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Review

A Review of Agrivoltaic Systems: Addressing Challenges and Enhancing Sustainability

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Abstract: Agrivoltaics is a relatively new term used originally for integrating photovoltaic (PV) systems into the agricultural landscape and expanded to applications such as animal farms, greenhouses, and recreational parks. The dual use of land offers multiple solutions for the renewable energy sector worldwide, provided it can be implemented without negatively impacting agricultural production. However, agrivoltaics represent a relatively new technology, facing challenges including economic viability, vulnerability to wind loads, and interference with growing crops. This paper reviews the recent research on integrating agrivoltaics with farming applications, focusing on challenges, wind impact on agrivoltaics, and economic solutions. The effect of agrivoltaics on temperature control of the lands is a critical factor in managing (1) water and the soil of the land, (2) animal comfort, and (3) greenhouse productivity, positively or negatively. In this review, a contradiction between the different versions of the American Society of Civil Engineers (ASCE) standards and the wind tunnel results is shown. Important factors affecting the wind load, such as damping and mass increase, optimum stow position, and aerodynamic edge modification, are highlighted with emphasis on the significant knowledge gap in the wind load mitigation methods.

Keywords: agrivoltaics; solar greenhouses; agriculture; wind loads; vortex; galloping; flutter derivatives; ground mounted; wind design standards; solar panels; PVs; ASCE standards

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1. Introduction

Fossil fuels are a major component of modern agriculture, contributing significantly to greenhouse gas (GHG) emissions through their use in energy-intensive processes such as fertilizers, irrigation, and mechanization [1]. Compared to 12% in industrialized countries, agriculture is responsible for 35% of greenhouse gas emissions in developing countries [1]. The primary factor in climate change is global warming, mainly driven by greenhouse gases, particularly carbon dioxide (CO_2) [2]. Nearly 85% of the emissions in the United States are carbon dioxide [3]. This phenomenon has had a significant effect on the ecosystem and is responsible for approximately 150,000 more fatalities annually [4]. Energy is currently seen as a crucial resource for industry, and concerns over its supply are threatening the global economy's development [5]. If the decision-makers applied new policies to increase the contribution of renewable energy of all types, the mitigation of climate change would be achieved [5]. Also, the carbon dioxide emissions will decrease; the carbon emissions of the solar panel systems are estimated as (14–73 g CO_2-eq/kWh) while gas is (607 g CO_2-eq/kWh), oil is (742 g CO_2-eq/kWh), and coal-fired power plants are (975 g CO_2-eq/kWh) [6]. After discussing the problems associated with using fossil fuels and the phenomenon of climate change, there has been a growing demand for renewable energy due to its cost-effectiveness and minimal contribution to greenhouse gas emissions [7]. The idea of agrivoltaics was first studied in 1980, including the use of solar photovoltaic panels in various agricultural fields [8]. Solar industry experts verified that agrivoltaics offered a beneficial option for land use and energy planning [9]. Also, community acceptance of agrivoltaics is essential for expanding the use of solar panels on agricultural properties [10]. This acceptance promotes leniency in legislation regarding the installation of solar panels and land restrictions [10]. Agrivoltaics may be categorized depending on the kind of agricultural land, including crop lands, animal farms, and solar greenhouses integrated into agricultural lands, as shown in Figure 1.

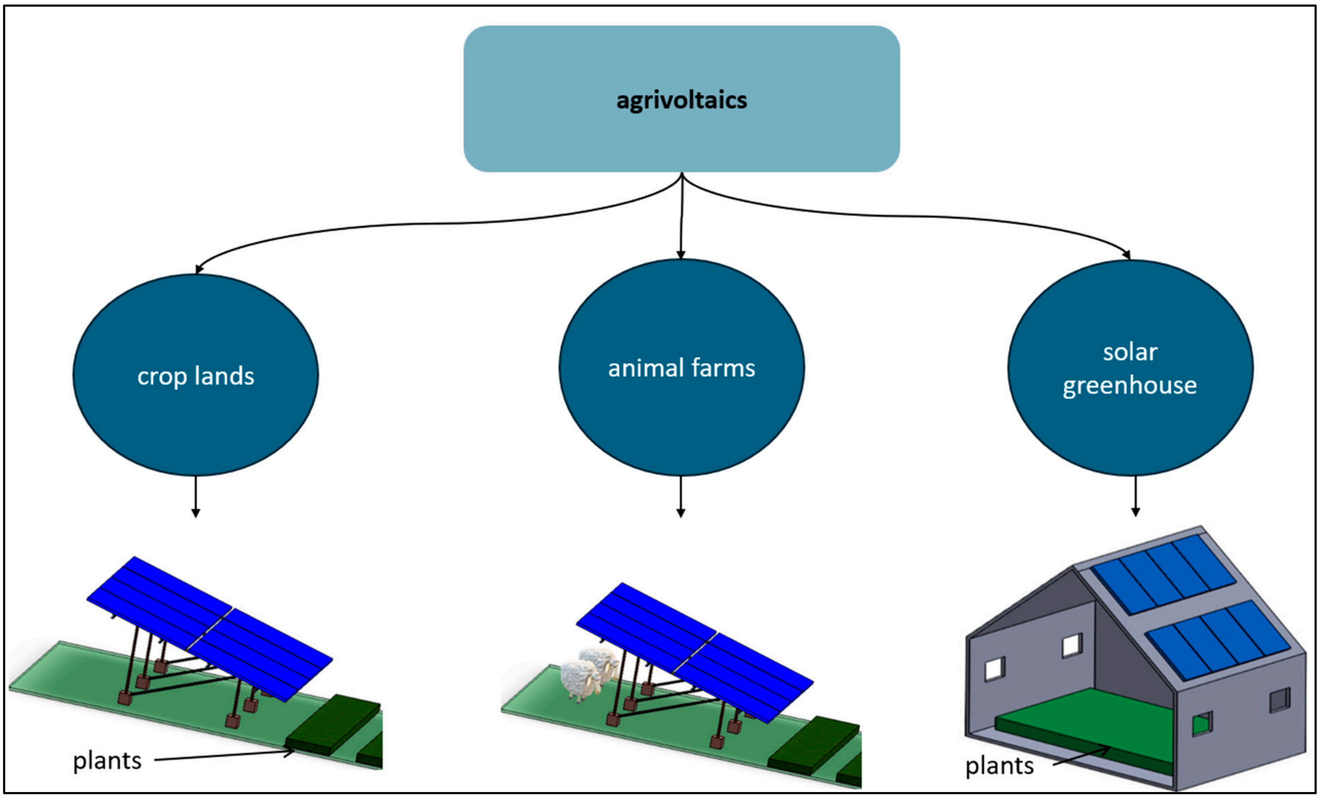


Figure 1. Different solar panel setups in agricultural lands.

Agrivoltaics with croplands has proven to be a dependable solution to land availability issues for renewable energy resources and plants. Agrivoltaics with animal farms are used in grazing with different kinds of animals, such as rabbits, sheep, cattle, poultry, and honeybees [10]. Solar greenhouse agrivoltaic projects have achieved several benefits, such as partial shading and light modulation [11,12]. Solar greenhouse configurations include transparent, semi-transparent, and opaque modules mounted on the roof or integrated with the building [13].

One of the issues is that the PV panels block the sunlight from reaching the crops in the lands or on rooftops of the greenhouses, creating partial shadowing that might impact crop growth, and this is clear in the case of maize crops [14]. Agrivoltaic array construction must be modified to meet the agricultural machinery's specific demands [15]. The photovoltaic panels (PV) need to be elevated to a suitable height to provide easy movement to agricultural machinery [15]. Soil erosion may happen when heavy rainfall causes significant runoff from the PV panels [15]. In recent studies, researchers have successfully cultivated aloe vera, tomatoes, biogas maize, pasture grass, and lettuce in agrivoltaics [16]. Certain types of lettuce yield more in the shade than in direct sunshine, while other types yield nearly the same amount in the open and in agrivoltaics [16]. Greenhouses are not facing major issues by adding solar panels on the rooftop. Shading could be avoided easily since multiple crop types of production remain nearly unchanged and, in some cases, the production amount even increased, in addition to other positive impacts [16]. Another solution to the greenhouses is implementing semi-transparent PV panels, which create more flexibility in mounting without sunlight blockage [16].

On the other hand, in the 1970s, researchers began studying the effects of wind on solar panels [17]. Wind-induced damage has increased in tropical and subtropical areas [17]. The interaction between wind dynamics and solar panels shows complex aerodynamic phenomena such as torsional galloping, flutter, and vortex shedding, which can all threaten PV installations' structural strength and stability.

The feasibility of agrivoltaics can be maximized to convince the private landowners as profit maximization is their priority in accepting solar panels in their agricultural lands. Other factors encourage landowners to invest in solar panels, such as water availability, the aesthetic and ecological of the land view, and land preservation and protection [18]. The development of renewable energy is situated within the context of the historical interest in energy solutions. Energy alternative initiatives demonstrate innovation, profitability, substantial source reduction, and employment creation based on the financial situation of agrivoltaics [19]. The paper layout and review topics are shown in Figure 2. The goal of the paper is to provide a comprehensive review of agrivoltaic systems that could be a reference for improvements in future work by discussing the current advantages and disadvantages of these systems on agricultural lands, thus improving the design of ground-mounted solar panels and creating stable designs that will help in adding panels to the lands and directing the research toward the examination of current drawbacks agrivoltaic systems and improvements.

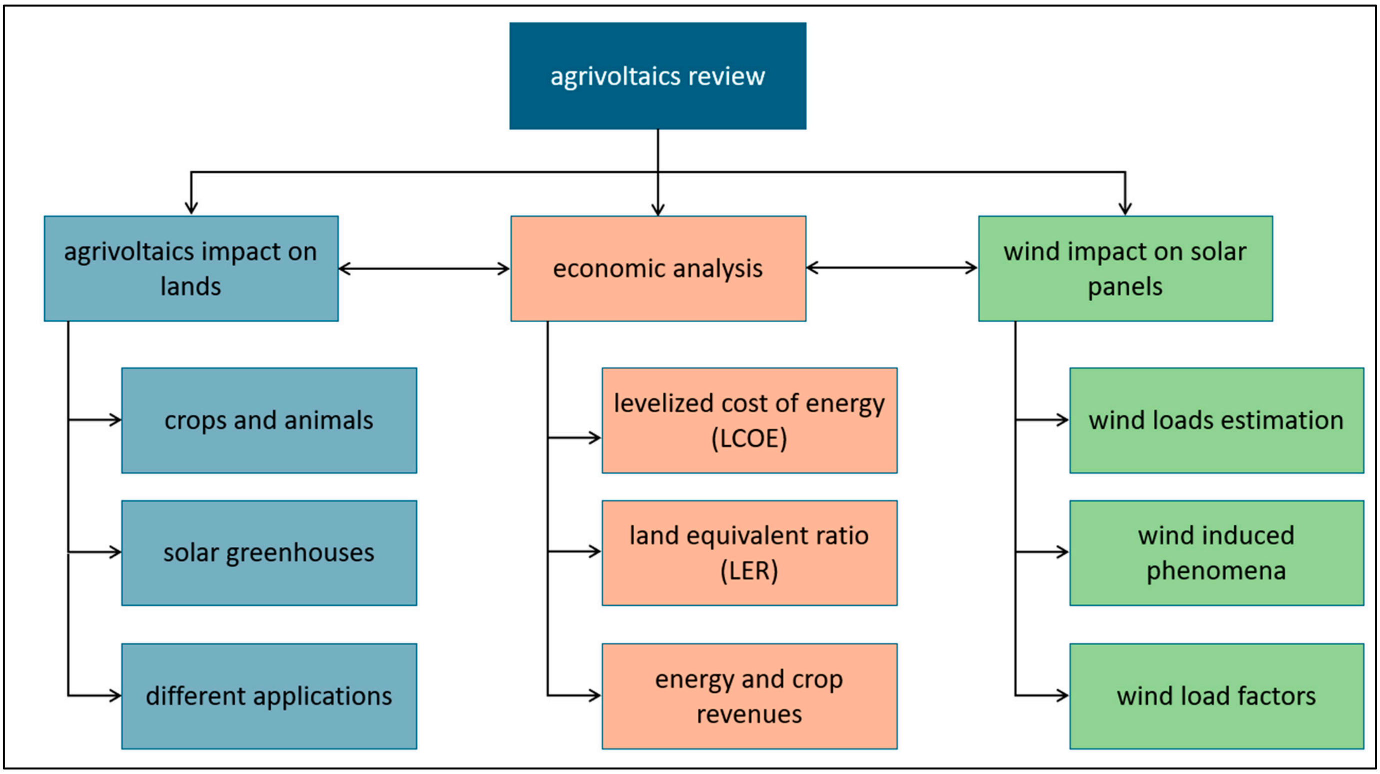


Figure 2. Paper layout chart and review topics.

2. Agrivoltaic Impact on Lands

The availability of land creates a problem for crop production and grazing livestock, as well as the spread of solar panels worldwide. Due to the increased demand for food on a global scale because of population growth and changes in consumption patterns, this restriction prevents potential energy savings [20]. In addition to that, the global energy demand (21 PWh) could be offset by solar production if less than 1% of agricultural land with a median power potential of 28 W/m^2 were suitable candidates for agrivoltaic systems and converted to dual use, according to a re-evaluation of the reduced order model [21]. This expansion will be limited by the absence of energy storage and the temporal variability in solar energy availability [21]. The global demand for crops is projected to increase by around 110% between 2005 and 2050 [22]. Integrating solar panels with crop areas was an effective approach to optimizing land use for both crops and solar energy production while avoiding deforestation or sacrificing land for solar panel installation [23]. In Germany, a study examined the shift from single-land use to agrivoltaic systems [24]. The study found that 15 out of 16 impact categories, including climate change, eutrophication, and fossil resource use, were reduced. The study highlighted agrivoltaics' role in expanding renewable energy production resources without compromising food production [24]. Agrivoltaic systems have nearly the same energy cost as ground- or roof-mounted solar panels, which reduces cost by installing the PV panels on top of the roofs using frameworks [25]. This cost-effective method encouraged farmers and owners to allow agrivoltaic systems on their lands if negative impacts on the plants were avoided [25]. Different types of ground-mounted agrivoltaic systems are used on agricultural lands, such as fixed, single-axis trackers; dual-axis trackers; and bifacial (vertical) solar systems [26]. A comparative study was conducted to analyze the differences between the fixed vertical and dynamic single-axis tracker for bifacial agrivoltaic systems with a focus on sugar beet cultivation [26]. The impact on crop yield and power production in various algorithms is examined [26]. Results showed that the dynamic single-axis tracker has better results than the fixed vertical setup in terms of energy generation and land use efficiency [26]. Energy generation and land use efficiency are increased by 30% and 20%, respectively, for the smart-tracking algorithm [26].

2.1. *Water and Soil Management*

Water and energy are interconnected [27]. Photovoltaic (PV) systems use water only for panel cleaning and dust suppression in areas where dust deposition is an issue [28]. Their lowest rates are 0.02 m^3/MWh [28]. Adding solar panels to the agricultural lands may impact the soil life and water management in the area. In some cases, agrivoltaics may help water distribution, consumption, and soil life, while in other cases, it might form an obstacle to land quality. A discussion was conducted on the impact of renewable energy integration in agrivoltaics on water consumption. For solar panel systems, water use during operations is negligible [29]. An experimental study shows that although frequent washing of the panels helps production, it is likely to result in financial deficits [29]. In wetter climates, the presence of solar panels introduces heterogeneity in soil moisture distribution due to changes in water distribution, as shown Figure 3 [30].

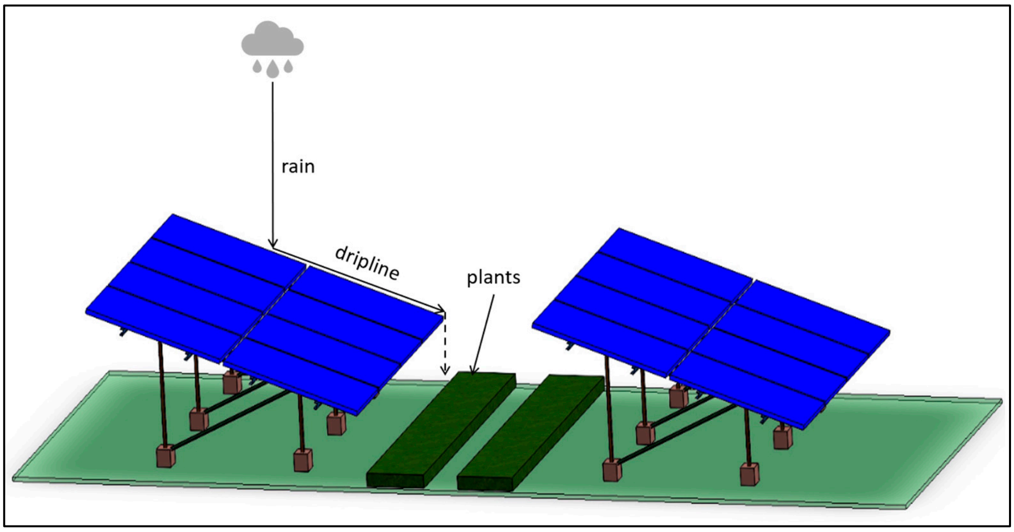


Figure 3. Significant hydrological phenomena in a solar farm resulting from the solar panels' influence on the plants' water distribution.

Precipitation accumulates along the dripline at the lower edge of the panels, potentially leading to increased runoff and erosion [30]. The suggested solution to this might be implementing appropriate management practices such as variable panel tilting as a consideration to mitigate the redistribution of water and minimize the risk of runoff and erosion [30]. However, the solar panels' existence might be beneficial for several types of crops. A study showed that measurements of the microclimate at crop level beneath PV panels in a dry area indicate that agrivoltaic systems may help conserve water [31]. A study confirmed that the plant under the solar panel systems was able to gain more moisture than the crops that grew in the open field planting location because of the decrease in direct sunlight exposure beneath the PV panels, which resulted in colder daytime temperatures and warmer nighttime temperatures [32]. A simulation was performed to create an artificial shade condition for growing lettuce, resulting in an average overall reduction of -20% in plant water demands [33]. In France, a model was developed by installing tilting-angle solar panels over agricultural land to enhance the control of the solar panels and water management. The model simulations successfully demonstrated the advantages of agrivoltaic installations, such as enhancing land use efficiency and water productivity simultaneously. This was achieved by reducing irrigation by 20% while accepting a 10% decrease in yield or slightly extending the cropping cycle [33]. An investigation carried out in arid environments revealed that the tomato had a 65% higher water usage efficiency (WUE) in the agrivoltaic system, compared to a 157% greater WUE for jalapeños [34]. When irrigation was performed every two days, it was discovered that soil moisture in the agrivoltaic system stayed 15% higher. In contrast, soil moisture stayed 5% higher before the next watering when daily irrigation was implemented [34].

The investigations stated above showed that the effect of agrivoltaics on the water and soil management of agricultural lands can be either beneficial or disadvantageous. Most of the studies showed that the lands would benefit from the agrivoltaics, such as the reduction in water consumption due to changes in temperature that the agrivoltaics create, soil moisture remaining higher, and water usage efficiency. At the same time, few studies have focused on soil erosion, unequal water distribution, and heterogeneity in soil moisture that happens due to agrivoltaics. Future research should focus on the methods of avoiding the bad influence of agrivoltaics on the lands and benefit more from the advantages these systems provide. Panel cleaning helps the maximization of the power generated, but a field should also be studied to find new feasible methods and dual use of the water.

2.2. Shading on Crops

A crop model was developed to measure the productivity of the partially shadowed crops [35]. The crop model simulates the light transmission through the solar panels to the crops [35]. For two panel rows, the increase in land production was 60–70% in the overall production [35]. Another study that supports that claim was conducted on broccoli crops in the agrivoltaic system. A comparison was created between the growth of the broccoli plants that are planted in the open environment and under the panels [36]. The results showed more vibrant green and consumer preference compared to those grown in open environments and no major change in the plant properties [36]. The type of solar panel mounting affects the productivity of the crops and the light transmission. In a study performed to find the impact of the agrivoltaic systems on the fixed solar panels and the tracking (moving) solar panels, it was found aside from the higher electricity generated by the trackers; it also claims that the biomass production of the lettuce remains the same or less in a few amounts under the shading conditions of agrivoltaic systems than the plants located in the open area [37]. To support the concept of agrivoltaics, a study was conducted on different crop species, and the results showed that if shade-tolerant crops, like lettuce, were utilized, the agrivoltaics concept would achieve a massive power generation without a loss in the crop yield [38]. The increase in power generation would be 70 GW instead of 40 GW if lettuce cultivation alone turned toward an agrivoltaic system in the United States [38]. Combining the shade-tolerant crops with solar electricity resulted in a 30% increase in the agrivoltaics system's economic value as well as maintaining the agricultural yield and providing stability for the commodity prices [38]. A model was created in Europe to analyze the shadowing effect for different configurations of the agrivoltaic systems: fixed PV panels with optimal tilt angle, bifacial vertically mounted, and single-axis horizontal tracking system. Results showed that vertical and single-axis tracking systems are consistent with irradiation on the ground [39]. This gives insights into the shadowing of the crops based on the method of installing solar panels. Selecting the right configuration will not only provide the best estimate of the shadowing of the cropland but will also enhance electricity production. It was proved that the potential capacity of agrivoltaics in Europe is 51 Terawatt (TW) [39]. It was found that agricultural areas might have solar panels in the Phoenix Metropolitan Statistical Area (MSA). According to the study's findings, agricultural regions receiving half-density panel installation received 60% direct sunlight of direct sunlight without panels [40]. However, with this partially shaded land, after two years, 50% of the sale of the agricultural land would have compensated for the sale price caused by agrivoltaic systems [40]. A simulation-based study was carried out to examine the effects of solar panel shading on the Paris metropolitan area. The solar panels' shadow partially increases (by 3%) the heating required in the wintertime [41]. But during the summer, it helps cut down on the energy required for air conditioning by 12%. Moreover, the urban heat island decreased by 0.2 K during the day and 0.3 K at night [41]. A similar investigation was carried out in Los Angeles County, California, to address the heat island effect by installing solar panels on the roofs of buildings. The study has demonstrated that buildings with green roofs experience increased energy savings [42]. The extent of these savings depends on elements such as the Leaf Area Index, soil depth, and irrigation saturation percentage. Additionally, it helps in the functioning of heating, ventilation, and cooling (HVAC) systems by providing colder surfaces, which allows HVAC systems to achieve the appropriate temperature while consuming less electricity [42]. An investigation was conducted to test the effect of installing solar panels on the grapevines and fruit trees [43]. The results showed that the panels contributed to reducing the soil and air temperature by 1–2 °C by changing the vines' activities, such as transpiration and photosynthesis [43]. This change creates better environments for the vines and has a positive influence on water consumption reduction [43]. However, the study findings apply to the dry and hot locations; more research into the effect of the panels in the cold and wet areas is needed. Another study determined the yield reduction percentage of winter wheat due to shading to be 27% [44]. The plants that might be affected by the high temperature and berries should be studied in future research with large-area experiments, longer study periods of up to several years, and allowance of the light spectrum separation by new solar panels [45].

A practical solution that could be provided to the shading issue on the crops is using tinted semi-transparent solar panels or organic photovoltaics (OPVs). An approach was applied to the agrivoltaics application using the different selected light wavelengths that open a new track beyond the current solar panel's practices [46]. The approach was tested on basil and spinach crops and showed a financial gain of up to +2.5% for basil and 35% for spinach [46]. The market price of these crops is the reason for the large difference in the financial gain [46]. However, the material availability of the tinted semi-transparent solar panels should be studied more, and a financial analysis, including all factors in this approach, should be performed. OPVs are also used in agrivoltaic systems [16]. The OPV can emit the selected light wavelengths, like the previous type [47]. The ductility and absorption coefficient enable the solar panel to be thin and flexible [47]. Traditional solar panels or inorganic solar panels were used in PV tomato greenhouses in Spain, showing that the restrictive impact of photosynthetically active light on plant growth is negligible, with a cover ratio of 9.79% [48]. However, there is no significant impact on plant growth in China PV tomato with a cover ratio of 20% [49]. In France, for the open field solar systems, it was found that in the case of a cover ratio of 30%, there is no major impact on the crop yield, while a 50% cover ratio impacts the crop yield significantly [37]. In Italy, a PV tomato greenhouse with a 50% cover ratio showed a reduction in crop yield [12]. Another aspect of research work on the OPVs is being conducted by changing the acceptor layer of the polymer [50]. Experiments showed that a non-fullerene acceptor called Y6 achieved an efficiency of 13.6% of the devices with Y6 acceptors [50]. The best implementation of the dual use of the land shows good results in producing electricity and maintaining the crop production rate; in addition to that, it can be a shelter for the plants from natural events like heavy rain or hurricanes and hail [51]. In dry locations, shading provided by the agrivoltaic systems might protect the crops from sunburn and decrease water consumption and evapotranspiration [51]. However, OPVs can only be used for roof mounting, which is applicable to buildings and greenhouses. More research is needed for their potential use in the ground-mounted solar panels.

Selecting the dimensions of solar panels in agrivoltaics could help the shading and the land arrangement. Experiments indicate a gap between the collectors will ensure the panels do not obstruct sunlight from reaching the crops. Moreover, a smart method for tracking or backtracking is proposed to avoid shadowing in situations where the crop can be protected from the shadow effect [52]. Overall, the study states that implementing N–S horizontal trackers and olive trees in hedges up to 3.0 m high and 1.5 m wide might potentially increase the land equivalent ratio of an agrivoltaics plant in Cordoba, Spain, by around 28.9% to 47.2%. Hence, solar photovoltaic (PV) systems can be flexible for agrivoltaic setups, so enabling renewable energy facilities to be compatible with a more efficient and sustainable agriculture model [52]. The vertical dimension of solar panels in agricultural fields has created a challenge for researchers due to variations in growth rates and heights among different crop species. The choice of solar panel height may be influenced by the soil type, as well as the geographical location and financial resources available. The minimum practical height for solar panels for vegetables growing underneath is 1.8 meters, while a desirable height of 2.4 m is recommended for crops [53]. Also, the surface temperature of the PV panels might be affected by multiple factors, such as ground albedo, panel height, and evapotranspiration. A study was conducted to investigate PV panel height in agrivoltaics by creating a Computational Fluid Dynamic (CFD) Simulation microclimate model. The results of the simulations showed that increasing the height of the panel by 2 m caused cooling of the panel surface by 0.4–1.1 °C in the morning period until 4 pm of the day, 1.5–2.9 °C when ground albedo increased by 50%, and 1.1–2.9 °C when evapotranspiration condition is applied [54].

The research papers stated above established the impact of agrivoltaic systems on crops has advantages and disadvantages. It depends on multiple factors, such as crop type, mounting method for the panels, and the location's climate. Selecting the shading-tolerant crops will help expand the agrivoltaics and keep the crop production unchanged. Agrivoltaic systems shield from hail or natural circumstances that might threaten plants and animals' lives. The shading caused by the PV panels affects the climate or creates a micro-climate that has a beneficial side, such as cooling the place in summer or warming it in winter. Also, the height of the panels should be selected wisely, considering the ground albedo and evapotranspiration factors affecting the panel's surface temperature. The disadvantages of shading for the plants are minimal; it also can be advantageous for the animals as it provides a cooler place and protection from extremely cold weather. Future research should concentrate on selecting the appropriate heights and angles of the agrivoltaics for the crops and animals. Thus, a review of agrivoltaics impact on animals is conducted in the following section.

2.3. Agrivoltaics with Animals

Utilizing the space underneath the solar panels in agrivoltaic systems for grazing the farm animals is becoming more common, and this kind of integration helps the farmers with the shade provided to the animals if the solar panels were installed based on the suitable heights for the animals. A study was conducted to examine the agrivoltaics with animal grazing [55]. The study investigates permitting sheep and other livestock to be around solar panel installations [56]. Results showed that agrivoltaics can improve lamb production and welfare. The animal weight gains and spring water consumption are other aspects of the study that are examined under open as well as partially and fully shaded conditions [56]. This shows that agrivoltaic systems will not decrease the production of lambs. However, further studies should be performed to collect farmers' and landowners' opinions about agrivoltaics with such encouraging results and studies that may motivate the farmers to go to agrivoltaics [56]. An investigation was conducted to observe the five lambs and six ewes' behavior with two types of shade structures: PV panels shade and 80% blockage cloth [57]. Results showed that the animals spent 1% of their time under the cloth shade, 38% under the panels shade, and 61% exposed to the sun [57]. As the radiation increases, the time spent under the PV panels increases based on the observations [57]. The savings based on the energy generation was around USD 740, and 2.7 tons of CO_2 were prevented [57]. However, the study failed to provide recommendations for improving the quality of the PV panels shade for the animals to increase the time spent under them. Future research should focus on providing designs for animals' food and drink based on records of their activity. In Michigan, US, research was performed investigating the idea of grazing rabbits under solar panels as part of an agrivoltaic system [58]. The study's technical, economic, and environmental analyses are based on rabbit husbandry that is pasture-fed [58]. Based on the location and rental ownership of the rabbits, the results show that co-locating solar and rabbit farms is a feasible form of agrivoltaics, increasing overall site revenue by 2.5% to 24.0% above projected electricity revenue while producing a high-value agricultural product with a much lower environmental impact per weight than cattle [58].

The studies above showed the good influence of agrivoltaic systems on animals. However, more work is needed to cover more investigations of this integration and highlight the effect on the animals and agrivoltaic systems. After analyzing the influence of agrivoltaic systems on the lands, another analysis is conducted on the greenhouses and recreational parks in the following sections.

3. Agrivoltaics with Greenhouses

Modern greenhouse cultivation of crops has become more popular as an applicable alternative to conventional agriculture due to the increasing concerns caused by environmental degradation and land deterioration [59]. However, doubts concerning greenhouse systems' overall environmental effect are raised by worries about their high energy consumption. Integrating PV panels into agricultural greenhouses, namely through solar greenhouse designs, appears to be a reliable approach to managing land availability issues and reducing greenhouse gas emissions. An overview of China's progress was made in creating solar greenhouses and looks at solutions to problems including heat loss, shading, and poor lighting [60]. The radiation emitted by the plants still creates a challenge for PV panel installation, which directs industry advancements in thin-film solar panels and transparent modules that maintain light levels for the plants [61]. The presence of solar panels also affects the temperature inside the greenhouse, raising concerns regarding the ventilation techniques that should be used in greenhouses that have solar panels. A further problem for this kind of integration is the absence of industrial standards [61]. A comparative study investigated the impact of semi-transparent organic PVs (OPVs) greenhouses with conventional greenhouses [62]. The results showed that the solar greenhouse design reduces the environmental impacts in warm regions [62]. In Arizona, the global warming of CO_2 eq/kg tomato was 3.71 kg and 2.36 kg for conventional and solar greenhouse, respectively [62]. In colder regions, the shading caused by solar greenhouse results in higher heating demands and environmental impacts. Economically, solar greenhouses showed a net present cost of USD 3.64 per kg of tomato, while it was USD 3.43 for conventional ones [62]. More study is needed to find optimal designs of OPVs in colder regions, and comprehensive economic studies are also needed. In a study on solar panels installed on greenhouse roofs in the Mediterranean region, the impact of radiation on crop water is evaluated using reference evapotranspiration, giving farmers the needed modifications to control irrigation [63]. The radiation reduction increased as the PV panel-covered greenhouse rooftop area increased, which led to an unequal distribution of radiation on the plants. The increased radiation has an impact on the amount of water needed, and transparent photovoltaic panels have been proposed to help ensure radiation uniformity. The simulation of the study is declared Figure 4a [63]. Mounting PV panels on the greenhouses is shown in Figure 4b [64].

(**a**) (**b**)

Figure 4. (**a**) Three-dimensional model of the solar panels on the greenhouses [63]. (**b**) PV panels mounted on the greenhouse roof (Almeria city, Spain) [64].

In Spain, profitability was enhanced by around 52%. Due to the temperature and solar radiation in this location, photovoltaic panels shade about 10% (9.8%) of the greenhouse area without affecting crop productivity [64]. In a similar study conducted in the same city, flexible solar panels were installed on the greenhouse roof in various configurations, resulting in a 10% shade on tomato crops [65]. Despite this shading, the plant production remained unchanged, indicating that the shade from the panels had no impact [65]. A case study was performed in Tehran to predict the air temperature inside the greenhouse by using an optimization tool [66]. The objective function is changeable and can be controlled to find the optimal solar greenhouse design yearly or seasonally [66]. It was found that 85% of the optimal greenhouse design energy is working passively every year. The results also showed that melon, watermelon, and cucumber cultivation is more important than other species [66]. A study investigated solar greenhouse vegetable production based on fertilizer input rates [67]. The study included analyzing the soil nutrients and properties after five years [67]. The results showed that a high amount of manure and mineral fertilizers caused faster accumulation of soil organic matter (SOM), total nitrogen, nitrate nitrogen, Olsen phosphorus, and potassium while increasing electrical conductivity and soil pH [67]. This led to average annual growth rates of 28.6% and 16.5% for soil nitrogen and nitrate nitrogen, respectively [67]. Precise fertilizer management, advanced fertilizer technologies, catch crops use, and enhanced water quality for preventing pollution are required in solar greenhouses [67].

4. Agrivoltaics with Different Applications

One of the areas where solar panels could be installed is recreational parks. Recreational parks offer physical activities and opportunities for relaxation to the population. It also helps the equilibrium for the environment of the city life by planting trees. Integrating renewable energy resources with these recreational areas should help in establishing sustainable communities and green areas. In Konya, Turkey, a study was performed to test the PV integration with recreational parks, and it showed a good result in generating electricity and providing shade for people, benches, and charge stations, too [68]. PV panels are facing challenges in integrating with recreational areas; they could damage the grass or be an obstacle to some activities in parks [68]. A study investigated the solar panels in the park's effect and their impact on the temperature of the park if installed on the roofs of the gardens. Designs were created for prototype implementation to create the placement of photovoltaic (PV) panels on the roofs of gardens, with a particular emphasis on flat roofs [69]. Upon conducting an analysis and testing of the prototype structure design, the findings indicated that the green roofs in parks and gardens, which have a lightweight construction, had the additional benefit of decreasing the urban heat island effect [69]. In addition to that, a study investigated the impact of solar panels on the cooling role of parks. The findings of the study revealed that solar parks offer a surface cool island effect that extends beyond the boundaries of the solar park. There was a cooling impact that extended 730 m away from the nearest 100 m buffer, and it reached a temperature of 2.3 °C [70].

Studying the greenhouse gas emissions, agricultural lands contribute to producing beneficial gases like methane (CH4) and nitrous oxide (N2O) but not carbon dioxide (CO_2) [71]. The source of these emissions generally comes from livestock, chemical and organic manure, fertilizers, rice cultivation, burnt crop leftovers, and savannahs [71]. Agrivoltaics are necessary to preserve agricultural fields and mitigate greenhouse gas emissions by installing the appropriate number of solar panels on these sites. Exploiting agricultural lands is key to reducing greenhouse gas emissions as well as expanding renewable energy resources around the world. Table 1 shows a comparative summary of the agrivoltaics types, illustrating the advantages and disadvantages of each type.

Table 1. Comparison of agrivoltaics types based on advantages and disadvantages.

Agrivoltaics Type	Advantages	Disadvantages
Crops	• Water consumption management. • Shield from hail and natural circumstances. • Controllable microclimates help in crop yield.	• Shading on some crop types. • Soil erosion is due to water distribution. • Reduce the soil porosities.
Animals	• Provide cooler place in summer and warmer in winter. • Higher lamb production and welfare. • Increasing overall site revenue.	• Some types of goats might chew the cables. • Windy weather is challenging to the stability of the panels.
Greenhouses	• 85% of the optimal greenhouse design energy is working passively. • Reduce evapotranspiration and water loss. • Provide the needed controlled irrigation modifications.	• Plaque solar panels decrease the light on the crops. • Temperature increase in the greenhouse and ventilation is needed.
Different applications	• Provide shade in solar parks for people. • Provide charge stations in recreational parks. • Create cooler places for people in the parks.	• Obstacle for specific sports activities. • Possibility of damaging the grass of the garden.

5. Economic Analysis of Agrivoltaics

Basically, the economics of agrivoltaics can be compared based on the cost of the ground-mounted solar panels and roof-mounted solar panels for the greenhouses. The cost of solar panels can be represented by the levelized cost of energy (LCOE) concept, which is used to describe the feasibility of using one method of energy by analyzing the cost-effectiveness of using any technology for energy consumption. Ground-mounted solar panels general formula of LCOE can be calculated based on Equations (1) and (2) [72]:

$$\text{LCOE} = \frac{\text{Total Lifecycle cost }(\$)}{\text{Total Energy generated for its lifetime }(\text{kWh})} \tag{1}$$

$$\text{LCOE} = \frac{\sum_0^N \frac{\text{I}+\text{O\&M}_\text{n}}{(1+\text{dr})^\text{n}}}{\sum_0^N \frac{\text{S}_\text{t}(1-\text{Dr})^\text{n}}{(1+\text{dr})^\text{n}}} \tag{2}$$

where I is the initial cost, $\text{O\&M}_\text{n}$ is the operating and maintenance costs, N is the lifetime of project, n is the corresponding year, S_t is the annual output energy for the operation's first year, Dr is the degradation rate, and dr is the discount rate.

The total cost of the agrivoltaic systems can be described based on the main factors forming the cost, as shown in Figure 5.

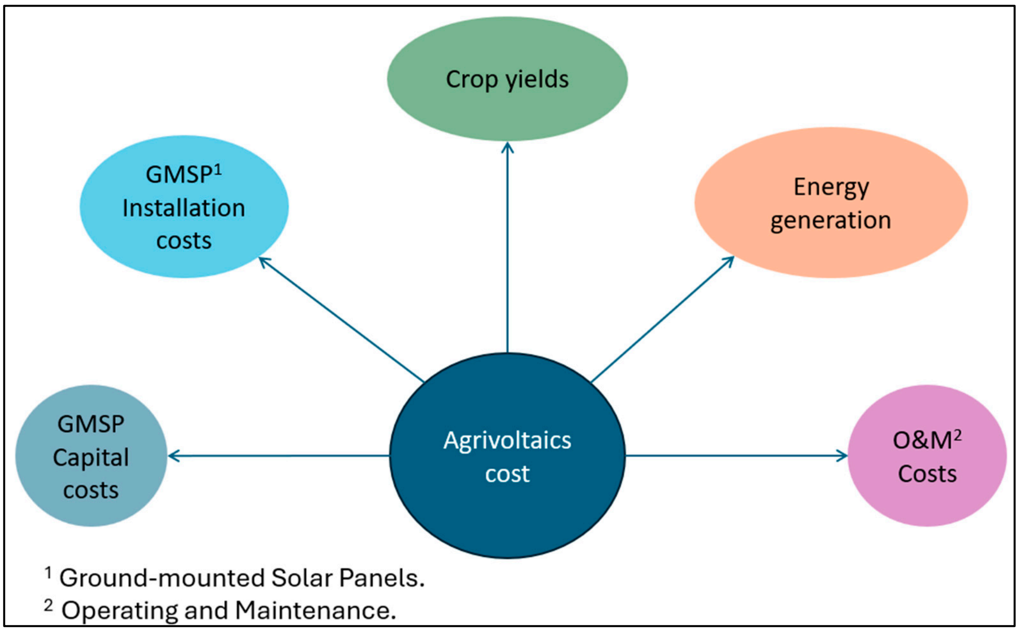


Figure 5. The main factors forming the cost of agrivoltaic systems.

5.1. Ground-Mounted Solar Panel Capital Costs

The capital costs of the solar panel system, including solar panels, installation costs, storage of and batteries for the off-grid systems, inverter price, and payback period, can be investigated to ensure the feasibility of the system. A study investigated the total cost of the ground-mounted solar panel system, including module, inverter, installation, labor, grid interconnection, and shipping and taxes [73]. The study determined the total cost of the system for two cities, Michigan in the US and Ontario in Canada [73]. The results showed that Ontario has slightly higher PV system costs (USD 22,759) than Michigan (USD 21,374) because of the taxes and differences in some parts prices [73]. Specifications of a practical example of the ground-mounted solar panels costs using the solar farm in Port Allen, LA, are mentioned in the last section of the paper. It is shown that the capital cost is USD 240 million for a 50 MW installed capacity solar farm, with USD 30 million expected in Entergy customers' savings.

When calculating the installation cost of the agrivoltaic system, labor costs cannot be neglected. A comparative study conducted between the United States and Germany calculated the average cost of pre-installed watts of residential solar systems [74]. The costs were USD 4.93 for the US and USD 2.21 for Germany; labor costs were determined at USD 0.49/W and USD 0.18/W for the US and Germany, respectively [74].

Another perspective of analyzing the cost of the agrivoltaic systems is to choose the type of the system either grid-tied or off-grid. In both grid-tied and off-grid scenarios, an economic analysis was performed to compare landowner returns on single against combination land use. A study was conducted in India for two types of solar panels, the on-grid and off-grid. It was found that the cost of energy for the off-grid system is USD 0.25/kWh for three different sectors: residential consumption, agriculture electricity consumption, and commercial consumption [75]. The calculation was made by taking their consumption of the diesel-based electricity, and assuming a power density of 400 kW/ha; ha is hectare (100 m^2 by 100 m^2 (a total of 2 MW for 5 ha plot)) [75]. The cost of energy for grid-tied systems is determined by the percentage of renewable energy that is supplied overall. Based on a study that looked at the cost of energy for both grid-tied and off-grid systems and found that the cost of energy in Dubai without any contribution from renewables was USD 0.08/kWh, the findings indicated that the cost of energy would increase by 2% at a percentage of 10% renewable energy and continue to decrease as more renewable energy is used; at 68% renewable energy, the cost of energy will be the lowest value needed to achieve a 12% reduction. Because the energy storage system is expensive, the off-grid system's energy costs are around 84% higher [76]. A study was conducted in Ghana to investigate a grid-tied 2.5 MW solar PV power plant [77]. The LCOE is around USD 0.24/kWh, with a 70% performance ratio of the plant, a 3547 MWh average yearly energy yield, a 16% capacity factor, 3852 metric tons of carbon dioxide emissions prevented, and system efficiency of around 97% [77]. A study investigated the financials of ground-mounted solar panels based on parameters such as payback period, net present value (NPV), and amount of greenhouse gas emission [78]. Four sites were created to calculate the payback period [78]. The existing sites were divided based on the payback period. The shortest period was recorded for a site with a 6.7-year payback period and was chosen as the best site to build a 10 MW solar panel plant [78]. Building a 10 MW power plant would surpass the release of around 10,000 tons of greenhouse gases yearly [78]. Another study investigated the rooftop solar panels' economics compared to ground-mounted ones [79]. The rooftop configuration was found to increase the capacity utilization factor by 2.9% and decrease the LCOE by 23.7%. Rooftop solar panels also provide shading and help the building's cooling energy requirements [79]. Such a comparative study opens the door to more work to estimate the LCOE of different solar panel systems accurately.

5.2. Operating and Maintenance (O&M) Costs

A study investigated the O&M costs of different ground cover for agrivoltaics based on data collected from 2019 to 2020 [80]. The data collection was performed from solar PV owners, O&M operators of service providers, vegetation maintenance companies, and solar grazers [80]. The analysis contained the mean cost, either calculated as USD/acre/yr or USD/kW_{dc}/yr for the different types [80]. Results showed that the mean cost for the vegetation for 28 different sites was around USD 350/acre/yr and USD 2.23/kW_{dc}/yr, the sheep grazing for 15 different sites was around USD 300/acre/yr and USD 1.55/kW_{dc}/yr, the turfgrass for 9 sites was around USD 265/acre/yr and USD 1.51/kW_{dc}/yr, and USD 293/acre/yr and USD 1.75/kW_{dc}/yr for the gravel in 2 sites [80].

5.3. Crop Yields

The crop yield income, the land cost, and the feed-in Tariff are investigated for the agrivoltaic systems, and the results showed that the costs for the agrivoltaic are currently slightly higher than the ground-mounted solar panels [81]. However, this can be improved by following some steps in agrivoltaic systems developments, such as for the land preservation cost compensation; high-revenue crops should be selected with low solar panel array densities (land costs are relatively lower than panels costs) [81]. Also, the standard density of panels should be followed with the low revenue crops even if land cost is small, and if the land costs are high, agrivoltaic cost shows high sensitivity for panel-to-land cost [81]. The analysis included most cases for the agrivoltaic systems' economics. However, land preservation costs might change in the future, and new mounting practices might be found to lower the total cost of the agrivoltaic systems. Crop type and panel orientation must be selected wisely to reduce the system's total cost [81]. In many sizes, from residential to industrial, the levelized cost of energy (LCOE) is already lower than the cost of grid electricity after net metering [73]. Two hypotheses were proved by a study conducted in Poland and Ukraine on ground-mounted PV panels and crop cultivation. The first hypothesis is that the net present value of the PV projects is higher than the crop cultivation ones [82]. However, the profitability of PV projects is lower than farm practices. The second hypothesis is that the PV system in Poland has higher savings in carbon dioxide than in Ukraine [82]. The study recommended that more financial studies should be performed on the "agro-photovoltaic systems" as they have a promising future [82]. One of the agrivoltaic performance indicators is the land equivalent ratio (LER); it represents the summation of the yearly energy yield in agrivoltaics to the open area ratio with the yearly crop yield in agrivoltaics to open area ratio. The land equivalent ratio can be represented by Equation (3) [83]:

$$\mathrm{LER} = \underbrace{\frac{\mathrm{YEY_{Agr}}}{\mathrm{YEY_{open}}}}_{\text{energy ratio}} + \underbrace{\frac{\mathrm{YCY_{Agr}}}{\mathrm{YCY_{open}}}}_{\text{crop ratio}} \tag{3}$$

where $\mathrm{YEY_{Agr}}$ is the yearly energy yield of the panels in agrivoltaics, $\mathrm{YCY_{Agr}}$ is the yearly crop yield in agrivoltaics, $\mathrm{YEY_{open}}$ yearly energy yield in open areas without crops, $\mathrm{YCY_{open}}$ is the yearly crop yield in open areas [83]. Comparison of Land Equivalent Ratio (LER) values between agrivoltaic systems and conventional agricultural conditions are shown in Table 2.

Table 2. Performance of the energy and crop integration for different land equivalent ratio (LER).

LER = 1	The agrivoltaics and the normal condition are showing the same results.
LER > 1	Agrivoltaics is showing better results than normal conditions.
LER < 1	The normal conditions are showing better results than agrivoltaics.

In the UK, a study investigated the land equivalent ratio of a vertical and tilted agrivoltaic system [84]. Results showed that the LERs were 0.91 and 1.52 for the vertical and tilted agrivoltaic, respectively [84]. Tilted agrivoltaic achieved a LER above 1 across all regions [84]. The levelized cost of the energy for agrivoltaics ($\mathrm{LCOE_{Agr}}$) has a close expression to the ground-mounted PV panels with the addition of other factors as expressed in Equation (4) [83]:

$$\mathrm{LCOE_{Agr}} = \frac{\mathrm{C_{PV}}}{\sum_0^{\mathrm{N}} \frac{\mathrm{YEY_n}}{(1+\mathrm{dr})^{\mathrm{n}}}} \tag{4}$$

where $\mathrm{C_{PV}}$ is the total cost of the PV panels.

A work has analyzed the agrivoltaic economy compared to ground-mounted PV panels. The study investigated different types of crops under the fixed tilt bifacial panels oriented north–south (N–S) or east–west (E–W) [81]. The extra revenue of the agrivoltaics comes from the crops, which offsets the total profit from the ground-mounted PV panels, as shown in Equation (5) [81]:

$$P_{\mathrm{Agr}} + P_{\mathrm{Crops}} \geq P_{\mathrm{GR-PV}} \tag{5}$$

where P_{Agr} represents the energy profit coming from the agrivoltaics, P_{Crops} is the crop revenues, $P_{\mathrm{GR-PV}}$ is the ground-mounted PV panels revenue [81].

5.4. Energy Generation

Maximizing energy generation will always enhance the cost if feasible methods are used. An investigation was conducted on the impact of installation conditions on the energy generation and economic feasibility of bifacial photovoltaic power plants in Germany [85]. The focus is on maximizing field design elements like row spacing, module elevation, tilt angle, and soil reflectivity for fixed-tilt and tracked bifacial PV panels [85]. The analysis also involves calculating the levelized cost of energy (LCOE) for different systems [85]. The LCOE is higher by 5–11% for a single-axis tracked PV system with an east–west axis whose modules follow the elevation angle of the sun (elevation-tracked) than a single-axis tracked PV system with a north–south axis whose modules follow the azimuth angle of the sun (azimuth-tracked) [85]. The lowest LCOE could be achieved when the solar panels are installed on a fixed tilt [85]. By changing the tilt and azimuth angles to an optimum position monthly, it was found energy generation would be increased by 4.01% [86]. More investigation is needed to analyze the cost of the agrivoltaic systems, taking into consideration all factors and any savings that could contribute to reducing the system's total cost and accurately estimating this system's costs.

6. Wind Impact on Agrivoltaics

Agrivoltaics is an integration of ground-mounted solar panels with agricultural lands. Ground-mounted solar panels face challenges in resilience to the wind, specifically the high-speed wind, such as hurricanes and tornados. Studying the wind is crucial for the safety of the land in a different shape of exploitation, such as croplands and livestock farms. Agrivoltaics in the greenhouses could be treated as roof-mounted solar panel designs. In this section, the design wind load standards, Computational Fluid Dynamics simulations and wind tunnel testing, dynamic response of PV panel supports, and current wind load mitigation methods are analyzed.

6.1. Wind Load Design Standards Analysis

A study examines the challenges associated with wind load design for ground-mounted PV power plants in Romania and makes a comparison between the wind tunnel test settings and those specified by the wind design codes of Romania, Germany, Europe, and the United States [87]. Development of the design code requirements from 1990, 2004, and 2012 is also analyzed for wind load design in Romania [87]. Different outcomes are obtained when the internal resultants for the PV panel's structural elements are evaluated while taking the force and pressure coefficients into account. Additional code explanations and design standards are needed for PV power plant wind design [87]. The findings indicate that pressure coefficients are the sole factors used in wind design in the German, American, and older versions of the Romanian wind load design code. Using one category of coefficients with unique safety requirements for various structural components may be a preferable option than using two [87]. A paper highlighted the Computational Fluid Dynamic (CFD) simulations for predicting design wind loads for ground-mounted solar arrays by comparing the pressure coefficients found by the CFD simulations to the ASCE design standards along with the drag and lift coefficient investigated [88]. For ASCE 7-10, the removal of the important factor, along with the improved design wind speed, increased the design wind pressure by approximately 48% when compared to ASCE 7-05 in the Puerto Rico site [88]. When comparing the wind loads determined from the ASCE 7-05 standard requirements with those from the CFD simulations, the results were noticeably higher [88]. The solar panels were probably designed with those provisions in mind. In the actual situation, this remark is accurate [88]. In the CFD calculations for one of the study phases, the panel still produces larger loads even with the improved standard provisions (ASCE 7-16), indicating that more adjustments to the standard are required [88].

Research that addressed the rigid structure description in the standard ASCE 7-16 provided a clear technique for calculating the design wind loads for multi-row ground-mounted solar arrays. This method included both static and dynamic wind load coefficients that were compliant with ASCE 7 [89]. This study has looked at two load effects: the moment of the panel center line and the normal force, also known as net pressure normal to the top surface of the panels. The mean, RMS, and peak coefficients from the wind tunnel are displayed first, followed by the collected wind tunnel data related to these load effects for the two aerodynamic zones (perimeter and field). Additionally, the tilt angles (ω) are categorized into one of three ranges: $0° \leq \omega \leq 5°$, $\omega = 10°$, or $20° \leq \omega \leq 60°$ [89]. However, the study's scope was quite narrow, and it omitted certain crucial characteristics and discoveries that may have contributed to the solar panels' robust construction. There is no comparison with the standard.

6.2. Example Analysis: A Comparison between ASCE 7-16 Wind Load and Wind Tunnel Test Results

To support the claim that the ASCE versions underestimate the wind loads and the wind tunnel test is more accurate, a comparison is made for the same solar panel's location and specifications. The wind loads are calculated based on the ASCE 7-16, and the wind tunnel results are taken from the literature [90]. ASCE 7-16 has not specified a chapter for calculating the design wind pressure for ground-mounted solar panels. However, solar panels could be considered a solid sign for a tilt angle greater than 45° and an open building with a monoslope roof for a tilt angle less than 45° in ASCE 7-16. Table 3 shows the specifications of the panels and the case properties.

Table 3. Wind calculation data and panel specifications.

Risk	**Category I**
Terrain	Category II
Panel Width (Wp)	1.55 m = 5.08 ft
Panel Length (Lp)	3.3 m = 10.82 ft
Panel Mounting Height	1.44 m = 4.59 ft
Tilt Angle	25–45°

Design wind pressure for ground-mounted solar panels will be taken for the open building with monoslope roof since the tilt angle is less than 45° and can be found by Equation (6) [91]:

$$p = qh(GC_N)\left(\frac{N}{m^2}\right) \tag{6}$$

where qh is velocity pressure at mean panel height in (N/m^2), given by the Equation (7) [91]:

$$q_h = 0.613K_hK_{hg}K_dK_eV^2 \tag{7}$$

where K_h is the velocity pressure exposure coefficient, K_{hg} is the topographic factor, K_d is the wind directionality factor, V is the basic wind speed (m/s), K_e is the ground elevation factor. The variables and assumptions made for finding the design wind pressure are listed in Table 4, with the assumption of a wind tunnel speed of 25 m/s [91].

Table 4. The parameters in equations and assumptions for finding the wind pressure based on the ASCE 7-16 standard.

Parameter	Assumption	ASCE Chapter
Risk category	I	Table 1.5-1
V, basic wind speed (mph)	84.15	Example wind speed
Exposure Category	C	Section 26.7
Kd, the wind directionality factor	0.85	Table 26.6-1
Ke, the ground elevation factor	0.982	Table 26.9-1
Khg, the topographic factor	1	Figure 26.8-1
Kh, the velocity pressure exposure coefficient	0.85	Table 26.10-1
G, Gust Factor	0.85	Section 26.11

After that, the net pressure coefficient values were found from ASCE 7 for a tilt angle of 25° less than 45° since the tilt angle and the values are shown in Table 5 [91].

Table 5. Net pressure coefficient for tilt angle < 45°.

Tilt Angle	Load Case	$\gamma = 0°$		$\gamma = 180°$	
		CNW	CNL	CNW	CNL
25°	A	−1.60	−1.67	1.83	1.90
	B	−2.43	−0.36	2.33	0.79
45°	A	−1.60	−1.80	2.20	2.50
	B	−2.30	−0.70	2.60	1.40

By comparing the pressure coefficients that are calculated by the ASCE 7-10 and 7-16 standards with the wind tunnel results [90] for 45°, as shown in Figure 6, measured by the experiment, it can be proved that the standard underestimates the wind pressure and force on the ground-mounted solar panels by around 9% and the edits made to ASCE 7-22 should include more parameters to obtain an accurate estimate of the wind load for the ground-mounted solar panels.

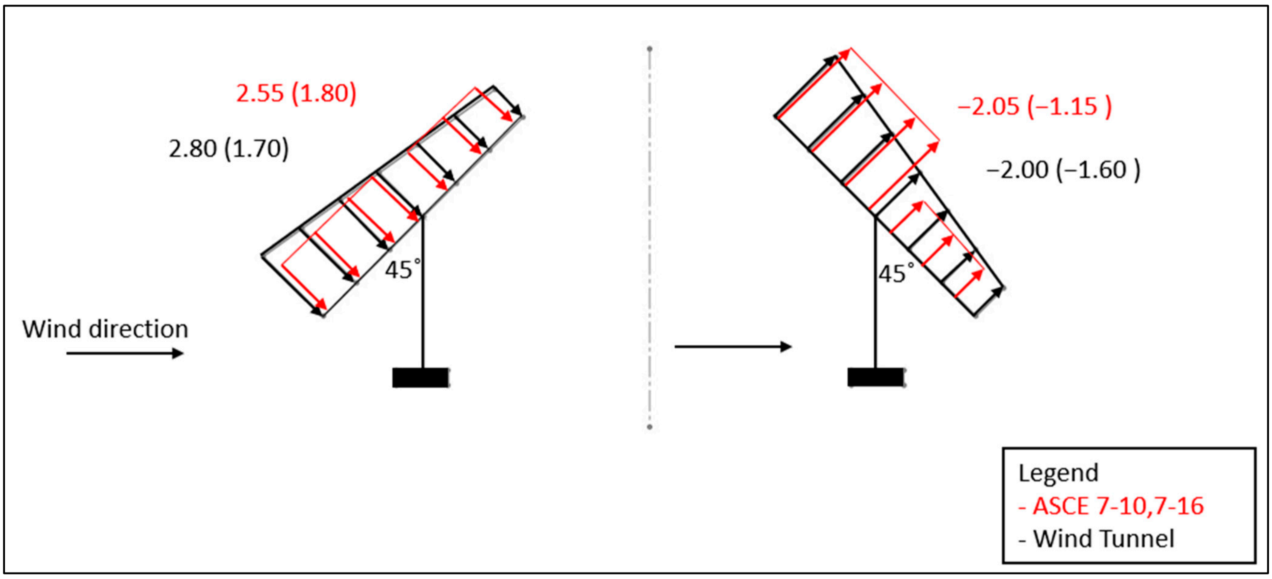


Figure 6. Comparison between two solar panels' wind load based on the wind tunnel test and ASCE 7 at 45° stow angle.

However, for 25° tilted panels, as shown in Figure 7, the same comparison was performed, and the ASCE wind load coefficients were higher than the wind tunnel test coefficient by around 30%. This shows the discrepancy that happens for the load calculations of the ASCE standard when the tilt angle of the panel is larger.

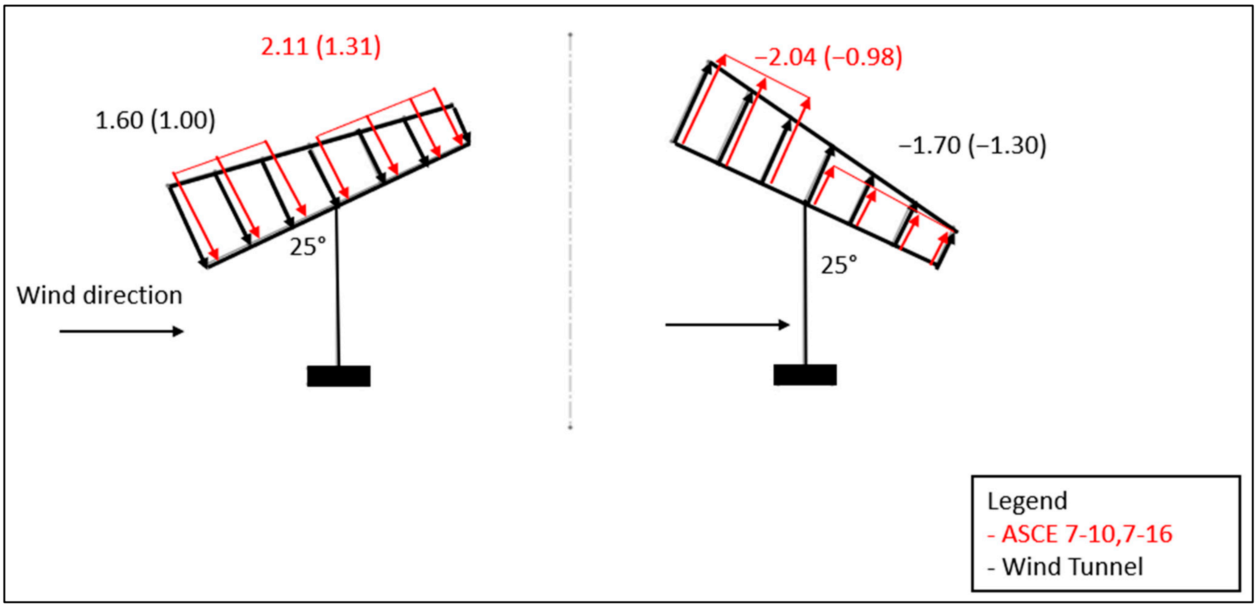


Figure 7. Comparison between two solar panels' wind load based on the wind tunnel test and ASCE 7 at 25° stow angle.

The comparison findings indicate that there are differences in the estimation of wind loads based on wind tunnel testing and ASCE standards. It is recommended that the solar panel scaling be improved for the wind tunnel test to provide more precise wind load values. Additionally, ASCE standards must be updated, and design loads for ground-mounted solar panels, whether single or in a row, must consider the wind tunnel results for the wind loads on solar panels. Future work should have precise findings determined by updated wind tunnel testing accuracy and amended ASCE standards with wind tunnel data supplied to guarantee a safer design for the solar panels.

6.3. Computational Fluid Dynamic (CFD) Simulations and Wind Tunnel Testing

The purpose of wind tunnel testing for solar arrays is to find the pressure coefficients and the type of failures that occur in the structure, such as torsional galloping and flutter derivatives [92]. In Australia, wind tunnel testing was carried out on a one-twentieth-scale wind tunnel model of solar panel arrays. The inclination angle was 20° [93]. The upward and downward pressures were measured at the leading edge of the panel for the wind blowing toward the bottom surface and toward the top surface, respectively [93]. The aerodynamic shape factor was given to the Australian wind load codes [93]. The results declared the angles of the largest net positive (downward) pressures and the largest net negative (upward) pressures were experienced on the bottom leading corner of the panel (320°) and on the leading corner of the panel (220°) [93]. A study used Computational Fluid Dynamic (CFD) simulations to calculate the resilience and deformation of PV panels under static wind stress. The study concluded that the average stress at the panel surface for 32 m/s wind speed is 1415 Pa, 42 m/s wind speed is 4379 Pa, and 50 m/s wind speed is 15,142 Pa, and installing thin-film photovoltaic panels at wind speeds higher than 32 m/s was not recommended [94]. It is also not possible to build a solar panel using crystalline technology at wind speeds higher than 42 m/s [94]. The displacement at a wind speed of 50 m/s is exceptionally high, roughly 2.5 times that of 32 m/s and 42 m/s [94]. A study examined the flexible solar panel systems' aerodynamic properties and wind-induced reactions [95]. According to the findings, flutter, vortex shedding, and chattering were examples of the aerodynamic instability encountered by the cable plate structure system with a highly flexible and nonlinear vibration [95]. Numerical calculations and wind tunnel tests were considered when studying flexible solar panels [95]. Scaling is a problem in wind tunnel testing, and numerical solutions are more effective and less expensive [95]. The study, however, needs to confirm how well the numerical simulation works or how it varies from wind tunnel testing. The flexible solar panel system's wind-induced reaction and aerodynamic properties were demonstrated by the wind direction angle and panel tilt angle [95]. A study was conducted to determine the wind loads on the PV panels using Computational Fluid Dynamic (CFD) methodology, which involved the use of Navier–Stokes equations [96]. The solar panels have dimensions of 1 meter by 2 meters by 50 mm, and the total dimensions of the array are 6 m by 4 m [96]. The objective is to determine the forces exerted on various inclinations (tilt), ranging from 10° to 60° for 90° and −90° wind attack angle [96]. Results proved that higher tilt angles cause higher net pressure, lift, and drag coefficients for different Navier–Stokes equation conditions [96]. The net pressure varies between 0.610 and 2.488, the drag coefficient ranges from 0.106 to 2.155, and the lift coefficient ranges from −0.601 to 1.244 for tilt angles ranging from 10° to 60° and wind attack angles ranging from 90° to −90° [96]. As per recommendations for preventing any potential damage, the panels should be safely installed at presented specific values within these ranges [96]. An array of solar panels tilted at a 30° angle was the focus of the study to investigate multiple mounting choices, temperature distribution, and energy output [97]. Based on the Computational Fluid Dynamic model, the results indicate that the vertical bifacial module's overall efficiency was higher than that of the ground-mounted modules because of lower average temperatures [97]. However, the scope of the study concentrated on the temperature distribution of the bifacial solar panels and ignored the wind problems that could happen in vertical mounting.

Part of the research focuses on finding the pressure coefficients or the critical velocities at which the wind causes damage by several phenomena, such as torsional galloping and flutter derivatives. This kind of research is reviewed in the following section.

6.4. Dynamic Response of Solar Panel Supports

Several phenomena occur to the structures due to high-speed wind and cause severe damage in some cases based on the resilience of the design and how strong the wind is. Galloping, fluttering, and vortex shedding are popular phenomena that happen in multiple locations around the world.

6.4.1. Galloping and Vortex Shedding

Galloping is an aeroelastic instability that incites oscillatory motion of elastic structures when subjected to an incident flow and for investigating the galloping oscillator behavior by the high frequency excitation [98]. Equation (8) represents the torsional galloping that happens to the solar trackers shown in Figure 8 [99]:

$$I_0\ddot{\theta} + 2I_0\zeta\omega_0\dot{\theta} + k_0\theta = M \tag{8}$$

where I_0 is the torsional inertia, ω_0 is the natural torsional frequency, ζ is damping coefficient, θ is the angular displacement variable, k_0 is the torsional stiffness, M is the aerodynamic torque and can be written as a function of flutter derivatives by Equation (9) [99]:

$$M = \frac{1}{2}\rho_a U C^3 \left(K\frac{C}{U}\, A_2^*\dot{\theta} + K^2 A_3^*\theta \right) \tag{9}$$

where ρ_a is the density of air, A_2^* and A_3^* are the aerodynamic flutter derivatives and function of the reduced velocity, U is the wind speed, C is the characteristic length (chord) [99].

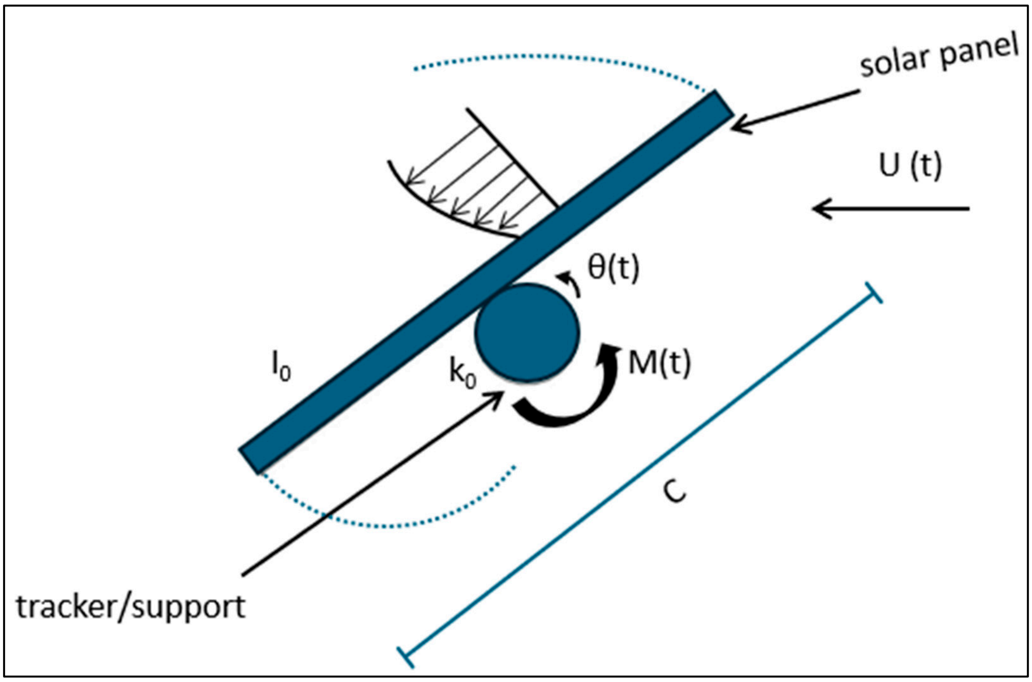


Figure 8. Representation of torsional galloping in solar trackers.

To deal with high-speed wind, current solar trackers, such as the solar farm technique covered in the last section of the paper, are made to change to the flat position when they detect specific wind speeds. Nevertheless, there are situations when this method is invalid and can lead to a structural collapse. Galloping was observed in different solar farms where the wind is a major problem to that location. Multiple studies analyzed the galloping at the solar trackers and provided a scenario of the damage that can occur based on the case. In Spain, a study was conducted to test the single-axis solar panel trackers prototype for experiencing aerodynamic instabilities due to high-speed wind [100]. The experimental testing showed that as the velocity increases, small vibrations can be observed due to vortex separation or turbulence [100]. The oscillations were observed under the wind load to the prototype of solar panels with the tracker at 25° tilt angle due to the torsional galloping or single degree of freedom of torsional flutter [100]. The aeroelastic interaction of vortex shedding at the edges of the panel causes galloping [100]. Flutter happens between the deformation and the fluid dynamic forces, and it occurs by the interaction between the torsion and bending [100]. It is not observed that flutter happened at the panels after the experiment while galloping was observed in the type of the torsional galloping [100]. Solar trackers are exposed to experience galloping or any other wind-induced phenomena if they are not protected properly. An investigation is conducted into the malfunction of a solar tracker caused by torsional galloping. A field analysis was conducted on the damaged structure shown in Figure 9, and subsequently, a numerical model of the structure was constructed [101].

The numerical model is built to determine the maximal stresses in the various components of the solar tracker and the natural frequencies of the structure [101]. The numerical analysis validated that torsional galloping, which happened in the presence of high-velocity winds and a zero-degree inclination angle of the solar tracker, was the root cause of the failure [101]. The nature of the fluid–structure interaction and torsional instability of a single-axis solar tracker was examined using a CFD model [102]. Testing in the wind tunnel revealed strong instability and a limited capacity to influence the vortices' aerodynamics [102]. With a small dependence on stiffness and damping (3–15%) to reduce the instability observed by the CFD model, the wind tunnel findings and the CFD model showed good agreement [102]. The vortex formed at the leading edge of the tracker creates a moment of the center chord. With the increase in the flow separation, the panels are twisted, and the tracker moves to the other side of the panels; another vortex forms, and the same happens repeatedly, causing the torsional galloping instability [102]. The results showed that in strong winds, solar trackers could avoid torsional galloping if the panels were placed at an incline (tilt angle > 0°) at wind speeds around 40 m/s [102]. However, higher tilt angles of the panels also experience buffeting in the interior array due to increasing static loads and dynamic excitation [102].

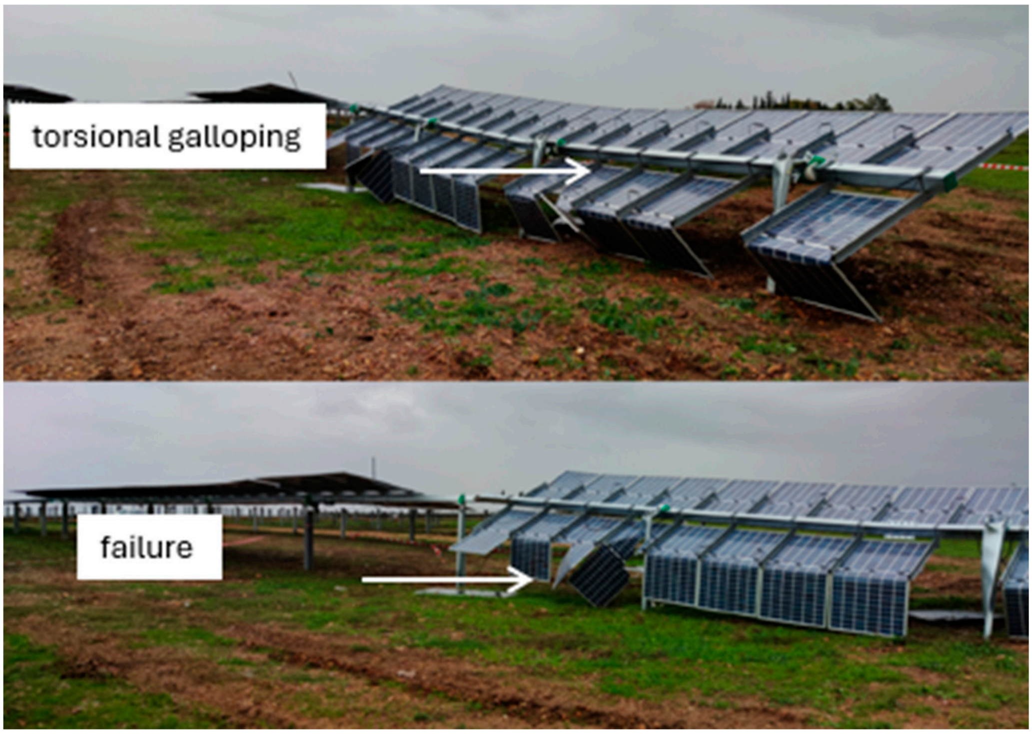


Figure 9. The solar trackers experience torsional galloping failure in the structure due to exposure to high-speed wind [101].

Multiple studies were concerned with studying the solar panel's failure due to wind, either by performing experimental studies, simulation-based studies, or both. Torsional instability is the main cause of single-axis tracker failures, which frequently happen at wind speeds lower than the site design wind speed and small tilt angles [103]. This instability has been the main cause of failures over the last ten years [103]. A study used the Delayed Detached-Eddy Simulation in modeling the turbulence and capturing the flow separation behind the panel [104]. Vorticity contours on the central plane and velocity vectors are used to study the formation of transient flow structures [104]. The interaction of the vortex shed from the inclined panel's leading edge close to the ground is investigated [104]. Results showed that the counter-rotating vortex created by the shedding vortex is visible at the ground during the flow-building stage, and as it grows, the shedding vortex traps it inside the wake zone [104]. An investigation of the panel's structures for vortex shedding was performed. The study used large-eddy simulations for analyzing the vortex shedding and the flow separation around the solar panels [105]. The results showed that three cases describe the vortex shedding and the flow separation [105]. In the first case, at a tilt angle of 10°, vortices are shed at the leading edge with no flow separation [105]. In the second case, at a tilt angle range of (10–35°), the vortex shedding is controlled by a large-scale structure operating at low frequencies, wherein the less energetic leading- and tailing-edge vortices are shed at higher frequencies [105]. In the third case, at a tilt angle range of (35–60°), because of the structure's closeness to the bottom, non-symmetric vortex shedding completely separates the flow on the suction side [105].

The studies established that solar trackers are exposed to vortex shedding and torsional galloping at specific wind speeds. A tilt angle is crucial for preventing instability from happening. The tilt angle selection is limited by having the maximum power generation and safety of the tracker. Small tilt angles are better than zero (flat position) in the case of torsional galloping. Higher tilt angles cause vortex shedding, which may result in torsional galloping at the end. Future research should be directed to find the needed modifications for the design of the trackers, study the instabilities in wind tunnels and CFD simulations for accurate designs, and find the optimum tilt angles for generating the maximum power generation and the safer design against wind.

6.4.2. Flutter and Fluid–Structure Interaction

Another type of wind-induced phenomenon that could be a factor in solar panel instability failures is the flutter, which can be a type of fluid–structure interaction. Flutter commonly occurs at the wind turbine blade, bridge decks, and aircraft wings. It can be described as vibration instability due to the interaction between the fluid and the elastic structure, which may cause structural failure [106]. In wind engineering, "flutter" refers to a dangerous and potentially destructive vibration phenomenon that can occur in structures subjected to wind forces. The so-called "flutter derivatives" are frequently used in the frequency domain to characterize unstable transverse wind forces on bridge sections during oscillatory motion [107]. Many techniques have been used, with wind tunnel studies, to analyze the aerodynamic instability of long-span bridges since the original Tacoma Narrow Bridge collapsed at half of its design wind speed. The bridge was only intended to handle static wind stress [108]. Throughout history, flutter control has been a goal, and how to stabilize the linked flutter instability depends on torsional vibration mode change or heaving [109].

Some studies show that fixed or tracking solar panels have experienced flutter and vortex shedding. A numerical model was built by the fluid flow control equations of the solar panel supporting system to find the simulation of aerodynamic characteristics of the supporting system, and then the CFD model provided the pressure results [110]. These values were loaded and coupled to the front and back of the panels. The study concluded the types of aerodynamic instabilities affecting the supporting system of the panels. Firstly, in a flat panel solar supporting system, the average wind pressure and direction have minimal effect on the modal frequency [110]. When designing a structure, low-order vibration should primarily be considered in the system's supporting components, but high-order vibration should typically be considered when assessing the vibrating risk of the solar panel [110]. Secondly, the flat panel solar supporting system's first six modal frequencies, when combined with fluid–structure interaction, are all marginally lower than the free modal frequencies [110]. Finally, the wind load perpendicular to the solar panel has the most impact on the solar supporting system, even when the wind speed is the same. The wind pressure and distribution of the solar panel vary with various wind directions [110].

A numerical approach simulates the fluid–structure interaction between the solar panels and the atmospheric boundary layer with a moving mesh. The results indicate that the fluid dynamic effect is what causes the flutter, the torsional galloping is caused by the leading-edge vortex formation, positive vorticity feedback linked to the initial deflection, and the growth and release of subsequent horseshoe vortical structures from the panel's sun-facing surface with the supporting torque tube's torsional stiffness [111]. In the Philippines, a low-rise gabled structure equipped with solar panels positioned on the roof has a Fluid Structure Interaction (FSI) in place [112]. A Computational Fluid Dynamics (CFD) study was used to simulate typhoon-force winds on this building [112]. The same building also underwent building energy simulation (BES) to consider solar PV energy generation and energy consumption [112]. The FSI findings displayed the areas of failure in the panels concerning installation position [112]. However, BES studies indicated that a building oriented at 90° with a roof pitch of 14° has the maximum potential for electricity generation [112]. It was advised to put the panel system configuration on a roof with a 26° pitch to support occupancy loads [112]. This framework, which integrates building energy performance with energy systems resilience, can assist the stakeholders in correctly planning and designing better infrastructures that are robust to disasters [112]. Another investigation was conducted to see how 30 panels rowing in two solar tracker configurations behaved when exposed to torsional divergence, vortex shedding, and flutter. The wind tunnel testing was to investigate the effects of different angles of attack and damping ratios of a spring mass system utilized for flutter derivatives [113]. The experiments did not demonstrate that torsional divergence affected the solar panels model, and the model's structure remained stable at high wind speeds of up to 55 m/s [113]. The flutter investigation started with a complicated experimental configuration that made it possible to assign two smaller models of the panels in the test chamber simultaneously to find all 18 flutter derivatives between the up- and downwind models [113]. Most of the studies focused on describing the wind-induced phenomena that solar panels experience in the case of high-speed wind locations. These phenomena could be explained or mitigated by analyzing the factors affecting the wind loads, such as damping and the mass of the panels, the wind direction and tilt angles, and aerodynamic edge modification.

7. Factors Affecting Wind Loads

7.1. Increasing Damping and Mass

For more resilient structures, increasing damping and mass has always been one of the solutions that might help the structure. Increasing dampers to absorb and disperse this energy or purposefully increasing mass to alter the dynamic response of solar panels are common solutions to fluttering or galloping problems. A full understanding of the physics behind this unstable occurrence might greatly help design decisions in both scenarios. Prior attempts to simulate such physics have concentrated on two-dimensional panel sections, which represent the vorticity's generation and shedding but ignore complicated three-dimensional interactions and material characteristics [102,111]. For the multi-panel solar array, a passive vibration-damping device is implemented for testing [114]. It also assures the solar array has original features, such as solar tracking, folding, and deploying [114]. Passive damping is provided via a viscous damper at the top strut [114]. Results from experiments and analysis support the usefulness of this parallel damping technique. The characteristics of the damping device are examined using the finite element models [114]. The results show that there is an optimal value for the damping coefficient and that, in cases where the initial structural damping ratio was low, passive vibration control significantly increases the modal damping ratio [114]. A particular kind of satellite solar array's passive damping mechanism was created. The findings of the simulation confirm that the real viscous damper can achieve the criteria and significantly increase the modal damping ratio [114]. The related tests, which use a test sample of a solar array, show that the passive damping device has a significant damping effect at large vibrations [114]. The damper has no damping effect when the vibration is minor, although it can help to reduce vibration [114]. The viscous damper design may be further enhanced for use in damping device applications in the future, particularly in reducing its static friction force. Further research with a genuine solar array will also help obtain further findings [114].

For another study to find the effect of the passive vibration control on the spacecraft solar panels, install dampers at the end of the solar panels to dissipate the dynamic energy in the translational root mounting method [115]. This method allows for translational freedom instead of rotational freedom [115]. As a result of this mode shape modification, the dampers will have room for working stroke without reducing the panel's frequency [115]. This method can be applied to solar panels in agrivoltaic systems; however, no previous work was performed with such methodology [115]. The ground-mounted solar panels could have dampers and springs in the middle of the panel and investigate the stability of the panel against the wind [115]. More research work needs to be performed in this field, and tests should be performed on the solar panels after adding dampers and mass.

7.2. Wind Direction and Tilt Angles of Solar Panels

The tilt angle of the solar panels (β) has a major impact on the power generation as well as the wind load. Tilt angle (β) could be defined as the angle between the horizontal line of the bottom edge and the panel, and the wind direction angle (α) is the wind attack angle of the panel, as shown in Figure 10.

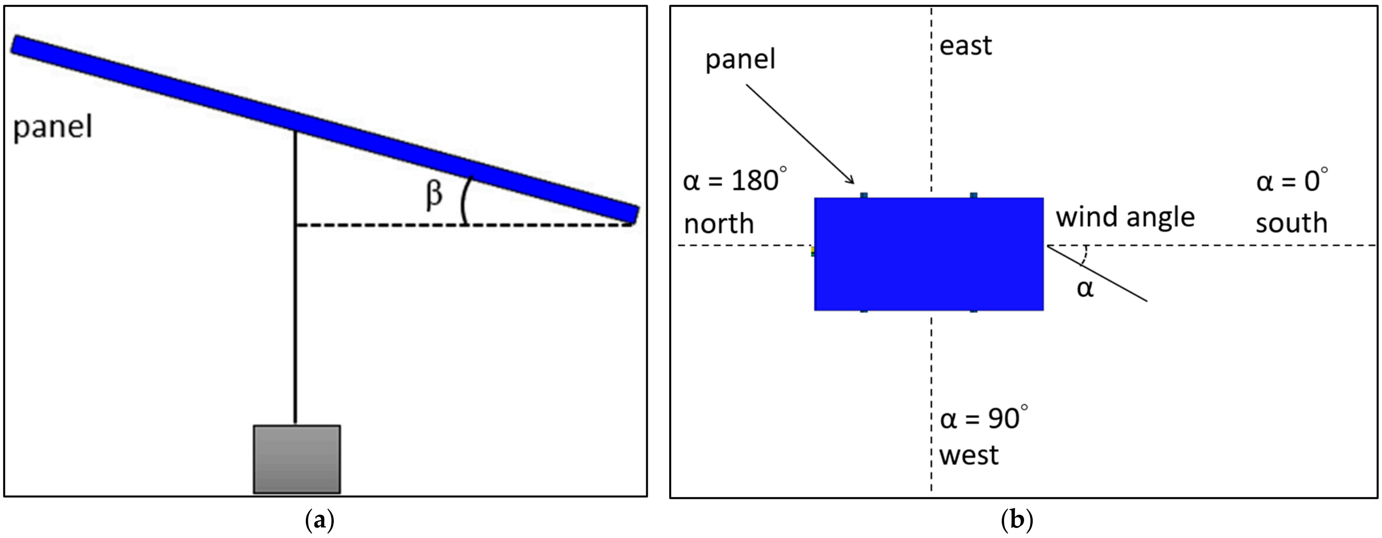


Figure 10. (**a**) Tilt angle (β) representation in a left view of a solar panel. (**b**) Wind angle representation of a top view of solar panel.

The effects of tilt and wind direction angles on ground-mounted solar panels have been investigated numerically and experimentally [90]. Two tilt angles, 25° and 45°, were tested, and the wind directions ranged in steps of 30° from 0° to 180° [90]. In the wind tunnel, the static pressure, velocity, and turbulence intensities were measured [90]. The findings found that greater tilt angles led to increased velocity zone shedding frequencies and stronger vortex shedding [90]. The same was true for the flow structure; it was shown that the panel angles and wind direction affect the design wind loads on the solar panel [90]. The higher the panel tilt angle, the greater the net pressure coefficients of the solar panel. In terms of overturning moments, the crucial wind directions were determined to be 30° and 150° while the critical wind directions for uplift and drag were 180° and 0°, respectively [90]. The experimental results and the numerical results of the wind loads agreed well [90].

A study investigated the wind load for a different tilt angle ranging from 10° to 80° to 0° and 180° wind angles [116]. The vortex formed at the corner of the panel caused a greater lift force on the right half of the inclined panel [116]. A study investigated the tilt angle effect on the wind loads using large-eddy simulations [105]. The results showed that at β = 10°, leading-edge vortices are shed and distributed along the panel's surface without significant flow separation; at β = 10–35°, a low-frequency large-scale structure dominates vortex shedding, with less-energetic trailing- and leading-edge vortices shed at higher frequencies; at β = 35–60°, non-symmetric vortex shedding fully separates the flow on the suction side due to the proximity to the ground [105]. However, the study failed to provide a new, safer design for the solar panels or an innovative solution to the aerodynamic instabilities. Also, the findings need to be validated by wind tunnel experiments as the accuracy of the CFD simulations is not enough to make the judgment.

A comparison was made between the annual worldwide irradiation incident on a panel at this optimal orientation, the solar radiation received by a two-axis tracking panel, and a flat horizontal panel [117]. The radiation at the optimal constant tilt rose by 10% to 25% annually as latitude increased, compared to the worldwide horizontal irradiation [117]. A two-axis tracking panel's annual radiation incidence was 25–45% greater than that of a panel at its ideal fixed orientation [117]. The southern states, where radiation was already high, had the largest increases in tracking radiation, resulting in yearly radiation of more than 3.4 MWh m^{-2} [117]. In the UK, the effect of wind direction on the overall performance of a utility-scale PV facility was investigated for the Hadley solar farm [118]. The solar PV facility has a fixed-tilt setup, with the PV panels angled 20° southward [118]. The expectation was that if all other variables, including solar irradiance, ambient temperature, and wind speed, remained constant, the overall power generation of a solar photovoltaic plant would increase when the wind blows from the south [118]. A total of 42 pairs with two cases with equal solar irradiance, ambient temperature, and wind speeds but different wind directions—winds blowing from the north in one case and from the south in the other [118]. All 42 pairs confirmed that wind blowing from the south always resulted in higher power output from the solar PV facility [118]. As a result of the study, it was found that to choose the best location for a solar PV facility, wind direction and wind speed frequencies must be considered in addition to other environmental considerations [118]. The amount of electricity that can be collected from the PV panels increases with the frequency of southerly winds [118]. The study's second useful finding is that power production increased by 24% for the south wind blowing, and locations facing west–east are better for fixed-tilt solar PV plant construction [118]. The study analyzed the impact of the wind direction on the power production of the PV panels. However, the scope of the studies should include the wind loads on the different panel configurations, which restrict the freedom to choose the angles, and they should focus on the best installation angles for facing strong winds.

An investigation was conducted into a model using a 1:200 geometric scale model of solar panel implementation. Three model panels were outfitted with 36 pressure taps on each surface [119]. Several configurations were examined to determine the impact of the panel's inclination and the significant wind direction angles [119]. It was determined that wind direction has a considerable impact, with a wind direction of 135° being the most important [119]. Extreme pressure coefficient values often fall between 105° and 180° [119]. Panel inclination has an effect, but only in critical wind directions [119]. A study used a Reynolds-Averaged Navier–Stokes (RANS) numerical approach to analyze the impact of wind on a standalone ground-mounted photovoltaic (PV) system under different wind directions [120]. It was found that wind loads are greatest near the leading edge of the solar panels regardless of wind direction [120]. Specifically, symmetrical wind load distributions and wake structures were observed for wind directions of 0° and 180°, and asymmetrical distributions, leading to higher overturning moments, were noted for 45° and 135° wind directions, which were identified as critical for causing maximum overturning moments [120]. The study also showed that no vortex shedding was observed, a limitation of the RANS approach, although corner vortices were present for 45° and 135° directions [120]. The calculated drag and lift coefficients aligned reasonably with the minimum design loads for monoslope-free roofs as specified by ASCE 7-10 standards, suggesting these standards can be cautiously applied to solar panels under certain conditions and more testing [120]. Overall, while the RANS model did not capture some complex flow structures like vortex shedding, it effectively predicted other important aerodynamic features such as drag, lift, and overturning moments, which supports its use in less computationally demanding scenarios [120]. The research should focus on finding an optimum design for the fixed solar panels or the solar tracking systems to sand against the different weather conditions and wind direction angles while keeping the tilt angle at the optimum value so that the power generation of the panels will not be affected.

Currently, research work is narrowed in the direction of studying these phenomena and trying to provide the appropriate solutions. Based on recent research that was conducted to evaluate the wind loads on the solar arrays, most of the solutions were to provide the optimal tilt angle for the fixed solar panels to minimize the wind load to the minimum or guide the tracking systems for changing the inclination of the panels in severe weather conditions considering the wind direction angle. The investigation for several articles on the wind direction angle to solar trackers and the findings for each paper on the wind influence on trackers for a certain angle range were included in a review paper [121]. Tracking panels have a greater wind load than fixed panels due to their considerable left–right clearance and narrow length-to-height ratio at 45° and 135° wind direction angles [121]. Increasing the wind direction angle will increase the wind pressure going from 0° to 180° [122]. For 0°, 45°, 135°, and 180° wind direction angles, the wind load of a PV support is greatly influenced by the wind direction angle and dip angle [123]. For PV arrays, the second row of the PV panel array showed the smallest size coefficient between 0° and 180° wind angles [124]. At the same time, row number 3 of the solar array showed the smallest wind load [120]. For the system structure, the wind load of the structure reached its greatest value at wind direction angles of 0° and 180° [125]. Table 6 shows a summary of two papers discussing almost all cases of the tilt and wind direction impact on the wind loads.

Table 6. Summary of the tilt and wind direct angles impact on the wind loads.

Tilt Angle β	Wind Direction Angle α	Impact on Wind Loads	Reference
25°, 45°	0°, 180°	The maximum positive pressure at 0° while maximum negative pressure at 180°	[90]
45°	0	Maximum drag coefficient.	[90]
25°	120°	Minimum drag coefficient	[90]
45°	0°, 180°	Highest positive and negative lift coefficient	[90]
25 °	60°, 120°	Lowest positive and negative lift coefficient	[90]
25°, 45°	30°, 150°	Maximum and minimum x-overturning moments at wind angles, respectively (higher at β = 45°)	[90]
25°, 45°	0°, 180°	Highest positive and negative values y-overturning moments	[90]
25°	30°, 150°	BLUE-peak values 29.4% and 25.7%, respectively	[90]
45°	30°, 150°	BLUE-peak values 24.1% and 23.5%, respectively	[90]
30 °	0°	Maximum negative pressure coefficient	[102]
10°–40°	30°, 45°, 135°	Maximum negative and positive pressure coefficient	[102]
≥50°	30°, 45°, 135°	Pressure coefficient is almost constant, and higher tilt angle cause higher values	[102]

The angle of solar panel installation influences the wind load on the solar panel structure. Future research should focus on finding an optimum design for the fixed solar panels or the solar tracking systems to stand against the different weather conditions and wind direction angles while keeping the tilt angle at the optimum value so that the power generation of the panels will not be affected.

7.3. Aerodynamic Edge Modification

A way of mitigating the wind load on the surfaces is aerodynamic edge modification. Aerodynamic edge modification could be performed by adding a new part to the design or modifying the edge to reduce the structural risk. A wind tunnel study investigated the aerodynamic effects on solar arrays with different tilt angles mounted on both a roof and the ground. The study identified two primary sources of aerodynamic loads: turbulence caused by the panels and pressure equalization [126]. The results indicated that higher tilt angles lead to increased turbulence and consequently greater wind loads, whereas at lower tilt angles, pressure equalization is more predominant [126]. Additionally, the study found that buildings significantly alter the aerodynamic loads on roof-mounted solar arrays compared to those on the ground [126]. The interaction between the building-induced vortices and the airflow around the solar array is complex and varies with the building's height, the distance of the solar array from the roof edge, and other architectural features [126]. A provisional study is being tested for modifying the aerodynamic edge of an array of solar panels [127]. By creating turbulence from the incoming flow and enhancing local convective heat transfer, a panel-edge-mounted module attaches an array of winglet-shaped devices along the panel's upstream edge, therefore changing airflow at the panel surface locally [127]. Added flow deflection devices allow for even more adjustments, capturing and redirecting high-velocity flow to previously blocked areas that are known to recirculate warm air. When compared to solar panels that do not modify flow, these devices can increase surface cooling by over 50% [127].

This method is limited to the solar panels field, and much testing is needed for more accurate results. Methods can be used for modifying the building edges to mitigate aerodynamic instability, and these could be used in solar panels by adjusting the edge of the panel that is vulnerable to wind. More research is needed in that area to include the results of that implementation.

8. Case Study: West Baton Rouge—Port Allen Solar Farm Visit

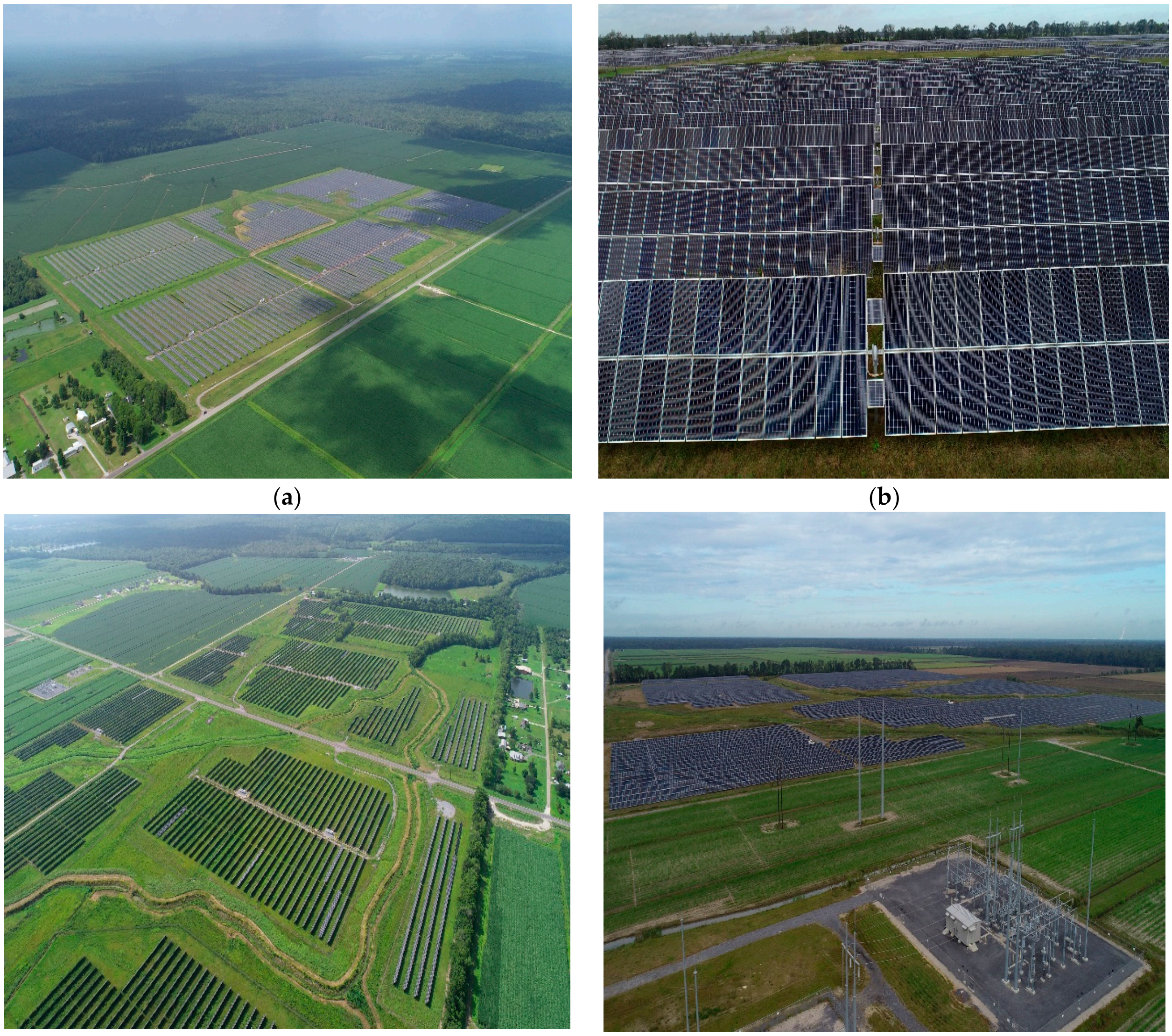
A site visit was conducted by the authors to a grid-tied solar farm located in Baton Rouge, Louisiana, to investigate a realistic example of the solar farm, and the specifications of the farm are mentioned in Table 7. Another intention of this visit was to obtain a clear image of current practices that are used in solar farms to endure windy weather, energy generation maximization, the usual operation and maintenance of inverters, and real numbers in terms of the costs in USD.

Table 7. Louisiana solar farm specifications—Port Allen (Entergy project 2016).

Location	West Parish Baton Rouge—Port Allen (Former Sugar Cane Land)
Area Covered	600 acres
#Number of Panels	197,000
Target Region	Southwest of Louisiana
Anticipated Finish Date	September (Fall 2024)
Power Generation	50 MW
#Number of Homes Powered	9600 daily consumption basis
Director of Resource Planning	Jonathan Bourg
Solar Panels Type	Tracking–axis 30% light captured more than the fixed.
Capital Cost	USD 240 million
Tilt angle of the panels	Changing over the day to track the sun
Land cost	Lease (113 USD/Acre) [128]
Height of solar panels from the ground	2.1 m (7ft)

The farm's top view is shown in Figure 11a, and the solar panels are double-sided, as shown in Figure 11b, and keep tilting to reach a level position at sunset and remain motionless through the night until the next sunrise. Figure 11c shows a top view of the solar farm, and it is declared that some of the solar panels were tilted to track the sun.

The panels go into flat mode (0-degree inclination angle) to decrease the impact of the wind on them and the structure when it is a stormy day. However, it shows a good result for the panels and not for the trackers because, according to the literature, at a 0-degree tilt angle, the failure happened to the tracker at a wind speed of 40 m/s, and the dynamic mechanism was the cause of damage such as torsional galloping [102]. The solar panels have an automated tracking system that uses a single-axis tracker and has a support of two sides for the outer row of panels due to the wind effect, as shown in Figure 12a. There are small solar panels to feed the motors for the tracking systems, and they are shown in Figure 12b.

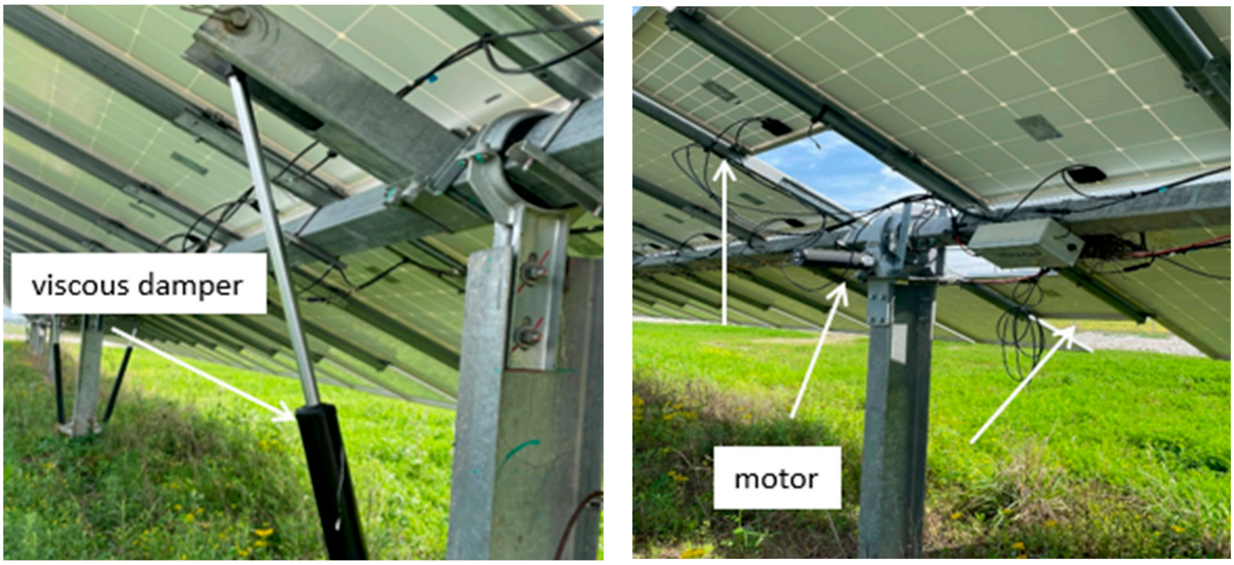


(**a**) (**b**)

(**c**) (**d**)

Figure 11. Drone-taken pictures showing top view of the Port Allen solar farm: (**a**) picture is taken from the southwest side. (**b**) Closer view of the double-sided panels. (**c**) Picture showing the tilted solar panels. (**d**) Solar farm site view with a large coverage area.

As a general note about the visit, the project's capital cost was lowered since the land where the panels were placed was leased for 35 years from the landowner. Since the system is connected to the grid, no extra costs are associated with energy storage. Solar panels provide direct current (DC), converted by inverters into alternate current (AC) that the grid uses. However, this creates a problem because inverters require regular maintenance, and the manufacturer sometimes fails to provide the parts needed to replace them, leaving clients waiting up to a month for a part. A study investigated different inverter topologies to the three-phase or single-phase grid [129]. The results of the study showed the limitations of using the centralized inverter for connecting a large number of PV modules to the grid [129]. The new microinverter topology showed a better result in harvesting more energy, shading effect reduction, mismatch losses reduction between the PV panels, low maintenance, and long lifespan [129]. An investigation was conducted on 45 different inverter topologies for the grid-tied and stand-alone systems [130]. Results showed that firstly, the central inverter should be used in the large-scale PV system due to its low cost [130]. Secondly, multi-stage inverters are preferred in ac cells and modules due to their high voltage amplification [130]. An investigation of the effectiveness of inverters in managing power methods during extreme events that result in high currents damaging the inverters was conducted [131]. The study shows how often these high currents happen by using 1 min data for 10 years from 7 different stations in the US [131]. The method was to divide the data into three configurations: minute to hourly resolution, single and bifacial panels, and three fixed-tilt angles and a tracking system [131]. Peak currents from brief over-irradiance occurrences cannot be effectively managed by the existing industry guidelines for choosing inverters, which are based on the 12–5% rule or three-hour averages, particularly for bifacial modules [131]. More precise inverter selection and system design are advised using a stronger 200% rule or high-resolution one-minute data simulations [131]. However, the study failed to include the fuse situation analysis and their failure, as well as a model for simulating inverter current input.



(**a**) (**b**)

Figure 12. (**a**) Extra cylinders are installed in sides to give system stability when tracking the sun. (**b**) The motor and the automated system for tracking with the two small panels for feeding tracking system with power.

The cost of leasing land in Louisiana will be based on the parish in which the land is located. For example, land in the center of Louisiana has a rental cost of (USD 150/Acre) while the southwest has a cost of (USD 113/Acre) [99]. This land (600 acres) is being leased for approximately USD 850,000 a year, which is a small amount considering the outcome of the electricity generated by the solar panels. In terms of the wind perspective, aerodynamic instabilities and wind-induced phenomena such as torsional galloping, vortex shedding, and flutter formed most of the issues for the solar panel support systems. However, the solar farm is in good shape since the panels go to the flat position by sunset as the galloping rarely happens at that position. High wind speeds with a specific wind direction angle might cause galloping or flutter. Recommendations could be given for dual use of the land by planting special types of crops as the farm covers a large area.

9. Conclusions

Agrivoltaic systems are widely known as promising solutions for renewable energy in exploiting agricultural lands. This paper reviews the impact of agrivoltaics on different types of lands, the economic analysis of the agrivoltaic systems, and the wind impact on the agrivoltaic systems. This paper provides a foundation for future research on the issues investigated based on recent studies.

The review starts with analyzing the impact of agrivoltaic systems on the lands and how it affects the crops through water and soil management, as well as the shading effect on crops. Many studies indicate that agrivoltaic systems can improve water management on agricultural land in various ways. For instance, they create cooler environments by reducing direct sunlight to the ground, which can decrease water consumption by up to 20% for lettuce crops. Additionally, PV systems help maintain soil moisture levels. However, some studies stated that soil erosion and heterogeneity might happen by affecting the water distribution. The investigations established that the type of tolerant crops to be selected to grow in the agrivoltaics will maintain the crop productivity, and some plants will benefit from the shading in greener color. The existing research should focus more on benefiting from the microclimate that the panels create.

The literature studies investigated the agrivoltaic systems with animals like lambs and rabbits. They showed that the agrivoltaic systems enhanced lambs' comfort without negatively affecting their productivity, while the rabbits increased the site revenue by around 3% to 20%. The review showed that PV in greenhouses reduces energy consumption and raises the water levels inside the houses. However, flexible thin-film PV panels show a better result for the plants by allowing more sunlight to pass. For specific types of species, OPVs increased the profitability by about 35% for spinach and 2.5% for basil because of their different market prices. The existing investigations focus only on the crops and sunlight inside the greenhouses. More work should be performed on the temperature and ventilation inside the greenhouses.

The literature established that the main factors that form the total cost of agrivoltaic systems are storage for off-grid systems, the payback period for the grid-tied systems, the labor cost of installing the PV system, the PV panel cost, and land cost. The literature showed that 10% usage of renewable energy will increase the cost of energy by 2% while utilizing 68% will reach the lowest cost, resulting in a 12% reduction. Future work should consider running a comprehensive analysis of agrivoltaic systems while considering crop productivity revenues.

The paper discusses the wind impact on agrivoltaic systems as it is crucial for increasing their reliability and feasibility. The wind load on the solar panels is analyzed and a comparative study is performed between the ASCE standards and wind tunnel tests. The newer versions of ASCE standards are improving for estimating the design wind loads and achieving 90% agreement with wind tunnel tests for small stow angles. However, discrepancies still exist for larger tilt angles as no specific section in the standards for ground-mounted solar panels designs wind loads for a single panel. In ASCE 7-22, they specify a section for ground-mounted solar arrays, not for a single panel. More tests are still needed to confirm the agreement between the wind loads found by the standards and the wind tunnel tests.

The dynamic response of the PV supports was analyzed, and the existing research focused on torsional galloping, flutter, and vortex shedding. The solutions only include the adjustments of the PV angles, studying the wind direction angle, and specifying the pressure coefficients on the panels. However, the research should focus on producing a new resilient design that stands against the strong winds without adjusting the angles beyond their limits of generating the maximum power.

10. Future Directions

Within the field of agrivoltaics, which focuses on integrating solar panels with agricultural lands, there are several recommendations and future research opportunities that might enhance the quality of agrivoltaic systems, as shown in Figure 13. This can be categorized into bullet points:

- Wind load mitigation methods need to be improved, and more advanced testing must be performed to obtain accurate results regarding the panels in the agrivoltaic systems at larger scales.
- Integrate the wind tunnel test results in the upcoming ASCE versions by specifying a chapter for solar panels in different mounting designs.

- Advanced wind tunnel (WT) testing and CFD simulations are needed on the solar trackers for different phenomena, such as vortex shedding, torsional galloping, and flutter.
- Work and research are required to find the exact cost of energy (COE) in the agrivoltaics lands, considering the amount of electricity provided, energy storage systems (off-grid systems), water consumption, operating and maintenance costs, crop productivity, and land cost. This will help in creating an image of the feasibility of agrivoltaic systems for stakeholders.
- Research might be performed on water consumption and use efficiency to find ways to employ solar panels to create microclimates, such as those found in greenhouses, or to improve irrigation water quality by enhancing runoff from the panels.
- Directing the research for more innovation in transparent or semi-transparent solar panels which could help in shading issues and benefit more in agrivoltaics as they are only used in greenhouses.
- The study of the solar panels on the greenhouse roof contributes to the regulated space inside. The research work should consider the ventilation and thermal management of the solar greenhouse.
- Wind testing is required for the flexible solar panels and OPVs on roofs as they have higher cost and losing them would be costly to replace.
- More work should be performed on the aerodynamic edge modification of the solar panels. New structures would help in safer designs against wind. The modification methods that are performed on the buildings and signboards could inspire solar panel designs.
- Testing the damping and mass for controlling the solar panels and trackers and preventing wind-induced failures.
- Large-scale data collection needs to be performed for solar panels to impact water management, soil, greenhouses, and croplands.
- Perform a cost analysis study on any new materials that would be used in solar panel designs to ensure their viability and reliability.

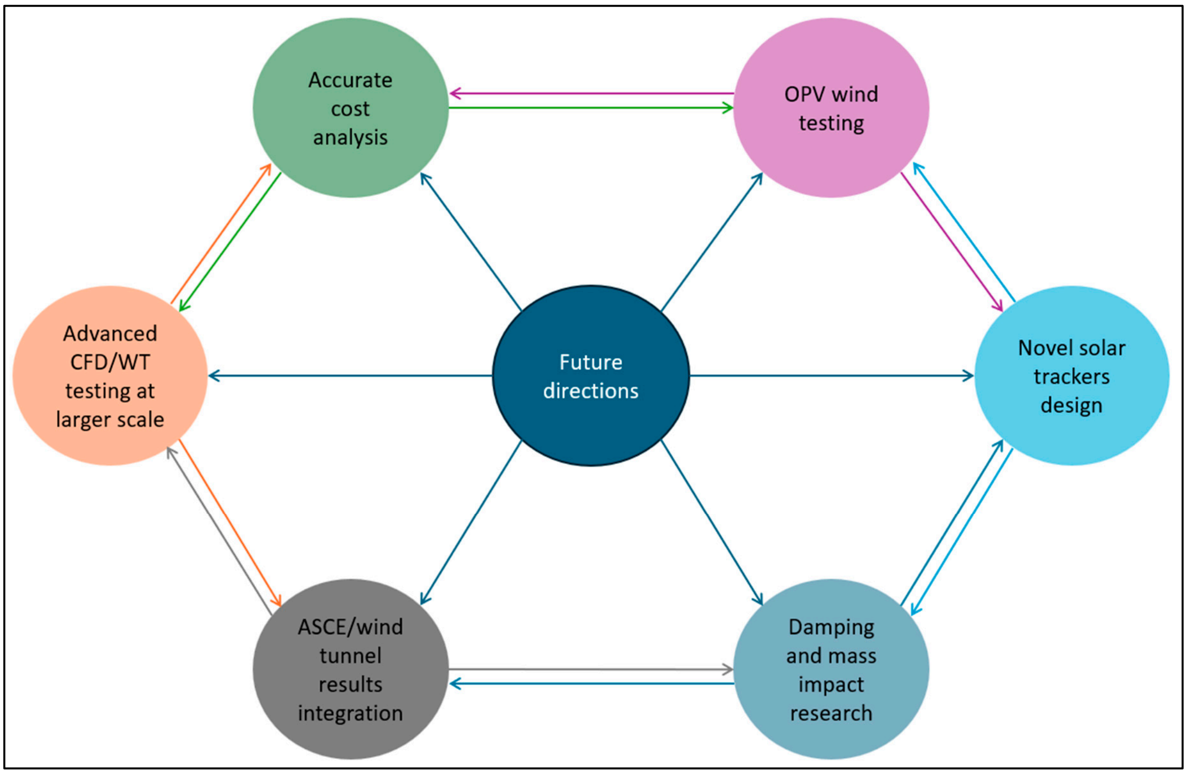


Figure 13. Recommendations and future research for agrivoltaic systems.

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