sustainable Energy Rev. **161**, 112351 (2022).

[65]M. Laub, L. Pataczek, A. Feuerbacher, S. Zikeli, and P. Högy, "Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: A meta-analysis," Agron. Sustainable Develop. **42**, 51 (2022).

[66]PVsyst SA, PVsyst, [Computer software], 2021, see https://www.pvsyst.com.

[67]Folsom Labs, HelioScope [Computer software], 2021, see https://www.folsom-labs.com.

[68]N. R. E. Laboratory, SAM (system advisor model), 2022, see https://sam.nrel.gov.

[69]Valentine Software, PVSOL [Computer software], 2022, see https://www.valentin-software.com.

[70]J. Bany and J. Appelbaum, "The effect of shading on the design of a field of solar collectors," Sol. Cells **20**, 201–228 (1987).

[71]Y. Cascone, V. Corrado, and V. Serra, "Calculation procedure of the shading factor under complex boundary conditions," Sol. Energy **85**, 2524–2539 (2011).

[72]P. Gilman, A. Dobos, N. A. DiOrio, J. M. Freeman, S. Janzou, and D. Ryberg, "SAM photovoltaic model technical reference 2016 update," Technical Report NREL/TP–6A20-67399, 1429291, Sandia, 2018.

[73]M. Prilliman, J. S. Stein, D. Riley, and G. Tamizhmani, "Transient weighted moving-average model of photovoltaic module back-surface temperature," IEEE J. Photovoltaics **10**, 1053–1060 (2020).

[74]C. Toledo and A. Scognamiglio, "Agrivoltaic systems design and assessment: A critical review, and a descriptive model towards a sustainable landscape vision (three-dimensional agrivoltaic patterns)," Sustainability **13**, 6871 (2021).

[75]M. Trommsdorff, J. Kang, C. Reise, S. Schindele, G. Bopp, A. Ehmann, A. Weselek, P. Högy, and T. Obergfell, "Combining food and energy production: Design of an agrivoltaic system applied in arable and vegetable farming in Germany," Renewable Sustainable Energy Rev. **140**, 110694 (2021).

[76]P. E. Campana, B. Stridh, S. Amaducci, and M. Colauzzi, "Optimisation of vertically mounted agrivoltaic systems," J. Cleaner Prod. **325**, 129091 (2021).

[77]M. Reasoner and A. Ghosh, "Agrivoltaic engineering and layout optimization approaches in the transition to renewable energy technologies: A review," Challenges **13**, 43 (2022).

[78]E. Mouhib, L. Micheli, F. M. Almonacid, and E. F. Fernández, "Overview of the fundamentals and applications of bifacial photovoltaic technology: Agrivoltaics and aquavoltaics," Energies **15**, 8777 (2022).

[79]T. Sarver, A. Al-Qaraghuli, and L. L. Kazmerski, "A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches," Renewable Sustainable Energy Rev. **22**, 698–733 (2013).

[80]S. Liu, Q. Yue, K. Zhou, and K. Sun, "Effects of particle concentration, deposition and accumulation on photovoltaic device surface," Energy Procedia **158**, 553–558 (2019).

[81]M. R. Maghami, H. Hizam, C. Gomes, M. A. Radzi, M. I. Rezadad, and S. Hajighorbani, "Power loss due to soiling on solar panel: A review," Renewable Sustainable Energy Rev. **59**, 1307–1316 (2016).

[82]M. S. El-Shobokshy and F. M. Hussein, "Degradation of photovoltaic cell performance due to dust deposition on to its surface," Renewable Energy **3**, 585–590 (1993).

[83]S. E. Smith, H. Djeridi, M. Calaf, R. B. Cal, and M. Obligado, "Particle transport-driven flow dynamics and heat transfer modulation in solar photovoltaic modules: Implications on soiling," Sol. Energy **265**, 112084 (2023).

[84]A. Ibrahim, "Effect of shadow and dust on the performance of silicon solar cell," J. Basic Appl. Sci. Res. **1**, 222–230 (2011).

[85]J. G. Garza, B. Chong, and L. Zhang, "Control of integrated Ćuk converter and photovoltaic modules for maximum power generation," in *Third IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG)* (IEEE, 2012), pp. 175–181.

[86]A. N. A. Ali, M. H. Saied, M. Z. Mostafa, and T. M. Abdel-Moneim, "A survey of maximum PPT techniques of PV systems," in *IEEE Energytech* (IEEE, 2012), pp. 1–17.

[87]T. Logeswaran and A. SenthilKumar, "A review of maximum power point tracking algorithms for photovoltaic systems under uniform and non-uniform irradiances," Energy Procedia **54**, 228–235 (2014).

[88]S. Silvestre, A. Boronat, and A. Chouder, "Study of bypass diodes configuration on PV modules," Appl. Energy **86**, 1632–1640 (2009).
[89]J. C. Teo, R. H. G. Tan, V. H. Mok, V. K. Ramachandaramurthy, and C. Tan, "Impact of bypass diode forward voltage on maximum power of a photovoltaic system under partial shading conditions," Energy **191**, 116491 (2020).
[90]B. B. Pannebakker, A. C. de Waal, and W. G. J. M. van Sark, "Photovoltaics in the shade: One bypass diode per solar cell revisited," Prog. Photovoltaics **25**, 836–849 (2017).
[91]M. Dhimish, V. Holmes, P. Mather, and M. Sibley, "Novel hot spot mitigation technique to enhance photovoltaic solar panels output power performance," Sol. Energy Mater. Sol. Cells **179**, 72–79 (2018).
[92]A. Woyte, J. Nijs, and R. Belmans, "Partial shadowing of photovoltaic arrays with different system configurations: Literature review and field test results," Sol. Energy **74**, 217–233 (2003).
[93]S. A. Kalogirou, "Applications of artificial neural-networks for energy systems," Appl. Energy **67**, 17–35 (2000).